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Tsunami

A Growing Disaster

Edited by Mohammad Mokhtari

TSUNAMI
– A GROWING DISASTER

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Meet the editor

Mohammad Mokhtari was born in Nosara, Neyshabur and has obtained his BSc from Azarabadegan, MSc from Southampton and PhD from Bergen Universities. He has worked as a scientific assistant at the University of Utrecht, principal geophysicist at Norsk Hydro and NIOC. As Director of Seismology Research Center and member of Board of Directors he has established the Iranian National Broad Band Seismic Network. He was the co-founder and Director of National Center for Earthquake Prediction and founding member of Risk Management Excellence Center, IIEES; coordinator of two International Conferences in Tehran; member of Passive Seismic Equipment Expert Panel, CTBTO; Visiting researcher, Geoscience of Australia, Indian Ocean Tsunami Hazard Assessment. He was a member of ICG/IOTWS Working Group 1 and 3; member of Editorial Board, WDR2009, report. Dr. Mokhtari supervised 18 MSc and 7 PhD students mainly in Exploration Seismology, Seismology and Tsunami. His publications consist of over 35 papers in international journals, over 85 conference presentations and four books in different earth science subjects.

Contents

Preface

The term tsunami comes from a Japanese word that means "harbor" (tsu) and "wave" (nami). In the past, the phenomenon was referred to as a tidal wave. However, in the international scientific community this word describes waves generated by sudden vertical movements of the ocean floor, triggered by large earthquakes, volcanic eruptions, or underwater explosions.

Tsunamis can be considered transition phenomena because of their impulsive origin. They are characterized by a long wave length and period. Tsunamis can travel for thousands of kilometers across the open ocean at speeds of 600–800 km per hour, and their effects can be seen hours later on shores. As a tsunami approaches the coast, it reduces the wave celerity and increases the wave height, reaching up to 20 meters with a very high destructive power.

In the recent years the world has experienced a few mega-tsunamis which have caused extensive material damage and death tolls. The most destructive ones were in December 2004 in Sumatra, causing more than 200,000 deaths, and in March 2011 in Japan, causing a nuclear accident. The 2004 catastrophe has triggered many global initiatives such as a new tsunami detection system, more detailed coastal modeling, tsunami compatible coastal developments, integrated approach for regional early warning system, an effort of educating the public, raising awareness and preparedness.

Bearing that in mind, this multi-disciplinary book intends to cover different practical aspects of pre- and post-tsunami management including: advance measurement technology as an early warning system, some important case studies and hazard assessments; lifeline, medical and psychological aspects.

For some practical reasons and to increase its accessiblity, the book is divided into four sections. Section 1 provides advanced methods for tsunami measurement and modeling such as: ocean-bottom pressure sensor, kinematic GPS buoy, satellite altimetry, Paleo tsunami and Ionospheric sounding, early warning system, and scenario based numerical modeling. Section 2 presents case studies in different tsunamigeneic zones around the world such as the Northern Caribbean, Makran region and Tamil Nadu coast in India. Furthermore, classifying tsunamis into local, regional and global, their possible impact on the region and its immediate vicinity is highlighted. Effects of tsunami hazard on the coastal environment and infrastructure (structures, lifelines, water resources, bridges, dykes, etc.) have been presented in section 3. Finally, in section 4, which deals with post-tsunami management, the need for preparedness of emergency medicine staff and the prevention of psychological consequences of the affected survivors has been discussed.

The objective of this book is to provide a collection of expert writing on different aspects of pre- and post-tsunami developments and management techniques. It is intended to be distributed within the scientific community and among the decision makers for tsunami risk reduction. The presented chapters have been thoroughly reviewed and accepted for publication.

We would like to express our gratitude to the contributing authors who are the key factor in this achievement. The Editor expresses his deep appreciation to Prof. M. G. Ashtiany for his support and encouragement. Finally, special thanks to InTech, the publisher that initiated this book and guided and helped the Editor in its completion.

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Part 1

Advanced Measurement Methodologies

1

Advances for Tsunami Measurement Technologies and Its Applications

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1. Introduction

After the Indian Ocean tsunami from the Sumatra earthquake on 26 December 2004 (Mw > 9.0), we have realized the importance of the early tsunami warning system and its necessity for mitigating the tsunami disaster. This catastrophic event was a cue for construction of the Indian Ocean early tsunami warning system, and first of all, a global tsunami forecast system was established together with the Pacific Ocean tsunami warning system operated by U.S. and Japan. The Indian Ocean tsunami motivated the international scieity to construct global tsunami warning systems, which include seismic and sea level monitoring measurements. National Centre of Geosciences in Germany, for example, would challenge to detect relative initial tsunami height distribution by GPS arrays and the seismic stations on land, and deploy GPS buoys along the Sumatra trench for establishment of an early tsunami warning system in Indonesia. And finally the German-Indonesian Tsunami Early Warning System (GITEWS) become into operation in 2010 (e.g., Rudloff et al., 2009; Münch et al., 2011).

Before the Indian Ocean tsunami in 2004, only tide gauge records are available data in the most countries surrounding the Indian Ocean (e.g., Merrifield et al., 2005; Matsumoto et al., 2009). Moreover, some of them were not transfered in real-time but were recorded and avaliable only inside the tide gauge stations. Instrumentally observed tsunami data acquired in real-time is qualitatively used for tsunami warning issue followed by its modification and cancellation. If characteristics of forthcoming tsunami would be understood in advance, it must be helpful and useful for tsunami related disaster mitigation. Tsunami height and arrival time are the most important information after the tsunamigenic earthquake occurrence, and they are often used as tsunami observation information. Tsunami observation is traditionally carried out by tide gauges at the coast. Recently, technological development has been promoted to estimate tsunami features as early as possible.

This chapter reviews tsunami measurement technologies and instruments, in particularly developed in Japan and introduces an actual tsunami observation in the source area, which became possible after the offshore tsunami observation in the last decade. In the end, potential use for early tsunami detection is discussed by applying to the presumed megathrust earthquake in the Nankai trough, SW Japan.

2. Tsunami measurement instruments

Tsunami measurements are usually carried out by tide gauge or bottom pressure sensor, or kinematic GPS buoy in Japan. The most traditional procedure is to measure by tide gauge, whereas the most modern is by kinematic GPS buoy actually being in operation. Distribution of tsunami measurement instruments in Japan is shown in Fig. 1. This section describes details of tide gauge, bottom pressure sensor, and kinematic GPS buoy in their basic mechanism, outstanding problems, and applications of actual tsunami observation.

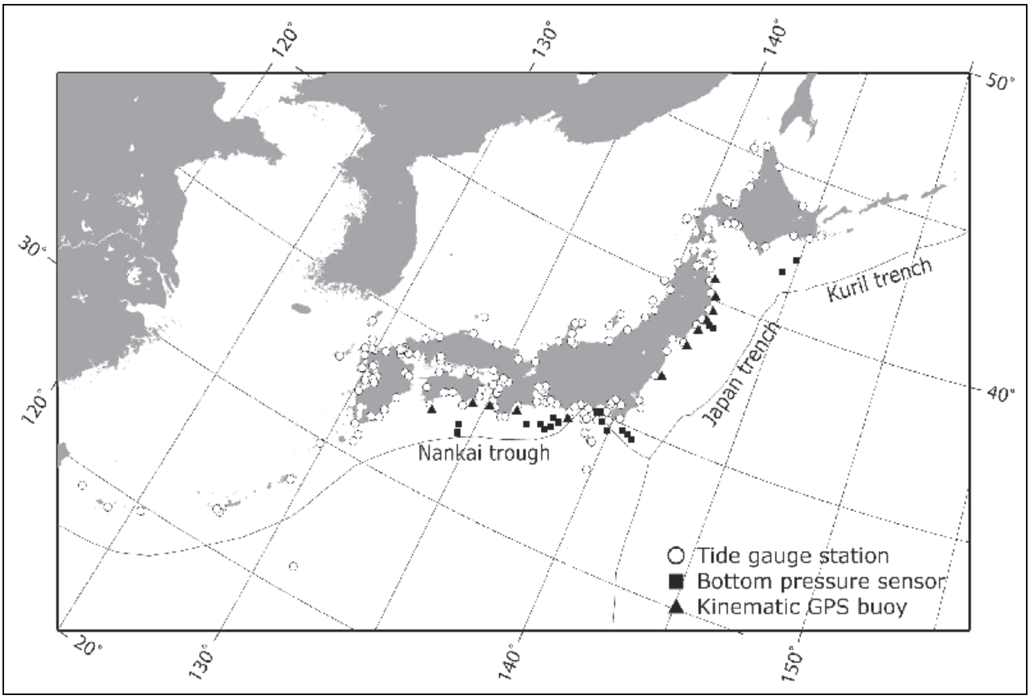


Fig. 1. Locations of tide gauge stations (open circles) and offshore tsunami observatories (kinematic GPS buoys: triangles; bottom pressure sensors: squares) in Japan.

2.1 Tide gauge

Tide gauges are deployed in order for measurement of usual sea level, i.e., astronomical tide level not only in Japan but also all over the world. Several types of tide gauges are being operated in Japan. The most typical tide gauge is to use a tide well which records vertical motion of a float buoy in a well connecting by an intake pipe to the open sea (Fig. 2). The first tide gauge was established in Japan is the in the early 1890s, for which Kelvin type tide gauge produced in England was employed (GSI, available at online). This type of tide gauge had used the analogue paper chart until the 1990s, and more recently digital decoding instrument is equipped on the tide gauge. The tide gauge using a paper chart requires replacement of recording paper at some intervals. Other types of tide gauges are as follows, e.g., a pressure type which measure hydrostatic pressure equivalent to the sea level at the station, and an acoustic type which measure distance between the sea surface and the acoustic receiver at the bottom. Generally, tide gauge stations are located inside the port or the harbour. This is why tsunami height based on tide gauge means tendency value where the tide gauge station is located. In fact, tsunami heights vary depending on both the local land and subsea topographies.

Another concern to make use of tide gauge is its response. Differences on tsunami heights between tide gauges and eyewitnesses have been pointed out in the past. Tide gauge generally uses a narrow intake pipe between the tide well and the sea as shown in Fig. 2. This is because the main purpose of tide gauge is to observe astronomical tide with its period of a few hours or much longer of a few years' sea level change caused by global climate change. Hence short period sea level changes such as surge wave or swell are structurally cut off. Tsunamis of their period less than a few ten of minutes can be recorded by tide gauges indeed, but some considerable responses were pointed out in the past. For example Okada (1985) examined the tide gauge response after the Japan Sea earthquake (Mw7.9) in 1983, and corrected tsunami waveform in terms of nonlinear response. Namegaya et al. (2009) carried out in-situ measurement of tide gauge stations and estimated liniear and nonlinear response and corrected the tsunami waveforms from the Niigataken Chuetsu-oki, Japan eartqhauke (Mw6.6) in 2007.

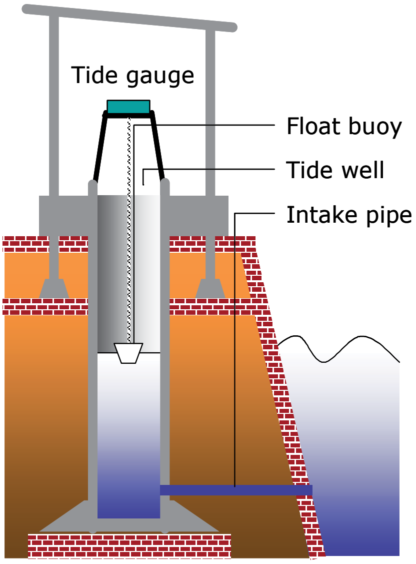


Fig. 2. Schematic drawing of typical float type tide gauge station in Japan.

2.2 Bottom pressure sensor

Offshore tsunami measurement makes us possible to predict tsunami arrival and provide time to evacuate from tsunami. Recent deep-sea technologies enable to observe tsunamis not only offshore but also in real-time. One of the facilities composing the early tsunami warning system is the offshore observatory. National Oceanic and Atmospheric Administration (NOAA) developed Deep-ocean Assessment and Reporting of Tsunamis (DART) system that receives water pressure from the ocean bottom firstly deployed in the Pacific and Atlantic Oceans (Gonzalez et al., 2005). Now the DART system has been extended to the Indian Ocean and each observatory is owned by not only U.S. but also Australia, Chile, Indonesia Thailand, and Russia. On the other hand, other sensors such as in-lined cabled bottom pressure sensors are developed and deployed in the seismogenic zone in Japan. Figure 1 represents the current bottom pressure sensors locations being operated in Japan either. The first offshore observatory in Japan has been deployed in 1978 off Omaezaki, central Japan, where the probability of the presumed Tokai earthquake is expected to be 87 % by the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion, i.e., the Japanese Government. Then this types of tsunami measurement have followed until now, and eight observatories in total have been deployed in Japan.

Fig. 3. In-lined cabled bottom pressure sensor deployed in the ocean.

Offshore tsunami detected by bottom pressure sensor is given by Filloux (1982) for the first time. Eble and Gonzalez (1986) performed the long-term observation on bottom pressure sensors and reported detection of offshore tsunami signals from three different earthquakes during their observational period. Hino et al. (2001) and Hirata et al. (2003), for example, used less than a few centimetres tsunamis from the moderate-to-large earthquakes occurred in the Japan trench and the Kuril trench, respectively, that could be detected by Japanese cabled bottom tsunami sensors. Matsumoto and Mikada (2005) and Satake et al. (2005) used offshore tsunami recorded by bottom pressure sensors in order to constrain fault models of the off Kii peninsula earthquake (Mw 7.4) in Japan, and demonstrated advances offshore observation for tsunami. Tsunami from the off Kii peninsula earthquake was also observed at the tide gauge stations along the coast nearby. Bottom pressure sensors could detect tsunami signals about 20 min before its arrival at the nearest tide gauge stations. Thus it shows that offshore tsunami observation has an advantage of the tsunami detection for far-field tsunamis.

2.3 Kinematic GPS buoy

Kinematic GPS buoy is a new technological system developed in the late 1990s to observe tsunami at the offshore sea surface (Kato et al., 2000). GPS, i.e. Global Positioning System technology widely used on land is to be applied to the sea surface. The current kinematic GPS buoy monitors a moving platform in real-time with an accuracy of a few centimetres by relative positioning. It requires two GPS receivers to measure the relative position, one is placed on the top of offshore buoy and the other is placed on land-based station. After practical operation period, about 10 kinematic GPS buoys have been deployed 10-20 km offshore from the coast in Japan (Figs. 1 and 4). Although GPS buoy cannot be deployed over several kilometres further offshore because of the limitation of communication distance between the GPS buoy and the base station, it has demonstrated an advantage for early tsunami detection. The tsunami from the off Kii peninsula earthquake was recorded by the GPS buoy for the first time 8 min before its arrival at the nearest tide gauge station (Kato et al., 2005). Tsunami from the off Kii peninsula earthquake was detected by both the offshore pressure sensors and the kinematic GPS buoys in which tsunami heights were recorded to be ca. 10 cm and ca. 20 cm in peak-to-peak amplitude, respectively, whereas the tsunami height recorded by the tide gauge was to be 50 to 100 cm. This is attributed to the shoreing effect.

Fig. 4. Kinematic GPS buoy deployed offshore of NE Japan (photo by Port and Airport Research Institute).

3. Tsunami measurement applications

Offshore tsunami observation has an advantage for far-field tsunami as mentioned above. However, for the near-field tsunamis that are generated near the tsunami measurement sensors it have not been experienced and discussed about usage of acquired data. This section describes an example of actual tsunami observations in particular in the near-source area by the bottom pressure sensors by the cabled observatory system, and discuss their unique phenomena during the tsunami generation process for use of tsunami early detections. Offshore tsunami observations have been done in the past as reviewed in the previous section. At the beginning of the offshore observation of tsunami, pressure fluctuation caused by the seismic wave apparently much intense than that by the tsunami wave (e.g., Filloux, 1982). This is why mathematical low-pass filtering is necessary to detect tsunami signals. In fact, low-pass filtering was applied in most cases of tsunamigenic earthquakes in order to identify tsunami signals afterwards for scientific purpose. In Japan, the Japan Meteorological Agency (JMA) is responsible for tsunami warning issue, and offshore measurement data are processed by using 1-2 min moving averaging technique. If a large earthquake would take place offshore and accompany a tsunami, i.e., a far-field tsunami, it would not be so difficult to notify tsunami signals as done by the present procedure. Most pressure sensors have been deployed in the tsunami source area. For near-field tsunami, however, there has not been established that data processing methods prepared so far. We urgently need data processing procedure for the near-field tsunamis.

3.1 Bottom pressure sensor off Hokkaido, Japan

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is operating four offshore observatories in the seismogenic zone in Japan; off Muroto cape and off Kumano in the Nankai trough, SW Japan, off Hatsushima Island in the Sagami trough, central Japan, and off Hokkaido in the Kuril trench, northern Japan. The present study introduces the offshore observatory off Hokkaido deployed in 1999 (Hirata et al., 2002). Figure 5 shows that the location of bottom pressure sensors connecting by the submarine cable. The cabled observatory has two bottom pressure sensors, and those data is telemetered to JAMSTEC in real-time. Two bottom pressure sensors as referred by PG1 and PG2 hereafter are deployed at the water depths of 2218 m and 2210 m, respectively, and their locations are listed in Table 1.

A megathrust M8.0 earthquake occurred in 2003 in this region (Watanabe et al., 2004), and then the seismic activities including aftershocks have become relatively high. A number of earthquakes over their magnitude 6.0 took place after 2003. In the present study, we focus on the near-field earthquakes in order to understand the observed fluctuation of water pressure during the tsunamigenic earthquake. Referring the earthquake database complied by JMA, earthquakes occurred inside ca. 100 km from the observatories are selected. Because a bottom pressure sensor is very sensitive, we focus on large earthquakes with their

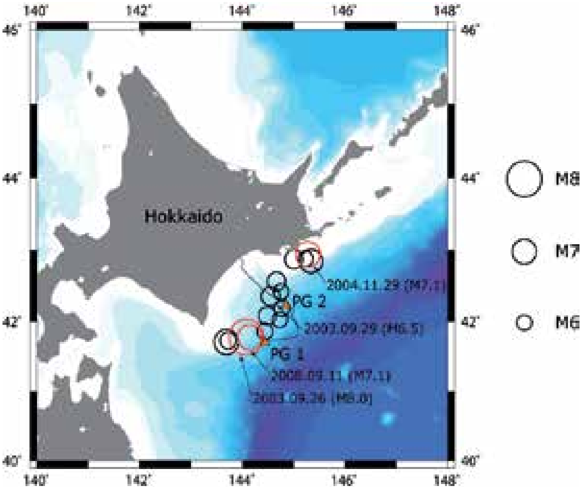


Fig. 5. Offshore observatory off Hokkaido, Japan with locations of significant earthquakes' epicenters. Red indicates a tsunamigenic earthquake.

magnitude over 6.0 by means of signal-to-noise ratio. Conditioning these criteria, 16 earthquakes were selected listed in Table 2. Among those 16 earthquakes, three earthquakes on 26 September 2003, on 29 November 2004, and 11 September 2009 generated the tsunamis which were observed at the tide gauge stations at the coast. Locations of the selected earthquakes and the PGs are compared in Figure 5. Both the 2003 and 2009 tsunamigenic earthquakes' epicenters were located beneath PG1, on the other hand, that of the 2004 earthquake was located out of PGs.

	Latitude (°N)	Longitude (°E)	Water depth (m)
PG1	41.7040	144.4375	2218
PG2	42.2365	144.8454	2210

Table 1. Location of bottom pressure sensors off Hokkaido, Japan.

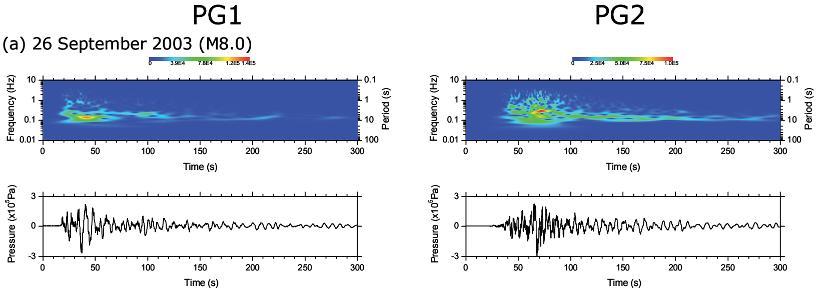
	Date	Time (JST)	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Tsunami
1	2003.09.26	04:05:07.42	41.779	144.079	45.1	8.0	observed
2	2003.09.26	06:08:01.84	41.710	143.692	21.4	7.1	
3	2003.09.26	15:26:58.10	42.189	144.776	27.4	6.1	
4	2003.09.27	05:38:22.31	42.026	144.728	34.4	6.0	
5	2003.09.29	11:36:55.06	42.360	144.553	42.5	6.5	
6	2003.10.08	18:06:56.79	42.565	144.670	51.4	6.4	
7	2003.10.11	09:08:48.15	41.864	144.440	27.8	6.1	
8	2003.12.29	10:30:55.40	42.419	144.756	38.9	6.0	
9	2004.11.11	19:02:46.17	42.083	144.486	38.6	6.3	
10	2004.11.29	03:32:14.53	42.946	145.276	48.2	7.1	observed
11	2004.11.29	03:36:41.19	42.884	145.236	45.6	6.0	
12	2004.12.06	23:15:11.81	42.848	145.343	48.8	6.9	
13	2005.01.18	23:09:06.65	42.876	145.007	49.8	6.4	
14	2007.02.17	09:02:56.63	41.732	143.723	40.1	6.2	
15	2008.09.11	09:20:51.35	41.776	144.151	30.9	7.1	observed
16	2009.06.05	12:30:33.80	41.812	143.620	31.3	6.4	

Table 2. Significant earthquakes occurred near the pressure sensors off Hokkaido, Japan.

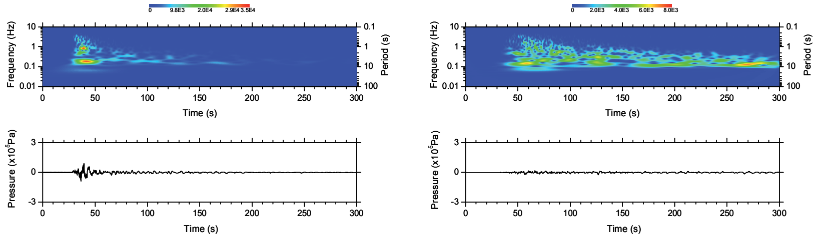
3.2 Data processing procedure

Generally, bottom pressure sensors measure the vibration regarding pressure and temperature, from which physical value is processed compensating the temperature collections. For the principal of the pressure sensors, narrow sample rate gives low resolution response. 10 Hz sampling is the minimum sample rate for the reliable value. We have analyzed the obtained PGs dataset to make spectrograms. Numerical technique to analyze 10 Hz time-series PGs dataset is as follows;

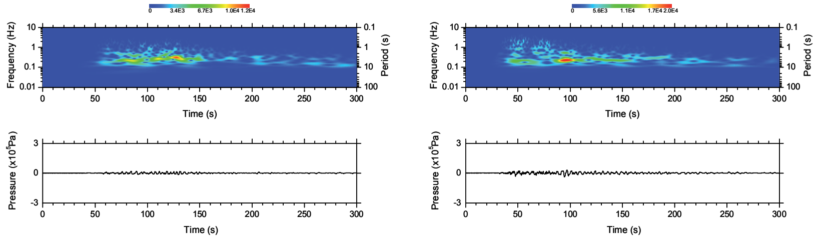
(a) 26 September 2003 (M8.0)



(b) 11 September 2008 (M7.1)



(c) 29 November 2004 (M7.1)



(d) 29 September 2003 (M6.5)

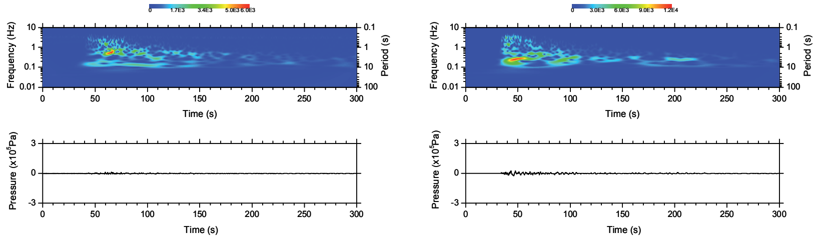


Fig. 6. Pressure waveforms' spectrograms and its original waveforms during the earthquakes.

1. 5min dataset of PG including each earthquake is collected.
2. We divide the frequency from 0.01 Hz to 10 Hz into 40 sections as formed by exponentially (i.e., linearly in logarithmic scale).
3. Band-pass filtering of each section above is applied to the entire 5min dataset.
4. Envelopes of the filtered waveforms for each section are layout to get absolute amplitude, and spectrogram of PGs during the earthquake can be made.

Spectrograms with the original pressure waveforms during the tsunamigenic earthquakes on (a) 26 September 2003 (M8.0), (b) 11 September 2008(M7.1), and (c) 29 November 2004 (M7.1) are plotted in Fig. 6, and the largest non-tsunamigenic earthquake on (d) 29 September 2003

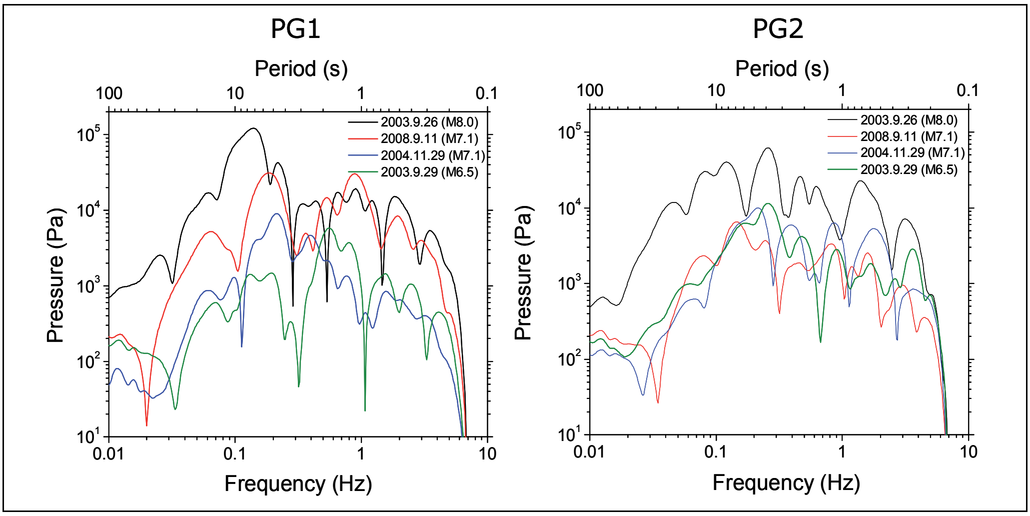


Fig. 7. Cross section profiles of spectrograms during the earthquakes.

(M6.5) is also displayed as an example. According to the spectrograms in the near-field, i.e., event (a) and (b), strong phase having 0.1 to 0.2 Hz is obviously observed during the tsunamigenic earthquake. Tsunamigenic earthquake out of the PGs, i.e., event (c), their characteristic phase appeared after the earthquake rather than during the earthquake. This is because this phase is reproduced in the tsunami source area, and then it propagates.

Cross section profiles of the spectrogram during the earthquakes are plotted in Fig. 7. Tsuamigenic events have peak from 0.1 to 0.2 Hz, which correspond to a natural frequency uniquely depending on the water depth. This is an acoustic resonant wave, i.e., a standing wave forming between the ocean bottom and the sea surface caused by the coseismic deformation (e.g., Nosov & Kolesov (2007)). The larger earthquake magnitude becomes, the larger water pressure amplitude responses in its narrow band.

Thus the tsunamigenic earthquake has a peak of frequency between 0.1 Hz and 0.2 Hz in the case of the water depth about 2000 m. And its peak attenuates in duration of 20 s. The same peak of frequency between 0.1 Hz and 0.2 Hz is involved during the non-tsunamigenic earthquake, but its peak is lower than the high frequency peaks associated with seismic waves.

3.3 Implication of water pressure

Maximum water pressure Pmax in the case of abrupt bottom deformation resulting in tsunami generation process is expressed as multiplication of density of water ρ, sound velocity in water v, and the bottom deformation velocity v,

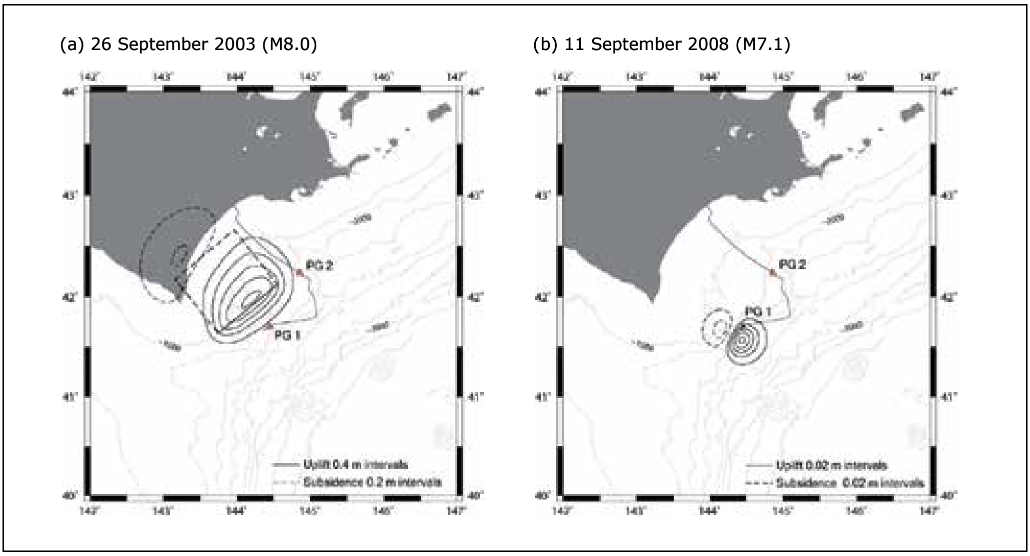
$$P_{max} = \rho\, c\, v \tag{1}$$

Because density and sound velocity are constant, i.e., 1.03 kg/m^3 and 1500 m/s, resptctively, Eq. (1) provide the bottom velocity. For example, (a) the 2003 and (b) the 2008 earthquake cases, the bottom deformation velocity are given to be 0.13 m/s and 0.03 m/s, respectively.

On the other hand, the empirical relation between earthquake magnitude M and rise-time of the seismic faulting τ is proposed by Sato (1979),

$$\tau = 10^{1.5M-1.4}/80 \tag{2}$$

Eq. (2) provides that the rise-times for (a) the 2003 and (b) the 2008 are 5.0 s and 1.7 s, respectively. Assuming the duration time of bottom deformation coincides with the rise-time of the seismic faulting, deformation is given by its velocity integrated by the rise-time. Thus derived deformations at the location of PG1 are estimated to be (a) 0.65 m and (b) 0.06 m, respectively. These values almost coincide with (a) the static deformation from the fault plate model by Geospatial Information Authority of Japan (GSI) (2003) and (b) the point source equivalent to the seismic moment (Fig. 8). This means that the displacement of the location of the pressure sensor deployment can be roughly estimated in terms of the water pressure amplitude.


(a) 26 September 2003 (M8.0)

(b) 11 September 2008 (M7.1)

Fig. 8. Deformation patterns from the seismic faults' dislocation

An early tsunami detection approach based on a physical phenomenon uniquely observed in the source during the tsunamigenic earthquake was presented in this section. Tsunami initial waveform is mostly depended on the static deformation of the ocean bottom. Hence the amplitude of the water pressure associated with the acoustic resonant wave may be a potential indicator of the tsunami generation.

4. Tsunami prediction along the Nankai trough

The first offshore observatory in Japan has been deployed in the Suruga trough targetting the presumed Tokai earthquake, central Japan, and followed by seven cabled observatories. The newest system is being operated in the presumed Tonankai earthquake sourece area by JMA and JAMSTEC off Kii peninsula (Fig. 9).

4.1 Tsunami monitoring system in the Nankai trough

The Nankai trough is one of the palte subduction zones in Japan, where the last megathrust earthquakes took place in 1944 and 1946, namely the Tonankai eartqhauke and the Nankai

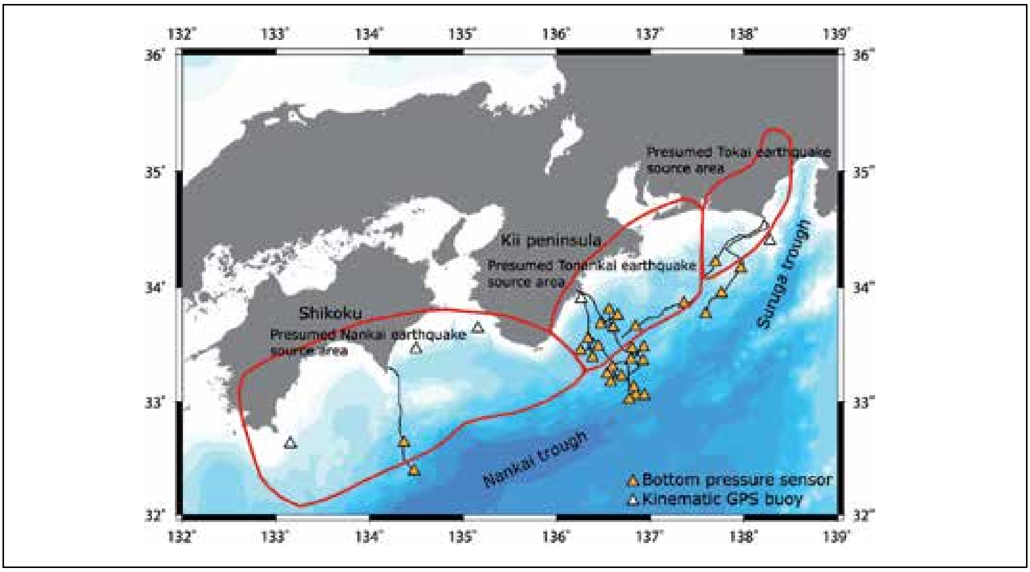


Fig. 9. Deformation patterns from the seismic faults' dislocation

earthquake, respectively. Because more than 60 years have past since the last earthquake, Japanese government evaluates that the probability of the next presumed megathrust earthquake along the Nankai trough is estimated to be 60-70 % within the next 30 years. Japanese government has constructed an offshore observatory network, which consists of dense 20 bottom seismic sensors and bottom pressure sensors in total in order for monitoring seismic activity and its consequence, megathrust earthquake, and followed by tsunami. JAMSTEC is operating the offshore observatory network. The observatory layout is shown in Fig. 10. As of May 2011, 17 observatories have been deployed, and it started to acquire their data in real-time. If megathrust earthquake and accompanied giant tsunami would be predicted before their arrival nearby the coast and effective warning would be issued, it must contribute to mitigate earthquake and tsunami related disasters. We should establish measurement technology including data processing and accumulate technical know-how for future meagathrust earthquake and tsunami in advance; hence we carry out tsunami computation of the last 1944 Tonankai earthquake.

Parameters	Value
Location	33.277 °N, 136.394 °E
Depth	10 km
Strike	226 °
Dip	10 °
Rake	90 °
Length	130 km
Width	60 km
Dislocation	2 m
Rise time	5 s
Rupture velocity	3 km/s

Table 3. Fault parameters used in the tsunami computation from the Tonankai earthquake.

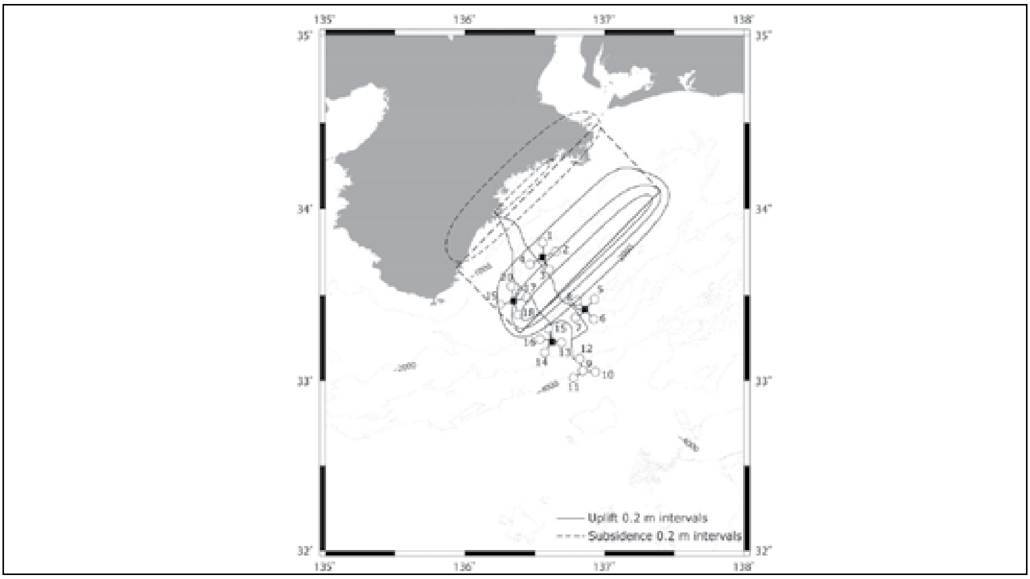


Fig. 10. Observaroty layout (open circles) and coseismic deformation caused by the seismic fault.

4.2 Tsunami computation from the presumed Tonankai earthquake

The latest study implies that the splay fault might contribute to the tsunami generataion process in addition to the main fault during the 1944 Tonankai earthquake (Park et al., 2002), however a simplified fault model is assumed and the pressure waveform is computed at the 20 observatories in the present study. Fault parameters are based on what has been estimated by Kanamori (1972) and they are listed in Table 3. Geometric relation between the fault plane and the observatories is shown in Fig. 10. It is assumed that the fault rupture starts from the bottom at the fault plane and propagate toward the top along the width direction, meaning uni-lateral faulting. Dynamic tsunami computation developed by Ohmachi et al. (2001) is applied to the present scenario. Dynamic tsunami computation can demonstrate fluid dynamic response due to the seismic fault rupture considering both the static deformation and the seismic wave in the tsunami computation. Dynamic tsunami computation can reproduce the bottom pressure because realistic 3D fluid domain is modeled.

Two different tsunami generation models are computed in the present study. One model is that the static deformation is given as a ramp-time function into the bottom of the fluid domain. The duration time, i.e., elapsed time to generate tsunami initial shape is assumed to be equal to the source time of the seismic faulting. Because the fault width and rupture velocity are assumed to be 60 km and 3 km/s, respectively, the time duration is solved to be 20 s divided by two parameters. In this model, the dynamic contribution of the ocean bottom is considered, but the seismic wave associated with the fault rupturing is not considered. Another model is that the seismic wave due to the fault rupturing is also considered, in which the ocean bottom is not displaced simultaneously in the tsunami source area. This model can demonstrate more realistic tsunami generation process than the former one.

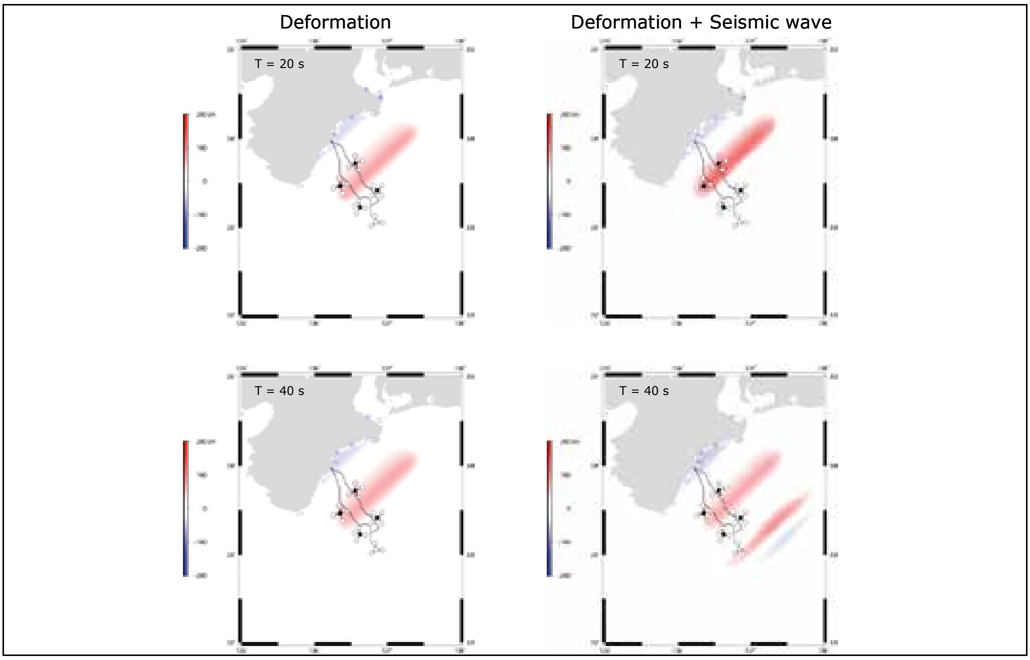


Fig. 11. Snapshots of wave height during the tsunami generation.

Snapshots of the tsunami generation are compared in Fig. 11. Although tsunami is generated after the fault rupture halt at 20 s in the both models, tsunami height in the source area is different. In the source area, dynamic effect is significantly appeared. This is because the acoustic wave by the seismic wave is superposed. At 40 s, the water wave propagating to SE direction is computed, which is Rayleigh wave. As for amplitude and source area of the tsunami are not so different each other.

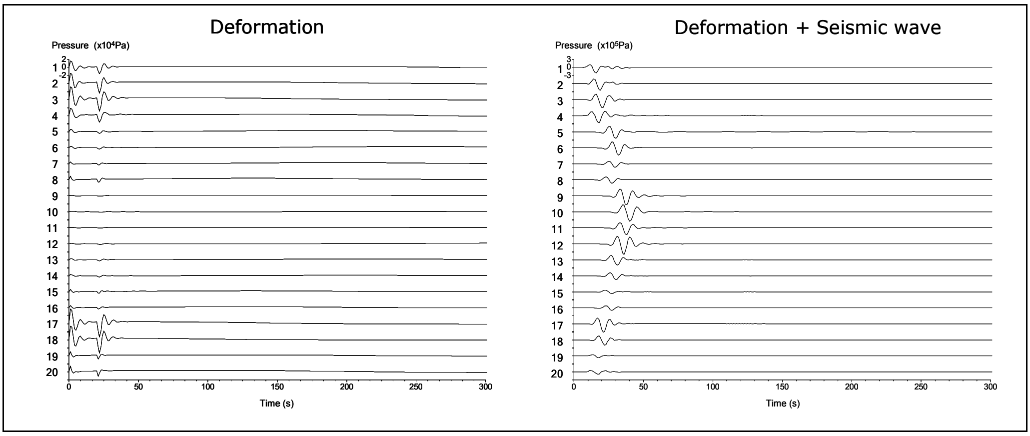


Fig. 12. Computed pressure waveforms during the tsunami generation at each observatory. Numberings represent that of the observatories in Fig. 10.

Time histories of water pressure at the observatories are shown in Fig. 12. In the case that only the bottom deformation is input, acoustic resonant wave is reproduced during the tsunami generation. The amplitude corresponds to the distribution of the static deformation due to the seismic faulting. On the other hand, in the case that seismic wave is input to the fluid domain either, water pressure fluctuation associated with the Rayleigh wave is reproduced in addition to the water resonant wave. It should be noted that the maximum amplitude (~ a few of 10^5 Pa) is fairly equal to that of the experienced in the 2003 earthquake discussed in the previous section. The amplitude is obviously large at the offshore observatories such as 9, 10, 11, and 12 sites in the Nankai trough. These observatories are located in deeper area than others, hence the water pressures tend to be amplified by the long period Rayleigh wave. The acoustic resonant wave is an unique phenomenon during the tsunami generation process. Precise measurement of the acoustic resonant would provide tsunami generation prediction in advance.

5. Conclusion

This chapter reviews some tsunami measurements being in operation. Traditional tide gauge deployed at the coast is unable to perform early tsunami detection because of its deployed location. Recent offshore tsunami measurement technologies such as bottom pressure sensor and kinematic GPS buoy enabled to detect far-field tsunamis before its arrival at the coast. As an on-going study, HF radar to detect tsunami current approaching coast at long ranges is being developed and theoretically examined in the Atlantic Ocean (Dzvonkovskaya and Gurgel, 2009). More recently, electromagnetic (EM) sensors eventually could detect tsunami signals associated with its water mass passage from the 2006 and 2007 Kuil Is. earthquakes (Toh et al., 2011). Thus new tsunami measurement technologies and relevant sensors have been developed and applied for early tsunami detection in order for improving conventional tsunami warning system using bottom pressure sensors.

Then the present chapter introduces the actual observation of the bottom pressure sensors deployed in the tsunami source area. The acoustic resonant wave that is significantly produced in the tsunami generation process may contribute to the early tsunami detection scheme. Tsunami from the presumed Tonankai earthquake being though to take place within a next few decades is computed, which predict pressure waveforms at the offshore observatory in the source area. Acoustic resonant wave is computed in the tsunami source area, suggesting that its large amplitude implies large deformation. This gives an opportunity to issue an automated tsunami alert during the real-time monitoring by the bottom pressure sensors in the tsunami source area.

6. Acknowledgment

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2

Tsunami Detection by Ionospheric Sounding: New Tools for Oceanic Monitoring

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1. Introduction

After the Great Sumatra Earthquake and the consequent Indian Ocean Tsunami scientific community puts their attention to alternative methods in ocean monitoring to improve the response of the tsunami warning systems.

Improvement of classic techniques, as the seismic source estimation (e.g., Ammon et al., 2006) and densification of number of buoys over the oceans (Gonzalez et al., 2005), was supported by a new effort in remote sensing: nominally the space altimetry observation of the tsunami in the open sea (Okal et al., 1999; Smith et al., 2005) and the tsunami detection by ionospheric monitoring (e.g., Occhipinti et al., 2006). Today the recent tsunamis declare, one times more, the importance to go forward in this direction.

The indirect tsunami observation by ionospheric sounding is based on the idea anticipated in the past by Hines (1972) and Peltier & Hines (1976) that tsunamis produce internal gravity waves (IGWs) in the overlooking atmosphere. During the upward propagation the IGWs are strongly amplified by the effect of the decrease of the density. The interaction of IGWs with the plasma at the ionospheric height produces strongly variation in the plasma velocity and plasma density observable by ionospheric sounding (Figure 1).

This chapter i) resumes the moderne debate based on the Sumatra event (2004) about the tsunami detection by ionospheric sounding to demonstrate the hypothesis anticipated by Peltier & Hines (1976), and identifies the technics that proved and validated it, nominally altimeters and GPS. ii) Supports, with the recent theoretical works, the coupling between the ocean, the neutral atmosphere and the ionospheric plasma during the tsunami propagation and explores, based on the numerical modeling, the remote sensing possibility with additional techniques as the over the horizon radar (OTH-R). iii) Presents the ionospheric observations of the recents tsunamis to prove the systematic detection capability; nominally we review the following tsunamigenic earthquakes: 12 September, 2007, in Sumatra; the 14 November, 2007, in Chile; the 29 September, 2009, in Samoa; and the recent Tohoku-Oki (Japan) earthquake on 11 Mars 2011. We anticipate here that this last event also allow to prove that the signature of tsunami in the ionosphere can be also detected by optical camera *via* the airglow.

It finally concludes discussing the role of ionospheric sounding and remote sensing in the modern evolution of tsunami detection and warning systems.

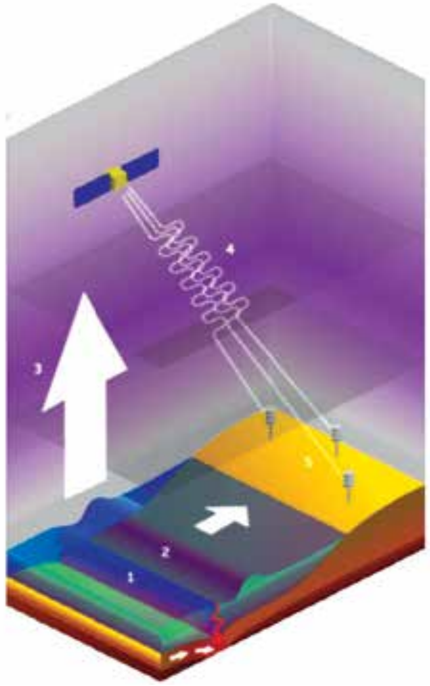

Fig. 1. Schematic view of the coupling mechanism and the ionospheric sounding by GPS. The vertical displacement of the ground floor (1) produced by an earthquake is directly transfered at the sea surface (2) following the incompressible hypothesis. The sea surface displacement initiate an internal gravity wave (IGW) propagating into the ocean (tsunami) as well as into the overlooking atmosphere. During the upward propagation the atmospheric IGW interact with the ionospheric plasma (3) creating perturbation in the plasma density and consequently in the local refraction index. The electromagnetic waves emitted by GPS satellites (4) to the ground stations (5) are perturbed by the plasma density variations and are able to image the signature of the IGW in the ionosphere.

2. The modern debate

The encouraging work of Artru et al. (2005) on the detection of the peruvian tsunamigenic quake on 23 June, 2001 (M=8.4 at 20:33 UT) in the total electron content (TEC) measured by the japanese dense GPS network GEONET opens the modern debate about the feasibility of tsunami detection by ionospheric sounding.

In essence, Artru et al. (2005) shows ionospheric traveling waves reaching the Japanese coast 22 hours after the peruvian tsunamigenic quake, with an azimuth and arrival time consistent with tsunami propagation (Fig. 2). Moreover, a period between 22 and 33 min, consistent with the tsunami, was identified in the observed TEC signals. The tsunami generated internal gravity waves (IGWs) were, however, superimposed by other signals associated with traveling ionospheric disturbances (TIDs) (Balthazor & Moffett, 1997). The ionospheric noise is large in the gravity domain (Garcia et al., 2005), consequently the identification of the tsunami signature in the TEC could be doubtful, and the debate still open.

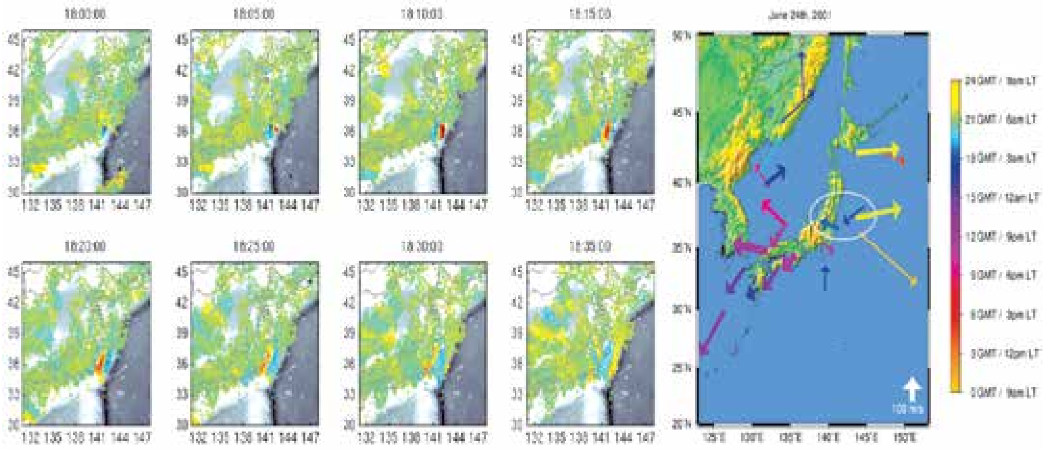

Fig. 2. Left-small-panels: TEC variations plotted at the ionospheric piercing points. A wave-like disturbance is propagating towards the coast of Japan. The perturbation presents characteristics of a tsunami IGW, and arrives approximately at the same time as the tsunami. Right-small-panels: Waves observed on the TEC maps throughout June 24th, 2001. The thickness of the arrows indicate the approximate amplitude of the wave (lower than 0.75 TECU, between 0.75 and 1.5 TECU, and between 1.5 and 2.25 TECU). The direction is the azimuth, and the lenght is proportional to the speed. Finally, the color indicate the time of observation (reddish colors are the local day time, blue is nighttime). The ellipse shows the possible tsunami signal showed in the left-panels. Figure after Artru et al. (2005).

The giant tsunami following the Sumatra-Andaman event (Mw=9.3, 0:58:50 UT, 26 December, 2004 (Lay et al., 2005)), an order of magnitude larger than the Peruvian tsunami, provided worldwide remote sensing observations in the ionosphere, giving the opportunity to explore ionospheric tsunami detection with a vast data set (Fig. 3). In addition to seismic waves detected by global seismic networks (Park et al., 2005); co-seismic displacement measured by GPS (Vigny et al., 2005); oceanic sea surface variations measured by altimetry (Smith et al., 2005); detection of magnetic anomaly (Balasis & Mandea, 2007; Iyemori et al., 2005) and acoustic-gravity waves (Le Pichon et al., 2005); a series of ionospheric disturbances, observed with different techniques, have been reported in the literature (DasGupta et al., 2006; Liu et al., 2006a;b; Lognonné et al., 2006; Occhipinti et al., 2006; 2008b).

Two ionospheric anomalies in the plasma velocities were detected North of the epicenter by a Doppler sounding network in Taiwan (Liu et al., 2006a). The first was triggered by the vertical displacement induced by Rayleigh waves. The second, arriving one hour later with a longer period, is interpreted by Liu *et al.* (2006a) as the response of ionospheric plasma to the atmospheric gravity waves generated at the epicenter.

A similarly long period perturbation, with an amplitude of 4 TECU[1] peak-to-peak, was observed by GPS stations located on the coast of India (DasGupta et al., 2006). These perturbations could be the ionospheric signature of IGWs coupled at sea level with the tsunami or the atmospheric gravity waves generated at the epicenter. Comparable TEC observations were done for five GPS stations (twelve station-satellite couples) scattered in the Indian Ocean (Liu et al., 2006b). The 30 sec differential amplitudes are equal to or smaller than

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[1] The TEC is expressed in TEC units (TECU); 1 TECU = $10^{16} e^{-}/m^{2}$.

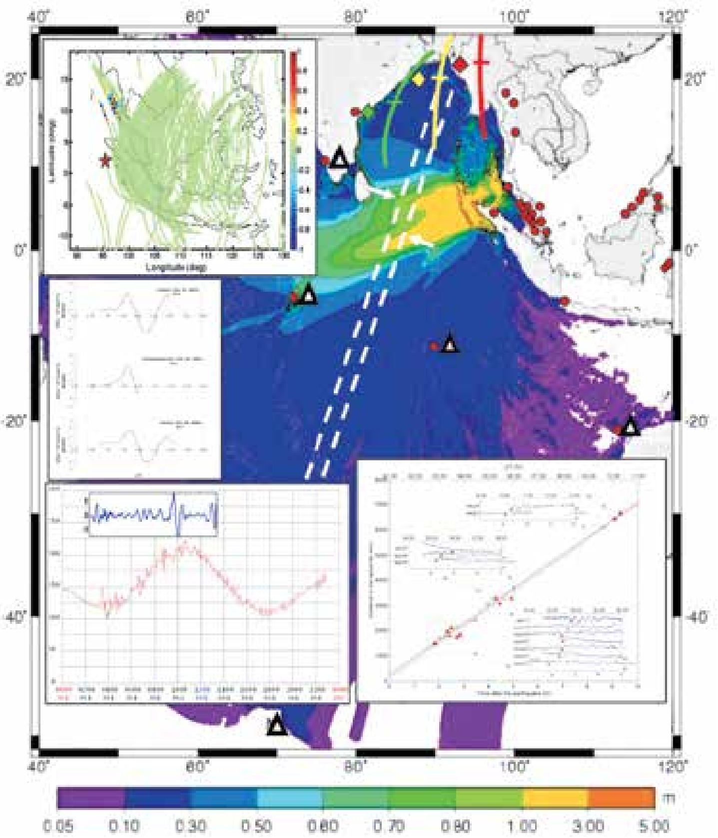

Fig. 3. Main: Maximum sea-level perturbation model produced by the propagation os the Sumatra tsunami (26 December, 2004). Top: TEC perturbation appearing within 15 min after the tsunami generation. The ionospheric piercing points (IPPs) obtained by satellites PRN01, 03, 13, 19, 20 and 23 coupled with the SEAMARGES network (red point in the main figure) are showed here during 40 min and highlight a clear early perturbation moving from the epicenter (the red star) to the North of Sumatra. Fugure after Occhipinti et al. (2011b). Middle: TEC perturbation observed by DasGupta et al. (2006) with the 3 satellite-station couples showed in the main figure by colored diamonds (station location) and lines (satellites) in the main figure. DasGupta et al. (2006) explain this signal as the IGW generated at the source by the vertical displacement but not link to the tsunami. Bottom-right: Average horizontal speeds of TIDs (red line) and tsunami (black line). The used GPS stations are indicated by triangle in the main figure. Figure after Liu et al. (2006b). Bottom-left: Tsunami signal measured at Coco Island by the tide gauge (red) and by the co-located GPS receiver (blue). The tide gauge measures the sea level displacement (tsunami + tide) and the GPS measures the TEC perturbation in the ionosphere. Both waveforms are similar in showing the sensitivity of ionosphere to the tsunami structure. Figure after Occhipinti et al. (2008b)

0.4 TECU (which generates amplitudes comparable to the DasGupta et al. (2006) observations for periods of ≈165 min, *i.e.* 30 points) and the arrival times coherent with the tsunami propagation. The observed satellites were located approximately at the station zenith.

Comparison between oceanic sea-level measured by tide-gauge at Coco Island and the TEC measured by the co-located GPS shows similarity in the waveform suggesting that the ionosphere is sensitive to the tsunami propagation as well as the ocean (Occhipinti et al., 2008b). We highlight that the tsunami reaches Coco Island 3 hours after the tsunami generation, this is the first oceanic observation of the Sumatra tsunami (Titov et al., 2005).

Close to these observations, the Topex/Poseidon and Jason-1 satellites acquired the key observations of the Sumatra tsunami with altimetry profiles. The measured sea level displacement is well explained by tsunami propagation models with realistic bathymetry, and provides useful constraints on source mechanism inversions (e.g. Song *et al.*, 2005). In addition, the inferred TEC data, required to remove the ionospheric effects from the altimetric measurements (Imel, 1994), showed strong anomalies in the integrated electron density (Occhipinti et al., 2006).

In essence, altimetric data from Topex/Poseidon and Jason-1 shows at the same time the tsunami signature on the sea surface and the supposed tsunami signature in the ionosphere (Fig. 4). By a three-dimentional numerical modeling Occhipinti et al. (2006) compute the atmospheric IGWs generated by the Sumatra tsunami and their interaction with the ionospheric plasma. The quantitative approach reproduces the TEC observed by Topex/Poseidon and Jason-1 in the Indian Ocean the 26 December 2004. Consequently, Occhipinti et al. (2006) closed the debate about the nature and the existence of the tsunami signature in the ionosphere. The results obtained by Occhipinti et al. (2006) was recently reproduced by Mai & Kiang (2009).

The TEC observation close to the epicenter using the local GPS network SEAMARGES, shows an early signal appearing at around 20 min after the tsunami generation and observable during 1 hour (Fig. 3). This signal could be contain both, an acoustic-gravity wave perturbation directly link to the vertical displacement at the source, and the tsunami signature in the ionosphere (Occhipinti et al., 2011b). The systematic observation of this early TEC perturbation could be used for tsunami warning system purpose. Anyway, we highlight that today the acoustic-gravity wave signature in the TEC observed close to the epicenter has not been reproduced by modeling.

3. Theoretical works

Tsunamis are long period oceanic gravity waves (Satake, 2002): their frequency is generally much smaller than the atmosheric Brünt-Vaïsalla frequency and, in the limit of linear analysis, they generate internal gravity waves in the overlying atmosphere (Hines, 1972; Lognonné et al., 1998; Occhipinti et al., 2006; 2008a). In other words, the coupling mechanism does not transfer a significant propagating energy in the acoustic domain. As a consequence of this theoretical hypothesis and the slow propagation velocity of IGW, a Bussinesq approximation, equivalent to incompressible fluid (Spiegel & Veronis, 1960), can be used in the ocean-atmosphere coupling mechanism and tsunami-IGW propagation.

Following those hypothesis Occhipinti et al. (2006; 2008a) developed a vertical pseudo-spectral propagator $\frac{dV}{dz} = A \cdot V$ (based on the Navier Stokes equations, the continuity equation and the incompressible hypothesis) explicitly described by the following

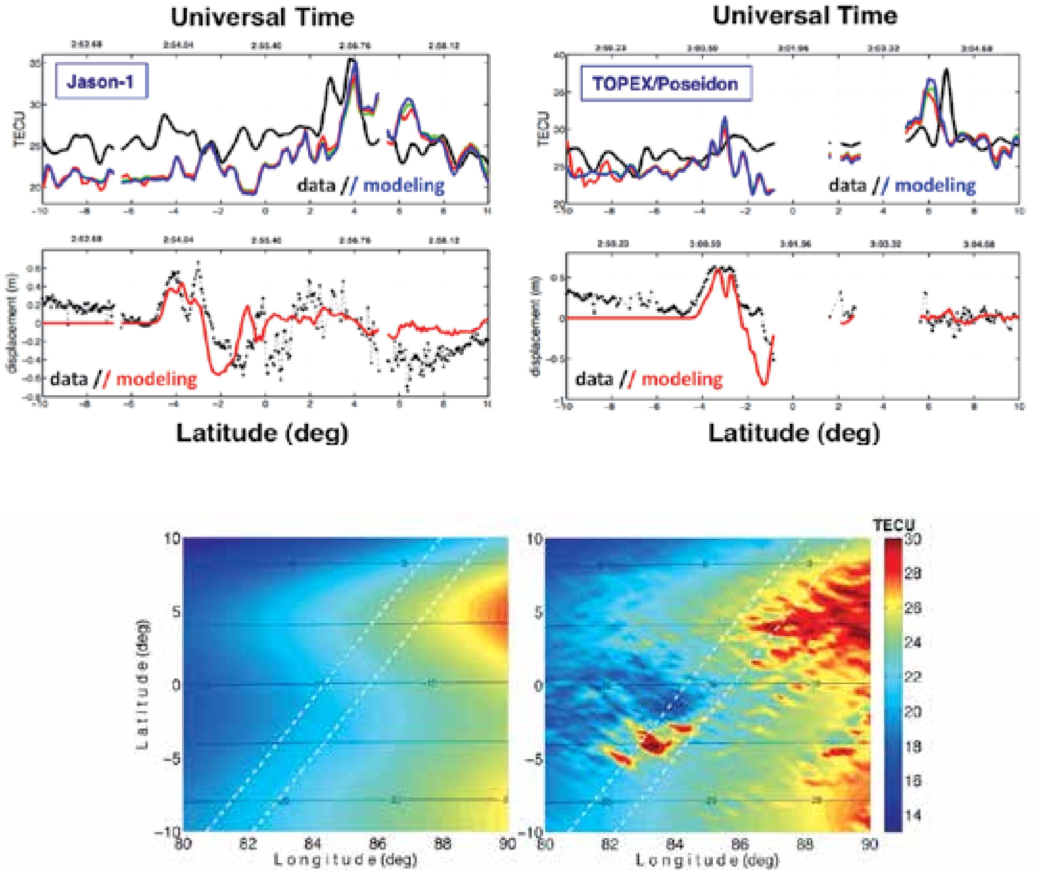

Fig. 4. Top: Altimetric and TEC signatures of the Sumatra tsunami. The modelled and observed TEC are shown for (left) Jason-1 and (right) Topex/Poseidon: synthetic TEC (top-panels) without production-recombination-diffusion effects (blue), with production-recombination (red), and production-recombination-diffusion (green). The Topex/Poseidon synthetic TEC has been shifted up by 2 TEC units. (bottom-panels) The altimetric measurements of the ocean surface (black) are plotted for the Jason-1 and Topex/Poseidon satellites, respectively. The synthetic ocean displacements, used as the source of IGWs in the neutral atmosphere, are shown in red. For each plot from the latitude and corresponding Universal Time are shown. Bottom: Tsunami signature (right) in the TEC at 3:18 UT and (left) the unperturbed TEC. The TEC images have been computed by vertical integration of the perturbed and unperturbed electron density fields. The TEC perturbation induced by tsunami-coupled IGW is superimposed on a broad local-time (sunrise) TEC structure. The broken lines represent the Topex/Poseidon (left) and Jason-1 (right) trajectories. The blue contours represent the magnetic field inclination. Figures after Occhipinti et al. (2006).

vector V and matrix A:

$$V = \begin{pmatrix} \tilde{u}_z^* \\ P^* \end{pmatrix};$$

$$A = \begin{pmatrix} -\frac{1}{\Omega}\left(k_x \frac{du_{x0}}{dz} + k_y \frac{du_{y0}}{dz}\right) & \frac{1}{2}\frac{d\ln\rho_0}{dz} - \frac{i(k_x^2+k_y^2)}{\Omega} \\ i\left(\Omega + \frac{g}{\Omega}\frac{d\ln\rho_0}{dz}\right) & -\frac{1}{2}\frac{d\ln\rho_0}{dz} \end{pmatrix}$$

Where $\tilde{u}_z^* = \sqrt{\rho_0}\tilde{u}_z$ and $\tilde{P}^* = \frac{\tilde{P}}{\sqrt{\rho_0}}$ are normalized vertical velocity $\tilde{u}_z$ and pressure $\tilde{P}$ in the *omega-k* domain: in essence the propagating plane waves with horizontal wave-numbers k_x, k_y and angular frequency ω; g is the gravity, ρ_0 is the unperturbed atmospheric density, u_{x0} and u_{y0} are the meridional and zonal background winds, and $\Omega = \omega - u_{x0}k_x - u_{y0}k_y$ is the intrinsic frequency relative to the flow induced by the winds (Nappo, 2002). The effect of the wind on the IGW propagation is fully explored by Sun et al. (2007): in essence the IGW propagating against the wind is amplified, and slow-down compared to the IGW going in the same direction of the wind. This result is corroborated here by figure XX following Occhipinti et al. (2008a).

The methodology entirely described by Occhipinti et al. (2008a) can be simply resumed as follow: the vertical velocity field, induced by the sea motion during the tsunami propagation, is decomposed in planar waves by a three-dimensional Fourier-transform in the Cartesian frame (x, y) and time, where $\hat{x}$ and $\hat{y}$ are eastward and northward. In essence, Occhipinti et al. (2008a) imposes the continuity of vertical displacement between the ocean and the atmosphere. Injected in the propagator described above, it produce the tsunami-related IGW. The other two components of the perturbed velocity $(\tilde{u}_x, \tilde{u}_y)$, and density perturbation $\tilde{\rho}$ are computed from $\tilde{u}_z$ and $\tilde{P}$ as follow:

$$\tilde{u}_x = \frac{1}{\Omega\sqrt{\rho_0}}\Big(-i\frac{du_{x0}}{dz}\tilde{u}_z^* + k_x\tilde{P}^*\Big)$$

$$\tilde{u}_y = \frac{1}{\Omega\sqrt{\rho_0}}\Big(-i\frac{du_{y0}}{dz}\tilde{u}_z^* + k_y\tilde{P}^*\Big)$$

$$\tilde{\rho} = \frac{-i}{\Omega\sqrt{\rho_0}}\frac{d\rho_0}{dz}\tilde{u}_z^*$$

Following Occhipinti et al. (2008a; 2011b), in the case of linearized theory for a realistic atmosphere with horizontal stratification and no-background wind, the vertical k-number k_z take the form (1) and consequently the dispersion equation the form (2).

$$k_z = \sqrt{k_h^2\left(\frac{N^2}{\omega^2} - 1\right) - \left(\frac{N^2}{2g}\right)^2} \qquad (1)$$

$$\omega^2 = \frac{k_h^2 N^2}{k_z^2 + k_h^2 + \left(\frac{N^2}{2g}\right)^2} \qquad (2)$$

Consequently it is possible to evaluate the vertical and horizontal group velocity v_g^z and v_g^h (Fig. 5):

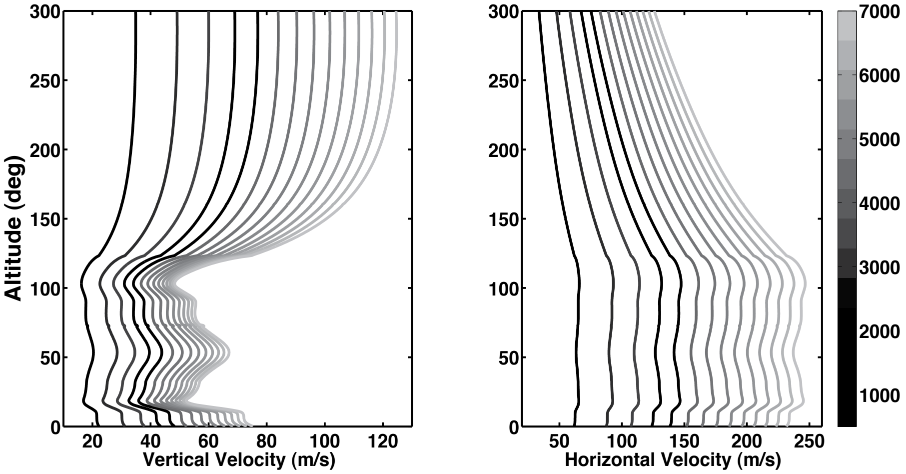

Fig. 5. Vertical (left) and horizontal (right) group velocity of the internal gravity wave coupled at the sea surface with tsunamis (generated at different oceanic deep *h*, see gray-scale) and a characteristic period *T* of 10 min. Tsunamis move at the speed defined by the relation $v_{tsuna} = \sqrt{hg}$, where *g* is the gravity. Consequently, the horizontal *k*-vector k_h that the tsunami transfer to the atmospheric internal gravity wave also depend by *h* following the relation $k_h = \frac{2\pi}{T\sqrt{hg}}$. Note that tsunamis generated/moving in the deeper oceanic zone produce faster IGW.

$$v_g^h = \frac{\delta\omega}{\delta k_h} = \frac{k_h N^2 (D - k_h^2)}{\omega D^2} \qquad\qquad v_g^z = \frac{\delta\omega}{\delta k_z} = \frac{k_z k_h^2 N^2}{\omega D^2}$$

where $D = k_z^2 + k_h^2 + \left(\frac{N^2}{2g}\right)^2$ is the denominator of the dispersion equation (2).

The horizontal group velocity don't play a role in the vertical propagation delay but it is useful to estimate the epicentral distance where the internal gravity waves start to interact with the ionosphere as well as the delay between the tsunami propagating at the sea surface and the internal gravity wave propagating in the atmosphere at the ionospheric altitude: *e.g.*, for a period of 10 min, the vertical propagation to reach 300 km is in the order of 1 hour, the horizontal epicentral distance 600 km and the delay between the tsunami and ionospheric IGW wavefronts is in order of 10 min.

The following interaction of IGW with the ionospheric plasma induces perturbation in the plasma density and plasma velocity. In essence, the variation in the neutral velocity $\vec{v}_n$ produced by IGW propagation in the atmosphere produces by dynamic and electromagnetic effect the ions movement with a perturbed speed $\vec{v}_i$ (eq. 4) that induce ion density variation n_i (eq. 3). The principal effect is produced by collisions between the neutral molecules and ions, secondly the ions drag the electrons by charge attraction to satisfy the neutral proprieties of

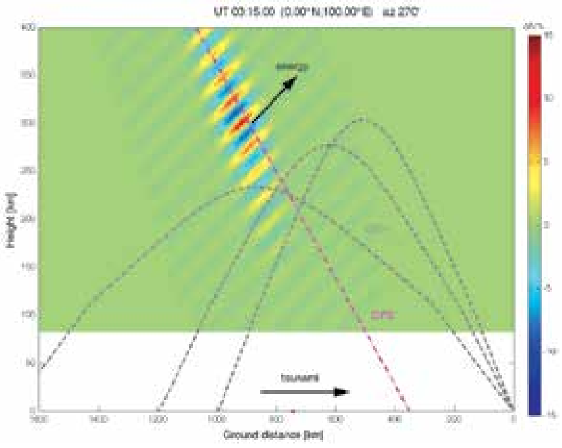

Fig. 6. Vertical cross section of the modeled tsunami-related electron density perturbation and ray-paths computed using a 10 MHz OTH radar signal at 19^o, 30^o and 35^o elevation (dashed gray lines). Dash-dotted purple line indicates a possible geometry of a nearby GPS station for a satellite at 25^o elevation. Arrows indicate the tsunami and IGW energy directions of propagation. Note that the vertical scale has been exaggerated. Figure after Coïsson et al. (2011).

the ionosperic plasma (eq. 5).

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \left(n_i \vec{v}_i\right) = \pm\, \beta n_i - \alpha n_i^2 \tag{3}$$

$$\begin{aligned} \rho_i \frac{d\vec{v}_i}{dt} &= -\nabla p_i + \rho_i \vec{g} + n_i q_i \big(\vec{E} + \vec{v}_i \times \vec{B}\big) \\ &\qquad - \rho_i \mu_{in} \left(\vec{v}_i - \vec{v}_n\right) \end{aligned} \tag{4}$$

$$n_e = \sum_{i=1}^{3} n_i \tag{5}$$

The method developped by Occhipinti et al. (2006; 2008a) is also used to estimate the role of the geomagnetic field in the tsunami signature at the E-region and F-region (Occhipinti et al., 2008a). Nominally the authors show that the amplification of the electron density perturbation in the ionospheric plasma at the F-region is strongly dependent by geomagnetic inclination as well as by the direction of propagation of the tsunami. This effect is explained by the Lorenz force term in the momentum equation explaining the neutral plasma coupling (eq. 4). Consequently, the detection of tsunamigenic perturbation in the F-region-plasma is easily observed at equatorial and mid-latitude then the hight latitude. The heterogenic amplification drove by the magnetic field is not observable in the E-region, consequently detection at low altitude by Doppler sounding and over-the-horizon (OTH) radar are not affected by geographical location. The theoretical possibility of detection by OTH radar is explored by Coïsson et al. (2011) for a simple tsunami-related IGW (Fig. 6) propagating in an dynamic ionosphere. Coïsson et al. (2011) demonstrate that, in absence of noise, the 3-dimentional pattern of the emission/reception beam of the OTH radar don't hide the tsunami signature (Fig. 7).

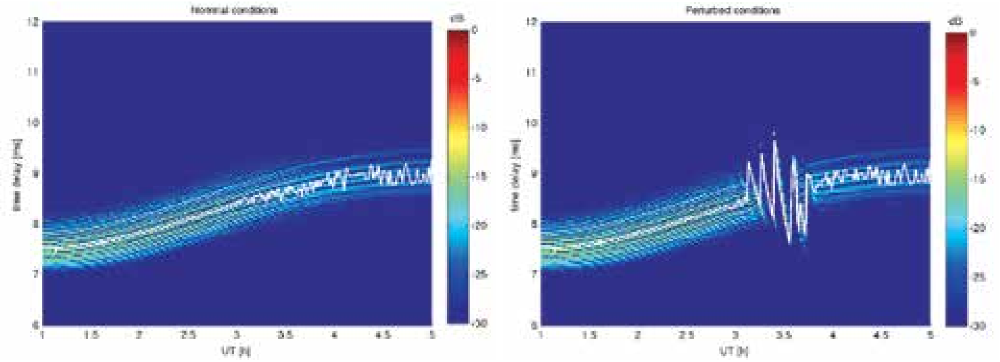

Fig. 7. Synthetic OTH radar record from 01:00 to 0605:00 UT at 270^o azimuth 30^o elevation during tsunami related IGW propagation showed in Fig. 6. Left: unperturbed ionosphere. Right: ionosphere with IGW perturbation. White points indicate the maximum signal strength at each UT. Figure after Coïsson et al. (2011).

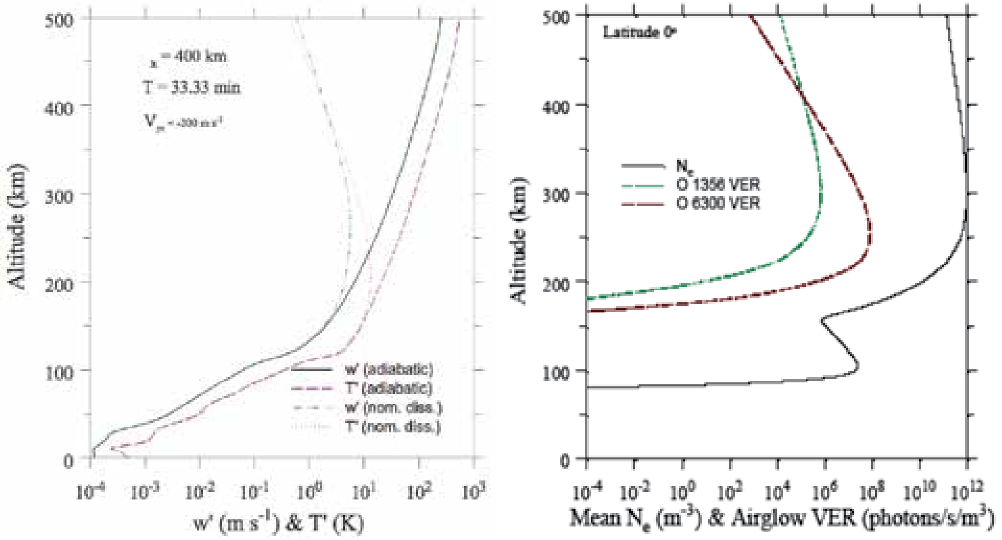

Fig. 8. Left: Relative electron density perturbation induced by tsunami related IGW. Right: Mean electron density (m-3), mean OI 6300 Ą VER (photons/s/m3), and mean O 1356 Ą VER (photons/s/m3). Figures after Hickey et al. (2009; 2010).

The effect of dissipation, nominally viscosity and thermal conduction have been taken into account in the tsunami atmosphere/ionosphere modeling (Hickey et al., 2009) showing that their effect become non-neglectable above 200 km of altitude (Fig. 8). Consequently, the main theoretical and numerical objective in near future is combine the attenuation effects with a full 3-dimentional modeling.

Theoretical works appeared recently, explore the possible detection by airglow monitoring (Hickey et al., 2010). The recent dramatic event of Tohoku Earthquake (Mw=9.3, 11 March,

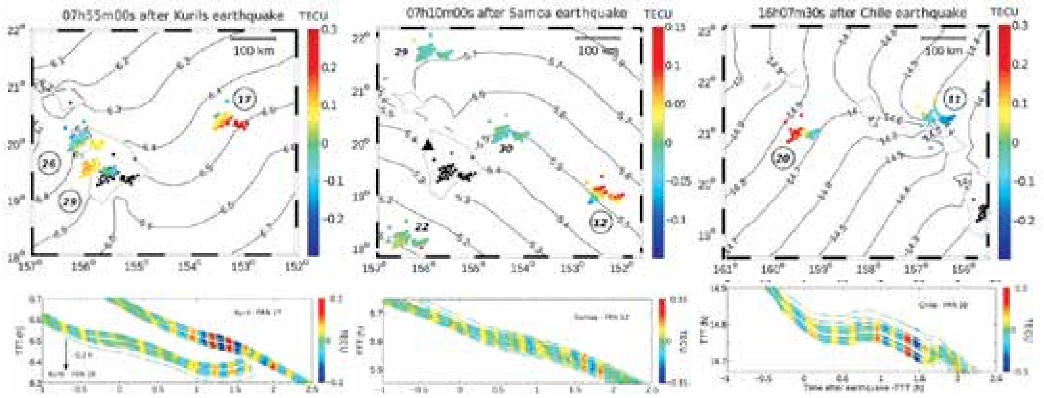

Fig. 9. Top: Instantaneous vTEC plotted about 1 hour after the theoretical tsunami arrival at sea-level, from left to right: after Kuril, Samoa and Chile earthquakes respectively. Bottom: Travel-time diagrams of the vTEC time-series at the time of tsunami arrival off Hawaii, from left to right: for Kuril, Samoa and Chile events, respectively. Time is related to the tsunami travel time to highlight coherence with the tsunami model. Figure after Rolland et al. (2010).

2011, 05:47:32 UT), detailed in the next section, allows to validate this hypothesis comparing measurement and modeling (Makela et al., 2011; Occhipinti et al., 2011a).

4. Recent tsunamis observations

After the ionospheric detection of the great Sumatra earthquake (26 December 2004) and the consequent tsunami, several works focalized on the minor tsunamis in order to generalize and validate the tsunami detection by ionospheric sounding (Galvan et al., 2011; Makela et al., 2011; Occhipinti et al., 2011a; Rolland et al., 2010; 2011).

Rolland et al. (2010) clearly showed the ionospheric detection in the far field for three tsunami events with a moderate magnitude compared to Sumatra: Kuril Islands 2006 (15 November, 2006, Mw 8.3), Samoa 2009 (29 September, 2009, Mw 8.1) and Chile 2010 (27 February 2010, Mw 8.8). Using the Hawaiian GPS network (50 stations) this work highlight the tsunami signature in the TEC. The ionospheric observations, supported by oceanic measurements by DART buoys, showed a signal coherent in arrival time and frequency-signature with the tsunami propagating in the ocean (Fig. 9). Galvan et al. (2011) showed similar coherent observations for Samoa 2009 and Chile 2010 not only in Hawaii but also in Japan, using the dense japanese GPS network GEONET.

Both those studies confirm, one time more, that detection of tsunami by ionospheric sounding is systematic and possible during the propagation in the open ocean.

Close to the epicenter, the coupling mechanism is more complex as the vertical displacement induced by the seismic rupture induces, in the same time, the generation of a propagating acoustic-gravity pulse in the atmosphere (Aframovich et al., 2010; Heki & Ping, 2005; Rolland et al., 2011a) as well as the tsunami formation if the epicenter is in oceanic regions (Occhipinti et al., 2011b). The following tsunami propagation induces, as described above, the formation of gravity wave propagating in the atmosphere and perturbing the ionosphere. Taking into account the theoretical vertical and horizontal speed of tsunami-related IGW (5), Occhipinti et al. (2011b) highlights that the signature of the tsunami with, e.g., a main period of 10 min, in the ionosphere is visible only after 1 hour and at the epicentral distance of 600 km, the

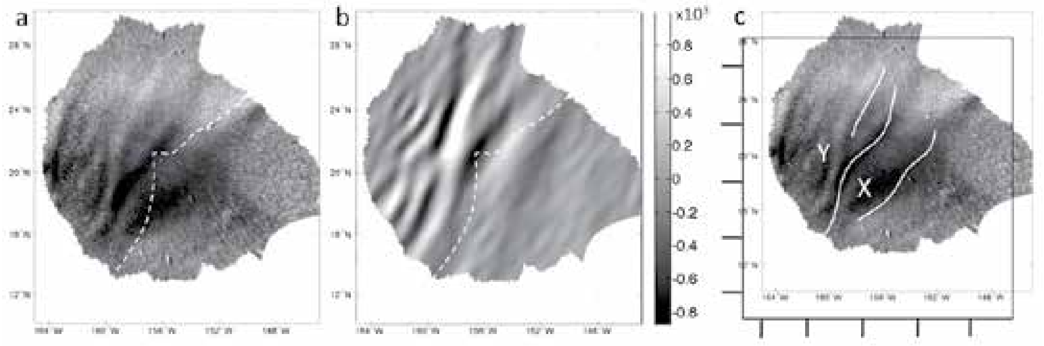

Fig. 10. a) IGW imaged by the 630.0-nm ground-based airglow camera located on the Haleakala Volcano on Maui, Hawaii, at 13:20 UT. b) normalized vertical velocity of the modeled IGW $((kg/m^3)^{\frac{1}{2}} m/s)$. The Y structure as well as the longer wavelength anticipating the Y (X) are present in both, airglow data and AGW synthetics. Those structures are observed between 12:12 to 13:32. The white dotted line in a and b shows the tsunami wavefront line at 13:20 UT. c) graphical estimation of the shift induced by the wind between model and data: the grid and the white lines are estimated on b, then shifted on a to fit with the position of Y and X. The estimated shift of 2° is coherent with previous observations Occhipinti et al. (2006). Figure after Occhipinti et al. (2011a).

theoretical estimation is supported by the observation of several tsunamigenic earthquakes: the 26 December, 2004, and 12 September, 2007, in Sumatra; the 14 November, 2007, in Chile; the 29 September, 2009, in Samoa; and the recent Tohoku-Oki (Japan) earthquake on 11 Mars 2011. Additionally, this last work highlight how the sensitivity of the TEC measurement is affected by the inclination angle of the station-satellite line-of-site: as a consequence of the integrated nature of TEC, the low inclination measurements have stronger sensitivity to tsunami signature in the ionosphere.

During the Tohoku-Oki event, close to the TEC measurements by GPS (Rolland et al., 2011) or altimeters (Jason-1), the tsunami related IGW propagating over the Pacific Ocean has also been detected for the first time by the airglow wide-angle camera system located at the top of the Haleakala Volcano on Maui, Hawaii Makela et al. (2011).

In essence, the camera is observing the airglow layer at approximately 250 km in altitude caused by the dissociative recombination of O2+ [Link and Cogger, 1988], which emits photons at 630.0 nm has predicted by Hickey et al. (2010).

Numerical modeling of IGW reproduces the main features observed in the airglow images (Fig. 10) showing interesting likenesses between the model and data, and explaining the nature of the airglow observation (Occhipinti et al., 2011a).

The tsunamic nature of the airglow observation is, first, clearly explained by the presence of a Y shape appearing in both synthetics and data; second, by the presence of a wave with a longer wavelength (indicated by X in Fig. 10) that is arriving before the tsunami front-wave. This observation is theoretically explained by Occhipinti et al. (2011a) as the combined effect of the low bathymetry around Hawaii and the period-dependence of the horizontal IGW speed propagation. In essence, the tsunami related IGW with longer-period go faster than shorter-period, consequently, when the tsunami slow-down by the effect of the low bathymetry close to the Hawaiian arcipelagos, the longer-period IGW goes over the tsunami wavefront.

5. Conclusion and perspectives

The analysis of tsunamigenic ionospheric perturbation observed after major events provides valuable information for understanding the physical processes and explore new techniques for tsunami warning systems. Along this chapter it has shown that early detection of tsunamigenic IGWs is possible using a bunch of remote sensing techniques as the TEC measurement by radar-altimetry and GPS, as well as the observation of the atmospheric airglow.

If the TEC measurement of tsunami seems today an established technique for tsunami observation, it present a large number of limits, primarily the observation geometry, that have to be taken into account for an eventual application in the oceanic monitoring.

The preliminary result about ariglow observation highlights that remote sensing of tsunamis via the atmospheric/ionospheric monitoring by ground-based or on-board camera could be a mature technique for oceanic monitoring and have to find a place in the future of tsunami detection technique.

By numerical modeling recents works prove the ability of additional techniques as the OTH-Radar who measure the perturbation at the ionospheric E-region (around 150 km) reducing, if used close to the epicenter, the response time of detection of the tsunami related IGW.

Anyway resuming, some of this techniques are able to highlight the presence of a tsunami several hours before that the wave hits the coast and could play a revolutionary role of remote sensing in the future tsunami warning systems.

6. Acknowledgments

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3

Proximal Records of Paleotsunami Runup in Barrage Creek Floodplains from Late-Holocene Great Earthquakes in the Central Cascadia Suduction Zone, Oregon, USA

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1. Introduction

A 100 km section of the central Oregon coast (Fig. 1) was surveyed for proximal creek floodplains, located at less than 500 m distance from the ocean shoreline, that could host sand sheet records of paleotsunami inundation (Peterson & Cruikshank, 2007). The study region is located near the center of the Cascadia margin, an active subduction zone that spans about 1000 km distance in the central west coast of North America (Atwater et al., 1995; Darienzo et al., 1994). Previous work in two distal floodplain localities within the study region, Neskowin and Beaver Creek, showed multiple paleotsunami inundations of one to several kilometers distance landward during the last ~ 2,500 years (see section 2.2) (Peterson et al., 2010a). It was not known how those distal records might relate to proximal or shoreline runup heights of the same paleotsunami events in the region. Such proximal or near-shoreline runup heights are needed to 1) demonstrate flooding hazards in coastal areas that have not suffered catastrophic flooding in historic time (Dengler, 2006), and 2) independently test flooding predictions based on assumed fault displacements and numerical tsunami runup models (González et al., 2009).

In this paper we document anomalous sand sheet layers in 8 small creek floodplains that exceed 6 m elevation thresholds for tsunami inundation. Target sand sheets are examined for evidence of marine shell fragments, tracers of marine surge origins, and the landward limits of sand sheet extent. The time span of continuous deposition in one representative floodplain locality is dated by radiocarbon. An adjacent floodplain locality is examined for landward trends of sand sheet composition, sand sheet thickness, microscopic tracers of marine deposits, and sand sheet radiocarbon age. Maximum sand sheet extent in the proximal floodplain locality is compared to maximum sand sheet extent in a distal floodplain locality (Peterson et al., 2010a) to yield a landward runup height gradient for the most recent event of large magnitude runup. The runup attenuation gradient is tested against previously reported runup elevations in another central Cascadia study area, Cannon Beach, Oregon (Fig. 1) (Peterson et al., 2008). The methods reported here should be applicable in similar settings to the documentation of paleotsunami runup heights in other susceptible coastlines around the world.

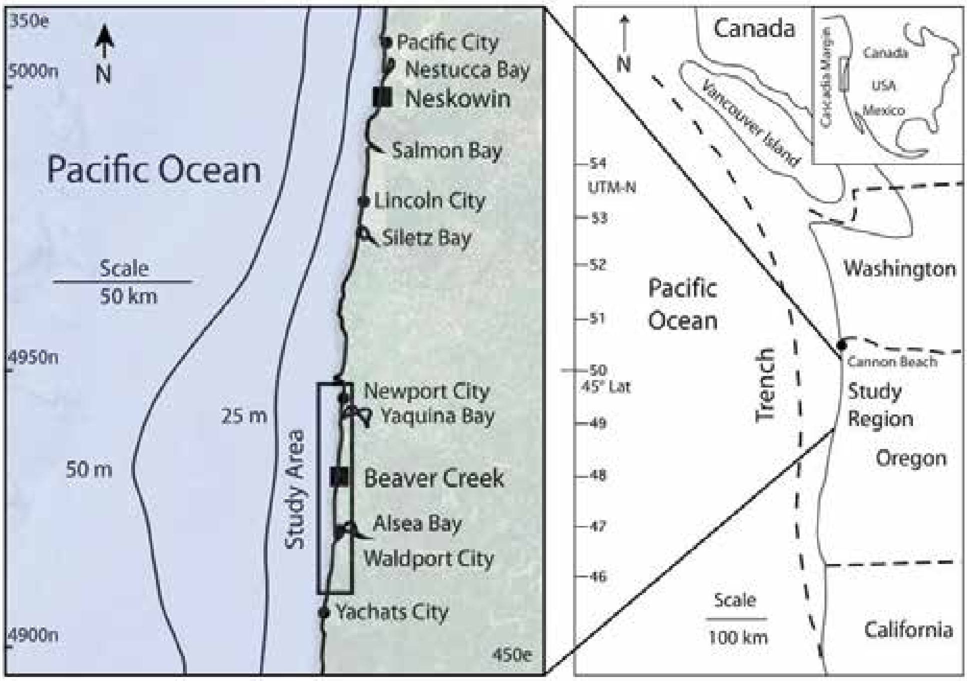

Fig. 1. The paleotsunami study region (~ 100 km in length) is located in the central Cascadia subduction zone (map at right). The Cascadia megathrust daylights along the trench (dashed line). The focused study area (~ 35 km in length) is shown in central Oregon coast (boxed area in inset map at left). Coastal communities (solid circles) and small estuaries (Bays) are named. Two localities investigated for paleotsunami inundation in distal floodplain settings are shown at Neskowin and Beaver Creeks (solid squares). Map coordinates for the study region (inset map at left) are in UTM x 1,000 m. Basemap is from Google (2011).

2. Study region

2.1 Paleoseismic evidence

A total of six or seven great earthquakes that ruptured though the central Cascadia margin during the last ~ 3,000 years are well recorded in Washington and northernmost Oregon where coseismic subsidence of least 1.0 m predominates (Table 1). Investigations of the associated nearfield paleotsunami inundations moved from the coastal marshes to overland inundation recorded in lakes, beach plains, back-barrier wetlands, and barrage lakes (Hutchinson et al., 1997; Kelsey et al., 2005; Schlichting & Peterson, 2006). The geologic records of paleotsunami sand sheet deposition that are located landward of foredunes, beach ridges, and other unstable coastal barriers provide minimum estimates of runup height (Peterson et al., 2006). To overcome these limitations some recent investigations have been redirected towards mapping paleotsunami sand sheets in small alluvial floodplains that are located on relative stable marine terraces (see Section 2.2 below).

Event	Atwater	Tsunami #	Age
Subsidence / Tsunami	Y	1	0.3 (AD1700)
? / Tsunami	-	2a	~ 0.9
Subsidence / Tsunami	W	2b	~ 1.1
Subsidence / Tsunami	U	3	~ 1.3
Subsidence / Tsunami	S	4	~ 1.7
Subsidence / Tsunami	H	5	~ 2.6
Subsidence / Tsunami	L	-	~ 2.8
Subsidence / ?	J	-	~ 3.2

Table 1. Central Cascadia Margin rupture and tsunami events. Subsidence related rupture events and ages are from Atwater et al., (2004). Tsunami correlations (Tsunami #) in the central Cascadia margin are from Peterson et al., (2010a). The source of the 2nd tsunami sand layer in the central Cascadia tsunami is not known (Peterson et al., 2008), but it might reflect a partial rupture in the northern part of the Cascadia margin (Clague et al., 2000; Schlichting & Peterson, 2006). Due to difficulties of discriminating the 2nd and 3rd tsunami events in some floodplain settings we assign them numbers of #2a and #2b, where they can be discriminated, and #2 where only one layer can be discriminated. Tsunami inundation has yet to be verified in the study area for the rupture events L and J at ~ 2.8 and 3.2 ka, respectively.

2.2 Distal paleotsunami runup records

Paleotsunami records have been reported from two alluvial floodplain settings in the central Oregon coast, Neskowin and Beaver Creek (Fig. 1)(Table 2) (Peterson et al., 2010a). The two localities differ in landward floodplain gradient and protective barrier ridges. A low-gradient floodplain (0 to 3 m elevation) in the Beaver Creek Valley records landward thinning sand sheets (20 to 1 cm thickness) over inundation distances of 1 to 4 km from the beach. In this paper all reported elevations are in the NAVD88 datum, which is about 1 meter below mean sea level (MSL).

The two longest paleotsunami runups in Beaver Creek correspond to dated paleotsunami deposits at 1520-1700 BP and 2960-3220 BP (Table 2). The age of the tsunami remobilized organic debris should predate the Cascadia rupture event, so we assign the two events to tsunami #3 and tsunami #5 or #6. The oldest three rupture events (H, J, and L) have short recurrence intervals (Table 1), so the radiocarbon ages of their associated tsunami deposits might overlap.

The Neskowin back-barrier wetlands are fronted by a barrier dune ridge (5–8 m elevation) and are backed by an uplifted terrace, which is dissected by small creeks. Sand sheets from four nearfield paleotsunami were traced across the back-barrier wetland (3 m elevation) and into a high-gradient creek floodplain, Hawk Creek, at elevations of 3 to 8 m at distances of ~ 0.5 to 1.0 km from the ocean shoreline (Table 2). The longest and highest tsunami runup at Neskowin, dated at 1114-1300 BP, is correlated to tsunami #3, which is coincident with the youngest of the two longest runup events in Beaver Creek.

3. Methods

The central Oregon coast was selected for this study based on a straight coastline, with low marine terraces that are dissected my numerous small creek valleys. Gouge coring (2.5 cm

Distal Record Locality	Rupture Age (ka)	TSL event (#)	Max. TSL thickness (cm)	Pinchout distance (km)	Terminal elevation (m, NAVD88)	Calibrated Radiocarbon (yr BP ± 2 σ)
Beaver Ck	0.3	1	20	2.5	0.0	320-520
	0.9	2a	8	0.5-1.0	0.0	
	1.1	2b	12	1.5	0.0	
	1.3	3	16	4.1	1.5	1520-1700
	1.7	4	5	1.5-2.0	0.0	
	2.6-2.8	5-6	6	4.0	0.7	2960-3220
Neskowin	0.3	1	20	0.6	3.0	-
	0.8	2a	5	0.6	3.0	-
	1.1	2b	8	0.8	6.5	940-1140
	1.3	3	40	1.0	8.3	1140-1300

Table 2. Overland paleotsunami runup records in distal alluvial flood plain settings, central Oregon coast. Rupture ages for the central Cascadia margin are from Atwater et al., (2004). Neskowin and North Beaver Creek data are from Peterson et al., (2010a) and Schlichting (2000). Distances from the ocean shoreline (km) are based on observed tsunami sand deposition, so they might underestimate maximum flooding distance. Elevations of terminal deposits (m NAVD88) shown here are not adjusted for late Holocene rise of sea level height. A net relative sea-level rise of 1m/1000 yr can be applied to the older paleotsunami events to correct for increased runup heights at the time of inundation. Radiocarbon ages (calibrated at ±2 sig. yr BP) are based on transported tsunami debris, so they should predate the corresponding rupture event age. Beaver Creek and Neskowin Creek floodplain localities are shown in Fig. 1.

diameter x 2.0 m core lengths) and/or ram coring (7.5 cm diameter x 2.0 m core lengths) were used to test the creek floodplain deposits for anomalous landward-thinning sand sheets. The surveyed core sites were investigated with 2 to 5 core retrievals prior to 1) core photography (50 mm macro-lens on a 10 megapixel DSLR), 2) subsampling for sand size, carbonate shell fragments, diatoms, and radiocarbon dating, and 3) logging at the 1 cm length scale. Core site positions are established by 12 channel WAAS-enabled GPS (e.p.e. 2.5-5.0 m). Locality elevations are taken from LiDAR (U. S. Geological Survey, 2011). Selected core sites are surveyed into registered benchmarks by EDM-Total Station for precise elevation control (elevation error ± 5 cm). Photos of target tsunami deposits, site position data, elevation surveying data, and initial field logs are archived in the Oregon Tsunami Database (Cruikshank & Peterson, 2011)

In the previous studies of paleotsunami runup in distal alluvial floodplains (see Section 2.2) heavy mineral tracers were used discriminate between beach sand and river sand sources to the target paleotsunami sand sheets (Peterson et al., 2010a). That approach could not be used in the proximal alluvial floodplains, due the presence of uplifted Pleistocene beach and dune deposits in the small alluvial drainages, which could contribute beach sand minerals to the creek sand bedload. The presence of marine diatoms has previously been used to establish paleotsunami inundation in some upland or inland freshwater settings of the Cascadia margin (Hemphill-Haley, 1996; Hutchinson et al., 1997; Kelsey et al., 2005). However, unexpected traces of marine diatoms in some control intervals, or non-tsunami deposits, from the central Cascadia beach plains and floodplains have suggested marine diatom transport by ocean wind/spray to distances of 2 km inland from the beach (Peterson et al., 2010a; Schlichting & Peterson, 2006). To further test these findings some target paleotsunami deposits and control intervals in the creek floodplains were examined for diatom taxa abundances following methods provided by Schilchting (2000).

Carbonate shell fragments provide an alternative marine source tracer for the target paleotsunami sand layers in proximal localities where the presence of small gravel size fractions (> 2 mm diameter) include marine shell fragments. Shell fragments in the granule and small pebble size ranges can usually be identified in the field with hand lens and 7.0 molar HCL for dissolution testing.

Another technique for indentifying carbonate shell fragments was used for the finer sand size fractions in the more landward sites of the proximal localities. Small carbonate fragments (0.2-0.5 mm diameter) in the sand size fraction are present at trace abundances (1,000 total grain counts per sample). They are identified in grain mounts by moderately high relief and high dispersion in polarized light under petrographic microscopy at 250x.

Sediment grain sizes are analyzed in the target paleotsunami deposits to establish any vertical trends and landward trends in grain size distributions. Upward grain-size fining trends are established by high-resolution digital photography at ~ 50x magnification. Landward fining trends are based on petrographic microscopy (250x) of grain counts (50 total grains per slide) of samples taken from the middle of target tsunami sand layers. Standard statistical methods for characterizing the sample grain size populations follow Folk (1980).

Samples of organic detritus, including leaves and twigs, were collected from tsunami sand sheet layers for radiocarbon dating by AMS method. Small samples (< 0.5 g) were air dried, weighed and submitted to Beta Analytic Inc. for dating. Sample dates are provided in isotope adjusted radiocarbon age and in calibrated radiocarbon years BP at the 2–σ analytical error level by Beta Analytic Inc.

3.1 High-gradient proximal floodplains

In this study we target high-gradient floodplains in the central Oregon coast for sand sheet records of proximal paleotsunami runup (Fig. 2; Table 3). The small creek floodplains rise from 5 m to as much as 15 m in elevation within short distances (0.5-1.0 km) from the beach. The incised creek valleys were downcut into Pleistocene dune sheets and underlying marine terraces during the last sea level lowstand. The perched creek floodplains formed after late-Holocene beach sand ramped against the sea cliffs and creek mouths in the study area (Hart & Peterson, 2007). The onset of surplus beach sand supply began between 4.0 and 4.5 ka based on dated buried stumps on the beach platform at Grant Creek and Deer Creek, and from a sea cliff dune ramp at Lost Creek (Fig. 2; Table 3). The excess supply of beach sand slowed or stopped by about 3.0 ka in the study area, based on a radiocarbon date from the top of the dune ramp that blocked Quail Creek. Seasonal flooding and shallow groundwater surfaces in the creek valleys permitted accumulations of peaty mud in the floodplains, which serve as hosting deposits for landward thinning layers of beach sand.

4. Results

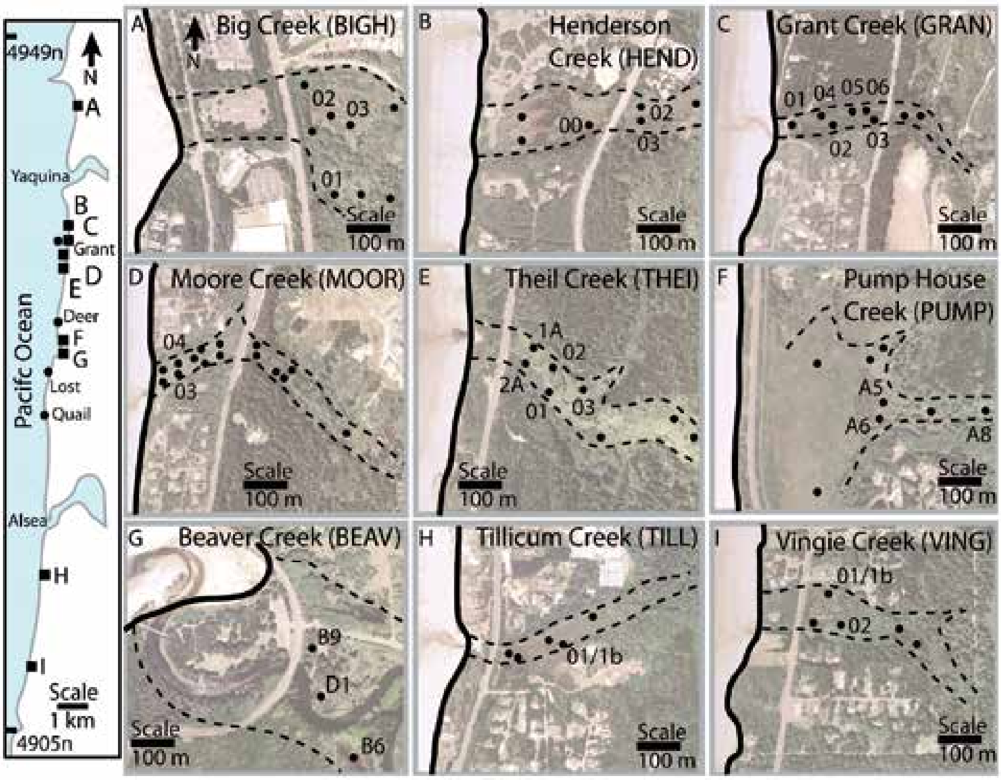

Fig. 2. Study area includes 9 creek floodplain localities (maps), and buried beach platform stumps or dune ramp forest soils at Grant Creek, Deer Creek, Lost Creek, and Quail Creek. Beach platform and dune ramp radiocarbon dates are shown in Table 4. Representative core sites are summarized in Table 3. Core logs and core site position data are provided in Cruikshank and Peterson (2011).

4.1 Paleotsunami records in proximal high-gradient alluvial wetlands

Eight proximal runup localities with inundation thresholds of 6.0 to 7.5 m elevation (NAVD88) in the study area are found to contain multiple anomalous sand sheets in creek floodplain deposits (Table 3). Alluvial mud hosts the anomalous sand sheets, which fine upward and thin landward in the small floodplain settings (Fig. 3). Additional creek floodplains exist within the 100 km long study region, but the tight grouping of eight localities within a 35 km study area permits comparisons of different catchment responses to similar conditions of tsunami surge forcing. The southern grouping of alluvial creek wetlands is divided on either side of the low gradient Beaver Creek valley that contains the longest overland inundation records reported to date for the central Cascadia margin (Table 2).

Six out of the eight creek localities record three or four prominent sand sheets, suggesting a similarity in age span of the alluvial hosting deposits. Radiocarbon dating of the alluvial section in Grant Creek, containing three sand sheets and one sandy debris layer, yields an age range from post-modern carbon (107pmc) to 3480-3690 BP (Table 4). The age span for

Locality/ Core Sites	UTM Northing (m)	UTM Easting (m)	Shoreline distance (m)	Threshold /core elev. (m)	TSL number	TSL max. thickness (cm)
BIGC2/3	4945660	416690	400	6.5/6.5	2	7
HEND3/4	4938210	415680	420	6.0/5.5	3	12
GRAN5/6	4936930	415250	120	6.0/8.0	3	10
MOOR3/4	4936080	415140	80	7.5/8.0	3	36
THEI1A/2	4935090	415110	100	6.0/5.5	3	12
PUMP5/6	4931050	414870	340	6.0/6.5	3	12
BEAV_D1	4930160	414990	400	4.5/2	4	13
TILL1/1b	4916010	413630	250	6.0/5.5	2	5
VING1/1b	4910390	412680	170	6.0/7.0	3	5

Table 3. Representative proximal runup core sites in the central Oregon coast. Core site elevation is based on core site surface elevations (m, NAVD88) taken from LiDAR (U. S. Geological Survey, 2011). Distance is the straight-line distance (m) of surge flow from beach backshore or sea cliff to the representative core sites. Threshold elevation (m, NAVD88) is based on the mean across-valley elevation at or near the shoreline. TSL number is the number of observed tsunami sand layers of least 1 cm sand thickness in each runup locality. TSL maximum thickness is the thickest target tsunami sand layer (cm) observed in the runup locality. Core sites in creek floodplain localities are shown in Fig. 2. Data from Cruikshank and Peterson (2011).

the Grant Creek silt alluvium, located just above basal creek gravel, is consistent with an expected onset of creek damming by dune ramp barrages that occurred at about 4 ka in the study area (see Section 4.1).

The tsunami sand layers (TSL) decrease in number and thickness with increasing landward distance and elevation in each runup locality (Fig. 2). The tsunami sand layers fine upward, terminating with thin laminae of very-fine sand or silt at the tops of the sandy intervals (Fig. 3). Sandy organic debris layers (TDL), which commonly cap tsunami sand sheets in distal alluvial runup localities of the Cascadia margin (Carver et al., 1998; Peterson et al., 2008), are uncommon in the proximal runup localities observed in the central Oregon study area. These data demonstrate that as many as four paleotsunami inundations substantially overtopped the barrage dune barriers (6.0 to 7.5 m elevation) at the mouths of corresponding creeks during the last several thousand years.

Site	Setting	adjC14 yr ± error	Cal RC 2-σ (yr BP)	Lab
Grant Creek beach	Beach platform stump	3750±60	3988-4228	B118658
Lost Creek beach	Beach dune ramp	3420±60	3600-3720	B148094
Deer Creek beach	Beach platform stump	3920±60	4255-4421	B81340
Quail Creek mouth	Top of barrage dune	2930±40	3018-3152	B172772

Table 4. Radiocarbon dates for dune ramps and creek barrage dunes in the study area. Data for Grant Creek beach platform stump (UTM 4936010n 415050e), Lost Creek beach dune ramp (UTM 4933080n 414770e), Deer Creek beach platform stump (UTM 4928880n 414110e, and Quail Creek top of barrage dune (UTM 4926060n 413880e) are from (Hart & Peterson, 2007). The dated sites of buried beach platform stumps and sea cliff dune ramps are shown in Fig. 2.

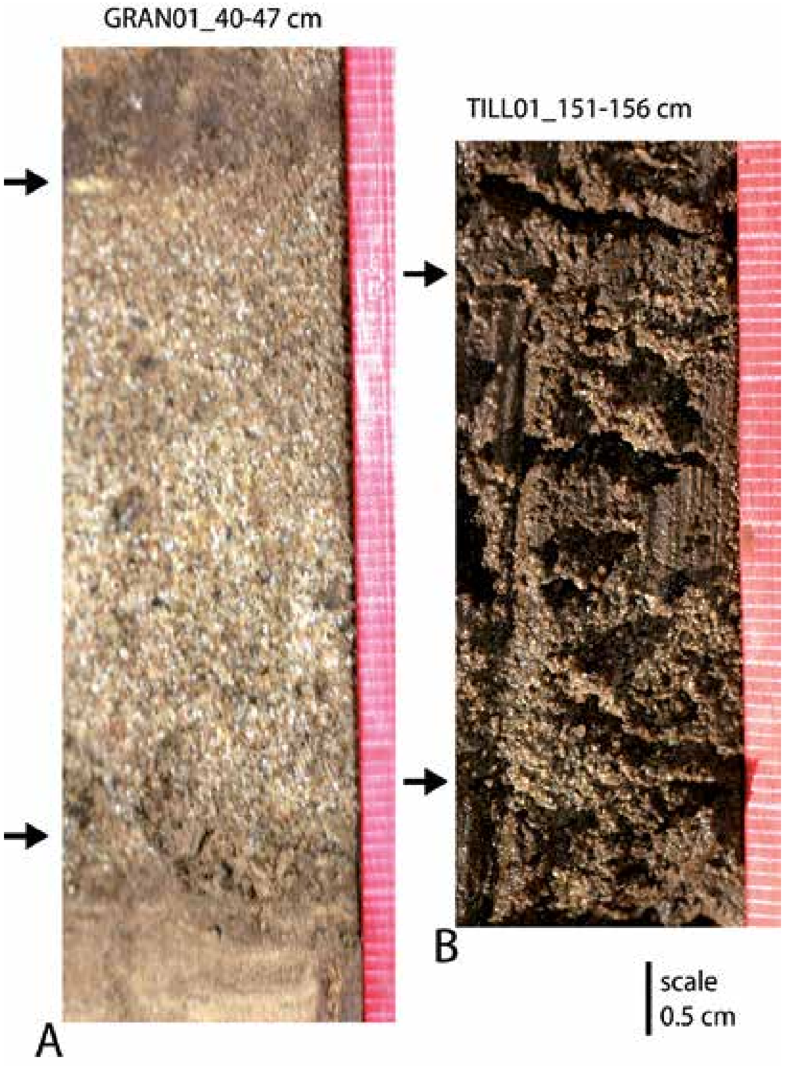

Fig. 3. Contrasting paleotsunami sand layers shown between black arrows for (A) Grant Creek (40-47 cm depth at core site GRAN1) and (B) Tillicum Creek (151-156 cm depth at core site TILL1). The sand sheet deposit from Grant Creek (5-6 cm thick) shows 1) an undisturbed tsunami sand layer (TSL), 2) clear contrast with oxidized hosting alluvium, 3) a sharp bottom contact, 4) fining-upward grain-size trend, and 5) a dark organic-rich debris layer (TDL). The sand sheet deposit from Tillicum Creek (~ 3-4 cm thick) is much disturbed by root bioturbation and the quartz-rich beach sand is obscured by the dark reducing hosting mud. However it does have a sharp lower contact, and it fines upward in grain-size, though no capping debris layer is apparent. Red tape rule is scaled at 1 mm intervals. See Fig. 2 for core site locations.

Several recent paleotsunami with limited inundations in distal runup localities, Neskowin and Beaver Creek, include the last three central Cascadia tsunami events TSL #1, #2a and #2b, (Table 3). Paleotsunami events with expected low runup heights, including events #1 and #2a, are recorded in the low elevation wetlands at the mouth of Beaver Creek in core site BEAV_D1 (Fig. 4). These lower runup events did broadly overtop minimum threshold elevations of the beach backshore at 4.5 m elevation that fronts the mouth of Beaver Creek (Fig. 2). Based on these minimum threshold elevations of recorded paleotsunami inundation we estimate minimum runup heights of at least 5.0 m for nearfield tsunami in the central Cascadia margin.

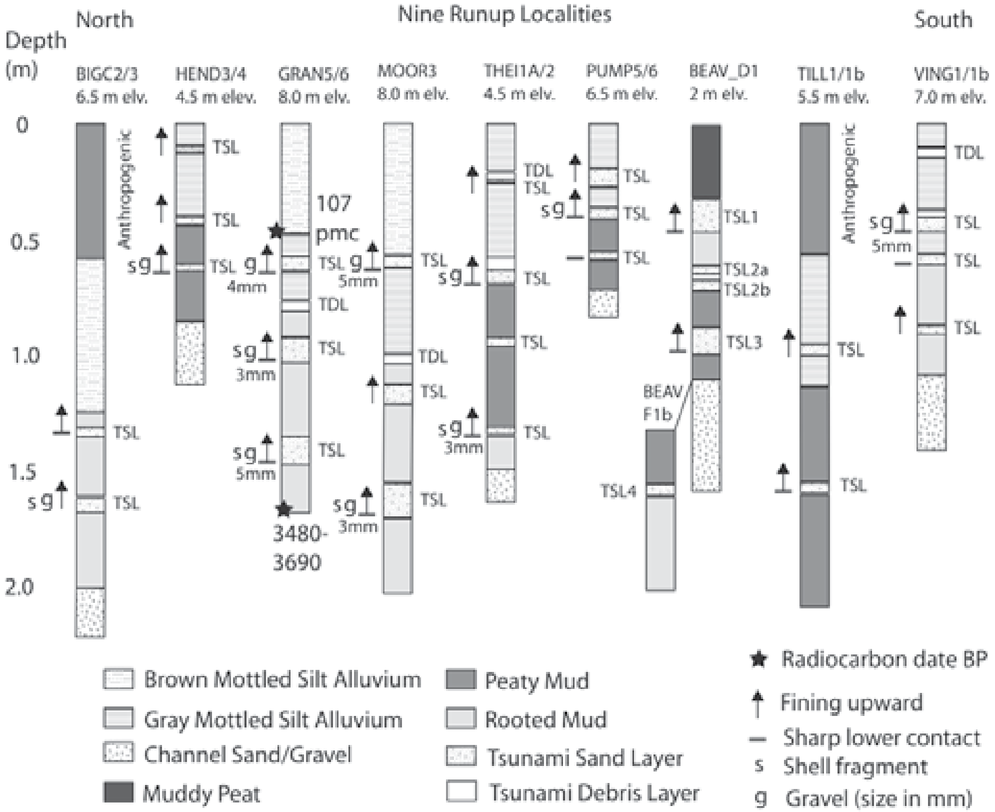

Fig. 4. Representative core logs from nine creek runup localities in the central Oregon coast study area, including Big Creek (BIGC), Henderson Creek (HEND), Grant Creek (GRAN), Moore Creek (MOOR), Theil Creek (THEI), Pumphouse Creek (PUMP), Beaver Creek (BEAV), Tillicum Creek (TILL), and Vingie Creek (VING). Target tsunami layers are verified in two adjacent core sites from each elevated floodplain, except Moore Creek, where additional core logs are shown in later sections of the paper. The position data for the localities and corresponding core sites are shown in Fig. 2 and Table 3. Core site elevations (m) are relative to the NAVD88 datum. One proximal locality (BEAV_D1) is a low elevation back-barrier wetland, whereas the other eight creek floodplain localities all exceed 6 m elevations at their shoreline barrage-dune thresholds.

Three runup localities in the study area, including Grant, Moore, Theil, and Vingie Creeks, contain anomalous sandy silt layers that can be correlated between successive target tsunami sand layers in adjacent core sites (Cruikshank & Peterson, 2011). Such isolated tsunami debris layers (TDL) are shown in core sites GRAN5/6 and MOOR3 (Fig. 4). These layers might represent terminal inundations by smaller tsunami events. Other smaller target layers (< 1 cm thickness) might exist in the seaward sites of the study area localities, but are not further addressed in this study.

Locality/ Site	Depth (cm)	adjC14 yr ± error	Cal RC 2-σ (yr BP)	Lab
GRAN6_54	54	107±0.5pMC	modern	B281145
GRAN6_161	161	3360±40	3,480-3,690	B281146
MOOR9_86	86	1,830±40	1,640-1,650	B230659
MOOR9_120	120	2,720±40	2,750-2,880	B228599
MOOR9_129	128.5	2940±40	2,960-3,230	B222512
MOO9-200	200	3,390±40	3,560-3,710	B228600

Table 5. Radiocarbon dates for paleotsunami in proximal runup sites, central Oregon coast. Radiocarbon dates are taken from base of tsunami sand layers, as shown by core depth (cm). See Fig. 2 for core sites and Fig. 4 and Fig. 7 for core logs.

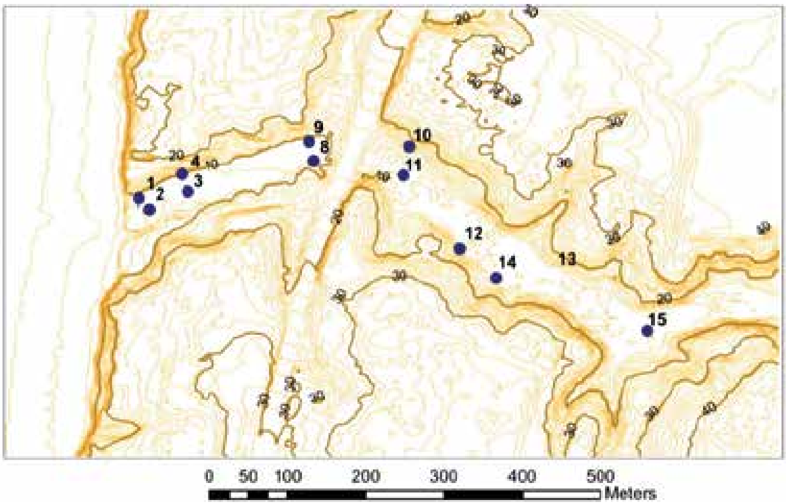

Fig. 5. Moore Creek core site map including 12 representative core sites ranging from 8 to 13 m in elevation (NAVD88). Contour base map is based on LIDAR DEM (U. S. Geological Survey, 2011). 1m contour interval, with bold contours at 10, 20, and 30 m elevation. See Fig. 2 for location of Moore Creek locality in the study area. Core photos and core logs are shown in Fig. 6 and Fig. 7, respectively.

Though flow height and duration are both important in surge magnitude, for this study we focus on estimating runup height in the proximal floodplain settings. To establish maximum-recorded runup elevations the tsunami sand sheets are traced to their most landward extent in several creek localities. The terminal sand sheet deposits that show the best preservation and continuity occur in the Moore Creek floodplain locality (Fig. 2).

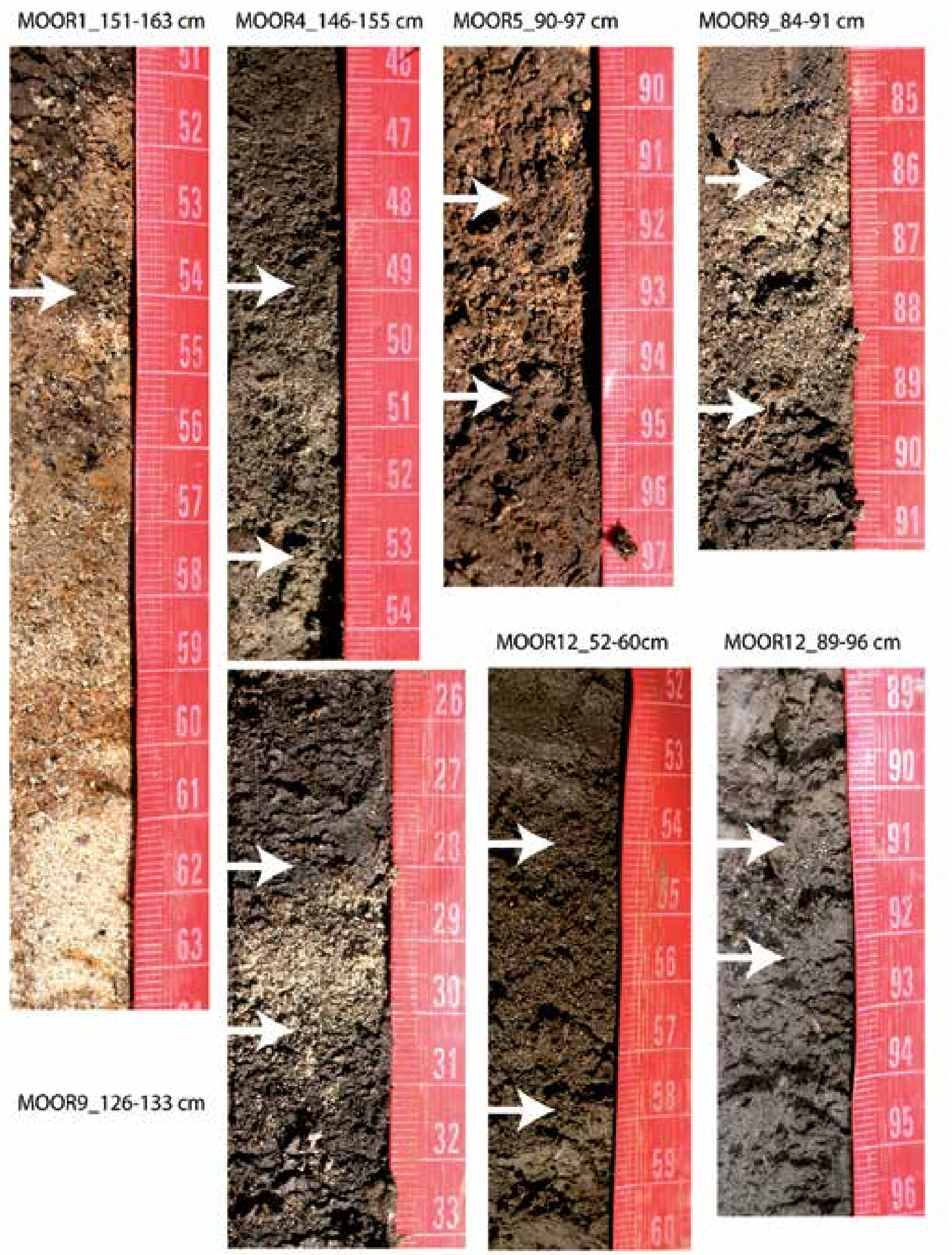

Fig. 6. Photos of representative tsunami sand layers (TSL) from the Moore Creek locality. Core sections are listed by core site number and depth (cm). Tsunami sand layers are bracketed by white arrows. The tsunami sand layer in MOOR01 continues 154–163 cm depth in the photo to 187 cm depth below the photo, totaling 33 cm in thickness. The thin sandy layer in MOOR12 at 91-92 cm depth is transitional between a tsunami sand layer and sandy tsunami debris layer. See Fig. 7 for core logs.

4.2 Moore creek runup locality

A total of 12 representative core sites are logged to document the landward thinning of sand sheets hosted in alluvial silts of the Moore Creek locality (Fig. 5). The sand sheets thin to only a few centimeters in thickness with increasing landward distance and elevation gain in the high-gradient floodplain setting. However, the quartz-rich beach sand layers are distinctive in the gray silt alluvium (Fig. 6).

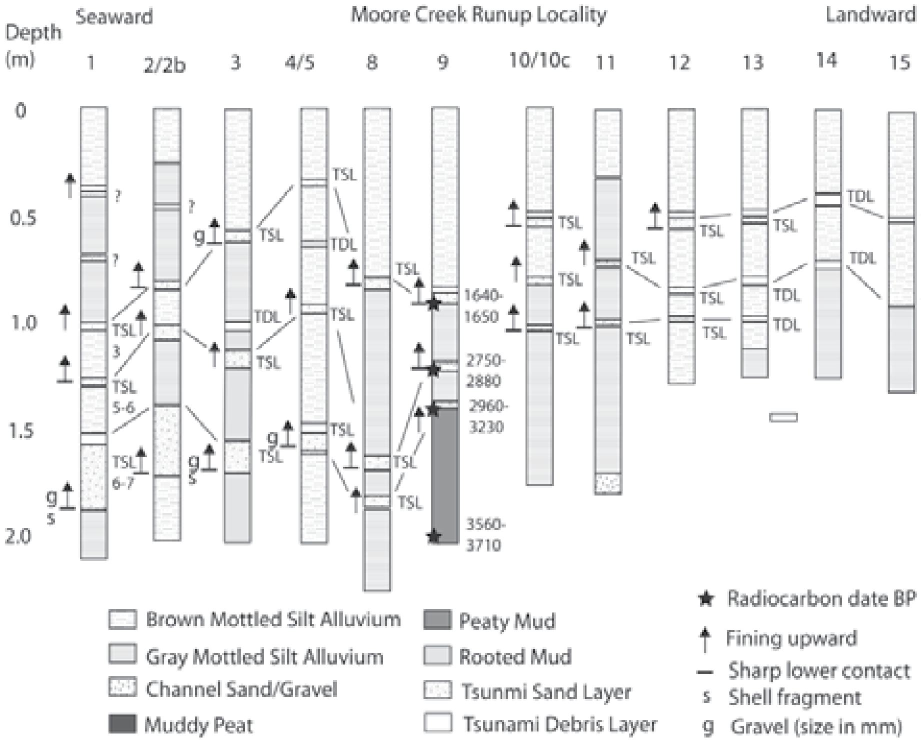

Fig. 7. Core Logs from the Moore Creek runup locality showing tsunami sand layers (TSL) and tsunami debris layers (TDL) in representative core sites. See Fig. 5 for core site positions and Table 8 for core site elevations.

The three sand sheets that largely span the length of the Moore Creek runup locality are dated by AMS radiocarbon analyses of organic debris in the base of the sand sheets in core site MOOR9 (Fig. 7; Table 4). The radiocarbon samples yield dates of 1640–1650 BP, 2750–2880 BP, and 2960–3230 BP, corresponding to Cascadia tsunami events #3, #5, and #6–7, respectively (Table 1). A radiocarbon date of 3560–3710 BP dates the onset of alluvial silt accumulation in the Moore Creek floodplain at site MOOR9. Several anomalous sand laminae (< 1 cm thickness) are apparent above or between the prominent sand sheets in the seaward core sites MOOR1, MOOR2, MOOR3 and MOOR4. The origins of these minor lamiane are not known, but could reflect terminal deposits of smaller runup events. Due to their lack of continuity in the landward core sites they are not further addressed in this paper.

Three depositional features are common in the three target tsunami deposit layers from the Moore Creek core sites, including sharp lower contacts, sediment fining-upward trends, and deposit layer thinning with increasing distance landward (Fig. 7). The combination of all three features in the three target sand layers is consistent with catastrophic marine surges but not with river flooding, paleoliquefaction, or hillslope debris flows. Further tests of marine surge origin are provided by marine source tracers in the target tsunami sand sheets (see Section 4.4 below).

4.3 Marine surge tracers

The use of marine diatoms to confirm paleotsunami inundation in the proximal flood plain settings that were investigated in this study proved to be problematic. Diatoms occur in the silt size range, and are potentially very useful in discriminating marine surge sources of target paleotsunami layers in the Cascadia margin (Hemphill-Haley, 1996; Kelsey et al., 2005; Schlichting & Peterson, 2006). In this study a composite sample was taken from the top of the target tsunami layer where the fine to very-fine sand in the tsunami sand layer grades into sandy silt or sandy detrital organics in the tsunami debris layer. Ocean derived diatoms including full marine and brackish taxa are present in the paleotsunami layers from the Moore Creek locality (Table 6). As expected, diagnostic freshwater diatoms are also present in the flood plain soils. Diagnostic ocean derived diatoms are also present in very-low abundance in control intervals are that are not associated with target paleotsunami sand layers or paleotsunami debris layers in the Moore Creek locality. The presence of marine and brackish diatoms in trace to minor abundances in non-tsunami control layers, argues for ocean diatom transport in wind driven ocean foam and/or spray in proximal settings (100-400 m from the beach). Additional evidence is needed to confirm the marine surge origins of the target paleotsunami sand sheets in the proximal floodplain settings.

Diatom Assemblage/ Taxa	Core Site	Depth (cm)	Target layer
Polyhalobous (marine)			
Hyalodiscus scoticus	MOOR9	55-60	control
Coscinodiscus radiatus	MOOR12	54-58	TSL/TDL
Cocconeis scutellum	MOOR12	54-58	TSL/TDL
Endycta sp.	MOOR12	100-101	control
Mesohalobous (brackish)			
Navicula lanceola	MOOR9	86-88	TSL
Pinnularia viridis	MOOR9	119-122	TSL
Pinnularia viridis	MOOR12	128-130	TSL/TDL
Opephora parva	MOOR12	128-130	TSL/TDL
Oligohalobous (freshwater)	MOOR9, 12		
Amphora ovalis	MOOR9, 12		
Eunotia pectinal	MOOR9, 12		
Gomphonema parvulum	MOOR9, 12		

Table 6. Presence of diagnostic diatom taxa in proximal alluvial deposits. Control layers are non-tsunami layers. TSL are target paleotsunami sand layers. TDL are target paleotsunami debris layers. Core sites and sample intervals are shown in Fig. 5 and Fig. 7, respectively.

	TSL number	Max. size (µm)	Min. size (µm)	Mean Size (µm)	Std Dev +/- (µm)	MeanN StdDev	Shell frag (%)
Beach		460	180	269	56	0.21	0.27
Creek		1030	150	470	234	0.50	0.00
1_100 cm	#3	610	190	341	79	0.23	0.14
1_126 cm	#5	740	230	375	107	0.29	0.00
1_151 cm	#6-7	550	120	350	94	0.27	0.21
9_86 cm	#3	510	190	331	87	0.26	0.36
9_119 cm	#5	480	160	278	65	0.23	0.00
9_128 cm	#6-7	400	100	275	68	0.25	0.10
12_54 cm	#3	430	150	245	68	0.28	0.10
12_82 cm	#5	420	100	229	69	0.30	0.15
12_91 cm	#6-7	490	90	231	69	0.30	0.00

Table 7. Sand grain size and shell fragment frequency Tsunami sand layer samples are from three core sites (MOOR1, MOOR9 and MOOR12 in the Moore Creek runup locality. Population characteristics including maximum sand size (Max), minimum sand size (Min), average (mean), 1 standard deviation (Std Dev), and mean normalized standard deviation (MeanNStdDev) (Folk, 1980) are based on 50 grain counts. Carbonate shell fragment frequency (Shell frag %) are based on 1,000 grain counts. Core sites and sample intervals are shown in Fig. 5 and Fig. 7, respectively.

Carbonate shell fragments were identified in the gravel size fractions of target paleotsunami sand sheets in 7 out of the 8 runup localities (Fig. 4). Shell fragments were found in 9 of the 12 sand sheet samples that contained minor abundances of granules (size range 2-5 mm diameter). The granule abundance abruptly decreases to trace levels with increasing distance from the beach (200-400 m) and with increasing elevation (8–12 m) in the Moore Creek locality. Petrographic microscopy of the carbonate grains in the sand fractions of the target paleotsunami sand sheets in the Moore Creek locality are shown in Table 7. Though not as distinctive as the larger shell fragments, the trace abundances of the carbonate sand-size grains in representative tsunami sand layers from core sites MOOR1, MOOR9, and MOOR12, confirm that the thin sand layers were derived from littoral or inner-shelf sediment sources. Other investigators have examined mollusan shells in paleotsunami deposits (Fujiwara et al., 2003) and have recently reported the presence of foraminfera tests in tsunami deposits from the Sumatra 2004 tsunami (Hawkes et al., 2007). The use of foraminfera was not tested in this study, but it could provide a complimentary technique to the use of carbonate shell fragments, as reported here.

4.4 Grain size

The sand grain size distributions from representative samples of tsunami sand layers in the Moore Creek locality demonstrate landward fining trends (Table 7). Population means of the sand grain samples decrease from 341–375 µm in the seaward site MOOR1 to 229-245 µm in the landward site MOOR12. The apparent differences between the sand population means from the seaward and landward core sites are statistically different at the 95% confidence intervals. Both the separation in distance (~ 350 m) and elevation (4 m) between the seaward and landward sites are thought to contribute to the small, but significant, landward fining of the mean sand size.

4.5 Runup elevations

Paleotsunami deposit elevations are taken from core site surface elevations and corresponding subsurface depths of tsunami deposits (Table 8**)**. There is a close correspondence between core site surface elevations as surveyed into registered benchmarks and as estimated by GPS located sites on the LIDAR digital elevation model (U. S. Geological Survey, 2011). For the runup elevation measurements shown here we use the benchmark survey elevation control (± 5 cm elevation accuracy) in all but 3 core sites. Elevation based on LIDAR is used for core sites MOOR13-MOOR15. Terminal sand sheet elevations reach 11–12 m NAVD88 in core sites MOOR12 and MOOR13.

The measured deposit elevations in the Moore Creek locality are corrected for paleo-sea level runup height based on the age of the paleotsunami event (Table 1) and an assumed net rate of sea level rise (1.0 m per 1000 years) for the study area during late Holocene time (Darienzo et al., 1994). Paleotsunami runup heights that are corrected for net sea level rise reach 13–15 m for tsunami events #3, #5 and #6 in the Moore Creek locality. It is assumed that the terminal sand sheet proxies for runup height underestimate actual flooding elevations. However, the apparent pinchouts of the corresponding paleotsunami debris layers near core site MOOR15 suggest that maximum recorded paleotsunami runup height is closely approximated by the terminal sand sheet deposits in the Moore Creek locality.

5. Discussion

5.1 Landward trends of paleotsunami deposits in proximal settings

Several parameters including tsunami deposit sand: silt ratio, sand layer thickness, and abundance of coarse grained shell fragments are found to substantially decrease with elevation gain (from 8 m to 12 m) over the short inundation distance of 450 m in the Moore Creek locality (Fig. 7). A small, but statistically significant, decrease of mean sand size is also documented in the paleotsunami sand layers in the Moore Creek cores sites (Table 7). We attribute these landward trends to decreases in tsunami flow velocity and turbulence with lansdward increases in floodplain elevation (Fig. 8). Terminal sand sheet layers are on the order of only a few centimeters in thickness, requiring extensive coring to recover tsunami sand layers from the bioturbated floodplain deposits.

5.2 Event runup heights

A total of three sand sheets that reach 11-12 m elevation are recorded during the last 3.2 ka in the Moore Creek locality (Fig. 8). The last two events (#5 and # 6) are attributed to large magnitude runups in other central Cascadia tidal basins, back-barrier wetlands, and beach plains (Peterson et al., 2010a; Peterson et al., 2010b; Schlichting, 2000). These two paleotsunami are correlated to long inundation events in the adjacent Beaver Creek floodplain (see Section 5.3 below). When adjusted for Paleo-sea level at the time of inundation (Table 8) the three paleotsunami sand sheets reach 13-14 m runup height at the landward side of the Moore Creek runup locality. Three of the 6–7 nearfield tsunami produced by ruptures of the central Cascadia megathrust during the last 3.2 ka yielded large runup elevations in the study area. These runups would have reached 15 m above the current O m NAVD88 datum. The remaining 3–4 paleotsunami exceeded 5 m runup height, as shown by tsunami deposits at the BEAV_D1 core site in the Beaver Creek locality (Fig. 4). These smaller magnitude tsunami did not leave sand sheet deposits above 9 m elevation in Moore Creek locality (Fig. 7). We assume that their maximum runup heights did not exceed 10 m elevation at the Moore Creek runup locality.

Core Site	Core top elev. (m)	Overland distance (m)	Tsunami deposit event #	Core depth (m)	Deposit elev. (m) NAVD88	Paleo-sea level (m)	Paleo-runup height (m)
1	7.98/8.0	10	# 3 TSL	1.00	6.98	-1.0	8.0
			# 5 TSL	1.26	6.72	-2.5	9.2
			#6-7 TSL	1.54	6.44	-3.0	9.4
2	8.14/8.2	20	#3 TSL	0.83	7.31	-1.0	8.3
			#5 TSL	1.00	7.14	-2.5	9.6
			#6-7 TSL	1.38	6.76	-3.0	9.8
3	8.29/8.2	90	#3 TSL	0.55	7.74	-1.0	8.7
			TDL ?	1.00	7.29	-2.0	9.3
			#5 TSL	1.15	7.14	-2.5	9.6
			#6-7 TSL	1.53	6.76	-3.0	9.8
4/5	8.40/8.4	130	#3 TSL	0.39	8.01	-1.0	9.0
			TDL ?	0.68	7.72	-2.0	9.7
			#5 TSL	0.91	7.49	-2.5	10.0
			#6-7 TSL	1.22	7.18	-3.0	10.2
8	9.33/9.5	180	#3 TSL	0.79	8.54	-1.0	9.5
			#5 TSL	1.66	7.76	-2.5	10.3
			#6-7 TSL	1.74	7.59	-3.0	10.6
9	9.69/9.7	180	#3 TSL	0.86	8.83	-1.0	9.8
			#5 TSL	1.19	8.50	-2.5	11.0
			#6-7 TSL	1.28	8.41	-3.0	11.4
10	10.57/11.9	270	#3 TSL	0.50	10.07	-1.0	11.1
			#5 TSL	0.78	9.79	-2.5	12.3
			#6-7 TSL	1.02	9.55	-3.0	12.5
11	10.52/10.6	280	#3 TSL	0.69	9.83	-1.0	10.8
			#5 TSL	0.98	9.54	-2.5	12.0
12	12.17/13.3	400	#3 TSL	0.54	11.63	-1.0	12.6
			#5 TSL	0.82	11.35	-2.5	13.8
			#6-7 TSL	0.91	11.26	-3.0	14.3
13	na/12.8	450	#3 TSL	0.51	12.3	-1.0	13.3
			#5 TSL	0.79	12.0	-2.5	14.5
			#6-7 TDL	0.98	11.8	-3.0	14.8
14	na/13.0	450	#3 TDL	0.4	12.6	-1.0	13.6
			#5 TDL	0.97	12.0	-2.5	14.5
15	na/13.2	540	#3 TDL ?	0.5	12.7	-1.0	13.7
			#5 TDL ?	0.85	12.3	-2.5	14.8

Table 8. Core site and paleotsunami deposit elevations in the Moore Creek locality. Core site data: core top elevation from total station survey to registered benchmark/LIDAR (m) NAVD88 and overland inundation flow distance (m) from the shoreline. Tsunami deposit: event number (#), depth in core (m) and computed elevation relative to NAVD88 datum. Paleo-sea level estimated for event ages #3 (~ 1.3 ka), #5 (~ 2.6 ka), #6 (~ 2.8 ka), and # 7(~ 3.2 ka) assuming 1 m/1000 year relative sea level rise. Tsunami runup height (m) equivalent to NAVD88 datum but adjusted for lower paleo-sea level at the time of inundation. See Fig. 5 for core site locations.

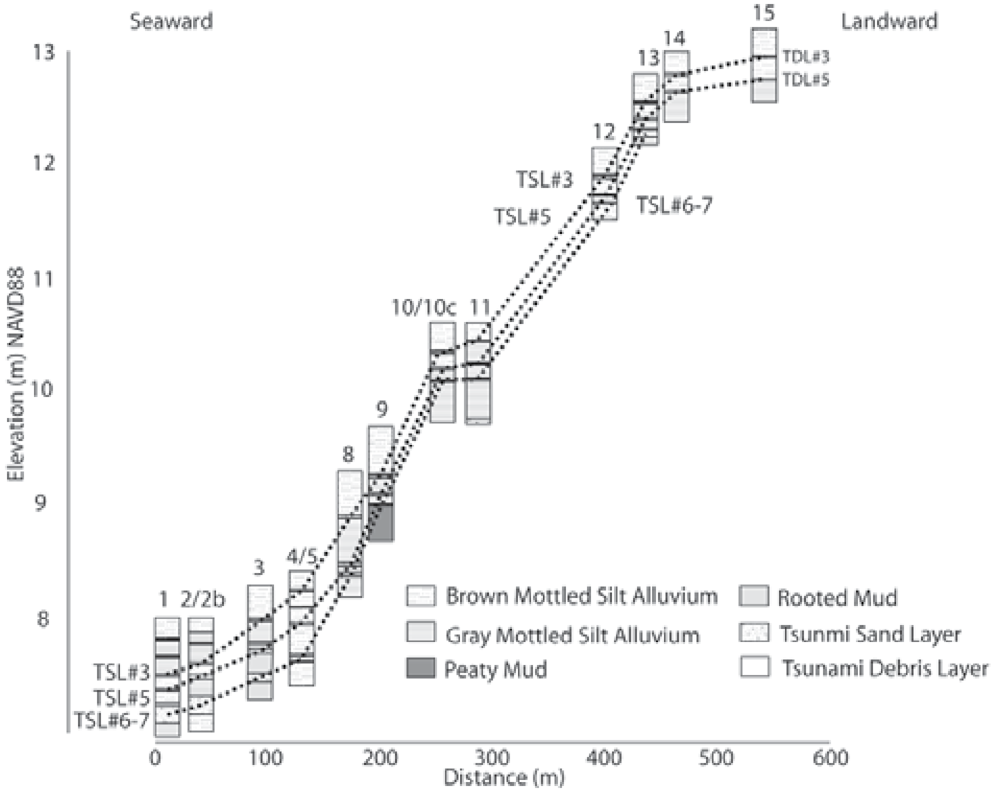

Fig. 8. Topographically corrected cross-section of stratigraphically correlated paleotsunami deposits (dotted lines) for events #3, #5, and #6–7 in the Moore Creek floodplain. Tsunami sand layers (TSL) pinchout to tsunami debris layers (TDL) with increasing distance and elevation from the present beach–terrace edge. Vertical exaggeration is ~ 100x. See Fig. 5 for core site locations.

5.3 Landward runup height attenuation in Beaver Creek

Using the maximum-recorded extents of tsunami sand sheet deposition as proxies for paleotsunami runup in Moore Creek and Beaver Creek (Fig. 2) we establish a runup height attenuation gradient for paleotsunami event #3 in the study area. Differences between paleotsunami event #3 sand layer elevations and runup distances in the proximal core site MOOR13 (12.3 m elevation at 0.45 km distance) (Table 8) and the distal core site BEAV03 (1.2 m elevation at 3.7 km distance) (Peterson et al., 2010a) yield an attenuation gradient of 3.4 m km^{-1} (Fig. 9). Using the attenuation gradient we extrapolate a shoreline runup elevation of 13.8 m at 0 m distance. Adjusting for Paleo-sea level (-1.0 m) at 1.3 ka we predict a runup height of 14.8 m based on paleotsunami sand sheet deposition. This extrapolated sand deposition height might underestimate actual surge height at the shoreline.

5.4 Test of runup height attenuation gradient at Cannon Beach

The landward gradient of runup attenuation is tested in another central Cascadia locality, Cannon Beach, Oregon (Fig. 1), which was previously surveyed for distal and proximal

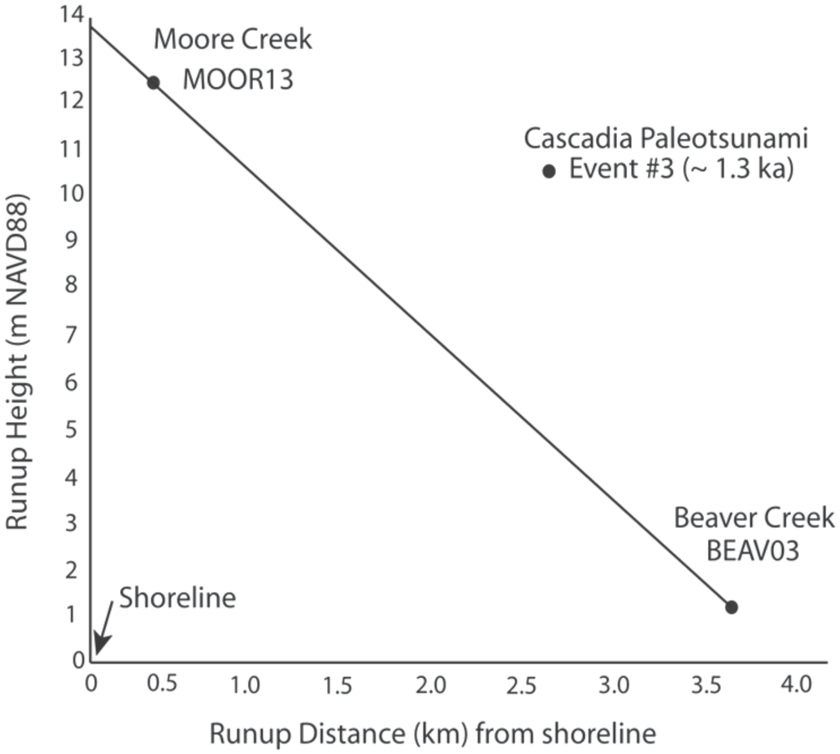

Fig. 9. Runup attenuation for the #3 paleotsunami event in Moore Creek and Beaver Creek in the study area. The position and elevation of terminal sand sheet deposition are from Table 8 in Moore Creek and from (Peterson et al. (2010a)) in Beaver Creek. The proximal runup site (MOOR13) represents terminal sand sheet deposition in a high-gradient creek floodplain perched on a seaward facing hillslope. The distal site (BEAV03) represents terminal sand sheet deposition in a low gradient floodplain developed in a broad alluvial valley.

runup records (Peterson & Cruikshank, 2007; Peterson et al., 2008). The terminal extent of paleotsunami sand sheet deposition from event #3 (~ 1.3 ka) was traced to site C72 (6.5 m elevation at 2.1 km landward distance). Using the attenuation gradient of 3.4 m km^{-1} over the runup distance of 2.1 km and the core depth corrected elevation of 6.5 m for the event #3 sand layer at site C72 (Peterson et al., 2008) a predicted shoreline runup elevation of 13.6 m is calculated for Cannon Beach (Fig. 10). The projected elevation of shoreline runup at Cannon Beach (13.6 m) is similar to that projected for the Moore Creek locality (13.8 m) at the shoreline for the paleotsunami event # 3 (Fig. 9).

Upland terrace sites in Cannon Beach lack ideal hosting deposits for recording paleotsunami deposits. However two localities in a very small gully floodplain adjacent to Coolidge Avenue in Cannon Beach (sites CANU116 and CANU119) were identified as potential runup sites based on anomalous sandy intervals (Fig. 10). CANU116 at 8.4 m elevation, and 220 m landward distance, contained two prominent quartz-rich sand layers at 14–16 and 49–51 cm depth (Fig. 11). The most landward extent of an anomalous sandy debris layer, including rounded granules, was observed at 64-67 cm depth in CANU119 at an elevation of

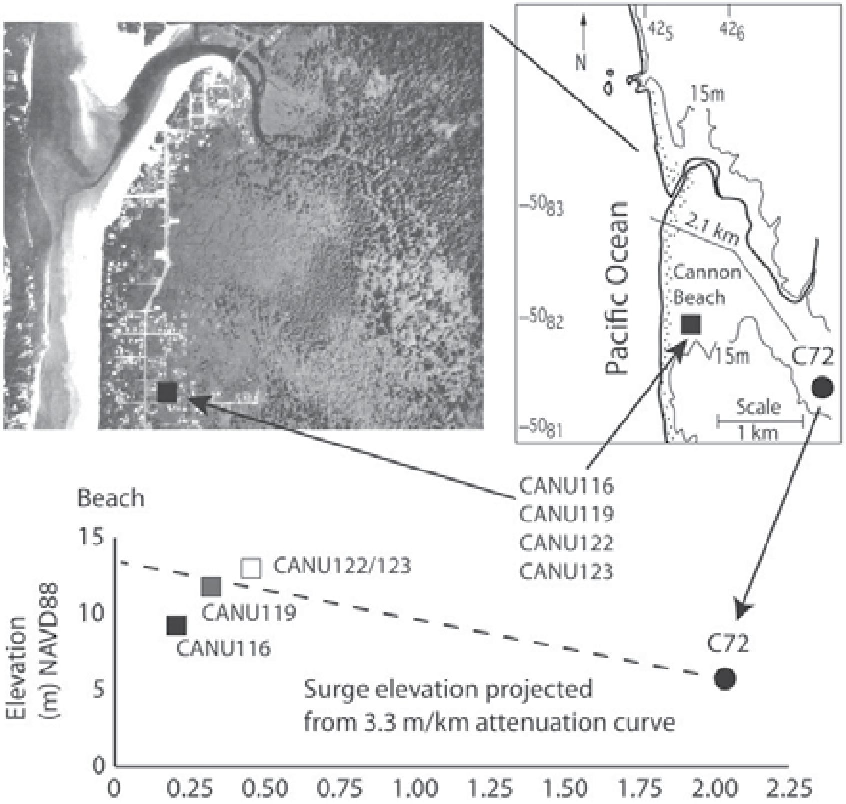

Fig. 10. Estimation of shoreline runup elevation for paleotsunami event #3 (~1.3 ka) in Cannon Beach, Oregon. Historic photograph of Cannon Beach shows Ecola Creek valley topography prior to extensive development in the middle to late 1900s. The proximal runup estimates are based on 1) terminal sand sheet deposition in core site C72 (solid circle in map inset) at 6.5 m elevation and 2.1 km flow inundation distance, and 2) reverse extrapolation of attenuation gradient 3.4 m km^{-1} (dashed line) to the shoreline (plot diagram). Adjustment for paleo-sea level yields a modern runup height of 15 m at the shoreline in Cannon Beach. Preliminary searches for possible paleotsunami sand sheets yielded two sand layers at CANU116 (UTM 5082190n 42542e) and a most landward extent of an anomalous sandy debris layer at CANU119 (UTM 5082054n 425584e) as shown in Fig. 11. No sand layer or sandy debris layers were observed at core sites CANU122 (UTM 5082134n 425662e) or CANU123 (UTM 5082078n 425654e). See Fig. 1 for the location of Cannon Beach in the central Cascadia margin.

11.3 m and a landward distance of 300 m. No sand layers were observed at CANU122 at 12.7 m elevation, or CANU1213 at 13.5 m, both at a distance of 440 m from the beach. The anomalous sandy layers at CANU116 and CANU119 were not radiocarbon dated at the time of the reconnaissance survey (2006) due, in part, to a lack of target runup elevations. Such target elevations are now provided by the projected runups from the attenuation gradient shown in Fig. 10.

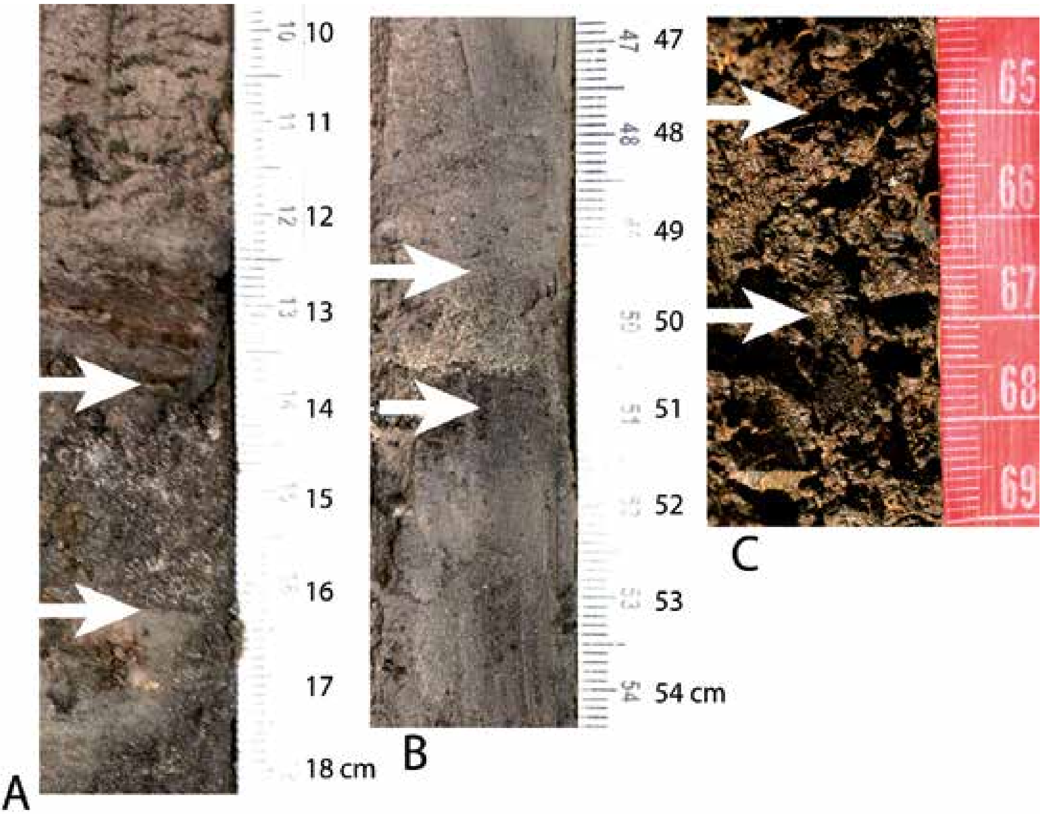

Fig. 11. Photos of target paleotsunami sand layers from CANU116 at 14-16 cm depth (photo A), CANU116 at 49-51 cm depth (photo B), and CANU119 at 64-67 cm depth (photo C). A detrital wood fragment at 13 cm depth overlies the upper sand layer in CANU116 (photo A). The lower sand layer in CANU116 shows a sharp bottom contact and fining-upward sand grain size, both features are characteristic of paleotsunami deposits. The sandy debris layer at 64-67 cm depth in CANU119 includes rounded granules, well above wind-blown grain size thresholds. All three layers contain rounded quartz grains (beach sand source mineralogy) but the target paleotsunami sand layers from CANU116 have yet to be radiocarbon dated.

6. Conclusion

Small creek floodplains (< 500 m from the shoreline and > 6-7 m elevation) provide stable hosting settings for recording prehistoric tsunami inundation events in the central Cascadia subduction zone. The floodplain silts extend back to 3–4 ka in time, permitting the potential geologic recording of anomalous sand sheets from 6–7 nearfield tsunami during that time interval. A total of 3-4 paleotsunami deposits exceed 8 m in elevation, and 3 paleotsunami sand sheets can be traced to 12 m elevation. Adjusting for Paleo-sea level at the time of inundation the estimated runup for the 3 paleotsunami at the shoreline is 15 m in height. Minimum runups for nearfield tsunami in the study area are greater than 5 m height, based on the geologic record of smaller scale tsunami in a creek setting with a low-threshold elevation (~ 4.5 m) for inundation. The measured runup heights for central Cascadia paleotsunami during the last 3.2 ka are 10+/- 5 m. An attenuation gradient of 3.4 m km^{-1} is estimated from terminal sand sheet deposition produced by the last large runup event (at ~ 1.3 ka) as recorded in both proximal and distal floodplain settings in the study area. The attenuation gradient permits an extrapolation of distal terminal runup records to yield estimated shoreline runup heights for this tsunami event in other similar floodplain localities in the central Cascadia margin. The prehistoric runup records can be used to test and/or calibrate numerically modeled tsunami hazard in the region. The methodology used here should have broad use in other susceptible coastlines that have not experienced catastrophic tsunami inundation in historic time.

7. Acknowledgments

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Part 2

Tsunami Effect on Infrastructures

4

Post-Tsunami Lifeline Restoration and Reconstruction

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Japan

1. Introduction

The 2004 Indian Ocean earthquake and tsunami caused severe damage to houses and infrastructure and resulted in massive human casualties in several countries. Although there have been several reports on the resulting damage to lifelines, processes for the restoration and reconstruction of the lifelines have not been reviewed well; these processes are important in view of the effects on people's life, the community, and industrial conditions. A lifeline refers to a vital infrastructure in our lives. As a city becomes modernized and its population increases, a lifeline service covers a larger area with a complicated network system. After the 2004 tsunami, it took as long as a few weeks, and sometimes several months, before the process of restoration and reconstruction was begun. The victims of the tsunami faced many problems that differed from those that occur after an earthquake. This chapter attempts to elucidate the post-tsunami lifeline restoration and reconstruction process from several points of view by using case studies from Indonesia, Thailand, and Sri Lanka. Tsunami restoration evaluation modeling and its application are discussed. Moreover, methods for town reconstruction planning for lifeline reconstruction are discussed.

Among the lifelines, adequate water supply is important to residential life. Most coastal residential areas, which are at the highest risk from a tsunami, use domestic water from shallow wells. After the 2004 tsunami, worldwide support facilitated the water-supply system to be reconstructed as part of the disaster reconstruction projects, and the residents in the affected areas changed their water-supply system from shallow wells to a pipeline network. The end of this chapter contains an analysis of the lifeline reconstruction and its long-term effects, with the focus on residential awareness of water use before and after the tsunami.

2. How are lifeline systems damaged by a tsunami wave?

In a lifeline system, electrical poles and facility buildings can be damaged by a tsunami wave in the same way that houses can be damaged. In the 2004 tsunami, pipelines were also damaged despite the fact that they were installed underground. The mechanism of lifeline damage under the tsunami wave is explained through spatial analysis of the underground pipeline damage and inundation distribution in a case study of southern Thailand.

2.1 Water-supply pipeline damage in Nam Kem village

The coastal area of Phang Nga province, in the southern part of Thailand, mostly uses domestic water from a shallow well. Only Nam Kem village uses water supplied through water-supply pipelines, with the water being drawn from Ta Kua Pa city (inland, east of Nam Kem village). At the time of the 2004 tsunami, the Provincial Water Works Authority [PWWA] of Ta Kua Pa had 2,000 customers, of which 300 resided in Nam Kem village. On the day of the event, the PWWA staffs closed valves on the upstream pipeline because the damage to the downstream pipeline was thought to be considerable. The main pipeline, with a diameter of 200 mm along the national main roadway, the Petch Kasem road, had no damage, whereas most of the pipelines near the shore were destroyed. Therefore, residents could not use water from the water-supply network. They could also not use water from shallow wells because of the inflow of salt water.

Many parts of the water pipelines were destroyed in the western part of Nam Kem village, as shown in Fig. 1, which illustrates the damaged and intact pipelines in the inundation zones. Whereas the water-supply pipelines located 200 m from the coastline were completely destroyed by the tsunami, no pipeline damage is seen in regions 500 m from the coast. The level of damage to houses is also confined to the inundation zone. The people of Nam Kem village were the most severely affected, with 199 killed and 255 missing, after the report of Bang Muang TAO (small district of Phang Nga province).

Pipeline damage was caused by collisions of driftwood and pebbles that were carried by the tsunami wave, as well as ground scouring caused by the tsunami. Coastal embankments and river bridge abutments were scoured, leaving the underground pipeline and surrounding facilities exposed (see Photo 1). There was extensive damage to the water meter because it was positioned above the ground and connected to fragile pipes (see Photo 2).

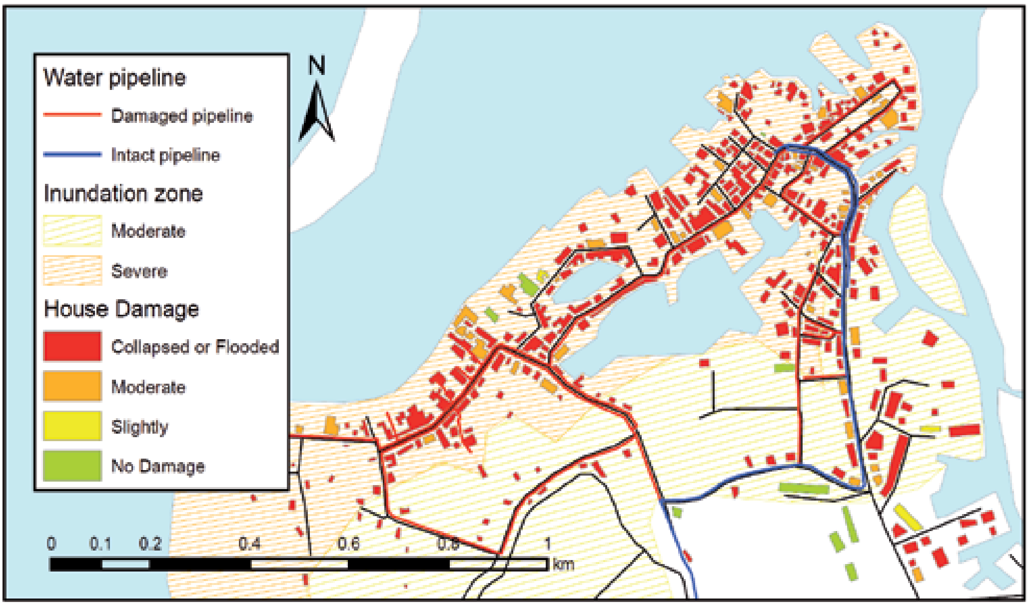


Fig. 1. Pipeline and house damage in Nam Kem village due to the 2004 tsunami. Inundation zones and house damage were taken from damage assessment reports of the local government. Water pipeline information is based on a PWWA report (PWWA, 2007)

The residential pipe on the customer side of the meter was generally a fragile vinyl pipe (VP), whereas the service pipe on the PWWA side of the meter was a flexible polyethylene pipe (PE). Although the vulnerable water meter sustained severe damage, the repaired meter and piping maintained the previous standards. In addition to the physical damage to the facilities, it is believed that the water-supply facilities were broken by scrapers during the recovery work after the tsunami since the location of the pipeline beneath the ruins could not be identified. Fortunately, the water purification plant was located in the mountains as far as 18 km from the coast, and it was undamaged.

Photo 1. Exposed pipeline after scouring of embankment soil (Phuket, Thailand)

Photo 2. Water meter above ground. Black-colored polyethylene pipe is the service pipe of PWWA, and the blue-colored vinyl pipe is the residential pipe (Khao Lak, Thailand)

2.2 Electric power supply network damage

The electric power supply for the 40,000 customers of Phang Nga province is managed by Provincial Electricity Authority [PEA] of Phang Nga. Out of the eight administrative districts, Khura Buri, Ta Kua Pa, and Thai Mueang sustained severe damage to their electric power facilities. The main facilities, including the aerial electric power line, service transformer, and electric power meter, were damaged. For instance, damaged lengths reached 36 km for the high voltage line and 28 km for the low voltage line. As shown in Fig. 2, the high-voltage line ran along the main roadway, the Petch Kasem road, parallel to the coastline. The interruption in the inland low-voltage line was caused by the tsunami striking the high-voltage trunk lines along the coast. The damage rate (damaged aerial electric line length per total line length) was 80 to 100% in the inundation zone, where the inundation height was estimated to be 6 to 7 m.

The electric power service interruption was caused by the collapse of electric poles because of the tsunami (Thailand witnessed a weak earthquake, so most of the damage was caused by the tsunami). Some poles had cracks at the bottom and others had cracks at the center. The locations of the cracks varied because of the random nature of the colliding driftwood (see Photo 3). The other cause of damage was the scouring of the pole foundations (see Photo 4), which caused the poles to tilt or fall, resulting in the snapping of the power lines.

The electric power supply through an underwater cable (400 m length) from Nam Kem village to Kho Khao Island was interrupted because the electric tower on the coast of Nam Kem village was flooded, although the underwater cable itself was not damaged. Similarly,

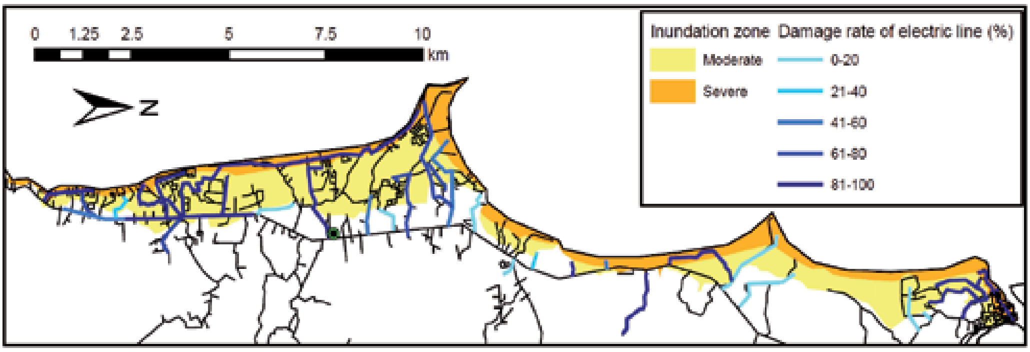


Fig. 2. Inundation zone and electric power line damage in Khao Lak, Thailand. Damage rate is after Provincial Electricity Authority of Phang Nga.

Photo 3. Electric pole tilted by collision with tsunami driftwood (Khao Lak, Thailand)

Photo 4. Electric pole tilted as a result of the scouring of the ground by the tsunami (Khao Lak, Thailand)

the underground electric power cable along Karon Beach in Phuket was not damaged. Underground cables seem to fare better in a tsunami. Even so, the underground cable was used only at Karon Beach in Phuket and but in Phang Nga province because of its high cost. Underground cables contribute to the preservation of the landscape in tourist areas, as well as disaster mitigation. Comprehensive regional planning of lifeline infrastructures focusing on land use is expected.

3. Lifeline-related business recovery

3.1 Business continuity management after a tsunami

Destructive natural disasters such as earthquakes, tsunamis, floods, and typhoons frequently occur all over the world and cause a great deal of property damage and loss of life. Many businesses are also damaged in these disasters. The recovery of business in the affected areas is a big issue for the local societies. Interest in "business continuity management (BCM)" after such disasters has recently been increasing among state governments, local governments, and business organizations. For example, the Cabinet Office of Japan (2005) created a guideline on business continuity. BCM involves the preparation of plans, the allocation of resources, and the implementation of processes such that an organization can recover quickly and safely from an interruption (crisis, emergency, event, etc.), with minimum negative impact to people, premises, assets, and operations.

Understanding the process of lifeline restoration and lifeline-related industrial business recovery helps in planning and preparing for future disasters. A method is proposed to evaluate the functionality of a business after a tsunami, with a focus on lifeline function. This method has several modules, including damage estimation of business base (building, equipment, and lifeline) caused by the tsunami, a rate-to-time model to restore the business bases, and the functionality of the business introduced by facility restoration and its influence on the business (Kuwata *et al.*, 2006). ATC-13 (Applied Technology Council, 1985) provided a methodology to evaluate the functionality of a facility, including lifeline effects after an earthquake in California. Referring to ATC-13, the present study proposes a new model of damage estimation and recovery curve for a tsunami. As a case study, the impact of a tsunami on industries and the subsequent restoration process were studied based on an interview survey done in southern Sri Lanka after the 2004 Indian Ocean tsunami, and the survey results were applied to the proposed model.

3.2 Post-tsunami business recovery in Galle, Sri Lanka

A survey on tsunami damage to a business base and the restoration process was carried out in Galle, southern Sri Lanka, in late September of 2005, 9 months after the 2004 tsunami. Interview respondents included company owners and other relevant people who have businesses from several industries around the coastal areas. The main industries in Galle are fishing and tourism, and each company is relatively small, with only a few employees (see Photos 5 and 6). The total number of responses in this survey is only 52, because the survey period was limited and the interviews were done face-to-face. The questions were on tsunami inundation levels, physical damages to buildings and equipment and recovery time in days, tsunami damages to lifeline services and recovery time in days, and business restoration processes with respect to the time since the tsunami.

Fig. 3 shows the business recovery process of the local industries, which is the average of responses in each industry, as shown weekly for the first three months and every couple of weeks after that. Here the rate of business recovery is defined as the sales of their products compared to that before the tsunami based on the interview of owners. As is readily seen, lifeline and financial (banking) businesses were recovered remarkably quickly. The reason for the rapid recoveries that office buildings did not have extensive damage and their officers could respond to those damages promptly. They could also receive emergency relief and repair workers from the unaffected offices thanks to mutual cooperation. The reason the banks recovered rapidly is that their main offices are in Colombo, and they served as a back-up system for customer information. Communications and relationships in non-crisis times are thus important and effective in cases of emergency.

The recovery of agriculture was relatively quick because the farmers were far from the sea and did not have major damage to their business base. However, it took a long time for the agricultural sectors to be completely restored because it was necessary to purify the soil, which contained saline due to the tsunami. Nine months after the tsunami tourism, manufacturing, and wholesale and retail trade businesses had been slowly recovered to the level of about 60%. In Galle, a large number of collapsed houses remained untouched at the time of the survey, and the local society was still in the process of recovery. Several hotels had resumed business, but most visitors were domestic tourists, restoration relief teams, or research groups. Foreign vacationing tourists had not returned as of yet. Some fishermen lost their boats in the tsunami and could not buy new boats. The other fishermen said that they could not sell fish during the few months after the tsunami because the local victims of the tsunami did not want to eat them. The effects of tsunami damage vary depending on the industry, and they go beyond the physical damage to the facilities.

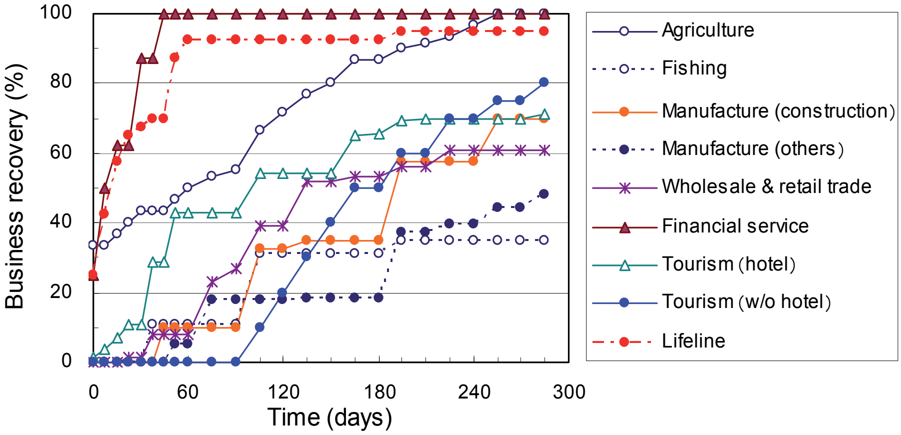


Fig. 3. Business recovery process of industry from tsunami in Sri Lanka

Photo 5. Rope production factory (Galle, Sri Lanka)

Photo 6. Ice production factory (Galle, Sri Lanka)

3.3 Post-tsunami business base restoration modeling

An evaluation method for tsunami damage and the restoration curve of the business base is proposed herein. The business base used in this study involves building, equipment, and lifeline service. Fig. 4 shows the schematic evaluation model, including damage estimation of the business base caused by the tsunami, rate-to-time model for restoration of the business bases, and the business recovery rate resulting from facility restoration and its influence on the business.

The restoration rate is expressed probabilistically by the damage state of a facility and its conditional restoration rate. Business restoration is not determined by the facilities and lifeline service because their effects vary depending on the type of business. This model just considers the business basis from a physical point of view. These effects are considered based on the importance factors.

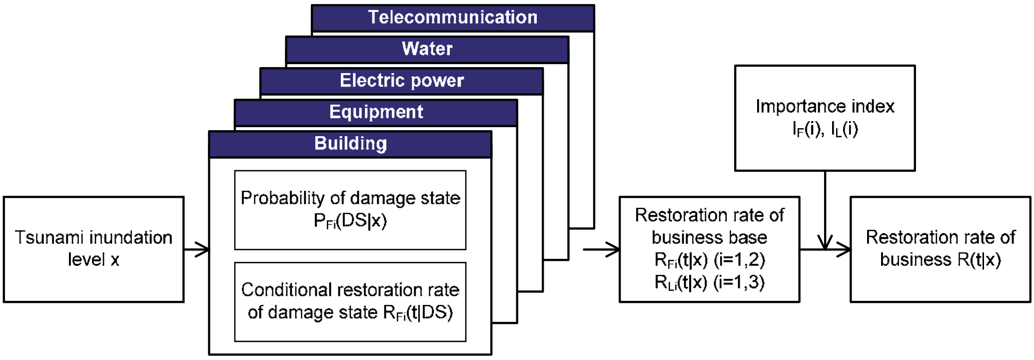


Fig. 4. Business restoration evaluation model after tsunami disaster considering facility and lifeline services

First of all, define the tsunami intensity level. When the hazard is an earthquake, ground motion such as peak ground acceleration and seismic intensity would be an index of intensity level. Shuto (1992) defined tsunami intensity by the square value of the tsunami inundation height and categorized damage based on previous tsunami damage records in terms of its index. This study does not use the tsunami intensity as the square value of inundation height because of the consideration of the limited inundation height in the case study area. The tsunami intensity levels are determined as five discrete levels of inundation height; levels 1 to 5 correspond to no inundation, less than 1, 2, and 3 m, and over 3 m, respectively.

The restoration of a facility such as a building and its equipment is defined such that the damaged facility is restored to the same state it was in before the tsunami. Since the damage state affects the expense and restoration time, the damage state (*DS*) is classified into five categories ranging from A (no damage) to E (severe damage). When the probability of the damage state of a facility under a given tsunami intensity level and the function of the conditional restoration under the damage state of a facility are given, the restoration rate of facility under a given tsunami intensity level is obtained by

$$R_{Fn}(t\,|\,x) = \sum_{DS=1}^{5} R_{Fn}(t\,|\,DS) P_{Fn}(DS\,|\,x) \tag{1}$$

where $R_{Fn}(t\,|\,x)$ denotes the restoration rate for the facility F_n at time t in days for a given tsunami intensity level x, $R_{Fn}(t\,|\,DS)$ denotes the conditional restoration rate for the facility F_n at time t in days for a given damage state DS, and $P_{Fn}(DS\,|\,x)$ denotes the probability of a damage state DS of the facility F_n for a given tsunami intensity x

The DS of a facility is classified into five discrete categories. Each of these categories corresponds to a damage rate of the facility, y, which is treated as a random variable with a corresponding probability distribution, $f(y\,|\,x)$, at every tsunami intensity level, x, as shown in Fig. 5. Each DS has a representative value of damage rate as listed in Table 1, and the probability of the damage state is expressed by section integral calculus of the distribution's lowest damage rate y_1 to the highest damage rate y_2 when given the damage rate distribution $f(y\,|\,x)$ as follows.

Damage state *DS*	Central value of damage state k_{DS}	Interval of damage rate ($y_1 \le y < y_2$) in %
A	1.00	$87.5 \le y \le 100$
B	0.75	$62.5 \le y < 87.5$
C	0.50	$37.5 \le y < 62.5$
D	0.25	$12.5 \le y < 37.5$
E	0.00	$0 \le y < 12.5$

Table 1. Definition of damage state *DS*

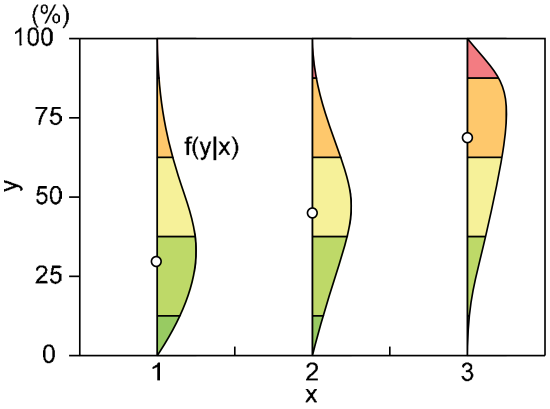


Fig. 5. Schematic model of tsunami intensity level *x* and damage rate, *y*

$$P_{Fn}(DS \mid x) = \int_{y1}^{y2} f_{Fn}(y \mid x) dy \tag{2}$$

A distribution model of the damage rate is assumed as the beta distribution between 0 and 1 as follows. Its parameters, *q* and *r*, are estimated by statistical inference.

$$f_{Fn}(y \mid x) = \frac{y^{q-1}(1-y)^{r-1}}{B(q,r)}\ ;\ 0 \le y \le 1 \tag{3}$$

Regarding the restoration rate model, the concept is based on the method by Nojima and Sugito (2005). The conditional restoration ratio of the damage state for a facility, $R_{Fn}(t \mid DS)$, can be expressed by the central damage rate of the damage state, k_{DS}, and the cumulative density function of the conditional restoration rate, $r_{Fn}(t \mid DS)$, as shown in Eq. (4).

$$R_{Fn}(t \mid DS) = 1 - k_{DS} + k_{DS} \int_0^t r_{Fn}(\tau \mid DS) d\tau \tag{4}$$

A probability density distribution of restoration rate, $r_{Fn}(t \mid DS)$, is assumed as the gamma distribution as shown in Eq. (5). Its parameters, v and k, are also estimated by statistical inference.

$$r_{Fn}(t \mid DS) = \frac{\nu(\nu t)^{k-1} e^{-\nu t}}{\Gamma(k)}\ ;\ t \ge 0 \tag{5}$$

Three kinds of lifelines, all of which are related to business activity, are considered: water supply, electric power, and telecommunication. Contrary to the business facility, the lifeline facility covers a widespread area, and therefore, the damage to the lifeline facility is also widespread. If the service to end users of a lifeline is functioning even after a natural disaster, the lifeline is not an obstacle for business recovery. Hence lifeline damage for business should be taken into account not based on its physical damage but rather on its functional damage. This study thus considers the functionality of lifelines on the user side.

The concept of an evaluation model of lifeline restoration is similar to that of the business facilities. Here, the damage state of lifeline systems is categorized into two states regardless of whether the lifeline is functioning. When the lifeline system is functional, the representative value k_{DS} of the DS becomes 0, and the state of restoration rate $R_{Ln}(t \mid DS, DS = \mathit{functional})$ becomes 1. In contrast, when the lifeline is not functional, k_{DS} becomes 1, and $R_{Ln}(t \mid DS, DS = \mathit{not\ functional})$ gives the cumulative density distribution of the conditional restoration rate.

3.4 Application of post-tsunami restoration model

3.4.1 Facility restoration

The proposed restoration model was applied to estimate the restoration curves according to the tsunami intensity based on the collected data in southern Sri Lanka. First of all, damage state parameters and restoration rate parameters were calculated based on the equations presented above. The restoration process and resistance to tsunami force vary depending on the type of building, the conditions of the facilities, and so on. In the present study, we do not have enough responses to analyze these factors separately. All the buildings for different industries are assumed to have the same resistance and are arranged without distinguishing between industrial classifications. Only answers from the fishing industry, which is dependent to fishing boats and is quite different from the others, were removed from this analysis.

Tables 2 and 3 list the mean and variance of the observed building and equipment damage rate, y, and beta distribution parameters for the different levels of tsunami intensity by the method of moment. If the tsunami level is 0 (no inundation), it can be concluded that there was no physical damage to the building and facilities. In addition, as the number of responders of tsunami intensity levels 2 and 3 is limited, their number is modified by adding weighted responders from the previous and the next intensity level.

As shown by the results in Tables 2 and 3, the mean damage rate increases according to tsunami intensity level, and the variance of levels 2 and 3 shows high values. Thus, the probability distribution function of damage rate has two peaks between borders.

x	N	$E(y)$	$Var(y)$	B-dstrb. parameter	
				q	r
1	3	0.167	0.021	0.94	4.72
2	8*	0.560	0.151	0.35	0.28
3	14*	0.669	0.119	0.57	0.28
4	15	0.783	0.115	0.37	0.10

Table 2. Parameters of building damage rate, y (%), due to the tsunami intensity level, x

x	N	$E(y)$	$Var(y)$	B-dstrb. parameter	
				q	r
1	3	0.167	0.083	0.11	0.56
2	6*	0.563	0.235	0.03	0.02
3	14*	0.769	0.115	0.42	0.13
4	17	0.912	0.031	1.47	0.14

Table 3. Parameters of facility damage rate, y (%), due to the tsunami intensity level, x

Tables 4 and 5 list the probabilities of the building and equipment damage state using the beta distribution's parameters. For the damage states A and B, the probability increases as the tsunami intensity level becomes large. Comparing probabilities between building and equipment, high probability appears at the severe damage state in the equipment rather than the building.

DS	Tsunami intensity level x (inundation height h (m))				
	0	1	2	3	4
	h=0	0<h≦1	1<h≦2	2<h≦3	h>3
A	0%	0%	36%	44%	67%
B	0%	1%	15%	18%	9%
C	0%	9%	11%	13%	6%
D	0%	41%	14%	13%	7%
E	100%	49%	24%	12%	11%

Table 4. Probability of building damage state, $P_{Fn}(DS\,|\,x)$

DS	Tsunami intensity level x (inundation height h (m))				
	0	1	2	3	4
	h=0	0<h≦1	1<h≦2	2<h≦3	h>3
A	0%	6%	54%	64%	80%
B	0%	6%	2%	11%	12%
C	0%	6%	1%	7%	5%
D	0%	10%	2%	8%	3%
E	100%	71%	42%	11%	1%

Table 5. Probability of equipment damage state, $P_{Fn}(DS\,|\,x)$

Then the parameters of the probability density distribution of the restoration rate, $r_{Fn}(t\,|\,DS)$, are estimated in every damage state of building and equipment. Even 9 months after the tsunami (at the end of September, 2005), most fisheries were under the process of restoration or had not been restored yet. Thus responders from the fishing industry were removed from the analyses. A total of 5 out of 29 responders (building/equipment or both) had not been recovered at the time of the survey. The government announced that the area within a 100 m buffer zone from the shore would not be supported. This regulation would also hamper a quick restoration. Here, the number of days until restoration completion of the above not restored building/equipments is considered to be 360 days.

In Tables 6 and 7, the parameters of the probability density distribution of restoration rate in the each damage state for buildings and equipment are presented, respectively, using the gamma distribution by the method of moment. The damage state "*D*" of Table 7 is assigned from relations with recovery days of other damage states because of a lack of records. As the damage state becomes severe, the mean of the restoration days gets longer.

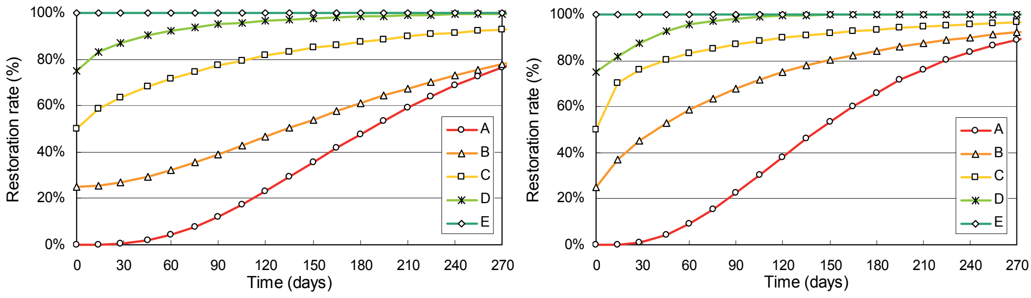
DS	*N*	$E(t)$	$Var(t)$	Gamma- dstrb. parameter k	v
A	14	204.6	11894.1	3.52	0.0172
B	3	220.0	22800.0	2.12	0.0096
C	2	130.5	23980.5	0.71	0.0054
D	10	54.9	4887.0	0.62	0.0112

Table 6. Parameters of restoration density function of damage states for buildings

DS	*N*	$E(t)$	$Var(t)$	Gamma- dstrb. parameter k	v
A	18	158.9	7607.5	3.32	0.021
B	4	113.8	16156.3	0.80	0.007
C	5	76.2	15702.2	0.37	0.005
D	2	36.4*	1000.0*	1.32	0.036

Table 7. Parameters of restoration density function of damage states for equipment

Furthermore, the conditional restoration rate of each damage state is shown in Figs. 6 and 7. If the building is in damage state "A" or "B", it has a dramatically slow restoration; in contrast, the restoration curve is convex if it is in another damage state. In other words, if the industrial building and equipments were completely destroyed or washed away by the tsunami wave, more time was needed for restoration because of the cost of new construction. Moreover, with regard to the equipment, the damage state A shows a concave restoration process, but other damage states show fast restoration.



(a) Building damage state, $r_{Fn}(t\,|\,DS)$ (b) Equipment damage state, $r_{Fn}(t\,|\,DS)$

Fig. 6. Restoration rate of damage state

3.4.2 Lifeline restoration

Here, we estimate the restoration process of lifeline systems such as electricity, water supply, and telecommunication. In this regard, the actual probability of the lifeline damage state and the restoration days indicated by the responders are employed because there is not enough information on the lifeline network system and the inundation area to be analyzed. Furthermore, the number of restoration days for the users is much higher than that of the main network reported by lifeline companies. Fig. 7 shows the supply interruption rate of the lifeline companies due to tsunami intensity level. It shows a 20 to 50% interruption of lifeline even though the area had not been hit by the tsunami wave. In addition, the electricity and water-supply services stopped completely when the inundation level was more than 2 m. Thus, it can be concluded that the above-ground lifeline facilities such as electric power and water meters are easily destroyed by tsunami waves. The interruption in telecommunication was less than that for other lifelines because of the functioning of mobile phones during and after the tsunami.

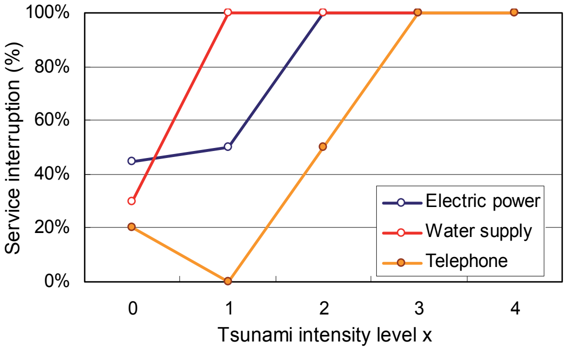


Fig. 7. Lifeline service interruption by tsunami intensity level

Similar to the facilities, the probability density distribution of the restoration rate was estimated using the gamma function by the method of moment as shown in Table 8. We had some responders whose lifeline services had not been recovered at that time. Because the outside buildings were still under construction, it was not possible to install inside facilities. In this study, we have removed those answers from the analyses. The mean number of days for water-supply restoration was 58 days, and that for electric power supply and telecommunication was 39 days. Fig. 8 shows the comparison of the values observed and the proposed model of lifeline services. The proposed model could express the characteristics of observation values appropriately.

Ln	*N*	*E*(*t*)	*Var*(*t*)	Gamma- dstrb. parameter	
				k	*v*
Water	18	58.3	3644.2	0.93	0.016
Power	26	38.5	2512.2	0.59	0.015
Telecom.	15	38.7	1381.1	1.08	0.028

Table 8. Parameters of the restoration density function of lifeline service

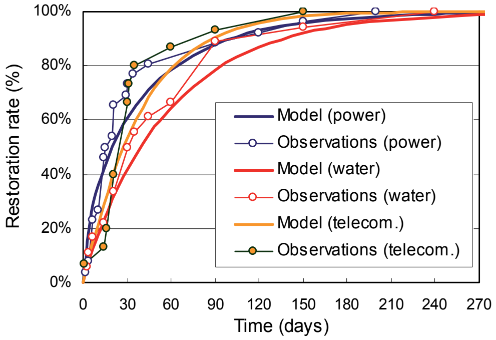
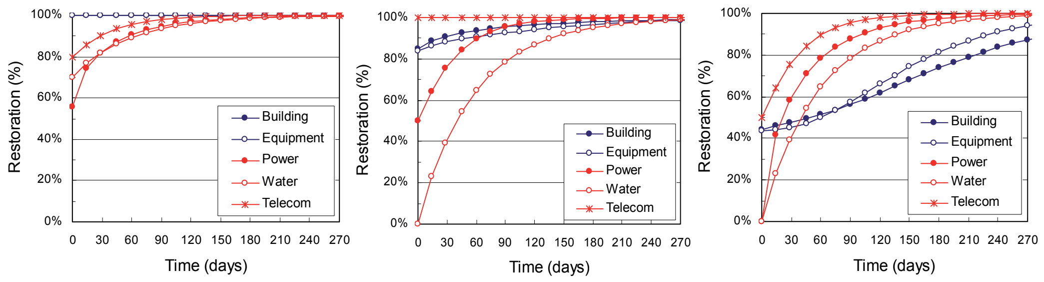


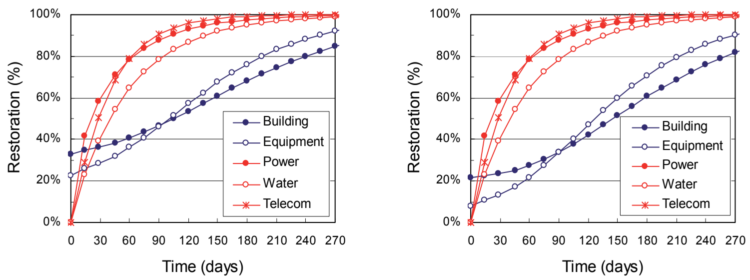
Fig. 8. Restoration curves of lifeline service

3.4.3 Business base restoration under inundation height

The restoration curves of business facilities and lifelines under the same tsunami intensity level are compared, as shown in Fig. 9. As can be seen in this figure, business facilities such as building and equipment are restored sooner than the lifelines if the tsunami intensity level is either 1 or 2. However, business facilities are restored slower than lifelines if the tsunami intensity level is 3 or higher. When the tsunami inundation height is higher than 1 m, the business recovery depends more strongly on the business facilities rather than the lifeline.



(a) Level 1(no inundation) (b) Level 2 ($h \leq 1$ (m)) (c) Level 3 ($1<h \leq 2$ (m))



(d) Level 4 ($2<h \leq 3$ (m)) (e) Level 5 ($h>3$ (m))

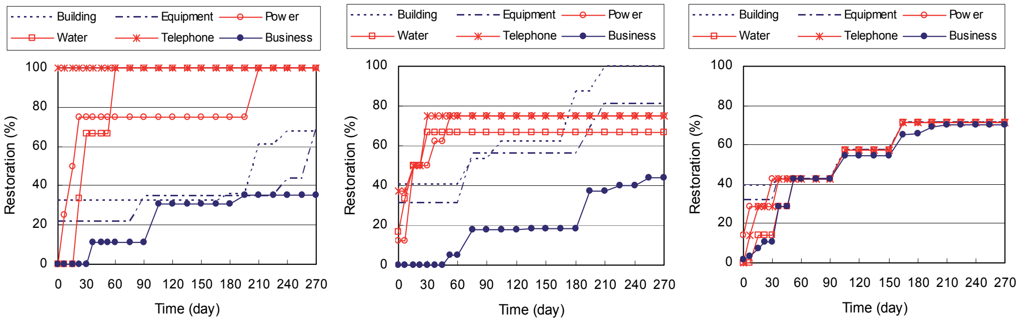
Fig. 9. Restoration curves of business bases by tsunami intensity level

It should be noted that lifelines are damaged even in places where the tsunami does not reach, as is shown in Fig. 9(a). This is because the lifeline is a system that works in a wide area. Moreover, since the lifeline is managed as a public service, its restoration is relatively rapid. The restoration of buildings and equipment, which are mostly private property, is very slow, especially in the first three month after a disaster, relative to the lifeline.

3.5 Restoration processes for business bases and entire business

Fig. 10 shows the temporal change of business base restoration rate for the three selected types of industry (fishing, manufacturing, and tourism). The observed temporal changes of entire business recoveries for each industry are also shown (same as Fig. 3). The entire business recovery is the same as or smaller than the restoration of the business base. For the fishing industry, sales depend strongly on equipment (fishing boat) restoration. While the lifeline is recovered soon in the manufacturing industry, business restoration is connected to facility restoration. For tourism (hotels), both the restorations of the entire business and the business base are almost the same. It is indicated that in the first few months, lifeline services were restarted at a slightly damaged hotel, and an extensively damaged hotel was restored with lifeline repair a few months later. In other words, the hotel industry cannot run without a lifeline service. The results of a comparison of restoration processes show that the influences of the business base on the entire business functionality are different among the industries.

The failure of the lifeline systems affects the residual function of societies in a variety of ways. ATC-13 (Applied Technology Council, 1985) provided a methodology for evaluating the impact of lifeline failures on the loss of function of particular facilities, and they also established an index called the importance factor. Important factors were developed based on the judgment of experts, and they were prescribed for California conditions only. Thus, the importance factors of lifeline systems are examined based on the results of a survey in Sri Lanka, with reference to the methodology of ATC-13.



(a) Fishery (b) Manufacture (others) (c) Tourism (hotel)

Fig. 10. Restoration processes of business bases and entire business

The importance factor examined in this study is only for three lifelines: water supply, electric power, and telecommunications. Each industry will be given three importance factors. The multiple regressions model considering three explanatory variables in terms of functionality of the lifelines is used. Observations of each variable are used from the data by the mean values taken every few weeks for each industry, as in Fig. 3. The results show that the estimated importance factors are mostly close to 1.0, which indicates that lifelines have a severe effect on business activity (Kuwata *et al.*, 2006). In particular, all the factors of financial institutions, hotels, and lifeline businesses are 1.0. These factors are much larger than those in ATC-13. When a business facility and several lifelines lose functionality at the same time, it is considered that the interrelation of business bases increases and the importance factor become large.

3.6 Remarks on business restoration model

The evaluation model of restoration curves for the business base was applied from the results of the interview survey of businesses in southern Sri Lanka. When buildings and equipment have extensive damage or are flooded completely, their restoration starts slowly in the first few months. The business restoration depends more strongly on business facility restoration than lifeline restoration if the tsunami inundation is higher than 1 m. The lifeline interruption caused by the tsunami affected business continuity more than in previous studies.

The concept of a restoration model is applicable to those businesses that are flooded by a tsunami. The damage rate and restoration curve estimated in this study is based on the limited number of responses. The parameters shown herein may have to be examined using additional responses.

Although the business recovery seems to be related to several social factors, such as regional policy of disaster recovery, regulation, culture, and psychological issues of customers, this model deals only with the physical aspect of facilities. These social factors should be clarified in future work.

4. Community-based lifeline reconstruction planning

Disaster reconstruction planning is generally necessary to make the affected area stronger than it was before the disaster. It provides the opportunity to review the vulnerability of the town to earthquakes and tsunamis, and to create a vision for development between government and community. If the planning vision or procedure fails, the community might not survive. Therefore, it is important for the suffering community to heal and persevere after the disaster. The disaster reconstruction planning discussed herein targets the area affected by the tsunami. Houses collapsed and were swept out by the wave, leaving an area of land with a cleared surface. Drastic town planning is easier to implement in this area rather than an earthquake-affected area, where the damaged houses are unevenly distributed.

Lifeline reconstruction planning follows the land readjustment of town lots. Through the reviews of disaster reconstruction planning at two tsunami-affected areas—Nam Kem village, Thailand and Aonae district, Japan—the implementation procedure between the local government and community is discussed. As part of disaster restoration including readjustment, the lifeline network can be completely renovated and become strong in terms of network system, although the general procedure of lifeline restoration after the earthquake is to replace only the broken or leaked pipe with the new pipe and to keep the former system of the pipeline network. Therefore, post-tsunami lifeline reconstruction has a sense of new construction.

4.1 Town reconstruction planning at Nam Kem village, Thailand

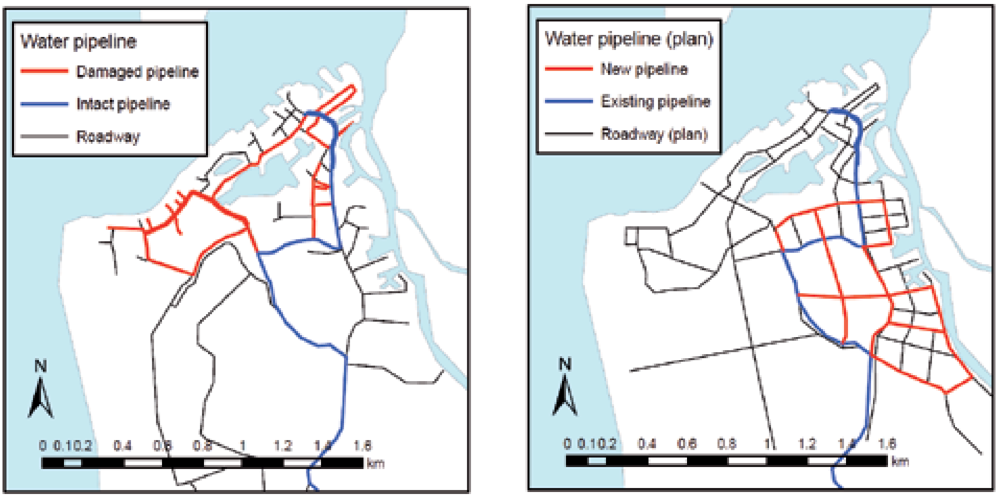
The tsunami damage to the underground water supply pipeline at Nam Kem village, Thailand was shown above. In addition to the water-supply pipeline, houses also almost collapsed near the coast. To secure the safety of residents and coastal property, the Department of Public Works and Town Planning (hereafter, DPT), Ministry of the Interior, Thailand proposed a town reconstruction plan for Nam Kem village shortly after the tsunami, as shown in Fig. 11. This plan divides the village into four types of land-use areas (public, fishery, living, and monument & sightseeing), and it provides new roadways, parts of which are suitable evacuation routes. It seems like an ideal land readjustment project from the point of view of land use planning. On the other hand, it would force local fishery residents to move far from the coast.

In fact, the destructive tsunami damage at Nam Kem village had received a lot of attention from domestic and international organizations. They sent much disaster relief and donations to help restore the houses of the victims. This support helped the village to recover earlier. Under military management, permanent houses built in a couple of weeks were provided to those who had lived in the same place as before. Within three months after the tsunami, the affected residents started coming back to their rebuilt houses. This process was so quick that the affected community, local government, and central government, such as DPT, could not participate in the town reconstruction. The community relationships were strong because the residents have lived there for a long time, spanning many generations. They did not accept the changes to their livelihoods and residences based on the DPT town readjustment plan, and they insisted on restoring the village to its pre-tsunami state.

Since the land readjustment planning was accepted in the disaster restoration planning and the house rebuilding was fast, the lifeline recovery in the village was also installed in the same place as before. According to the DPT planning, the cost of the planned water-supply pipeline is estimated by the network map, as shown in Fig. 13 (2). When the repair costs of the damaged pipelines and the construction costs of the planned pipeline are compared, as shown in Fig. 12, the costs are 117 thousand USD and 105 thousand USD, respectively, which are not so different. Similarly, the costs for the electric power line are also not very different from each other. It is observed that the cost for lifeline facilities is not different between the new plan and the repair scenario.

Whether residents move and live in a safer place or remain in the community depends on the communication between the local community and the government. The roadway administrator and lifeline companies may join the discussion, providing information for safer town development. Although they reject the idea of moving, the town designer and infrastructure organization would agree to rebuild better facilities. Three years after the tsunami, most houses were rebuilt within 500 m from the coast, as before. The population did not increase very much, but water users increased from 300 customers to 600 customers. The vulnerable parts, including the water meter mentioned above, have not improved from the former equipment. The shallow well filled with seawater cannot be restored.

Fig. 11. Nam Kem village reconstruction planning (Source: DPT, Thailand)



(1) Current pipeline after tsunami (2) Planned pipeline based on DPT planning

Fig. 12. Nam Kem village reconstruction planning (DPT, Thailand)

4.2 Town reconstruction planning of Aonae district, Okushiri

The Hokkaido southwest-off earthquake (M7.8) that hit Okushiri Island at 22:17 (local time) on July 12, 1993 caused extensive damage and resulted in 172 deaths and 27 missing people; the population of the island was 3700. Aonae district at the south cape of the island, where fishing was the main industry, was the most severely affected part of the island. Tsunami and post-earthquake fires were the main causes of death and destruction. In total, 107 people were killed or missing in Aonae district alone. Those who had escaped to the hill survived. In inundated or burned areas, very few wooden houses remained. Incidentally, half of the direct damage from the tsunami was inflicted on infrastructure and port facilities.

The victims evacuated the shelter after one and a half months, and they stayed in temporary houses for three and a half years, with 900 people in total. Okushiri town established a disaster restoration office three month after the tsunami and aimed to complete the disaster restoration planning in five years. Its disaster reconstruction planning was supported by the national government and the Hokkaido prefecture. The reconstruction project that was presented to the Aonae district consisted of four parts: the fishery village environmental renovation project, the roadway reconstruction project, the disaster recovery project (construction of a tide wall), and the group relocation project for disaster prevention. The tide wall, which was built to a height of 6 m after the tsunami in 1983, was reinforced with a height of 5 additional meters. The wall height of 11 m is the same as the wave height of the last tsunami. The fishery village environmental renovation project was responsible for the reclaimed land development behind the high-raised wall. New roadways, water supply, and waste water drains were constructed over the reclaimed land, as shown in Fig. 13. When constructing the reclaimed land, the local government bought all the lots from the residents and readjusted the roadway and the lots. After the lot readjustment, residents bought land from the government. This process requires land renovation for disaster prevention, financial contribution from the local government, financial support from the national government, and the patience of the residents during reconstruction. In parallel to the land development at the coastal area, the group relocation project led the victims (except the fishery people) to live on the hill, as shown in Fig. 14.

Based on the reclaimed land development and new roadway construction, the water-supply pipeline used before was left under the surface before the tsunami, and the new pipeline was constructed over it, as shown in Fig. 15. A polyvinyl chloride pipe (PVC) was adopted in the reconstruction work in spite of the ductile iron pipe (DIP), which was used before the tsunami. As shown in the plan of pipeline networks in Fig. 12, the pipeline in Aonae district was completely reconstructed. In contrast to the previous pipeline, the new pipeline draws streamline.

The completion of reconstruction was declared in Okushiri-Island in March, 1998, 4.5 years after the disaster. Houses and infrastructure reconstruction took a long time. Incidentally, the fishery residents could live in the coastal area under safer condition.

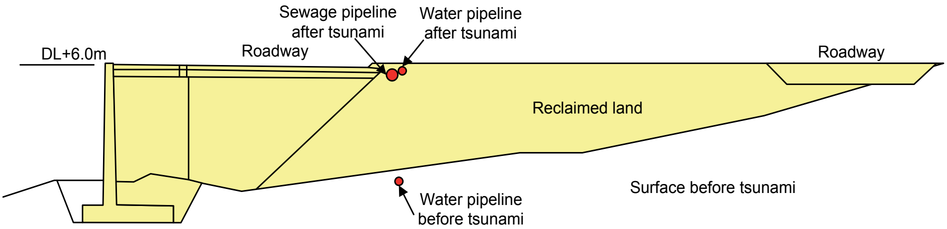


Fig. 13. High-raised tidal wall and reclaimed land development at Aonae district

4.3 Comparison of town reconstruction planning between two districts

In Aonae district, the victims were evacuated to shelters at first and then moved to temporary houses for about three years. They were finally settled in permanent houses on reclaimed land. It took such a long time for Aonae district to complete reconstruction because the residents and administrative people worked together to put in place measures that would safeguard them against future large earthquakes and tsunamis. On the other

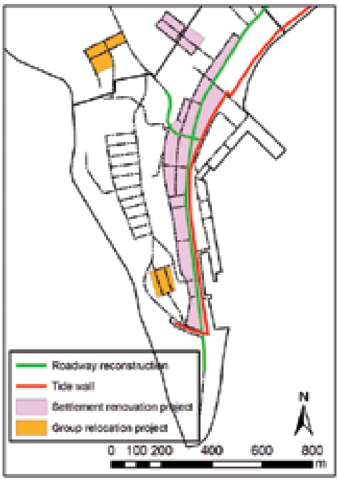
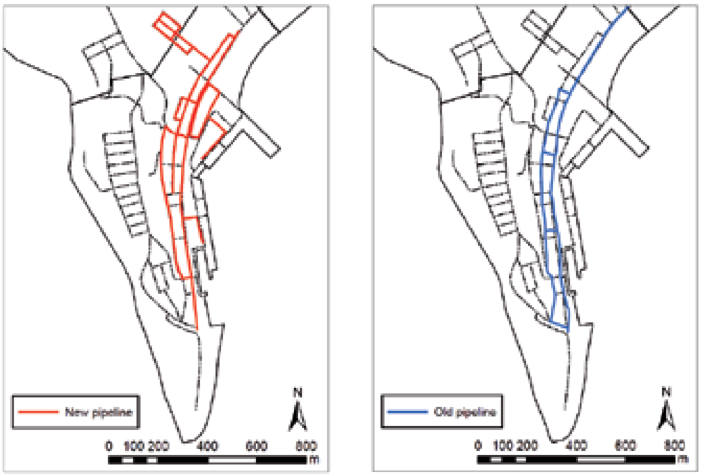


Fig. 14. Disaster reconstruction projects of Aonae district



(a) New pipeline (PVC) (b) Old pipeline (DCIP)

Fig. 15. Water supply pipeline networks of Aonae district before and after tsunami, underlying on the new roadway

hand, the victims in Nam Kem village needed only three months to move from the temporary shelter to permanent houses because they wanted to rebuild the village as before. The reconstruction in Nam Kem village was focused on going back to the previous state before the tsunami without any improvement of facilities in terms of seismic safety.

Infrastructure, including lifeline facilities, cannot be reconstructed in a short amount of time. Extensive discussions between roadway authorities and other lifeline companies are required to develop a detailed disaster reconstruction plan. Of course, the residents' opinions should be reflected in the plan to maintain the original community. The disaster reconstruction concept in Japan seeks to give more priority to community opinions, even if it takes a long time to complete the reconstruction. For instance, the temporary houses were closed five years after the Kobe earthquake disaster in 1995. The tsunami-affected community in Nam Kem village did not have the opportunity to have detailed discussions with the government, and they wanted to retain their traditional lifestyle.

In the reconstruction process, the reconstruction speed, environmental condition after the tsunami, financial support of the government, organization acting as the interface between the government and the community, and traditional and cultural living style are closely related. From the point of view of lifeline reconstruction, it is also important to foster a close relationship among the local government, lifeline companies, and the community and to establish a strong foundation for people-to-people links in order to prepare for an emergency.

After the 2004 Indian Ocean earthquake and tsunami, many villages and towns in Indonesia faced many problems during the reconstruction processes. A lifeline reconstruction process considering community-based planning had not been reviewed in detail so far. This kind of study would be necessary for an effective lifeline reconstruction strategy.

5. Residential awareness of water use after tsunami

In suffered area from the 2004 tsunami, residents had mostly used domestic water from shallow well. The domestic water became unavailable after covered with salty water. The salt damage to the shallow well seems to affect residential life quality for a long time. The water-supply system in Banda Aceh, Indonesia was reconstructed and the residents changed their water-supply from shallow wells to a pipeline network. In this section, an analysis on the lifeline reconstruction and its long-term effects, with the focus on residential awareness of water use before and after the tsunami is considered.

5.1 Reconstruction of water supply system in Banda Aceh

Banda Aceh is the nearest big city from the epicenter and was suffered severely from the 2004 tsunami. Worldwide institutions helped its reconstruction projects. One of them is the water supply system of Perusahaan Daerah Air Minum (PDAM, meaning provincial drinking water supply authority). The water purification plant of PDAM located at about 10 km far from coast was fortunately not flooded by the tsunami but had physical damage to facility due to seismic ground motion. Switzerland government supported rehabilitation on of water purification plant, whereas Japan government planned and installed the water-supply pipeline network of 198 km. The repaired purification pant enables to make water for 50,000 customers. By October in 2010 (almost 6 years after the tsunami) the PDAM supplies water to 32,000 customers and is extending service for additional 8,000 customers, who can use PDAM water with no charge until completion of pipeline and other accessories installs. Population of Banda Aceh increased from 170 thousands to 220 thousand with moving people from tsunami-suffered suburb. The water-supply system user also increased from the 2004 tsunami. In Banda Aceh the PDAM user was large comparing the other cities so that underground water is naturally in high level and contains salt.

5.2 Interview survey on residential awareness of water use after tsunami

Interview survey on residential awareness of water use before and after the tsunami was carried out at four districts in Banda Aceh in the beginning of October, 2010. The interview was held at resident's home one by one through Indonesian language and the questionnaire sheet was collected at once. The questions are about water use at home, residential satisfaction rating on water quality and stability, emergency use and so on, and suspension limit of water-supply service during a disaster. Fig. 16 shows the interview districts of Banda Aceh, and Table 9 lists the details of responses in each district. 143 answers were obtained as a whole. District A is resettlement house district donated by the Tsuchi religious body, in which all the residents moved from the tsunami-suffered area in and outside Banda Aceh as shown in Fig. 17. The water-supply system was installed at the same time of house construction after the tsunami. Districts B, C and D were suffered from the tsunami by different damage level. With regards of inundation damage report, Districts C, Kuta Raja and D, Meuraxa had inundation and more than 50 % of houses damage, and District B, Syiah Kuara had inundation and less than 50% of house damage. 80 % of residents live before the tsunami in District B, whereas half of residents moved from the other districts or the suburbs in Districts C and D.

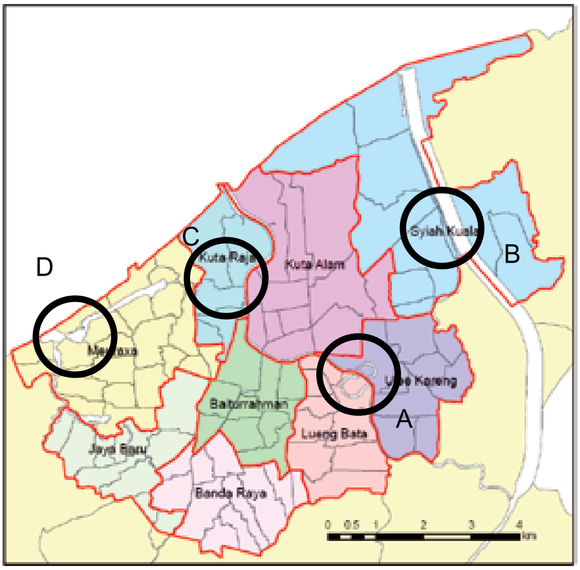


Fig. 16. Location of interview survey district in Banda Aceh

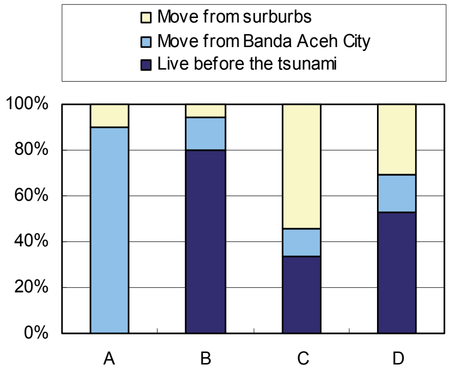


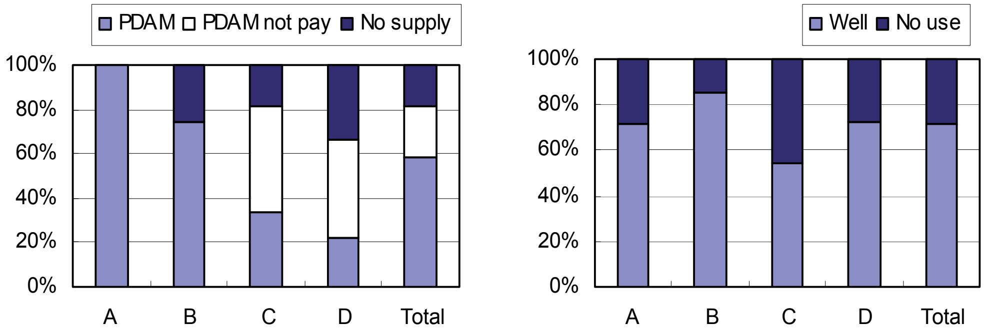
Fig. 17. Location of answers at the 2004 tsunami

District ID.	Name	Responses	Remarks (the 2004 tsunami damage)
A	Tsuchi	39	Resettlement houses
B	Syiah Kuara	35	Inland area (moderate damage)
C	Kuta Raja	33	Riverside area (destructive damage)
D	Meuraxa	36	Seaside area (destructive damage)
Subtotal		143	

Table 9. Responses of interview survey on water use after tsunami

The number of answers are not enough statistically, but the rate of PDAM customers in each district as shown in Fig. 18(a) is confirmed to be similar to the statistics of customer number by the PDAM. In resettlement district, A, residents uses 100% PDAM water-supply, and 70 to 80 % of residents do in the other districts. The PDAM customers without charge in Districts C and D are those live in the area under pipeline construction. Those who do not use the PDAM water use domestic water from shallow well. As a whole, 20 % does not use the PDAM water, 50 % uses both the PDAM water and domestic water as shown in Fig.18(b) Well user increases in inland Districts A and B.

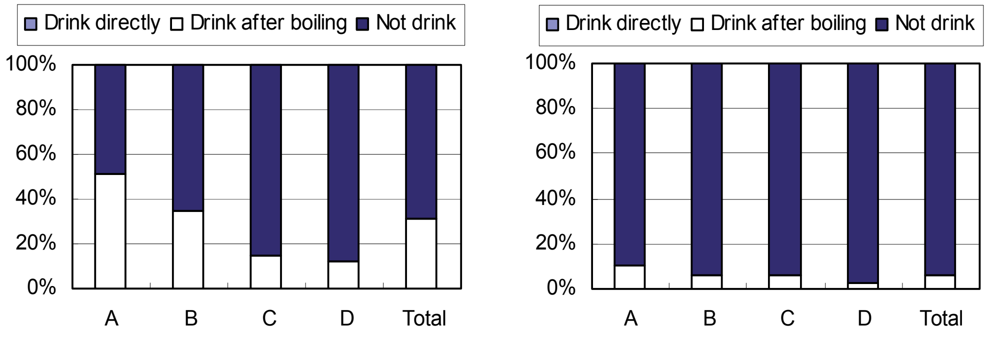
Among the PDAM users, 10 to 50 % drinks the water after boiling as shown in Fig.19(a). The severely suffered districts, C and D, indicates low rate of drinking customer. Less 10 % drinks domestic water after boiling as shown in Fig.19(b). Water use in Indonesia is



(a) Rate of PDAM customer

(b) Rate of PDAM customer

Fig. 18. Water use in Banda Aceh



(a) PDAM water

(b) Domestic well water

Fig. 19. Water use for drinking

Photo 7. Drinking gallon-size bottle water

Photo 8. Shallow well in front of house

generally drinking from Gallon-sized bottle water (Photo 7) and living from PDAM water or domestic water (Photo 8). Indonesian residents rarely drink the pipe-water directly.

The residential awareness on water use is examined considering disaster experience and difference between pipe-supply water and domestic water. Here, the residential satisfaction was asked in terms of water quality, water supply stability, emergency stability and water cost by 5 satisfaction options; (1) satisfy very much (2) satisfy (3) reasonable (4) dissatisfy a little and (5) dissatisfy. The response gives grating points from 5 (satisfy very much) to 1 (dissatisfy) for each option. Means of grating point for satisfaction was analyzed by one-way analysis of variance between three groups. Group I is the residents who use the PDAM water before and after the tsunami. Group II is those who started using the PDAM water after the tsunami. Group III is those who have not used the PDAM water. The grating point by Groups I and II is given about the PDAM water, and that by Group III is about the domestic water. Table 10 summarizes the variance analysis results for four questions.

Group	N	μ	σ^2	Test statics	
I	45	3.78	0.27	0.78	
II	71	3.69	0.39		5.60*
III	27	2.78	0.95	5.42*	
	143				

(a) Variance analysis on water quality. P value 5.67×10^{-9} (Significant)

Group	N	μ	σ^2	Test statics	
I	45	2.56	1.16	1.75	
II	71	2.92	1.14		4.53*
III	27	3.67	0.69	3.26*	
	143				

(b) Variance analysis on supply stability. P value 9.79×10^{-5} (Significant)

Group	N	μ	σ^2	Test statics	
I	45	2.13	1.53	3.08*	
II	71	2.76	0.87		0.18
III	27	2.19	0.93	2.68*	
	143				

(c) Variance analysis on emergency supply. P value 2.90×10^{-2} (Significant)

Group	N	μ	σ^2	Test statics	
I	45	3.09	0.36	0.29	
II	71	3.04	0.96		0.58
III	27	3.19	0.62	0.67	
	143				

(d) Variance analysis on water cost. P value 7.52×10^{-1} (Non significant)

Table 10. Variance analysis on residential awareness on water use. Group I: PDAM customer before the tsunami, Gtoup II: PDAM customer after the tsunami, and Group III: Shallow well usr. * indicates significant diference between two groups (significant level 1%)

The mean of grating point between the PDAM user (Groups I and II) and the domestic well user (Group III) differs significantly on water quality and supply stability. The PDAM users satisfy water qualities by around 3.7 grating point, but supply stability by 2.56 to 2.92 grating point. Significant difference between PDAM users staring before and after the tsunami can not be seen. During the interview, the responder pointed out the water for washing clothes. Since the domestic water contains salt rather than before, even 6 years after the tsunami, they use it by the PDAM water or the water filtered by house strainer. The residents who do not satisfy the supply satiability replied that they cannot receive adequate water volume in day time and they install house pump at home and take water. The number of house pump seen in the interview survey is not small. These uncontrolled water pressures may provoke malfuctiionality of whole water supply system.

For the emergency supply stability after disasters, there is significant difference between groups. Those who continue the same water use before the tsunami (Groups I and III) give 2.1 grating points, while the new PDAM user gives 2.76. The new PDAM user is thought to be evacuated people to Banda Aceh city. Emergency water delivery by tanks and expanding new pipeline install by the PDAM may contribute high grating to residential satisfaction.

Water charge is not much effective factor to identify residential awareness in terms of water use and disaster experience as shown in Table 10 (d). By the way, the reason why 100 % of residents do not contract the PDAM water seems to be financial issue. Fig. 20 shows relation between the rate of water cost per income and the residential satisfaction on water charge for PDAM water users. Income rating is classified into 7 classes as shown in Figure. Water cost indicates the PDAM water charge and gallon-sized water bottle purchasing cost per month. The residential satisfaction on water charge is the rate of those who think water charge as inexpensive and half of those who think as reasonable to the all answers, when asked for the water charge in options; expensive, reasonable, and inexpensive. As it can be seen, the residential satisfaction on water charge increases as income increases. A half of residents having over 1.25 million Indonesian Rupiah satisfy the water charge from the PDAM. Their PDAM water charge is less than 10 % of income. When the PDAM water charge increases more than 10 %, it interferes with their daily lives. When compared the amount of the PDAM water use, there is little difference of the personal daily water demand in each income class. The life style related to water demand does not differ by the income and the satisfaction depends on the incomes.

It should be noted that the water charge from the PDAM water is almost same as the bottle purchasing cost. The responders buy a monthly average of 11.7 gallon-sized water bottle. One bottle (about 3.785 liter) costs about 5,000 Rupiah and the bottle water costs 1,321 Rupiah per liter. Meanwhile the PDAM water costs about 3 Rupiah per liter. If the PDAM can obtain residents satisfaction on the water quality and residents can drink it even after boiling, the whole residential water charge decreases less than 10 % and the residents also satisfy the water charge. It should be discussed that how much the pipeline network completion for better water quality at the customer side can be invested considering the water charge. These assessments of water pipeline install would be necessary for future work.

In Banda Aceh City the water supply pipeline network install is almost completed. There are many small cities and town around the coast of Sumatra Island, in which the tsunami wave was covered by the 2004 tsunami but the water supply system is not installed yet. Even they do not drink domestic water directly, the salty underground water affects on living use water for long time. The water pipeline network, which may damage by the earthquake and tsunami, would be necessary as reconstruction works to these coastal areas.

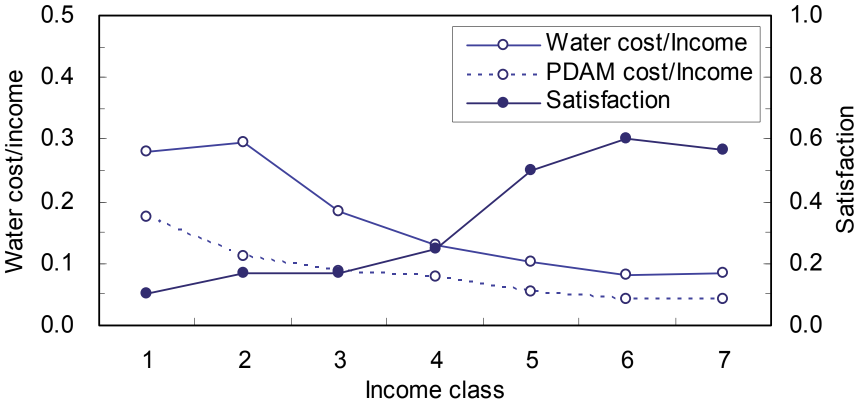


Fig. 20. Water cost rate to income versus water satisfaction regards to monthly income class. Income class 1: < 350,000 IDR, 2: 350,000 – 500,000 IDR, 3: 500,000 – 750,000 IDR, 4: 750,000 – 1,000,000, 5: 1,000,000 – 1,250,000, 5: 1,250,000 – 1,500,000 IDR, 6: >1,500,000 IDR. IDR=Indonesian Rupiah (1,000 IDR = 0.12 USD =9.4 JPY, 2011)

6. Conclusions

This chapter discussed the lifeline restoration and reconstruction after the tsunami, especially focusing on the 2004 Indian Ocean earthquake and tsunami. Followings can be summarized.

- The business restoration depends more strongly on business facility restoration than lifeline restoration if the tsunami inundation is higher than 1 m. The lifeline interruption caused by the tsunami affected business continuity more than in previous studies.
- In the reconstruction process, the reconstruction speed, environmental condition after the tsunami, financial support of the government, organization acting as the interface between the government and the community, and traditional and cultural living style are closely related. From the point of view of lifeline reconstruction, it is also important to foster a close relationship among the local government, lifeline companies, and the community and to establish a strong foundation for people-to-people links in order to prepare for an emergency.
- The salty underground water affects on living use water for long time. The water supply from the pipeline gives high satisfaction to water quality. The pipeline network construction is important to the suffered people.

In the writing of the chapter, east Japan was hit by strong seismic motion and covered with huge tsunami. Many civilized areas changed catastrophic ruins. What we learned from Indonesia, Thailand and Sri Lanka introduced herein may be not applicable directly to Japan, because of different living environment and water use, but founding in business recovery and reconstruction planning would contribute to reconstruct the suffered area.

7. Acknowledgment

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5

Tsunamis as Long-Term Hazards to Coastal Groundwater Resources and Associated Water Supplies

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1. Introduction

Tsunamis are potential hazards in most of the world, (Figure 1), but risks are higher in areas associated with close and direct proximity to high seismic activity areas in marine and coastal areas, such as Indonesia, Japan, Chile, Peru, and SIDS (small island developing states) (UNISDR, 2009) (Figure 2). They generally hit in relatively limited areas: the coastal zone - up to few kilometres inland from the shore.

Tsunamis are short-term events, but impacts on human infrastructure and environment can be severe and enduring. Especially coastal freshwater resources, most often the source of public and private water supplies, are vulnerable to the imprint of saltwater that comes along with the tsunami flooding event. Safe, adequate, accessible, and socially acceptable water supply is of essential importance, both as a priority in the immediate aftermath of a disaster like a tsunami, but also in the longer term to ensure proper human health and prosperous livelihoods. Time horizon and severity of tsunami impacts on water resources and water supply systems depend on: magnitude and extent of the event, type of land mass hit (island vs. large mainland, low topography vs. rising coasts) and its natural protection (e.g. mangroves), population density, type and extent of freshwater resources present, and dependence on them for water supply. Often, alternative water supply solutions can be provided in the interim of a tsunami, from external sources and with external support because of the often limited geographical extent of the impacted areas. However, this is not always possible e.g. islands, and other aspects are relevant: recovery and sustainability of fundamental and primary freshwater resources, human health, optimal and efficient use of resources at any time of the disaster risk management cycle (Figure 3). Here, a distinction between groundwater and surface water systems is relevant. Groundwater systems are generally much slower in recovering due to longer internal residence times. However, since groundwater sometimes is the only freshwater resource available in coastal areas and on small islands, it is critical to assess the vulnerability and potential impacts.

Since significant coastal populations around the world depend on groundwater for their water supply, either from decentralized, often small schemes and private wells, primarily in rural and peri-urban areas, or from larger centralized schemes, primarily in urban areas,

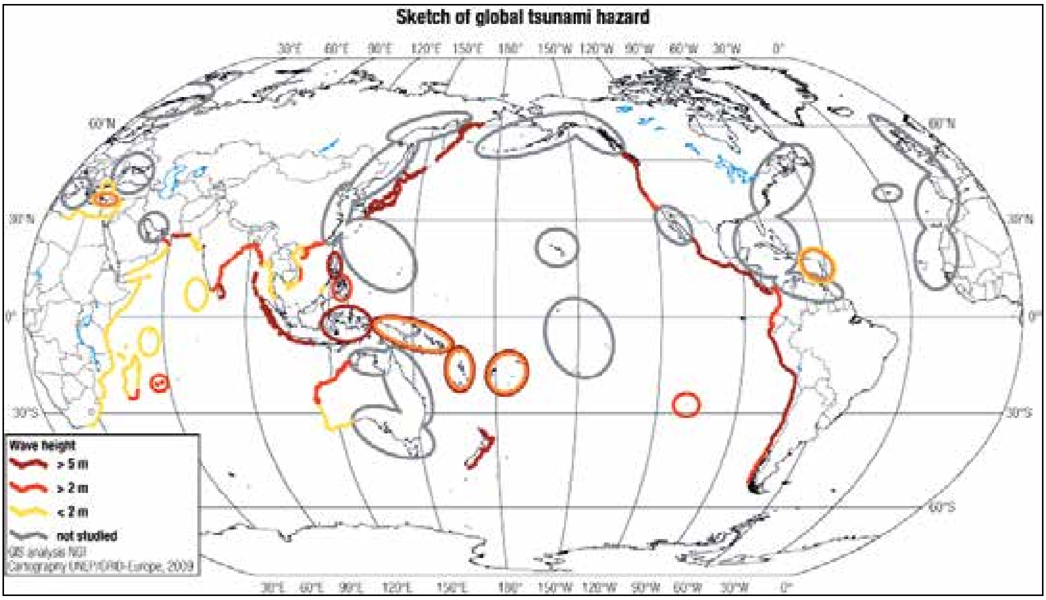

Fig. 1. Global map of tsunami hazard (From UNISDR, 2009)

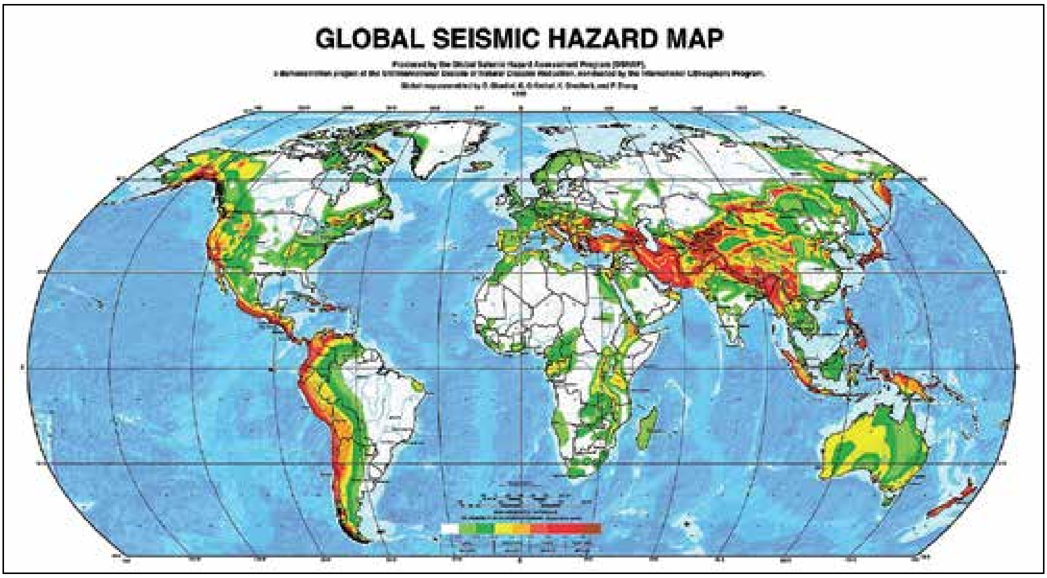

Fig. 2. Global seismic hazard map (From Giardini, 1999)

it is of critical importance to know the risks associated with these supplies from natural and other types of disasters and extreme events, in this case from tsunamis. Furthermore, it is equally critical to bring that knowledge into frameworks for prevention, protection, recovery, response, and rehabilitation strategies, plans and actions. Though water supply receives principal attention during disasters, there is a general lack of focus on the link to the (potentially long-term) impacts on the water resources and in particular on the groundwater

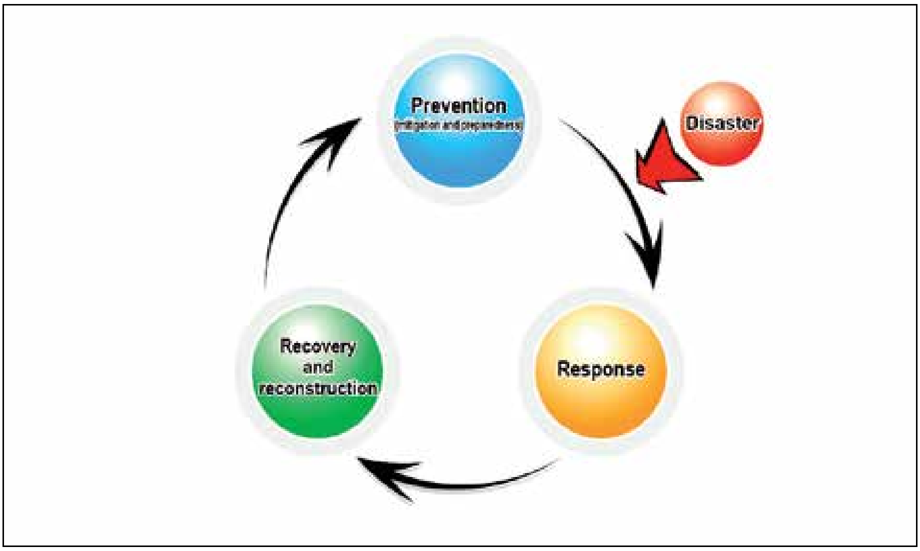

Fig. 3. Phases of disaster risk management (From JICA, 2008)

resources. This paper intends to enhance the knowledge and the dissemination of such knowledge. It is proposed to advance this work through further detailed guidelines and frameworks as described in Section 4.

The present paper addresses tsunami events as potential hazards to groundwater resources and associated water supply systems in coastal areas around the world. The objective is to provide a coherent framework for understanding these potential hazards and for managing the risks and impacts associated with them, with focus on salinity impacts. The paper accordingly first reviews and summarizes the present knowledge and experience of impacts, and secondly, presents a framework for managing the risks and impacts associated with these events. This relates to practical as well as policy implications and also to which continued research efforts are essential. The ultimate goal is to enhance water security and human health in tsunami-prone areas of the world.

2. Effects of tsunamis on coastal groundwater and water supplies

Focusing on the impacts of a tsunami on water, two aspects and systems are essential: the freshwater resource itself and the systems of water supply derived from it. Accordingly, the consequences of a tsunami are two-fold. Firstly, there is a direct and immediate physical shock on water infrastructure, like water pipelines, sewer systems, water storage tanks, and groundwater wells that break down due to the force of the incoming and retreating waves and masses of water and debris. Secondly, the water resources and their quality are often severely impaired by the tsunami.

2.1 Effects on water supplies

Severe impacts on water and sanitation infrastructure were observed from the 2004-tsunami in the countries of Indonesia, Sri Lanka, India, Thailand, and the Maldives (Tang et al., 2006; ADB et al., 2005; UNEP, 2005). Water main pipes in estuaries broke, water wells supplying inter-mediate size populations and industrial areas located coastal-near were destroyed or their quality impaired. Pit latrines and other sanitation structures were destroyed and sewage disposal lines discharging to the sea were affected and possibly led to conduits for tsunami water[1] entry into main sewers (UNESCO-IOC, 2008). Open and natural drainage canals conducting drainage water from agricultural fields and public wastewater were disturbed and in many cases blocked due to coastal erosion and sedimentation processes. However, only limited systematic research and reporting on the consequences of the 2004 tsunami on water infrastructure in affected regions was carried out and knowledge is mostly based on rapid impact assessments immediately after the event. Larger water infrastructure systems, like dams and larger urban water supply schemes were not impacted, simply because they were not located within the affected areas (Ballantyne, 2006). Also, no major or mega city was affected by the 2004-tsunami. Water supply systems, as they relate to hardware and infrastructure, were mostly rehabilitated and built back to previous conditions within relatively short timeframes, in the order of months to half a year after the tsunami. In some cases, new systems were constructed to replace damaged ones, within same or slightly longer time horizons. A critical issue here was the establishment of interim water supplies for people displaced in temporary camps as coastal-near settlements were completely destroyed (Fernando et al., 2009).

The maybe most severe and enduring impact of the 2004-tsunami in terms of water supply was the destruction and contamination of drinking water wells in the coastal strips inundated by the flood waves. A large percentage of the coastal population in the affected areas of the hardest-hit countries, like Indonesia, Sri Lanka, India, Thailand and the Maldives, depends on wells, often relatively shallow (< 10 m deep) household wells, and large proportions of these wells were inundated and impacted by infiltrating tsunami water. No rigid inventory on the number of wells impacted exists but they number in many thousands throughout the region. In Sri Lanka alone, 40-60.000 (ADB et al., 2005; UNEP, 2005) and most likely many more (Villholth et al., 2010) were influenced and similar reports exists from Indonesia, the Maldives, and Thailand (UNEP, 2005). A predominant part of these populations are poor farmers and fishermen who live in dispersed communities along the coast, but with locally relatively high population densities. Though the 2004-tsunami waves reached relatively short distances inland, up to 2 km (Chidambaram et al., 2010, Kume et al., 2009; Villholth et al., 2005), and hence alternative water sources from further inland could temporarily replace damaged ones, the immediate and longer-term impacts were considerable.

2.2 Effects on water groundwater resources

A tsunami affects groundwater through a number of mechanisms. During the run-up of the tsunami (could be more than one wave during an event) on the shore and further inland and subsequent partial retraction, soils and land mass previously not affected by saltwater get inundated for a relatively short time (5 min up to one or few hours), leaving a period for saltwater to infiltrate and enter through the soil and subsequently to the groundwater table below. Some tsunami water gets trapped in local landscape depressions or other sinks leaving this water to potentially further contaminate the groundwater. A special case of this is open wells that have direct contact with the groundwater and hence constitute a very fast pathway for contamination of the subsurface. Which of these various sources is more

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[1] Tsunami water in this context means seawater, potentially mixed with inland (clean or contaminated) freshwater, sediments and debris.

important cannot be assessed unilaterally as it depends on the local conditions but neither should be overlooked. The infiltration from the land surface during the inundation is short-lived but covers a large area, whereas the percolation from depressions comprises large localized volumes infiltrated over much longer times (Chidambaram et al., 2010). Prolonged effects of saltwater leaching has been documented from the entrapment of tsunami water in the soil profile during dry periods leading to precipitation of salts that subsequently get washed out in rainy periods (Chidambaram et al., 2010; Sivakumar & Elango, 2010; Violette et al., 2009).

If the Tsunami run-up is high enough to overflow a local topographical divide, larger parts of the tsunami water will flow inland and not retract to the sea, with an overall larger impact. Coastline configuration, bathymetry, and natural coastal protection from e.g. mangroves, may initially modify tsunami wave impact even before entering land. Finally, river mouths may serve as 'highways' (Mitamura et al., 2006) for tsunamis increasing inundation distances significantly in adjacent areas with subsequent impact on underlying groundwater. Coastal lagoons and estuaries may also be flooded with impacts on surrounding and further inland areas. While such areas may initially be more severely impacted, they may also be relatively rapidly rinsed due to flushing of these water bodies by freshwater from upstream catchments (Fesselet & Mulders, 2006).

The underlying shallow groundwater will be primarily and initially affected while deeper groundwater will be affected later as a pulse or plume of infiltrated saltwater spreads and migrates downwards and laterally back to the sea (Figure 4). If multiple overlying aquifers are present, lower confined aquifers may be partly protected from the tsunami impact (Figure 4). Identifying and utilizing such aquifers may provide tsunami-resilient water supply.

Secondary impacts on the groundwater system involve the potential displacement or disturbance of the freshwater-saltwater interface or balance below the shore (Figure 4) due to the incoming force and increased hydraulic pressure of the waves (Cartwright et al., 2004). This, however, has not been documented, e.g. through direct monitoring of the

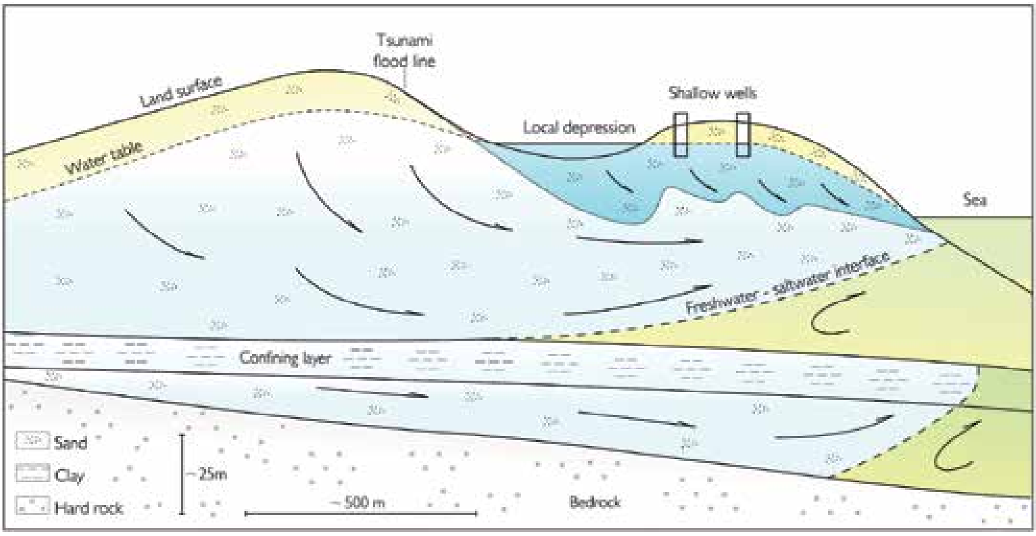

Fig. 4. Conceptual sketch of tsunami salinisation impacts on groundwater.

interface before and after a tsunami. Observations of gushes or geysers of water from wells just prior to a tsunami have been reported (Kumar & Alam, 2010) as well as sudden and intermittent rise in groundwater levels (Muralideran et al., 2005), which gives testimony to large forces in play from the earthquake and ensuing tsunami. Incidentally, such phenomenon may also be used in the local early warning of an event.

Groundwater and interactions between pre-tsunami fresh and saltwater may also be influenced by coastal erosion processes launched by the tsunami, which may shift the coast line with accompanied landward displacement in the transition zone between fresh and saltwater[2]. Subsidence and activation of sink holes in coastal limestone aquifers in Thailand and Malaysia have also been reported (Al-kouri et al., 2008; UNEP, 2005). This could be attributed either directly to the seismic impact or indirectly to the seismically induced fluctuations in groundwater.

Seawater has much higher salinity content than most natural water bodies and environments in coastal areas. Previous sources of drinking water, be it surface water or groundwater bodies, easily reach salinity levels well above drinking water quality standards and guidelines[3]. Even a 5% mix of seawater with freshwater will render it unsuitable for drinking (Violette et al. 2009), indicating the vulnerability of freshwater systems towards tsunami risks, and in general seawater flooding, and the critical issue of reverting contaminated sources to pre-tsunami fresh conditions.

Salinity is here used as a relatively simple, but yet critical indicator of tsunami impact in groundwater. Two aspects of this should be noted. Firstly, broader impacts of seawater flooding on coastal aquifers could occur, like chemical shifts in ionic composition of groundwater (Andersen et al., 2005) and potential contamination with micro-constituents, like heavy metals, from the seawater itself or from marine sediments washed to land (Ranjan et al., 2008; Szczuciński et al., 2005). Especially the latter could have (even) longer term impacts on soil and groundwater quality.

The second aspect of using salinity as an indicator relates to the inherent complexity of saltwater-freshwater interactions in coastal zones. Aquifiers may be influenced by pre-tsunami saltwater, complicating the assessment of post-event impacts. These pre-event influences involve primarily the natural, and more or less stable, ingress of saltwater below the freshwater in the aquifers, which is manifested through a triangular shaped wedge of saltwater, which is kept in balance by out-flowing freshwater discharging at the upper limit of the wedge (Figure 4). Pre-event salinity may also be present in the groundwater due to remnant salinity partially entrapped in formations influenced by earlier tsunamis or cyclonic storms or longer-term sea transgressions associated with pre-historic sea-level rises (Singh et al., 2011; Riedel et al., 2010). This is more likely in deeper and less permeable formations where flow and circulation is slower. Hence, general knowledge of the salinity profile of coastal aquifers and pre-historic events is important to qualify post-tsunami salinity impact assessments. Finally, pre-event groundwater salinity could be influenced by coastal land-use practices, such as irrigation, wastewater disposal and prawn farms.

Secondary contamination factors induced by tsunamis, which sometimes tend to be forgotten or neglected, are due to the rupture of sanitary systems, storage facilities for

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[2] http://www.igrac.net/publications/140 (Accessed on May 12, 2011)

[3] There are no health-based water quality guidelines or standards for salinity, as the lower potable levels are governed more by taste and habit than by health considerations. Here, we use a measure of electrical conductivity of 1000 µS/cm as the threshold for drinking water.

chemicals and wastes, which are released and mixed with previous freshwaters and the incoming saltwater. This causes a situation where waters present and available immediately after a tsunami have to be considered contaminated with a known source (the sea), as well as a wealth of unknown but very likely additional sources. A typical and wide-spread problem here relates to the release of and spread of pathogenic bacteria via floodwaters derived from sanitary installations (Vaccari et al., 2010; Navaratne, 2006; Piyadasa et al., 2005). Secondary effects were also observed in the March 2011 Great East Japan earthquake (also called Tohuko earthquake) and tsunami where nuclear contamination posed risks to drinking water supplies (WHO, 2011).

2.2.1 Time scales for impact and recovery in groundwater

An immediate concern after recognition of salinity impacts of a tsunami on groundwater and associated water supply is the duration of the problem. This can typically only be evaluated through continuous post-tsunami monitoring and contrasting with background pre-tsunami levels or the situation in comparable non-affected areas. Alternatively, and additionally, numerical modelling may inform assessment and projection of long-term impacts. From a literature review, the recovery time of groundwater systems after the 2004-tsunami has been assessed to between 1.5 to 15 years in affected regions (Table 1). The figures clearly depend on whether only the upper shallow groundwater is considered or the entire aquifers are the unit of focus, with the small figures representing groundwater down to 5-10 m while the larger figures apply for entire aquifer extensions down to about 30 m. Such figures should be taken only as indicative and as a guide. The recovery will depend on a number of factors, most notably the hydrogeological conditions, including the excess rainfall that infiltrates over the affected area and recharges groundwater, accelerating the displacement and dilution of tsunami-entrapped saltwater.

Most areas investigated to date are located in low-lying sedimentary (fluvial and marine) coastal basins, with unconsolidated materials, consisting mostly of sands but also finer-textured materials. They are quite common in relatively flat dune-type coastal areas due to the coastal processes of sedimentation. These systems are permeable with continuous porosity rendering flow and transport of water and solutes easy and relatively fast. This relates both to the ingress of salinity during the tsunami as well as the flushing out of chemicals post tsunami. Hence, what appear to be fragile systems from a contamination point of view may also be systems that get rinsed fairly easily. This is opposed to other systems where flow mechanisms are significantly different, such as fractured and fissured systems, typically fractured rock, where saltwater may, or may not, enter fairly easily and rapidly but retention may be much longer due to long term capture in, and very slow release from, secondary pores between the fractures (Berkowitz, 2002). Such systems have not been investigated as part of tsunami research, but could potentially present systems where recovery could be extremely slow.

Tsunami groundwater impact modelling is still relatively new and some issues need further research. The impact and importance of density effects in such large scale systems are not clear. This is the phenomenon that saltwater, due to its higher density relative to freshwater, tends to sink and create unstable and heterogeneous flow when accumulated on top of freshwater, which is the typical case in tsunami-impacted groundwater systems. This has been observed and documented in laboratory (Hogan et al., 2006) as well field investigations (Andersen et al., 2005). The overall impact of this is an initially faster and more heterogeneous downward movement of the saltwater pulse from the upper groundwater

	Lit. source	**Method**			**Recovery time (depth[b])**	**Rainfall[c] (mm/yr)**	**Location**
		Field	**Model**				
				DDF[a]			
1	Vithanage et al., 2011	Transect of 20 piezometers	HST3D + HYDRUS-1D, 2D cross-section	yes	15 years (28 m)	1500	East coast, Sri Lanka
2	Sivakumar & Elango, 2010	20 wells over 2 km coastline	Feflow, 2D distributed	no	2 years (15 m)	1220	Southeast coast (Tamil Nadu), India
3	Piyadasa et al., 2009	90 wells over 8 km coastline	-	n/a	> 4 years (7 m)	2400	South coast, Sri Lanka
4	Violette et al., 2009	16 wells over 21 km coastline	MODFLOW + HYDRUS-1D	no	6-10 years (12 m)	1220	Southeast coast (Tamil Nadu), India
5	Kume et al., 2009	10 wells over 62 km coastline	-	n/a	1.5 years (5 m)	1200	Southeast coast (Tamil Nadu), India
6	Villholth, 2007	150 wells over 4 km coastline	-	n/a	1.5 years (~3 m)	1500	East coast, Sri Lanka
7	IGRAC, 2005[d]	-	MOCDENS3D	yes	10 years (7 m)	2000	Maldives

[a] DDF: density-dependent flow considered

[b] Depth: maximum depth to which freshening of upper aquifer is assessed

[c] Rainfall: Average annual rainfall. Actual rainfall and groundwater recharge after the tsunami may vary significantly

[d] http://www.igrac.net/publications/135#ref4 (Accessed on May 12, 2011)

Table 1. Recovery times assessed from the 2004-tsunami in similar hydrogeological conditions

with zones of high salinity intermixed with zones of lower salinity, relative to a smooth and homogeneous plug-like flow of uniform density fluids. Later in the leaching process, these density effects dissipate and flow becomes dominated by ordinary convective and diffusive processes.

Related to the importance of the density effects is the vertical disaggregation and resolution of flow processes in the modelling system and associated with that whether a 2D-cross-sectional representation of processes is better at capturing the saltwater movement than a 2D lateral and distributed representation (Reilly & Goodman, 1985). From Table 1, it appears that the former tends to estimate longer recovery times (6-10 years) (Violette et al., 2009) compared to the latter (2 years) (Sivakumar & Elango, 2010) for the same affected area in southeast India, which suggest that representation of the vertical flow component is important. Supporting such knowledge generation would be to ensure monitoring of deeper groundwater in the affected systems, as so far, only upper groundwater has been monitored. Finally, having better knowledge of the source of contamination is critical in the simulations.

This entails knowing the duration of inundation(s), the depth of the wave(s), and any secondary sources from accumulation of saltwater in depressions (Violette et al., 2009).

Anthropogenic factors may also influence the recovery time of aquifers affected by tsunami flooding. Post-event extraction of groundwater may influence the natural processes of saltwater sinking and movement, and field investigations suggest that excessive pumping of shallow wells, performed to rinse the wells of saltwater, may actually disturb the natural sinking of groundwater and displacement with freshwater, in effect prolonging and exacerbating the saltwater problem (Villholth et al., 2010; Vithanage et al., 2009; Chandrasekharan et al., 2008; Leclerc et al., 2007; Fesselet & Mulders, 2006; Saltori &. Giusti, 2006).

The knowledge gained as part of the assessment of impacts of tsunamis on groundwater and associated time-scales with implications for disaster risk reduction (DRR) are summarized in Box. 1.

- Most influential factors in the persistence of tsunami-salinity in groundwater are the local geology, rainfall and recharge conditions
- Shallow aquifers are impacted first, then deeper layers are affected as saltwater moves through the aquifer
- Pumping of groundwater post-tsunami should take the natural recovery processes into account, e.g. by not pumping to rinse wells
- Deep groundwater extraction may be feasible just after a tsunami, but it may also induce saltwater ingression from the saltwater zone at the bottom of the aquifer close to the coast (Figure 4) or from pre-event saline formations
- Saltwater effects in groundwater may protract in the vicinity of larger stagnant flooded water bodies, while they may diminish in areas close to flowing freshwater sources such as rivers
- Deeper confined coastal aquifers may be relatively protected from the influence of a tsunami (Figure 4)

Box 1. Lessons-learned for disaster risk reduction from impact assessment of tsunamis on coastal groundwater

3. Framework for risk management of tsunami-related hazards to groundwater and associated water supply

Tsunamis are normally relatively low-frequency, but high impact events. Also, they are impossible to prevent. Hence, emphasis in risk management tends to be on the recovery and rehabilitation efforts, rather than on prevention. However, with improved seismic science and technology, increasingly, early warning systems are put in place (Antony, 2011). These systems and increased dissemination of information on natural and local signs of an arriving tsunami (UNESCO-IOC, 2010) still do not prevent a tsunami from occurring but potentially significantly minimizes the impacts and human losses and degree of disaster involved, mostly through pre-event evacuation of susceptible and to-be-hit areas. So, while some damage and losses can be avoided due to evacuation and other protective measures, significant efforts in risk management is related to minimizing the damage occurred after an event, attending to immediate needs and recovering as fast and well as possible.

The 2004 Indian Ocean tsunami, which had an unprecedented impact, in terms of physical destruction and human death toll, significantly increased the attention to tsunamis, especially in developing countries because of its strike in countries like Indonesia, Sri Lanka, the Maldives, and India. What characterize these regions are relatively dense semi-rural to peri-urban populations in the coastal areas with already insecure access to water supply. Recognizing the backdrop against which the tsunami impacts should be seen, it is clear that on the one hand, the tsunami severely restricted a functioning and safe water supply in these regions and on the other hand may serve to generally improve the water supply situation in these countries.

A framework for addressing tsunamis in a water supply context needs to take into account both the significant weight on post-disaster emphasis while pushing for further development of pro-active and preventative measures. A framework will also, though generic to a certain level, need to be 'context-specific. While drawing on available broad experience, focus in this paper is on vulnerable and susceptible regions like the ones hit by the 2004 tsunami. Finally, while tsunamis are particular in their origin and nature, their expression in terms of coastal flooding is not unique. These impacts are also characteristic of cyclones, hurricanes, typhoons, tidal waves, and sea surges. Hence, to some degree, the framework developed here may also serve for risk management of these types of events.

3.1 Achievements and gaps

In devising a framework for risk management of tsunami-related hazards to groundwater and associated water supply, Table 2 summarises the achievements and gaps, primarily as accumulated and identified from or since the 2004-tsunami.

The 2004-tsunami revealed the vulnerability of coastal groundwater systems and the populations dependent on them, and as relief and recovery progressed and experiences were collected, called for better, integrated, pro-active and knowledge-based approaches (Villholth & Lytton, 2008). Achievements obtained based on these post-tsunami lessons include field and numerical investigations of groundwater salinity impacts and best procedures for rehabilitation of salinised wells, including a set of guidelines indorsed by the World Health Organization as part of their technical notes for emergencies (WHO, 2008). It was realized that the impacts and processes affecting groundwater after a saltwater flooding event differs significantly from an inland and freshwater flooding event, entailing the need for separate guidelines for rinsing wells and protecting the groundwater resource. Geophysical investigations of groundwater resources, including impacted and pre-tsunami saltwater resources and protected freshwater resources, were conducted (Steuer et al., 2008). Experience with alternative water sources or water treatment for tsunami relief water supply, like desalination by reverse osmosis (Weerasinghe et al., 2006) and water harvesting (Song et al., 2009), has been collected.

It is important to improve water supply from groundwater in tsunami-prone or impacted areas. As open wells easily get contaminated and exacerbate the problem of groundwater salinisation, sealed wells improve the resilience of the water supply system (Chandrasekharan et al., 2008). In addition, re-enforcing well heads and raising standpipes in the terrain, either by placing them in naturally higher positions or placing them on raised platforms (Figure 5) is an option if placing wells outside the tsunami flood risk zone is infeasible.

	Achievements	Gaps
Technical		
Prevention	-Experience with climate-proofing water supply	-Hazard maps of areas and populations in risk of tsunamis -Identification of fresh GW[a] resources -Better water supply and sanitation infrastructure in risk areas -Coastal protection -Protection of GW
Response	-Experiences and guidelines on rehabilitating water supplies -Experience with water treatment and new water sources	Rehabilitating water supplies with GW protection in mind
Rehabilitation	-Numerical models of impact assessment -Geophysical techniques for identification of impacted and protected freshwater aquifers	-Further testing and validation of models
Institutional		
Prevention	-Networks for GW in emergency situations -Documents of lessons learned from 2004-tsunami	-Guidelines for impacts of tsunami on GW and improvement to water supply -Liaison of hydrogeologists with DRR[b] community -Coastal GW monitoring -Building codes that consider water supply -Water safety plans that consider GW
Response	-Experience with WASH[c] clusters	-Hydrogeological response unit -Follow guidelines for well cleaning and GW protection
Rehabilitation		-Involvement and information of affected communities

[a] GW: groundwater; [b] DRR: Disaster risk reduction; [c] WASH: Water, sanitation and hygiene

Table 2. Achievements and gaps in addressing tsunami impacts on groundwater and associated water supply

On the institutional side, awareness and initiatives related to the role and vulnerability of groundwater in emergencies and extreme events have increased. The UNESCO-spearheaded project Groundwater for Emergency Situations made an analysis of the importance of groundwater and observed impacts under various theoretical disasters as well as concrete cases (Vrba & Salamat, 2007; Vrba & Verhagen, 2006). A second phase of the project strives to consolidate the findings of the 1st phase and implement pro-active measures to safeguard disaster-prone areas. This is exemplified with a pilot area of coastal Odisha, which is susceptible to severe cyclones and seawater flooding[4]. Such interventions

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[4] http://www.indiawaterportal.org/sites/indiawaterportal.org/files/GWES%20Workshop%20Brochure.pdf. (Accessed on May 12, 2011).

Fig. 5. Example of 'flood-proofed' water well (Photo: courtesy of Jørgen Kristensen, Danish Red Cross)

aim at risk assessment through mapping of previous events and impacts, identification of protected and accessible freshwater aquifers in the vulnerable areas, capacity building and preparedness planning. The project also takes its cue from the World Conference on Disaster Reduction and ensuing Hyogo Declaration (ISDR, 2005), which categorically noted the importance of national and local institutional and technical capacity building to effectively address disaster prevention, preparedness and emergency response.

Experiences and lessons-learned so far on tsunami hazards for groundwater and associated water supply need to be consolidated and integrated into wider on-going initiatives for DRR. Though water supply receives paramount attention during emergency situations, groundwater, as an important source of this supply, generally receives little and often inappropriate attention (Lytton & Bolger, 2010; Lytton, 2008). This is often due to insufficient knowledge and technical capacity on part of the actors involved on the ground. However, without the development of capacity and management plans that can be quickly and effectively implemented, such events may compromise the viability of groundwater resources, and hence also the water supply, in the longer term (Chave et al., 2006).

In order to enhance such capacity and management strategies for risk reduction during disasters and in particular for tsunamis, it is recommended to address the gaps listed in Table 2. These build on accumulated achievements and relate to both the prevention and preparedness phase as well as the response and rehabilitation phase.

It is important to assess the risk of tsunami impacts on groundwater in tsunami-prone areas and incorporate this knowledge into planning for better water supply and sanitation infrastructure as well as protection of critical groundwater resources. Such plans should be integral to water safety plans (Davison et al., 2005), coastal zone management and environmental protection. In addition, groundwater monitoring of water quality and quantity aspects needs to be an operational part of such plans, in all disaster phases as a basis for proper decision making.

Further, development of awareness raising material and guidelines for best practices aimed at the general public and partners involved in DRR on the impacts of tsunamis on groundwater and the proper protection of coastal aquifers is needed (Violette et al., 2009; Villholth & Lytton, 2008). Along with this is the need for further scientific improvement of modelling and projection of tsunami and other coastal groundwater salinity impacts and integration of this into strategic planning.

An overriding requirement is the availability of capacity for professionally and effectively incorporating hydrogeological knowledge and information into the disaster risk management process. To further enhance such development it is recommended to establish hydrogeological response units, which can enter into emergency situations and act as sounding boards for best response options and interact with the DRR community. In this context, such units could support the UNICEF initiative of WASH clusters that aim to coordinate efforts within the humanitarian water, sanitation and hygiene sector, both at the global as well as country level (Bourgen & LeTurque, 2009). Such need for general technical support to groundwater in DRR has been expressed by the global WASH cluster at their meeting in 2007[5].

4. Perspectives

Groundwater is a strategic resource during disasters. While the analysis performed in this paper applies primarily to tsunami hazards to groundwater and associated water supplies, it is recognized that groundwater plays a critical role in water supply in most parts of the world and hence improving disaster resilience of water supplies to a large extend depends on proper knowledge and protection of groundwater resources, not the least in coastal areas, where large majorities of populations live, where groundwater is already under great stress from human exploitation and degradation and natural salinisation processes, and where risks of a large number of disasters prevail. Experience from tsunami research and response relate mostly to rural and peri-urban areas where wells are small and numerous and poorly protected, rendering pro-active measures for decreasing vulnerability difficult compared to more centralised and urban schemes. Nevertheless, lessons learned need to feed into preventive and preparatory strategies that limit hazard impacts.

The framework proposed for risk management of tsunami-related hazards to groundwater and associated water supply is interdisciplinary in scope, drawing on capacity and expertise of water, and especially groundwater, professionals, chemical and health experts, social scientists as well as the practitioners of NGOs, humanitarians and international relief and donor organizations, and national and local authorities. As such, the challenge may be more on the aspects of coordination and communication. However, it is hoped that with relatively simple frameworks, such coordination and collaboration is rather enhanced than complicated. Also, it is hoped that the integrated approach, looking at water supply as well as the broader water resources, will provide a more coherent and sustainable approach to DRR related to coastal flooding (Schmoll et al., 2006).

The occurrence of large devastating tsunamis is infrequent; hence the investment to prevent and counteract impacts should be weighted against other risks and requirements. However, the recent catastrophic Tohuku earthquake and resulting tsunami have put a very different

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[5] http://oneresponse.info/GlobalClusters/Water%20Sanitation%20Hygiene/publicdocuments/Cluster%20Minutes%20April%2007%20FINAL%20070607.doc (Accessed on May 12, 2011).

tone to the way tsunamis are now perceived. Nevertheless, coastal water supply systems are vulnerable to a wide variety of hazards that could potentially limit their ability to perform satisfactorily. Hence, it is important to assess the diversity and multitude of uncertainty sources present and prepare for a variety of risks, including that of tsunamis, in order to optimize water resource and water supply systems design, planning and management.

5. Conclusions

This paper analyzes, based primarily on experiences and research from the 2004 Indian Ocean tsunami, the short and longer term impacts of tsunamis on groundwater resources and water supplies derived from it. Groundwater pollution from a tsunami occurs at a relatively short time-scale, whereas the rehabilitation of these resources generally takes a much longer time. Though infrastructure around water supply may be rehabilitated relatively shortly after a tsunami, recovery of the aquifers may lag behind. This has to be factored into response, rehabilitation and recovery planning, in order not to compromise groundwater availability for extended times as groundwater is often the only available water resource for many human uses, sustaining health and livelihoods in coastal areas around the world.

Furthermore, the paper presents a framework for the integration of groundwater aspects into DRR strategies for tsunamis. This framework emphasizes the importance of integration of technical and scientific knowledge of groundwater into DRR and WASH cluster activities and is partly relevant for other coastal salinity flooding events as well.

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6

Experimental and Numerical Modeling of Tsunami Force on Bridge Decks

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1. Introduction

Tsunamis are destructive waves which contain a series of long period waves. These waves propagate at very high speed and travel transoceanic distance with very litter energy losses. When tsunamis approach a shore, their tremendous energy remains nearly unchanged and the high inundation level and the fast moving water of tsunami flow cause loss of human lives and catastrophe to coastal structures including bridges (Figure 1). The extensive bridge damage caused by recent tsunamis in particularly in the unprecedented 2004 Indian Ocean tsunami event demonstrates an urgent need for an effective method to estimate tsunami forces on bridges.

Due to the complexity of wave propagation on shore and wave-structure interaction, physical and numerical approaches have been adopted to investigate tsunami-induced forces on bridges. Even though tsunami force acting on vertical wall-type coastal structures has been studied by many researchers since last five decades, but the assessment of tsunami force on bridge is still in its early stage. There has still no conclusive argument on how big tsunamis are. The occurrence of the 2004 Indian Ocean tsunami shows the enormous force exerted by the tsunami which had floated a 10-MW barge-mounted diesel station 3 km inland in Banda Acheh, shifted a heavy dredger onto the wharves in Sri Lanka and drifted a police patrol boat 1.2 km inland in Thailand. This disastrous wave force is once again shown in the most recent tsunami triggered by the 2011 Tohoku Region Pacific Ocean Offshore Earthquake.

The post-tsunami survey have evidently demonstrated the damage of bridges in Sumatra, Sri Lanka, India and Thailand during the 2004 tsunami event as reported by Kusakabe et al. (2005), Unjoh (2005), Iemura et al. (2005), Yim (2005), Saatcioglu et al., (2005), Tobita et al., (2006), Ballantyne (2006), Maheshwari et al. (2006), Scawthorn et al. (2006), Sheth et al. (2006), EEFIT (2006) and IIT (2011). These bridges suffered failure through a total or partial wash-away of bridge deck from their abutments and excessive settlement of foundation. The failure of bridges disrupts the accessibility of the community; nevertheless, the great concern is hamper the emergency relief efforts that are needed immediately after this disastrous event.

(a) Total Wash-Away of Deck (Unjoh, 2005) (b) Excessive Deck Displacement (Yim, 2005)

Fig. 1. Bridge damage due to tsunami attack in Banda Aceh

The report on the post-tsunami survey done by a team from Japan Society of Civil Engineers (Unjoh, 2005) has stated that more than 100 bridges in which their superstructures were washed out or heavily damaged by tsunami with a height of 5 m to over 30 m in Aceh Province. Out of these bridges, there are simple supported reinforced concrete bridges, prestressed concrete bridges and steel truss bridges. Indian Institute of Technology Kanpur reconnaissance team discovered several bridges in Andaman and Nicobar Islands were heavily damaged (IIT, 2011). Three road bridges and two railway bridges suffered severe damage and some bridges suffered damages to abutments and approaches in Sri Lanka while no apparent damage to reinforced concrete bridges in Thailand was reported by EEFIT (2006). About four bridges suffered severe damage in India (Sheth et al., 2006). A four span reinforced concrete bridge across Palyar River in India was totally washed away (Narayan et al., 2005; Jain et al., 2005).

2. Damage mechanism of bridges

Various types of damage on bridges have been demonstrated in past events through post-tsunami survey. It can be categorized into two main types, i.e. damage to substructure and superstructure. Damage to bridge substructure can be resulted from scouring of foundation and excessive settlement of the embankment whereas damage to bridge superstructure range from partial transverse movement of bridge deck to total collapse or wash out of bridge deck due to the action of both horizontal and uplift forces. The extent of bridge damage is closely related to the shape or form of the structure apart from the wave height and wave velocity which are topographic dependent.

2.1 Damage to bridge substructure

Tsunami with high flow velocity can erode the embankment of bridges if no sufficient protection is provided. This can cause the access road approaches the bridge disconnected or the settlement of bridge abutment. Collapse due to erosion and scour damage to the abutment should be prevented on the seaward side from the incoming wave attack and on the landward side from the receding water.

2.2 Damage to bridge superstructure

Most of the bridges constructed in countries surround the Indian Ocean are not designed to withstand large lateral load such as tsunami. Bridges are simply supported on abutments without any installation of shear key or other lateral movement restrainers. When tsunami strikes the bridge deck, the huge force can displace the deck laterally once the resistance due to friction is exceeded. The deck may experience substantial dislocation and the whole deck will be washed away from the abutment. Uplift force and hydrodynamic force contribute to this failure mechanism. If the bridge deck is submerged into the water during tsunami attack, the deck can be floated due to buoyant force and only minimum hydrodynamic force is sufficient to move the bridge deck.

3. Hydraulic experiments

Numerous researches have been carried out to investigate the behavior of bridges and estimate tsunami forces on bridges through physical modeling in recent years. As a result of the paucity of the tsunami wave force study on bridges and the complexity of tsunami propagation at nearshore region, physical modeling was carried out to investigate the occurrence of tsunami acting on an inland bridge. Hydraulic experiments in various scales of wave flume were conducted using various configurations of downscaled bridge models.

3.1 Reviews on related experimental studies

Experimental studies of tsunami forces on bridges have only been conducted after the unprecedented 2004 Indian Ocean tsunami event by Kataoka et al. (2006), Shoji & Mori (2006), Iemura et al. (2007), Lau et al. (2008), Sugimoto et al. (2008), Moriyama et al. (2008), Araki et al. (2008 and 2010), Shoji et al., (2009a, 2009b and 2010), Nakao et al. (2009) and Nii et al. (2009 and 2010). All these studies employed rigid bed models. Various model scales from 1/18 to 1/150 were adopted.

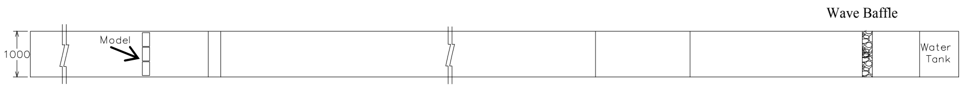
Previous researchers omitted the piers or making piers sizes un-proportionally small in the physical models as done by previous researchers, they essentially ignore the influence of the piers and deck on the flow condition around each individual component. Therefore, a more realistic model was employed in this research which included both the piers and decks in the actual proportion. The experimental results show that the presence of bridge deck in a complete pier-deck model can increase the hydrodynamic pressure acting on the pier as much as 50 % than the one calculated based on the stand-alone pier model (Lukkunaprasit & Lau, 2011).

3.2 Experimental study

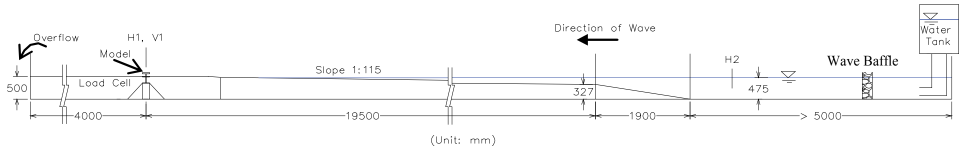
The basic principle of physical modeling is to simulate the characteristics of the prototype by the model which is generally at a reduced scale under certain similitude criterion. A wave flume experiment was conducted to obtain the time histories of pressures and forces on an inland bridge model subjected to tsunami loading.

3.2.1 Experimental setup

Figure 2 illustrates the setup of this experimental study. The hydraulic model experiments were carried out in a wave flume of 1 m × 1m in cross section and 40 m in length. The rigid bed of the flume with a compound bed slope of 1/115 (0.5^0) and a flat platform where the model is located was constructed from painted steel plates supported by structural steel sections. The coastal geometry was downscaled in the model study with the length scale of 1/100.



Plan view



Cross-sectional view

Fig. 2. Schematic diagram of the experimental setup

The water stored in the elevated tank at the farthest right end of the flume in Figure 2 was released abruptly in order to generate a tsunami-like solitary wave. Solitary-like waves with different wave heights were generated by varying the amount of released volume of water.

Figure 3a shows a single solitary wave that was formed at the location near to offshore region (H2). The wave with almost a vertical wave front (Figure 3b) broke in the finite depth of still-water as a plunging-type breaker (Figure 3c) after losing its stability. The wave then transformed into bore by shoaling a solitary wave at a distance of about 20 m offshore. The turbulent bore runup on shore takes the form of a surge (as described by Camfield (1994) and Yeh (2007)) striking the bridge model which is rigidly installed at the downstream end of the flume.

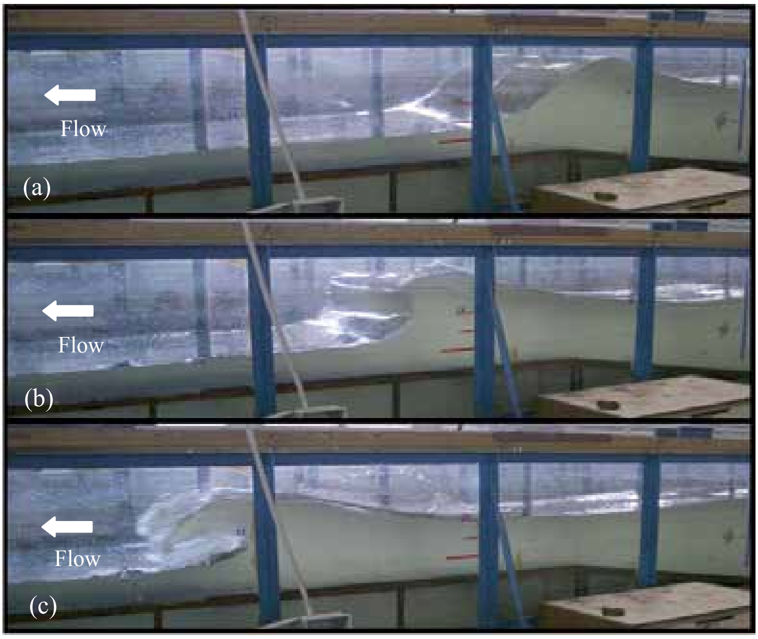
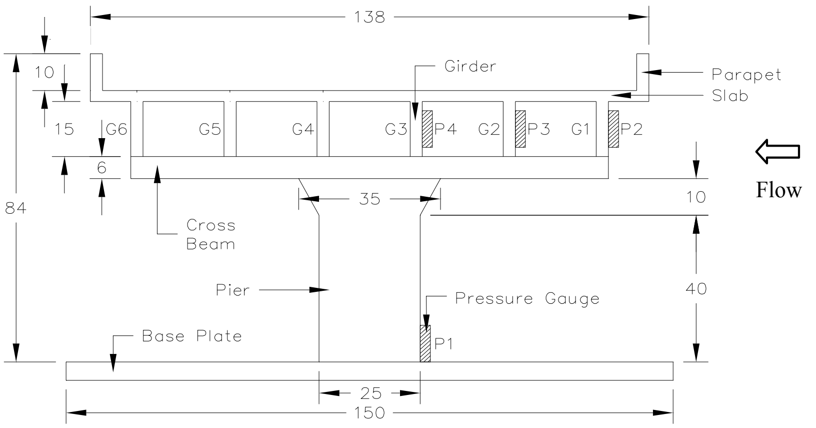


Fig. 3. Simulated tsunami wave

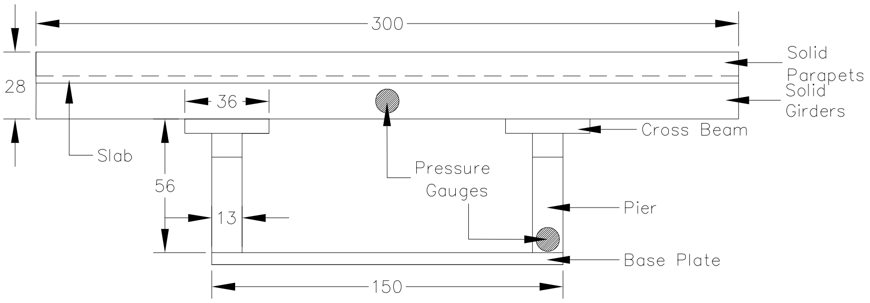
3.2.2 Target bridge and bridge model

The target bridge prototype is a reinforced concrete bridge with I-beam girder which is widely constructed in countries surround the Indian Ocean. The bridge, spanning 30 m apart, consists of a deck 13.8 m wide supported by 1.5 m deep girders, and 1 m high parapets. The deck clearance (height from the ground to the girder soffit) is 5.6 m. A ground level of 2.5 m above the mean sea level is considered. The expected tsunami inundation depth at the site is about 8 m with reference to the ground and the wave hits perpendicularly to the longitudinal axis of the bridge. Since the tsunami force is normally not taken into consideration during the design of inland bridges, these structures are highly vulnerable to damage should a tsunami attack.

The 1/100 scaled complete pier-deck bridge model constructed from clear acrylic plates was mounted on a base plate flushes with the surrounding dry bed located downstream. Figure 4 illustrates the typical cross-sectional and front views of the bridge models, respectively. Three spans of the bridge deck with each span of 138 mm in width by 300 mm in length were installed across the width of the flume and perpendicular to the flow direction. Out of these three spans, only the middle span was instrumented with pressure gauges and a load cell. The model included the bridge piers spaced at 137 mm apart. The base plate was mounted on a high frequency load cell which was used to record the total horizontal wave forces acting on the complete pier-deck bridge model. Also shown in the figures are the positions of pressure gauges on the model. P_1 designates the pressure gauge location at the base of the pier while P_2, P_3 and P_4 are those at the mid-span of girders G1, G2 and G3, respectively.



(a) Cross-sectional view (Unit: mm)



(b) Front view (Unit: mm)

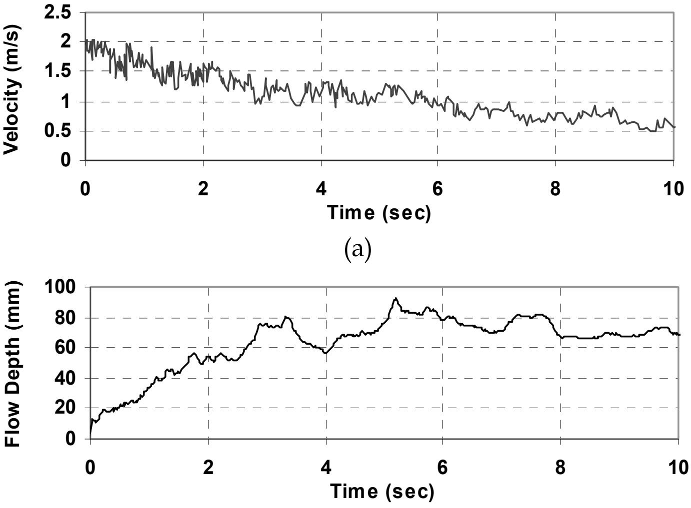
Fig. 4. Bridge model

3.2.3 Instrumentation

Capacitance type wave gauges were used to measure the wave profiles at onshore (H1) and offshore (H2) locations as illustrated in Figure 2. The velocities of the flow in the flume for various wave heights were recorded by a propeller type current meter at V1 (Figure 2). Both wave gauge and current meter were installed at H1 and V1 with the absence of the model during measurement. During the testing of the model, only the wave height at H2 was measured in order to avoid the interference from the instruments on the flow regime in the vicinity of the model. Tsunami forces in the horizontal direction were measured by a calibrated high frequency load cell which was mounted at the base of the bridge model. The recorded value from the load cell represented the total horizontal wave forces acting on the deck and the piers as a result of the wave pressure and the drag. The wave pressures were measured by miniature pressure gauges with high frequency response.

3.3 Measured time histories of forces and pressures

The typical time histories of the velocity and the height of the wave at the location of the bridge model (in the absence of the model) are depicted in Figure 5. The instant when the wave first hits the bridge model is taken as t = 0. It is to be noted that the leading edge of the wave attains a practically maximum velocity at the instant it reaches the location of the bridge model when the wave height is still very small. As the wave increases in height, the velocity decreases significantly, and the maximum wave height is attained at some time later than the instant the velocity is maximum. Therefore, the peak flow velocity does not coincide with the maximum wave height.



(a)

(b)

Fig. 5. Measured time histories of flow depth and velocity

Figures 6 and 7 present typical time histories of the wave force and wave pressures measured. As the leading edge of the wave (Figure 8a) strikes the bottom of the bridge piers with a high velocity, part of the upward splash hits the soffit of the cross beams while the remaining splash is diverted sideways. The pressure gauge reading P1 (at the pier) almost instantaneously attains the peak value (more than 3 times the hydrostatic pressure as shown in Figure 7a) while no pressure is recorded at the girders. At this instant, the wave height

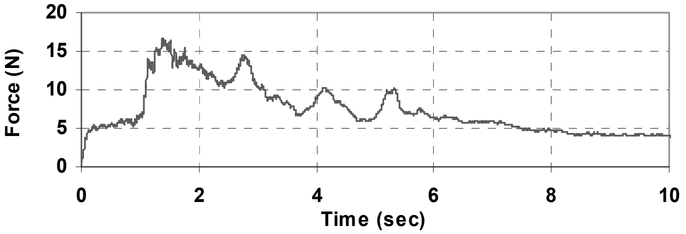


Fig. 6. Measured time histories of force

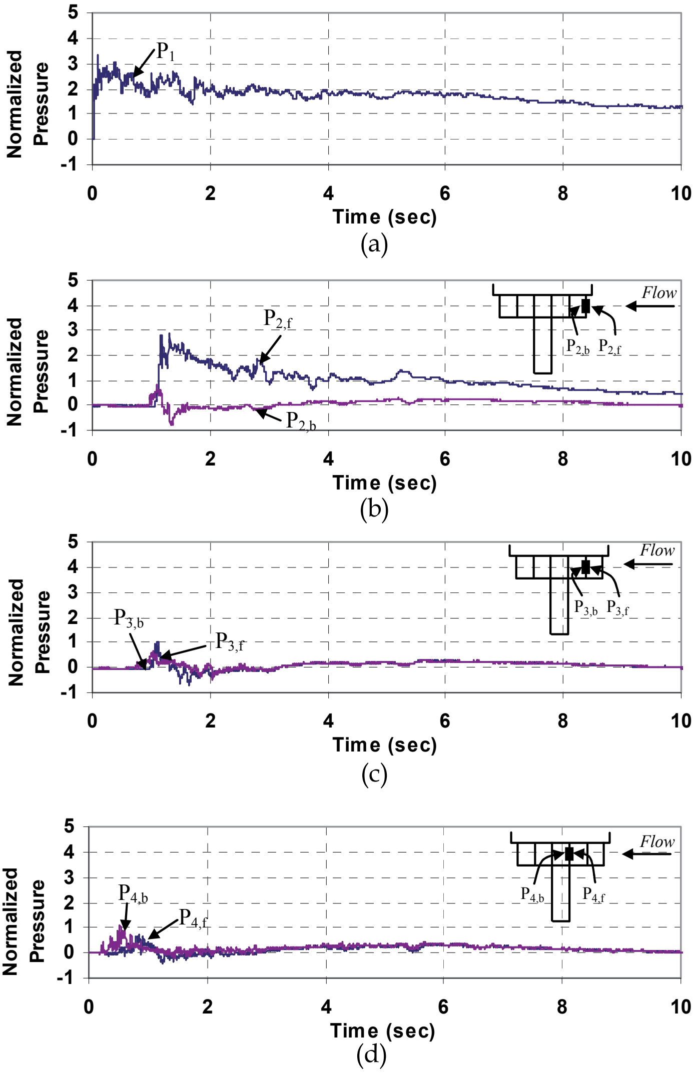
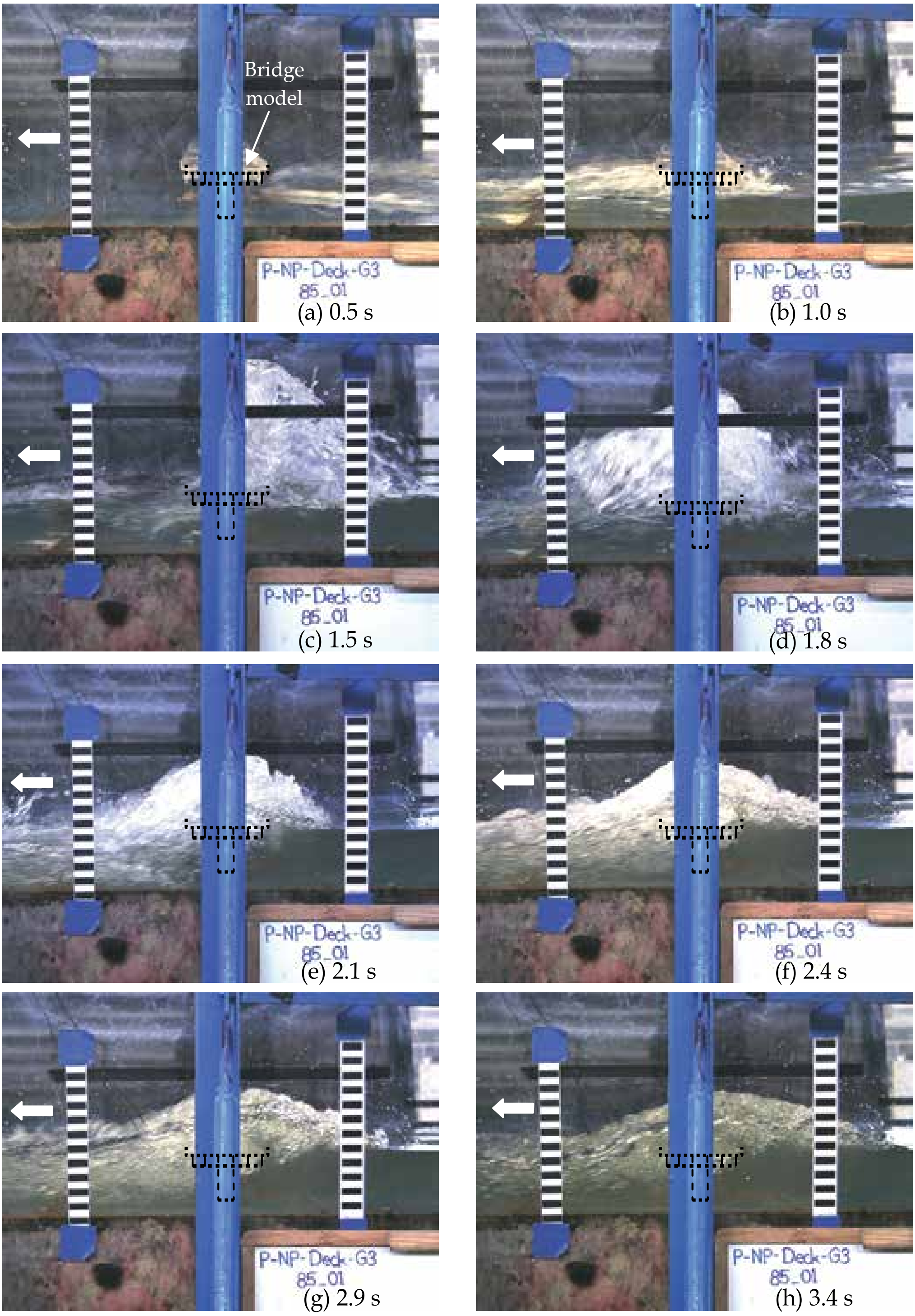


Fig. 7. Measured time histories of pressures



(a) 0.5 s
(b) 1.0 s
(c) 1.5 s
(d) 1.8 s
(e) 2.1 s
(f) 2.4 s
(g) 2.9 s
(h) 3.4 s

Fig. 8. Sequential events of wave impingement on a model bridge from experiment

and the wave force are relatively small, but they increase rapidly with time, and the force records the first peak value of 5.5 N at second 0.3 (Figure 6). These forces may be regarded as the peak forces on the piers. Thereafter the wave height increases but the velocity decreases as mentioned earlier with the result of the force being sustained near the peak value for nearly one second.

The pressures on the girders remain zero (except P4 which is most likely due to the minor splash-up) until the height of the wave rises to the lower part of the bridge girders (Figure 8b) when the wave splashes over the bridge deck with a height of three times that of the incident wave as shown in Figure 8c. This results in a rapid increase of wave force and the second peak is attained. The wave forces reach their peaks at second 1.4. In the meantime, pressure gauge $P_{2,f}$ (Figure 7c) attains its peak value but the pressures at $P_{2,b}$, $P_{3,f}$, $P_{3,b}$, $P_{4,f}$ and $P_{4,b}$ are recorded initially with small negative values consistently in all tests. The deflected column of water collapses, falls back on the wave with substantial amount of entrained air. The wave then overtops the bridge deck and travels away from the bridge model (Figures 8e - 8h).

One may observe from Figures 6 and 7 that the maximum wave force on the bridge model almost coincides with the occurrence of the peak net pressure at girder G1. Girder G1 is subjected to the highest wave forces compared to the others (girders G2 and G3) because it is exposed to the direct wave attack. The maximum pressure which is 2.9 times the hydrostatic pressure are obtained at the front face of girder G1. Compared to girder G1, the net pressures on girders G2 and G3 are insignificant, especially when the maximum forces are gained. It is also observed that the pressures at the back faces of girders G1, G2 and G3 pick up slightly earlier than the pressures at the front faces.

4. Numerical modeling

Numerical simulations were performed subsequently to further investigate tsunami flow around inland bridges. To ensure the appropriateness of the numerical model in simulating tsunami flow, wave flume experiments (under free flow condition without the bridge model) as performed in the experiment during calibration was reproduced numerically using a two-dimensional (2D) model as the first step. It was then followed by a detailed investigation of tsunami flow around the bridge model using a three-dimensional (3D) numerical model. The 3D model is then extended to the prototype scale in order to simulate the real flow mechanics around the target bridge prototypes.

4.1 Reviews on related numerical simulation

Several numerical studies of tsunami forces on bridges have only been conducted such as Nimmala et al. (2006), Endoh & Unjoh (2006), Ikari & Gotoh (2007), Lau et al. (2009), Murakami et al. (2009), Shigihara et al. (2009a and 2009b), Kosa et al. (2009) and Usui et al. (2010). Numerical studies on bridges subjected to tsunamis were carried out by Nimmala et al. (2006), Endoh & Unjoh (2006) and Ikari & Gotoh (2007). Nimmala's work focused on the determination of the design tsunami force on a real bridge in Oregon, U.S. under the predicted tsunami scenarios from the fault models. A two-dimensional bridge deck model (simplified as a rectangular box with top rounded edges) was considered. The fluid-structure interaction analysis of the bridge was conducted using the state-of-the-art computational mechanics software. Endoh & Unjoh (2006) and Ikari & Gotoh (2007) used the particle method where the motion of the fluid is described in a Lagrangian coordinate. The former study used the Particle Flow Code to simulate an I-girder bridge in a two-dimensional model. The target bridge was located over a dry bed in Banda Aceh, subjected to 30 m high tsunami and a constant velocity of 68 km/h. The latter study used the Moving Particle Semi-implicit (MPS) method to simulate tsunami flow around a simplified rectangular box girder bridge over a wet bed based on the experimental study by Shoji & Mori (2006). Both studies reproduced the failure mechanism of bridges subjected to tsunami attacks.

4.2 Numerical study

The state-of-the-art Computational Fluid Dynamics (CFD) program, Flow-3D®, was used to simulate tsunami flow around I-girder bridges. A detailed investigation of tsunami flow around the bridge model as in the experiments was carried out.

4.2.1 Numerical methodology

Flow-3D® is a general purpose CFD package that is used to solve transient and three-dimensional flow problems. It was developed by Flow Science, Inc., formed by Dr. C. W. Hirt in 1980, and first released in 1985 and has a comprehensive track record in CFD modeling. Though, the application in modeling tsunami on bridges is a new attempt. Flow-3D® is developed based on the fractional volume of fluid (VOF) free surface tracking method as discussed in Hirt & Nichols (1981). Under this method, cells are defined with a value between zero and one for empty to fully filled cells with fluid. For partially filled cells, the slope of the free surface is determined by an algorithm that uses the surrounding cells to define a surface angle and a surface location. This method allows the steep fluid slopes to be defined and it is applicable to describe the breaking wave (bore or surge) in tsunami run-up zone.

The model constructed in this research is an incompressible and viscous flow model. Flow-3D® employs the finite-volume method to solve the fluid equations of motion of the time dependent Reynolds Averaged Navier-Stokes (RANS). The computational domain is defined in a fixed rectangular grid or structured system. The fluid momentum equations, Navier-Stokes equations, can be expressed as follows (Flow-3D, 2007),

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+g_x+f_x \tag{1a}$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial v}{\partial x}+vA_y\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+g_y+f_y \tag{1b}$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left(uA_x\frac{\partial w}{\partial x}+vA_y\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial z}+g_z+f_z \tag{1c}$$

where u, v and w are the velocities in the x-, y- and z-directions; V_F represents the volume fraction of fluid in each cell; A_x, A_y and A_z are the fractional areas open to flow in the x-, y- and z-directions; ρ is the fluid density; p is the fluid pressure; g_x, g_y and g_z are the body accelerations in the x-, y- and z-direction and f_x, f_y and f_z are the viscous accelerations in the x-, y- and z-direction for which a turbulence model is required for closure. For cells fully filled of fluid, V_F, A_x, A_y, and A_z equal to one.

For an incompressible fluid, the following condition (i.e. continuity equation) must hold:

$$\frac{\partial}{\partial x}(uA_x)+\frac{\partial}{\partial y}(vA_y)+\frac{\partial}{\partial z}(wA_z)=0 \tag{2}$$

Boundary conditions are categorized as symmetry, rigid-free or no-slip walls, continuative outflow, periodic and specific pressure boundaries. No flux is allowed to cross the symmetry and wall boundary; however, viscous shear stresses occur at the wall boundary only. Flow variables (velocity, pressure, etc) are constant across boundary (zero gradient). A continuative boundary condition consists of zero normal derivatives at the boundary for all flow quantities; thus, there is no acceleration or deceleration of the flow as it crosses the boundary. Free slip is defined as zero normal velocity component with zero tangential velocity derivatives ($v = 0$ and $\partial u/\partial x = \partial w/\partial z = 0$). No slip is defined as zero tangential and normal velocities ($u = v = w = 0$).

Hydraulic forces that fluid flow exerts on the solid structures are calculated by integrating the pressure acting on these structures over the open surface. Hydraulic forces which comprise the pressure and viscous forces are defined as

$$F = \int p\bar{n}dA + \int \bar{\tau}dA \tag{3}$$

where p is the pressure, dA is the solid surface area in the cell, $\bar{n}$ is the unit vector normal to area dA and $\bar{\tau}$ is the shear stress vector.

The computational domain was discretized into an orthogonal and staggered grid of variable-sized hexahedral meshes in a Cartesian coordinates. Due to the complex bridge model, multi-block gridding with nested and linked grids (will be explained in Section 4.2.2) were applied in order to reduce the computational cost while maintaining the accuracy of the results. Also due to symmetrical orientation, only half of the wave flume was modeled. Under this discrete structural grid system, average values of the flow parameters were placed at the center of each cell (for pressure and fractional volume of fluid) and the center of cell faces normal to their associated direction (for velocity).

The basic algorithm for the computation consists of three main steps. The first step is the computation of flow velocity based on the initial conditions or previous time-step values from the explicit approximations of Navier-Stokes Equations. Next, the pressure values will be adjusted to satisfy the continuity equation. It is followed by the determination of the fluid free surface or interface and update of the new fluid configuration based on the VOF method. This computation is then advanced to the next time-step and those three steps are repeated.

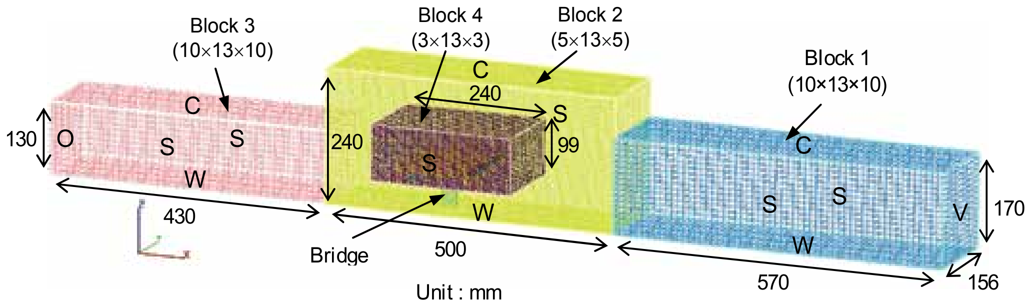
On top of that, bridge and other auxiliary structures were constructed as obstacles in the numerical model. The flow obstacle was defined using a porosity technique in rectangular cell meshes called the Fractional Area/Volume Obstacle Representation (FAVOR) method as outlined in Hirt & Sicilian (1985). For cells without obstacle, the grid porosity is one and the fluid dynamic equations are to be hold. In contrast, the grid porosity is zero for cells within obstacle where no flow volume is allowed in the obstacle region. For cells that are partially filled with an obstacle, the grid porosity has a value between zero and one, based on the percent volume that is open. The surface angle and the surface location are determined based on the same principal of VOF as stated in the above section.

4.2.2 Computational model

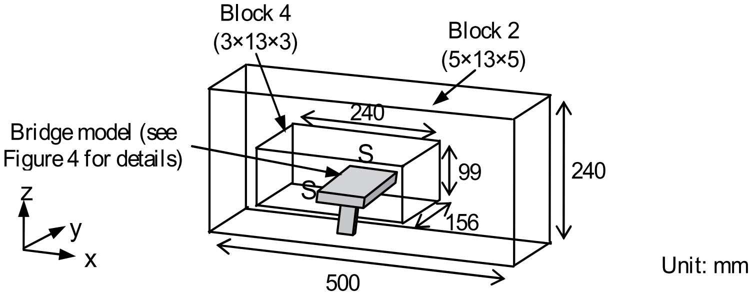
Three-dimensional bridge models were constructed in the computational domain of 1.5 m long by 0.24 m high (maximum) by 0.156 m width as shown in Figure 9. The computational domain consisted of three linked blocks (Blocks 1, 2 and 3) and a nested block (Block 4) of meshes as highlighted in Figure 9. The bridge model was located in Block 2 where the bridge deck was enclosed in Block 4 with higher resolution meshes as listed in Table 1. Six different boundaries of each block were defined. Sidewalls were defined as free slip/symmetry (S), the bed was no slip/wall (W); the top was continuative (C); the upstream and downstream were velocity boundary (V) and the outlet (O), respectively.

The bridge model as shown in Figure 4 was installed at the location of about 0.9 m from the right boundary. The calculation was first carried out under the free flow condition (the case without bridge model) and followed with the case with the bridge model placed on a dry bed as performed in the experiment.

Newtonian viscosity with renormalized group (RNG) k-ε turbulence model was adopted. The inflow properties were input at the upstream (right) boundary with time-dependent velocity and flow depth data, assuming these quantities were uniformly distributed along the width and the height of the flume at each time step. The other numerical input data were set as 1000 kg/m^3 for fluid density, 1.225 kg/m^3 for air density, 0.001 kg/m/s for fluid viscosity and -9.81 m/s^2 for gravitational acceleration. The simulated wave represented the wave propagation over a 1/115 bed slope at near-shore. The wave hits the model at the right angle to the longitudinal axis of the bridge.



(a) Linked block



(b) Nested block

Note: Mesh size is shown in parentices (Δx × Δy × Δz)
Notations for boundary condition: S - symmetry; W - wall; C – continuative; V – velocity; O - outlet

Fig. 9. Computational domain

Block	Type	Total Length (m)			Interval (mm)		
		x	y	z	Δx	Δy	Δz
1	Linked	0.57	0.156	0.17	10	13	10
2	Linked	0.5	0.156	0.24	5	13	5
3	Linked	0.43	0.156	0.13	10	13	10
4	Nested	0.24	0.156	0.099	3	13	3

Table 1. Mesh properties for bridge model

4.2.3 Model validation

Due to the complexity of the problem and the scarcity of the theoretical background in the current research focus at this stage, the only available method to ensure the appropriateness of the computational model is through the comparison of the computed results with the independent data measured from the physical modeling. Figure 10 highlights the wave profile from the numerical simulation when the generated wave strikes the model at selected time intervals. The phenomena of the wave impingement on the bridge model as those observed in the experiments (as shown in Figure 8) are well simulated in the numerical analysis.

Wave pressures were measured in the front center face of the pier at a point of 0.5 cm above the bed (P1,f) and the front and back face of girders at mid-span of the girders and 6.35 cm above the bed (P2,f and P2,b) as shown in Figure 4. For better representation, all pressure values are normalized with the nominal flow depth (maximum water level at the location of interest). The normalized pressure time histories obtained from the physical and numerical models are compared in Figure 11 while the time histories of the total horizontal force acting on the entire bridge model are shown in Figure 12. The variations of the calculated and the measured results are not significant.

It should be noted that the vertical force computed by the numerical model is not validated due to the unavailable measured data. Good agreement of the pressures and the force throughout the considered time domain has evidently justified that this numerical bridge model can reproduce the physical bridge model with high confidence. As a result, this qualitatively and quantitatively validated model is extended for the simulation of bridge prototypes as discussed in the following section.

4.2.4 Simulation of bridge prototype

This section presents simulation results of bridge prototypes subject to the scenario flow depth (*H*) of 8 m. Bridge prototypes are constructed by scaling up bridge models with the length scale of 100. The grid size in the numerical model is also scaled up to 100 times that in the downscaled model. To develop the generalized force and pressure distributions on the bridge deck, seven types of bridge prototypes namely CR36, CR41, CR46, CR51, CR56, CR66 and CR76 that correspond to the deck clearances (*h*) of 3.6 m, 4.1 m, 4.6 m, 5.1 m, 5.6 m, 6.6 m and 7.6 m are employed. The ratio of the deck clearance to the nominal flow depth (*h/H*) of these prototypes ranges from 0.45 to 0.95 (Table 2). The required time to complete the running time of 50 s at 0.5 s interval in the Intel® Core™ 2 Duo processor with a 3.16GHz and an 8GB RAM's computer for all cases are given in Table 2.

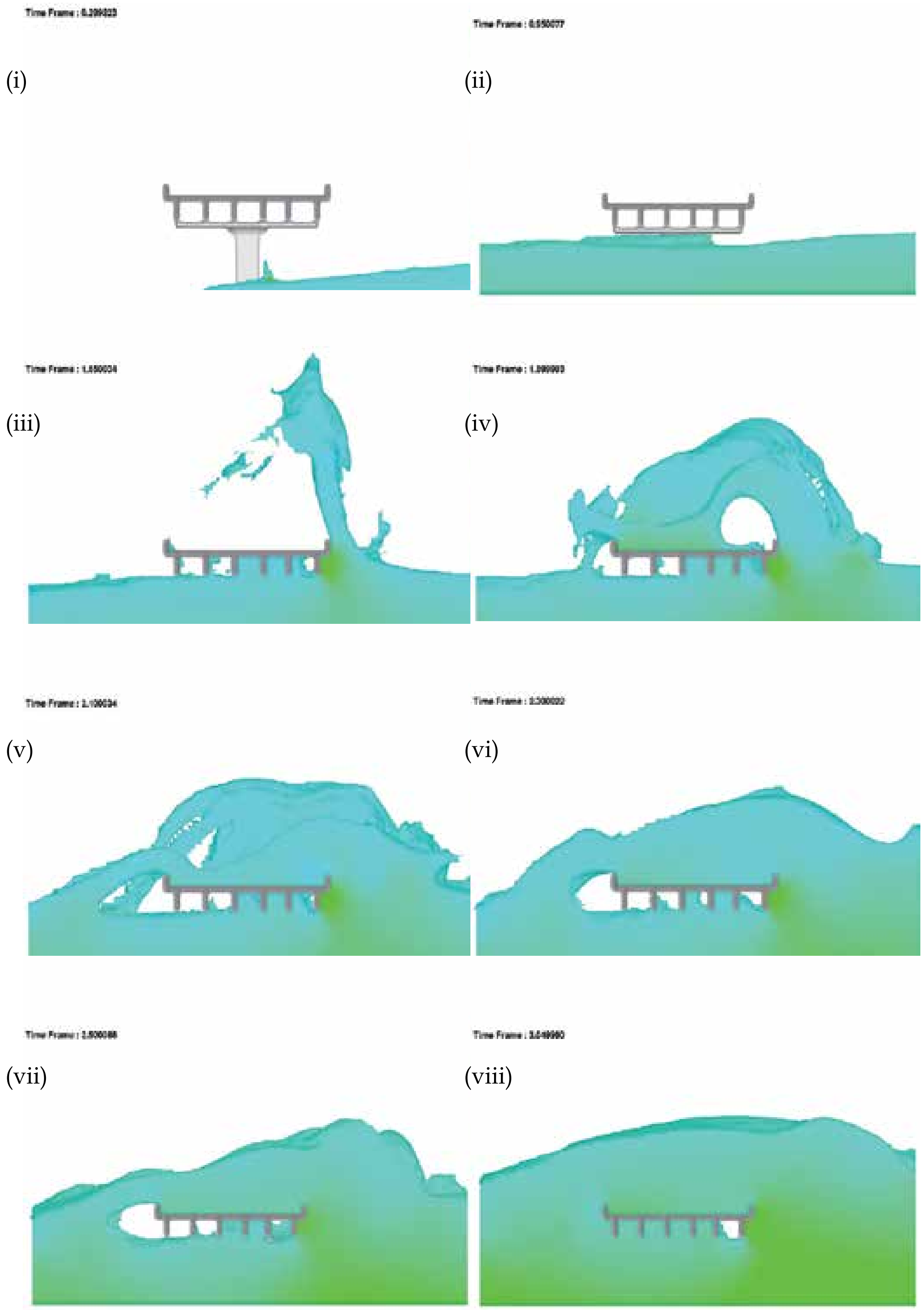
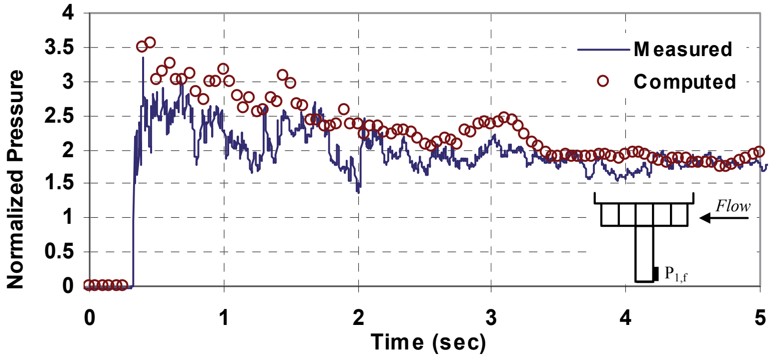
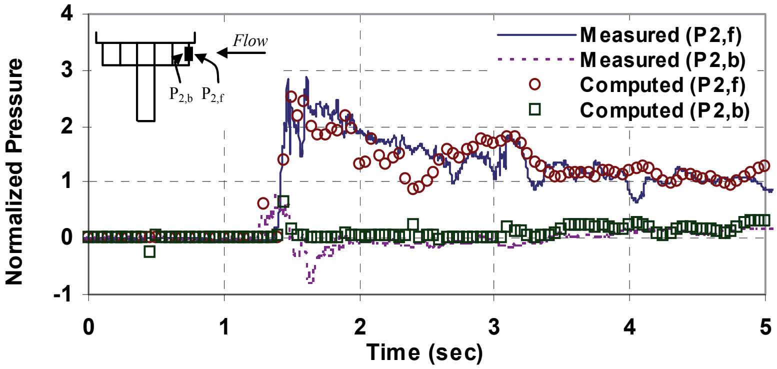


Fig. 10. Sequential events of wave impingement on a bridge model from numerical simulation



(a) P1,f



(b) P2

Fig. 11. Time histories of front face pressure on (a) pier, and (b) front girder

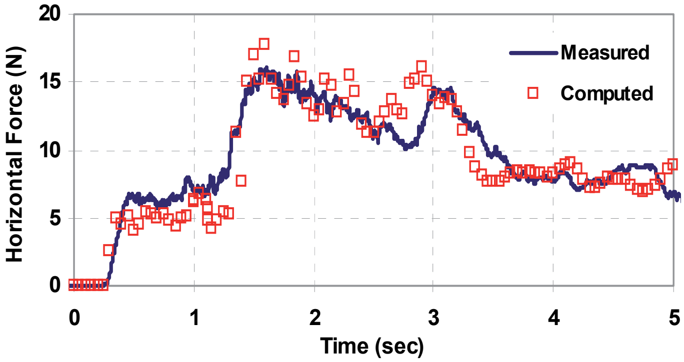


Fig. 12. Time histories of the force on bridge model

Cases	Deck Clearance, *h* (m)	*h/H*	Computational Time
CR36	3.6	0.45	8 hours 44 minutes
CR41	4.1	0.5125	9 hours 38 minutes
CR46	4.6	0.575	7 hours 32 minutes
CR51	5.1	0.6375	7 hours 50 minutes
CR56	5.6	0.70	7 hours 21 minutes
CR66	6.6	0.825	6 hours 24 minutes
CR76	7.6	0.95	4 hours 57 minutes

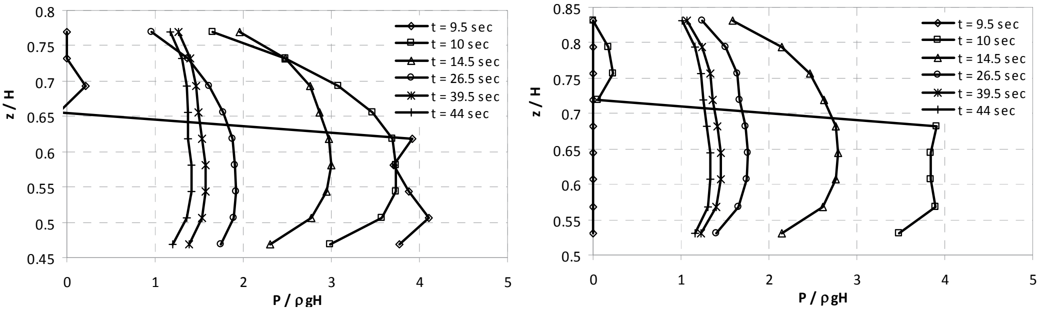
Table 2. *h/H* ratio and computational time

4.3 Computed wave pressures and forces

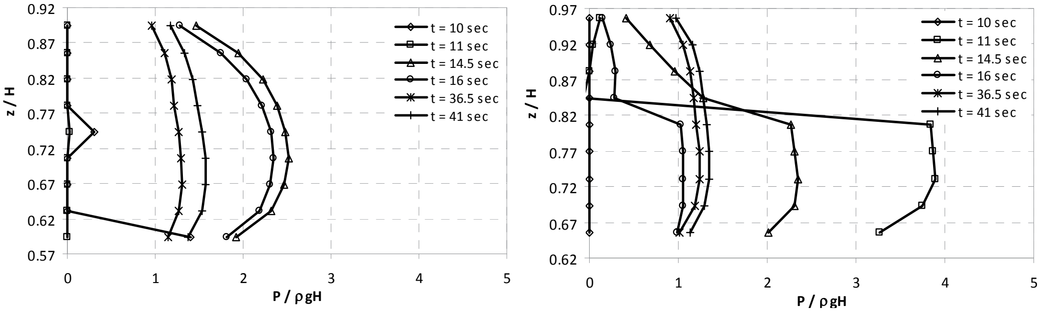
The pressures distribution along the height of the girders discussed in the following are normalized with the hydrostatic pressure based on the scenario flow depth of 8 m. Figure 13 presents the vertical pressure distribution at the front face of the bridge deck of seven deck clearances. As the unique configuration of the I-beam girder deck where the parapets protrude from the vertical planes of the front and back girders, the pressure distribution discontinues at the slab level (z/H = 0.6375 for CR36, 0.7 for CR41, 0.7625 for CR46, 0.825 for CR51, 0.8875 for CR56, 1.0125 for CR 66 and 1.1375 for CR76). As anticipated, the higher the deck, the smaller the maximum pressure is attained. The maximum normalized pressure of larger than 4 is observed for CR36 and CR41 while the normalized pressure for CR66 is below 2. When the wave initially hits the front girder or front parapet, some proportions of the hydrostatic pressure impart on the front face of the girder and parapet. Thereafter, the wave flows through the deck and it exerts almost uniform pressure over the height of the deck (except near to the free ends at the top and bottom of the deck) especially when the wave becomes nearly steady (about second 40). At the instant when the maximum wave force is attained, the pressures on the front girder and front parapet are practically dominated by the hydrodynamics and hydrostatic pressures, respectively.

Computed time histories of total horizontal and vertical forces on bridge decks subject to tsunamis with the scenario flow depth of 8 m are shown in Figure 14. The positive sign in the horizontal force represents the force in line with the flow direction while the positive and negative signs in vertical force represent the vertical uplift and the additional gravity force, respectively. The horizontal force can be generally characterized into two types, i.e. impulsive and slow-varying forces. Force measurement is firstly recorded for CR36, followed by CR41, CR46, CR51, CR56, CR66 and CR76. Impulsive forces vary substantially from case to case up to second 20 except the cases of CR66 and CR76 ($h/H \geq 0.825$) where practically no impulsive forces are recorded (Figure 14a). The peaks of the impulsive forces in the horizontal direction are obtained at second 10 (CR36), second 14.5 (CR41 and CR46) and second 16 (CR51 and CR56), which mark approximately 2 to 3 times the slowly-varying forces. As oppose to impulsive forces, all cases (except CR76) have the similar horizontal slowly-varying forces regardless their deck clearance after second 35, i.e. about 7 MN.

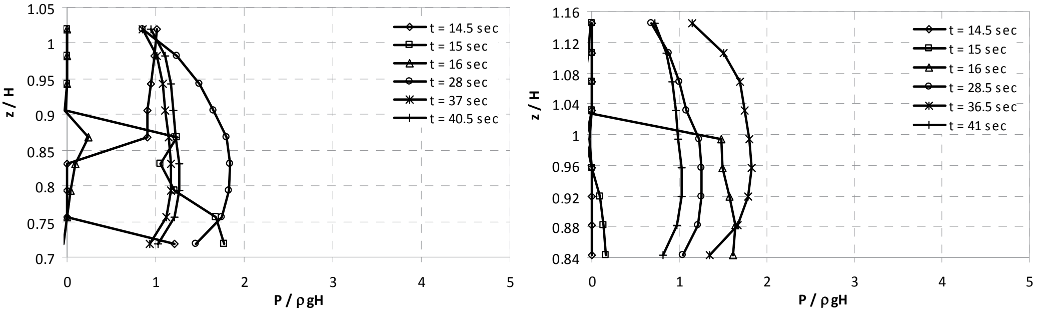
Vertical force time histories (Figure 14b) exhibit different trends. The vertical uplift force is firstly exerted on the deck and it followed by the additional gravity force after the wave falls on and overtops the deck. The uplift force is denoted by positive value whereas the additional gravity force is denoted by negative value based on the sign convention in the computation. CR36 and CR46 show longer period of vertical uplift force action up to



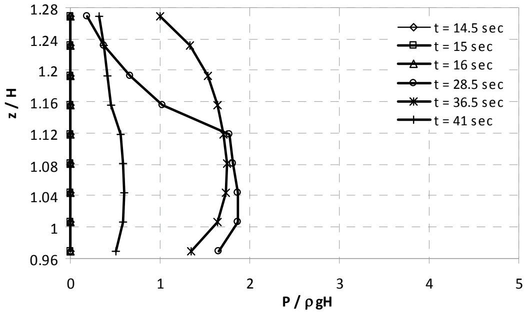
(a) Case CR36 (b) Case CR41



(c) Case CR46 (d) Case CR51



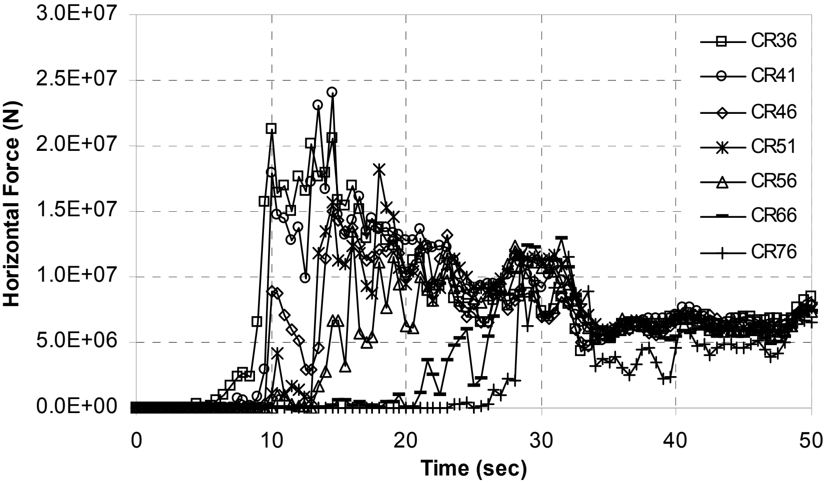
(e) Case CR56 (f) Case CR66



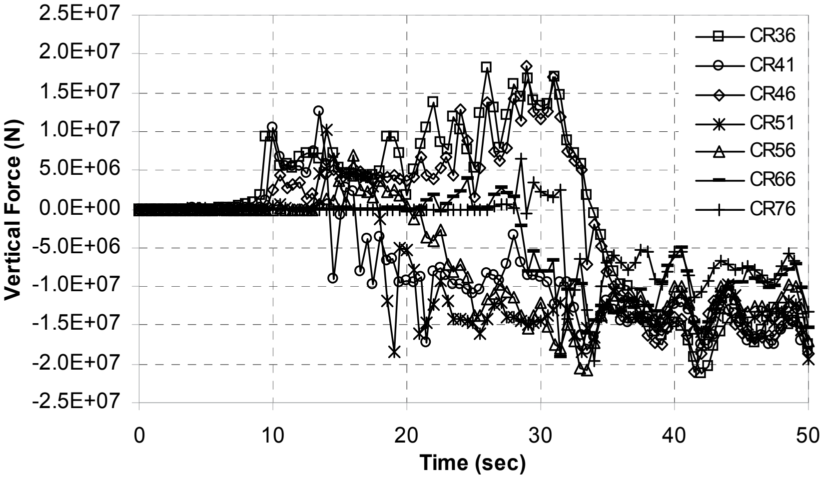
(g) Case CR76

Fig. 13. Vertical pressure distributions at mid-span

second 34. This is due to the water jet (that is pushed upward) drops beyond the deck. For the case of CR41, the water jet is pushed almost upright and it drops on the deck soon after. The maximum vertical uplift forces are attained from 3.8 MN (CR66) to 18.5 MN (CR46) or 0.5 to 2.6 times the slowly-varying forces. CR66 and CR76 have relatively small vertical uplift forces. Similar to the horizontal force time history, the variation of the vertical force is not significant after second 35, where the wave with much higher flow depth flows through the bridge deck at nearly steady state. The maximum additional gravity force marks about 21 MN which is 3 times the horizontal slowly-varying force.



(a)



(b)

Fig. 14. Time histories of total force in horizontal (a) and vertical (b) components

From the results, it is observed that the front girder suffers the highest wave pressure. Therefore, it is the most critical member of the bridge deck subjected to tsunami flow. To avoid the bridge deck from washing away, it is recommended to reinforce the front girder so that it is strong enough to withstand both the horizontal and vertical forces acting on it. The other method to reduce the tsunami forces on bridges is to reduce the exposed area to tsunami by using the perforated bridge deck as presented in Lau *et al.* (2010).

5. Tsunami force estimation

Based on the results from the numerical analysis, the formulation of tsunami wave forces on bridges is presented in this section. A method of tsunami force estimation is proposed. Tsunami forces in horizontal and vertical components are derived. Horizontal forces are categorized into peak and slowly-varying forces whereas vertical forces are categorized into uplift and additional gravity forces.

5.1 Estimation of slowly-varying forces on bridge decks

One of the important observations shown in the horizontal force time-histories (Figure 14a) are the independency of the slowly-varying forces from the deck clearance. This argument holds for h/H between 0.45 and 0.825. Pressure distributions of the slowly-varying forces on the bridge decks subject to 8 m scenario flow depth are presented in Figure 15. At the instant the slowly-varying force acts on the front face of the deck, the back face of the deck is subjected to the wave attack as well. Front and back face pressure distributions are presented in Figures 15a and 15b, respectively. It is found that the distributions can be regarded as somewhat hydrostatic. The mean values are determined from the linear least square approximation. Also plotted are the values of mean plus one standard deviation (mean + 1SD) and mean plus two standard deviations (mean + 2SD) corresponding to 68 % and 95 % confidence levels, respectively.

For the mean value the triangular shaped of the pressure distribution on the front face of the deck (Figure 15a) marks $2.48\rho gH$ on the ground and acting up to $1.64H$. The pressure distribution of the wave at the back face of the deck is shown in Figure 15b where the distribution of $0.96\rho gH$ on the ground and acting up to $1.12H$ are obtained. The wave pressure at the back face of the deck is almost similar to the hydrostatic pressure. By subtracting the back face pressure from the front face pressure, the net dimensionless pressure acting on the bridge deck are determined which can be expressed in the bilinear relationships as follows,

For mean,

$$P = \rho gH\,(2.3246 - z/H)\,/\,1.5302, \quad 0.4 \le z/H \le 1.12 \tag{4a}$$

$$P = \rho gH\,(1.642 - z/H)\,/\,0.6626, \quad 1.12 \le z/H \le 1.3 \tag{4b}$$

Similarly,

For mean + 1SD,

$$P = \rho gH\,(2.4168 - z/H)\,/\,1.5302, \quad 0.4 \le z/H \le 1.16 \tag{4c}$$

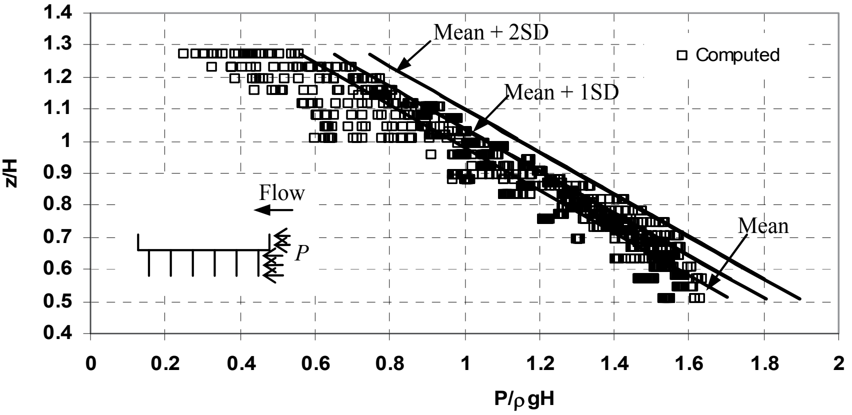
$$P = \rho gH\,(1.7024 - z/H)\,/\,0.6626, \quad 1.16 \le z/H \le 1.3 \tag{4d}$$

For mean + 2SD,

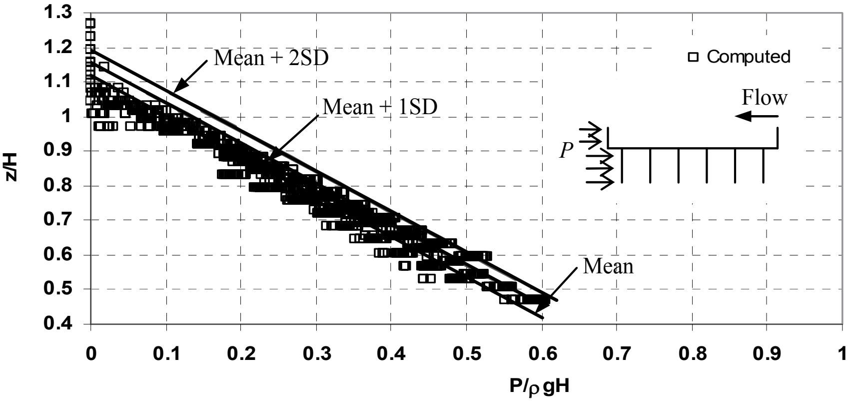
$$P = \rho gH\,(2.5093 - z/H)\,/\,1.5302, \quad 0.4 \le z/H \le 1.19 \tag{4e}$$

$$P = \rho g H\,(1.7628 - z/H)\,/\,0.6626, \quad 1.19 \le z/H \le 1.3 \tag{4f}$$

where z is the height of the point of interest that is measured from the ground level.
Eq. (4a) to Eq. (4f) are used to calculate the forces acting on the bridge decks with various clearances within the limits of the deck heights. Except for the cases which the decks are placed at extreme low and high position (CR36 and CR76), the results indicate that the mean + 2SD pressure distribution can adequately predict slowly-varying forces.



(a) Front face pressure distribution



(b) Back face pressure distribution

Fig. 15. Distribution of slowly-varying pressure on front (a) and back (b) faces of bridge deck

5.2 Proposed formulae for predicting tsunami forces on bridge decks

To make the prediction of the horizontal impulsive, vertical uplift and additional gravity forces possible, the method for estimating coastal wave forces on bridge decks suggested by Douglass et al. (2006) is proposed. This approach has been adopted in the Federal Highway Administrative Hydraulic Engineering Circular No. 25 (HEC-25, 2008). The fundamental idea of this approach is to determine the reference forces in the horizontal and vertical components which are 'apparent hydrostatic forces' and the maximum impact forces correspond to those components are then computed as some multiple of these reference forces.

The reference forces stipulated in HEC-25 (2008) which based on the level of submergence are not applicable for broken waves (tsunami bores or surges) because the crest of the wave is not easily predicted using the current knowledge. Therefore, the reference forces based on the pressure distribution of slowly-varying forces derived in Section 5.1 are proposed for tsunami cases. The selection of the slowly-varying force as the reference force is the appropriate one due to the aforementioned characteristics of: (1) independency from the deck clearance; (2) occur at near steady state flow region; and (3) insignificance of forces on the intermediate girders.

This reference forces are associated to the height of the deck and the scenario flow depths which are known values. The reference force, F_{ref}, is expressed as

$$F_{ref} = PA \tag{5}$$

where P = the pressure acting on the deck that can be estimated from Eq. (4), and
A = the vertical projected area of the deck.

The maximum forces acting on bridge decks, i.e. horizontal slowly-varying, horizontal impulsive, vertical uplift and additional gravity forces are estimated from the following expressions:

$$\text{Maximum horizontal slowly-varying force, } (F_{sv})_{max} = c_{sv}F_{ref} \tag{6a}$$

$$\text{Maximum horizontal impulsive force, } (F_{imp})_{max} = (c_{sv} + c_i)F_{ref} \tag{6b}$$

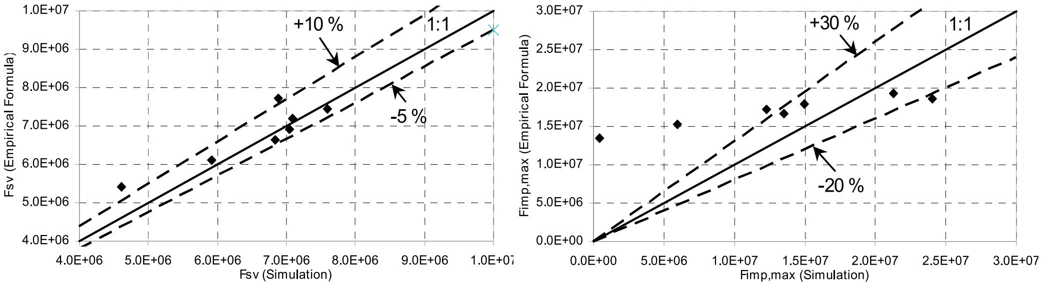
$$\text{Maximum vertical uplift force, } (F_{uplift})_{max} = (c_{sv} + c_u)F_{ref} \tag{6c}$$

$$\text{Maximum additional gravity force, } (F_{ag})_{max} = (c_{sv} + c_a)F_{ref} \tag{6d}$$

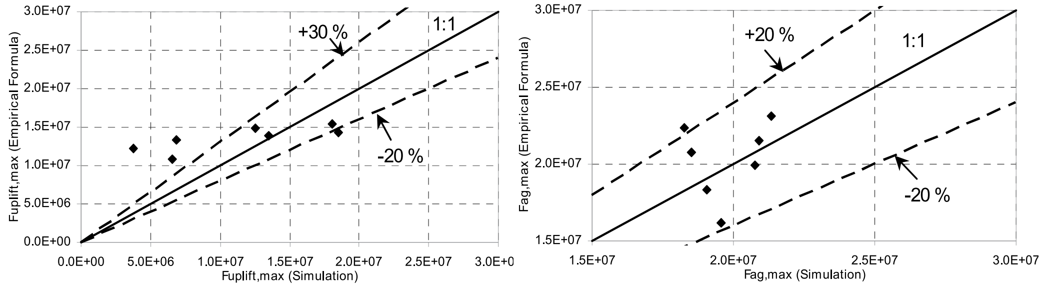
where c_{sv} = an empirical coefficient for the horizontal slowly-varying force,
c_i = an empirical coefficient for the horizontal impulsive force,
c_u = an empirical coefficient for the vertical uplift force, and
c_a = an empirical coefficient for the additional gravity force.

The empirical coefficients in Eq. (6) are determined based on the numerical simulation results in the current stage of the study. Under the circumstances where the reference force subjected to high uncertainties, the coefficient of c_{sv} can be increased to a value that equivalents to the desired factor of safety. The cases considered here are limited to seven different deck clearances subject to the scenario flow depth of 8 m. For a better representation, these empirical coefficients should be refined by adequate data from the experimental and analytical simulations in the future.

The accuracy of the proposed method is evaluated and compared with the computed results from the simulation. By using the pressure distribution based on the mean + 1SD for not a conservative estimation and the empirical coefficients of $c_{sv} = 1$, $c_i = 1.5$, $c_u = 1$ and $c_a = 2$, the relations of forces predicted from the proposed formulae (Eq. 6) and the computed results from the numerical model are shown in Figure 16. The computed forces from the proposed empirical formula give close estimation with those from the numerical simulation, except for the decks with large clearances which are overestimated.



(a) Slowly-varying force (b) Impulsive force



(c) Uplift force (d) Additional gravity force

Fig. 16. Comparisons of the forces calculated from the empirical formula and numerical simulation

6. Conclusion

Both physical and numerical simulations have been carried out to investigate the behavior of bridge deck subjected to tsunamis and to formulate tsunami forces on bridge decks. Laboratory experiments give realistic insight into wave flow through the bridge model, however, small scale effect, time consuming and cost implication are the shortcomings. Numerical modeling is another powerful tool to investigate the flow mechanics around bridge decks. The well validated numerical model was employed to simulate tsunami flow around bridge prototypes to overcome the shortcomings of the physical simulation. The results reveal important findings which provide beneficial information on tsunami forces on bridges to engineers and scientists. Tsunami forces on bridge deck are categorized into four types, i.e. impulsive, slowly-varying, uplift and additional gravity forces. A method to predict the maximum values of these forces are proposed.

7. Acknowledgments

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Part 3

Case Studies

7

Comments About Tsunami Occurrences in the Northern Caribbean

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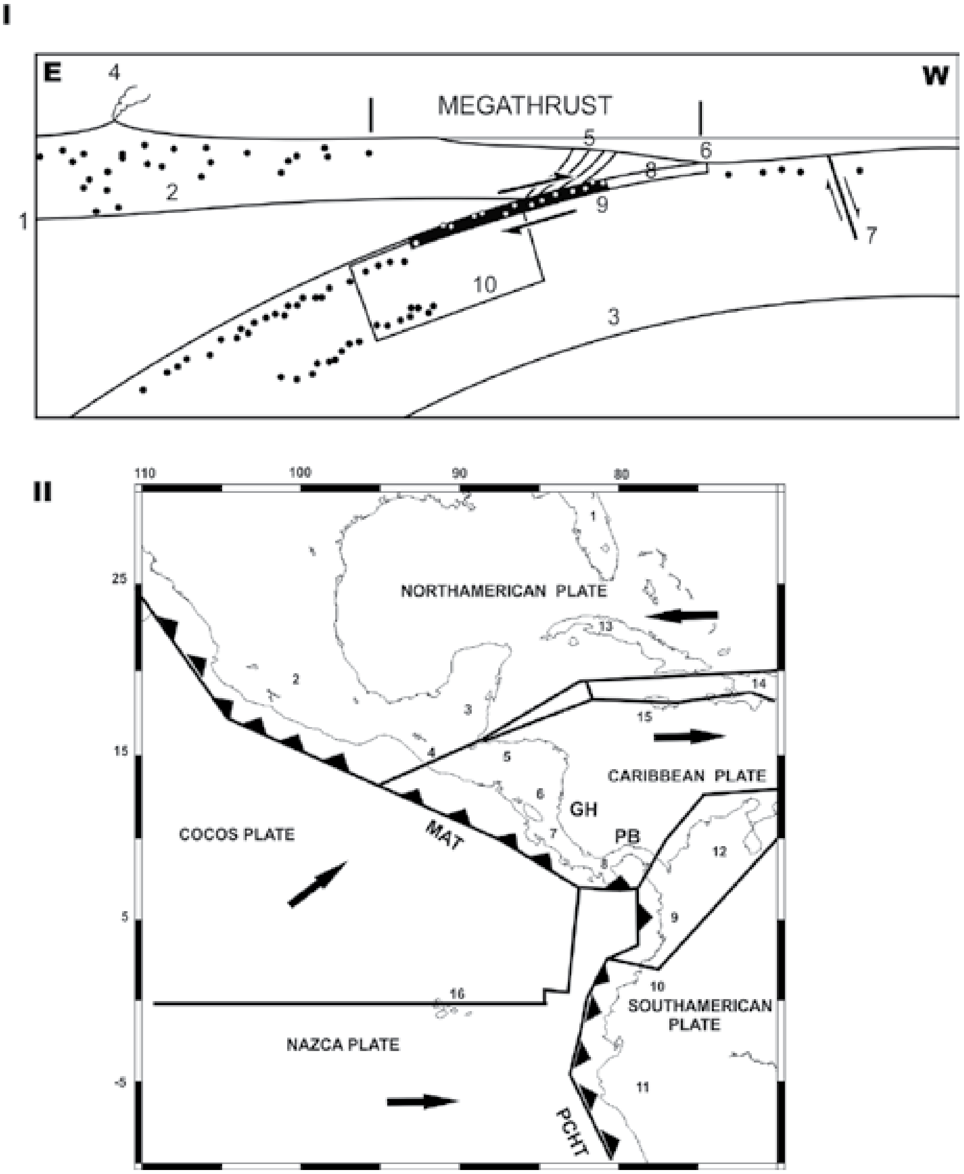
1. Introduction

Tsunamis [the Japanese word for "harbor wave"] are gravitational sea waves produced by any large-scale, short-duration disturbances of the ocean floor, principally by shallow submarine earthquakes, but also by submarine earth movement, subsidence, or volcanic eruption. They are characterized by long periods [~5-60 minutes] and low observable amplitudes on the open sea, although they may pile up to heights of 30 m or more and can cause extensive damage on entering shallow water along an exposed coast, often thousand of kilometers from the source. In other words, tsunamis are water displacements produced by fault movement, whereas seismic waves are directly caused by the fault motion. Earthquakes are a clear manifestation of rock deformation.

The general features of tsunamis are well known and have been discussed extensively in the literature. In order to clearly present the exposition, we define some specific terms in table 1. A further characteristic of tsunamis is that the fault in a sedimentary layer structure can generate a larger tsunami than a fault in a rigid structure. The study of tsunami deposits has only recently begun. Therefore, it is a good opportunity to get a more complete register of such phenomena.

Tsunami waves as a long-period ocean wave have a very low speed in deep water, of about ~0.2 km/s and often slower near the coastline producing the refraction phenomena and the increment of wave height. In the ocean where the depth can be considered constant the velocity is estimated by the following expression [$v=(gh)^{1/2}$, where v= speed [m/s], $g= 9.8\ m/s^2$, and h= ocean depth [m]]. Tsunamis triggered by an earthquake occur when a slab of oceanic crust descends near vertically along a fault, or where the vibration of a quake sets an underwater landslide into motion. Once formed, the tsunami advances across the ocean at speeds of 500 to >900 km/h. A tsunami can pass undetected in the open ocean because its height is generally around one meter, and the distance between wave crests [λ] is 100–700 km. In contrast, when a tsunami enters shallow water near the coast, it becomes a destructive wave that moves slowly with the water piling up to heights of ~30 m. Since the speed of a tsunami is greater in the deep sea, the direction of propagation of a tsunami traveling in an open sea of variable depth gradually veers toward the shallowest zone. This process is known as wave refraction, and it is an important parameter in tsunami modeling.



I [1= Moho; (Black circles= focus of earthquakes); 2= Crustal earthquakes; 3= Subduction plane; 4= Volcanoes; 5= Accretionary wedge; 6= Trench; Earthquakes (7= Outer rise; 8= Tsunami; 9= Thrust; 10= Slab).]
II [Localities (1= U.S.A.; 2= Mexico; 3= Guatemala; 4= El Salvador; 5= Honduras; 6= Nicaragua; 7= Costa Rica; 8= Panama; 9= Colombia; 10= Ecuador; 11= Peru; 12= Venezuela; 13= Cuba; 14= Hispaniola; 15= Jamaica; 16= Galapagos Islands); Structures (MAT= Mesoamerican trench; PCHT= Peru-Chile trench; PB= Panama block; GH= Gulf of Honduras); Heavy black arrows= sense of the plate movements.]

Fig. 1. I.- Model of megathrusts [modified from Satake and Tanioka], II- Tectonic contact zone between Caribbean and the Pacific plates.

The majority of tsunamis are caused by large earthquakes. While volcanic eruptions and landslides can also produce tsunamis, these occur less frequently than with earthquakes. Tsunamis can result from earthquakes in subduction zones (Figure 1 I), where sudden vertical movements or subsidence of the sea floor are generated by faulting. Subduction is a complicated physical process in which a tectonic plate descends beneath another one. This process produces a large and narrow mountainous belt in the relief with a great number of earthquakes and some volcanoes. Such regions can be studied using the concept of a Wadati-Benioff zone (Table 1). In this, the earthquake foci [up to tens of kilometers] appear as a sequence in the depth.

The models of sea-floor spreading and plate tectonics show that the more important seismic zones on the arc islands are directly related with major underthrusts, along which the lithosphere plates converge and descend. Examples of this are the Aleutian arc [Gulf of Alaska] and the Chile-Peru arc [western margin of South America]. These segments are tectonically active and coincide with the two largest lithosphere plates [Pacific and America]. These two regions share some similarities, such as: 1) deep oceanic trenches; 2) a belt of active seismicity [Wadati-Benioff zones]; and 3) active volcanoes inside of subparallel, discontinuous mountain chains. Nevertheless, they differ in the type of contact. The Chile-Peru region is an ocean-continent transition along its entire length, with maximum foci at ~650 km and large packages of Mesozoic and older crystalline rocks with clear, undeformed Tertiary sediments layers. In contrast, the Aleutian arc marks a transition between ocean and continent in its eastern part, where the true arc of islands is located. It has a maximum depth of occurrence for earthquakes of 170 km and a thick package of Mesozoic–Cenozoic deformed sediments. Two important earthquakes occurred in these regions, in 1960 in Chile and 1964 in Alaska, each of which generated a tsunami, of the thrust-fault type.

Term	Description
Arrival time	Time of the first maximum of the tsunami waves.
Backarc	It is the region landward of a volcanic chain on the other side from a subduction zone.
Benioff zone (Wadati-Benioff)	A dipping planar zone of earthquakes that is produced by the interaction of a downgoing oceanic plate with a continental plate. These earthquakes can be produced by slip along the subduction thrust fault or by slip on faults within the downgoing plate as a result of bending and extension as the plate is pulled into the mantle.
Breakwater	Artificial structure such as a wall or water gate to protect a beach or harbor from the force of waves.
Forearc	The region between the subduction zone and the volcanic chain (volcanic arc).
Forecast point	The site or location where the authorities estimate the arrival of tsunami.
Interplate coupling	It is the ability of a fault between two plates to lock and accumulate stress. Strong interplate coupling means that the fault is locked and capable of accumulating stress whereas weak coupling means that the fault is unlocked or only capable of accumulating low stress.

Landslide tsunami	It can be produced by landslides of different origin (earthquake, volcano, etc.). The effects are local and limited in area.
Mareograph	Instrument to record the sea level gauge.
Oceanic trench	It is a linear depression of the sea floor caused by the subduction of one plate under another.
Paleotsunami	A tsunami that occurred prior to the historical record.
Recession	The drawdown of the sea level prior to tsunami flooding.
Run-up	Value of the difference between the elevation of maximum tsunami penetration on the coast and the sea level at the time of the tsunami occurrence. It is only measured where there is a clear evidence of the inundation limit on the shore.
Sea level	The height of the sea at a given time measured.
Seiche	A sea movement initiated by a standing wave oscillating in a partially or fully enclosed body of water. It can be start by long period seismic waves, wind and water waves as a tsunami.
Slab	It is the oceanic crustal plate that underthrusts the continental plate in a subduction and is consumed by the earth's mantle.
Subduction	A process of the oceanic lithosphere colliding with and descending beneath the continental lithosphere.
Subduction zone	The place where two lithospheric plates come together, one riding over the other. Most volcanoes on land occur parallel to and inland from the boundary between the two plates.
Tidal wave	The wave motion of the tides. An erroneous synonymous of tsunami and storm surge.
Tide	The alternate rise and fall of the ocean surface, or bodies of water connected with the ocean.
Tide station	The place where is obtained the tide data.
Travel time	Time that the first tsunami wave required to propagate from its source to a given point on a coastline.
Tsunameter	The instrument to detect in real-time tsunamis.
Tsunamigenic	It is referring to those earthquakes, commonly along major subduction zone plate boundaries such as those bordering the Pacific Ocean that can generate tsunamis.
Tsunami zoning	The designation of distinctive zones along the coastal areas with varying degrees of tsunami risk and vulnerability, planning, construction codes or evacuation of populations.
Wave height	Symbol H. The vertical distance between the trough and the crest of the sea wave while the tsunami is traveling toward the land.

Table 1. Some terms used to measure and describe tsunamis.

On the other hand, fault motions such as a strike-slip displacement are not capable to generate a tsunami because they are horizontal and do not change the sea floor. Different authors have stated that on gently sloping coasts, such as in the California area, large tsunamis are quite rare, and the relatively small tsunamis are probably generated by faulting at the bottom of the ocean. Table 2 contains the main fault types. As we mentioned before, most tsunamis are caused by large shallow earthquakes that occur on major plate boundaries. Thus, many tsunami sources are located in the Circum-Pacific Ocean zone [the Aleutian Islands, Central America, Japan, Kuril Islands, and Tonga]. Nevertheless, no large tsunamis are generated where the plate motion is a transform-fault type, as found in the west coast of North America, where the large earthquakes are strike-slips that occur on land. Historical geological data show that landslides sometimes generate tsunamis and increase tsunami magnitude. Nevertheless, the occurrence of tsunamis induced by landslides is minimal. A good example of that phenomena occurred in the locality of Loma Prieta [California, U.S.A.]. It was affected in 1989 by a small earthquake. Although the epicenter was located on land, this seismic event produced underwater local slums [landslides] that generated a small tsunami in Monterey Bay. Another example of this is the 1998 tsunami of Papua, New Guinea.

Fault type	Description
Normal	They are developed in crust undergoing extension in which the maximum principal compressive stress is vertical. Also, a dip-slip fault on which the hanging wall has moved downward relative to footwall.
Reverse	A fault on which the hanging wall appears to have moved upward relative to the footwall. The dip of a reverse fault is relatively steep, greater than 45°.
Thrust	A fault with a dip of 45° or less over much of its extent on which the hanging wall appears to have moved upward relative to the footwall.
Strike-slip (transcurrent)	They are faults that have slip vectors parallel (horizontal) to their strike. It is frequent to find some comments using the term lateral as a synonym for strike-slip. The fault surface is usually near vertical and the footwall moves either left or right or laterally with very little vertical motion. A strike-slip fault with left-lateral motion is known as sinistral fault. And the other type (right-lateral motion) is also known as dextral fault.

Table 2. Main fault types.

Tsunami earthquakes are those tsunamis with greater amplitudes than would be expected from their seismic waves. They have low magnitudes that can be not felt by the population, who may thus not take precautionary evasive measures. Some results have shown that sources in tsunami earthquakes cannot be explained by a regional signal identifiable for other moderate to major events along the same subduction system. Also, it is difficult create fault models that fit the distribution of tsunami heights.

Magnitude scales allow tsunami sizes to be determined. Some scales are available for this, such as the Imamura–Ida scale in five levels. Also, intensity scales [Sieberg-Ambraseys] exist, such as the one used for earthquakes. This scale is principally employed for old tsunamis for which no instrumental records exist [$m = \log_2 H$, where m is the magnitude and H is tsunami height [run-up height]]. Another scale is the Abe magnitude scale, developed for trans-Pacific tsunamis, of M_T= log H + C + 9.1. A range of 100 to 3,500 km is included the expression: M_T= log H + log Δ + 5.8. In both formulas, H is the maximum amplitude [meters] on tide gauges. This scale allows the seismic moment of the tsunamigenic earthquake to be measured as the overall size of a tsunami at the source. Table 3 shows classifications of tsunami sizes. Table 4 shows a classification of three levels of tsunamis, taking into account the distance from the source. Three types of tsunamis and tsunami earthquakes were proposed to occur in subduction zones, by examining the source and the tsunami earthquakes at the source locations: 1) typical interplate earthquakes; 2) intraplate earthquakes; and 3) tsunami earthquakes (Table 5). Tsunamis from typical interplate earthquakes can be used to demonstrate that the slip is concentrated in asperities. Intraplate earthquakes at the outer rise in the subducted slab and in the overlying crust can all be tsunamigenic [i.e., 1995 in the Kuril Islands]. It was suggested that there are two types of tsunami earthquakes: 1) very anomalous; and 2) moderate (Table 6). We can mention four cases of this: 1) 1896 Sanriku Islands; 2) 1946 Aleutian Islands; 3) 1992 Nicaragua; and 4) 1996 Peru. All of these had sources between the trenches and were at depths of 10 km beneath the accretionary wedge. This source is a shallow extension of the seismogenic zone for typical interplate earthquakes.

N°	**Classification**	**Mw / Rupture length (km)**
1	Giant tsunami	Mw≥ 9,1 / > 550
2	Major tsunami	8,4 <Mw< 9 / < 550
3	Local tsunami	Mw< 8,4 / < 240

Table 3. Classification of tsunamis according to Mw and size of source areas (Furumoto).

Schematic cross-sections of faults for a subduction zone earthquake and the vertical deformation of the ocean floor show a vertical deformation pattern along the cross-section of the subduction earthquake. If the fault is 100 km wide, the vertical uplift extends toward land, and the tsunami arrives early. In contrast, if the fault is narrower, 40 km, the vertical deformation is limited to a smaller area, and the tsunami arrives at the coast later. Also, there are two models of the relationship between normal fault earthquakes and tsunami earthquakes. These were generated despite the relatively small magnitude of two of the largest and most widespread tsunamis in history. The 1929.03.27 Aleutian Islands earthquake [M=8.1, h=50 km] was located beneath the Aleutian trench. It is interesting and striking that, in the Aleutian and Sanriku regions, large normal-fault earthquakes occur along the trench axis. The 1933 Sanriku earthquake is the largest of such a type of event. Normal-fault earthquakes may imply the presence of a weak zone along the inner margin of the trench. It is in this part of the trench that the tsunami earthquake of 1896 occurred. The situation is slightly different along the Aleutian zone. The two tsunami earthquakes, the 1896 Sanriku and the 1946 Aleutian Islands earthquakes, are very similar to each other.

N°	**Classification**	**Distance from the source (km)**
1	Local	<100
2	Regional	100 – 750
3	Distant - Teletsunami	>750

Table 4. Classification of tsunamis according to the distance from the source.

Type	Description
Typical interplate earthquake	Occur at the seismogenic interface or megathrust between subducting and overlying plates.
Intraplate earthquake	There are two types: A) Outer-rise event when its location is outside the trench; B) Slab-earthquake when it occurs within the subducting slab. The slab earthquakes include deep earthquakes. In the overlying crust are also intraplate earthquakes.
Tsunami earthquake	Locate at a shallow extension of the interpolate seismogenic zone, beneath the accretionary wedge.

Table 5. Types of tsunami and tsunamigenic earthquakes in subduction zones.

Type	Description
Very anomalous	It occurs at an accreting margin with large amounts of sediments and the accretionary prism where occasional slumping causes the tsunami earthquake.
Moderate	It occurs in a subduction zone with little sediment where rupture in subducted sediment is responsible for large tsunamis.

Table 6. Types of tsunamis earthquakes (Kanamori and Kikuchi).

There is currently a lot of scientific data about tsunamis in the field, generated mainly since the 1950s. These contributions increased dramatically in quantity after the Nicaragua tsunami of 1992. We list some of the most relevant papers and books used here to guide readers who are interested in the topic. Each section lists this crucial reference information. This chapter will include a first section listing the most significant aspects of the research on tsunamis. The second section contains the most relevant information on reported and registered tsunamis in the Pacific Ocean. This is the region with the largest number of tsunamis, and examining these will allow the comparison with the following two sections, on the Atlantic Ocean and the Caribbean region. In particular, our goal is to analyze the northern Caribbean. The last section includes the techniques and resources used for tsunami detection, as well as data and recommendations that can serve the people who live in the coastal zones.

2. Tsunamis studies and historic tsunamis

The sources for this section include: Bryant, 2001; Cotilla and Córdoba, 2010; Dmowska and Saltzman, 1998; Iida and Iwasaki, 1981; NOAA, 2004; Polet and Kanamori, 2000; Satake, 2005; Sauber and Dmowska, 1999; Shuto, 1993; Sieberg, 1932; Titov, 2009; and UNESCO-IOC, 1998.

The data about most historic tsunamis can be found in old literature. That information can contain descriptions about casualties, damages, and observed run-up heights. The authors prepared in 2010 a world tsunami catalog. They listed the most significant tsunamis [479 B.C. - 2011]. Among them is the Aleutian Islands event [1946], where the magnitude of the earthquake was relatively small but produced one of the largest and most widespread tsunamis in history. This historical relationship of tsunamis [522 events] was prepared in order to show in a simple way the time and geographical distributions of such natural phenomena. The catalog includes the 18 great tsunamigenic earthquakes [M≥ 8.6], 12 of which occurred in the 20th century. It has two columns containing the date and the geographical localization of tsunamis. An additional column includes the main characteristics of the event. The two further columns give the code of tsunamigenic region proposal by other authors [for the Pacific Ocean], or by us [this is the most complete as it includes all regions]. We have found in our research that some catalogs merely repeat other results, incorporating very little new information. Nevertheless, it is possible to identify clear repetitions of mistakes. We also prepared a set of tables which clearly present the time distribution, the quantities, and the distribution by region of the largest tsunamis that have occurred (Tables 7, 8, 9 and 10). The majority of the largest tsunamis were located in the Pacific Ocean [17 of 18]. Specifically, table 9 shows the largest tsunamigenic potential of the Pacific region.

Time period	Total	Time period	Total
684-1600	1	1901-2000	10
1601-1900	5	2001-2011	2

Table 7. Great tsunamigenic earthquake by time period.

Nº	Site	Date	By region	By large regions
1	U.S.A. (Alaska)	1964.03.28	1	7
2	Aleutian Islands	1946.04.01	3	
3		1957.03.09		
4		1965.02.04		
5	Kuril Islands	1918.09.08	1	
6	Russia (Kamchatka)	1841.05.17	2	
7		1952.11.04		
8	Chile (Valdivia)	1837.11.07	5	6
9	Chile (Arica)	1868.08.13		
10	Chile (Iquique)	1877.05.10		
11	Chile (Atakama)	1922.11.10		
12	Chile-Perú	1960.05.22		
13	Ecuador-Colombia	1906.01.31	1	
14	Japan	684.11.29	4	4
15	Japan (Sanriku)	1896.06.15		
16	Japan (Tsugaru Peninsula)	1983.05.26		
17	Japan (Sendai)	2011.03.11		
18	Indean Ocean	2004.12.26	1	1

Table 8. Relation of great tsunamigenic earthquakes.

	Tsunamis	**Great tsunamis**	**Maximum M_T / Deaths**	**Run-up (m)**
Maximum	522	18	9,4 / >1 million	>100
Pacific Ocean	393	17	9,4 / >1 million	>100
Central America [eastern / western]	[14 / 47]= 61	[0 / 1]	[? / 8,7] / [- / 5]	[- / >50]
Lesser Antilles	19	-	- / 40	20
Northern Caribbean	61	-	- / ~9.000	18
Southern Caribbean	27	-	8,1 / 18	10

Table 9. Brief comparison between tsunamis' characteristics to four regions.

Region	**Year**	**Region**	**Year**	**Region**	**Year**
Mediterranean Sea	479 B.C.	Jamaica	1688	Alaska	1788
Indonesia	416	Virgin Islands	1690	Marianas Islands	1819
Japan	684	Mexico	1732	Aleutian Islands	1827
Venezuela	1530	Kuril Islands	1737	El Salvador	1859
Honduras	1539	Russia (Kamchatka)	1737	Guatemala-El Salvador	1859
Chile	1562	Hispaniola	1751	Hawaiian Islands	1868
Panama	1621	Lesser Antilles	1751	New Hebrides Islands	1875
Peru	1664	Haiti	1769	Puerto Rico	1918
Philippine Islands	1677				

Table 10. First reports of tsunamis by region.

Several shallow subduction zone earthquakes have caused destructive tsunamis. These phenomena are produced by large shallow earthquakes beneath the ocean floor. It is known that a great shallow earthquake beneath the ocean floor should be expected to be followed by a tsunami caused by the large displacement of water near the ocean floor. Subduction of the oceanic lithosphere occurs along massive interplate thrust faults that are the contact surfaces between overriding and underthrusting plates in convergent margins. The megathrusts accommodate the convergent motions by varying portions of seismic and aseismic slips, with significant variations on geometry and maximum earthquake size from region to region. About 90% of the seismic moment released by global earthquakes occurs near subduction zones, with most events, including the largest recorded events, involving slip on a megathrust. Interplate thrust faults in subduction zones host the largest earthquakes and a majority of the seismic energy released in the world. The seismically-coupled portion of the megathrusts extends ~100 km across the depth range of 5-60 km, with the convergent motions between underthrusting and overriding plates accommodated by a mixture of these processes: 1) earthquake slip; 2) postseismic deformation; and 3) interseismic creep. This models the great earthquake sequences.

Studies of the largest earthquakes along megathrusts in different subduction zones have suggested some correlations between convergence rate, lithospheric age, sediment supply, bathymetric features, and back arc spreading (Table 1). It contains a model of a typical earthquake in a subduction zone. This type of earthquake occurs at the seismogenic boundary between the subducting and overlying plates. On the other hand, intraplate earthquakes include out-rise events, slab events, and crustal earthquakes. The source region of tsunami earthquakes is beneath the most trenchward part of the accretionary wedge. Figure 1 shows a comparison between a typical interplate earthquake and a tsunami earthquake. It is easy to observe the slip at varying depths on the megathrust and the resulting surface vertical displacement. Large slips at very shallow depths in low rigidity sediments cause large ocean bottom displacements relative to comparable seismic moment events with a lesser slip in higher rigidity material at greater depths along the megathrust.

Some outer-rise events have caused significant tsunami damage, such as the mentioned before 1933 Sanriku earthquake [Mw=8.4, 3,000 casualties] and the 1977 Sumba earthquake [Mw=8.3, 150 casualties]. Further examples are the 1896.06.15 Sanriku earthquake, and the 1946.04.01 Aleutian Islands earthquake [M=7.4]. Earthquakes occurring in the crust of the overlying plate can also be tsunamigenic, as seen for the 1992 Flores Indonesia earthquake [Mw=7.8] and the 1993 Southwest Hokkaido Japan earthquake [Mw=7.6]. Earthquakes in the subducting plate are commonly called slab event [i.e., the 1993 Guam earthquake, Mw=7.7, and the 1994 Kuril earthquake, Mw=8.2]. The last one mentioned was one of the strongest earthquakes that occurred in and around Japan.

Tsunami generation is one of the most important subduction processes. Most shallow large earthquakes in subduction zones caused tsunamis. An earthquake is tsunamigenic if it generates a tsunami, and it is a tsunami earthquake if it generates a much large tsunami than expected from its seismic waves. Most, but not all, large or great tsunamigenic earthquakes are typical interplate earthquakes. In these events, the fault plane is located along the interface of the subducting and overlying plates. At most subduction zones, the seismogenic interface extends from a depth of about 10–40 km. The source extent of large interplate earthquakes is limited to the seismogenic zone. As a result of underthrusting, the seismogenic zone is uplifted while the surface above the deeper end subsides. The coseismic deformation is generally in the direction opposite to the interseismic deformation, with the gradual crustal deformation in earthquake cycles. Also, some tsunamis in subduction zones result from shallow intraplate earthquakes.

3. Tsunamis in the Pacific region

We assumed in our world catalog the division in 24 tsunamigenic regions proposed by other authors for the Pacific Ocean. The majority of tsunamis have been generally local to a particular area. It seems like the tsunamis such as in Alaska [1964.03.29] and Chile [1960.05.22] are not characteristic of this region. The Alaskan–Aleutian zone is a typical subduction zone where great tsunamigenic interplate earthquakes repeat. Also, the Pacific coast of Central America–Mexico region has been the setting of several great earthquakes (Table 11). Many of these produced tsunamis in the same period.

The Alaska–Aleutian region is a typical subduction zone where great tsunamigenic interplate earthquakes repeat in time. In this zone, the North American plate [from the north] is subducted by the Pacific plate in the Aleutian trench. This zone is a large island arc from southern Alaska to the western Aleutian. Some strong earthquakes have occurred in it, such as those in 1938 [Mw=8.2], 1946 [Mw=8.3], 1957 [Mw=8.6], 1964 [Mw=9.2], 1965 [Mw=8.7], 1986 [Ms=8.0], and 1996 [Ms=7.9]. Thus, the Cascadia Subduction zone is a type of convergent plate boundary which stretches from northern Vancouver Island to northern

California [with two triple junctions at its north and south ends]. It is a very long, sloping fault that separates the Juan de Fuca, Explorer, and Gorda plates from the North American plate. The ocean floor moves towards and beneath the North American plate at approximately 4 cm/year. The Cascadia Subduction zone is where the two plates meet, and some large, offshore earthquakes have occurred here, producing devastating tsunamis.

Zone / Region	Year / Mw	Zone / Region	Year / Mw
Chile / Pacific	1960 / 9,5	Assam / Mediterranean	1950 / 8,6
Alaska / Pacific	1964 / 9,2	Aleutian / Pacific	1957 / 8,6
Kamchatka / Pacific	1952 / 9,0	Kurile Islands / Pacific	1963 / 8,5
Ecuador / Pacific	1906 / 8,8	Chile / Pacific	1922 / 8,5
Aleutian / Pacific	1965 / 8,7	Banda Sea / Indic	1938 / 8,5

Table 11. The largest earthquakes to the 20th century.

The tectonic setting of Central America is given by the interaction of the Cocos, Caribbean, and Nazca plates (Figure 1 II). The Cocos plate subducts under the Caribbean plate along the Middle American trench. From Mexico to Central America, the subduction process is normal, and the Wadati-Benioff zone is well-defined by intermediate and deep earthquakes. But in southern Costa Rica, subduction becomes its shallowest due to the presence of Cocos Ridge. This structure collides with the Cocos plate, generating a buoyant effect. That process makes it difficult for the Cocos plate to penetrate under the Caribbean plate. This effect is responsible for the lack of deep seismicity there as well as for inhibiting volcanism and the uplift of the Talamanca Range, Costa Rica. The limit between the Cocos and Nazca plates is the Panama Fracture Zone. It is composed of north-south trending faults located in front of the Pacific coast of Costa Rica and Panama. The boundary between the Caribbean plate and Nazca plate is quite ambiguous. The Panama Deformed Belt lies towards the Caribbean coast of Costa Rica and its convergent margin.

The Middle America margin off Costa Rica–Nicaragua converges with the Cocos plate at an equivalent rate; it also has sparse trench sediment but it varies in crustal structure and the subducting oceanic crust. The morphology of this convergent region is well known as the variation of arc volcanism. The main features of this Wadati-Benioff zone geometry are: 1) a smooth contortion of the seismically active slab under the Nicaragua–Costa Rica border; 2) a decrease in the maximum depth of earthquakes from 200 km under Nicaragua to less than 50 km under southern Costa Rica; 3) a segmentation of the slab under Central Costa Rica; and 4) the abrupt termination of the seismically active slab at 83° W coincident with the southeastern end of the Central America active volcanic chain. No evidence of a Wadati-Benioff zone deeper than 50 km is found southeastern of Punta Vista. The subduction zone from Nicaragua to Costa Rica is divided into four segments: 1) Nicaragua; 2) Northern Costa Rica; 3) Central Costa Rica; and 4) Southern Costa Rica. Also, the differences in coupling between the Cocos and Caribbean plates for Nicaragua and Costa Rica can be correlated with the characteristics [bathymetric features] of the subducted ocean floor. It is important to note that, historically, large underthrust earthquakes [Ms>7.0] have occurred along the NW and SE segments but not within the Central segment.

The epicentral distribution of earthquakes shows a high level of seismic activity along the whole Middle American trench. The Panama Fracture Zone also has intense seismic activity. In the north [Mexico], the seismic activity suggests the shallowest mode of subduction;

similarly, in the south, there is no seismicity below 50 km. Most of earthquakes are shallow and related to the Cocos–Caribbean subduction zone. Some large earthquakes have occurred that are associated with the Middle American trench. These earthquakes are differentiated into two groups according to the depth of occurrence [0–30 and 40–200 km]. It is well known that the seismicity on the Caribbean coast of Central America is low. Within it, only three large earthquakes occurred during the last century, each of which generated small tsunamis. If the probability of tsunami occurrence is proportional to the rate of seismicity, the possibility of tsunamis occurring should be lower. Nevertheless, it was found that the area has been hit by numerous tsunamis, which have caused damage and loss of life. In table 12, we list the largest earthquakes and tsunamis of the Pacific coast of Central America. However, these tsunamis might not have been dangerous if the earthquake source was inland. Regional tsunamis from elsewhere in the Pacific region have also hit the coasts of Central America. These tsunamis flooded villages, washing out houses and producing great damage to property, and have produced ~350 casualties. As we mentioned previously, the majority of the tsunamis of Central America have taken place at the Pacific coast. This is normal considering that the most active margin of the Caribbean plate is the Middle American trench that is located in front of the Pacific coast of Central America. Based on this data set, it seems that Cocos–Central America is the most important environment for generating tsunamigenic earthquakes on the Pacific coast of Central America. The largest tsunamis of this area were the Guatemala–El Salvador tsunamis [1902.02.26 and 1902.04.19] and the Nicaragua tsunami [1992.09.01], which produced 185 and 170 deaths, respectively.

Date	Coordinates	H (km)	Ms	Tsunami locality	Runup (m)
1844.05	11,20N/84,0W	30	7,4	Nicaragua Lake	
1854.08.05	08,50N /83,00W	33	7,3	Dulce Gulf	
1884.11.05	40,00N /76,00W	100	7,5	Colombia (Acando)	
1902.04.19	14,90N /91,50W	60	7,5	Guatemala (Ocos)	
1906.01.31	01,00N /81,30W		8,1	Ecuador-Panama-Costa Rica	2,5
1915.09.07	13,90N /89,60W	60	7,7	El Salvador (South coast)	
1916.05.25	12,00N /90,00W		7,5	El Salvador	
1934.07.18	08,10N /82,60W		7,5	Panama (Chiqui Gulf)	0,6
1941.12.05	08,70N /83,20W		7,6	Costa Rica (Dominsal)	0,2
1950.10.05	10,00N /85,70W	60	7,7	Costa Rica-Nicaragua-El Salvador	
1950.10.23	14,30N /91,80W		7,3	Guatemala-El Salvador (coast)	
1956.10.24	11,50N /86,50W		7,2	Nicaragua (San Juan Sur)	
1957.03.10	51,63N /171,4W		8,1	El Salvador (Acajutla)	>2
1960.05.22	38,20N /73,50W	32	8,5	Guatemala-El Salvador	

Table 12. The largest earthquakes [$Ms \geq 7{,}2$] and tsunamis of the Pacific coast in Central America.

4. Tsunamis in the Atlantic Ocean

Many sources have been consulted in order to develop this section, including: Cotilla, 2007; Cotilla and Córdoba, 2010; Grindlay *et al.*, 2005; Lander *et al.*, 1992; McNamara *et al.*, 2005; Polet and Kanamori, 2000; and Rubio, 1982.

The vast majority of the area of the Atlantic Ocean is not tsunamigenic [for example, the Gulf of Mexico]. The region is clearly divided into different areas: Mediterranean, Caribbean, Azores, Portugal, and the eastern part of South and North America. Our interest focuses on the Caribbean area, and in particular on the northern Caribbean area. We will later discuss and include data on the tectonic, seismicity, and focal mechanisms, in order to understand the actual tectonic behaviour of the region. Note that, in 1962, a seismic sea waves catalog was prepared for the eastern Mediterranean [31º–44º N/18º–36º E], which included 141 events. Our world catalog contains the most significant tsunamis in the Atlantic area. The oldest data about tsunamis came from the Mediterranean area [479 B.C.]. The second most important tsunamigenic area of the Atlantic Ocean is very well-defined and corresponds to the Mediterranean Sea (Table 13). In it, there are several seismic sources that are active and important, such as: 1) the Azores Islands; 2) the eastern end of the PBZ Europe–Asia [SW of Portugal] associated with the earthquake and tsunami of November 1, 1755; 3) Assam [north of Africa]; and 4) Greece–Turkey. This region has a very high level of risk for many populations and tourist facilities. Nevertheless, there have not been any reports of great tsunamigenic earthquakes in the Atlantic Ocean. Table 10 contains the year of the first report of tsunamis in 25 regions. From this, it is easy to understand that the first reports are associated with human settlements.

Region	Total	Region	Total	Region	Total
Caribbean Sea	114	Canary Islands	1	Azores Islands	15
Mediterranean Sea	24	England	1		

Table 13. Tsunamis in the Atlantic Ocean.

The main differences between the tsunamigenic sources of both the Pacific and the Atlantic Oceans are given in Table 9. Among other things, the first zone is far more active, dangerous, and complex than the other. Nevertheless, the event of November 1, 1755, was without a doubt one of the most important in all history, and while it occurred just southwest of Portugal, it reached areas as far away as the Caribbean about 7–8 hours later.

5. Tectonic of the Caribbean region

The following sources were used here: Cotilla, 2007; Cotilla and Córdoba, 2011, 2010, 2009, 2007; and Cotilla *et al.*, 2007.

The Caribbean domain and Central America form a small lithospheric plate inserted between the North American and South American plates that is moving eastward relative to the North American plate (Figure 2 II). The North American and Caribbean Plate Boundary Zone [PBZ] is an irregular seismogenic area, 100–250 km wide, with left-lateral strike-slip deformation extending over 2,000 km along the northern border of the Caribbean Sea. The main structural element in the PBZ is the Cayman trough, a submarine pull-apart basin of 1,100 km of oceanic crust at the Mid-Cayman spreading centre, a 100 km long-jog between left-lateral faults of the plate boundary. This spreading centre has been active since the Middle Eocene and has a rate of 1.5 cm/yr. Further to the east of it are the islands of Jamaica, Hispaniola, and Puerto Rico.

The Cayman strike-slip system is divided into two branches: 1) the northern branch from the Cayman spreading centre to the Puerto Rico trench; and 2) the southern branch from Central America to Haiti (Figures 2 II). The western part of the southern branch, the Walton–

Plantain Garden–Enriquillo fault, is clearly active and runs from Jamaica up to the Muertos trough. Within the North America–Caribbean PBZ, two microplates have been defined, Gonave and Hispaniola–Puerto Rico (Figure 2 II). A continuous northern strike-slip fault bordering both microplates runs from the northern coast of Haiti and the Bartlett-Cayman [Oriente] fault zone, Cibao valley of northern Hispaniola, Septentrional fault zone to Puerto Rico island slope and Puerto Rico trench.

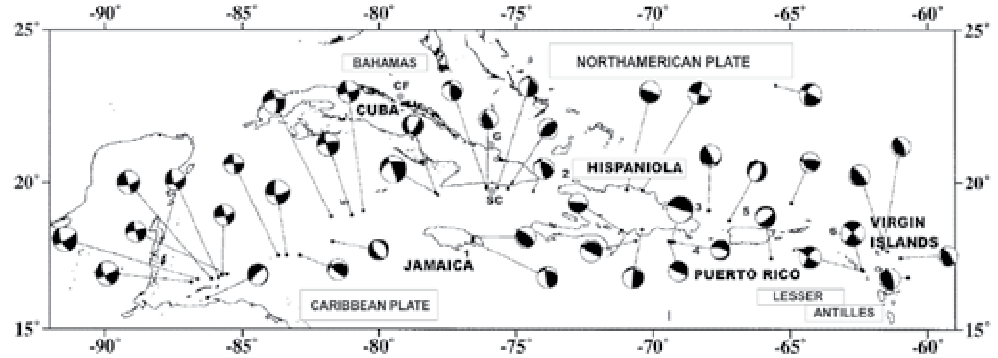
The strike-slip fault type appears in the Northern of Caribbean region and constitutes the northern boundary of the Caribbean plate; it includes Motagua, Chixoy-Polochic, Swan, and Oriente (Figure 2 II). The main function of such system faults is to accommodate horizontal extrusion in zones of continental collision, and to serve as an agent for boundary-parallel slip between obliquely convergent oceanic and continental plates. At the western edge of this region, the Swan Islands fault zone, with left lateral strike-slip motion, defines the plate boundary. This fault zone terminates at the southwestern edge of the Cayman spreading center. Following this is the Morant trough, which is an active pull-apart basin between Haiti and Jamaica of ~60 km. This is a submarine structure that limits rates of movements on the aforementioned fault zone, the Enriquillo–Plantain Garden. Further to the east, the Mona Canyon is a narrow, deep depression in the Caribbean Sea in northwestern Puerto Rico. It is part of the inner wall of the Puerto Rico trench and is related with normal faults. All this suggested that an E–W extension process occurs here. The Muertos trough is an E–W striking bathymetric feature of ~5 km depth to the south of Puerto Rico and the Dominican Republic. Between Puerto Rico and the Virgin Islands [north of the Lesser Antilles] is the ENE-trending Anegada Passage.

On the other side, the plate boundary between Caribbean and North American plates in the north–western region is located near the Pacific trench [with the active left-lateral sense Motagua fault and the Cayman trough] (Figures 1 II, 2 I and 2 II). This is an active region in which the seismicity is shallow [$h \leq 70$ km]. The Middle America Trench delineates quite well a subduction zone where the Caribbean plate is underthrust by the Cocos plate. Near to Mexico and Guatemala, a triple junction of the three aforementioned plates is formed. Farther to the south, near the northeast of Panama and Colombia, the boundary between the South American, Caribbean, and Cocos plates is much more complex [forming other triple junction]. There is a mix of a strike-slip fault system with underthrust fault systems. A weak subduction process is located around Panama. In the Colombia–Ecuador region appears the subduction of the Nazca plate under the South American plate. As we mentioned before, the Central America subduction zone is not uniform based on different points of view. The volcanic information confirms this situation, and the seismicity permits us to establish at least four distinct segments.

The Southern Caribbean region is characterized as a deformed belt with Panama, Colombia and Venezuela along its border. The contact between the South American and Caribbean plates is defined as a PBZ. It can be divided in the area around Venezuela into at least seven segments, all of these with clear east-west trending belts, constituting a transpressive boundary with a combination of strike-slip faults and thrust belts that produce a positive flower structure.

The Hess Escarpment is a great feature of the Caribbean seafloor, with a defined NE strike (Figure 2 III). It is located from South America to Hispaniola. Another important structure is the Beata Ridge. It extends 400 km south from Beata Cape, Hispaniola, dividing the Caribbean into the Colombia [with crustal thickness of <10 km] and Venezuela [with crustal thickness of 10 km] basins. It is a ~20 km Cretaceous volcanic plateau that goes nearly 10 km into the Aruba area. To the west, the ridge is bound by a steep escarpment with a regional slope of 15°–25° that rises 2,500 m above the Colombia abyssal plain. To the east, the ridge drops down to the centre of the Venezuela basin in a series of steps. The Beata Ridge is an oceanic plateau whose edges have been reactivated by differential motion between the two aforementioned structures. Hispaniola and Puerto Rico are separated from the Venezuela Basin by the Muertos trough.

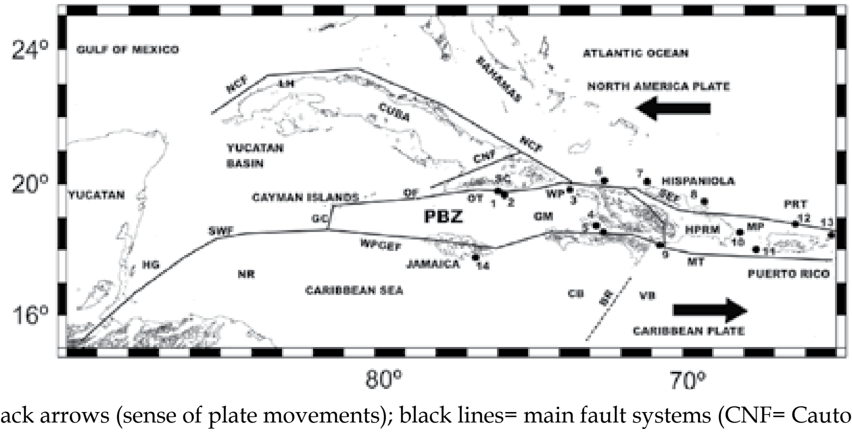
I



[Tsunsamigenic zones (1= Jamaica; 2= Haiti; 3= Dominican Republic; 4= Muertos trough; 5= Puerto Rico trench; 6= Virgin Islands).]

Fig. 2. I.- Selection of the focal mechanisms in the northern Caribbean and the tsunamigenic zones in the northeasterrn Caribbean.

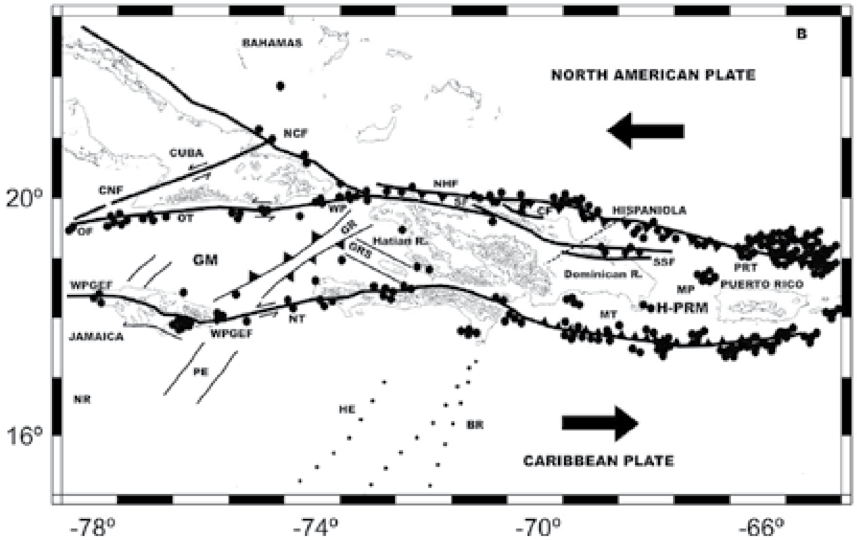
II



[Heavy black arrows (sense of plate movements); black lines= main fault systems (CNF= Cauto-Nipe, NCF= Nortecubana, HG= Honduras-Guatemala, OF= Oriente, SEF= Septentrional, SWF= Swan, WPGEF= Walton-Platain Garden-Enriquillo); other structures (CB= Colombia basin, MP= Mona Passage, MT: Muertos trough, NR= Nicaragua Rise, OT= Oriente trough, PBZ= Plate Boundary Zone, PRT= Puerto Rico trench, VB= Venezuela Basin, WP= Winward Passage); localities (LH= La Habana, SC= Santiago de Cuba); Strongest earthquakes (Black circle= epicenter including year (magnitude): 1= 1766(6.8), 2= 1852(6.4), 3= 1887(7.9), 4= 1770(7.5), 5= 2011(7.0), 6= 1842(8.2), 7= 1897(7.5), 8= 1946(7.8), 9= 1673(7.5), 10= 1943(7.5), 11= 1918(7.3), 12= 1887(8.0), 13= 1867(7.3), 14= 1692(7.5).]

Fig. 2. II.- Simplified tectonic map of the Caribbean with the strongest earthquakes in the northeastern Caribbean.

III



[Heavy black arrows (sense of plate movements); black points (epicentres); black lines= main fault systems (CF= Camú, CNF= Cauto-Nipe, HG= Honduras-Guatemala, NCF= Nortecubana, NHF= North Hispaniola, OF= Oriente, SF= Samaná; SEF= Septentrional, SWF= Swan, WPGEF= Walton-Platain Garden-Enriquillo); the drawing of the points outlines the structure BR= Beata Ridge, HE= Hess Escarpment; passages (MP= Mona, WP= Windward); islands (Cuba, Hispaniola, Jamaica, Puerto Rico); microplates (GM= Gonave, HPRM= Hispaniola-Puerto Rico); troughs (MT= Muertos, NT= Navassa, OT= Oriente, PRT= Puerto Rico); other structures (CB= Colombia Basin, GR= Gonave Ridge, GRS= Gonave).]

Fig. 2. III.- Tectonic map of the central – northeastern Caribbean.

The Lesser Antilles volcanic arc results from a subduction of the American plate under the Caribbean plate. It runs from the Anegada Passage [to the north] to South America. The volcanic arc draws a curve of ~850 km in length and a 450 km radius. It is considered to have a high seismic risk because of its active geodynamic context. Movements of two of the aforementioned plates control the tectonic, volcanic, and seismic activities in the region. Each plate is also the seat of a network of major faults. The north and the east of the Caribbean correspond to an active margin, related to the subduction of the American plate under the Caribbean plate [~2 cm/year]. The subduction angle is stronger in the centre of the arc [60° N, Martinique] than in the north [50° N, Guadeloupe] and in the south. This type of subduction is considered as an intermediate type between the Mariana type [low speed of convergence with weak subduction earthquakes], and the Chile type [high speed of convergence with strong subduction earthquakes [M >8]].

6. Seismicity and focal mechanisms in the northern Caribbean

We determined 141 earthquakes with M $\geq$6.4 that have affected the Caribbean territory (Tables 14 and 15). This is a significant magnitude for the region if we take in consideration the seismic history. Table 16 has the first seismic reports in the Caribbean region. The stress and strain distributions deduced from focal mechanism analyses infer a small N-S to NE-SW convergent component associated with the major strike-slip motion of the Caribbean and North American plates (Figure 2 I). Northern Hispaniola's tectonic regime is transpressional, with the main compressive stress axis being sub-horizontal and striking about N50°.

Magnitude	Total
6,4-7,0	75
>7,0-7,5	48
>7,5	19

Table 14. Earthquakes by magnitude range.

Time period	Total	Time period	Total
1940-1960	16	1981-2000	35
1961-1980	22	2001-2011	16

Table 15. Earthquakes of $M \geq 6,4$ by time period.

Year	Site	Year	Site	Year	Site
1502	Santo Domingo	1530	Venezuela	1657	Martinique Is.
1516	Panama	1538	Honduras	1663?	Puerto Rico
1526	Guatemala		El Salvador	1667	Jamaica
1528	Cuba	1566	Colombia	1669	Guadaloupe Is.
	Nicaragua	1608	Costa Rica		

Table 16. First reports of Caribbean earthquakes.

In the Northern Caribbean, the most intense seismicity is located around restraining bends such as southern Cuba and northern Hispaniola (Figure 2 II). In particular, the seismicity of Hispaniola is plainly justified by its geodynamic position, both with respect to the frequency of occurrence and to the magnitude of the seismic events. Thus, in a catalog of the 1502-1971 period, there appear 15 intensity VII, 12 intensity VIII, and 10 intensity IX earthquakes, and one earthquake of X degrees of intensity [MSK scale], which the authors place in two independent bands to the north and south of Hispaniola. On the other hand, three bands of seismic activity were described, one to the north and two in a NW transversal direction, of which the one found in the southeastern area corresponds to deep earthquakes. This zone was studied and recognized much earlier. Additionally, eight active zones have been described in the northeastern Caribbean. However, five of them have not been associated with seismicity in the last 40 years. On the basis of this data and statistical treatment, two seismogenic bands were described to the north and the south, and one transversal band in a NW direction. The seismic potential for the Cuba–Jamaica–Hispaniola sector was later defined, and it was determined that the strongest events [M=8.0] could occur in two sectors in the northern region, in Haiti and the Dominican Republic. Figure 2 II shows some of the strongest earthquakes in the Caribbean area, all occurring within the PBZ.

A large earthquake [Ms=7.8] occurred in the northeastern Hispaniola on August 4, 1946. The epicenter was at 15 km off the coast in the South Samna Bay. It was located ~25 km to the south of the Septentrional Fault Zone. There have been some interesting discussions about this earthquake and its focal mechanism. Nevertheless, we consider that the north central part of the Caribbean region is tectonically well-characterized by strain partitioning above a south–southwest dipping thrust interface along the top of the underthrust North American slab below the Caribbean plate. The aforementioned earthquake in the city of Julia Molina [northeastern of Dominican Republic] produced a maximum intensity value of X degrees [Mercalli scale]. In the vicinity of the Samana–Sanchez–Moca–Santiago–Puerto Plata localities, the value was IX degrees. In addition, the first village suffered the effects of a tsunami, but they were minimal. Southeast of Julia Molina [in the Matanzas village], only 3 km away, damage was heavier and caused 100 fatalities. No earthquake faulting was detected. According to the prepared isoseismal map, it is possible to assume that the epicenter lay to the NE of Julia Molina, about 50 km offshore. This tsunami affected Puerto Rico.

Reports of the 1751.10.18 earthquake [M~8] showed large and extensive damage only to the south of Hispaniola, which suggests that the earthquake occurred along the southern margin of Hispaniola–Puerto Rico. A tsunami was triggered that affected Hispaniola. Also, the 1984.06.24 earthquake [M=6.7] occurred south of Hispaniola beneath the San Pedro Basin, and shallow earthquakes occurred between Hispaniola and Puerto Rico. These events show the seismic activity of the Muertos trough and suggest that these islands lie on two separate microplates.

A portion of the Caribbean plate that is seismically active is oriented NNE, and a dip to the NNE is subducted below the North of Colombia. Thus, the north of Venezuela is part of the boundary between the Caribbean and South American plates. The contact zone has produced a system of dextral strike-slip faults with an E-W strike along a 150 km mountainous belt. It is formed by the mountain systems of the Venezuelan Andes and the Central and Eastern Cordilleras, termed the Oca–Ancon–Bocono–San Sebastian–El Pilar fault system. The Venezuela East has two distinct tectonic regimes, namely, the dextral strike-slip system El Pilar and the subduction zone between the NW of the region and the Lesser Antilles Islands. The seismicity of the Venezuelan territory is superficial and is concentrated at a ~40 km depth, except for that detected in the subduction zone of the NE at ~20–120 km. The magnitudes are low [$M \leq 5$], yet we point out a strong event [Mb=7.7] on March 26, 1812, that caused ~20,000 deaths. In addition, Venezuela has had at least five strong earthquakes [Ms>8.4] that have produced tsunamis.

7. Tsunamis in the Caribbean

References used for this section are: Cotilla, 2007; Cotilla and Córdoba, 2010; Cotilla *et al.*,1998; Grindlay *et al.*, 2005; Hillebrandt-Andrade and Huerfano Moreno, 2004; Lander *et al.*, 2002; McNamara *et al.*, 2005; and Rubio, 1982;.

Within the Caribbean region, there are multiple fault segments and submarine features that could be sources for earthquakes and landslides, triggering tsunamis. The perimeter of the Caribbean plate is bordered by no fewer than four plates [the North American, South American, Cocos, and Nazca]. Subduction occurs along the eastern and north-eastern margins of the Caribbean plate. Normal, transform, and strike-slip faulting characterize the northern South American, eastern Central American, the Cayman Ridge, and the northern PBZ. All of these elements are in direct relation to the focal mechanisms determined in the region (Figure 2 I). In the north-eastern Caribbean, the Puerto Rico trench lies roughly parallel to, and about 130 km off of, the northern coast of Puerto Rico and is about 900 km long and 100 km wide. At 8,350 m below the surface, it is the deepest trench in the vicinity of the Atlantic Ocean. The Hispaniola trench parallels the north coast of the Dominican Republic and Haiti and is 550 km long and 4,500 m deep. The Virgin Islands and Anegada troughs cut across the Antilles arc between the northern Virgin Islands and St. Croix and the Lesser Antilles. The Muertos trough, ~5,000 m deep, is an E-W striking bathymetric feature south of Puerto Rico–

Hispaniola. Tsunamis could be generated along these structures, but the direction of the waves would depend on many factors, including where the earthquake occurred.

Examining tables 10 and 16 confirm that the first European settlements [16th century] in America reported earthquakes and tsunamis. Considering the year of arrival of the first European settlers to the Caribbean as the initial time of tsunami observations we get a rate of 0.12 tsunamis/yr, while the rate for the Pacific Ocean is 393 tsunami /1,327 yr, or 0.30 tsunamis/yr. Tsunamis have been documented in the Caribbean [1688-2011]. Rubio (1982) lists 16 tsunamis associated with earthquakes, the strongest [Ms=7.8] of which occurred on August 4, 1946, in the northeast of Hispaniola. A list of 38 Caribbean tsunamis can be found at {http://webserver2.ineter.gob.ni/geofisica/tsunami/tsu-caribe-list.html} [published by Caribbean Tsunami Awareness, Florida Inst. Technology, Univ. Publ. EN-158-399]. Of the 38 events, three are stated to have occurred in Cuba [1755, 1775, and 1932]. Table 17 gives 5 reports on Cuba, following Rubio (1985). The probability of tsunami occurrences in Cuba is very low, because of certain focal mechanisms and the arrangement of the seismogenic marine structures that surround the island. Interestingly, the tsunami caused by the earthquake on 1755.11.01 in Lisbon was perceived in Santiago de Cuba: *"The severe earthquake of 1755 was accompanied by a sea-wave which almost completely inundated the town"*. A comparison of data using two sources appears in table 18.

We would like to suggest that there is an error in the assigned magnitude [8.1] of the 1939 earthquake in Cayo Frances (Figure 2 I). This region belongs to the North–Center of Cuba, and it has never had such a high magnitude earthquake. Indeed, an earthquake of that magnitude has never even occurred in the south–eastern part of the island [Santiago de Cuba], which is the most active. As an example, we point to the 1914.02.28 earthquake [21.30 N / 76.20 W; h=50 km; 05:19; M=6.2]; this was the strongest earthquake in the north coast of Cuba [in the vicinity of Gibara–Holguin] (Figure 2 I).

Region	Total	Largest	Date
Cuba	5		
Haiti	10	2	1770.06.03; 1842.05.07
Dominican Republic	4	2	1946.08.04; 1946.08.08
Jamaica	8	4	1692.06.07; 1780.10.03; 1881.08.12; 1907.01.04
Puerto Rico	3	1	1918.10.14
Virgin Islands	3	2	1690.04.16; 1867.11.18

Table 17. Tsunamis in the Northern Caribbean (Lander *et al.*, 2002).

N°	Date	Site	Rubio	Lander	Note
1	1755.11.01	Santiago de Cuba	X	X	Teletsunami
2	1766.06.12	Santiago de Cuba		X	Cotilla, 2007 (no agree)
3	1775.12.18	Santiago de Cuba	X	X	
4	1852.07.17	Santiago de Cuba	X	X	Cotilla, 2007 (no agree)
5	1931.10.01	Playa Panchita-Rancho Veloz		X	Cotilla, 2007 (no agree)
6	1932.02.03	Santiago de Cuba	X	X	Montelieu, 1933 (no agree)
7	1939.08.04	Cayo Frances		X	Cotilla, 2007 (no agree); Ms5,6

Table 18. Tsunamis in Cuba according to two sources.

On the western Caribbean coasts, tsunamis are concentrated near the Honduras Gulf, which includes the coasts of Belize, Guatemala, and Honduras, and on the Costa Rica–Panama coasts (Tables 19 and 20). They are related to seismic activity in North American–Caribbean and Panama Deformed Belt tectonic environments, respectively. The majority of the tsunamis have been small, causing little damage. However, along the Pacific coast many tsunamigenic earthquakes are inland or close to the coast and this might have reduced the height of the sea waves.

Nº	Date	Coordinates	Ms / H(km)	Nº	Date	Coordinates	Ms / H(km)
1	1798.02.22	10,2 N/82,9 W		5	1904.12.20	09,2 N/82,8 W	7,3 / 25
2	1822.05.07	09,5 N/83,0 W	7,6 / -	6	1916.04.26	09,2 N/83,1 W	6,9 / -
3	1873.10.14	10,2 N/80,0 W		7	1991.04.22	09,6 N/83,2 W	7,6 /20
4	1882.09.07	10,0 N/79,0 W	7,9 / -				

Table 19. Tsunamis earthquakes in the Caribbean - Central America area.

Nº	Region	Verified / Possible = [Total]	Comments
1	Costa Rica	-/ 1 [1]	
2	Cuba	2 / 3 [5]	Cotill1a, 2007 (no agree) [0]
3	Dominican Republic	2 / 1 [3]	
4	Guiana (British)	-/ 1 [1]	
5	Haiti	4 / 6 [10]	
6	Honduras (western area)	1 / 1 [2]	
7	Jamaica	2 / 6 [8]	
8	Panama (western area)	1 / 4 [5]	
9	Puerto Rico	-/ 4 [4]	
10	Venezuela	7 / 19 [26]	M_T=8,1
11	Virgin Islands	11 / 8 [19]	
	Total	**30 / 54 [84]**	**28 / 40 [58]**

Table 20. Local tsunamis in the Caribbean.

The Caribbean region has not had a great tsunamigenic earthquake. However, most of the tsunamis [58] occurred in it, and at least two teletsunamis were triggered from far away by earthquakes [near the coasts of Portugal and the Indonesia Krakatoa Volcano] (Table 18). These represent only 10% of the world's oceanic tsunamis. It has been estimated by authorities that they have caused the death of ~9.000 people in the region. It was stated that the Caribbean region has been affected by tsunamis from both near and far sources. In particular, the areas with the most tsunamis are in the West [Middle America] and East [Lesser Antilles]. These areas have direct contact with the Pacific and Atlantic Oceans, respectively. These edges have troughs, volcanoes, and undersea sediments with defined subduction profiles. The subduction profile of the eastern edge of the Caribbean has a lower seismic activity than the western one and is characterized by the typical island arc. As explained above, these two parts have often been studied, but there are still many gaps in our knowledge to explain its geodynamic behavior.

Regional tsunamigenic sources are also present in the Caribbean. They are able to produce tsunamis but have never, based on the data presented here, greatly affected the North Caribbean. These sources are located in: 1) the southern edge of the Caribbean; 2) the eastern edge of the Caribbean; and 3) the westerner part of the Caribbean Sea. We would like to point out that tsunamis generated in Venezuela did not seriously affect the northern Caribbean. Other areas outside the Caribbean plate are the Gulf of Mexico, the South of the U.S.A., and the Bahamas Platform, these likewise do not constitute a great hazard. In addition, the Caribbean islands are also susceptible to tsunamis generated within the region and to distant earthquakes, such as the 1755 Lisbon earthquake.

According to table 16, Haiti and Jamaica are the tsunamigenic structures of the Caribbean that has the highest number of events [10 and 8]. The Hispaniola [Haiti–Dominican Republic] has 14 events, while Puerto Rico and the Virgin Islands together have six. However, taking into account the location of Puerto Rico on the Greater Antilles arc, and to the surrounding structures [Puerto Rico trench, the Anegada trough and Muertos trough, the Atlantic Ocean, and the active faults system], Puerto Rico turns out to be where the risk of tsunamis is highest in the Northern Caribbean. And looking at the focal mechanism types [thrust fault and normal fault] (Table 1) which are more inclined to generate tsunamis in the northern Caribbean, two zones must be considered, southern Hispaniola–Puerto Rico, and northern Hispaniola–Puerto Rico–Virgin Islands. These are also the zones in which the strongest earthquakes and the most important tsunamis have occurred. Thus, these zones exhibit the highest probability of tsunamis.

The recent tsunami history is quite unusual for the Caribbean. Therefore, with our experience about hurricanes and polar fronts in the tropical region, we can assume that some of these phenomena could have been reported in the last centuries [15th-18th] as tsunamis. Thus, the Caribbean is historically more dangerous for cyclones, then hurricanes, and finally tsunamis, based on the frequency of occurrence. In addition, the first two phenomena cause frequent and important floods from the sea to the land. Floods are also produced with the arrival of north and south fronts. The period with the greatest probability of front occurrences is December–February, while that of cyclones and hurricanes is September–November. These situations of sea movements could have affected the first reports on tsunamis; we shall discuss this in the next section.

The area of the Caribbean Pacific has been investigated by segments according to the financial possibilities of each country involved (Figure 1 II). In general, 393 tsunamis have been accounted for, while 155 tsunamis are documented for the Atlantic area. This region being adjacent to large basin, it is clear that the danger of seismic sea waves is very high. Furthermore, the fact that strong seismic events [$M \geq 8.5$] occur in a range of depths, from superficial to deep, adds an element to generating local and regional tsunamis. As we indicated, the northern and southern edges of the Caribbean plate also differ in terms of contacts and movements. The northern border is more regular and homogeneous, although there are two deep troughs [Oriente and Puerto Rico] in its outline, and it has been affected by several local tsunamis and teletsunamis. Our interest is centered on the northern edge. Major tsunamis in the Northern Caribbean are indicated in table 17. Table 21 contains information about tsunamis in Venezuela (southeastern Caribbean).

Nº	Date / Time	Coordinates	M_T / I (MM)	Locality
1	1530.09.01 / 14:30 UT	10,7 N / 64,1 W	- / X	Cumana
2	1868.08.13	18,5 N / 70,3 W	8,5 / -	Rio Caribe
3	1900.10.29	10,9 N / 64,1 W	8,4 / -	Cumana
4	1906.01.31	2,4 N / 79,3 W	8,9 / -	Cumana
5	1929.01.17	10,0 N / 64,0 W	8,1 / -	Cumana

Table 21. Strongest earthquakes with tsunamis in Venezuela.

8. Final remarks

It is first necessary to be clear about two concepts: 1) a hazard is a potentially perilous event; and 2) the risk is the probability that the hazard will occur repeatedly and affect a locality, region, and population. Included in this last concept is magnitude, frequency of occurrence, and exposure. Therefore, these multiple parameters present a large problem to the scientists when attempting to estimate the tsunami risk. This is also highly complex because of the technical, economic, and social factors that are additionally involved. Given these elements, it is necessary to collect all available data, and the analyses performed should be used to initially generate a basic scheme of tsunami risk. After that, it is necessary to continue localizing those areas and zones with the higher hazard and risk potential. The results obtained should be first discussed with other specialists and public officials before being transmitted to the general public. Afterwards, such document can be used as "the guidelines for correct tsunami response and community preparedness from local emergency managers".

Nº	Date	Category	Denomination	Damages
1	1844.10	5	La Tormenta de San Francisco de Asís	>100 deaths
2	1846.10	5	La Tormenta de San Francisco de Borja	>100 deaths
3	1870.10	5	San Marcos	>800 deaths
4	1910.10	5	Huracán de los Cinco Días	>100 deaths
5	1926.10	5	Huracán de 1926	~600 deaths
6	1930.09	4	San Zenón	~6.000 deaths
7	1932.11	5	Huracán de Santa Cruz del Sur	~3.500 deaths
8	1944.10	5	Huracán de 1944	~300 deaths
9	1963.10	5	Flora	~2.000 deaths
10	1966.09	4	Ines	Unknown
11	1979.08	5	David	~4.000 deaths
12	1988.09	4	Gilbert	Unknown
13	1992.08	5	Andrew	~29 deaths
14	1998.09	3	George	Unknown
15	2001.11	4	Michelle	Unknown
16	2004.09	4	Ivan	Unknown
17	2005.07	5	Dennys	~20 deaths
18	2008.09	5	Paloma	Unknown

Table 22. Some hurricanes affected Caribbean.

The Caribbean region is well-known for its hurricanes and much less so for tsunamis. Historically, a significant amount of deaths have been connected not only with tsunamis in the region (Tables 9 and 22). In particular, the northern Caribbean distinguishes some tsunami sources: 1) Mona Canyon; 2) Puerto Rico trench; 3) Mona trench; 4) Septentrional fault; 5) Pedro Bank; and 6) Western Caribbean Sea (Figure 2 III). The Caribbean is a region of islands, and it can be considered potentially from the tsunami hazard point of view (Table 23). Here in the islands exists a strong coastal culture. There are a lot of residential buildings, hotels, large tourism activities areas, etc. In general, the population has increased greatly, as has the risk for natural hazards [hurricanes, earthquakes, etc.]. Therefore, the region is vulnerable, and several programs need to be taken into consideration to attempt to minimize any future possible disasters.

	Probable / Verified	**Note**
Tsunamis	18 / 19	
Teletsunamis	3 /3	Lisbon (1755, 1761), Krakatoa (1883)
Total	**37**	

Table 23. Other data from the Caribbean catalog.

We know that the Caribbean region is made up of poor developing countries. It is also known that tsunami defenses that could protect the inhabitants and their properties could be quite costly. Additionally, the cultural behaviors and the scholarly resources are very limited. A first logical and economic option is to leave a strip of land by the sea that is to be occupied only by construction necessary for the port, bay, and structures that require close proximity to the sea, such as beach clubs, warehouses, etc. The width of this strip would depend on the wave's height at the coast and how far it would advance inland.

The occurrence of natural disasters is difficult to predict based on observations from a restricted period of time. Ancient writings are important sources of information but are restricted either locally or historically. The possibility exists, however, that large-scale tsunamis are recorded in coastal sediment deposits. Disturbances of normal sedimentary processes by a tsunami may remain in lacustrine deposits and be represented by unusual sedimentary layers. These tasks fall to scientists and take time and money.

As we said before, the Puerto Rico–Virgin Islands region (Figure 2 III), which should be considered to be one of highest risk areas in the Caribbean, has around 4 million inhabitants. It was affected at least by large earthquakes of Hispaniola [08.09.1615], Virgin Islands [20.04.1824, 18.11.1867, 17-09.1869], and Mona Passage [28.07.1943] (Figure 2 II). Some tsunamigenic earthquakes have occurred in that region in the last few hundred years, such as the 1867 Virginia Islands and 1918 Puerto Rico quakes. In this sense, Grindlay *et al.* (2005) stated that the northern Caribbean is under a high risk of tsunami, while Rubio (1982) takes the opposite side. Based on the recommendations by Rubio, Cuba should not be considered to be at risk for tsunamis when planning works in the coastal zones. However, the UNESCO IOC, U.S. Natural Tsunami Hazard Mitigation Program and Warning Coordination Subcommittee organized the Exercise Pacific Wave 08 from October 28–30, 2008. Additionally, they prepared the Exercise Caribbean Wave 11/Lantex 11 on March 23, 2011, because they consider that tsunamis represent a significant hazard to society in this area.

Specifically studying a given coastal area to assess the tsunami risk is quite a complex task. It involves some variables that are difficult to model because of their great variability, such as: 1) topography; 2) bathymetry; 3) shape of the coast type; 4) strike of sea wave movements; 5) earthquake magnitude; 6) focal depth; and 7) focal mechanism. This is more complicated when considering the periodicity of the sea waves after the event has occurred. Currently, the velocity differences between the seismic and tsunami waves are used for tsunami warning systems. We mentioned before that the velocity of a tsunami is very fast for an ocean wave [0.2 km/s for a water depth of 5,000 m], but this is still considerably slower than seismic waves [5-10 km/s]. Thus, there is time to issue a tsunami warning after seismic wave detection in seismological stations but before the actual tsunami arrives. The parameters used in order to judge the tsunamigenicity are seismic magnitude and focal depth.

A proven method of protecting coastal villages from the damage of tsunamis is by planting trees in front of the residential areas. A zone of arranged trees [greenbelt] cannot prevent sea water from flowing into the villages, but we can expect it to effectively dissipate the energy of the incident waves of the tsunamis and to reduce the number of victims. In order to improve the dissipation efficiency, we should select varieties of trees that have many low branches with a high leaf density. A wide coral reef is another effective obstacle for dissipating part of the tsunami energy. The roots, trunks, and branches of mangroves are an effective defense against tsunamis and tropical storms. Also, thick rows of trees and shrubs are used to increase resistance to the sea waves on land. Stakes are even driven into the ground for this purpose. Inhabitants of a possible tsunami–inundation zone may be protected at different steps with a master emergency plan whose most important component is evacuation. It is critical that this action is very well studied and practiced with citizens. The two basic pieces of information are: 1) the arrival time of the first wave; and 2) delimitation of the inundation zone [floods]. Next, it is very important that a plan of action has been previously prepared by the local and regional authorities, together with scientists, civil defense specialists, the police and fire departments, and medical emergency teams. It is necessary to plan and locate places of refuge and evacuation routes; it is also essential to organize the community, clearly signal the escape routes and strategically place speakers and sirens, create educational programs for the population, and plan the use of the coastal land, among other things.

Table 24 contains some general recommendations to the population in order to protect again a tsunami occurrence. There are three groups of tsunami warning systems: 1) Pacific-wide system; 2) regional systems; and 3) local systems. The website http://www.usgs.gov/ science/science.php?term=304 contains valuable information and videos about: 1) tsunami preparedness along the U.S. West Coast; 2) tsunami preparedness in California; 3) tsunami preparedness in Oregon; and 4) tsunami preparedness in Washington. Normally, the first warning of a tsunami approaching the coast is a relatively quick withdrawal of water from the beaches. Following this, in the time interval of 5–30 minutes later, the recoil is followed by a wave capable of extending hundreds of meters inland. Thus, we can observe a rolling in and out with the resulting eddies. Estimates made in the Pacific Ocean suggest that a tsunami generated in the vicinity of the Aleutian Islands will arrive about 5 hours later to Hawaii, while one produced offshore of Chile will take about 15 hours to reach Hawaii. And studying tsunami travel times, in order to generate different charts for tsunamis in the Caribbean, has revealed that the estimated time for a complete crossing of the Caribbean is ~3 hours laterally and only 1.5 hours transversally. The experience with the 1755.11.01 tsunami of SW Portugal shows that the sea waves arrived to the Caribbean area ~7–8 hours later. These times are long enough to be able to adequately inform the population.

Nº	Information / recommendation
1	Tsunamis that strike coastal areas are almost produced by earthquakes. They can be generated near or far away of the place where you are situated.
2	Low coast areas may be affected by tsunamis.
3	Tsunami can move faster than any person.
4	The water near the shore can be receding before to the arrival of a tsunami.
5	The force and energy of a tsunami are enormous. Tsunamis may transport heavy rocks, boats and other debris inland hundred of meters.
6	The occurrence of tsunamis can be at any time.
7	Tsunamis can travel up rivers and streams from the ocean.

Table 24. Some general information and recommendations.

In general, the energy carried by a tidal wave, when it originates in an earthquake, is small in relation to the tremor that generate it. It has been found that the ratio between the energy carried by a tsunami and an earthquake is between 0.1 and 0.01. This is, however, an important level of energy. Different specialists have argued that the Indian Ocean, the Atlantic Ocean, and the Caribbean Sea have a tsunami [with a 10 m wave height] return period of 1.000 years. However, for the Hawaiian Islands, the value is only 200 years.

A wealth of information about tsunamis can be found in some websites:

1. The institutions of the National Weather Service: NWS Tsunami Centers of: (a) the West Coast Alaska Tsunami Warning Center [WC/ATWC], (b) the Richard H. Hagemeyer Pacific Tsunami Warning Center [PTWC], and (c) the International Tsunami Information Center [ITIC] are located at the website http://tsunami.gov/;
    a. This institution provides tsunami warning guidance for all U.S. coastal states, except Hawaii, and the Canadian coastal provinces;
    b. Tsunami warning to Hawaii and the countries in the Pacific and Indian Oceans, and Caribbean Sea, are supported by the PTWC;
    c. ITIC is operated on behalf of the intergovernmental Oceanographic Commission of UNESCO in order to coordinate the tsunami warning and mitigation systems globally;
2. The Tsunami Society [International Journal: *Science of Tsunami Hazards* {STH} Mitigating the impact of tsunami disasters through research and dissemination of knowledge; ISSN: 8755-6839]. http://www.tsunamisociety.org/
3. Tsunami data resources [NGDC Tsunami Database; Tsunami Field Survey Photographs; Atlas of Canada; Tsunamis; Centro International de Tsunamis] are included here:
4. http://www.geophys.washington.edu/tsunami/miscellaneous/relsites.html
5. The ITIC [International Tsunami Information Centre] located in Honolulu since November 1965, under the intergovernmental Oceanographic Commission of the UNESCO, has the following address: http://www.prh.noaa.gov/itic/
6. The National Oceanic and Atmospheric Administration–Pacific Marine Environmental Laboratory [NOAA Center for Tsunami Research], which has a primary task of developing methods to reduce tsunami hazards and protect life, appears at the following address: http://www.pmel.noaa.gov/tsunami/
7. The preliminary catalog of tsunamis occurring in the Pacific is located at: http://www.soest.hawaii.edu/Library/Tsunami%20Reports/Iida_et_al.pdf.

The study of occurrence of cyclones and hurricanes in the Caribbean region indicates that there have been 108 events during the June–November season [1785–1984], of which 14 were high intensity hurricanes (Table 23). The surf factor is conditioned mainly by synoptic situations [hurricanes and polar fronts–south fronts]. Thus, we can present three examples for Cuba: 1) 1932 [high sea level of Santa Cruz de Sur, South–Central Cuba]; 2) 1988 [hurricane Gilbert, with wave heights of 12 m, considered to be the most intense hurricane of the century, with a minimum pressure of 880 Mb and a wind speed of 85 m/s]; and 3) 1961, 1979 and 1993 [tropical storms with wave heights of 5 m in the Caribbean].

9. Conclusions

Tsunami is a Japanese word meaning "harbor wave". It is a set of gravity waves propagating in seawater away from an important disturbance of the sea floor, such as an earthquake, a submarine volcano, or a submarine landslide. These phenomena can cause great levels of destruction and loss of life in coastal regions since waves can transport large heavy blocks [tens of tons] hundreds of meters inland. In island arcs [such as the Caribbean], the oceanic lithosphere underthrusts beneath a continent when a large earthquake occurs. The continental lithosphere is dragged with the descending oceanic type slab prior to the earthquake occurrence. With this scope, UNESCO IOC, U.S. Natural Tsunami Hazard Mitigation Program and Warning Coordination Subcommittee prepared the Exercise Pacific Wave 08, on October 28–30, 2008. Additionally, they prepared the Exercise Caribbean Wave 11/Lantex 11, on March 23, 2011, because they consider that tsunamis represent a significant hazard to the society.

The Caribbean region is better known for its hurricanes and less so for its tsunamis. Nevertheless, the amount of deaths [~9,000] historically connected to tsunamis in the region is very important. In fact, ~120 tsunamis have been well documented. The sea waves generated by teletsunamis, such as that the one caused by the 1755.11.01 earthquake in SW Portugal, took ~7–8 hours to arrive. In the northern Caribbean, there are some tsunamigenic sources: 1) Mona Canyon; 2) Puerto Rico trench; 3) Mona trench; 4) Septentrional fault; 5) Pedro Bank; and 6) Western Caribbean Sea. From our point of view, the second is the area of highest hazard, and the island of Puerto Rico is under the greatest risk.

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8

Tsunami in Makran Region and Its Effect on the Persian Gulf

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1. Introduction

The Makran Subduction Zone characterizes by the subduction of the oceanic part of the Arabian plate beneath the Eurasian plate. The offshore Makran region located in the Oman Gulf shows relatively low seismicity in comparison with the surrounding regions (Figure 1). In spite of low seismicity, 3 tsunamis in the Makran region has been reported. 2 of them had known seismic source, and the other one has unknown origin. The most recent tsunamigenic event was on November 1945 associated with an earthquake of magnitude 8.1, affecting along the Makran coastlines of Iran, Pakistan, Oman and United Arab Emirates; with the loss of life of around 4000. Since then a long silence poses a potential threat of major tsunamigenic disaster for the coastal region.

Makran Subduction Zone is unique region in the world due to its geological and seismological characteristics. High sediment input of 7 km, shallow angle of dip and rate of subduction are interesting and distinctive features of this zone.

The Makran subduction zone appears to be divided into at least two segments - the west and the east, separated by a sinistral fault known as the Sonne Fault. This has been supported by Kukowski et al., (2000) where they introduce a new boundary coinciding very well with the Sonne strike-slip fault. In contrast to east, the western segment characterizes by absence of inter-plate events. The lack of major earthquakes in the western segment either means the segment has been locked and accumulating strain energy for hundreds of years or it is creeping aseismically. This movement supported by the regional GPS study that indicates a convergence of about 2 cm/year (Bayer et al., 2006). In addition, the existence of Holocene (10,000 years) marine terraces (Page et al., 1979) indicates that this segment is active, although the recurrence period of earthquakes (> 8.0) may be much longer (i.e. thousands of years). In this context, it is important to mention that the western segment of the Makran subduction zone may have experienced a large offshore earthquake in 1483 (Ambraseys and Melville, 1982). Although recent work suggests this may have been a moderate event near the Qeshm Island, Strait of Hormuz in association with the Zagros seismically active region (Musson, 2008).

Based on the 2D offshore seismic reflection data the main structural provinces and elements in the Gulf of Oman are (i) the structural elements on the northeastern part of the Arabian Plate and (ii) the Offshore Makran Accretionary Complex Elements. On the northeastern part of the Arabian Plate, five structural provinces and elements being defined: the

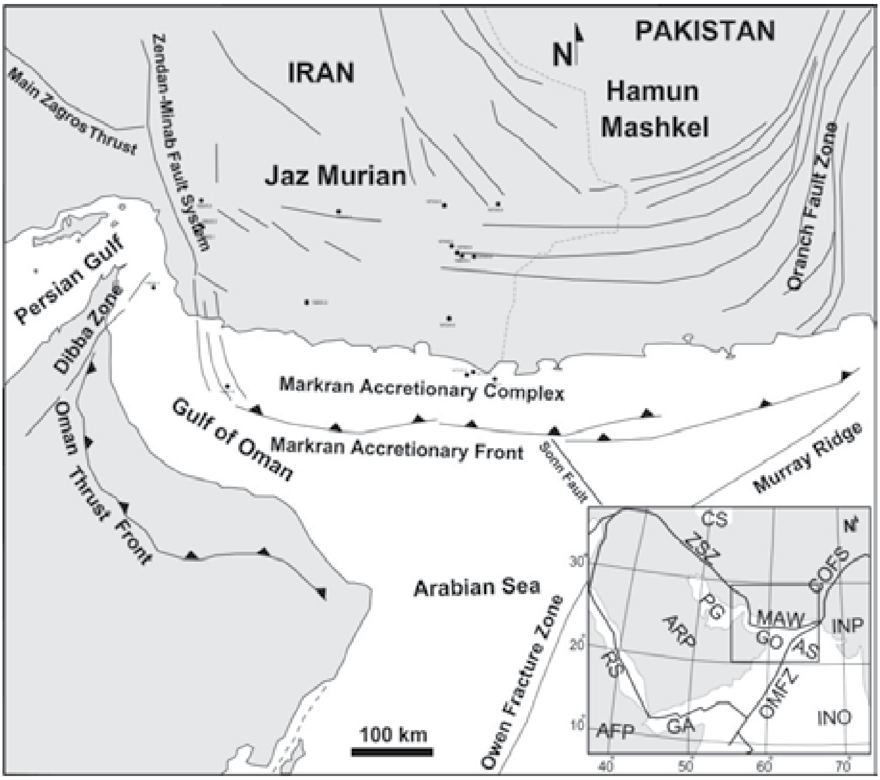

Fig. 1. Plate tectonic setting of the Oman Sea and the main structural elements, the plate boundaries in the north of the Indian Ocean and some major earthquakes locations are also shown. AFP; African Plate, ARP; Arabian Plate, AS; Arabian Sea, COFS; Chaman Oranch Fault System, CS; Caspian Sea, GA; Gulf of Aden, GO; Gulf of Oman, INO; Indian Ocean, INP; Indian Plate, MAW; Makran Accretionary Wedge, OMFZ; Owen Murray Fault Zone, PG; Persian Gulf, RS; Red Sea, ZSZ; Zagros Suture Zone (modified after Mokhtari et al. 2008)

Musendam High, the Musendam Peneplain, the Musendam Slope, the Dibba Zone, and the Abyssal Plain (Mokhtari et al. 2008). The Zendan-Minab Fault System and the Accretionary front define the western and southern boundary of the Makran Accretionary Complex, respectively. The Oranch Fault Zone is located in the eastern side of this complex and being considered as the western boundary of the Indian Plate, while the Murray ridge system defines the offshore boundary of the Arabian and Indian plates. These seismic reflection data (covers both Persian Gulf and eastern part of Oman Gulf, (PC2000) acquired by National Iranian Oil Company) has been further analyzed for refinement and better understanding of the structural elements and their tectonic significance. Kopp et al. 2000 has applied wide-angle and seismic reflection data and achieved the similar result on the western side of the Oman Gulf.

It is believed that the smaller fault system can act as superimposing (secondary) elements in strengthening the tsunami effect. Thus, in this respect a better understanding of the main structural elements and their tectonic behavior can be important. This information could be implemented in future for more detail hazard assessment.

The tsunami threat faced by Indian Ocean countries in general and Makran in particular consists of a tsunami from local, regional and distant sources, whose effects at any location are highly dependent on variations in bathymetry between the source and the affected area. These factors if not being implemented accurately will make the design of an effective tsunami early warning system problematic.

In this chapter after discussing the tectonic setting of Makran Subduction Zone, its effect on tsunami generation has been elaborated and tsunami hazard assessment as key element for the early warning system has been introduced. Although the Persian Gulf due to its seismotectonic setting and shallow water depth could not be classified as tsunamigenic zone, but effect of tsunami generated in the Makran region on this area will be specially emphasized due its major recent inhabitant growth and industrial developments.

2. Tectonic setting

The latest major plate tectonic event causing most changes in the structural evolution in the Oman Sea is related to the evolution of the Sheba Ridge, accompanied by opening of the Gulf of Aden and rifting/opening of the Red Rea (Figure 2). This event has been dated to 23 Ma-Oligocene-Early Miocene (Edwards et al., 2000). The change in the plate configuration also resulted in compression in the Owen Fracture Zone. It might even be that the transform

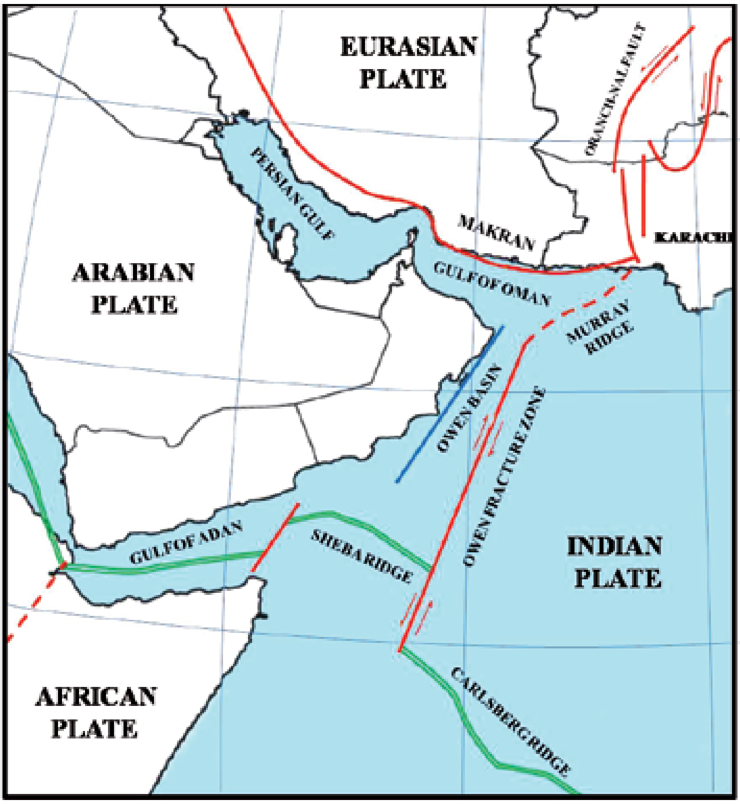

Fig. 2. Major structural elements and the plate boundaries in the study region. The blue line indicates “the initial location of plate boundary?”.

defining the eastern boundary of the Indian Plate prior to this event was located further west (Figure 2), jumping to its present location at the Owen Fracture Zone when the Sheba Ridge was formed (Barton et al., 1990).

The breaking of the Arabian Plate from the African Plate probably resulted in an increase in subduction rate. At this stage the evolution of the mountain chains along the Himalayan continent-continent collision zone was uplifted and eroded, resulting in a major increase in sediment input into the Indian Ocean and the Oman Sea.

3. Characteristics of the Makran Accretionary Complex

Based on the seismic reflection, wide-angle reflection data and mapping, both east and west Makran and the plate tectonic setting of the area several structural provinces and elements have been defined (Mokhtari et al. 2008 and Kopp et al. 2000).

It is important to mention that the evolution and deformational history of an accretionary complex is the result of a continuous process, not series of separate events. Therefore, some of the provinces defined do not represent different tectonic/structural settings or events, but as different stages in the evolution of an accretionary complex. Also, what has been observed and defined offshore is an integrated part and continuation in time of the onshore areas, only younger in age and to some extent less deformed. Therefore, understanding the onshore is important, for both the offshore tectonic/structural evolution and the depositional history.

The following gives a summary of some of the characteristics of the Makran Accretionary Complex. Two-thirds of the accretionary complex is located onshore and bounded to the east and west by large transform faults defining plate boundaries. It is oriented in the east-west direction with a total length of more than 900 km long. The distance from the accretionary front to island arc volcanic (the Bazman, Taftan and Sultan) is about 500-600 km. The island arc volcanics are located where the subducting plate is at approximately 100 km depth. But there are no indications of active volcanism or intrusions in the accretionary complex. The subducting plate has a northward dip of >20 till 270N, then bending down to an angle of approximately 300. Oligocene-Present ocean ward coastline regression is ~250 km; i.e. 6-10 km/my (Ahmed 1969). The accretionary complex is being cut by north-south, northwest-southeast and northeast-southwest oriented wrench faults. The thrust faults are oriented nearly perpendicular to the direction of convergence as shown in Figures 3 and 4.

There is no obvious topographic trench associated with the present accretionary front. This could be related to a thick sedimentary cover of terrigenous sediments as mentioned above. In addition, there are no obvious magnetic anomalies related to ocean floor spreading in the Oman Sea. The earthquake activity is low and majority of the small and moderate earthquakes appear to be associated with the above-mentioned wrench faults. Earthquake fault plane resolutions show predominantly shallow northward dipping thrusts, with dips increasing northward, away from the accretionary front.

3.1 Seismic expression

Seismic expression of main structural elements based on seismic reflection data has been shown on Figures 3 and 4 for east and west Makran, respectively. The lengths of the seismic profiles are different. In addition the Figure 3 is depth migrated seismic section so the dips shown are more closely resemble the actual values, while the Figure 4 is time migrated and the dipping geometry is apparent. As it can be seen from the figures, the main structural elements are similar on both east and west side of the Makran region, despite their different seismological behaviors. In these figures, for example northward dipping thrust pack is easily detectable within the accretionary prism. Also, the southward converging reflectors beneath the abyssal plain representing north side dipping geometry of the underlying oceanic crust.

4. Seismicity

In Makran, the oceanic crust of the Oman sea subducts with a very low angle beneath the Eurasian plate. This subduction zone exhibits different seismic behavior from the west to the east. The eastern Makran experienced large earthquakes and currently shows very low seismic activity (Ambraseys and Melville, 1982).

The most recent instrumentally recorded earthquake occurred in eastern Makran in 1945, which generated a tsunami that affected the coasts of Iran, Pakistan, Oman, United Arab Emirates and India (Pendse, 1946; Ambraseys and Melville, 1982; Byrne et al., 1992). Due to a difference between the origin time of the earthquake and the arrival of the tsunami, the latter being delayed by about 30 minutes at locations within the rupture zone (Bilham et al., 2007), so there is speculation that a submarine landslide may have been an important contributor to the tsunami excitation.

The western segment lack any significant event, but it may have witnessed the occurrence of a large onshore earthquake in 1483 (Ambraseys and Melville, 1982), although recent work suggests that a moderate event has occurred in the vicinity of Qeshm Island near strait of Hormuz. This event may have been incorrectly associated with a separate event in the

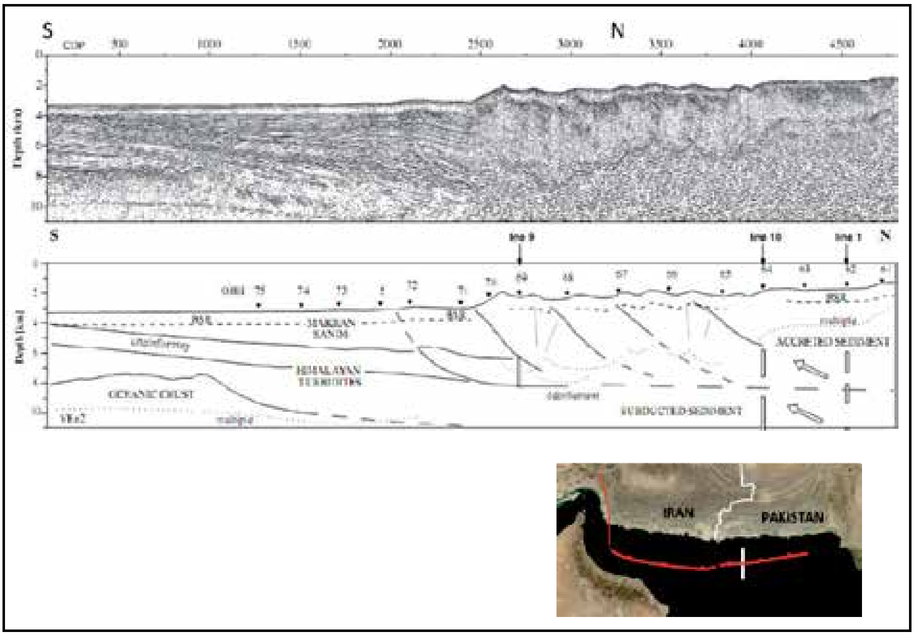

Fig. 3. The offshore seismic reflection profile in the Pakistani side of the Makran and it interpretation as line drawing below. The seismic section is depth migrated. The location of the seismic profile shown on the index map at the right corner (from Kopp et al. 2000).

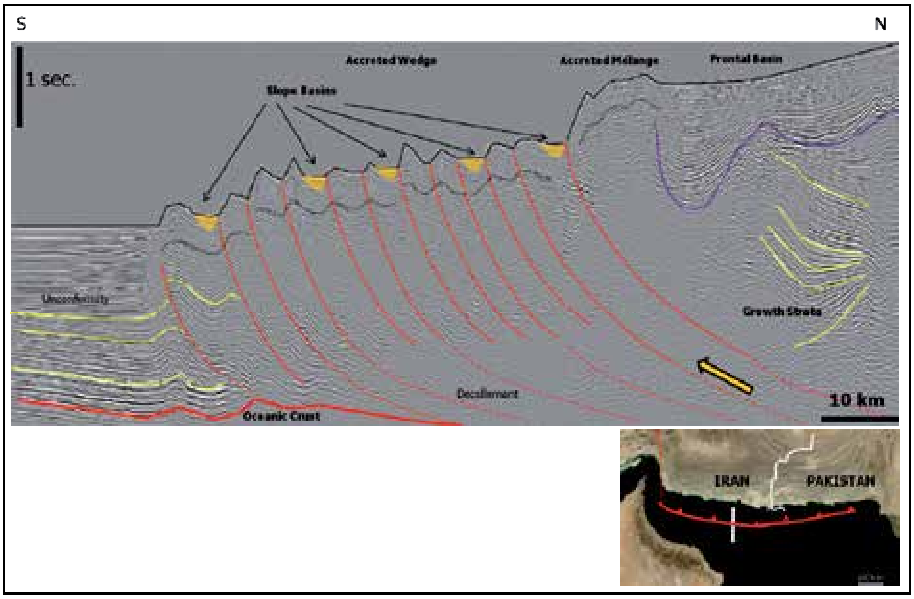

Fig. 4. The offshore seismic reflection profile in the Iranian side of the Makran and the interpretation is superimposed as line drawing on the seismic section. The seismic section is time migrated. The location of the seismic profile shown on the index map at the right corner. The yellow arrow indicates the displacement direction (modified after Mokhtari et al. 2008).

Zagros region (Musson, 2008). Despite the above fact, the lack of major earthquakes in the western segment means either the segment has been locked for hundreds of years or this segment is creeping aseismically. However, the regional GPS measurements indicate a convergence rate of about 2 cm/year (Bayer et al., 2006). In addition, the existence of Holocene (10000 years) marine terraces (Page et al., 1979) indicates that this segment is active, although the recurrence period of megathrust earthquakes events may be much longer (i.e. thousands of years).

4.1 The Persian Gulf seismicity

The Persian Gulf with a maximum depth of only 60m and not being in the subduction zon, has little chance of being a tsumanigenic zone. Nevertheless, there is a non-conclusive record of 1008 A.D. in the Siraf area within the Persian Gulf where inundation has been reported. This may have caused generation of waves, as a result a number of ships were sunk, with the loss of life. In addition, many people were killed when "the sea inundated the land" McEvilly and Razani (1973). Although, Ambraseys and Melville (1982) concur on the loss of several ships, they state that there is no evidence of waves inundating the land. Other records show that high winds affected the region during the same time period, thus the reported flooding and destruction of ships could have been caused by storm surge.

It is important to mention a similar more destructive 978 A.D. earthquake occurred in the same location shows no record of wave generation (McEvilly and Razini, 1973;Ambraseys and Melville, 1982). It is therefore, possible that the reported waves may have been generated by an earthquake triggered coastal landslide. Although the historical records do not indicate that one occurred in conjunction with this particular event, or any other earthquake in the Persian Gulf region. Given the fact that wave activity was only reported in the earthquake's epicentral region, the implication is that this event was localized and if a tsunami was indeed generated, its energy was quickly attenuated, given the shallowness of the Gulf.

4.2 The Oman Sea seismicity

The following historical and instrumental tsunamigenic events have been reported in the Oman Sea. The first historical even occurred in 325 B.C. in the Port of Alexander (Near present day Karachi, Pakistan). A large wave believed to be a tsunami, damaged the Macedonian fleet of Alexander the Great while at anchor east of the present day Karachi. The damaging waves probably originated in the same source region (east) as the destructive 1945 Makran tsunami. Its effects on the Makran region would likely have been similar to those in 1945 event.

In 1851 a large event occurred in the eastern Makran, Pakistan. The event has occurred west of 1945 tsunamigenic earthquake but with no details as to whether a tsunami was generated (Okal et al. 2006). However, given the proximity of this event to the 1945 tsunami source, it is possible that a tsunami was generated.

The most recent tsunamigenic event occurred in western Makran, Pakistan at 03:26 IST (Indian Standard Time) on 28 November 1945 with a magnitude of 8.1 (Berninghausen, 1966; Quittmeyer and Jacob, 1979; Ambraseys and Melville, 1982). It is the only large earthquake that recorded instrumentally, which allows to be used as validation in modeling and simulation. The earthquake was felt in Karachi, Pakistan, where ground motions lasted approximately 30 seconds, stopping the clock in the Karachi Municipality Building and interrupting the communication cable link between Karachi and Muscat, Oman (Omar, 2005). Ground motions were felt as far away as Calcutta, on the eastern side of the Indian subcontinent (Ambraseys and Melville, 1982; Byrne et al., 1992; Pacheco and Sykes, 1992; Pararas-Carayannis, 2006; Omar, 2005). The damage from the earthquake was great, but the greatest destruction to the region was caused by the tsunami that was generated. Tsunami waves "swept the whole of the Oman Sea coast" (Berninghausen, 1966). It is estimated that 4,000 people were killed.

5. Tsunami risk assessment

The term tsunami risk refers to the potential risk of coastal community due to the occurrence of tsunami, including the physical, human and economic losses. The assessment of that risk depends on the: 1) vulnerability of the exposed buildings and infrastructures; and 2) the level of the community's preparedness which has high impact on the human and economic losses due to tsunami, as it has been formulated by the following convulsion relation:

Tsunami Risk = Tsunami Hazard * Vulnerability * Exposed assets / Preparedness

5.1 Tsunami hazard

Tsunami hazard in Oman Sea is mainly due to the occurrence of the near-field earthquake in Makran region; as well as far-field earthquake such as 2004 Sumatra earthquake that had caused tsunami in the region, recorded on the tidal gauges (personal communication) in Chabehar coast, with no report of any major damage.

A tsunami generated in the region could reach the Iranian and Pakistani coast under 15-20 minutes and Arabian Peninsula within an hour (Figure 5). In this calculation, a tsunami assumed to occur in the close vicinity of the 1945 tsunamigeneic earthquake and with the same parameters. Such a tsunami can propagate in any direction and thus, dependent on the location of the source, path of propagation and near-shore morphology form a risk to any vulnerable coastline surrounding the area.

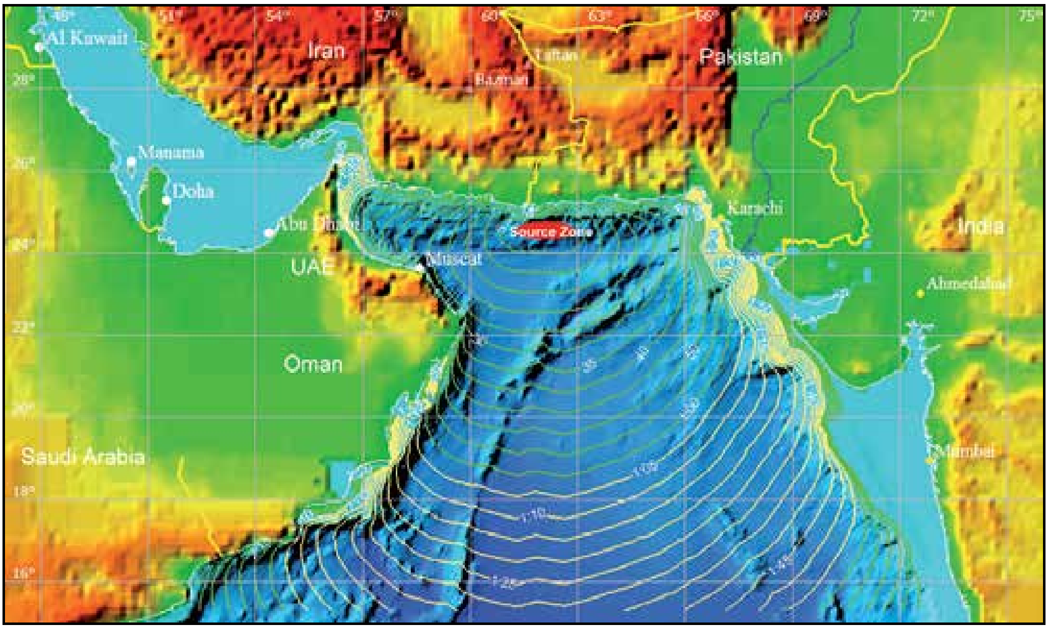

Fig. 5. Shows the tsunami travel time in the North West of Indian Ocean, the isoclines intervals are 5 minutes (based on modeling program winITDB/PAC package).

In this context tsunami risk maps in the region in a rather regional sense has been prepared and will be discussed in the following section.

5.1.1 The Oman Sea

Several tsunami hazard assessment has been done for the Makran region such as Mleczko et al. 2009, Heidarzadeh, et al. 2010, Rafi, et al. 2010. Here the result of Mleczko et al. 2009 has been presented due to its comprehensiveness and taking into account maximum feasible cases. Their approach consisted of the following steps: 1) Determination of the earthquake source zones; 2) identification of the probability of occurrence of earthquake; 3) Simulation of the tsunami based on synthetic earthquake and estimation of the maximum tsunami amplitudes that result from each case at selected locations; and 4) calculation of the probability of occurrence of a given maximum tsunami amplitudes. The result are being plotted as "low" and "high" hazard in an integrated manner to cover the Makran region.

The main differences between the two cases are the size of the maximum earthquake that is possible to occur in the region. In the case of the low hazard, the Wells and Coppersmith (1994) empirical relationship assuming full length and half width of eastern

Makran and for the high hazard the maximum earthquake with magnitude of 9.2 to occur using the full length and width of the entire subduction zone have been used. The 1945 tsunamigenic earthquake has been used as validation of the result for the low case. Meanwhile, as there is no certain and reliable record in the western side of the Makran region, the low hazard has been eliminated by Mleczko et al. 2009. Probabilities were assigned to each of the synthetic events (low and high) using the historical record and the available geophysical information. The most important factors controlling the earthquake probability are the rate of convergence across each segment, the overall global rate of earthquake occurrence at subduction zones observed historically and the maximum magnitude assumed for this zone.

Numerical computations had been performed to simulate the propagation of tsunami waves from the earthquake source zones to the model output points (Mleczko et al. 2009). The results of these simulations were used to estimate the maximum tsunami amplitude at each model output point due to each synthetic earthquake.

Table 1 shows the expected maximum tsunami amplitude with probability of exceedance of 1 in 2000 (return period of 2000 years) for any point in the affected area.

Impacted coast	Low Hazard (m)	High Hazard (m)
Iran	0.15-0.50	0.9-3.0
Oman	0.15-1.0	0.6-3.0
Pakistan	1.0-2.0	0.5-3.0
UAE	0.15	1.00

Table 1. Expected maximum tsunami amplitude for the probability of exceedance of 1 in 2000 (return period of 2000 years) for Makran subduction zone.

The assumed source zone in the Makran region for low hazard case and the maximum expected tsunami amplitude for each nation facing the source zone are shown in Figure 6. Whereas, Figure 7 shows the source zone in the Makran region for high hazard and the maximum tsunami amplitude expected to impact the coastal region. Summary of hazard assessment for Iran, Pakistan, Oman and United Arab Emirates coastal area has been discussed.

The 2000 year maximum amplitudes offshore Iran are quite uniform, but is slightly higher in the west than in the east as shown in Figure 6. For the high hazard case the maximum amplitude is around 3.0 m (Figure 7).

The hazard in the offshore Pakistan has a great deal of variability in the low hazard map (Figure 6 and Table 1). In the case of high hazard, the maximum exceedence amplitude for western Pakistan is much higher than that for eastern Pakistan (Figure 7). The offshore Oman the maximum amplitudes increase from south to north (Figure 6). In the high hazard assessment the hazard off northeast Oman which directly faces the western Makran is significantly larger than any other part of the Omani coast (Figure 7 and Table 1).

The offshore United Arab Emirates the hazard low case everywhere quite low (Figure 6), while the hazard from the high hazard assessment was noticeably higher (Figure 7 and Table 1).

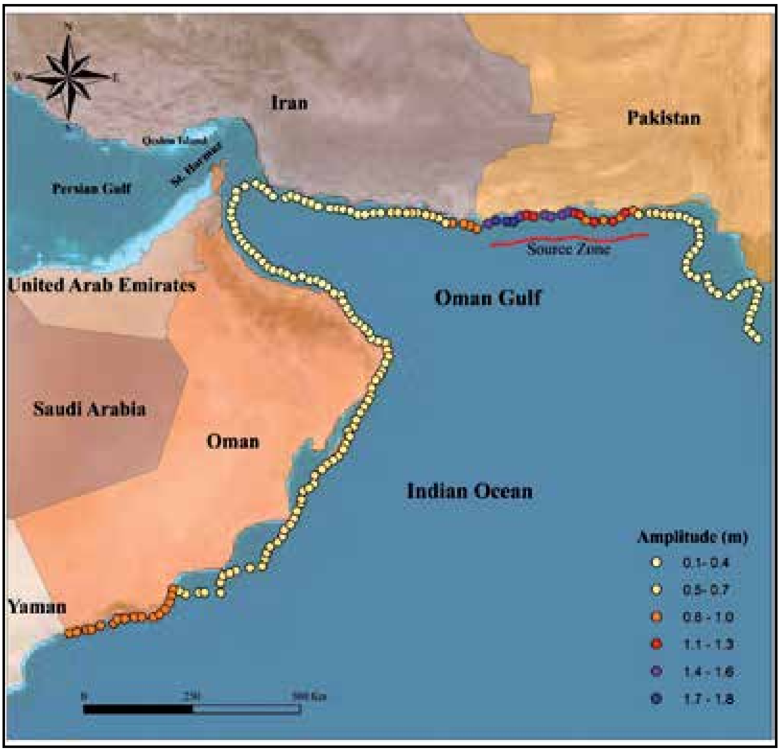

Fig. 6. Integrated "low" hazard map for the Makran region, also the source location has been shown. The dots show the 2000-year maximum amplitudes (modified after Mleczko et al. 2009).

It is important to note that due to quality and resolution of the bathymetric dataset (two arc minutes) used, the result on the modeled tsunami amplitude in the vicinity of shoreline must be interpreted with caution. It is also important to emphasize that the results presented here should not be directly used on onshore inundation, run-ups or damage assessment. Such phenomena are strongly dependent not only on the offshore tsunami height, but also on factors such as shallow bathymetry and onshore topography. A study of inundation therefore requires detailed bathymetric and topographic data and involves even more intensive numerical computations than those discussed here.

5.1.2 The Persian Gulf

Although the onshore of the Persian Gulf is a tectonically active region, most of the earthquakes take place inland, away from the coasts. With the exception of the 1008 A.D event, which is not conclusive (as it may have been the result of storm surge)?

There is no direct record of 1945 tsunami in the Persian Gulf, but at the Ras al-Khaimah, United Arab Emirates, there was a large sandbar that ships use to transport goods over. It was noted that sometime before 1964 this bar was breached by a "tidal wave", which formed a direct channel from the open sea to the harbor (Jordan, 2008). Ambraseys and Melville (1982) have suggested that this wave was associated with the 1945 Makran tsunami. It is important to note that, it seems that Musandam Peninsula in the Strait of Hormuz can play as a buffer in protecting the Persian Gulf from Tsunami effect even from Makran region.

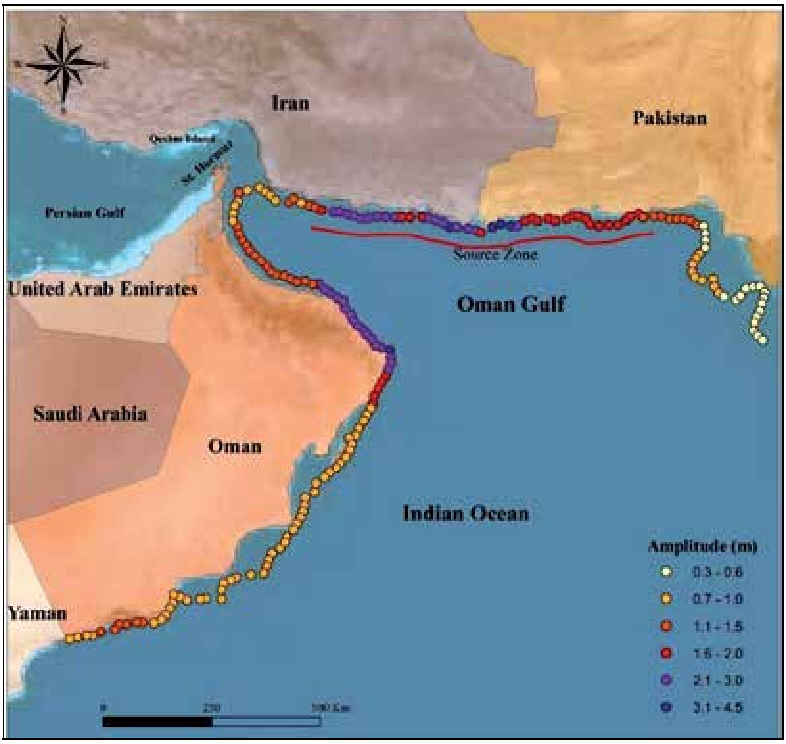

Fig. 7. Integrated "high" hazard map for the Makran region, also the source location has been shown. The dots show the 2000-year maximum amplitudes (modified after Mleczko et al. 2009).

6. Prevention and recommendation

Risk posed by tsunami in addition to its destruction could also cause flooding, contamination of drinking water in the coastal region, fires from ruptured tanks or gas lines and loss of vital community infrastructures, etc. In this regard one should not forget that a local tsunami generally produces run-up significantly higher than that of a distant generated tsunami, provided that the source earthquakes were of similar magnitude. Therefore, the tsunami waves produced in Makran may be more destructive along its coasts. For such cases, one should think of natural preventive measure. In this respect, the effect of tsunami can be minimized on flat coastal plains area by planting tree belts and mangrove plant between shorelines and areas needing protection. In addition, manmade marine structures, such as barrier wall could be considered if economically and practically is feasible.

A monitoring system for acquisition of seismic signal and water level displacement simultaneously (Tidal Gauge) must be installed in the region of the selected area. Figure 8 shows the seismic stations distribution in the region. But the key elements in this regard is the integration of data gathering, analysis and local and regional distribution of analyzed result in timely manner to be able to reach the potentially effected nations. In addition at least two tsunami-meters should be installed in the region for prevention of false alarm and tsunami generation and identification.

In addition, implementation of national education and training programs about tsunami hazard is vital especially in the case of near field tsunami such as Makran. In this way, the damaging effect of a disaster could be minimized.

The role of governments of the region is of utmost importance for proper implementation and application of above-mentioned information. In addition, the modeling and tsunami simulation should be conducted using regional and local bathymetric information to be used for the early warning purposes by trying many different possible scenarios.

The effectiveness of an Early warning system also depends on the timely communication of warnings to communities, businesses and households at risk. If information on impending hazard events, risk scenarios and disaster preparedness strategies fails to reach those at risk on time, then an early warning system will have failed *a priori*. The development of national and local capabilities for early warning system must therefore include the design and implementation of communication strategies, taking into account both the content and form of warning information and the media used to communicate with those at risk.

Fig. 8. Seismic station distribution in the region complied from seismic networks of, Iran, Oman, UAE, Saudi Arabia and Yemen (websites and personal communications)

Effective tsunami early warning system also requires the existence of institutional capacity for warning, risk analysis, disaster preparedness and communication at the local level. As mentioned above, given the need to generate high resolution risk scenarios and to develop appropriate preparedness and communication strategies, targeted at specific vulnerable sectors and groups and given the need to involve these sectors and groups in early warning system design and implementation, the local dimension is fundamental to the overall early warning system goal of transforming hazard warnings into risk reduction.

7. Conclusions

There are only a few recorded tsunami events that have affected the Makran region. The most recent and destructive one is the 1945 event that has affected the region and caused both human and property losses in Iran, Pakistan, Oman and United Arab Emirates. It is important to note this conclusion is based on the historical events, if a paleotsunami investigation being conducted in the region, this conclusion might be revised.

There is an uncertain tsunami event in the Persian Gulf that was small and localized. Given the shallow nature of the Persian Gulf and the lack of confirmable tsunami events in the past, it can be concluded that the risk of tsunamis (although active, due to its proximity to Zagros) in the Persian Gulf is very small. On the other hand, the effect of Makran tsunami on the Persian Gulf due to recent population and industrial growth should not be ignored.

Over the past 15 years, there has been enormous progress in the understanding of tsunami generation, propagation and inundation. While the timing and source of a tsunami are not predictable, modeling technology now exists to effectively predict tsunami propagation, and to a lesser extent inundation, given a known source mechanism. The tsunami modeling in the Makran showed the expected tsunami amplitude in the coastline of the northwestern Indian Ocean in the case of "high" hazard model could reach up to 3.5 meters.

This progress should be translated into sound approaches to prepare communities (from coastal planners and emergency responders to the general population) for the event of a tsunami. Preparation should be focused on the priority of saving human lives. The detail maps (locally suitable) of predicted inundation, for a range of source scenarios, should be produced for courtiers in the vicinity of the Makran subduction zone, namely, Iran, Pakistan, Oman and United Arab Emirates to be a basis for coastal zoning, future coastal construction and also for planning of evacuation routes.

The public education especially in case of near-field hazard such as Makran is vital in risk and vulnerability reduction. People who live in coastal settings should be provided with timely and reliable information on the risks of that environment.

Although there is small chance for tsunami generation in the Persian Gulf and in addition the Musandam Peninsula in the Strait of Hormuz can play as a buffer in protecting this area but the effect of large tsunami in the Makran region should always be considered as serious threat to this region.

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9

The Place of a Village Within a Tsunami Early Warning System

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1. Introduction

As the 2004 tsunami demonstrated, south- and southeast-Asia countries contain many villages with no history of a tsunami in this generation. Also, in many villages the people were not connected to modern communications technologies, they had little or no local disaster preparedness, and they lived in high risk locales next to the sea. Therefore, even the best tsunami detection and notification technology need not have the desired impact in these villages.

The content of this chapter is defined by first-hand experience in monitoring the recovery, reconstruction and livelihood rehabilitation in twelve villages in coastal southeast India, which had been devastated by the 2004 tsunami. The vulnerability of the people that led to destruction, loss of life and erosion of community livelihoods are identified. The accumulated evidence forms the basis for an outline of the essential role of a village in an effective tsunami early warning system.

2. A vulnerable people

Along coastal southeast India numerous fishing villages are located next to the shoreline. Per capita income of less than a dollar per day, evidence of malnutrition among some of the children and limited literacy, especially for women, is still the order of the day (Rempel, 2010, p. 109). *The Economist* (2005, p. 18) described the people affected by the tsunami in India as "...subsistence farmers and fishing people eking out precarious living in, or at the edge of, a fickle ocean."

Given the poverty of the area the purchase of insurance as a way to mitigating risk was not an option. Even if property and life insurance was available in the local market, the majority of the families would not be able to afford the insurance premiums required.

A community-based approach to reducing the vulnerability of the people would be a defined, enforced exclusion zone along the shoreline for all village dwellings. In theory, a 500 metre exclusion zone was in place in the state of Tamil Nadu, but it had not been enforced in these villages. The churches and temples, plus some of the more substantial homes were located back from the shore on higher ground. Many of the low income families lived next to the shore. In part this was a preferred location as it enabled the fishing families to store boats, nets and fish-vending utensils next to their homes. These homes had no protection from the destructive power of a tsunami.

A proven form of protection is the presence of a mangrove forest along the shore. Dubinsky, Chomsky and Brenner (2011), demonstrate there is scientific basis for the anecdotal evidence that mangrove forests absorbed a significant portion of the tsunami destructive force in selected communities in south- and south-east Asia. With a combination of a coral reef and a mangrove forest most of the destruction caused by the 2004 tsunami could have been avoided.

Mangrove forests require specific environmental conditions. The locale needs to be low lying with relatively high tidal wave action and protected from high-energy waves. It is a wetland ecosystem. Where there are some mangrove forests in coastal districts of northern Tamil Nadu state, the southern districts are identified as tropical dry deciduous. With high, unprotected sand beaches and with limited rainfall conditions, the potential for establishing a viable mangrove forest to protect these twelve villages was not an option.

Without protective vegetation cover within the exclusion zone it is important to construct affordable, low maintenance cost houses that can resist the destructive intrusion of the ocean. The project houses built in the twelve villages were designed and built by Methodist Engineering Company. Noel Vaghela (2008), Managing Director, designed a "tin box" model, with a semi-flexible and semi-rigid structure, utilizing local construction materials. These houses may not withstand the force of a major tsunami but they should be able to stand against the more common threat in the area, storm surges during cyclones.

In addition, several storm shelters, designed to withstand a tsunami, were constructed in the region. These were three-story buildings with the lower level made up of stilts. There were separate facilities for males and females. A water tank was located on the roof and the shelter was stocked with emergency food rations. On a day-to-day basis the buildings were used extensively for community meetings and activities.

The combination of actions under taken during the reconstruction phase reduced significantly the risk of death and loss of habitat. The actions, though, did not address the vulnerability of loss of the primary livelihood. The boats and nets were too bulky to be hauled twice daily a distance of at least 500 metres. A tsunami or a major storm surge would still wreck havoc among all things located on the seashore.

3. An early warning system

The technology to detect tsunamis is evolving. The challenge is early detection of a tsunami, to provide warning on a timely basis, and minimizing the incidence of false positives. Warnings that cause people to move to safer areas but prove to be false will reduce faith in the system, reducing compliance in the future.

Existing technology is expensive to implement and has limitations. The expectation is that both hardware and methodologies will advance significantly in the near future (Beltrami et al., 2011; Curtis, 2011; Hamlington et al., 2011). Therefore, the existence of an early warning system is likely in south- and south-east Asia, as exists now in the Pacific Ocean.

The success of this emerging technology in the region will become an early warning system only if the information provided by the technology is transmitted on a timely basis to the village level. The challenges involved in realizing this final stage of a comprehensive, effective early warning system are demonstrated by experience with cyclones in the Bay of Bengal region. The existence of a cyclone and its likely path is known several days in advance. This enables warnings to be delivered in days, versus in hours or minutes for a typical tsunami.

In 1970 there was a major cyclone in Bangladesh that resulted in 500,000 deaths. This tragedy caused Bangladesh to establish an early warning system and to build shelters designed to withstand cyclones. Nonetheless, Cyclone Sidr, with winds estimated at 240 km/h and a five metre tidal surge, caused extensive casualties in 2007. With an estimated 10 million people in the path of the storm, the early warning was not received by many rural people who had neither radio nor television (Foster, 2007). Police and local volunteers travelled to a number of villages and used megaphones to alert people. Not all people received the message; others were unable or unwilling to act on the early warning received. Where the authorities ordered all boats to return to the shore, an estimated 150 fishing boats did not receive that message (BBC News, 2007).

Building disaster management capacity into foreign assistance forms part of contemporary literature on natural disasters. For example, protective – ability to withstand external shocks – forms one of the elements in DAC's list of conditions for effective foreign assistance.[1] As of 2007, the United Nations Development Programme (2007) initiated action designed to link the drive to achieve the nine Millennium Development Goals to reduced disaster risk. Action Aid International (2006, p. 3) has declared disaster preparedness and disaster response as an essential right "... to reduce the loss of life, human suffering and homelessness resulting from disasters in the future."

In response to the 2004 tsunami disaster management national policy in India shifted from responding to disasters to disaster preparedness. During the inauguration of a Disaster Management Congress Prime Minister Manmohan Singh pronounced: "I do believe that the time has come for a paradigm shift in disaster management from a 'relief-centric' and 'post-event' response, to a regime that lays a greater emphasis on preparedness, prevention and mitigation."[2] This suggests a process of establishing the requisite good governance for risk reduction may be beginning. Completing such a process needs to encompass national, state, district and village levels of government.

Within an effective disaster preparedness program the village level government, *Panchayat Raj*, would carry specific responsibilities. These range from fostering community organisation, provision and maintenance of village infrastructure, setting and enforcing local codes and by-laws, and delivery of services such as water, sewage and garbage collection. The Indian and international non-governmental organisations assembled at a tsunami end-of project meeting concluded the *Panchayats* in project villages had been marginalized as active participants in the response to the disaster.[3] The *Panchayats* were dependent on other levels of government for funding so they were not free to pursue community-based initiatives. The *Panchayats* were responsible for zoning and building codes, but they lacked the technical expertise to define and implement village changes that would address the hazards and risks within each village. In the twelve project villages, the respective *Panchayats* did not have an early warning system in place.

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[1] For example, note Table 1, Tackling the Poverty Complex, in OECD (2001), p. 52. The DAC Model is formulated by the Development Co-operation Directorate of the Paris-based Organisation for Economic Co-operation and Development (OECD).

[2] As quoted in the Hindustan Times, "PM Talks of Robust Disaster Plan," *Hindustan Times.* (November 30, 2006): 8.

[3] CASA organized an End-of-Project Symposium, at the Saaral Resort, Courtallam, (18 – 19 September, 2008), which included the non-governmental organizations that received project funding from the Canadian International Development Agency for tsunami relief and reconstruction in India.

To fill this gap the Indian project partner, Church's Auxiliary for Social Action (CASA), organized and trained volunteer Disaster Mitigation Task Forces.[4] The decision to build and promote Disaster Mitigation Task Forces flowed from a paradigm shift from relief programming to building a culture of preparedness (CASA, 2008a: p. 22). This new paradigm is defined as:

- People are not victims but responders where in individual, family, community and especially vulnerable people such as women, children, elderly, the otherwise abled are well taken care of.
- The approach is no longer reactive but pro-active.
- People move from dependency to self-reliance.
- Community moves from a vantage point of powerlessness to inclusive empowerment.
- Sustainability mechanisms are in place with local governance playing an important role.

To make this paradigm shift operational CASA developed training curriculum and organized training workshops in the following subject areas:

- awareness building;
- hazard, risk and resource mapping;
- shelter management;
- appointment of Disaster Mitigation Task Force members consisting of local volunteers;
- warning systems and restoration of lifeline;
- search, rescue and evacuation;
- first aid and primary health;
- relief, counselling and filling of claims; and
- workshops and consultations of local representatives and village captains; region level disaster management consultations for all important actors (CASA, 2005b, p. 12).

CASA's response to the 2004 tsunami in the state of Tamil Nadu put in place a Task Force in each village with a total of more than 200 persons (mostly young people), trained in five disaster-mitigation activities. One of these activities is "early warning". This activity within the Task Force intervention has two essential provisions: 1) a point of contact within the village that will receive the warning when it is transmitted from the national, state and district levels; and 2) a means of notifying the residents of their village of an impending disaster such as a cyclone or tsunami.

The Task Force members are relatively young and, in general, without direct access to authority personnel and institutions within the village. Therefore, the means to notifying village residents of an impending disaster proved to be a challenge. As most of the villages had a Catholic church, the initial response from Task Force members was to call on the Priest to ring the church bells. The solution adopted was a portable, crank-driven siren that could be operated throughout the village.

The Task Forces have conducted safe guarding and mock drills in the event of a disaster in ten *Panchayat* schools. This has covered a minimum of 500 children in each school. Children were trained to respond to warning sirens and signals that would be used by the school managements and by the community during disasters. In addition, a second Task Force

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[4] CASA first organized Disaster Mitigation Task Forces in the state of Orissa in response to a 1999 cyclone. The effectiveness of these Task Forces during the 2003 flood in Orissa was noted and commended by the International Federation of Red Cross and Red Crescent (2004, Box 3.1).

activity, “search and rescue”, has a list and map location of persons in the village requiring assistance to evacuate. These persons will be warned directly by designated village volunteers.

4. Disaster action plan

An early warning system becomes operational only if the residents know the appropriate action needed and a willingness on their part to act accordingly. These aspects of an early warning system require a disaster action plan at the village level.

An effective disaster action plan needs to address the vulnerability – a combination of measure of risk and a level of social and economic capability to cope with a disaster – specific to each village. At a generic level CASA (2005b, p. 14) identified three forms of vulnerability: physical, social and economic. Physical vulnerability involves the structures, houses infrastructure and various means to livelihood generation that can be destroyed, damaged or disrupted during a disaster. Where this occurs people are traumatised if homes are destroyed plus the capability to cope with the disaster is impaired, if not destroyed.

Social vulnerability refers to social marginalised groups within the village. Primary groups involved are women,[5] children, the elderly and the physically challenged. By virtue of some degree of being socially ostracised they tend to face the brunt of a disaster. Further, they tend to have special needs at the same time that their support mechanisms are eroded, reducing their capabilities to cope with a disaster.

Economic vulnerability refers to the lower-income groups within a community, especially the members of Scheduled Castes and Scheduled Tribes within Indian society. By virtue of their poverty they are less likely to carry any form of insurance and they are more likely to be excluded from livelihood rehabilitation and reconstruction assistance. After all, if they had few, legitimate possessions before a disaster struck they have less need for assistance to recover from the disaster. These forms of discrimination, combined with initial poverty, limit severely their capabilities to cope whenever a disaster strikes.

Direct action programs to address vulnerability require an awareness of the benefits presented by disaster preparedness. Only if villager recognized their respective forms of vulnerability and they sensed they had the ability and means to reduce such vulnerability could a program become successful. To generate awareness CASA (2008a, p. 27): “...commenced with a series of mass-awareness campaigns in the villages. All the members of the village were gathered together in the common area such as a school compound, community hall or temple. The campaign generated awareness about natural calamities and benefits of community-preparedness to combat such disasters. Concepts of DMTF, village contingency plans, grain banks, seed banks, etc were explained in detail to the villagers.”

It is reported these campaigns generated both curiosity and interest among villagers to initiate planning direct action plans. Communities began to discuss the concept of community-based disaster preparedness, including means required to obtain the claimed benefits of being prepared.

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[5] During the end-of-project symposium it was reported many women had never learned to swim. Their clothing, full-length saris, and their long hair increased their vulnerability as the sea water surged inward during the 2004 tsunami and then carried back into the sea what had been torn loose. In communities where fatalities were tabulated the number of women exceeded that of men, in some cases by a considerable margin (OXFAM International, 2005).

The means to a disaster action plan at the village level was the creation of Disaster Mitigation Task Forces (DMTF's). The DMTF structure had two (in some cases three) levels with five tasks at each level (see Figure 1). The 1st Line members from the various villages were trained by CASA at a central location. These five Task Force members then trained the 2nd Line members, four in each of the five tasks shown. A 3rd Line Task Force was chosen in some villages. Given the relatively young age of the volunteers it was expected that some volunteers will move on to attend school or pursue employment elsewhere. Other members might lose interest. With a 3rd line trained volunteers could be promoted upward whenever vacancies occurred.

The 1st and 2nd Line Task Force members were selected through a process of voting within the village. To be eligible for selection the criteria set were:

- age group between 18 to 36 years;
- healthy body and sound mind;
- commitment and attitude;
- selected on the approval of the community members; and
- approval by the elected *Panchayat* members (CASA, 2008a, p. 29).

There was an effort made to obtain some semblance of gender balance plus representation from within the various castes in the community.

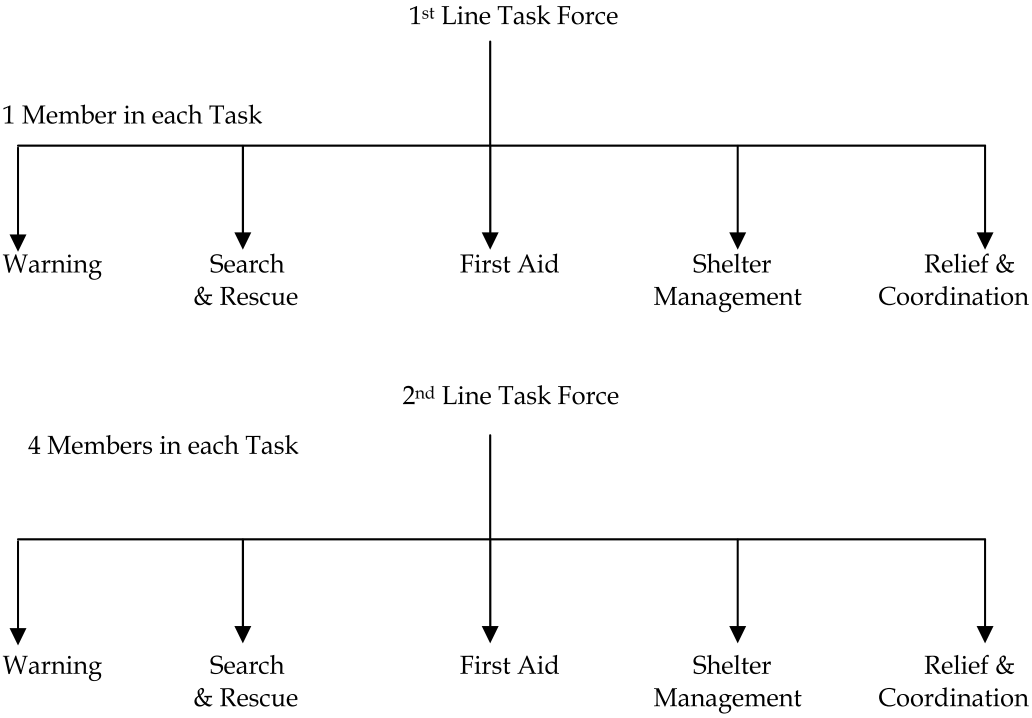

Fig. 1. DMTF Structure

The job description for the first task, warning, was provided in the previous section. The other four tasks cover actions in preparation for and subsequent to an early warning received in the village. Their respective job descriptions are drawn from CASA (2008a, pp. 32 – 33).

Search and Rescue Task – The members of this group are provided training on evacuation and rescue methods. They are trained to identify safe routes, ensure that transportation is ready and conduct periodic inspections of the safe routes. They are provided with rescue kits: a paddle, ropes, rafts, containers to bail out water, torches, transistor, anchors and first-aid kits. They also have to keep tools in a handy location, such as cutting saw, blades, crowbar, hammer, nails etc.

First Aid and Medical Task – Villagers with some knowledge of nursing are preferred for this group. Intensive training is provided to this group on first-aid and immediate medical relief. This group has to maintain a list of pregnant women, infants, differently abled, old and sick in the village. It is the responsibility of this group to ensure that the medical needs of these people are met immediately. A first-aid box with disinfectants, water-purifying tablets, vaccines, antiseptics and medicines is provided to this group.

Shelter Management Task – The members of this group look after the shelters and arrange for the evacuee's food, water, and medication requirements. They check the shelters and safe houses that have been identified to house people. They have to ensure that the shelters are intact and necessary repairs are made to make them safe and liveable. They have to ensure that sufficient supplies of food, water, medicines, milk powder, candles, matchboxes, are available for at least a week to be used by the evacuees. They should also ensure that sanitation facilities are available and usable.

Relief and Coordination Task – The members of this group collect and distribute relief materials such as food supplies, utensils, clothes, kerosene, etc., and coordinate all the relief requirements of the other tasks. During a disaster, this group mobilizes stocks from the government to be stocked in cyclone shelters in advance. In the event of disasters, they move the stocks to the respective shelters, monitor the relief stocks and ensure that no one leaves the shelter during the disaster.

Effective operation of Disaster Mitigation Task Forces requires acceptance throughout the village of its Task Force's mandate and capability. To promote this acceptance the project organized meeting of all villagers, including especially the groups identified as being more vulnerable, to formulate a village contingency plan. This planning process requires community members to assess the situation within their village and to agree on a list of activities to minimize death and destruction should a disaster occur. To facilitate plan implementation houses were allotted serial numbers as well as house numbers. The plan agreed to at these village meetings had to be accepted formally by the village residents. Once approved, the Disaster Mitigation Task Force carried responsibility for implementing the village's contingency plan.

Details common to contingency plans developed in project villages included:

- a village profile;
- review and analysis of the most recent disaster;
- resource mapping;
- risk mapping;
- reduction of opportunity mapping;
- list of Disaster Mitigation Task Force members with their house number, their contact number and the Task Force to which each member belonged;
- coping mechanisms at the local level; and
- roles and responsibilities of Disaster Mitigation Task Forces (CASA, 2008a, p. 35).

Project reports indicated initial response to this planning process lacked enthusiasm with villagers not convinced of either the need for or the importance of a contingency plan.

During the process, though, the villagers realized the importance of being prepared better to meet future hazards. As the villagers analysed the most recent disaster and as the observed Task Forces demonstrate what they were trained to do they became convinced that a contingency plan would be a desirable. They recognized that in the panic of an impending disaster people were not in a condition to make sound decisions.

Finally, a good disaster preparedness action plan requires resources. The advantage of establishing Disaster Mitigation Task Forces as part of a response to a disaster typically provides funds to purchase the requisite resources. As noted, specific Task Forces required equipment to rescue people, to move the most vulnerable and to provide first aid and primary health care. This included both equipment and supplies for training purposes as well as held in store for use during a disaster. Another major expense is creation of storage facilities for strategic food reserves and filling these with basic food stuffs needed to cover the first response to a disaster. CASA enabled villagers to store rice in 500 kilogram drums where each drum was estimated to contain basic food for forty families during an emergency.

In addition, CASA (2008a, p. 42) decided to provide project funds to enable clusters of Disaster Mitigation Task Force to set up a Capital Generation Fund. Rupees 20,000 was provided for each village in the cluster. The intent was for clusters to invest these funds to generate a stream of income over time. Each village-level Task Force had a bank account to receive their share of this investment income. This income then served to cover the day-to-day expenses involved in maintaining Task Force facilities, records, maps, equipment and supplies. This action was designed to motivate volunteers to remain active in assuring the village contingency plan was being implemented well.

End-of project interviews in the CASA – PUMA project villages provided evidence that residents now felt more secure as well as better prepared to meet disasters in the future. This perception by villagers of being safer and better prepared is warranted. The organization of DMTFs, with requisite training and basic equipment, has advanced significantly the ability of the people in the project villages to minimize the disaster effects of a natural hazard whenever it occurs. Also, the capacity within 12 villages to mobilize access to government departments responsible for maintaining basic services such as schooling, roads, water, sanitation and electricity has been advanced.

5. Developing requisite institutions, systems and knowledge

In 2008, at the conclusion of the 2004 tsunami disaster project, CASA hosted an end-of-project symposium. It included the Indian and international non-governmental organization that had financial support from the Canadian International Development Agency. The participants included personnel from these organizations, selected villagers from the project areas, Indian disaster specialists and representation from the Canadian International Development Agency.

This forum devoted considerable time to evaluating their cumulative experience gained during their projects in preparing local people to meet disasters in the future. A dominant theme within this discussion was the limits of what non-governmental organizations can do with projects with merely a local scope. Without extensive, effective coordination among projects regional policy is not an option. Second, non-governmental projects lack the authority to require evacuation or to undertake major rescue operations. Third, the disaster preparedness is dependent on volunteers. In contrast, in countries with major emergency measures and with disaster preparedness plans, there are personnel employed to maintain and implement such programs. At the local level there still may be a strong reliance on volunteers during an emergency, but initiating action and coordinating the response is located with trained persons employed for this purpose.

To realize this in India, it was the conclusion of the symposium that disaster risk reduction needs to become a government priority from the national to the local level, complete with an institutional basis for implementation. It was observed that India did not have a national disaster policy. The legislation brought to bear in time of a disaster is the National Policy for Resettlement and Rehabilitation.[6]

This National Policy covers: "Compulsory acquisition of land for public purpose including infrastructure projects displaces people, forcing them to give up their home, assets and means of livelihood." The stated objectives are:

- to minimize displacement and to identify non-displacing or least-displacing alternatives;
- to plan the resettlement and rehabilitation of Project Affected Families, including special needs of Tribals and vulnerable sections;
- to provide better standard of living to Project Affected Families; and
- to facilitate harmonious relationship between the Requiring Body and Project Affected Families through mutual cooperation.

The implementation of this National Policy was located with an Administrator for Resettlement and Rehabilitation who shall perform the following functions/duties:

- minimize displacement of persons and identify non-displacing or least displacing alternatives in consultation with the requiring body;
- hold consultation with the project affected families while preparing a resettlement and rehabilitation scheme/ plan;
- ensure that interest of the adversely project affected families of Scheduled Tribes and weaker sections are protected.
- prepare a draft plan/ scheme of resettlement and rehabilitation as required under Chapter V of this Policy;
- prepare a budget including estimated expenditure of various components of acquisition of land, resettlement and rehabilitation activities or programmes in consultation with representatives of the project affected families and requiring body for whom the land is acquired;
- acquire adequate land for the project and also for settling the project affected families;
- allot land and sanction benefits to project affected families; and
- perform such other functions as the appropriate Government may, from time to time, by order in writing, assign.

The intent of this legislation was to deal with displacement of people in large industrial projects. Moving people up to three kilometres, as is typical in risk-reduction strategy for cyclones and tsunamis, does not constitute displacement under the National Policy for Resettlement and Rehabilitation. Therefore this National Policy is not particularly relevant for vulnerable communities, at the coast or away from the coast.

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[6] The Department of Land Resources, Ministry of Rural Development authored the National Policy on Resettlement and Rehabilitation for Projected Affected Families – 2003. It was published in the Gazette of India, dated 17th February, 2004. Quotes related to this legislation are taken from this Act as presented on the web site: *rural.nic.in/Rrpolicy.Doc.*

This conclusion gave rise to two symposium recommendations:

- non-governmental organisations to be active in a mediating role between people and the government plus advocacy intended to influence government; and
- advocacy for national policy for disaster management.

During the 2004 to 2008 tsunami projects there were a range of issues between the people affected and their District and State governments that needed to be resolved. An important role of non-governmental organizations, such as CASA, was to give these people a voice in addressing politicians and government officials. The first recommendation identified this mediating and facilitating role as a continuing responsibility for Indian and international non-governmental organizations. The second recommendation gives specific content to the first recommendation: lobby the Government of India to put in place legislation, with reach from the national to village-level governments, which addresses the disaster risk reduction and emergency planning needs of India.

The symposium's call for a national policy related to disasters had three important elements. First, the policy should clarify the roles of stakeholders involved: various levels of government, the private sector, non-governmental organisations and the people in communities at risk. As part of this recommendation there was included a call for a focus on gender issues, vulnerable groups and marginalized peoples.

The call for greater inclusion is illustrated with the special problems CASA (2005a, pp. 12 – 13) encountered in efforts to include *Dalits*, given project conditions set by the State of Tamil Nadu:

> The poverty of the *Dalits* is proving to be a special challenge for CASA. 'The *Dalits* … have come to terms with their fate of being discriminated by the fisherfolks, who themselves belong to some of the backward castes.' CASA reports claims made by *Dalits* that at tsunami relief camps: 'The government says we will not be given anything as we are not affected much.' Also, the condition set by the Government of Tamil Nadu that a family had to surrender a deed to a house to be eligible for a replacement or re-location house (beyond 500 meters from the seashore), excluded virtually all the *Dalits* resident in the area at the time of the tsunami. In an interview with CASA, Mr. Sredhar, a *Dalit* leader, said: 'You people will come and go. But we have to live here with these (fishermen) people. We do not want any tension here. There was discrimination before the Tsunami and now after Tsunami. Hence it does not matter to us. We are used to it.' (Rempel, 2010, p. 111).

A second example of exclusion was the place of women within various responses to the tsunami disaster. First, women were excluded from the primary local decision making units, the *Panchayats* and the Parish Councils of the Catholic Church. Second, women and girls were especially at risk in the relief camps and group shelters established by the Government and some non-governmental organisations (OXFAM International, 2005). Third, initial livelihood rehabilitation initiatives focused almost exclusively on re-establishing the men in their fishing activities. The place of women and the needs of the women in the processing and sale of fish within these communities were overlooked by Government and by some non-governmental organisations.

In response to these observed affects of the aid response to the tsunami the symposium recommended: more focus be placed on educating women as leaders, for example, to be effective if elected to a *Panchayat Raj*; and women's groups should be strengthened to enable them to play their part in disaster management.

The second element focused on the place of the *Panchayat Raj*. As noted in the previous section, the village-level *Panchayat Raj* were marginalized during the tsunami as they lacked financial and technical capacity to respond. A national policy should promote empowering the *Panchayat Raj* and hold each one responsible for disaster mitigation and risk reduction within their respective villages. This recommendation was based on a conclusion that unless empowered and made efficient to function well during normal times, *Panchayats* could not deliver during disasters. A symposium conclusion assumed village-level disaster preparedness undertaken by non-governmental organisations opened the door for *Panchayats* to become active players in the drive to reduce and mitigate risk. It was recognized that incorporating this into a national disaster preparedness program remained a major challenge. This challenge called for non-governmental organisations to sharpen the extent and content of their advocacy to assure a national policy, operational at the local community level, is devised and implemented.[7]

The third element of the recommended national policy was a call for flexibility for individual states, allowing states to modify disaster management. Also policy at the state level should place greater emphasis on mitigation and risk reduction. This aspect of a proposed national policy recognised traditional disaster response knowledge has been lost. As a result, the symposium participants called for the use of knowledge, innovation and education to build a culture of safety and resilience at all levels.

The call for flexibility, in part, was a plea for non-governmental organisations to have a say in defining a response to the disaster. For example, in the area of providing shelter for people affected by the 2004 tsunami, the symposium concluded:

- There were no uniform state-wide policies; discretion was left to District Collectors.
- Participants were not consulted in the selection of housing sites; selection was done by government. Some sites selected were deemed to be unsafe by the residents and the non-governmental organisation involved.
- More time would be needed in the construction phase of disaster reconstruction to maximize community involvement.
- The tsunami was a unique experience with more money committed for reconstruction and rehabilitation of communities than in disasters more generally.
- Some argued for government exercising stringent selection procedures in registering non-government organisations for relief, rehabilitation and reconstruction.
- Joint husband-wife ownership of houses built empowers women.
- Preferred approach is to allocate specific houses to beneficiaries at the outset so families can participate in the process of their house being built.

To follow up on these conclusions it was recommended:

- People should be consulted in selection of the relocation site.
- Ownership titles and other legal documents should be issued to people before the beginning of reconstruction.

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[7] A national policy with *Panchayats* responsible for reducing risk and mitigating the effects of disasters is not on the immediate horizon. It is a major challenge to maintain a system of volunteers for disasters that occur occasionally, such as tsunamis. CASA is trying to meet this challenge by incorporating a *Panchayat* ward member as a member in each of the Disaster Mitigation Task Forces. Also, *Panchayats* are requested to issue identity cards to all Task Force volunteers. Third, CASA has engaged in additional fund raising from its Canadian project partners to finance continued project activities with the Task Forces now operational.

- Land acquisition should be near existing livelihood areas.
- Training be provided during the construction phase on maintenance of houses and infrastructure to increase a sense of ownership.
- Non-governmental organisations and Government should implement a common policy for all affected communities.
- Provide space for advocacy by non-governmental organisations for defined rules and policies related to reconstruction.
- Strengthen community organizations for advocacy.

A second aspect of this call for flexibility recognized the diverse nature of disasters in the region. In addition for preparing for cyclones and tsunamis the symposium recognized the need to for awareness within communities of indicators of change in coastal conditions affecting their livelihoods. For example a large nuclear plant was being built along the shore upwind and within ten kilometres of three of the twelve CASA project villages. These residents needed awareness of the risks associated with possible nuclear disasters. Both expansion of port facilities and mining in the sand for rare minerals was likely to affect the primary livelihood of the villagers, fishing. Disaster could take the form of fish stocks seriously decimated as well as fish contaminated from the effects of such industrial developments. In recognition of these impending risks, the symposium recommended the promotion of diversification of activities in income generation projects.

It was also an assessment of the symposium that there was a need to create awareness of climate change and its implications for coastal villages. CASA's commitment on this issue is evident in the one-day National Consultation on climate change incorporated into the November 2007 Diamond Jubilee of CASA as a relief and development organization. For CASA (2008b, p. 8): "Climate change is not an environmental issue any longer. It undermines the achievement of the Millennium Development Goals and generates new questions regarding security."

Within the project villages a visible sign related to climate change was rising sea levels. In one village the foundation of Catholic Church could be observed in the water some metres from the shore. There is mixed evidence on whether or not fish stocks are declining. In most of the villages the fishermen claimed their fish catches were down. Once the men had left the women informed us that the tsunami had changed the sea from being their friend, their source for food and income, to something to be feared. They claimed the men were hesitant to venture forth to fish whenever the sea was rough. Fish catches were down because the men were fishing on fewer days than before the tsunami. It was also their perception that the sea was rough more frequently than had been the case in the past. This would be consistent with climate change predictions, but more definite data are required to confirm whether this impression is correct.

As a result of these and other contemporary drought and flood disasters CASA (2008b. p. 11), sees a need to expand the scope of disaster awareness campaigns. "CASA needs to strengthen local communities in developing adoption strategies to deal with the adverse impacts of climate change ensuring community participation in the mitigation plans."

These conclusions and recommendations of the end-of-project symposium assessment of disaster preparedness carry credibility given what these non-governmental organisations have accomplished in their respective responses to the tsunami of 2004. They have constructed new houses designed to withstand natural hazards, constructed multi-purpose disaster shelters in selected villages, assembled basic rescue equipment and stores of staple food, organized Disaster Mitigation Task Forces at the village level and provided extensive training of Task Force members in disaster preparation and rescue techniques. A base has been created to move forward both at political levels and at local institutions for emergency planning and action.

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10

Post Tsunami Heavy Mineral Distribution Between Cuddalore to Kanyakumari Along the Tamil Nadu Coast, India – A Review

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1. Introduction

Placer deposits are formed as a result of the selective concentration of valuable minerals from the disintegration and redeposit ion of the rock fragments. Beach sands contain the most economically important minerals accumulations; wave action deposits sand on the beach and the heavy minerals are concentrated when backwash carries some of the lighter minerals such as quartz back into the sea.

Onshore winds which preferentially blow lighter grains inland can lead to higher concentrations of heavy minerals at the front of coastal dunes. Old 'fossil' shorelines known as strandlines can now be found some distance inland.

Minerals with following inherent characteristics can be accumulated as placers such as high specific gravity and, chemical strength to resist the denudating action of transporting agent. Placer deposits can be broadly classified on the basis of mode of origin and transportation into eluvial, deluvial, proluvial, alluvial (sub divided into bar, channel fill, valley delta and bench or terrace placers) lateral (subdivided into lacustrine, beach, marine beach, and offshore placers) glacial (subdivided into marine and fluvioglacial) and Aeolian placers (Smirnov, 1976). Rajamanickam (1993) has classified (l) marine placers including raised beaches (2) offshore placers including (i) ongoing and (ii) palaeo/fossil placers of both buried and exposed types. Many works are concentrated on beach placers (Angusamy and Rajamanikcam, 2000, Cherien, 2003, Mohan, 2001) however, only limited work has been carried out for tsunami placer mineral studies. Worldwide tsunami impacts of the last century have been documented by many researchers (Heck, 1947; Iida et al., 1967; Nakata et al, 1993; Lander and Whiteside, 1997; NGDC, 2001 and Shi et al 1995, Maramai et.al., 2005; McMurtry et. al., 2004; Scheffers and Kelletat, 2003; Tappin et.al., 2001; Nanayama et. al., 2000; Clague et.al., 2000; Dominey-Howes et. al., 2000; Papadopoulos and Chalkis 1984; Monge and Mendoza, 1993; Mörner, 1999). (Angusamy & Rajamanickam 2000) have studied

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the distribution of heavy minerals between Kanyakuami and Mandapam. World reserves of ilmenite are estimated at 460 MT. The total world production of ilmenite in 2001 was 6523 thousand tones. Of this Canada ranks first, consisting 29% followed by Australia (25%). south Africa (23%) while India accounted for 5% (www.tzmi.com). India is rich in placer mineral deposits, but three is an uncertainty about the extent of mineral resources due to the non availability of inventory of resources. India's coastline of 6800 km is hosted by placer deposits of various grades and size. Indian resources constitute about 35 % of world resources of ilmenite, 10 % of rutile, 14 % of zircon and 71.4 % of monazite (Rajamanickam, et al., 2005). Loveson et al., (2008) observed the inferences from sudden changes in the sedimentological processes during the December 26, 2004 tsunami along the east coast of India. In India the detailed investigations have been done around 28% of the beaches and still many parts of inlands and offshore regions along east and west coasts of India remain unexplored.

Hence, an attempt has been made on detailed exploratory studies from post tsunami sediments along the Tamil Nadu coast by an integrated approach. This paper is mainly focused on record of heavy minerals during the post tsunami events.

2. Heavy mineral

Heavy Minerals having a density greater than 2.9 g/cm3. The term is most commonly used to denote high-density components of siliciclastic sediments. Most heavy mineral studies are undertaken to determine sediment provenance, because heavy mineral suites provide important information on the mineralogical composition of source areas. Since heavy minerals rarely constitute more than 1% of sandstones, their study normally requires them to be concentrated.

Heavy minerals have important economic applications. Their use in paleogeographic reconstructions, especially in elucidating sediment transport pathways, is of particular value in hydrocarbon exploration, and their use in correlation has important applications in hydrocarbon reservoir evaluation and production. Recent advances have made it possible to utilize the technique on a real-time basis at the well site, where it is used to help steer high-angle wells within the most productive reservoir horizons. Heavy minerals may become concentrated naturally by hydrodynamic sorting, usually in shallow marine or fluvial depositional settings. Naturally occurring concentrates of economically valuable minerals are known as placers, and such deposits have considerable commercial significance. Cassiterite, gold, diamonds, chromite, monazite, and rutile are among the minerals that are widely exploited from placer deposits. See also Dating methods; Monazite; Placer mining; Well; Zircon.

Heavy minerals have important economic applications. Their use in paleogeographic reconstructions, especially in elucidating sediment transport pathways, is of particular value in hydrocarbon exploration, and their use in correlation has important applications in hydrocarbon reservoir evaluation and production. Recent advances have made it possible to utilize the technique on a real-time basis at the well site, where it is used to help steer high-angle wells within the most productive reservoir horizons. Heavy minerals may become concentrated naturally by hydrodynamic sorting, usually in shallow marine or fluvial depositional settings. Naturally occurring concentrates of economically valuable minerals are known as placers, and such deposits have considerable commercial significance. Cassiterite, gold, diamonds, chromite, monazite, and rutile are among the minerals that are widely exploited from placer deposits. Recently heavy mineral studies widely used in distinguish the tsunamisediment deposits from modern beach sediments.

3. Study area

The present study area extends from Cuddalore in the north to Kanyakuamri in the south of Tamil Nadu. The drainage pattern of the study area is control mainly by the perennial river like Gadilam, Pallar, Cavary, Tamiraparani. The beaches in the study region are composed of rocky/sandy material. Coralline rocks are exposed in the coastal segment of the Tuticorin – Alantalai region. At a few places, the calcareous sandstone shows a clear stratification with a seaward dip of less than10°.

4. Methodology

A systematic coastal survey done from 2005 to till-date by seasonal sample collection. In the coastal stretch from Cuddalore to Knanyakuamri, more than 150 sediment samples have been collected using a hand auger at an interval of 5 to 10 km between the sampling stations. Using a hand held Magellan GPS, geographical co-ordinates were fixed for the sample locations. Beach samples were washed and dried. After coning and quartering, carbonates, organic matter and ferruginous coatings were removed from the samples by treatment with 1:10 HCl, 30 % by volume H_2O_2 and $SnCl_2$, respectively. The dry samples were sieved at Ro-Tap sieve shaker for 15 minutes. Heavy mineral separation was carried out by using bromoform of 2.89 specific gravity following the procedure of Milner (1962). Separated heavies were washed and then mounted on the glass slide using the Canada balsam.

5. Results

5.1 Cuddalore and Pondicherry (M.Suresh Gandhi & A.Solai,2010)

The heavy minerals are dominant in Cuddalore (26.43%) and Kannikovil (28.48%) regions in the surface samples when compare to other regions. The percent of enrichment in other zones are Kottaikupppam(8.14 %), Veeranampattinam (12.18 %) and Pudukuppam (12.83 %). In Cuddalore the heavy mineral weight % shows that at the depth of 0-25 cm the percentage is gradually increasing and from the depth of 40 cm to 80 cm a sudden decreasing trend is noticed. **Zircon and Garnet** is found in the high percentages at Pondicherry - Cuddalore region. Kyanite is dominated in the Pondicherry (Kottaikuppam) region whereas in the other zone it is generally lesser. Chlorite is dominant in all the zones. The non opaque distribution in the sector the different grain sizes within the sector has established the prevalent presence of chlorite, kyanite, garnet, zircon and epidote.

5.2 Nagapattinam (D.Soosai, R. Chandrasekaran, A.R.Gujar, V.J.Loveson, N. Angusamy, N Chandrasekar and G.V.Rajamanickam)

In the present study, it is evident, that though all the stations are located in N-S trending coastal configuration, annual profile has hardly brought in any drastic variations in the beach profiles. It has resulted in substantial addition or erosion of the sediments. It has also brought out that beaches in the study area were under equilibrium conditions before tsunami. But however, after tsunami, a total change in the beach morphology is observed. Even though all the stations are located in N-S trending coastline, tsunami has brought in deposition of sediments in Nagoor and Chinnankudi. This has brought out the influence of shelf bathymetry in the redistribution of tsunami effects along the beaches. The present study highlights that destruction left by tsunami is enormous in the beaches of Poompuhar and Karaikkal and it calls for undertaking beach nourishment techniques to restore the beach to its original condition. After the tsunami, the modality is shifted to a slight coarser grade in all the beaches in such a way an enrichment of concentration is noticed in 50 mesh size grade also. In the Total heavy mineral by wt %, shows that post-tsunami samples Chinnankudi an upshoot of heavies to a tune of 93% in the Berm of Nagoor and HT of Chinnankudi. At Poompuhar, the distributions of heavy minerals are found to be different to other two stations. While Poompuhar establishes overall rise in the Wt % of heavy minerals during Post Tsunami like other stations, from Dec.2003 to Dec. 2004 unlike other stations, it is not giving any higher percentage in LT and Berm samples. Chinnankudi maintains always a higher percentage in LT, HT and Berm too, except post tsunami conditions when compared to Nagoor. When the distribution of heavy minerals in LT, HT and Berm is considered station wise during the years 2003, 2004 and 2005. Poompuhar is seemed to behave different to others. The heavy mineral enrichment increases from North (Poompuhar) to the South (Nagoor) in the study area. The same may be attributed to the inner shelf gradient.

5.3 Mandapam to Vedaranyam (G.V.Rajamanickam, 2005)

Placer mineral are formed as a result of disintegration of heavy minerals as suitable places. The heavy minerals serve as an index for stratigraphic correlation of unfossilferrous strata. The study area extends from Thondi to Manamelkudi in the Palk Strait, Southeast coast of India.

The highest percentage of heavy minerals shown at R.Pudhupattinam (38.64 %), is ascribed it accurate coast line and lowest percentage of heavy minerals recorded at Thondi 0.86%. The landforms help to infer the various stages of sea level regression and transgression takes place in the study region.

5.4 Tamiraparani Estuary and Off Tuticorin (A. Solai, M. Suresh Gandhi, K. Chandrasekaran and V. Ram Mohan, 2009)

90 sediment samples were collected during Feb 2005, at Tamirabarani river, estuary and offshore using Vanveen grab sampler. An alternate higher and lower percentage is noticed in the river samples may be due to the nature of the river course. Over all the higher percentage is noticed in the river and estuary samples (34.8 %) may be due to due to the fast moving action of wind and water. In few places in the estuary the heavy mineral distribution are lesser in amount (0.8% to 11.6%). Due to the movement of sediments from river and the erosional activities, the deposition of heavy mineral is not feasible the station near Estuary and rivermouth received higher percentage. The remaining stations show less than 7.0% distribution. Marine sediments show 1.4% to 18.0% of heavy mineral distribution the offshore region received higher percentage than the deeper parts in the marine sediments. Heavy minerals are concentrated as patchy and disseminated forms. The alternate higher and lower percentage of heavy mineral in the marine sediments may be due to the bathymetric conditions. Further due to the erosion activities band longshore current movements, the distribution of heavy mineral is lesser in few stations compared to the other origin. Due to the constant wind action, heavy minerals deposition with varying contents of heavy and light minerals in the form of alternate layers is noticed. Generally, heavy minerals are found to be abundant in erosive beaches, where the winnowing action takes place, leading to the accumulation of heavies. When high wave activity generally expected that the

accumulation of heavies would be greater. The heavy mineral assemblage of the study region is governed by the distribution of different type of minerals. However, the assemblage is restricted to the dominance of few selective minerals like garnet colourless, garnet pink, zircon, rutile, chlorite, etc.

5.5 Tuticorin and Ovari, Tamil Nadu, India (M. Suresh Gandhi , E.Vetrimurugan, N.Angusamy, and G.V. Rajamanickam, 2007)

The heavy mineral assemblage of the study area is given in Table.5a&b and Figure.7. The heavy mineral assemblage of the study region is governed by the distribution of different type of minerals.

However, the assemblage is restricted to the dominance of few selective minerals like colourless garnet, garnet pink, zircon, rutile, chlorite, etc. From the variation of colour, the garnet is differentiated into two varieties as colourless and pink.

These garnets are identified as pyrope/almandine while the variation in colour is ascribed to certain minor substitutions leading to the formation of pink colour. In Thiruchendur, a complete reduction in zircon is observed with a subsequent increase in chlorites.

In Periyathalai, a clear variation in the abundance of heavy minerals is noticed. In Alanthalai and Manappad beaches, zircon is reduced to a secondary position. An assemblage of colourless garnet, pink garnet and flaky minerals is found to be predominant in this zone. At Ovari, zircon establishes a clear dominance over other minerals. The predominant variety is marked by the abundance of rounded zircons. Only at Ovari, monazite makes an appearance. The dominance garnet helps to demarcate this group into two zones (i) north of Manappad and (ii) south of Manappad. These two zones are characterised by the abundance of garnet and depletion of garnet assemblage respectively. Zircon is found to be less in the north of Manappad coast whereas south of Manappad is dominated by zircons. The highest percentage of zircon is recorded at Ovari beach which is a typical zone of wave convergence. Like other zones, here too the difference in the distribution of various heavy minerals may be assigned to a change in the coastline configuration from NNE-SSW to NE-SW. In Kanyakumari zone, more or less similar assemblages are found in the entire coast. Zircon is represented by the predominant concentration of rounded form over other varieties. Monazite is characteristically distributed in all the beaches. A total reduction in flaky mineral distribution is noticed in all the beaches. Thiruchendur zone is represented by more or less equal distribution of garnet. Periyathalai zone is differentiated from other zones by equal percentage of garnet with topaz, andalusite and sillimanite. Kanyakumari zone is distinguished by slightly higher percentage of zircon, monazite and least amount of chlorite.

5.6 Tuticorin to Kanyakumari (Saravanan and Chandrasekar, 2005)

The low concentration of heavy minerals in the samples of Thiruchendur beach and Alanthalai beach is attributable to the oscillation in lowtide zone in the middle layer and hightide zone in the lower sample. In Periyathalai, an oscillation from berm to hightide zone of the present day level is noticed in Periyathalai beach. The variation in heavy mineral concentration in Ovari suggests the condition of lowtide zone.

Kuttankuli and Vijayapathi samples establish similar oscillatory conditions but to a minor level in hightide zone as evidenced from the grain size variation and limited variation in distribution of heavies. Kuttapuli samples establish a high percentage of heavy minerals.

The enrichment of lower layer with 48% of heavies and its reduction to 8% in middle layer and 2% in top layer is accounted by oscillations as well as by differing energy conditions in the segregation of heavy minerals. However, Kanyakumari beach samples suggest the withdrawal of sea level to lowtide zone from the existing hightide zone. This is indicated by the presence of very low percentage of heavy minerals in lower and middle layers.

6. Discussion

According to Loveson et al (2007) except for Nagoor, all other stations showed erosion of the beaches, with a maximum of 2.5 m, particularly in the Karaikkal area. The study identified two major geomorphologic parts, the first extending from northern Poompuhar to Karaikkal and the second from southern Karaikkal to Nagoor. Changes in the geomorphologic characters observed at these two areas were attributed to the nature of the inner shelf bathymetry. Examination of heavy mineral composition in sediments indicates a dramatic shift in concentration, ranging from 19 to 76 % in the Nagoor area. At Cuddalore to Pondicherry the tsunami affected region is found to have a concentration of coarser fraction in addition to the finer fraction of opaques. The same may be attributed to an added source of Cuddalore sandstone which is in the vicinity of this zone. It is the factor very uncommon to the other zones. Rajamanickam (1968) has projected the preponderance of opaques in the Miocene- Cuddalore sandstones, that too of coarser nature. Such coarser opaques may be added to this zone. Such view has also been supplemented by the distribution of coarser epidote, staurolite and abundance of blue kyanite, which are common in the Cuddalore sandstone. Wave conditions observed during most of the year at stations from Pondicherry to Cuddalore are marked by a strong convergence of wave orthogonals in the SW, NE, and nonmonsoon periods in both 8 s and 10 s wave periods.

Under this prevailing high energy environment, flaky minerals such as chlorite, biotite, muscovite, and glaucophane may be moved offshore and reduced in abundance. Denser minerals are abundantly found in these stations due to the continuous winnowing action of the shoaling waves. According to Rajamaickam et al (1983).When one finds the distribution of heavy minerals by weight percentage from low tide to high tide, the number of poly - modalities prevails uniformly. There is difference in abundance.

In other words, the source show distinct of heavy minerals is expected to remain one and the same. The low tide and high tide show distinct shift in the abundance in six stations studied.

With so much of high energy input, one can easily expect the addition or deletion of certain heavy mineral fraction in this region. When the tsunami is able to shift the deep water forams and outer shelf forams to the beach (Hussain et al., 2006a&b) it can also add some other heavy minerals present in the route of tsunami waves. It reflects that the heavy minerals deposits are going on for years for only from the shelf sediments. Alternatively the landward migration of the shelf sediments must have been responsible for the type of heavy mineral assemblage in the study area.

Further the frequency distribution between the pre and post tsunami behaves more or less similarly in such a way that the 2 to 2.5 phi grains shows maximum shift in the low tide. It may also be surmised that the tsunami energy must have been remained to carry optimum size of 2.5 phi sized heavy minerals in high order of suspension. from the heavy mineral size, one can interpret that the normal energy prevailing in the area may be around 2.5 phi size including the cyclonic stage because the high order of presence of 2.5 phi size grains in the pre tsunami is also seen.

7. Conclusion

The analysis of heavy mineral variation has been well established. The eroded areas are associated with fine grained beach sands rich in heavy mineral sands. The difference in the concentration of heavy minerals and the nature of sediments suggest that apart from the river source, some other additional source such as offshore and alongshore must have played a role in making up the compositions of these beach minerals. Further the pattern of enrichment of heavy minerals reflects the nature of longshore grain sorting with reference to the energy conditions prevail in the study area. With all the pre-tsunami beach profiles, it was observed that at least 15 days earlier, there was significant sediment deposition, irrespective of coastline character and behaviour.

After tsunami in many locations, the depositional beaches became erosional and vice versa. The data obtained during pre- and post-tsunami helped assess the selective impacts of the tsunami within a short distance along the shore. Within a coastal distance of 35 km alternate erosion and deposition of sediments were observed. The various changes observed in sediment landforms and mineralogy indicates the possibility of greater impact through the inner-shelf bathymetry. The concentration of heavy minerals indicates that the outer shelf is the source of origin.

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Part 4

Post-Tsunami Preparedness

11

The Management of Medical Services in the Early and Late Phase of Tsunami: A Preparation for Humanitarian Health Assistance

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1. Introduction

Tsunami is a series of ocean waves produced by a submarine earthquake, landslide, or volcanic eruption. These waves may reach enormous dimensions and may have sufficient energy to travel across the entire ocean and to destroy human lives near the beach up to a distance of some kilometers from the shoreline. Severe damage can be caused by large tsunamis to boats and other fishing equipments, to houses, to tourist resorts, to schools, to water and sanitation, and to infrastructures. In addition they can cause substantial damage to health services, which becomes an essential issue since these services are immediately needed for a quick medical response. If the medical response is late, then it leads to prolonging the provision of medical assistance especially to persons severely injured as well as to spreading of infectious diseases [1]. Indeed, suddenly after tsunami strikes the land, many people suffer traumatic injuries, that are caused by the impact of sharp or blunt objects. In this phase, sometimes there can be a further trouble when treating traumatic patients, because medical equipments might be broken as a consequence of the tsunami. Tsunami produce mud, causing contamination of water, which in turn results into sanitation and hygiene problems that may cause infectious diseases that may be complicated to treat. There are conditions that can be more difficult compared to other types of disasters. For example, the logistical problems of distributing goods could be very difficult due to bad weather, problematic access and limited transportation. Air, sea and land transportations need much more effort for distribution of medical services. Because of the tsunami damage, aircrafts could not land, ships or boats could only anchor at 500 m – 1 km far from the new coastline, made by tsunami, and trooper cars, trucks, and other land transportation vehicles could find it impossible to reach the disaster area. Usually, there is only one way to distribute the medical supplies in the early phase of tsunamis, i.e. by helicopter. Based on this situation, the medical assistance can be divided into two phases, that is the early and the late phase of a tsunami attack.

2. Time periods of medical assistance

Disastrous tsunamis have a bad impact on human beings causing severe health problems, that can be typically distinguished into critically ill patients due to traumas in the early phase and into infectious diseases in the late phase of the disaster. Indeed, the time period and the characteristics of the medical assistance after a tsunami attack can be divided into two phases, that is, an early phase and a late phase as shown in Fig. 1.

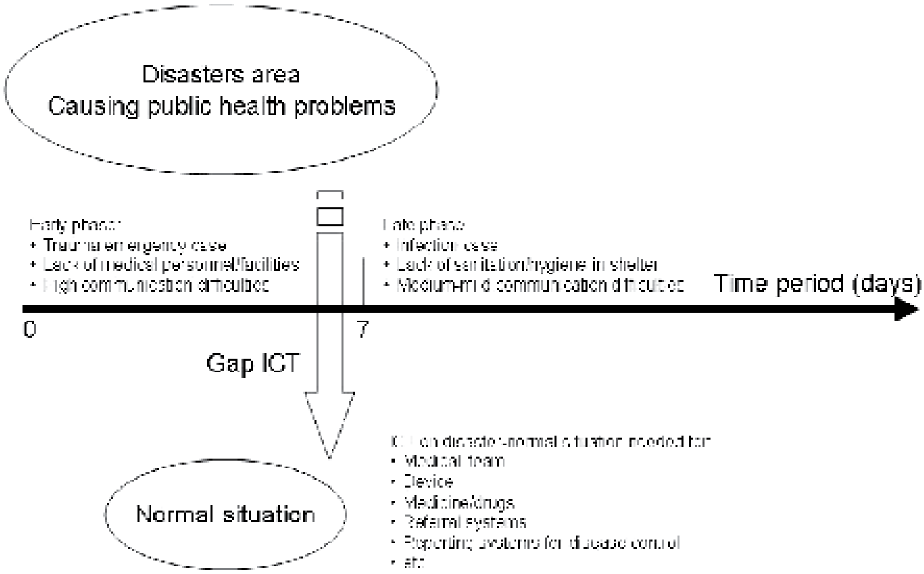


Fig. 1. Early and late phases after a tsunami attack

In the early phase, most patients are surgical cases due to traumas. This period is within 7 days after the tsunami. For the first 2-3 days, usually access to the disaster affected area is very difficult, especially in rural zones. The medical team should be formed by persons with different expertise. There should be not only medical personnel in the team, but it should consist for example of 1 medical doctor, 2 nurses, 1 telecommunication amateur radio staff, 2 members from the army (for security), some logistic support and 2 red-cross staff.

Basic surgical devices and medicines, VHF (very high frequency) and HF (high frequency) radio communication devices should be brought by the medical team for backing up communication according to request or to order further medical devices and medicines. The team should perform rapid health assessment as well as provide medical services for the basic emergency treatments. It should also try to explore the remaining medical services that can be used to treat the patients. And further it should prepare the portable devices for sanitation water.

After 7 days, the disease pattern usually changes, because of lack of clean water, sanitation and hygiene, and at the same time, the immune systems get weaker due to lack of food distribution. Therefore contagious diseases start to appear, such as upper respiratory tract infections, diarrhea, and water transmitted diseases like typhoid [2]. This period can be called the late phase of a tsunami. In this phase, the medical team should focus on the infectious diseases and on wounds remained after surgical treatments that mostly are done in the early phase of disaster. The order of medical devices, of medicines and referring patients to other hospitals can be requested through amateur radio links since official communications systems may have collapsed and satellite telephone still remains expensive in several countries, and especially in developing countries. Consider that even radio communications sometimes cannot be used properly, but it is certain that unavailability of communications can be a fatal drawback for patients and the medical team.

3. Medical care in the early phase

In fact, the first 7 days after tsunami are a critical period because many traumatic injured patients have to be evacuated as well as the critically ill ones. The existing hospitals next to the tsunami-affected area take the highest responsibility role of being referral hospitals before other health facilities can come and be set up. This situation becomes worse in case that electricity, drugs, medical devices, personnel might not be available properly [3]. Looking at past tsunami experiences, it is necessary to devise plans for health service centers that are found in areas having potential for a tsunami. For the local health officers, a referral hospital should have drugs and medical supplies stocks that can cover at least 20% of the total population, because this percentage may reflect the number of injured and critical victims after the strike of a tsunami. The hospital has to be established at least more than 5 km away from the sea coast or, if it is located closer to the coast, the minimum altitude above the sea should be more than 20 meter for contingency plans. Extra beds, clean water machines, helipads, electric generators, communication devices need also to be available.

In the day after the disaster, there should be at least one medical team already operational and ready to access the affected area, and in days 2-4 further medical teams could come possibly facing a lot of difficulties in transportation on land. If a hospital unfortunately is not available as back medical post, a field hospital needs to be installed with specific drugs and medical devices. Among them, one could mention aseptic materials, antiseptic drugs, broad-spectrum antibiotics, analgesics, local-general anesthesia, resuscitation drugs, portable oxygen cylinders with masks and nasal canules as well as endotracheal tubes for children and adults, resuscitation solutions like NaCl 0.9%, lactated ringer solutions, glucose 5% and 10%, neck collars and boards for evacuation. During the early phase, the most important issue is patients stabilization from life threatening, before providing definitive treatment. One crucial operation is a proper triage by labeling patients into red (critical), yellow (emergency, but not critical) and green (walking wound) categories, followed by black (dead), since making decision on priorities is very important for management of mass casualties.

Further, for the medical first responders working in disaster areas, personal kits should be prepared, including among others flashlights with extra batteries, portable batteries, emergency ready-to-eat food and water, cash and credit cards. The basic idea is that the team should be autonomous and should not depend on local society or resources, because the purpose of the team is to help the victims, not to annoy them.

4. Medical care in the late phase

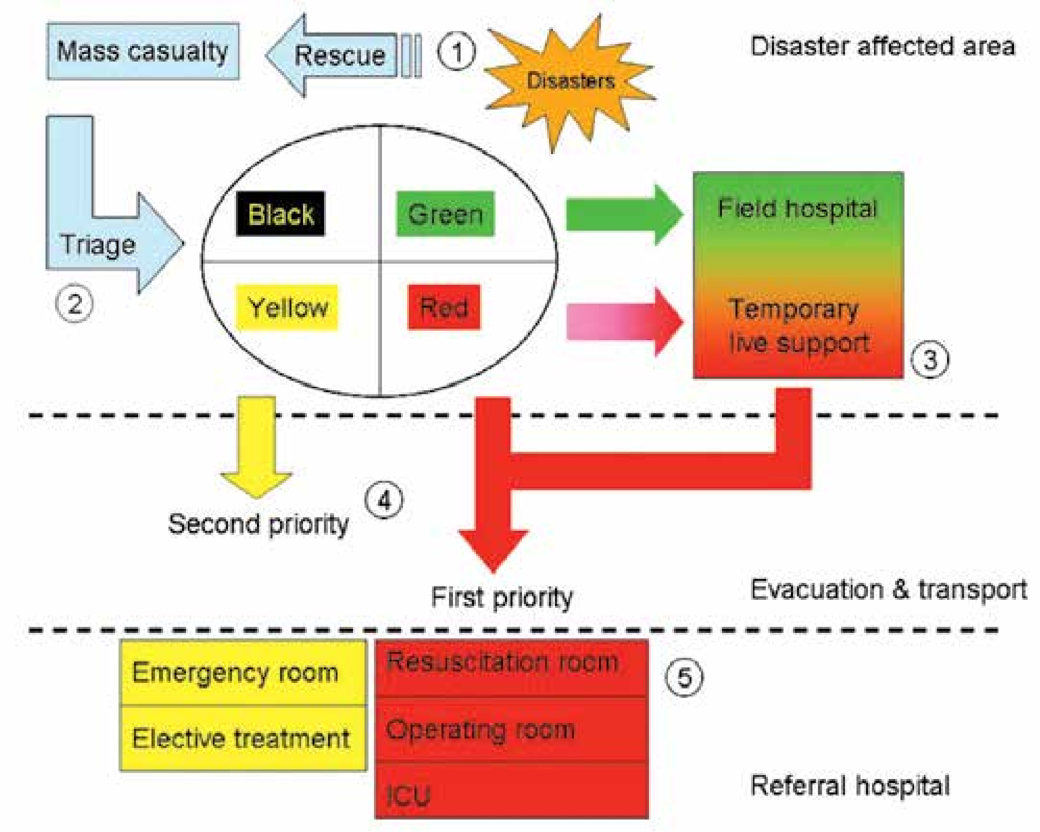
In the late phase which starts about 7 days after the occurrence of the tsunami, health problems and medical needs differ from those found in the first 7 days. In the late phase, the emergency surgeries usually decrease and become elective surgeries. It is the beginning of sub-acute and chronic medical problems which may be indicative also of lack of adequate healthcare infrastructures before tsunami [4]. Usually, at this stage, international medical teams come to bring medical care, medicines and supplies to all people affected by the massive disaster. There should be still a great concern in this phase, since shortage of clean water, lack of electricity, improper shelter, sanitation and hygiene problems may arise. The new medical teams should consider carefully what they have to bring with. At clinical examination, survivors could show upper respiratory tract infections as the beginning of infectious diseases. Gastrointestinal infection can occur due to lack of sanitation and hygiene, if clean water cannot be supplied immediately, and furthermore febrile illness and wound infection can manifest. This was the experience after the 2004 Indian Ocean tsunami of eight countries, namely, India, Indonesia, Malaysia, Maldives, Seychelles, Somalia, Sri Lanka, and Thailand [5]. In the late phase, the medical assistance teams should consist of not only medical doctors and paramedics, but should also include sanitarians, epidemiologists, water technicians, social workers, volunteers, and psychologists for post traumatic stress disorder (PTSD) treatment. This phase could last from months to several years. Therefore multidisciplinary teams must be formed in order to adapt to the chronic situation. Medical equipments such as quick laboratory test devices, portable x-rays, elective surgical instruments, antibiotics for aerobic and anaerobic bacteria, multivitamins, field hospital with extra beds and infuse hangers, bedside vital signs monitoring devices and portable ventilators with oxygen are needed.

5. Difficulties in medical assistance

In the first phase, when casualties start to arrive at a hospital from a disaster area, the initial step is the triage of patients, and the main concern at triage is trying to preserve the capacity of the hospital to treat those casualties with serious injuries or illness, but with a high probability of survival. The estimation of victims is difficult during the early phase, and therefore the cooperation among team members as well as the communication staff and logistic staff is important. The logistic staff has the task of searching for other hospitals where it is still possible to refer and distribute patients, and at the same time the communication staff should connect with other medical facilities.

The concepts of undertriage and overtriage are important to the overall understanding of the triage process. Undertriage is associated with triage sensitivity in identifying patients needing critical care interventions. This skill can be practiced on the daily activities in the emergency room for speeding up the triage ability. Undertriage occurs when the triage evaluation underestimates the severity of injuries and classifies the patient as noncritical. This has an obvious impact on the morbidity and mortality of the individual patient. Because no triage system is perfect, our acceptable undertriage rates have been defined as 5% or less. Overtriage occurs when a noncritical patient is triaged as a critical casualty. Rates of overtriage up to 50% have been historically defined as acceptable in our experience in an effort to reduce undertriage. Initial efforts in disaster triage have been directed at decreasing the level of undertriage with its logical and apparent adverse impact on the individual casualty. In the reality of triage, very high overtriage rates have been detected during mass casualty disaster settings like tsunami. Typical victims in tsunami become critical not only as the effect of traumatic injuries, but also in association with the drowning after they have been swept by water. Further, it is also to mention that it is more difficult to identify the level of triage because sometimes all of the body is covered by mud. A scheme of trial is shown in Fig. 2.

The main difficulties found in the late phase are related to the public health control. In the aftermath of tsunami, public health must often address issues such as damage to health, to sanitation, and water facilities, as well as to housing and agriculture. This may lead to a rapid increase of malnutrition and of communicable diseases, like measles, infectious diarrhea and pneumonia or even tetanus due to open wounds contamination. Fortunately, the provision of adequate clean water and sanitation, timely immunization, simple treatment of dehydration, supplementary feeding, micronutrient supplement and an adequate surveillance system greatly reduce the health risks associated with the harsh environment of refugee camps. Notice that after the early phase, usually the latrine construction begins for excreta disposal, but initial sanitation measures may be nothing more than simply designating an area for defecation in each camp. This preparation also has to be considered for the medical team during humanitarian assistance.



Source: Sutiono et al. [1]

Fig. 2. Communication network in emergency disaster

6. Discussion

A tsunami is a series of traveling ocean waves of extremely long length generated by disturbances associated primarily with earthquakes occurring below or near the ocean floor. Tsunamis are a threat to life and property for anyone living near the ocean [6]. In addition to the impact on infrastructures, there is a direct impact on human beings, who may be killed or severely injured. The first phase of the medical assistance is defined here as the one needed in the first 7 days after tsunami. The medical team should be equipped with food, water, tents, generators and sleeping equipments. It should be a multidisciplinary team including also security members that can join from army forces/police to guard the team itself, as was experienced in Aceh, Indonesia, in case of the 2004 tsunami where protection was needed due to a long civilian conflict going on in the affected area. The most significant deficit in this phase is the lack of surgical equipments that usually are not sufficient to treat the so many injured victims [7]. Team should be supplied with stocks at least for one week of medicine and medical equipments. Such teams should be organized into three working shifts, namely morning to evening, evening to night and night to morning. Each team member can work for a maximum period of two weeks. The rapid health assessment is one of the tasks of the first team. Later, it should be replaced by the next medical team ready for this major humanitarian assistance, that works in the late phase of tsunami.

The main surgical problems are the vital signs monitoring and wound stabilization before continuing to the elective surgical treatment. This condition will be worse for elderly victims due to previous pre-existing chronic or underlying diseases.

Another important item is the network communication system. In developed countries like Japan these networks are well established, while in developing countries they are not, so that radio amateur communications or other data transmission systems are to be used (see for example the utilization of low-altitude platforms for emergency communication [1, 8]). Without communication systems, the medical assistance in this period faces great obstacles, because some of the victims have to be evacuated to other hospitals, and one has to order medical devices or medicines for surgical treatments from other places.

For a big city in which other hospitals may still be operative, the referral distribution of victims should be done in order that no hospitals be overloaded by patients. However, in a rural area where only one hospital is located the situation may be different. This was the case for the small hospital in Phi Phi island, Thailand. They considered that effective communication facilities must be ensured, by making a simple evacuation plan in advance. These plans should be made to ensure automatic reinforcement of remote areas with evacuation vehicles, medical equipments and personnel, efficient cooperation with medical volunteers, and every member of the hospital has to participate in an educational program periodically [9].

The late phase starting 7 days after the tsunami disaster has clinically and epidemiologically the same profile as that of a cyclone or a hurricane with resulting flooding. The causes of death are drowning and traumas from blunt or sharp objects, and injuries among survivors arise from complications of near drowning and traumas [10]. The short-term public-health needs of the surviving population are familiar: water, sanitation, food, shelter, and appropriate medical care administered to persons remaining in place and to the thousands who live in self-settled displaced communities. At this phase, the medical team consists of sanitarians, epidemiologists, social workers, technicians. Indeed the major public health priorities of ensuring the availability of clean water, adequate sanitation, emergency food rations and temporary housing are not technically complex, but accomplishing these goals in such a large geographic area as the one affected by a big tsunami presents tremendous challenges in terms of coordination and logistic capacities for transporting and delivering the necessary goods. Usually in this stage, international or national humanitarian assistance is also present to help the affected people.

Categories	Early phase (first 7 days)	Late phase >7 days
Team members	1 surgeon, 1 anesthesiologist, 1 general doctor, 3 nurses (from emergency and intensive care), 2 logistic staff, 1 communication staff, 1 security staff (army forces/police)	2 surgeons, 2 anesthesiologists, 2 general doctors, 4 nurses (emergency and intensive care), 3 logistic staff, 1 communication staff, 1 security staff (army forces/police), 2 epidemiologist, 3 social workers.
Medicines and equipments	Analgesics, antipyretics, aseptic antiseptics, anesthesia, broad-spectrum antibiotics, oxygen portable, 2 sets of minor and major surgical instruments including other supporting sets (neck collar, sterile gaze bandage, etc), sanitation water devices	Analgesics, antipyretics, aseptic antiseptics, anesthesia, antibiotics for aerobic and anaerobic bacteria, antitussives for coughing due to upper respiratory tract infections, anti- diarrhea due to lack of sanitation hygiene, surgical instruments
Transportation to access the disaster area	Mainly helicopter (or vehicles if possible)	Helicopter, vehicles, aircraft if possible (Hercules)
Working periods	Maximum 2 weeks	Maximum 1 month
Communications	If telecommunication infrastructure collapsed, use VHF radio communication for short distances (less than 2 km) and HF over long distances (more than 2 km). Satellite mobile phone if available, but very expensive.	Use telephone if already available. If not, radio communication is still necessary. Alternatively low-altitude communication platforms can be set up for broad connection access to internet network and mobile phone.
Personal equipments	Flashlight with spare batteries, ready foods and small snack like bread, water drinking, personal hygiene (toothbrush, soap, etc), sleeping bag, multiple penknife and scissor, matches, anti-mosquito cream e.g. endemic malaria, boot shoes, rain coat, etc	The same like in early phase, but the amount is more than in early phase due to long period of humanitarian assistance.

Categories	Early phase (first 7 days)	Late phase >7 days
Activities	Security assessment, triage mass casualties, resuscitation and stabilization for injured victims as well as surgical resuscitation, wound debridement and treatment, rapid health assessment for medical needs, preparing communication network to the remaining hospitals and field medical post, preparing other disaster possibility (e.g. nuclear, chemical contamination)	Security assessment, continuing medical treatment and scheduling elective surgery, sanitation and hygiene action promotion to the people, ordering the lack of medical tools and medicine using telecommunication network, managing referral patient, helping people from post traumatic stress disorder (PTSD), preparing other disaster possibility(e.g. nuclear, chemical contamination)

Table 1. The difference of medical activities between early and late phases after tsunami

The medical activities are mainly for elective surgical treatments and sanitation hygiene actions. The team may work for the maximum period of one month and can be replaced by the next team for the next one month. In Table 1, the main differences of medical activities between the early and late phases after tsunami are summarised. Although the late phase is not as busy as the early phase, however, the medical activities should be prepared properly. Preventing the complication after the initial and the stabilization medical treatments is also difficult. The long period of rehabilitation will make the patients to fall into the post traumatic stress disorder (PTSD) as well as into infectious diseases, and it may occur not only to the victims but also to the relief forces and medical workers. By this reasons, limiting the work of the medical team involved in humanitarian assistance operations in the tsunami affected area is very important [11].

Helping children after tsunami is also another challenge for the medical team. As tsunami is a rapid-onset type of disaster, children are at substantially increased risk for death. Typically, this is due to the dependent non-autonomous nature of a child and the relative lack of physical abilities to escape danger. Additionally, when children suffer severe traumas or near drowning submersion episodes (as they did in the recent 2004 Asian tsunami), the relative lack of pediatric expertise in critical care and tertiary pediatric facilities add to the mortality rate. The large number of refugees created by tsunami along with the frequent separation of children from families substantially increases the rate of child trafficking, baby snatching, and child conscription following the tsunami. This is unfortunately a common phenomenon to face for the medical teams in humanitarian assistance. An aggressive effort is needed to identify and register unaccompanied children displaced by the tsunami and a great deal of energy has to be consumed in the first 7 days (early phase) following the event. Respiratory illness and enteric disorders resulting in fluid loss are the most common causes of pediatric mortality in the immediate follow-up of the tsunami. Deployment of health care resources and rapid reconstitution of at least a basic public health infrastructure in the hit area will do much to alleviate the impact of such illnesses.

7. Conclusion

In tsunami aftermath, one can distinguish between two kinds of medical assistance activities. The first one is the early phase, which means that surgical cases are dominant as well as the preparation of security team, telecommunication staff, sanitation portable devices that are very important and should be dispatched by helicopter as soon as possible for early rapid health assessment. Instead, in the late phase of tsunami, the pattern of disease usually changes into infectious diseases due to lack of sanitation, hygiene and clean water, that among others may impact on infected wounds. Therefore, medical devices and teams must be prepared in a different way according to the time period where they are expected to operate in the post-tsunami.

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12

Prevention of Psychopathological Consequences in Survivors of Tsunamis

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1. Introduction

During the last decade three massive tsunamis have affected the world. On December 26, 2004, a Mw 9 earthquake, with epicenter at 250 kilometers northwest of Sumatra, caused a devastating tsunami [T-2004] that swept through a large part of the Indian Ocean, the Bay of Bengal and the Andaman Sea (Yamada et al., 2006), causing an estimated death toll of 280,000 and millions of victims along 13 countries, including Indonesia, Thailand, Sri Lanka and India was among the most affected (Rajkumar et al., 2008). Six years later, during the morning of February 27, 2010, the south central region of Chile was devastated by an Mw 8.8 earthquake with epicenter in the city of Cobquecura. After the quake, several tsunamis devastated the seaboard [T-2010], causing the disappearance of some localities as well as a considerable number of victims and changing the morphology of the coast. In the end, the death toll was 521 and 56 people were missing due to the natural disaster. Of these, 156 dead and 25 missing were caused exclusively by the tsunami (Fiscalía Nacional del Ministerio Público, 2011). The last tsunami occurred on Friday, March 11, 2011 in Japan, when a Mw 9 earthquake at 14:46 local time (05,46 GMT), caused a tsunami that stroke vast areas of the Pacific coast, whose waves reached even far-off locations as the Chilean coast, affecting the same areas that had already begun to be reconstructed after the T-2010. It is stated that one of the biggest waves (38,9 meter high), arrived in the coast of Miyako, Japan at 15:55 hrs. (ANSA, 2011, April 15). The real magnitude of this disaster remains unknown, but the number of victims is estimated in the thousands because many people failed to reach safety and were drowned by the wave.

In the case of T-2010, the loss of life would probably have been lower if there were not coordination and prediction failures of the authorities, who were unable to give the alarm for the population’s safety. On the contrary, they asked the population to stay calm saying that there was no tsunami risk before the waves reached the coast (Marin, 2010). In the T-2004 it was impossible to alert the population to the tsunami. These failures show a lack of training in communities to cope with these events and prevent the loss of lives.

In Chile, these human errors caused the population's distrust of official information, creating a state of constant alarm at every aftershock that occurred in the following days and months, many of them with a magnitude of more than 6 MW. These aftershocks caused a mass exodus to higher ground even though they did not cause another tsunami. Fear in Chile remains. The press published, almost a year after the earthquake, studies of geologists like Lorito et al. (2011), who state that another big earthquake can occur. Regarding the possibility of another earthquake in Chile, Lorito et al. conclude: "increased stress on the unbroken patch may in turn have increased the probability of another major to great earthquake there in the near future".

Despite the prediction (Lorito et al. 2011), the vast majority of scientists agree that earthquakes are difficult to predict. On the other hand, tsunamis can supposedly be anticipated since they are generated as a result of earthquakes of great magnitude (Gaborit, 2001). However, their predictability depends on the mechanisms designed to alert the population, the same ones that failed in the T-2004 and in the T-2010. On the other hand, the destructive wave can move to areas that have not been shaken by earthquakes, making it difficult to implement actions to prevent harm to people, as happened in Thailand or Sri Lanka in 2004 or Juan Fernandez Islands, 650 miles off the coast of Chile, in 2010. In Juan Fernández, the wave arrived an hour after the quake and destroyed the only village, without the possibility of alerting the population.

The traumatic character of an event of this nature is undeniable. Not only in the natural disaster itself, but also from the consequences of destruction, death, displacement, social chaos and deficits in the satisfaction of basic needs. On the other hand, aftershocks cause constant re-experiencing and difficult adjustment to a more normalized lifestyle. Therefore it is important to first consider the emotional consequences that these events cause to people, than to differentiate risk and protective factors for mental health problems and to finally promote the use of early intervention models that could reduce the prevalence of different psychopathologies associated with these disasters. Regarding the psychopathological consequences, responses of the survivors tend to be more varied than people might think.

2. Psychological responses

Gaborit (2006) states that, in view of an earthquake, the individual routines are abruptly altered for an indefinite period of time. Many plans, projects and lifestyles must change as a result of the earthquake. The need to adapt is strong and apparently not everyone is prepared.

Sasson (2004) advised that during disasters basic beliefs about own invulnerability, life´s meaning and events control are lost. These beliefs are strongly affected after a disaster and not only psychological consequences are caused to the population but also change the view of themselves, the world and others, towards a more negative view. Janoff-Bulman (1992, as cited in Paez et al., 1995) suggests that disaster victims reduced their belief that the world makes sense and lose the illusion of control. However, he concluded that as time passes people end up readjusting. In the T-2010, it can be stated that there were two types of disaster: one with a natural origin including an earthquake and a tsunami, and a human catastrophe, caused by looting and social chaos, both with a highly destructive and traumatic capability. If we add to that, that everyday life stressors increase, such as uncertainty, frustration, indolence or political advantage (Cova & Rincon, 2010), all of them consequences of the earthquake, we can hypothesize a high impact on the belief structure of the population.

In identifying the phases in the reaction of people after a natural disaster, Paez et al. (1995) indicate the following: a) a first phase characterized by a sense of victimization and abandonment experienced by those affected, b) a second phase increases, characterized by adaptive behaviors such as distance from the events, seeking an explanation to understand what happened, by emotional expression and early action to protect themselves from danger, even though there are also collective panic, escape and complaint; c) a third phase in which rumors increase, self-esteem is retrieved, helping each other and losing control of the situation restoring, d) finally, the fourth, or post-critical phase; depending on the subjects in particular and the social support available to them, as well as on their beliefs about the world and ways of coping, it may show two opposing tendencies: some thinking and ruminating about the events, while others develop avoidance behavior, refusing to recall and talk about what happened.

From another perspective, Marcos et al. (2002) classified the possible reactions to a disaster in three types: a) adapted reactions, characterized by the ability to remain calm. Here, care on protection is taken, and sometimes a solidarity behavior and assistance towards others is observed, b) inappropriate reactions, corresponding to panic behavior, emotional overflow, inhibition, stupor, denial and opposition; c) influenced by reactions. In these cases people who show themselves insecure and indecisive and, acting according to circumstances, can be mobilized to help or to a more negative sense as inhibition, panic and escape. The type of reaction would be mediated by perceived personal risk assessment of the survivors (Perry et al., 1980, as cited in Costa & De Gracia, 2002). In this regard, there are two evaluation forms: primary focuses on threat assessment, and secondary on individual capacities for risk perception and cognitive ability to manage those risks and acting accordingly. Thus, if the situation is perceived as dangerous or hazardous and people feel that their coping skills are limited, it is common to overreact with inappropriate responses that can increase the risk of emotional stress.

According to Flynn and Norwood (2004), normal psychological responses after a disaster include fear, anger and anguish. Considering that all those who experience a natural disaster are affected by it, psychological reactions are expected. However, the nature, duration and magnitude of responses may vary (Galambos, 2005). Figueroa et al. (2010) state that although it is well known that most of those affected by a disaster will not develop psychopathology, a significant group will. Among the most common psychological consequences of a natural disaster are the subclinical distresses, acute stress disorder, post - traumatic stress disorder (PTSD), major depression, increased alcohol and drug consumption such as heroin (Yamada et al., 2006), other anxiety disorders and somatic symptoms (Batniji et al., 2006). In relation to tsunamis, among the most common symptoms reported by the European population exposed to the effects of T-2004, we found dissociation, flashbacks, sleep disturbance, hyperarousal, ideation and attempts at suicide, loss of appetite and mourning reactions (Bronisch, 2006).

A separate comment should be made concerning PTSD, because it is the most expected psychopathological response by both the general population and specialists after a traumatic experience (Echeburúa, 2010). McNally et al. (2003) notice that many of the reactions are normal and expected, and do not necessarily mean disorder. On the other hand, it is noteworthy that while many people in their lives have been exposed to traumatic situations, it is rather a small number who develop PTSD; in other words, traumatic events do not cause PTSD, at least not in a linear cause-effect relationship. For example, McNally et al. cite the National Comorbidity Survey in the U.S. revealed that 60.7% of randomly selected adults reported exposure to traumatic events, but from these people only 20.4% of women and 8.2% of men had developed PTSD. Moreover, Shinfuko (2002) suggests that while the PTSD should be considered as part of the variety of mental health problems among survivors of an earthquake, people tend to use this diagnosis to refer to all mental problems, just as in the earthquake that occurred in Kobe, Japan, in 1995, where the concept was widely used and accepted by the Japanese press and was used incorrectly as a synonym for the whole range of psychological problems.

Perhaps this confusion, coupled with problems relating to the instruments and access to the affected population, may explain the great variability of results in studies on the prevalence of PTSD in survivors of a natural disaster. For example, following the 1999 earthquakes in Taiwan and Greece, a prevalence of only 4.4% (Wu et al., 2006) and 4.5% (Roussos et al., 2005) was found respectively in the surveyed groups. Ketumarn et al. (2009) measured the prevalence of PTSD in Thai students after the T-2004, obtaining 15.1%, 23 months after the event. On the other hand, after the earthquake in California in 1994 (McMillen et al., 2000) and the T-2004 (Dewaraja & Kawamura, 2006), found 48% prevalence of posttraumatic symptoms and 42% of PTSD respectively. Lommen et al. (2009) notice the prevalence of 52.2% of PTSD 15 months after the T-2004 in adult population of Sri-Lanka. John et al. (2007) revealed a prevalence of 70.7% for acute PTSD in Tamil children from southern India affected by the T-2004. As we can observe, the results of different studies show staggering differences. Even more noticeable were the differences in Wenchuan earthquake survivors who obtained a 21.5% prevalence measured by a scale and 40% with DSM-IV (Xu & Song, 2010). This difference, obtained by different instruments in the same population, forces you to evaluate with skepticism any study on the prevalence of PTSD.

In Chile, recent epidemiological studies comparing the prevalence of PTSD and other psychiatric disorders in children and adolescents before and after the T-2010, indicate no significant differences between the two measurements (Diaz, 2011). Tharyan et al. (2005) also summarized studies indicating that PTSD has not been a significant mental health problem in Asian tsunami survivors in Tamil population in India. This shows that the fear of an increased prevalence of psychiatric disorders after T-2010 is unfounded and apparently the population has natural recovery mechanisms which should also be investigated.

3. Risk factors

Considering then that not all people exposed to a natural disaster develop psychopathological consequences, it is necessary to direct efforts to identify at an early stage the most vulnerable people in order to intervene early, as proposed by many authors, who have been concerned about the topic (Dewaraja & Kawamura, 2006; Karakaya et al., 2004; Ranawaka & Dewaraja, 2006).

Some vulnerability factors that have been found in survivors of earthquakes and tsunamis are:

a. female sex (Baddam et al., 2007, Batniji et al., 2006, John et al., 2007, Tang, 2006, Tural et al., 2001, Xu & Song, 2010).

b. objective experience of the event, suffering from the loss of life or property as a home, as well as from physical injury, being a witness of the death of someone close, being without food or water, prolonged displacement (Baddam et al., 2007, Dewaraja & Kawamura, 2006, Irmansyah et al., 2010, John et al., 2007, Tang, 2006, Tural et al., 2001, Wickrama & Kaspar, 2007).

c. subjective experience of event: fear of dying or being hurt, lack of perceived control, negative evaluation of the stress response (eg, see as a sign of personal weakness), negative interpretation of the memories of trauma (Batniji et al., 2006, Figueroa et al., 2010, Lommen et al., 2009, Roussos et al., 2005, Tural et al., 2001, Wahlstrom et al., 2008, Xu & Song, 2010)

d. previous psychiatric history of anxiety disorders, mood disorders, introvert personality features or low IQ (Batniji et al., 2006, McNally et al., 2003, Tang, 2006, Wahlstrom et al., 2008).
e. have suffered physical or sexual abuse during childhood (McNally et al., 2003).
f. family instability during childhood (McNally et al., 2003).
g. low social support after the disaster (Batniji et al., 2006, Figueroa et al., 2010, Tang, 2006, Xu & Song, 2010)
h. the type of peri-traumatic emotional response and the level of peri-traumatic dissociation (Figueroa et al., 2010, Lommen et al., 2009).

There is controversy concerning the last factor mentioned. McNally et al. (2003) discussed several studies which suggest that the presence of posttraumatic symptoms or dissociation one or two days after the event is not a good predictor of future PTSD, but it certainly is if they continue a week or two later. Some authors find that even dissociation and peritraumatic depersonalization are more adaptive mechanisms. Apparently, this "PTSD-dissociation" link may be mediated by how individuals appraise their dissociative reactions, making it more severe when the interpretation of them is catastrophic. For example, an individual who interprets emotional numbing as a normal response to a traumatic event may have less difficulty than another individual who interprets the emotional anesthesia as a sign of insanity.

It is also necessary to emphasize that in order to be considered as an at-risk population, you do not have to directly experience the trauma. Ketumarn et al. (2009), in a study with Thai students after the T-2004, concluded that indirect exposure through parents, neighbors, community and media, may also be related to PTSD, which is consistent with other studies that emphasize influence of observation and oral transmission.

4. Protective factors

We have already seen several risk factors that scientific literature states. However, we have also reported that not everyone exposed to a traumatic event develops psychopathology in the future. Apparently, a number of protective factors must be recognized and strengthened, either in survivors or in relief teams.

For example, Bronisch et al. (2006) analyzed the protective factors in rescue workers who provided support to European survivors of the T-2004. Among the protective factors they found: group cohesion, telephone contact with their families, dissociation or disconnection of negative emotions during the relief efforts and the perspective of seeing their own work as valuable.

Regarding the survivors, chilean researchers who studied the prevalence of PTSD before and after the T-2010 in the infant and adolescent population of the Bio Bio region, found no significant differences between the two moments, which indicated that the population apparently has resilient characteristics that explain the absence of changes. We also hypothesized that this result could be due to the effects of initial interventions which were performed after the catastrophe (Díaz, 2011, January 23). This absence of significant psychopathology was also mentioned by Rajkumar et al. (2008) after the T-2004 in India, who even detected positive effects on the population studied, which apparently depended on the coping strategies used, whether individual, collective or spiritual. Specifically, among the positive coping strategies used there were: personal trauma collectivizing, meaning re-building after the disaster by using a fatalistic perspective, a problem-focused coping style, extended social supports using, public grief and mourning displaying, and strongly rooted spiritual beliefs and practices. Of all the strategies outlined by Rajkumar, there are two that are insistently repeated in studies concerning this topic: the social support network availability and meanings making.

Social support can be conceived as the feeling of being appreciated and valued by others and belonging to a network (Barra, 2004), and seems to positively influence a better quality of life, low psychological morbidity and extended survival. Its importance has been demonstrated by several studies that indicate, for example, that the lack of social support is a risk factor for the onset of PTSD (Brewin et al., 2000) or that it is a good predictor for the occurrence of this disorder in survivors of an earthquake (Altindag et al., 2005). McNally et al. (2003) emphasize that the vast majority of trauma survivors are able to recover without professional help, as they have good networks and prefer to rely on their close acquaintances. They highlight that a support environment after a traumatic event may reduce acute symptoms and the risk of developing PTSD. This implies that the sensitive and respectful attitude on behalf of emergency equipment, health services and police personnel can help the survivors to prevent the development of PTSD.

Armenian et al. (2000) found that, along with a higher educational level and the ability to make friends after the tragedy, the immediate support was an important protective factor to prevent PTSD in survivors of the earthquake in Armenia in 1988, measured two years after the disaster. They conclude that early support to survivors with high levels of losses may prevent PTSD. Tang (2006), by assessing Thai T-2004 survivors, found that the difference between those who achieved a positive adjustment and negative one was that the first ones had a job before the disaster, and often sought support from others. On the other hand, positive relations between mother and child have a compensatory effect for depressive symptoms and posttraumatic stress disorder in adolescents in Sri Lanka affected by the T-2004 (Wickrama & Kaspar, 2007). All these studies help to emphasize the need to strengthen support networks of survivors, in order to prevent psychopathology.

On the other hand, the making of sense has been highlighted by Black and Tufnell (2006), who state that in children, the best results in post-disaster settings are associated, among other factors, with the ability to make sense of the experience, plus the availability of consolation and understanding. The emphasis on making sense in preventing or lightening trauma consequences has been raised by the narrative therapy, which will be discussed further on.

5. Psychological interventions

One of the main aims of psychological interventions for survivors of a catastrophe is not only reducing the associated symptoms, but also improving the quality of life, usually disturbed as a result of a natural disaster.

Several studies suggest that certain methods of cognitive-behavioral therapy can reduce the incidence of PTSD among people exposed to traumatic events (Echeburúa, 2010, Pineda & López, 2010). These methods are more effective than supportive counseling or no intervention. Among the therapies used, which have proven effective are: brief psychotherapy focused on trauma / grief, used in young survivors of the earthquake in Armenia in 1988 (Goenjian et al., 1997); exposure techniques in seismic simulator, used by

Basoglu et al. (2003) in survivors of the same earthquake; cognitive therapy focused on the interpretation of the memories of trauma (Lommen et al., 2009); the eye movement desensitization and reprocessing or EMDR (Fernandez, 2008) in survivors T-2004 in Sri Lanka and Thailand; and cognitive-behavioral group therapy in children between 8 and 12 survivors of the earthquake in Athens in 1999 (Giannopoulou et al., 2006).

Also, it has been used Narrative Exposure Therapy for survivors of political violence in Romania, several years after the traumatic experience, achieving promising results in reducing symptoms of PTSD and depression compared with psychoeducation (Bichescu et al., 2007). The same technique has been applied to children survivors of the T-2004, with better results than no treatment and equivalent to an intervention based on meditation and relaxation techniques (Catani et al., 2009). This therapy involves the exposure to emotional memories of traumatic events and the reorganization of these memories into a chronological coherent narrative (Robjant & Fazel, 2010).

McNally et al. (2003) and Ruzek et al. (2007) warn that while clinical interventions (especially those found in cognitive-behavioral spectrum) have proven effective, this has not been empirically examined in the immediate aftermath (0-14 days) in trauma. Therefore, it does not correspond to models of early intervention and prevention. On the other hand, Ruzek et al. indicate that the post-traumatic event can reduce the energy and time required to participate in a process of psychotherapy, so they recommend that a process of cognitive-behavioral psychotherapy may not run until the secondary stressors in the environment are under sufficient control to enable the person to focus on intervention, usually not less than three weeks after the incident.

6. Models of early intervention

Most studies on the psychological effects of natural disasters, conclude that early intervention is necessary to prevent the occurrence of various psychological problems as time passes. However, this need is facing a number of obstacles.

For example, McNally et al. (2003) referred to studies indicating that, if given the choice, only 10% of trauma survivors accept to discuss their experiences with mental health professionals. Faced with this, it might be believed that this initial reluctance is a dysfunctional form of avoidance which can hinder recovery. However, this apparently allows them to better adapt to the survivors making it possible for them at the same time to start rebuilding their lives and focus on the practical problems they face. This will help to leave the event in the past. Furthermore, memories tend to fade over time, and it remains unproven whether early exposure to traumatic memories promotes or retards this process.

Similarly, Shinfuko (2000) says, referring to the earthquake in Kobe, Japan, 1995, that the most appreciated by the victims was the support for their daily life rather than mental health professionals. The victims shared their experiences along with the volunteers who helped them. The work of mental health professionals was to prepare simple guidelines for volunteers on how to listen, encourage and maintain confidentiality.

Complementing this, McNally et al. (2003) warn that after the attack on the Twin Towers in New York, very few survivors sought counseling after the attack. According to McNally et al., apparently people were more concerned with seeking help in more practical matters such as finding work, doing paperwork on insurance companies, among other activities, but it is also likely that people have spontaneous recovery mechanisms or count on support networks of family, friends and church groups that make professional psychological help unnecessary. At the lack of interest in obtaining free counseling, New York authorities were prepared to receive a lot of people who present delayed-onset PTSD, but this did not happen. The authors conclude that not all people exposed to trauma need or want psychological services.

A second obstacle lies on the fact that, contrary to popular belief, pushing people to talk about their feelings and thoughts immediately after trauma may not be beneficial (McNally et al., 2003). Perhaps the systematic exposure to traumatic memories should be reserved for those who cannot recover by themselves. Brewin (2001) as well concluded that any intervention that takes place two or three days after minor trauma, or within a month after a severe trauma, is likely to coincide with natural recovery processes. An obvious concern is that intervention should interfere as little as possible with these processes, at least until the presence of an obstacle to recovery becomes evident. Therefore, clinicians working with trauma survivors soon after the event face a dilemma. On the one hand, any interventions they attempt should not interfere with natural recovery. In contrast, it is their duty to provide immediate care to the most exposed survivors, to shorten their suffering and prevent the development of secondary problems such as job loss, relationship problems or substance abuse. Faced with the possibility that early psychological intervention may be iatrogenic, Figueira (2005) warns that care must be taken to use only those interventions that have proven results, to avoid the risk of creating damage. He proposes, first, to avoid pathologizing the survivors, especially, given the clear evidence that very few people will eventually develop PTSD. Second, he proposes avoiding the use and abuse of benzodiazepines as an exclusive strategy for symptoms of stress, since studies show harmful effects. Finally, he suggests avoiding the use of debriefing, a technique which will be discussed below, due to the disparate findings regarding its effectiveness.

This brings us to the third problem: the almost impossible rigorous studies with control groups and random assignment to the same, in order to report the effectiveness of early intervention models. Ruzek et al. (2007) note that there are many barriers to conducting research on intervention strategies in the immediate aftermath of disasters and it is likely that more rigorous methodologies to evaluate mental health interventions (ie, randomized clinical trials) will never be possible. Immediate investigation after a disaster is so difficult that some authors warn about the ethical issues involved, proposing a series of guidelines to be followed in order to do so (Sumathipala & Siribaddana, 2005).

By assuming the need for intervention in crisis despite these obstacles, Galea et al. (2003, as cited in Ruzek et al., 2007) suggest to remember, before launching an intervention that: (a) the reactions of people should not necessarily be regarded as pathological responses or even as precursors of subsequent disorder; (b) many people will have temporary stress reactions in the aftermath of mass violence, and such reactions may occur, occasionally, even years later; (c) rather than traditional diagnosis and clinical treatment, most people are likely to need support and resources supply to ease the transition to normalcy; and (d) some survivors may experience great distress and require community and sometimes clinical intervention

The objectives of an initial intervention would be: to provide systematic support to facilitate emotional expression; to resolve conflicts and inconsistencies and provide strategies to accept reality and reorganize attitudes (Costa & De Gracia, 2002). Ruzek et al. (2007) also remind us that the various studies on the subject have identified the following five principles to guide intervention in both the early and medium term. These principles are: (a) to promote sense of safety, (b) to promote calm, (c) to promote a sense of self- and community-efficacy, (d) to promote connection with support networks, and (e) hope instilling.

Until now, there are at least four early intervention models with efficacy studies, even if their results are inconclusive or even negative: Debriefing, Psychological First Aid, Pennebaker´s Emotional Disclosure Technique, and Narrative Therapy. It becomes necessary to detail these models.

6.1 Debriefing

Psychological debriefing has its roots in World War I (McNally et al., 2003, Vera, 2004), when after a great battle, commanders met with their men to keep them aware. Mitchell (1983, as cited in McNally et al.) drew a parallel between the stress of combat and stress suffered by the medical emergency service, arguing that a similar approach could reduce stress reactions among firefighters, police, emergency technicians, physicians, and others exposed to what he called "critical incidents" (i.e. traumatic events). In his seminal article, Mitchell stressed that many people mistakenly believe that emergency services personnel are impervious to emotional trauma. By contrast, Mitchell says that helping the main victims of trauma can be a major stressor for the helpers themselves. Accordingly, Mitchell asserted that the mental health of emergency personnel is best protected when they participate in a structured session that allows them to talk about the traumatic event and vent their emotions, especially in the company of peers who have experienced the same incident. The debriefing is designed to mitigate the adverse psychological consequences of traumatic events by attenuating the intensity of acute stress symptoms, reducing the risk of subsequent psychiatric problems. Over time, the debriefing began to be considered useful even for "primary victims", i.e. those directly exposed to trauma.

In general terms, a session of debriefing lasts 3 to 4 hours and takes place between 2 and 10 days after a critical incident, except in cases of mass disasters. In that case, it could be done 3 to 4 weeks after the disaster (Everly & Mitchell, 1999, as cited in McNally et al., 2003). According to its proponents, the debriefing is successful because of its immediacy, since it provides psychosocial support and an opportunity to express emotions and thoughts about the trauma, and because it provides tips on how to address this situation and education about stress and its management.

A session of debriefing has seven phases:

1. Introduction phase, the facilitator explains the process of debriefing to participants by answering any questions they may have.
2. Fact phase: the person tells the facts of the traumatic event.
3. Thinking phase: it allows each participant to describe their cognitive reactions to the traumatic event.
4. Reaction phase: designed to foster emotional processing of trauma, participants make catharsis of their experience through expressing their feelings about the event.
5. Symptoms phase: its purpose is to identify stress reactions that members want to share.
6. Teaching phase: the objective is to demonstrate that stress reactions that participants have been experiencing are normal and not necessarily a medical problem,
7. Re-entry phase: it seeks to achieve closure of the traumatic event.

Regarding the results evaluation, McNally et al. (2003) note that, considering that only some individuals exposed to trauma develop PTSD, and most of them recover on their own, the efficacy of debriefing can be measured only by comparing the results for those who did received and not received this intervention. In this regard, studies show that debriefing does not seem to generate significant differences between those who participate in these sessions and those who do not (van Emmerik et al., 2002). Other researchers have shown that even iatrogenic damage generated in the participants (Aulagnier et al., 2004; Rose et al., 2002; Sijbrandij et al., 2006; Woods, 2007). On the other hand, Chan and Huake (2004) conducted a study where they assess the effects of this technique in health care workers in Singapore who came to help their neighbors in Southeast Asia after the T-2004. The results of this intervention first revealed the high levels of acute stress experienced by rescue teams but also showed how beneficial it was for them, according to their own testimony. The same positive result reported a group of journalists from Singapore who participated in debriefing sessions after the T-2004 (Sin et al., 2005). Costa and De Gracia (2002) only presents evidence that supports the use of debriefing in disaster situations. Vera (2004) and Santacruz (2008) have reviewed studies for and against the effectiveness of this technique.

McNally et al. (2003) note that the main difference between studies developed by critics and defenders of the debriefing would arise due to the absence of a control group in studies that approved the debriefing, who defended themselves by pointing out that to leave people exposed to trauma without psychological support is hardly ethical. However, studies that follow an appropriate methodology conclude that, given a lack of satisfactory evidence for debriefing, it is best to seek other methods to prevent psychopathological consequences in people exposed to trauma.

There are several possible explanations to the iatrogenic effect that would cause the debriefing in some people. Aulagnier et al. (2004) propose that the debriefing involves a re-exposure to the traumatic memory that can interfere with the natural course of recovery. The attempt to forget or distance themselves may be an adaptive response and intervention may interfere with this mechanism. Rose et al. (2002) suggest that it could even lead to "secondary trauma" due to the intense imaginary exposure to a traumatic incident within a short time from the event. It is possible that for some individuals this results in additional trauma and exacerbates their symptoms without helping the emotional processing. Although exposure therapy, practiced for the routine treatment of PTSD, may cause a slight initial exacerbation of symptoms as they remember the images of distress, it is reduced as the person reaches the habituation over time. However, in a single intervention, as in the debriefing, this habituation may not occur unless the recipient engages in additional exposure directed by himself or herself.

On the other hand, studies have shown that certain conditions are necessary to facilitate emotional processing of distressing material: "The material, especially in the early stages of treatment, should be made predictable, controllable, presented in small chunks, and tackled in a progressive but gradual way" (Rachman, 2001, p. 166, as cited in McNally et al., 2003). These conditions are not met in the debriefing, because it is more cathartic. Therefore, encouraging survivors to discuss their thoughts and feelings right away may increase the risk of feeling overwhelmed by the experience, which would be counterproductive.

Another explanation is that the "debriefing" can consider normal anxiety as a "medical condition" and therefore could increase the expectation of developing psychological symptoms otherwise it would not have been presented. While studies show that only a minority of people exposed to a traumatic event develop PTSD, the debriefing, since it raises awareness about the symptoms, may paradoxically induce this disorder which otherwise would not have been developed. Thus, the normal responses to stress produce expectations of developing subsequent pathologies (Raphael, 1995, as cited in Vera, 2004).

Finally, the treatment that promotes the debriefing, which includes all people exposed to a traumatic event, is excessive and ignores the positive effects of coping strategies that people naturally have and the potential of every human to learn and grow as a result of a traumatic experience (Vera, 2004). In addition, it focuses too much on the trauma, excluding other more relevant stressors, and may not be compatible with the natural coping strategies of many.

Summerfield (2006) indicates a darker aspect of the use of debriefing. This author argues, in relation to survivors of the T-2004 in Sri Lanka, that despite the alarmist voices which predicted up to 25% of children with PTSD and reported to have found up to 70% of these children with PTSD, demonstrated a rather remarkable resilience and joy in the survivors, and that the children seemed more inclined to return to school to talk about the events of 26 December. For this reason, they were described as "clearly in denial". There were a large influx of Western counseling teams specialized in trauma, most of them with little or no knowledge of the views and local culture. In Sri Lanka there are reports of survivors that say they had been led to virtually mandatory counseling.

Rose et al. (2002) concluded in an exhaustive way that the use of mandatory debriefing of trauma survivors must stop. Instead of that, the authors recommend early detection of those at risk of developing psychopathology to conduct early intervention only to this group.

6.2 Psychological First Aid (PFA)

MacNally et al. (2003) summarized studies that conclude that the provision of practical help can be seen as more useful and positive than specific psychological care. Trauma survivors have many immediate needs in their efforts to adapt to the event. For example, survivors may need a roof, help for overcoming exhaustion, for getting financial support, for finding relatives and friends, for protecting children, etc. There are also studies that emphasize the need for survivors to receive information from both the traumatic event, and the location of relatives or the ability to recover from an injury.

Although the provision of information by itself does not appear to promote recovery, it is generally recommended to provide information on common reactions to trauma, including natural recovery. Bryant (2006) recommends that after a trauma, victims should receive assistance in order of priority. The first priorities are basic requirements like food, water and shelter, followed by emotional support for physical suffering and psychological interventions. In the end only for those with acute stress disorder or PTSD. Black and Tufnell (2006) note that for survivors of traumatic events, access to support and information networks is crucial to get a sense of security.

With all this evidence at hand, PFA were designed by a collaborative effort of the National Center for PTSD and the National Child Traumatic Stress Network, of USA, intended for use by disaster mental health responders and others, including mental health counselors, who may be called upon to provide immediate support for trauma survivors (Ruzek et al., 2007). One of the qualities of the PFA is that they can be provided by people who are not necessarily mental health professionals, even though it requires a basic training for implementation. Another advantage is that they can be applied wherever there are survivors of trauma (Uhernik & Usson, 2009). In addition, the PFA are consistent with the concept of resilience in individuals and communities, which encourages self-efficacy and decreases the victimization and dependency.

The Pan American Health Organization [PAHO] (2006) notes that the PFA should be the first aid provided to those who are affected in an emergency, crisis or disaster, especially when there is a predominance of certain emotions such as fear, sadness, anger, tears and pain, after the event. Its objectives are: a) providing immediate relief of emotional suffering,

b) reduce the risk of normal reactions into something more serious and c) help meet the survival and basic needs that suffer most of the people who survive disasters (PAHO, 2006). Figueroa et al. (2010) recommend PFA for those most affected, even though they not present formal psychiatric disorders. Parallel to the PFA it should be done a psychological screening for detecting risk population that requires more specialized support.

According to Vernberg et al. (2008), the principles, objectives, and techniques of PFA are designed to meet four basic standards:

1. Consistent with research evidence on risk and resilience following trauma.
2. Applicable and practical in field settings.
3. Appropriate for developmental levels across the lifespan.
4. Culturally informed and deliverable in a flexible manner.

Figueroa et al. (2010) suggest not forcing the affected to talk about their feelings, since the psychotherapeutic interventions that do so, as does the debriefing, has not been shown to reduce the development of later psychiatric disorders and worse, it could increase them. However, the PFA also recommends making it possible for survivors to construct a "trauma story" narrative and to expose their feelings. But what differentiates it from a debriefing? The difference is that the PFA respects the desire of the person to talk or not, about the trauma. The goal of the PFA is not to maximize emotional processing of the traumatic event, but to respond to the urgent need that arises in many people who want to share their experience. At the same time the PFA respects those who do not want to talk about what happened (McNally et al., 2003). The conclusion is that in the immediate after-effects of trauma, practitioners should take their lead from the survivors and provide the help needed, instead of mentioning how the survivors will get better.

It still remains to be proved empirically if the PFA is effective in preventing or recovering from PTSD and other psychopathological consequences of natural disasters. However, its nature of general support and its proposal of non-directive intervention, as well as empirical support that sustain many of its components (satisfaction of basic needs, providing information, formation of social support networks and facilitation of emotional expression) suggest that it is unlikely to generate damage. Fortunately, the procedure of PFA is governed by standardized guidelines, making it susceptible to evaluation (Vernberg, 2008).

A complete guideline of PFA can be downloaded from
http://www.ptsd.va.gov/professional/manuals/psych-first-aid.asp

6.3 Emotional disclosure

Different research guided by Pennebaker or made following their postulates, has shown that the emotional disclosure of the meanings associated with the trauma prevents long-term health problems and generates an increase in immune function, among other consequences (Owen et al., 2006; Pennebaker, 1997; Pennebaker et al., 1988; Pennebaker & Seagal, 1999; Petrie et al., 1998). Pennebaker (2004) has developed an emotional writing exercise that has been applied in different contexts and that, according to a review of Cabrera (2006), has led to improvements in the physical and psychological health of participants.

On the other hand, Cabrera (2006) notes that certain ways of writing seem to show better effects on health than others. For example, it is important to identify and properly label the positive and negative emotions, to build a consistent and significant history of traumatic events and to be able to tell of the experience from different perspectives. Cabrera says that people who would be favored from the writing exercises are those that have experienced a trauma and have difficulties in confronting the facts with others and consequently keep their difficulties secret.

McNally et al. (2003) note that studies of Pennebaker would confirm one of the main tenets of debriefing: that expressing thoughts and feelings about the trauma accelerates healing, and that "encapsulating" these feelings prevents it. However, Pennebaker (2001) noted that his research focused on the psychobiological benefits of writing about traumatic events that had remained hidden for months or years. Therefore, Pennebaker's work cannot be invoked in support of the psychological debriefing that occurs soon after the traumatic event. On the other hand, Vera (2004) uses the opinion of Pennebaker meaning that writing can be seen as a form of spontaneous social communication that is quite different from the forced expression used in a group debriefing, and that social pressure to speak and express emotions in front of a professional can awaken feelings of humiliation and shame for many people.

Pennebaker's methodology has been tested with survivors of different types of trauma, including terrorist attacks (Fernández et al., 2004) or newly diagnosed women with breast cancer (Garcia & Rincon, 2009).

6.4 Narrative therapy

Given the importance of emotional expression and social support, the narrative intervention model, whose development was also influenced by the research of Pennebaker (Galarce, 2003, Tarragona, 2003), could be a useful model for preventing psychopathological symptoms in survivors of natural disasters. However, the relative newness of this approach has provided less evidence about its outcome. Among these, the revision of O'Kearney and Perrott (2006) who analyzed 19 studies stands out, which described the narratives of trauma in individuals diagnosed with PTSD symptomatology. Kaminer (2006), in turn, makes a review of other studies focusing on the influence of the narrative of trauma on recovery from PTSD, focusing on identifying the psychological processes involved in each of them, suggesting that the specific process involved in the narrative therapy is to identify the purpose and value of adversity.

The importance of attributing the meaning of traumatic experiences can be found in a study by Norman (2000) which concluded that while exposure to traumatic events can lead to PTSD, not all people develop the syndrome. The difference, according to Norman (2000), would be that "some people know how to find meaning for their horrific experiences, while others can’t" (p. 305). The attempt to give meaning to negative experiences has been highlighted by recent positive psychology, a school that incorporates constructions such as resilience. This is a quality that some people have for overcoming adversity and traumatic events. The narrative model of White and Epston (Epston, 1994, White, 2002a, 2002b, White & Epston, 1993), consistent with this, states that the adverse experiences are stories of resilience and survival and that these aspects can be expanded and enriched through the therapeutic process (Kaminer, 2006).

The narrative approach of White and Epston is based on the assumption that the narratives do not represent people’s identity and problems, rather the narratives are the identity and problems. In this regard, Carr (1998) points out that human problems arise and are maintained by oppressive histories that dominate the lives of people. But these stories do not only determine the meaning attributed to his experiences, but also determine what aspects of the experience they select to assign them a meaning.

The goal of narrative therapy is to help clients to rewrite their life story, incorporating pieces of their history that have been marginalized from their experience, events that are exceptions to the current narrative: then the people will be able to give a new meaning to their past life and to plan a future less oppressive than the one manifested today. This approach also points out that new meanings assume greater value if they are transmitted and shared with the social network (family, friends) that surrounds and supports the patient, encouraging, therefore, several instances where it is possible to establish this connection, either symbolic (therapeutic letters) or directly (forums, workshops, family gatherings).

Narrative therapy is based on the principle that people categorize their experiences through language. However, in the process of putting the experience in the form of a story, certain parts are left out because they are not much considered than other parts. As people remember these neglected parts, they are able to formulate a more complete story of their experience. If patients are encouraged to attend to the neglected parts of their experiences, they can create full stories and give a new meaning to their experiences. In other words, narrative therapy invites the survivors to engage in a reassessment, to construct new meanings and integrate them into their experience (Petersen et al., 2005).

The narrative approach is also characterized by stimulating discussions to find personal resources to facilitate coping with difficulties in life, so it becomes a respectful approach to the experiences, beliefs and the times that a person takes to decide to address their difficulties. This shows a closer relation with some of the principles of the PFA than psychological debriefing. Within this respectful attitude there is an emphasis on finding and validating local narratives over the narratives of the dominant culture. In that sense, it is important to note the existence of studies that question the universality of the conceptualization and interventions on psychological trauma, suggesting adaptation to local situations (Miller, 2006). The same emphasis on ethno-cultural particularities before providing a standard psychological support to survivors of trauma was indicated by Rajkumar et al. (2008) regarding the T-2004 in India. The author argues that cultural practices should be included in any model of intervention. This is what Silove and Zwi (2005) say in their analyses of early psychosocial interventions in the disaster zone of T-2004, noting that the need for any intervention of this kind should be adopted in consultation with local professionals before implementation, otherwise it would be arrogant to decide so without their permission. According to Silove and Zwi (2005), those communities affected by the disaster should be the architects of their own psychosocial recovery. They warn that to come and go in with quick-solution approaches can cause more damage than good and may leave a bit of resentment and unfulfilled promises. Simons et al. (2004) suggest the same need to build on community resources rather than imported techniques. They worked with survivors of the T-2004 from a psychological community perspective. Summerfield (2006) also calls for the adaptation of the types of assistance to local cultures, in addition to questioning the concept of "disaster mental health" considering that initial aid should be primarily social and community. This emphasis on local culture can even have a repairing role before the deficit of the central organization to go in support of survivors. Therefore, when government agencies or the community are harmed as a result of the disaster, it is necessary to strengthen local networks; concluded Mendez et al. (2010).

Silove and Zwi (2005) propose that instead of using ineffective high-cost strategies, such as debriefing, appropriate culturally-social strategies should be emphasized to provide protection for the vulnerable, to bring families and communities together wherever it is possible, to create meaningful roles and livelihoods, and to restore institutions and services (religious, cultural, mental health) that promote community cohesion and a sense of order.

Considering this background, it seems that the narrative approach, focused on the meaning of experience and reconnecting people with their social support networks, but at the same time respecting the rhythms of people and knowledge of local culture, could become a model for preventing or reducing symptoms of PTSD, so it is necessary to conduct studies to prove its effectiveness. One of those studies was developed by García and Rincón (2009) to prevent the occurrence of PTSD in patients that were just diagnosed with breast cancer and later used for individuals and group work for survivors of the T-2010 in Chile (García & Mardones, 2010; Avalos & Balic, 2010).

Model	DEBRIEFING	PSYCHOLOGICAL FIRST AID	EMOTIONAL DISCLOSURE TECHNIQUE	NARRATIVE THERAPY
Author	Jeffrey Mitchell	National Center for PTSD and the National Child Traumatic Stress Network	James Pennebaker	Michael White & David Epston
Emotional Expression	Compulsory	Facilitated	Compulsory, but written	Facilitated
Moment of application	Between 2 and 10 days after the event	The day after the event	Several days after	Several days after
Research outcomes	Inconclusive or even negative	Based on conclusive evidence	Positive mid-term and long-term effects	Further investigation is needed

Table 1. Comparative table of the four models

7. Conclusion

The psychological reactions to a natural disaster like a tsunami are varied. Many of them are normal behaviors faced with an event of great emotional intensity, even if they are perceived as unpleasant. Focusing only on the psychopathological reactions prevents us from addressing more adaptive responses and also it has the risk of qualifying many of these normal reactions as symptoms of mental illness. In this regard, Cova and Rincon (2010) believe particularly valuable the responses aimed at strengthening the skills and resources of individuals and communities to be able to address their own problems and those that not only aim at specific "symptoms", but also at their quality of life.

Therefore, it is relevant to design and evaluate early intervention strategies that are able to prevent future maladaptive reactions in tsunami survivors, among others natural disasters.

However, aid interfering with natural recovery, or causing more harm than good, should be avoided. These interventions must take into account risk factors, in order to detect the vulnerable but also personal- and community-protective factors that must be recognized and encouraged by any model that is offered to help immediately after a natural disaster. Unfortunately there are difficulties for developing effectiveness studies of these interventions in a natural context.

McNally et al. (2003) claim that in recent times, it seems that the focus of crisis intervention is shifting, since it directly encourages people to review and make known their traumatic experiences, as reflected in debriefing, and it provide support and a forum for people to talk about their reactions, if you will, as in the PFA or narrative therapy.

The interest of this chapter was to report the results of studies on these factors and intervention models that have been studied to date.

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The objective of this multi-disciplinary book is to provide a collection of expert writing on different aspects of pre- and post- tsunami developments and management techniques. It is intended to be distributed within the scientific community and among the decision makers for tsunami risk reduction. The presented chapters have been thoroughly reviewed and accepted for publication. It presents advanced methods for tsunami measurement using Ocean-bottom pressure sensor, kinematic GPS buoy, satellite altimetry, Paleotsunami, Ionospheric sounding, early warning system, and scenario based numerical modeling. It continues to present case studies from the Northern Caribbean, Makran region and Tamil Nadu coast in India. Furthermore, classifying tsunamis into local, regional and global, their possible impact on the region and its immediate vicinity is highlighted. It also includes the effects of tsunami hazard on the coastal environment and infrastructure (structures, lifelines, water resources, bridges, dykes, etc.); and finally the need for emergency medical response preparedness and the prevention of psychological consequences of the affected survivors has been discussed.

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