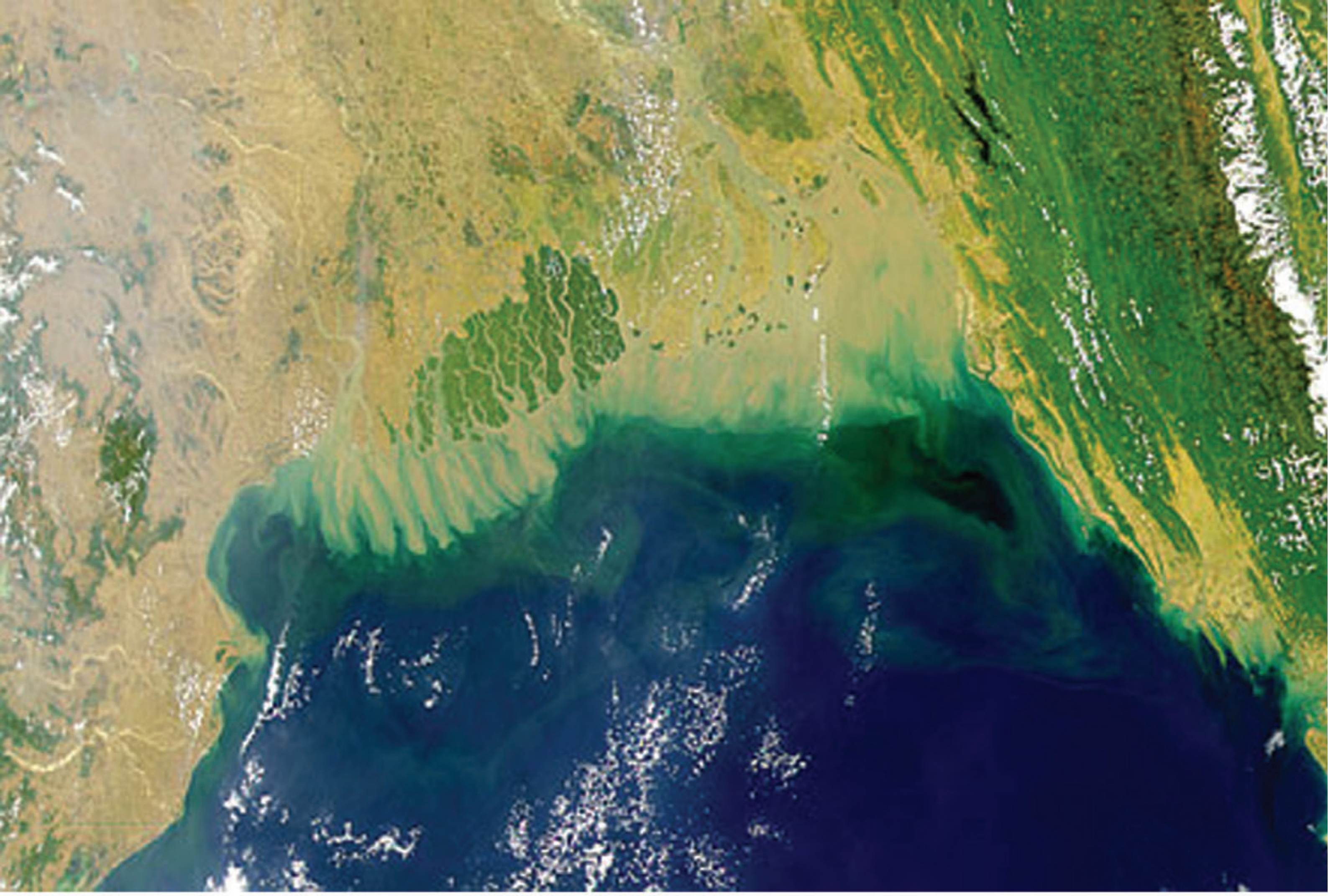

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP

Tsunami and Storm Surge Hazard Assessment and Management for Bangladesh

DHAKA, 21-22 JANUARY 2009

Ministry of Food and Disaster Management (MoFDM)
Comprehensive Disaster Management Programme (CDMP)

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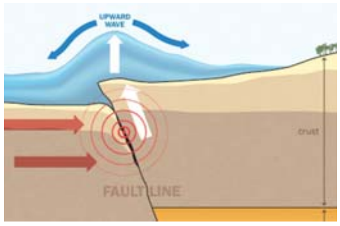

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PROCEEDINGS OF THE INTERNATIONAL WORKSHOP

Tsunami and Storm Surge Hazard Assessment and Management for Bangladesh

EDITOR

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National Expert, Earthquake and Tsunami Preparedness

United Nations Development Programme (UNDP), Bangladesh

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MESSAGE

Bangladesh is a disaster prone country. The country has had a long experience of severe cyclonic events, floods, landslides and earthquakes. Bangladesh, being a low-lying country, is also vulnerable to the effects of global climate change. The location of Bangladesh in the complex deltaic zone of three major rivers greatly increases its disaster risk. The major victims of these disasters are the people living in coastal areas, who make up approximately 30 percent of the total population. Current population growth indicates that the coastal population will reach 44 million in 2015 and 61 million in 2050. So mitigating the risks poised against the lives and livelihood of coastal dwellers is a key issue.

People of this sub-continent still remember the devastation of the Indian Ocean tsunami of 2004 that killed 250,000 people and rendered millions more homeless across 11 countries. In 2007, Cyclone Sidr took the lives of more than 4000 people and caused approximately 1.7 billion USD in damage to coastal infrastructure. It is beyond our power to simply eliminate these hazards, but it is well within our capacity to reduce our disaster vulnerability and prevent the loss of lives and property. We have improved the accuracy and efficiency of our early warning systems. We are improving the resilience of coastal housing. We are redesigning coastal infrastructure so that community buildings can readily double as shelters. We are also developing ways to shelter cattle to ensure coastal livelihoods are maintained in the aftermath of a hazard event.

Though disasters like storm surge are extreme natural phenomena that frequently occur in Bangladesh, tsunami is not that common. Since the 2004 Indian Ocean tsunami though, this phenomenon has become a major concern for coastal countries. Though Bangladesh was not affected by 2004 tsunami, historical evidence shows that the country was affected by tsunami and seiche in 1762 following an earthquake that occurred off the Myanmar coast. This tsunami threat creates an add-on effect to our vulnerable coastal communities as preparedness for this type of hazard is extremely low.

In recent years considerable progress has been made to reduce the impacts of disasters, but more emphasis needs to be given to disaster risk reduction, especially in light of increasing impact of climate change. We have to improve our disaster management systems and infrastructure, and incorporate the knowledge local stakeholders have of the risk environment.

Bangladesh has come a long way in reducing its vulnerability to the numerous hazards it faces. The Comprehensive Disaster Management Programme (CDMP) of the Ministry of Food and Disaster Management (MoFDM) of the Peoples Republic of Bangladesh has been a key part of the effort to move the country's disaster management practices from a response and relief focus to a broader and more encompassing risk management framework.

This workshop, titled 'Tsunami and storm surge hazard assessment and management', organized by CDMP will put the country in a better position to manage the complex mechanisms of tsunami and storm surges.

Through this message, I would like to offer thanks to the national and international experts who attended the workshop and contributed to the publication of this proceeding.

Dr. Md. Abdur Razzaque, M.P
Minister
Ministry of Food and Disaster Management (MoFDM)

PREFACE

Bangladesh is a country which is considered to be among the most disaster prone countries in the world. The country has learnt to live with floods, cyclones and storm surges and has, over the years, developed quite a good system for reduction of disaster risk. During the last twenty years, considerable progress has been made in identifying the risks associated with earthquake. Since 2003, the Comprehensive Disaster Management Program (CDMP), funded by UNDP, EC and DFID, with the Ministry of Food and Disaster Management, Government of Bangladesh, has been involved in a number of studies related to inter alia an in-depth analysis of earthquake risks, particularly for Dhaka, Chittagong and Sylhet Cities and Earthquake Vulnerability and Risk assessment for each of the three cities.

It was thought by most people that there is very little risk of Bangladesh being hit by Tsunamis. However, after the December 26, 2004 earthquake and tsunami in Sumatra, it was thought that an investigation of tsunami risk of Bangladesh should also be carried out. The efficacy of using the large number of existing and planned multipurpose community shelters and the associated warning system developed for cyclone and storm surge for tsunamis also need to be explored.

The Technical Advisory Group for Earthquake and Tsunami Preparedness Component (component 4a) of CDMP suggested that experts in fields related to Earthquakes and Tsunamis should be invited to an International Workshop on Tsunami Hazard Assessment and Management for Bangladesh. In addition to the consultants working on this component (viz. Institute of Water Modeling, Dhaka), experts from a number of countries in the region participated by presenting papers and/or contributing to the discussions in the Inaugural Session and the 7 technical sessions.

This is for the first time such a workshop on Tsunami has been organized in Bangladesh. I am confident that the deliberations of the workshop have lead to a much better assessment of the risks and possible measures for risk reduction. The proceedings of the Workshop will be a valuable document for anyone interested in this field.

Professor Jamilur Reza Choudhury
Vice-chancellor, BRAC University

Convener
Technical Advisory Group, Component 4a, CDMP

INTRODUCTION
OUTCOMES OF THE TSUNAMI AND STORM SURGE WORKSHOP 2009

Bangladesh has a long experience of cyclone events and their accompanying storm surges but tsunamis have historically been an extremely rare event The north Sumatra earthquake of that generated the 2004 Indian Ocean tsunami killed approximately 250000 people across eleven countries but Bangladesh largely avoided its impact, recording only 2 deaths. There has been intense debate as to how vulnerable the country is to tsunami events considering its seismo-tectonic and physiographic lay-out. This has made it difficult for policy makers to determine what priority should be afforded to tsunami events in development plans and processes.

Considering the frequent occurrence of cyclonic storm surges and undefined risk of tsunami, Earthquake and Tsunami Preparedness component of CDMP (component 4a), has undertaken a 'Tsunami and Storm Surge Inundation Risk Assessment for the Coast of Bangladesh'. The component is also updating available information on cyclone shelter management for tsunami and storm surge preparedness; identifying critical coastal infrastructure and community buildings that may be vulnerable to tsunami and storm surge and evaluating their capacity to double as shelters; identifying the economic risk that tsunami and storm surge pose to coastal livelihoods (e.g. fishing/tourism industry); and improving training and awareness strategies with regard to tsunami hazard management.

The 'Tsunami and Storm Surge Inundation Risk Assessment for the Coast of Bangladesh' assignment was awarded to the Institute of Water Modeling (IWM). CDMP organized a workshop to assess IWM's study in Dhaka on 21-22 January 2009, titled "Tsunami and Storm Surge Risk Assessment and Management in Bangladesh". The specific objectives of the workshop were:

- Evaluate the tsunami and storm surge risk environment and strategies to manage it.
- Assess the quality of the scientific documents produced by IWM.
- Determine follow up activities to reduce Bangladesh's vulnerability to tsunami and storm surges.

The workshop was addressed by the Honorable Minister - Ministry of Food and Disaster Management (MoFDM), Secretary - MoFDM, Vice Chancellor - BRAC University, Country Director - United Nations Development Program, Counselor and Head of Cooperation and Delegation - European Commission to Bangladesh, Chairman - International Tsunami Commission and Director General - Disaster Management Bureau (DMB), Bangladesh. Around 200 national and international delegates were present in the inaugural session. Along with 30 nationals, 11 international experts attended the workshop from Japan, USA, Malaysia, Indonesia, Thailand and India.

Out of 17 papers presented in the workshop, 13 complete papers have been published in the proceeding.

IWM identified eleven tsunamigenic fault sources in the Bay of Bengal, but experts recommended using the 4 sub-duction zone sources to develop the tsunami propagation and inundation risk maps. Workshop experts also suggested using a series of advanced equations and a relatively moderate to fine mesh size in undertaking their assessment. Following the workshop comments, IWM developed scenarios on the propagation of tsunami waves. Compilation of the scenarios revealed that the inundation risk map for tsunami shows that the Sundarban area, Nijhum Dwip, area south of Hatia (outside polder) and Cox's Bazaar coastline remains vulnerable during tsunami. Maximum inundations have been found at Nijhum Dwip in the range of 3-4 m, and at the Sundarban area and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary have been inundated by 1-3 m.

Satake Kenji and Fujii Yushiro developed a tsunami generation and propagation simulation study using a fault model proposed by Cummins (2007). They computed maximum tsunami heights of approximately 5 m along the Bangladesh coast.

Sarker Netail Chandara Dey produced a paper to determine the arrival time of tsunami to the coast of Bangladesh from some inferred sources in Bay of Bengal. It was determined that a local tsunami would take only minimal time to arrive.

Two more papers (Karim Md. Fazlul, and Kaneko Fumio) have been dedicated on the effect of tsunamis along the coastal belts of Penang Island in Peninsular Malaysia, Phuket Island in Southern Thailand, and the Istanbul coast of Turkey.

Shishikura Masanobu et.al dedicated a paper to the geomorphological evidence of a repeated large earthquake that occurred from the subduction zone of the Rakhine Trench along the western coast of Myanmar in the last 3000 years.

IWM developed a inundation risk map of the Bangladesh coastline for storm surge based on the maximum inundation depths of the past 18 cyclones. It was determined that the highest inundation depth is in the order of 5 m to 7.5 m within the Meghna Estuary area.

Center for Environmental and Geographic Information Services (CEGIS), Bangladesh, has mapped and detailed the present operational condition of cyclone shelters and assessed their vulnerability to a variety of hazards, including tsunami. It was determined that there are currently 2,591 usable cyclone shelters offering varying protection against cyclone and storm surge. IWM determined that most coastal infrastructure (informal shelters) would be unable to stand up to even a minor tsunami.

Two papers (Kilonsky Bernard; Merrifield Mark; and Srivihok Patchanok et. al) floated the development of tsunami and storm surge monitoring stations in the Indian Ocean and the real time collection and dissemination of sea level data.

Niran Chaimanee described the activities taken for disaster prevention and mitigation by the Coordination Committee for Geo-Science Programs (CCOP) in East and South East Asia.

The workshop determined that although Bangladesh is less threatened by transoceanic tsunami, local tsunami have the potential to cause enormous damage to coastal areas. Workshop experts also recommended further follow up studies in the following areas:

- A detailed bathymetric study of the Bay including an update of the coastal zone contours.
- Development of forecasting techniques to detect storm surge propagation.
- A historical investigation into tsunami events that hit coast of Bangladesh.
- Improving the structural integrity of embankments in coastal regions.

We believe that this document would be a strongly tool for physical interventions in reducing the vulnerability of storm surge and tsunami. We do acknowledge the agency and individual who contributed for the successful completion of the workshop and proceeding.

Dr. A. S. M. Maksud Kamal
National Expert
Earthquake and Tsunami Preparedness, CDMP

Ian Rector
Chief Technical Advisor and
Team Leader, CDMP

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP

Tsunami and Storm Surge Hazard Assessment and Management for Bangladesh

CONTENT

CONTENT

WORKSHOP PROGRAMME

21-22 January, 2009

Summer Palace Hotel, 35 Suhrawardy Avenue, Baridhara Model Town, Dhaka

21 January, 2009 — Inaugural Session

Time	Activities	Organizations/Person
08.45 - 09.30	Registration	Comprehensive Disaster Management Programme (CDMP) & Institute of Water Modeling (IWM)
09.30-09.35	Guests take their seats	
09.35 - 09.40	Welcome address	**Mr. K. H. Masud Siddiqui** Director General, Disaster Management Bureau
09.40 - 09.45	Overview of the tsunami and storm surge activities by Sub-Implementing Agency (SIA)	**Mr. Emaduddin Ahmed** Executive Director, IWM
09.45 - 09.50	Speeches of Special Guests	**Professor Kenji Satake** Chair of IUGG (International Union of Geodesy and Geophysics) Tsunami Commission
09.50 - 09.55		**Mr. Milko van Gool** Counselor, Head of Cooperation Delegation of the European Commission to Bangladesh
09.55 - 10.00		**Mr. Stefan Priesner** Country Director, UNDP
10.00 - 10.05		**Professor Jamilur Reza Choudhury** Vice Chancellor, BRAC University
10.05 - 10.15	Speech, Chief Guest	**Dr. Md. Abdur Razzaque** Honorable Minister, Ministry of Food and Disaster Management (MoFDM)
10.15 - 10.25	Address by Chair	**Mr. Molla Waheeduzzaman** Secretary, Ministry of Food and Disaster Management (MoFDM)
10.25-10.30	Vote of thanks	**Mr. Ian Rector** Chief Technical Advisor and Team Leader, CDMP
10.30 - 11.00	Tea and Snacks	

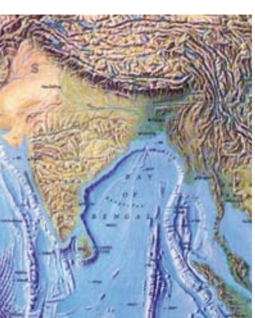
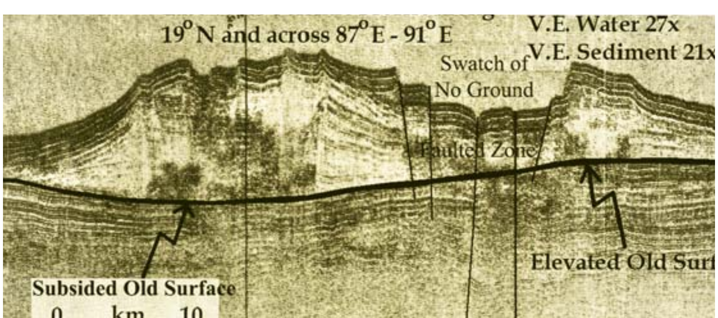
21 January, 2009 — Technical Session I

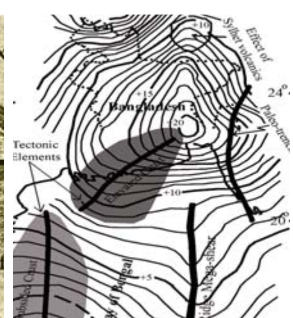
Chair ● Professor Dr. Kenji Satake

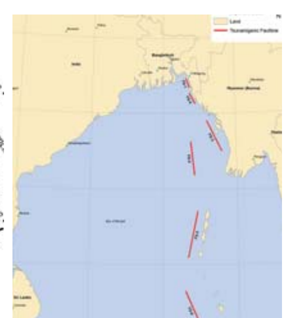
Co-chair ● Dr. Vineet K. Gahalut

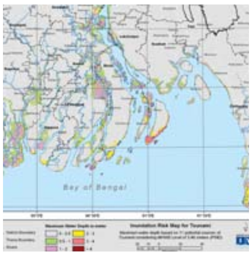
Rapporteur ● Dr. A.S.M. Woobaidullah, Mr. Reshed Md. Ekram Ali & Mr. Zahirul Haque

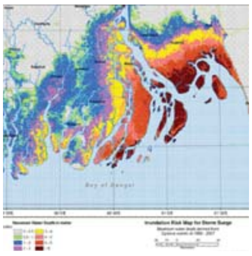
Time	Presented By	Title of Presentation
11.00 - 11.45	Institute of Water Modelling (IWM)	Identification and characterization of potential sources for generating Tsunami in the Bay of Bengal.
11.45 - 12.30	Discussions	
12.30 - 12.45	Concluding Remarks by the Chair	
12.45- 14.00	Lunch and Prayer	

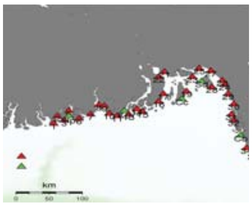



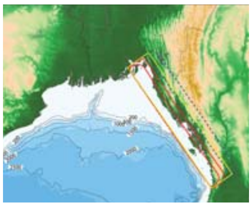


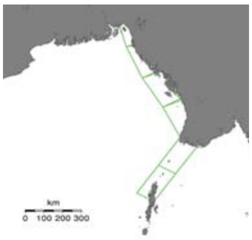


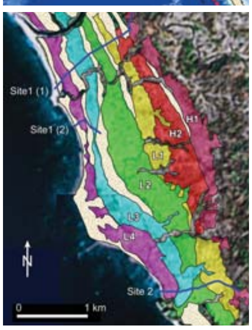












21 January, 2009 — Technical Session II

Chair ● Professor V. Sunder,
Co-chair ● Dr. Masanobu Shishikura
Rapporteur ● Dr. K. Murali, Dr. Sirajul Islam Khan and Dr. Umme Kulsum Navera

Duration	Presented By	Title of Presentation
14.00 - 14.45	Institute of Water Modelling (IWM)	Propagation of Tsunami Wave to the Coast of Bangladesh and Corresponding Inundation Towards Inland.
14.45 - 15.30	Discussions	
15.30 - 15.45	Concluding Remarks by the Chair	
15.45 - 16.00	Tea Break	

21 January, 2009 — Technical Session III

Chair ● Dr. A. M. Choudhury
Co-chair ● Dr. E. Uma Devi
Rapporteur ● Dr. Bernard Kilonsky, Dr. D.A. Quader and Mr. Md. Monjur Jahid Ahmed

Duration	Presented By	Title of Presentation
16.00 - 16.30	Institute of Water Modelling (IWM)	Storm surge modelling and Inundation risk map of the coast of Bangladesh.
16.30 - 16.50	Discussions	
16.50 - 17.00	Concluding Remarks by the Chair	

22 January, 2009 — Technical Session IV

Chair ● Professor Monirul Hoque

Duration	Presented By	Title of Presentation
09.00 - 09.15	**Mr. Netai Chandra Dey Sarker** Assistant Director, Disaster Management Bureau Government of the people's Republic of Bangladesh	Tsunami simulation and Hazard assessment of the Bangladesh coast.
09.15 - 09.30	**Dr. Vineet K. Gahalut** Senior Scientist, National Geophysical Research Institute Hyderabad, India	Tectonics and earthquake occurrence processes in Indo-Burmese arc.
09.30 - 09.45	**Dr. Kenji Satake** Chair of IUGG (International Union of Geodesy and Geophysics) Tsunami Commission	Tsunami Numerical Simulation for the Bangladesh Coast.
09.45- 10.00	**Dr. Masanobu Shishikura** Senior Researcher Active Fault Research center, Geological Survey of Japan	Geo-morphological evidence of great Holocene earthquakes of Western Myanmar.
10.00-10.25	Discussion and remarks by the chair	
10.25 - 10.45	Tea and Snacks	

22 January, 2009 — Technical Session V

Chair ● Professor A. M. M. Safiullah

Duration	Presented By	Title of Presentation
10.45- 11.00	**Dr. V. Sundar** Professor, Department of Ocean Engineering Indian Institute of Technology, Madras, India	Flooding due to Natural Coastal Disaster: Role of Vegetation.
11.00 - 11.15	**Dr. K. Murali** Associate Professor, Department of Ocean Engineering Indian Institute of Technology, Madras, India	Role of Vegetation on Run-up and Forces on Beaches and structures.

22 January, 2009 — Technical Session VI

Chair ● Professor A. M. M. Safiullah

Duration	Presented By	Title of Presentation
11.15 - 11.30	**Mr. Fumio Kaneko** Chief Engineer, OYO International Corporation	A simulation Analysis of Possible Tsunami affecting the Istanbul Coast, Turkey.
11.30 - 11.45	**Dr. Md. Fazlul Karim** Assistant Professor, Department of Mathematical Sciences Malaysian University of Science, Malaysia	Tsunami Simulation along Peninsular Malaysia and Southern Thailand Using A Nested-Grid Model: A Case Study of Indonesia Tsunami 2004.
11.45 - 12.00	**Dr. Edupuganti Uma Devi** Project Scientist, Ministry of Earth Sciences Government of India, Delhi	Indian Tsunami Early Warning System.
12.00 - 12.15	**Dr. Bernard Kilonsky** Senior Associate, University of Hawaii, Honolulu, USA	Indian Ocean Tsunami-enabled Coastal Sea Level Stations: Specifications and Communications.
12.15-12.40	Discussion and Concluding remarks by the chair	
12.40 - 13.45	Lunch and Prayer	

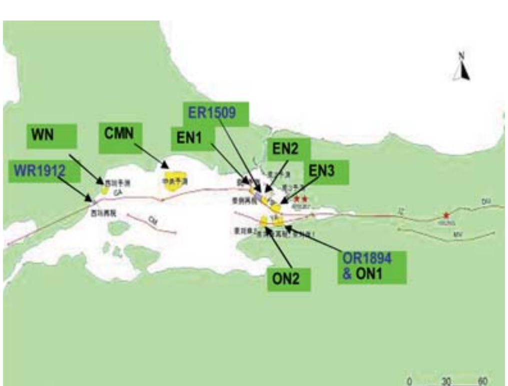
22 January, 2009 — Technical Session VII

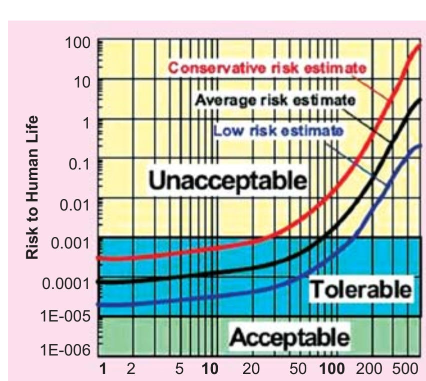
Chair ● Professor Jamilur Reza Choudhury

Duration	Presented By	Title of Presentation
13.45 - 14.00	Asian Disaster Preparedness Center (ADPC)	Establishment of Rimes End-to-end Early Warning System for Tsunamis in the Indian Ocean and South-east Asia.
14.00 - 14.15	**Mr. Niran Chaimanee,** Geo Environment Sector Coordinator Coordination Committee for Geosciences Promotion in East and South-East Asia (CCOP)	Role of CCOP as a regional organization for Tsunami risk reduction and hazard mitigation in South-east Asia.
14.15-14.30	Center for Environmental and Geographic Information Services (CEGIS)	Spatial Distribution of Existing Cyclone Shelters for Tsunami and Storm Surge Preparedness.
14.30-14.45	Institute of Water Modelling (IWM)	Structural Strength Analysis of Infrastructure Vulnerable to Tsunami and Storm Surge of Bangladesh Coast.

22 January, 2009 — Concluding Session

14.45-15.00 ● Discussion and Concluding remarks by the chair
15.00-15.15 ● Discussion on Tsunami and storm surge risk reduction strategy in Bangladesh from regional experiences.





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Finance & Admin Assistant, EC Component, CDMP

Silvia Oly Sinha
Secretary, EC Component, CDMP

KEY-NOTE PAPERS

The International Workshop

Tsunami and Storm Surge Hazard Assessment and Management for Bangladesh

IDENTIFICATION AND CHARACTERIZATION OF THE TSUNAMI GENERATING POTENTIAL SOURCES IN THE BAY OF BENGAL

Institute of Water Modelling*

ABSTRACT

Tsunami is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. The genesis of a tsunami depends on geodynamics (the nature and direction of convergence of the plates), tectonics (geological forces and the nature and types of fault rupture), seismicity (earthquake) pattern and the water depth. The orographic pattern of the Bay of Bengal suggests the nature and magnitude of the tsunami wave propagation. The entire Bay of Bengal has been studied from the above geological and geophysical aspects to determine potential fault rupture source zones. The earthquake distribution in the Bay of Bengal clearly identify the various fault source zones those are intrinsically associated with the locations of earthquake epicenters. Further the source zones are distinctly correlated with the occurrence of known tectonic elements such as Ninety East Ridge Mega-shear, Eighty Five Ridge Mega-shear (Raiverman, 1986), Sunda Trench, Andaman Trench, Chittagong-Arakan Fault Zone, and Peri-craton & Basin-margin Fault Zone (Khan & Akhter, 1999). Sumatra fault zone and Chittagong-Arakan fault zone are already geologically established fault zones those are available in the scores of publications. Andaman fault zone has also been documented (Paul and Lian, 1975). The regional structural configuration of the Bay of Bengal as envisaged from the vertical component magnetic anomaly map is quite consistent with the regional crustal features of the Bay of Bengal like Ninety East Ridge, Eighty Five East Ridge, and the elevated crust in the north Bay of Bengal. East-West seismic section along 19oN latitude in between 87oE and 91oE longitudes clearly exhibits a regionally long wavelength crustal feature representing an elevated and subsided older surface respectively (Curray amd Moore, 1971). Further, the normal faults occurring along the location of "Swatch of No Ground" in the 19oN seismic section suggest that the zone occupied by the "Swatch of No Ground" is a faulted zone resulted from the upward bulge of the older crust. The western part of the Bay of Bengal along the Eastern Ghat Mobile Belt, the focal mechanism solutions of four earthquake events also show pure strike-slip faulting (Khan, 1991). The potential fault source map of the Bay of Bengal has been prepared based on the geophysical and the geological data mentioned above. The parameters of the fault sources required to generate tsunami such as rupture length, slip offset, dip angle, slip angle, strike angle and moment magnitude have been calculated from the geophysical and the seismological data. All together 11 fault source zones are identified in the Bay of Bengal.

Keywords : The Bay of Bengal, Tsunami, Earthquake, Potential Fault Sources, Geophysical and Geological Data.

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INTRODUCTION

Tsunami is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. The genesis of a tsunami depends on geodynamics (the nature and direction of convergence of the plates), tectonics (geological forces and the nature and types of fault rupture), seismicity (earthquake) pattern and the water depth. The orographic pattern of the Bay of Bengal suggests the nature and magnitude of the tsunami wave propagation.

CDMP commissioned Institute of Water Modelling (IWM) to carry out a study titled "Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region" in December 2007, where the entire Bay of Bengal has been studied from the geological and the geophysical aspects to determine potential fault rupture source zones.

GENESIS OF TSUNAMI

Prior to characterizing an area from tsunami vulnerability, it is important to know the genesis of a tsunami. Most great water waves are caused by rupture and displacement along the submarine faults without which no tsunami would occur. Most large magnitudes (> 7.5 Mw) and shallow focus (" 15 km) earthquakes under the sea are tsunamigenic and are located mostly along the active subduction zones of the lithospheric plate collision margins. The nature, extent, and magnitude of fault ruptures play an important role in the genesis of tsunami. Tectonically, an active subduction zone is characterized by under thrusting of oceanic crust and up-thrusting of continental crust. This mechanism produces series of thrust sheets riding over the oceanic segments resulting in the development of thrust fault ruptures. Any thrust sheet when encounters water column in front and above can cause water column to be stressed and moved. However, this would happen only when the subduction direction is perpendicular to the line of convergence. When subduction direction is oblique to the line of convergence a combination of vertical and horizontal movements occur along the rupture planes resulting in the development of combination of thrust and strike-slip fault rupture. In such condition, the outward stress vector is a resultant one thus reducing the impact on the water column in front and above of the rupture plane. Devastating episode of a tsunami depends on the volume of on-rush stressed water and the velocity of the on-rush water front. Hence, the genesis of a tsunami depends on geodynamics (the nature and direction of convergence of the plates), tectonics (geological forces and the nature and types of fault rupture), seismicity (earthquake) pattern and the water depth. The orographic pattern of the Bay of Bengal suggests the nature and magnitude of the tsunami wave propagation.

ANALYSIS & INTERPRETATION

The orographic map of the Bay of Bengal (Figure 1) clearly demonstrates that the continental shelf-break occur all along the coasts of the bay close to shore-line starting from Sumatra to Srilanka except Bangladesh where

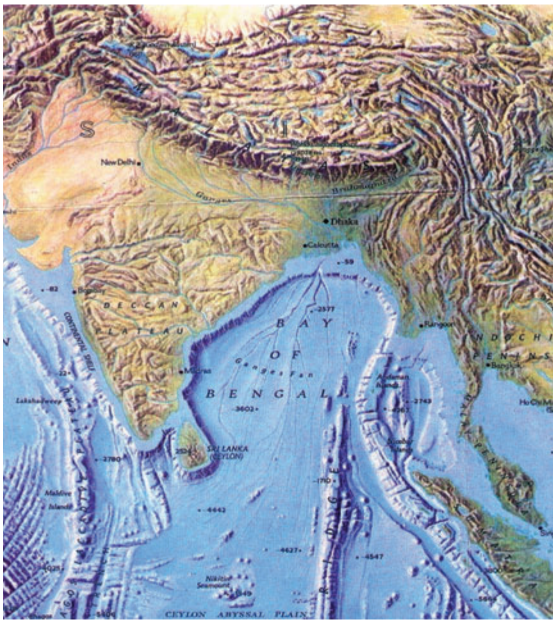

Figure 1: Orographic map of the Bay of Bengal

the shelf-break occurs about 200 km ocean-ward from the coast. In addition, the extended shallow bathymetric profile of the continental shelf plays a key role in flattening the waveform through a defocusing process (Ioualalen et al., 2007) that has greatly reduced the impact of any trans-oceanic tsunami.

The earthquake distribution (Figure 2) in the Bay of Bengal clearly identify the various fault source zones those are intrinsically associated with the locations of earthquake epicenters. Further the source zones are distinctly correlated with the occurrence of known tectonic elements such as Ninety East Ridge Mega-shear, Eighty Five Ridge Mega-shear (Raiverman, 1986), Sunda Trench, Andaman Trench, Chittagong-Arakan Fault Zone, and Peri-craton & Basin-margin Fault Zone (Khan & Akhter, 1999). Sumatra fault zone and Chittagong-Arakan fault zone are already geologically established fault zones those are available in the scores of publications. Andaman fault zone has also been documented as in the Figure 3 (Paul and Lian, 1975).

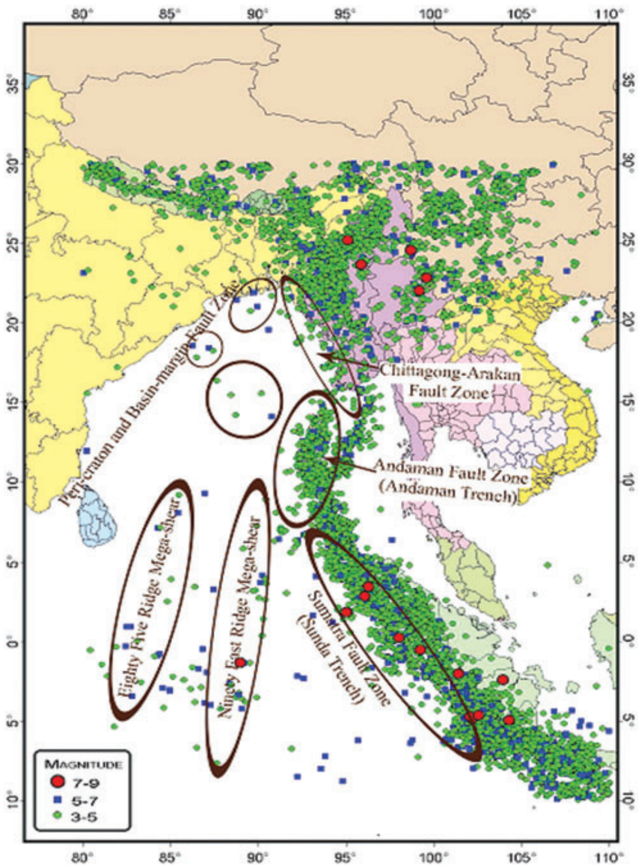

Figure 2: Inferrd fault source map derived from seismological data

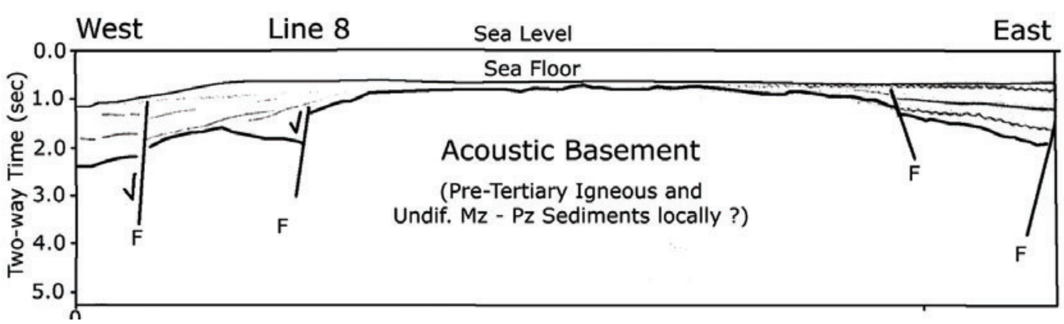

Figure 3: Inferrd andaman Fault zone derived from seismic section

The regional structural configuration of the Bay of Bengal as envisaged from the vertical component magnetic anomaly map (Figure 4) is quite consistent with the regional crustal features of the Bay of Bengal like Ninety East Ridge, Eighty Five East Ridge, and the elevated crust in the north Bay of Bengal.

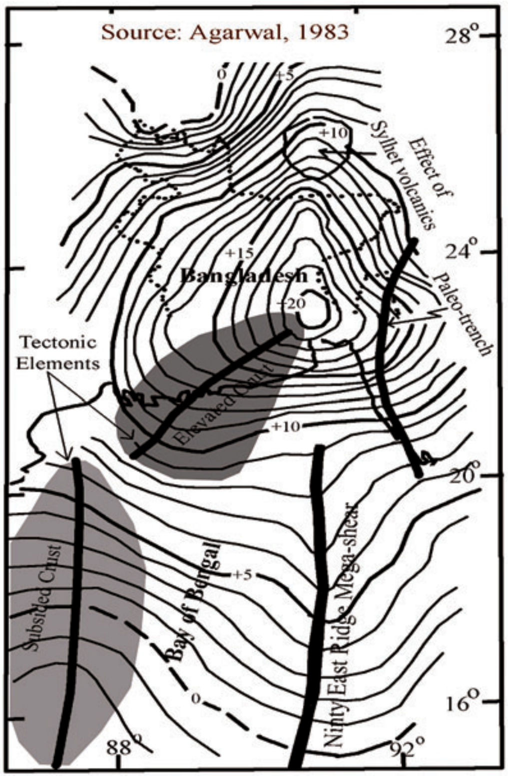

Figure 4: Regional crustal features of the Bay of Bengal derived from vertical magnetic data.

East-West seismic section along 19^{o}N latitude in between 87^{o}E and 91^{o}E longitudes (Figure 5) clearly exhibits a regionally long wavelength crustal feature representing an elevated and subsided older surface respectively (Curray amd Moore, 1971). Further, the normal faults occurring along the location of "Swatch of No Ground" in the 19oN seismic section suggest that the zone occupied by the "Swatch of No Ground" is a faulted zone resulted from the upward bulge of the older crust. The western part of the Bay of Bengal along the Eastern Ghat Mobile Belt, the focal mechanism solutions of four earthquake events also show pure strike-slip faulting (Khan, 1991) (Figure 6).

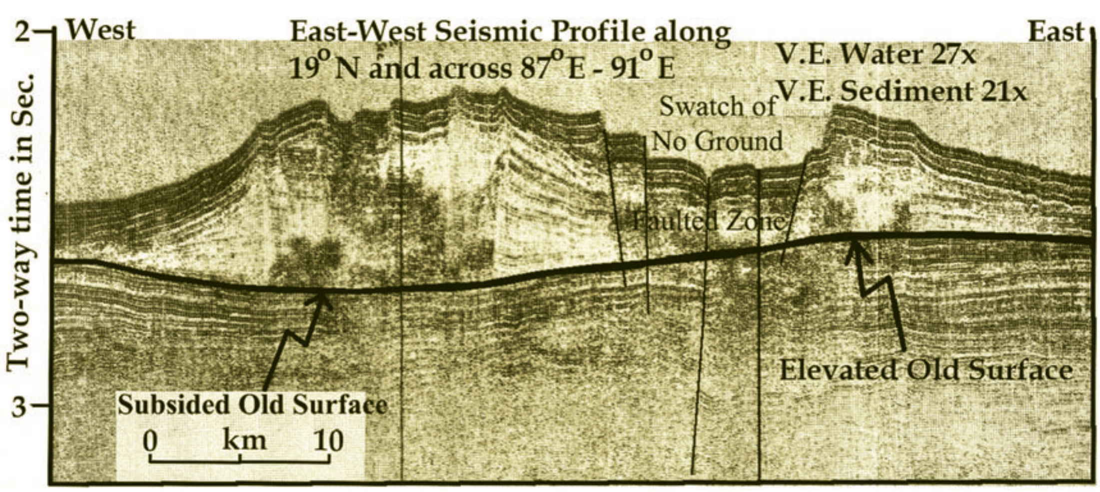

Figure 5: Seismic section showing crustal features of the Bay of Bengal

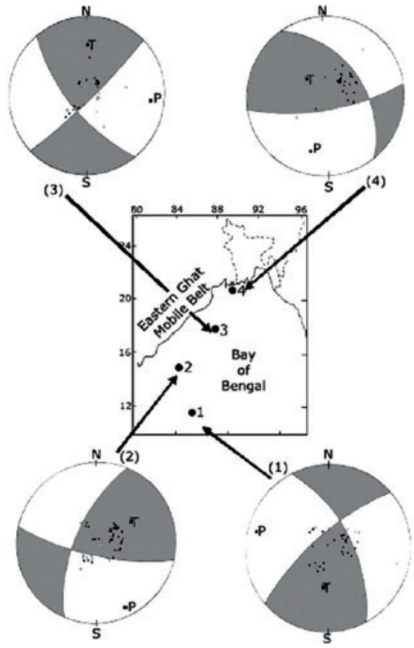

Figure 6: Western region of the Bay of Bengal exhibit a clear strike-slip fault mechanism.

TSUNAMIGENIC FAULT SOURCE

Based on the aforesaid geophysical and geological data, the potential fault source map of the Bay of Bengal is prepared (Figure 7). The parameters of the fault sources required to generate tsunami simulations such as the rupture length, slip offset, dip angle, slip angle, strike angle, and the moment magnitude have been calculated accordingly from geophysical and seismological data in order to develop tsunami model for worst scenario case. All together 11 fault source zones have been identified in the Bay of Bengal. After the international workshop on "Tsunami and Strom Surge Hazard Assessment and Management for Bangladesh" organized by CDMP, six (6) potential tsunamigenic fault-sources have been finalized.

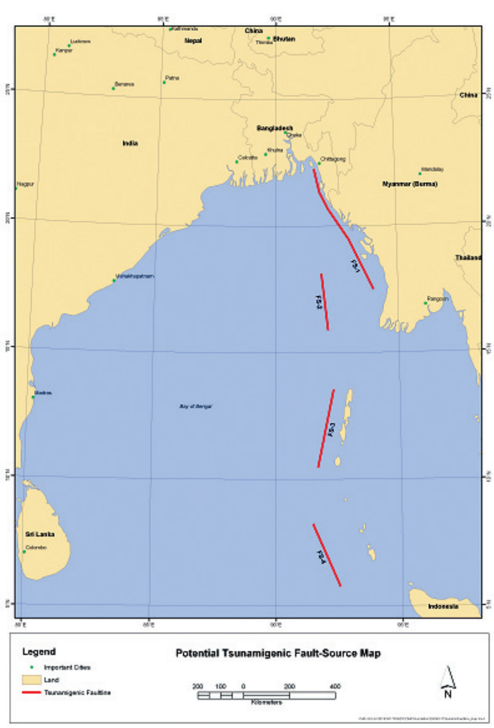

Figure 7: Potential fault-source map of the Bay of Bengal.

The position of the potential sources of tsunami with earthquake parameters are presented in Table-1.

Table 1: Potential Earthquake Sources With Parameters

Potential Sources of Tsunami	Fault Location	Fault Segment's Length	Max Fault Slip (Δ)	Initial Rupture Time	Fault dip angle (δ)	Fault slip angle , (λ)	Fault strike angle, (φ)	Focal depth (d)	Moment magnitude (Mw)
		(km)	(m)		(deg)	(deg)	(deg)	(km)	
FS-1	(22N, 91.7E)-(18.5N, 93.5E	410	3-7	0	30-40	45-65	340	10	**8** (Potential)
FS-2	17N, 92E	250	5	0	50	40	20	10	**8**
FS-3	12N, 92E	350	5	0	50	45	30	10	**8** (Potential)
FS-4	07N, 92E	300	9	0	40	50	320	10	**9**

CONCLUSIONS

All together four (4) potential fault sources of earthquake which may trigger tsunami in the Bay of Bengal have been identified in this study based on the geophysical and geological data. The parameters of the fault sources required to generate tsunami such as the rupture length, slip offset, dip angle, slip angle, strike angle, and the moment magnitude have been calculated from geophysical and seismological data.

ACKNOWLEDGEMENT

Authors express their heartist gratitude to Comprehensive Disaster Managment Programme (CDMP) of the Ministry of Food & Disiaster Management (MoFDM) for awarding the financial support to invistigate the vulnerability of the coastal area of Bangladesh with regard to Tsunami hazard. Authorts are also indepted to the members of the Technical Advisory Group (TAG) under Earthquake and Tsunami preparedness component of CDMP for their continuous guidence and technical supports in carrying out this investigation.

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Propagation of Tsunami Wave to the Coast of Bangladesh and Corresponding Inundation Towards Inland

Manjur Murhsed Zahid Ahmed[1], Zahirul Haque Khan[2], Niels Hvam Pedersen[3], Upal Mahamud[4] and A. S. M. Maksud Kamal[5]

ABSTRACT

In recent years, the threat of tsunamis has taken on added urgency after a 9.3 magnitude earthquake off Indonesia's Sumatra island in December 2004 triggered a tsunami that killed more than 230,000 people and left a half million homeless in a dozen countries. Bangladesh suffered relatively minor damage from the tsunami, with 2 people killed.

Tsunami is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. In order to assess the vulnerability of the coastal region of Bangladesh due to tsunami a tsunami model has been developed covering the Indian ocean, the Arabian sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system of DHI Water.Environment.Health. The model is two-way nested and it is driven through the release of the applied initial surface elevation only. The coastal region of Bangladesh is resolved on a 600m grid resolution. The Regional model having size of 16,200m has been used to absorb energy at the boundary and to avoid reflection from internal boundaries. All the boundary conditions at the regional model have been set to zero. The Coarse grid model which covers the Bay of Bengal, is the actual domain where initial surface deformation due to sub-sea earth quakes has been applied. The intermediate grid model serves only as a transition to the local fine grid model. The fine grid Model is used for detailed study of the inundation and flood risk due to the Tsunami wave. The model has been calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to the earthquake.

In total four scenarios of tsunami have been identified based on the potential sources of earthquake in the Bay of Bengal. Initial surface level maps for all the scenarios of tsunami have been generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all tsunamis have been simulated with respective initial surface level maps under Mean High Water Spring (MHWS) tide condition. The maximum inundation map for each scenario of tsunami has been generated based on the simulation results. Finally inundation risk map has been generated using GIS tool.

The inundation risk map for tsunami shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast remains vulnerable during tsunami. Maximum inundations have been found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area and Cox's Bazar coast in the range of 2-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 2-3 m.

Keywords: Tsunami, Propagation, Inundation, Coastal Region, Model, MIKE 21, QuakeGen and GIS Tool.

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INTRODUCTION

In recent years, the threat of tsunamis has taken on added urgency after a 9.3 magnitude earthquake of Indonesia's Sumatra island in December 2004 triggered a tsunami that killed more than 230,000 people and left a half million homeless in a dozen countries. Bangladesh suffered relatively minor damage from the tsunami, with 2 people killed. CDMP commissioned Institute of Water Modelling (IWM) to carry out the study titled "Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region" in December 2007. Under the study IWM prepared inundation risk map for the coastal region of Bangladesh based on the simulation results of 6 potential scenarios of tsunami. In this paper vulnerability of the coastal region of Bangladesh due to tsunami has been assessed based on the simulation results.

APPROACH OF THE STUDY

The tsunami model has been developed using existing data and MIKE 21 modelling tool. The model comprises four (4) nested levels having grid sizes vary from 16200 m to 600 m. The regional model covers the Indian ocean, the Arabian sea, the Bay of Bengal and the coast of Bangladesh and the fine grid model covers the coastal region of Bangladesh. In total six scenarios of tsunami have been identified based on the potential sources of earthquake in the Bay of Bengal. Initial surface level maps for all the scenarios tsunami have been generated using QuakeGen, a geological model and MIKE 21 modelling system. Then all tsunamis have been simulated with respective initial surface level maps. The maximum inundation map for each scenario of tsunami has been generated based on the simulation results. Finally inundation risk map has been generated using GIS tool.

Decay factors of the propagation of tsunami wave on land have been incorporated in the model using Manning number (M, m1/3/s) which is reciprocal of Manning's coefficient of roughness (i.e. M=1/n).

DATA

Bathymetric data have been collected from different sources and used for the generation of bathymetry of tsunami and storm surge models. Main source of bathymetric data of the Bay of Bengal, Indian Ocean and Arabian sea is the ETOPO2 of National Geophysical Data Centre and C-Map of Hydrographic Office of UK. Bathymetric data for the Meghna Estuary have been collected from Meghna Estuary Study I & II (1998-99), Land Reclamation Study (2007) and Nijhum Dwip X-dam Study (2006) and for the internal rivers from Mongla Port Study (2004), IPSWAM (2008) and KAFCO Study (2007). Digital Elevation Model (DEM), Geo-morphological map and Landuse map developed under this study and the polder levels and alignment surveyed under 2nd CERP have been used for model development.

Main source of data of the DEM is the FINNMAP land survey. The relative accuracy of the data within Sundarban Reserved Forest (SRF) is (x, y) 10's of centimetres and (z) 1m and the absolute accuracy is +/- 2 m (including the difference between Datum and reality) according to the Technical Report-TR No. 09, Sundarban Biodiversity Conservation Project, 2001.

NUMERICAL MODELLING OF TSUNAMI

Tsunami (pronounced tsoo-nah-mee) is an oceanic gravity wave generated by submarine earthquake resulting from tectonic processes and other geological processes such as volcanic eruptions and landslides in the sea. Tsunami is a Japanese word meaning harbor wave. Its amplitudes are typically small in the open sea but can reach to damaging amplitudes near the shore or in shallow or confined waters. They are also called oceanic seismic waves.

When two ocean plates move towards each other and one of the plates form uplift during Earth Quake causes tsunami. Figure 1 shows the subduction of one plate under another continental plate during earthquake.

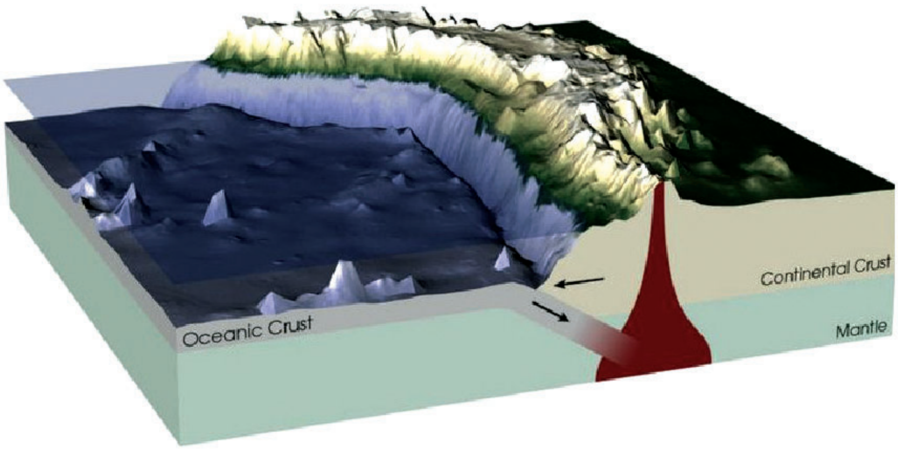

Figure 1: Subduction of one plate under another continental plate

During earthquake three different types of slip occur between two ocean plates along the fault line: normal dip-slip, reverse dip-slip and strike-slip (shown in Figure 2). But the reverse (forming uplift) and the normal dip-slip (forming subsidence) are tsunamigenic.

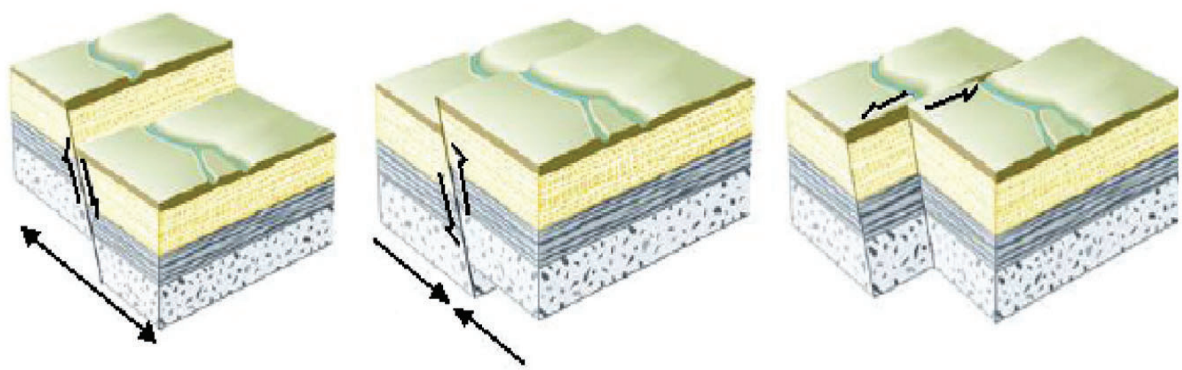

Figure 2: Normal Dip-Slip (left one), Reverse Dip-Slip (middle one) and Strike-Slip

The numerical modelling of the tsunami waves from the source to the coastal inland can be considered in three stages:

1. Source Modelling: simulation of initiation of tsunami generated by sea floor displacement;
2. Tsunami Wave Propagation Modelling: simulation of tsunami wave propagation from the source to the coast; and
3. Tsunami Inundation Modelling: simulation of tsunami waves propagation from the coast to the inland over dry land

SOURCE MODELLING

The most important part of tsunami modelling is to create initial water level displacement due to the impact of the Earthquake. A geological model named QuakeGen model has been used for calculation of deformation in bed level based on the geophysical and seismological data.

The model is based on the theory of Manshinha and Smylie 1971. It calculates a displacement of the seabed that results from seismic fault movements in the earth's crust, assuming that the crust consists of an elastic body and fault shape is rectangular. The model describes the deformation of the bed level due to a double coupled model developed by Yoshimitsu Okada in 1985 (Figure 3 and Figure 4).

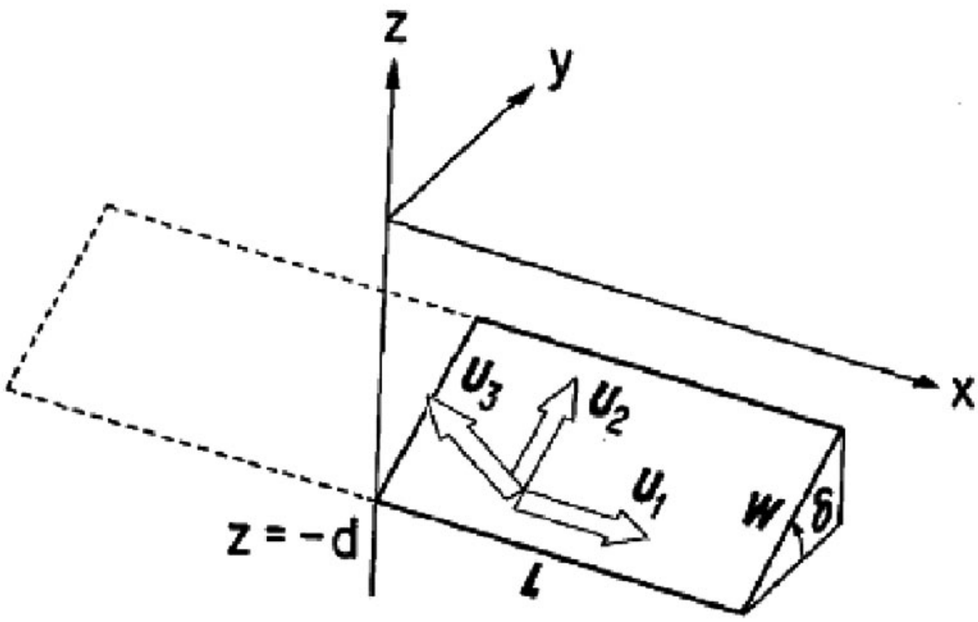

Figure 3: Geometry of the Okada model

The model uses the following fault parameters: Dip, Slip and Strike angel, the Depth of the Quake and the Length, Width and Height of the Slip vector. Based on these values, the Elasticity module ? and the specific Poisson number the displacement in the bed level is calculated.

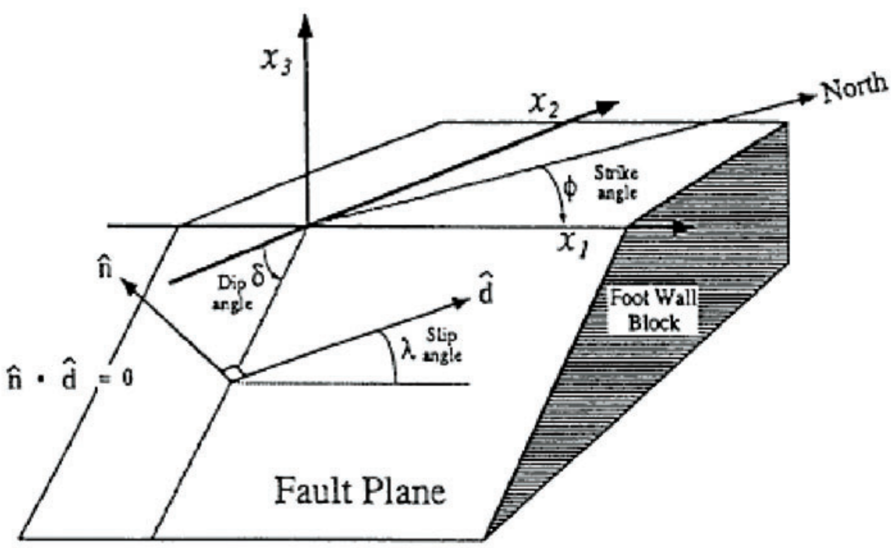

Figure 4: Parameter descriptions in the Okada model

Strike is the azimuth of the fault plane (fault strike line) measured from North, and dip is the azimuth of the fault plane measured from the horizontal line. Slip is the angle of the fault slip direction measured from the horizontal line. The result from QuakeGen is the Initial displacement of the bed level.

Based on the output from QuakeGen the initial surface level has been calculated using hydrodynamic module of MIKE 21 modelling system. In this way initial surface level maps for four (4) potential sources have been generated based on the geological parameters. A sample plot of initial surface level of tsunami (FS-3) has been presented in Figure 5.

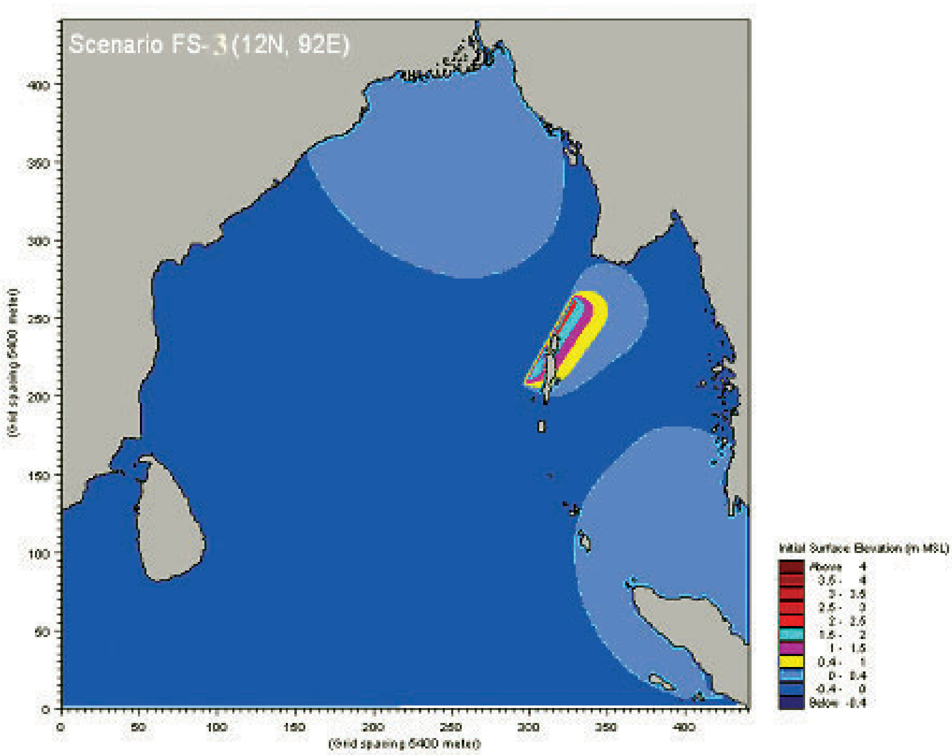

Figure 5: Initial Surface level of tsunami scenario FS-3

TSUNAMI WAVE PROPAGATION AND INUNDATION MODELLING

Tsunami wave propagation and inundation modelling from its sources to the Bangladeshi coast have been carried out using hydrodynamic module or flow module of MIKE21 modelling system. The scientific background of these two modules has been described below:

The flow model is two-dimensional hydrodynamic simulation program which calculates non-steady flow resulting from tidal and meteorological forcing on rectilinear grid. The model solves the non-linear shallow water equations on a dynamically coupled system of nested grid using finite difference numerical scheme. It simulates unsteady two-dimensional flows taking into account density variations, bathymetry and external forcing such as metrology, tidal elevations, currents and other hydrographical conditions. The basic partial differential equations are the depth integrated continuity and momentum equations (shallow water equations):

$$\frac{\delta\xi}{\delta t}+\frac{\delta p}{\delta x}+\frac{\delta q}{\delta y}=0$$

$$\frac{\delta p}{\delta t}+\frac{\delta}{\delta x}\left(\frac{p^2}{h}\right)+\frac{\delta}{\delta y}\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta x}+\frac{gp\sqrt{p^2+q^2}}{C^2h^2}-fq-C_w\frac{\rho_A}{\rho_W}WW_x+h\frac{\delta}{\delta x}\left(\frac{p_a}{\rho_w}\right)=0$$

$$\frac{\delta q}{\delta t}+\frac{\delta}{\delta y}\left(\frac{q^2}{h}\right)+\frac{\delta}{\delta x}\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta y}+\frac{gq\sqrt{p^2+q^2}}{C^2h^2}+fp-C_w\frac{\rho_A}{\rho_W}WW_y+h\frac{\delta}{\delta y}\left(\frac{p_a}{\rho_w}\right)=0$$

Where, xy is the horizontal coordinates [m], t is time [s], h is the water depth [m], ζ is the Surface elevation [m], p and q is the flux densities in x and y directions [$m^3/s/m$], g is acceleration due to gravity [m/s^2], C is Chezy's bed resistance coefficient [$m^{1/2}/s$], f is Coriolis parameter [s^{-1}], Cw is the wind friction factor [-], W (Wx, Wy) is the wind speed and its components in x and y directions [m/s], P_a is the atmospheric pressure [$kg/m/s^2$], ρ_A is the density of air [kg/m^3], ρ_w is density of water [kg/m^3].

MIKE21 allows the use of nested grids, which is especially important for the simulation in coastal areas with complex geometries of land-water boundaries. The model uses dynamically consistent two-way nesting technique. The detailed resolution near land and large gradients in the water depth are necessary to describe the local shoaling effect of the tsunami. The correct propagation of tsunami waves depends primarily on the initial conditions of the wave and secondly on the bathymetry of the area. After the calculation of water surface deformation from source model or from empirical equations, the tsunami propagation model will then be initialized with the deformed sea surface, after which it simulates the spreading and propagation of the wave in different directions and finally produces inundation at the land area.

TSUNAMI MODEL FOR BANGLADESH

A tsunami model has been developed for the Indian ocean, the Arabian sea, the Bay of Bengal and the coastal region of Bangladesh using MIKE21 modelling system of DHIWater.Environment.Health. The model has been applied to simulate the tsunami propagation and inundation from its sources to the coast of Bangladeshi. The tsunami model comprises four (4) nested levels with the following grid sizes:

- Regional model having grid size of 16200m
- Coarse model having grid size of 5400m;
- Intermediate model having grid size of 1800m and
- Fine model having grid size of 600m.

The model is two-way nested and it is driven though the release of the applied initial surface elevation only. The Meghna Estuary is resolved on a 600m grid resolution. The fine grid model domain covers the coastal region up to Cox's Bazar. Technaf and Saint Martin's are not included in the coarser grid model. The Regional model has been used to absorb energy at the boundary and to avoid reflection from internal boundaries. All the boundary conditions at the regional model have been set to zero. The Coarse grid model which covers the Bay of Bengal, is the actual domain where initial surface deformation due to sub-sea earth quakes has been applied. The intermediate grid model serves only as a transition to the local fine grid model. The fine grid Model is used for detailed study of the inundation and flood risk due to the Tsunami wave. Figure 6 shows the regional model domain.

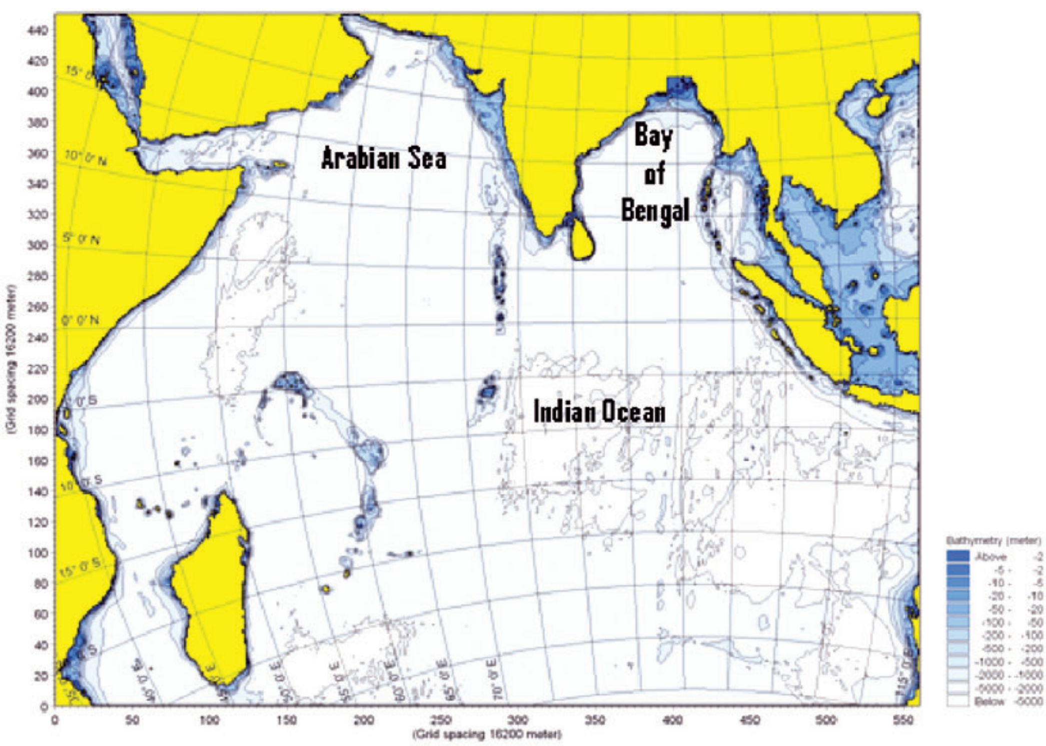

Figure 6: Regional model domain

The simulation parameters of the tsunami model are shown in Table 1.

Table 1: Tsunami Simulation Parameters

Tsunami Simulation		
Period Start	01 - 01 - 2008	00:00
Period End	01 - 01 - 2008	12:00
Time Step	30 second	
No of Time Steps	1440	
Manning	64 ml/3/s	
Constant Eddy	1 m2/s	
Wind	0 m/s	
Flood depth	0.3 m	
Dry depth	0.2 m	

The regional grid model of tsunami was calibrated with the tsunami of December 26, 2004, which occurred at the West Coast of Sumatra due to the earthquake.

INCORPORATION OF DECAY FACTOR IN THE MODEL

Decay factors of the propagation of tsunami and storm surge waves on land have been incorporated in the model using Manning number (M, m1/3/s) which is reciprocal of Manning's coefficient of roughness (i.e. M=1/n).

The land use map for coastal area of Bangladesh shows that the coastal area is covered mainly by agriculture, settlement and reserved forest. For simulation of tsunami wave, two categories of the land use have been considered; one is for agriculture and settlement and other one is for Sundarban reserved forest. The Manning number of 25 m1/3/s (n=0.04 s/m1/3) has been considered for the agriculture and settlement area and 15 m1/3/s (n=0.07 s/m1/3) for the Sundarban reserve forest.

INUNDATION RISK MAP OF TSUNAMI

Inundation risk map for the coastal region of Bangladesh has been prepared based on the four scenarios of tsunami originated from four potential sources of earthquake in the Bay of Bengal. The map has been prepared considering the land level based on digital elevation model and the existing polders in the coastal region of Bangladesh.

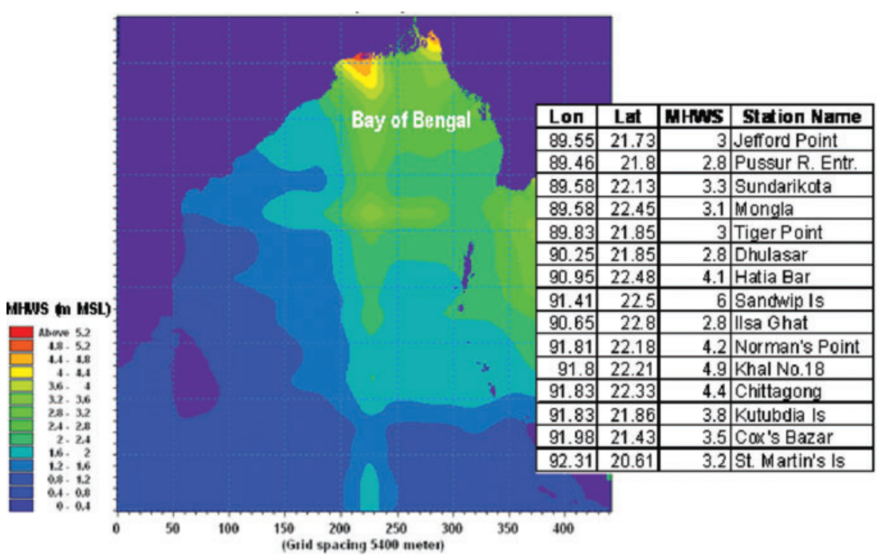

Figure 7: MHWS level in Bay of Bengal

Initially all the tsunamis generated from the potential sources have been simulated using MIKE 21 modelling system. Simulations have been carried out for Mean Sea Level (MSL) condition and for Mean High Water Spring (MHWS) level condition. In all the simulations only the MHWS condition shows the influence of tsunami along the coast of Bangladesh. Maximum inundation maps for all of the tsunami events (i.e. 4 scenarios) have been generated from the simulation results under MHWS condition. Finally the inundation risk map has been generated based on the maximum inundation maps using GIS tool.

In order to determine the MHWS level for the coast of Bangladesh, a map has been produced for the Bay of Bengal. The MHWS data at different locations have been taken from the Admiralty Tide Tables (1995). Figure 7 shows the MHWS level along the coast of Bangladesh, which is 3 m MSL at western coast and higher in Sandwip channel. In this study 3.46 m PWD has been considered for the simulation of tsunami at the coast of Bangladesh.

Maximum inundation maps for 4 scenarios of tsunami show insignificant influence in the coastal region of Bangladesh under MSL condition. But some influence has been found under MHWS tide condition.

Inundation risk map for tsunami has been generated based on the maximum inundation maps of four tsunamis and presented in Figure 8. It shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast are likely to be inundated during tsunami. Maximum inundation is seen at Nijhum Dwip in the range of 3-4 m, and at Sundarban area and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 1-3 m. Bauphal upazila of Patuakhali district is low lying area which may experience inundation of 1-2 m in MHWS tide. In this area the influence of tsunami wave is insignificant.

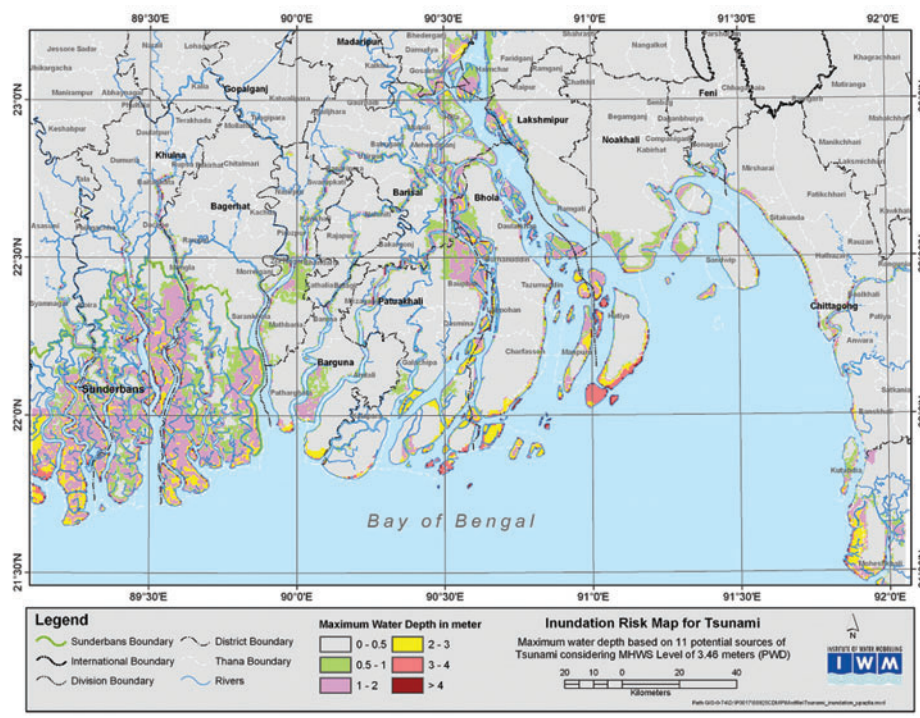

Figure 8: Inundation risk map of tsunami in the coastal region of Bangladesh

CONCLUSIONS

A tsunami model has been developed for the Bay of Bengal and the coastal region of Bangladesh.

Inundation risk map prepared based on simulation results of 4 scenarios of tsunami shows that Sundarban area, Nijhum Dwip, south of Hatia (outside polder) and Cox's Bazaar coast remains vulnerable during tsunami. Maximum inundations have been found at Nijhum Dwip in the range of 3-4 m, and at Sundarban area and Cox's Bazar coast in the range of 1-3 m. Small islands and part of the Manpura island in the Meghna Estuary get inundated by 1-3 m.

In this study the inundation risk map of tsunami has been prepared considering 4 potential sources of tsunami, there might be other potential sources which may cause different level of risk at other areas. That needs further investigation to ascertain the level of risk.

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Authors express their heartist gratitude to Comprehensive Disaster Managment Programme (CDMP) of the Ministry of Food & Disiaster Management (MoFDM) for awarding the financial support to invistigate the vulnerability of the coastal area of Bangladesh with regard to Tsunami hazard. Authorts are also indepted to the members of the Technical Advisory Group (TAG) under Earthquake and Tsunami preparedness component of CDMP for their continuous guidence and technical supports in carrying out this investigation.

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Storm Surge Modelling and Inundation Risk Map of the Coastal Area of Bangladesh

Zahirul Haque Khan[1], Manjur Murhsed Zahid Ahmed[2], Upal Mahamud[3] and A. S. M. Maksud Kamal[4]

ABSTRACT

Cyclonic storms affecting the coastal region of Bangladesh cause heavy loss to life and property. The coastal region bordering the Bay of Bengal suffer the worst because most of the tropical cyclones have genesis over the Bay of Bengal and strike the coast of Bangladesh. The vulnerability of coastal area to storm surge flooding considerably high, since it is predominantly low-lying and characterized by numerous tidal rivers and polders. Due to the increase in the developmental activities in these thickly populated coastal region, the vulnerability of this regions to storm surges and the need for quantitative estimates have increased in recent years. During pre-monsoon (April to May) and post monsoon (October to December) disastrous tropical cyclones form in the Bay of Bengal. Most of the cyclones hit the coasts of Bangladesh with north-eastward approaching angle. Over the last 47 years (1960-2007) about 18 severe cyclones hit the coast of Bangladesh.Hindcasting (Modelling of past) of the storm surge has been made using available storm surge model in IWM to assess the storm surge height and risk of inundation of the coastal area.. The available Bay of Bengal model for surge simulation is based on MIKE21 modelling systems. Hindcasting of storm surge height induced by the past cyclones provide essential data on the coastal plains for developing zoning map of high risk area. Eventualy this zoning map will be instrumental for planning of adequate number and proper location of cyclone shelters, re-engineering of existing coastal infrastructure and planning and design of future infrastructure in the coastal area as well as planning of mangrove afforestation for reduction of surge height and damage of embankment. The inundation risk map has been prepared based on the maximum inundation depths of past 18 cyclones. The map has been prepared considering land level of the coastal area and the existing polders in the coastal region of Bangladesh.It is seen that the highest inundation depth is in the order of 5 m to 7.5 m within the Meghna Estuary area. The eastern coast experiences maximum inundation between 4m and 6 m and western coast experiences inundation within the range of 3-5 m.

Key Words: storm surge, numerical model, hindcasting, inundation risk map, digital elevation model, vulnerability, disaster reduction, planning cyclone shelter.

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INTRODUCTION

Storm surges are rapid sea level variations induced by cyclone wind fields. Cyclonic storms affecting the coastal region of Bangladesh cause heavy loss of life and property. The coastal regions bordering the Bay of Bengal suffer the worst because most of the tropical cyclones have genesis over the Bay of Bengal and strike the coast of Bangladesh. About one-tenth of the global total cyclones forming in different regions of the tropics occur in the Bay of Bengal. About one-sixth of tropical storms generated in the Bay of Bengal usually hit the Bangladesh coast. In many cases the observed maximum water level was 4-12m and the death toll was 4000 to 3000,000. The main factors contributing to disastrous surges in the Bay of Bengal, especially Bangladesh are (a) Shallow coastal water (b) Convergence of the Bay, (c) High astronomical tides (d) Thickly populated low lying island and (f) Complex coastline and a number of tidal inlets including one of the worlds largest river system Ganga-Brahmaputra-Meghna. Bangladesh Meteorological Department (BMD) forecasts the propagation of cyclone track, timing and location of landfall quite accurately. Institute of Water Modelling has maintained a storm surge model for the Bay of Bengal including the coastal area since 1995, this model has been calibrated and validated with the observed storm surges of 1991 and 1988. The potential of the model has been shown in hindcasting the past cyclone and to generate the spatial and temporal variation of surge level and coastal flooding. The available Bay of Bengal Model, with further improvement, is also capable of forecasting the surge height and coastal flooding at local level, which is eventually very useful for disaster preparedness and early warning system. In the present study storm surge inundation risk map has been prepared based on maximum inundation depth of past 18 cyclones.

STUDY AREA

The coastal zone (Figure 1) covers 19 out of 64 districts facing, or in proximity to, the Bay of Bengal, encompassing 153 upazilas/ thanas (MoWR, 2005). The zone constitutes 32 percent of the area and 28 percent of the population of Bangladesh. In 12 of these districts, 48 thanas face a combination of cyclone risk, salinity and tidal water movement above critical levels and are designated as "exposed coast" (MoWR, 2005). The coastal zone covers an area from the shore of 37 to 195 kilometres, whereas the exposed coast is limited to a distance of 37 to 57 kilometres. The coastal zone of Bangladesh forms the lowest landmass and is part of the delta of the extended Himalayan drainage ecosystem. Sixty-two percent of the land of the coastal zone has an elevation of up to three metres and 86 percent up to five metres (MoWR, 2005). The coastal zone of Bangladesh is prone to multiple threats such as cyclones, storm surges and floods, as well as earthquakes, tsunamis, and above all, climate change.

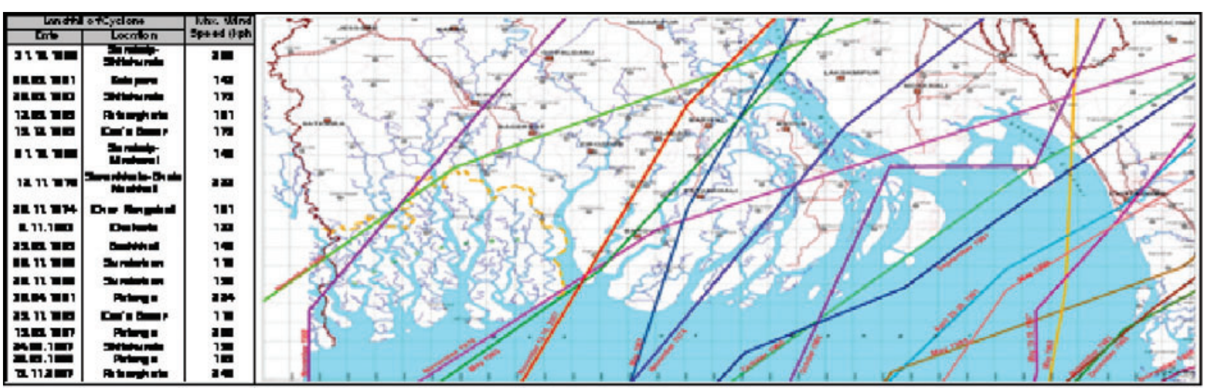

Figure 1: Past Cyclones and -SIDR 07 Tracks

PAST CYCLONES

Cyclones are extreme meteorological events in the coastal region of Bangladesh. They occur mainly in the pre (April-May) and post (October-December) monsoon when the meteorology becomes unstable and develops into tropical cyclones. The wind generated surge during a cyclone can be quite high. The funnel shape of the bay tends to concentrate the surge, and the transition from deep to shallow waters on the continental shelf amplifies the surge. There were about 42 events of severe storm surges in India and Bangladesh during the period 1800-2001 (NIOT, 2002). The combined death toll in those storms stands around one million people, according to the records of the meteorological department. The severe cyclone track along with cyclone-07 is shown in Figure 1. It has been seen that the land fall of most of the cyclone is at Noakhali-Chittagong coast.

STROM SURGE MODEL

The available Bay of Bengal model for surge simulation is based on MIKE21 modelling systems, which is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two dimensional flows in one layer fluids and has been applied in many studies. Storm surge model comprises of Cyclone model and Hydrodynamic model. In the hydrodynamic model simulations meteorological forcing like cyclone is given by wind and pressure field derived from the analytical cyclone model. The model complex comprises of two modules; a two-dimensional depth integrated hydrodynamic model (MIKE 21 NHD) and a cyclone model (CYWIND).

HYDRODYNAMIC MODEL

The model is two way nested and includes four different resolution levels in different areas (Figure 2). Nesting of the models has been necessary to obtain a proper resolution of the hydrodynamic processes and at the same time, minimise the number of computational points. A Coarse model with a grid spacing of 5400 metre covers the Bay of Bengal above latitude 16˚ north. Inside this grid is an intermediate model with a grid size of 1800 metre covering the Bay above latitude 21˚. Enclosed by these two models fine grid models with a grid size of 600 and 200 metres covering the most of the Bangladesh coast, describes local effects in the coastal area. The model has a wide, deep, open ocean boundary in the south situated along line extending from the Vishakhapatnam in India and Gwa Bay in Myanmar.

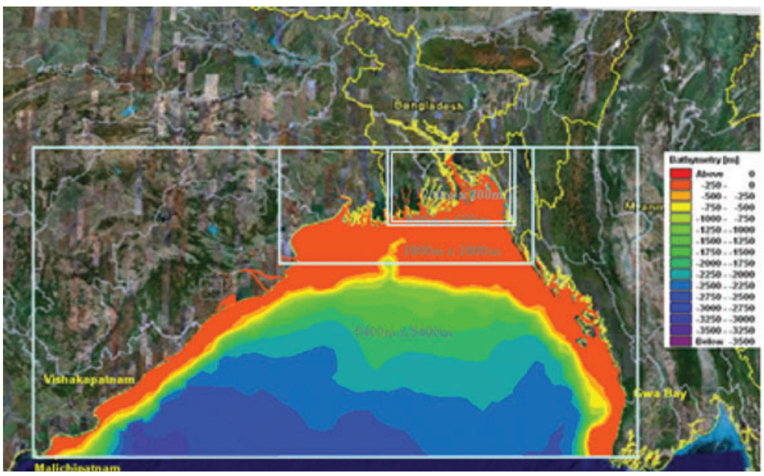

Fig 4: Bay of Bengal Model

CYCLONE MODEL

The description of a cyclone is based on few parameters related to the pressure field, which is imposed to the water surface and a wind field which is acting as a drag force on the water body through a wind shear stress description. The pressure field creates a local level setup close to the eye up to one metre only. Whereas the wind shear contributes more to the surge giving a level setup on the right side of the eye and a level set down on the left side. A reasonable description of maximum wind and especially the extent of the high winds in the cyclone are important to obtain the right level setup and set down. Cyclone eye is almost circular and it coincides with the area of lowest pressure (maximum pressure drop) where the cyclonic wind speed is nearly zero.

Cyclone model needs following data/information for the description of wind field and pressure field:

- Radius of maximum winds, Rm,
- Maximum wind speed, Vm and
- Cyclone track forward speed Vf and direction.

The pressure field is defined by the following parameters:

· Central pressure, Pc

· Neutral pressure, Pn

The calibration of cyclone model has been made against pressure and wind speed of Cyclone 2007. The cyclone model has been validated against pressure and wind for April 1991 cyclone data and also for November 1988 and November 1995 cyclone data. The simulated wind and pressure field of cyclone 2007 (SIDR) is shown in Figure 3.

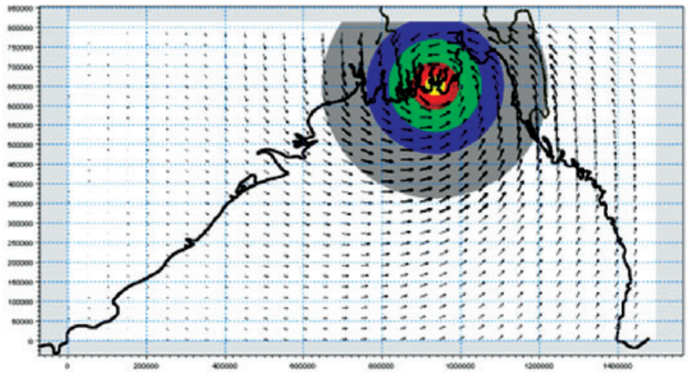

Figure 3: Wind and pressure field of Cyclone during land fall

STORM SURGE MODELLING

The tidal calibrated and validated hydrodynamic model with input from cyclone model is used to calibrate the surge level using the wind friction factor as calibration parameter only. A wind friction factor of 0.0026 (Dube et al., 1985) is used for the calibration. The surge level is calibrated against cyclone at Hiron point and validated against the 1991 and 1988 cyclones. In this study the available storm surge model has been validated for the cyclone of 2007 at Hiron Point, for the cyclone of 1998 at Charchenga and Khepupara and for the cyclone of 1988 at Khepupara. Sample comparison plots of water level during the cyclone 2007.

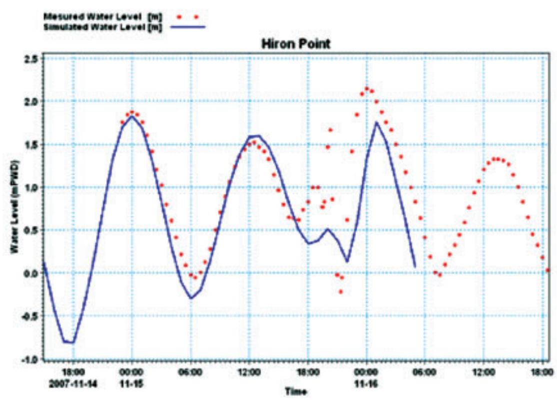

Figure 4: Sample calibration plot at Hiron Point during Cyclone SIDR, 2007

MAXIMUM INUNDATION OF DIFFERENT CYCLONES

Maximum inundation depths of different cyclones occurred from 1960 to 2007 have been generated based on model results. Simulations of different cyclones have been carried out considering existing polders in the coastal region. It is seen that the different coast of Bangladesh gets inundated due to different tracks of cyclones. Table 1 shows the coast of Bangladesh affected by cyclones during the period 1960-2007.

Table 1: Cyclones Caused Inundation At Different Coast Of Bangladesh

Coast of Bangladesh	Affected by Cyclones	Cyclones caused maximum inundation
Central coast lies in the Meghna Estuary	1960, 1963, 1966, 1970, 1974	1970, 1974
Eastern Coast	Dec. 1965, 1983, 1985, 1991, 1995, Sept. 1997, May 1997, 1998	1991
Western Coast	1961, May 1965, 1986, 1988, 2007	1988, 2007

It has been seen that maximum inundation at the central coast occurred in 1970 and 1974 cyclones, at the eastern coast in 1991 cyclone and at the western coast in 1988 and 2007 cyclones.

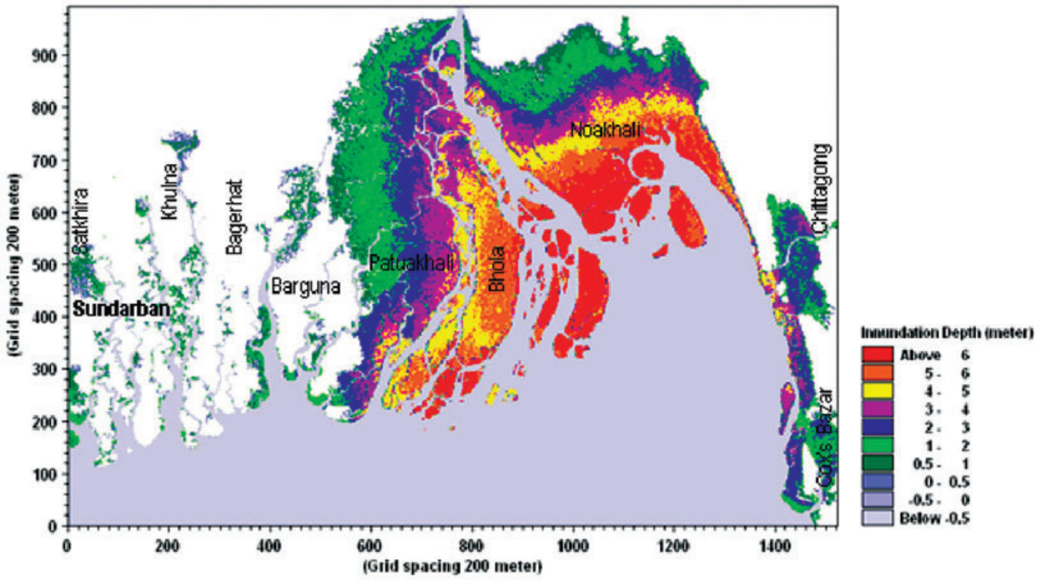

Figure 5: Maximum inundations caused by the Cyclone of 1970

1970 cyclone crossed Barguna district, Patuakhali district, Bhola island, Noakhali coast and Urirchar island with a maximum wind speed of 222 Kilometre per hour (kph). The cyclone made the land fall during high tide. Simulation result shows that the cyclone-induced storm surge inundates all the coasts and islands in the Meghna Estuary and also the eastern coast of Bangladesh. Maximum inundation has been found in the range of 5-7 m at Bhola island, Hatia, Nijhum Dwip, Noakhali coast, Sandwip and Urirchar. 1974 cyclone made landfall at Char Rangabali in the Tetulia River and crossed Bhola and Noakhali districts with a maximum wind speed of 161 kph. Simulation result of 1974 cyclone-induced storm surge shows that maximum inundation takes place in the range of 2-4 m at Hatia, Nijhumdwip, Noakhali coast, Sandwip and Urirchar..

INUNDATION RISK MAP

The propagation of storm surge in land and its extent of inundation vary widely along the coast, which depends on several regional and local factors related to hydrology, topography and oceanography. Some of the important factors are:

- Storm surge height at the coast;
- Angle of cyclone track with respect to the coast line;
- Tidal condition;
- Offshore and near-shore bathymetry;
- Slope of the land;
- Curvature of the coastline;
- Width and depth of river mouth through which the surge travels;
- Presence of islands and chars;
- Land topography; and
- Land use.

During the period 1960 to 2007, 18 cyclones and its associated storm surges hit the Bangladesh coast at different locations and inundated different coastal areas of Bangladesh time to time. The inundation in land due to these cyclones covers the entire coast of Bangladesh. In this study inundation risk map has been prepared based on the maximum inundation depths of 18 cyclones and considering the digital elevation model and the existing polders in the coastal region of Bangladesh (Figure 6). It shows that the highest inundation depth of 5 m and 7.5 m lies within the Meghna Estuary area. The eastern coast experiences maximum inundation between 4m and 6 m and western coast experiences inundation within the range of 3-5 m. Upazila-wise inundation area in the coastal region of Bangladesh has been prepared based on the inundation risk map.

A statistical analysis shows that Urirchar, Nijhum Dwip, Noakhali coast, Shitakunda coast and the small islands of the Meghna Estuary are inundated more than 1 meter about 50% time during the occurrence of 18 cyclones. The Cox's Bazar Area is flooded by more than 30 % time, Anwara and Bashkhali coasts by more than 15 % time, Bhoal island by more than 5 % time and the western coast gets inundated by more that 10 % time during the occurrence of 18 cyclones.

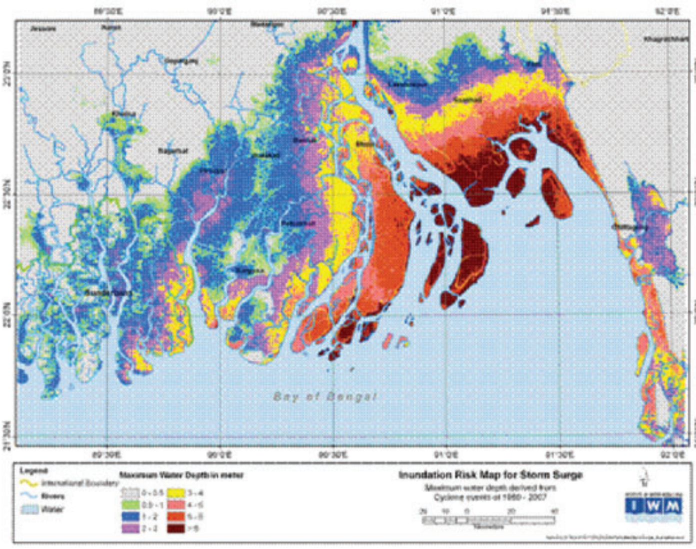

Figure 6: Inundation risk map prepared from 18 cyclones from 1960-2007

Four worst case scenarios of cyclone-induced storm surge have been developed considering wind and pressure field of 2007 cyclone, four different tracks covering different coasts of Bangladesh and landfall during high tide. Another risk map has been generated based on 18 real cyclones and four synthesized cyclones (Figure E.6). It shows that inundation increases at the Sundarban coast and around Baleshwar River by 1-2 m, at Bhola island by 0.5-1 m, at Sitakunda coast by 2-3m, at Anwara and around the Karnaphuli River mouth by 2-3 m, at Bashkhali by 1-2 m, at Kutubdia island by 0.5-1 m, and at Cox's Bazar by 0.5-1 m. There is no increase in Noakhali Coast under the worst condition.

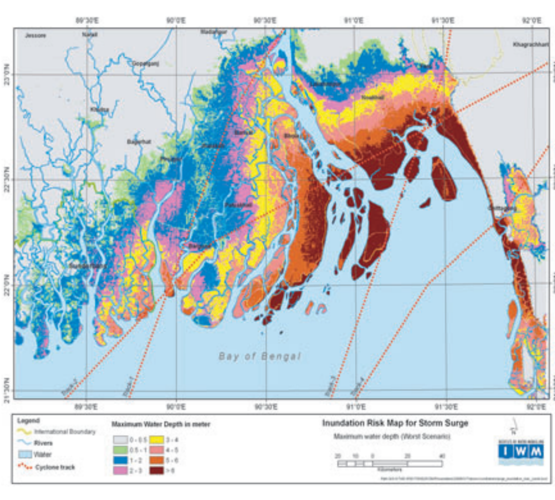

Figure 7: Inundation risk map for worst case scenarios

The area inundated by more than 1 meter of water depth may be considered as High Risk Area (HRA) according to the criteria of Multipurpose Cyclone Shelter Programme (MCSP, 1993).

CONCLUSIONS

A comprehensive analysis on storm surge induced inundation has been made with the available data and model. Storm surge induced inundations by the past cyclones provide essential data on the coastal plains for developing zoning map of different risk area. This zoning map can be useful for planning of adequate number and proper location of cyclone shelters, re-engineering of existing coastal infrastructure and planning and design of future infrastructure in the coastal area as well as planning of mangrove afforestation for reduction of surge height and damage of embankment.

The inundation risk map has been prepared based on the maximum inundation depths of past 18 cyclones and considering the available digital elevation model of the coastal area. The reliability of this map largely depends on digital elevation model and the bathymetry of the Bay of Bengal. There is a need of improvement of digital elevation model on the basis of new topographic survey data and the storm surge model with the updated bathymetry.

However, early warning and disaster preparedness require effective and timely forecasts on storm surge along the Bay of Bengal and coastal area of Bangladesh for reduction of loss of life and property. The benefit of forecasting of storm surge induced flooding are reduction in damage to coastal infrastructure and improved cost effective design of local coastal defences. The available Bay of Bengal Model, with further improvement, is also capable of forecasting the surge height and coastal flooding at local level.

Currently Bangladesh Meteorological Department (BMD) forecasts the propagation of cyclone track, timing and location of landfall quite accurately, but the forecasting of inundation depth at local level is missing that needs to be developed.

It is of immense importance to develop operational frameworks for sustainable coordination, collaboration and information sharing and management across DMB, BMD,FFWC, IWM and with main disaster management stakeholders during storm surge induced flooding.

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Authors express their heartist gratitude to Comprehensive Disaster Managment Programme (CDMP) of the Ministry of Food & Disiaster Management (MoFDM) for awarding the financial support to invistigate the vulnerability of the coastal area of Bangladesh with regard to Tsunami hazard. Authorts are also indepted to the members of the Technical Advisory Group (TAG) under Earthquake and Tsunami preparedness component of CDMP for their continuous guidence and technical supports in carrying out this investigation.

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TSUNAMI SIMULATION AND HAZARD ASSESSMENT ON THE BANGLADESH COAST

Netai Chandra Dey Sarker*

ABSTRACT

The study was aimed to assess tsunami hazard on the Bangladesh coast, particularly to estimate tsunami heights as well as tsunami arrival times considering three tsunami source models. The 2004 Sumatra earthquake (Mw 9.1) source and several scenario earthquakes with Mw 8.0 and Mw 8.5 were considered along the pre-assumed trench. For Sumatra case fault parameters were used similarly to a very recent study. For scenario earthquakes with Mw 8.0 and Mw 8.5, 10 (Case1 – Case10) and 6 (Case01–Case06) tsunami sources were considered, respectively, where tsunami source parameters for a rectangular fault model and slip amount were estimated for each case using scaling laws. It was found for the 2004 Sumatra case that tsunami arrived first after the earthquake within 2.2 hours with the maximum height of 31 cm at St. Martin Island. For scenario earthquakes, case9 and case05 where sources exist nearby the coast of Cox'sbazar were identified as the most severe cases with Mw 8.0 and Mw 8.5, respectively. Tsunami arrived within several tens of minutes after the earthquake with the maximum height of 110 cm and 184 cm for the case9 and case05, respectively, at the coast of Cox'sbazar. Case8-case10 of scenario earthquakes with Mw 8.0 and case05-case06 of scenario earthquakes with Mw 8.5 may appear as threat to local tsunami at Meghna estuarine-Chittagong-Cox'sbazar cost of Bangladesh in future.

Keywords: Tsunami Source Model, Tsunami Simulation, Tsunami Height, Travel Time

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INTRODUCTION

Considering the potential seismic sources and high density of population (741/sqkm) with more than 70 percent vulnerable population, the coastal belt of Bangladesh can be identified as susceptible risk areas for tsunami. In fact, the coastal belts lacking all sorts of physical and non- physical measures to withstand the tsunami devastation, in case of future occurrence of tsunami in Indian Ocean, might create more devastation. It is well known that Bangladesh narrowly escaped from the 2004 Sumatra Tsunami. This escape was only for the some reasons, so far identified. Though the 2004 Sumatra Tsunami did not affect Bangladesh directly, it fits with nation's vision of comprehensive disaster management especially in tsunami hazard mitigation.

TSUNAMI VULNERABILITIES AT BANGLADESH COAST

The study area chosen for the Tsunami hazard risk assessment is Bangladesh coast. The coast and its adjacent area, is called coastal zone of Bangladesh (Figure 1) and lies between 21-23˚ N and 89-93˚ E within the tropical zone which represents about 32 percent of the country with an area of 47,211 sqkm and population of about 35 million according to Bangladesh National Census, 2001. In administrative point of view, out of 64 districts 19 are considered as coastal district.

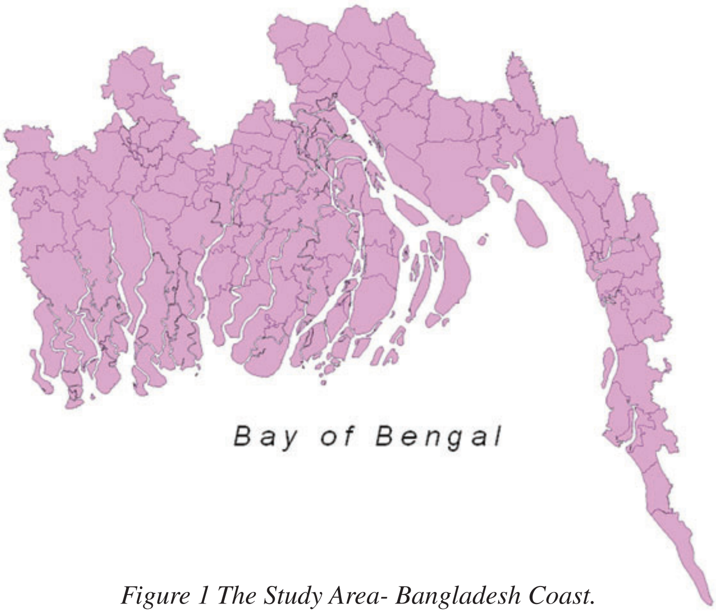

Figure 1 The Study Area- Bangladesh Coast.

Bangladesh occupies the most active tectonic boundary zone between Indian Plate and Myanmar Plate that stretches up to Sumatra via Andaman-Nicobar zone of severe seismicity. The Sitakund-Teknaf fault along the Chittagong-Cox'sBazar coast, which suggested a seismic gap, is alarming for Bangladesh coast to face great Earthquake and Tsunami. A major Earthquake in this seismic gap may have possibility to trigger submarine mudslide of continental slope of Bangladesh coast, which in turn will generate local tsunami (Akhter, 2007: personal communications). Another seismic gap stretching from Teknaf to the Andaman Islands is a great threat which could cause a strong earthquake in and around Bangladesh, and may turn into a local tsunami if earthquake occurs under the Bay of Bengal. The 200 km long continental shelf is also susceptible to earthquakes and landslides along its margins are extremely potential for generation of local tsunamis.

OBJECTIVES OF THE STUDY

Infrequent occurrence of tsunamis in the Bay of Bengal kept the geoscientists of this region almost unconcerned about the potentiality of tsunami hazard. There are some evidences of Paleo-Tsunamis and low height tsunamis (Aung et al., 2006). So far evidences of devastating tsunamis are not available but threats of tsunamis in the coastal belt of the country cannot be ruled out. The study addressed tsunami hazard assessment with the following objectives:

- Compute tsunami propagation numerically to obtain tsunami wave forms, and travel time;
- Analyse tsunami waveforms in terms of tsunami heights and tsunami arrival times to investigate the tsunami threats at Bangladesh coast.

METHODOLOGY OF THE STUDY

Tide Gage Stations and Bathymetry data

Tsunami propagation was calculated at 39 tide gauge stations as outpoints along the Bangladesh coast (Figure 2). Out of 39 stations 33 are assumed at front face of sea using Google Earth and GMT (Generic Mapping Tools) and 6 are operated by Bangladesh Inland Water Transport Authority (BIWTA). The stations operated by BIWTA demanded very minor correction of locations due to bathymetry grid resolution during preparation of location data on bathymetry grid using GMT. GEBCO bathymetry data which is available in the internet (www.ngdc.noaa.gov/mgg/gebco) is used in this study. This is 1 arc-minute grid size data digitized from contour map.

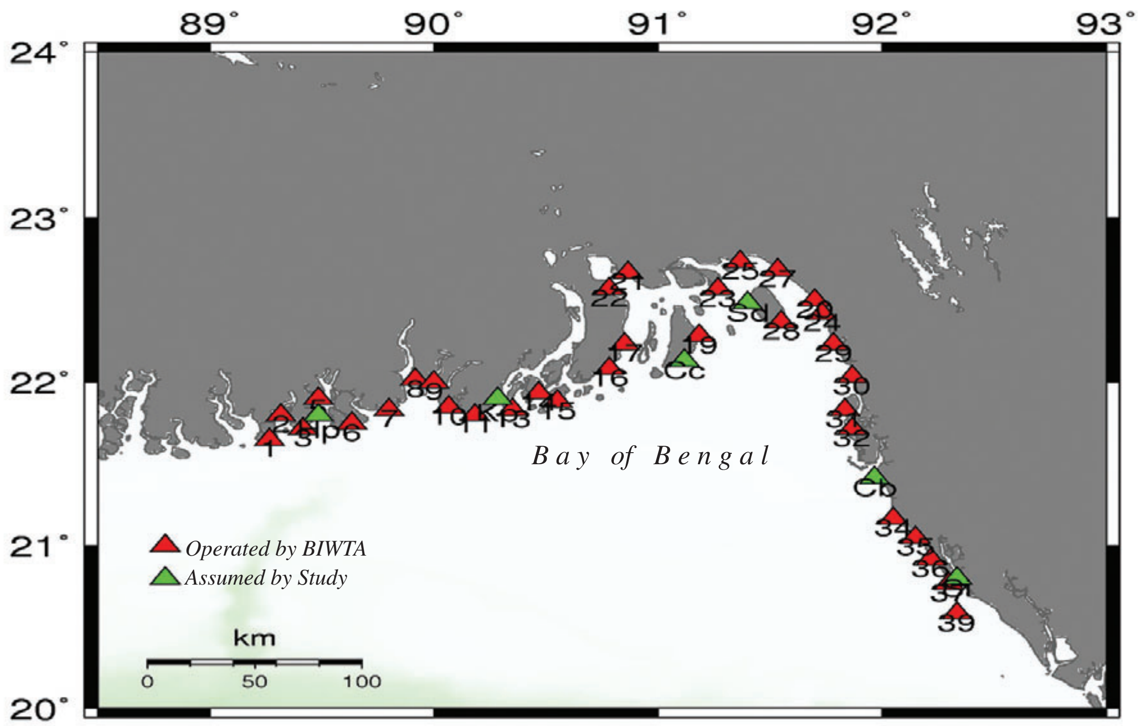

Figure 2 Tide Gauge Stations as Outpoints at Bangladesh Coast.

TSUNAMI SOURCE MODEL

The extent, geometry and slip distribution of a fault rupture and other parameters of a fault play important roles in tsunami generation. It is envisaged that a tsunamigenic earthquake would be of magnitudes 8.0 and greater, however, local tsunami may occur with magnitudes 7.0-8.0 provided necessary conditions are fulfilled (Khan, 2005). A recent study also predicts that a major earthquake of Mw 8.5 may occur every century on this segment of the subduction (Socquet et al., 2006). Due to lack of historical data and previous study of the area, in this study 2004 Sumatra earthquake source and several scenario earthquakes (Figure 3, 4) sources are considered from Bangladesh coast to north Andaman Island along the pre-assumed Arakan trench alignment (Socquet et al., 2006; Nielsen et al., 2004) to estimate the extent of tsunami source and slip distribution. For Sumatra case, the geometry of each subfault, slip amount and other fault parameters are used similarly to the study by Fujii and Satake (2007) where tsunami source is divided into 22 subfaults covering the aftershock area for a day after the mainshock. For scenario earthquakes with Mw 8.0 and Mw 8.5, 10 and 6 tsunami sources were considered respectively. Tsunami source parameters for a rectangular fault model (Okada, 1985) and slip amount (Table 1, 2) were estimated for each case using scaling laws based on the Emile A. Okal's (2006) equations. The depths and dip angles are assumed to be 3km and 10° respectively, for all the cases. Strike angles are based on pre-assumed trench alignment and rake angles (slip) are based on the averaged compressional axis direction.

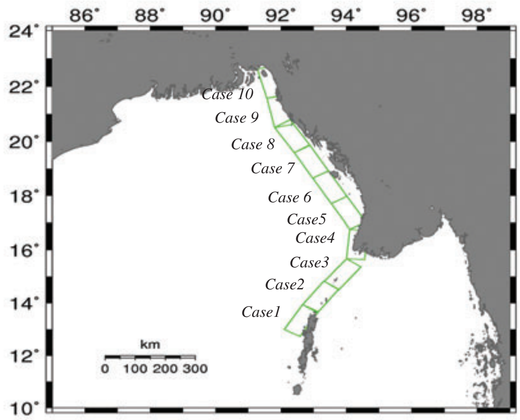

Figure 3 Tsunami Source Model (Mw 8.0).

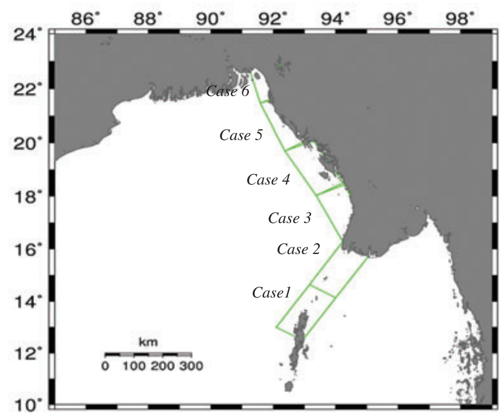

Figure 4 Tsunami Source Model (Mw 8.5).

TABLE 1 TSUNAMI SOURCE PARAMETERS FOR SCENARIO EARTHQUAKES (MW 8.0)

Case No.	Length (km)	Width (km)	Depth (km)	Strike (˚)	Dip (˚)	Rake (˚)	Longitude (˚)	Latitude (˚)	Slip (m)
Case1	120.22	60.11	3	30	10	160	92.100	13.000	3.48
Case2	120.22	60.11	3	36	10	166	92.664	13.941	3.48
Case3	120.22	60.11	3	37	10	167	93.328	14.820	3.48
Case4	120.22	60.11	3	5	10	154	94.007	15.688	3.48
Case5	120.22	60.11	3	330	10	120	94.105	16.770	3.48
Case6	120.22	60.11	3	330	10	120	93.539	17.710	3.48
Case7	120.22	60.11	3	330	10	120	92.973	18.650	3.48
Case8	120.22	60.11	3	328	10	118	92.407	19.590	3.48
Case9	120.22	60.11	3	348	10	130	91.808	20.511	3.48
Case10	120.22	60.11	3	345	10	127	91.572	21.573	3.48

TABLE 2 TSUNAMI SOURCE PARAMETERS FOR SCENARIO EARTHQUAKES (MW 8.5)

Case No.	Length (km)	Width (km)	Depth (km)	Strike (˚)	Dip (˚)	Rake (˚)	Longitude (˚)	Latitud e (˚)	Slip (m)
Case01	213.79	106.89	3	32	10	160	92.100	13.000	6.19
Case02	213.79	106.89	3	32	10	160	93.164	14.639	6.19
Case03	213.79	106.89	3	335	10	120	94.228	16.278	6.19
Case04	213.79	106.89	3	330	10	115	93.377	18.028	6.19
Case05	213.79	106.89	3	337	10	125	92.371	19.700	6.19
Case06	213.79	106.89	3	345	10	127	91.584	21.478	6.19

NB: Latitudes, Longitudes and Depths indicate the left bottom corner of each subfault or fault of scenario cases.

COMPUTATIONAL DOMAIN

The 1min grid spacing computational domain is derived from the 1min GEBCO bathymetry extending from 0˚ - 24˚ North in latitude and 82˚ - 100˚ East in longitude for the Sumatra case and from 10˚ - 24˚ North in latitude and 85˚ - 99˚ East in longitude for the scenario earthquakes in all cases (Figure 3, 4). There are 1441×1081 and 841×841 grid points for Sumatra case and scenario cases (Mw 8.0 and 8.5) along the latitude and longitude directions respectively, where bathymetric grid interval is 1 arc-minute. A time step of 0.5 sec is used to satisfy the stability condition. Total number of time steps is 10 hours for computation.

TSUNAMI SIMULATION

Tsunami propagations were simulated with a view to obtain tsunami waveforms and tsunami travel times at coast for all the cases. To calculate tsunami propagation initiated at each case, the nonlinear shallow water long wave equations were numerically solved by the TUNAMI code (TUNAMI-N2) developed by Disaster Control Research Center of Tohoku University, Japan. For the initial condition, static deformation of the sea floor is calculated using the three source models' parameters for all the cases (Fig 5).

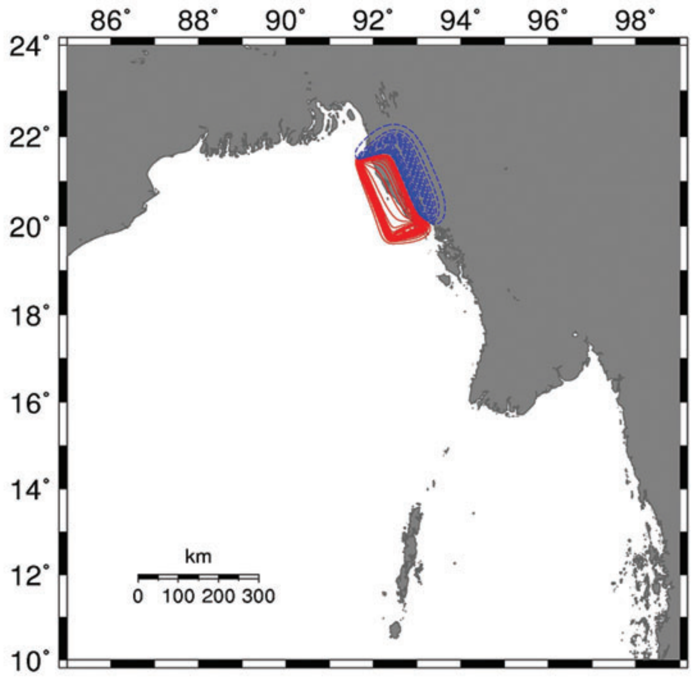

Figure 5 Sea Floor Deformation for Case05 of Scenario EQs (Mw 8.5).

RESULTS AND DISCUSSIONS

MAXIMUM TSUNAMI HEIGHTS

2004 Sumatra Earthquake (Mw 9.1)

The graph (Figure 6) shows that for this devastating event, maximum tsunami height was limited only in the south-east and western part of the coast of Bangladesh. Tsunami height rose over 20cm only at 6 outpoints where maximum tsunami height was 31cm. Because of lack of the observation data, it is quite difficult to compare the results obtained for this study. However, this result is very similar to the eyewitness which was 25-30 cm as published in the media and mentioned in the several national dialogues.

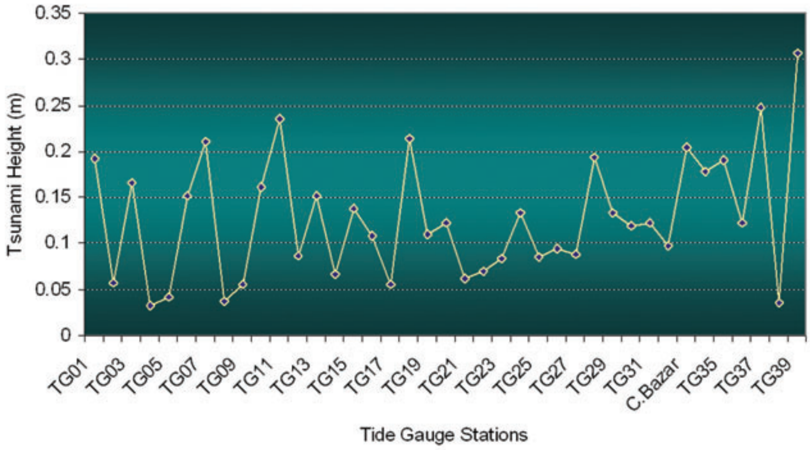

Figure 6 Maximum Tsunami Height at 39 Outpoints for Sumatra Earthquake (Mw 9.1).

Scenario Earthquakes (Mw 8.0)

Graph (Figure 7) shows the tsunami height at 39 outpoints for 10 cases of scenario earthquakes with Mw 8.0. Case9 is the most severe case (Figure 8) for which maximum tsunami height rose 1.1m according to the waveform data. Tsunami height rose bellow than 20cm in the Meghna Estuarine Coastal Belt (TG20-27) for all

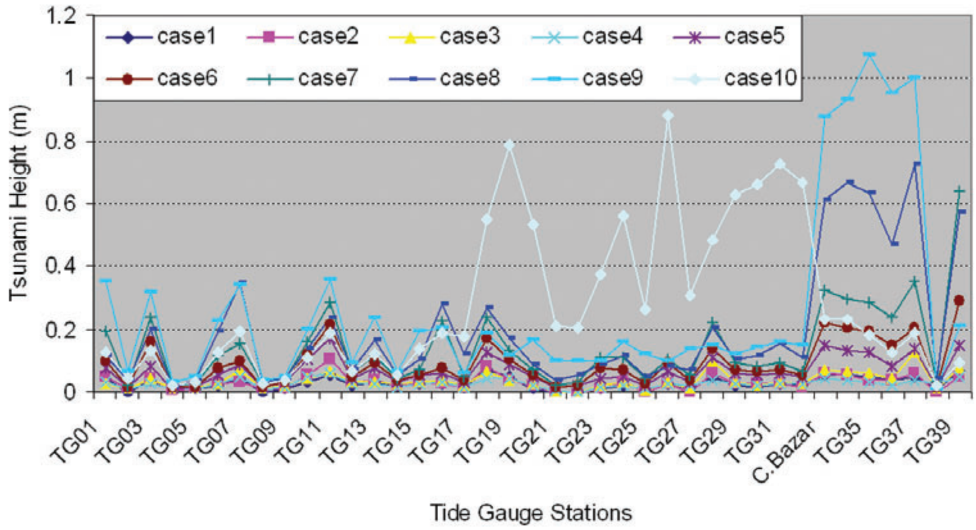

Figure 7 Maximum Tsunami Heights at 39 Outpoints for 10 cases of Scenario Earthquakes (Mw 8.0).

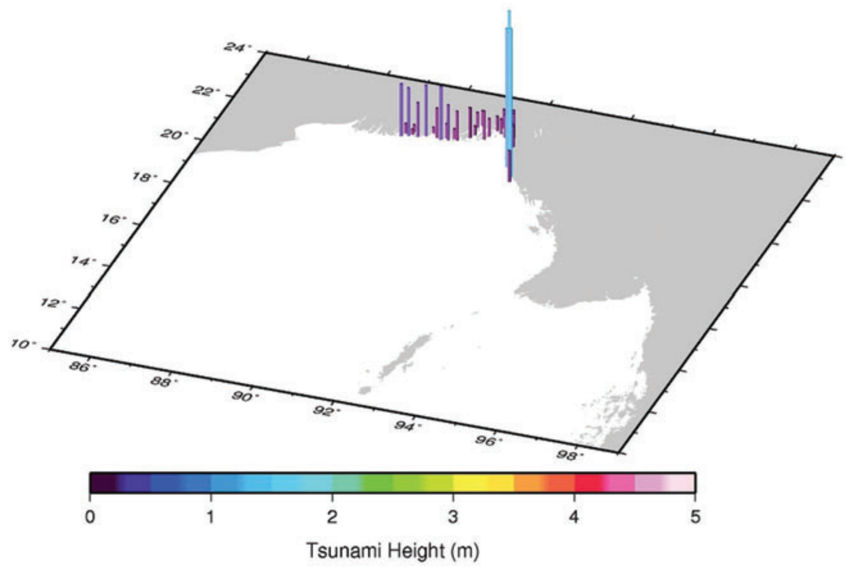

Figure 8 Maximum Tsunami Heights at 39 Outpoints for Case9 of Scenario EQ (Mw 8.0)

the cases except case10 (Figure 7). For case10 tsunami height rose over 80cm. Tsunami height varied at some adjacent outpoints in the western part of the coast probably due to location far from the coast. Only 4 sources (case7-case10) may appear as threat to local tsunami at Bangladesh coast for which tsunami height has risen over 50cm at maximum.

Scenario Earthquakes (Mw 8.5)

Graph (Figure 9) shows the tsunami height at 39 outpoints for 6 cases of scenario earthquakes with Mw 8.5. Case05 is the most severe case (Figure 10) for which maximum tsunami height rose 1.84m according to the waveforms. Tsunami height rose bellow 40cm in the Meghna Estuarine and Chittagong Coastal Belt (TG20-31) for all the cases except case06 (over 130cm). Out of 6 sources 4 sources (case03-case06) may appear as threat to local tsunami at Bangladesh coast for which tsunami height has risen maximum over 50cm.

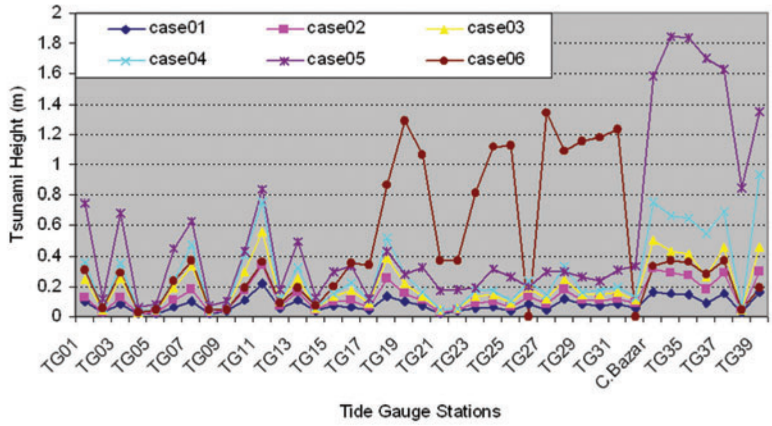

Figure 9 Maximum Tsunami Heights at 39 Outpoints for 6 cases of Scenario Earthquakes (Mw 8.5).

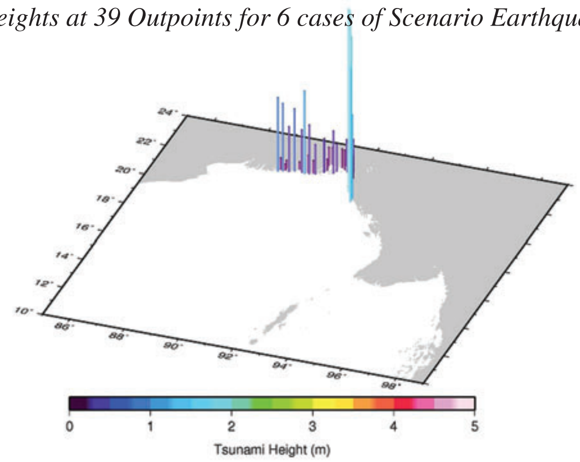

Figure 10 Maximum Tsunami Wave Heights at 39 Outpoints for Case05 of Scenario EQs (Mw 8.5).

TSUNAMI TRAVEL TIMES AT COAST

Tsunami travel times were obtained at 39 outpoints along the Bangladesh coast for the 2004 Sumatra earthquake with M_w 9.1 and scenario earthquakes with M_w 8.0 (10 cases) and M_w 8.5 (6 cases). In order to calculate travel time it was compared with the result calculated by TTT and those obtained from waveforms at first for the most severe cases. It is found that travel times are almost the same between the both methods. Sometimes, it is also quite confusing and time consuming to obtain travel time using waveforms. Therefore, tsunami travel times were calculated by TTT for all the cases of scenario earthquakes with M_w 8.0 and M_w 8.5 except Sumatra case. For Sumatra case, travel time is obtained from tsunami waveforms.

2004 Sumatra Earthquake (M_W 9.1)

Tsunami arrived first at St. Martin Island (TG39) southernmost part of Bangladesh coast within 2.2 hours after the occurrence of earthquake. In the southern part of the coast- near cox'sbazar (TG33-37) tsunami arrived

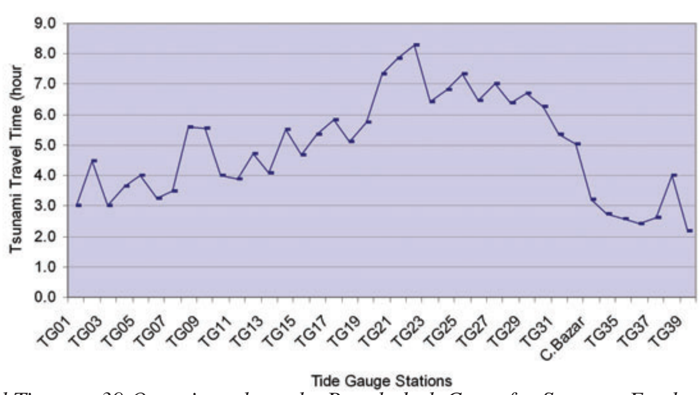

Figure 11 Tsunami Travel Times at 39 Outpoints along the Bangladesh Coast for Sumatra Earthquake (Mw 9.1).

approximately within 2.5 hours and in the western part of the coast- near Sundarban (TG01, TG03) tsunami reached within 3.0 hours after the Sumatra earthquake (Figure 11). Tsunami arrived earlier in the southern and western part than the Meghna estuarine coast line (TG21-30) of the coast of Bangladesh. In the Meghna estuarine coast line tsunami arrived more than 6 hours after the earthquake.

Scenario Earthquakes (M_W 8.0)

Tsunami arrives spending no time at Bangladesh coast for 3 sources (Case8-Case10) specifically in the eastern part of Meghna estuarine and Chittagong coast line (TG20, TG23-32) for Case10, and in the Cox'sbazar-Teknaf coast line (TG32-39) for Case7 and Case8 (Figure 12). In general tsunami reaches earlier in the western part of coast- near Sundarban (TG01-07) and in the south-eastern part of coast- along cox'sbazar coast line (TG34-37, TG39) approximately 2.0-3.5 hours and 1.5-3.0 hours respectively than Meghna estuarine and Chittagong coastline (TG20-30) after the earthquake. In the Meghna estuarine and Chittagong coast line tsunami arrived 5.0-7.5 hours after the earthquake.

Scenario Earthquakes (M_W 8.5)

Tsunami arrives spending no time at Bangladesh coast for 2 sources (Case05-Case06) specifically in the eastern part of Meghna estuarine and Chittagong-Cox'sbazar coast line (TG20, TG23-34) for Case06, and in the Cox'sbazar-Teknaf coast line (TG30-39) for Case05 (Figure 13). In general, tsunami reaches earlier the western part of coast- near Sundarban (TG01-08) and the south-eastern part of coast- along cox'sbazar coast line (TG34-37, TG39) approximately 2.0-3.5 hours and 1.0-3.0 hours respectively than Meghna estuarine and Chittagong coastline (TG19-32) after the earthquake. In the Meghna estuarine and Chittagong coast line tsunami arrived approximately 4.0-7.0 hours after the earthquake except case05 and case06.

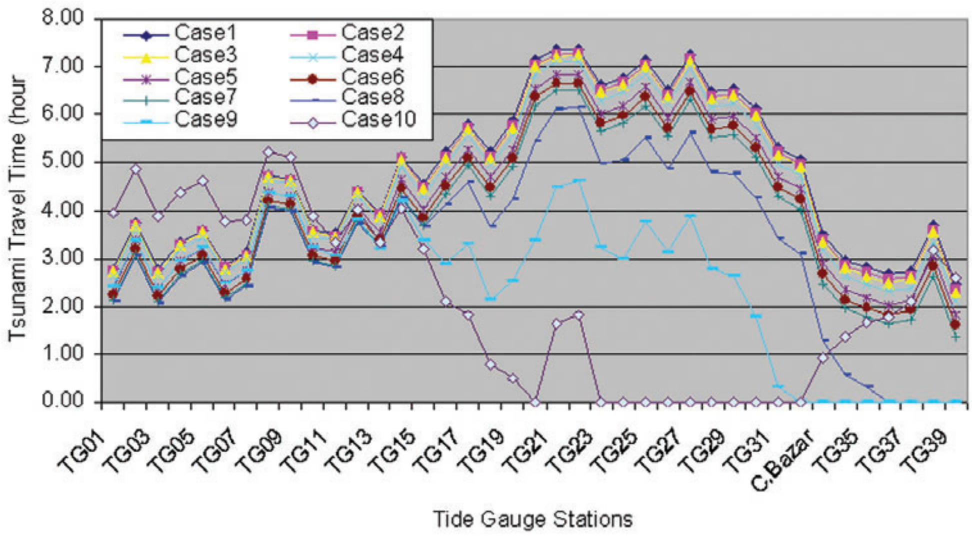

Figure 12 Tsunami Travel Times at 39 Outpoints for 10 Cases of Scenario EQs (Mw 8.0).

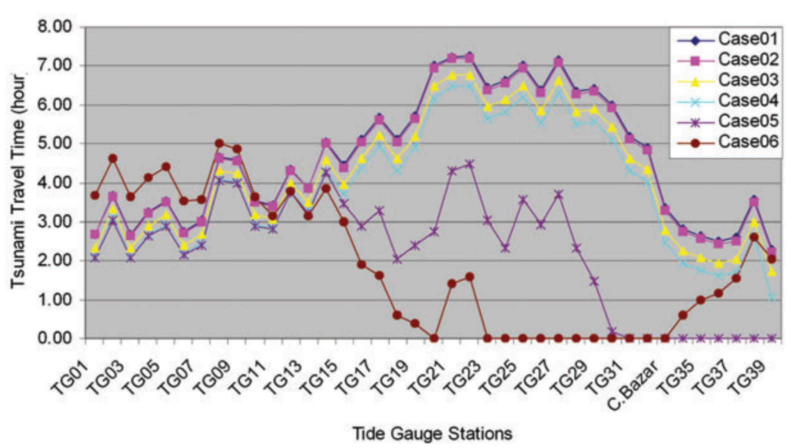

Figure 13 Tsunami Travel Times at 39 Outpoints along the Bangladesh Coast for 6 Cases of Scenario EQs (Mw 8.5).

CONCLUSION

In this study three source models were considered, mainly, the 2004 Sumatra tsunami source, scenario earthquakes with M_w 8.0 sources (10 cases) and M_w 8.5 sources (6 cases) from Bangladesh coast to Andaman Island along the assumed trench axis to assess the tsunami hazard risk on Bangladesh coast.

Tsunami height rose highest 0.31m for Sumatra case, 1.1m for case9 and 1.84m for case05 of scenario earthquakes with M_w 8.0 and M_w 8.5, respectively. The maximum tsunami height rose over 50cm for case7 - case10 and case03-case06 of scenario earthquakes with M_w 8.0 and M_w 8.5, respectively. The area with the maximum tsunami height of over 50cm was limited along the Cox'sbazar-Chittagong, the Meghna estuarine, and in the western part of the coast. It can be mentioned here that the limitations were due to existence of tsunami source nearby the area and the direction of principal tsunami wave from the source.

Tsunami first arrived within 2.2 hours after the earthquake at St. Martin Island for Sumatra case, spending no time for 3 sources (Case8-9) and 2 sources (Case05-06) of scenario earthquakes with M_w 8.0 and M_w 8.5 respectively. In general tsunami arrived earlier in the south and south-eastern part of the coast than western and Meghna estuarine part of the coast for most of the cases except case10 and case06 of scenario earthquakes with M_w 8.0 and 8.5 respectively. For those 2 cases tsunami arrived earlier spending no time at Meghna estuarine part than other part of the coast. It can be assumed that if earthquake takes place in future with M_w 8.0 or M_w 8.5 at the sources described before tsunami will not take time to reach Meghna estuarine, Chittagong and Cox'sbazar cost of Bangladesh.

Finally, considering the existence of Arakan trench, seismic gap and results of tsunami simulation it can be assumed that those sources (case8-case9 and case05-case06 of scenario earthquakes with M_w 8.0 and M_w 8.5 respectively) may appear as threat to local tsunami at Bangladesh coast in future. The residents of these coastal areas will not get enough time to take shelter and escape from the devastation of the first wave of local tsunami.

ACKNOWLEDGEMENTS

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Tsunami Numerical Simulation for the Bangladesh Coast

Kenji Satake[1] Yushiro Fujii[2]

ABSTRACT

A tsunami generation and propagation simulation has been conducted in this study using a fault model proposed by Cummins (2007). The fault length and width are 700 km and 125 km, respectively. The average slip on the fault is 10 m, hence the moment magnitude Mw is 8.8. The southernmost corner of the fault is located on latitude of 17.2ºN and longitude of 95.5ºE. The focal mechanism is a pure thrust type whose parameters are strike of 325º, dip of 15º and slip angle of 90º. Tsunami propagation snapshots based on the mentioned parameters indicate that the tsunami wavefront is originally along the fault strike, or roughly in N-S direction, but has been rotated clockwise to reach the southern coast of Bangladesh. The maximum tsunami heights along the Bangladesh coast are computed as about 5 m on a coast gird , although more detailed computation would be needed for hazard assessments

INTRODUCTION

Tsunamis are generated by submarine geological processes such as earthquakes, volcanic eruptions or landslides. If the source is known, the tsunami propagation process can be simulated by numerically solving shallow-water (long-wave) equations on actual bathymetry. Computed tsunami arrival times and amplitudes can be used for tsunami warning system and/or hazard assessment. The tsunami source, however, is usually not well known and needs to be estimated by instrumental data for recent tsunamis or by geological method for old tsunamis.

The 26 December 2004 Sumatra-Andaman earthquake generated tsunamis that propagated across the Indian Ocean and caused the worst tsunami disaster in history. The tsunami source, particularly its northern end, was not well resolved. Although the aftershocks and crustal deformation were extended from off northwestern Sumatra Island through Nicobar Islands to Andaman Islands, seismic wave analyses indicated a shorter source length, several hundred km. We used tsunami waveforms recorded at 12 tide gauge stations around the source and the sea surface heights measured by three satellites (Fujii and Satake, 2007). Inversion of satellite data indicated the tsunami source extended to Andaman Islands with the total length of 1,400 km, but such a model would produce much larger tsunami waveforms than observed at Indian tide gauge stations. Inversion of tide gauge records and the joint inversion indicated that the tsunami source was about 900 km long. The largest slip, about 13 to 25 m, was located off Sumatra Island and the second largest slip, up to 7 m, near Nicobar Islands. The computed tsunami heights along the Bangladesh coast are small, less than a meter.

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METHODS, MATERIALS AND RESULTS

On the northern extension of the 2004 tsunami source, in the Bay of Bengal, an earthquake occurred in 1762. Although no tsunami damage was recorded, tsunami potential from a future earthquake has been pointed out (Cummins, 2007). We simulated tsunami generation and propagation from a fault model proposed by Cummins (2007). The fault length and width are 700 km and 125 km, respectively. The average slip on the fault is 10 m, hence the moment magnitude Mw is 8.8. The southernmost corner of the fault is located on latitude of 17.2ºN and longitude of 95.5ºE. The focal mechanism is a pure thrust type whose parameters are strike of 325º, dip of 15º and slip angle of 90º. The static seafloor deformation due to the fault model was calculated by using a rectangular fault model (Okada, 1985) assuming the fault's top depth of 0 km. The seafloor deformation causes -1.9 - 2.7 m of coastal subsidence and uplift along the Myanmar and Bangladesh coasts (Fig. 1). This is used as the initial condition for tsunami simulation. Paleoseismological studies along the Rakhine coast of Myanmar (Aung et al., in press) showed three steps of marine terraces of which the lowest one corresponds to the 1762 earthquake.

The computation area for tsunami simulation extends from 70ºE to 110ºE and 25ºS to 25ºN. The bathymetric grid interval is basically 2 arc-minutes (about 3.7 km); hence, there are 1200 × 1500 grid points along the longitude and latitude directions, respectively. The bathymetry data is the ETOPO2 grid data merged with the depth points digitized from the nautical charts to improve the accuracy in the shallow ocean, which was also used in Fujii and Satake (2007). It should be noted that near the Bangladesh coast the bathymetry data is the original ETOPO2 grid data, because the nautical charts at that region were not digitized. To calculate tsunami propagation, the linear shallow-water, or long-wave, equations were numerically solved by using a finite-difference method (Satake, 1995). For the initial condition, the seafloor deformation described above were used assuming the rise time or slip duration of 10 min. The snapshots of the tsunami propagation are shown in Figure 2, indicating that the tsunami wavefront was originally along the fault strike, or roughly in N-S direction, but was rotated clockwise to reach the southern coast of Bangladesh. The maximum tsunami heights along the Bangladesh coast are computed as about 5 m on a coast gird (Figure 3), although more detailed computation would be needed for hazard assessments

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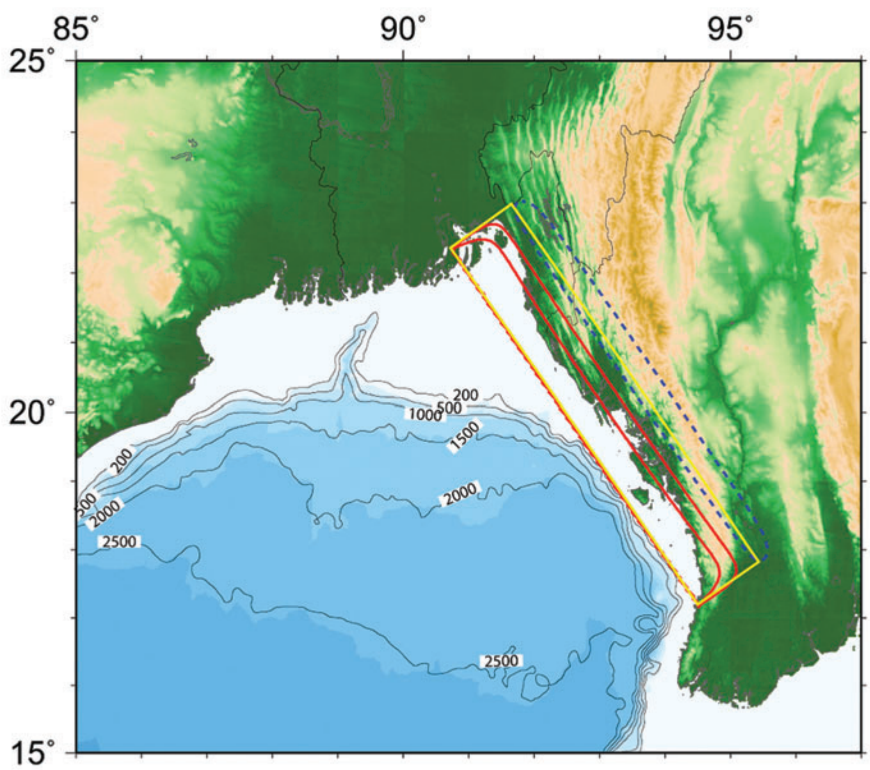

Figure 1. Crustal deformations computed from the fault model of Cummins (2007). The solid contours in red indicate uplift, whereas the dashed contour in blue indicates subsidence with the contour interval of 1.0 m. The rectangular fault projected to the surface is also shown by solid line in yellow.

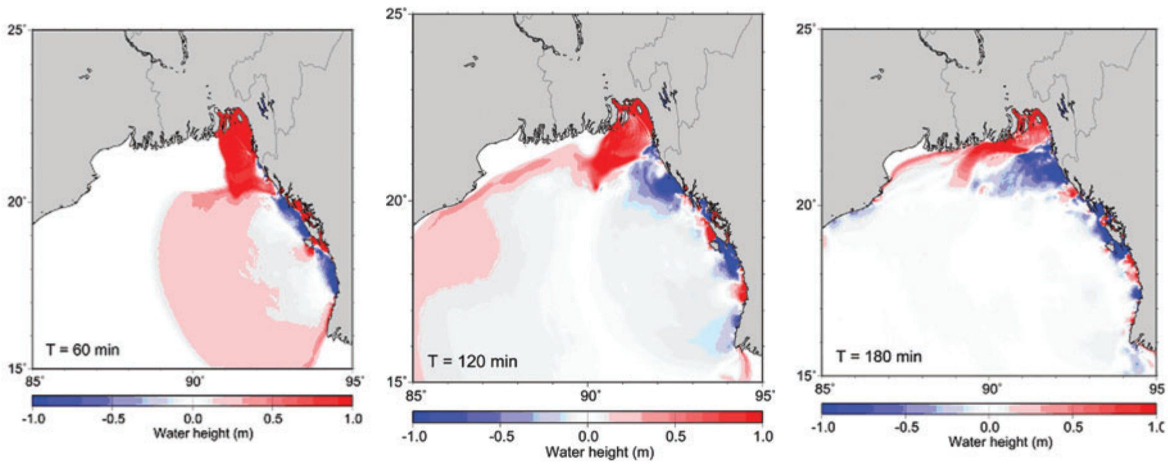

Figure 2. Snapshots of the tsunami propagation. The elapsed time (min) is shown on the left bottom in each figure.

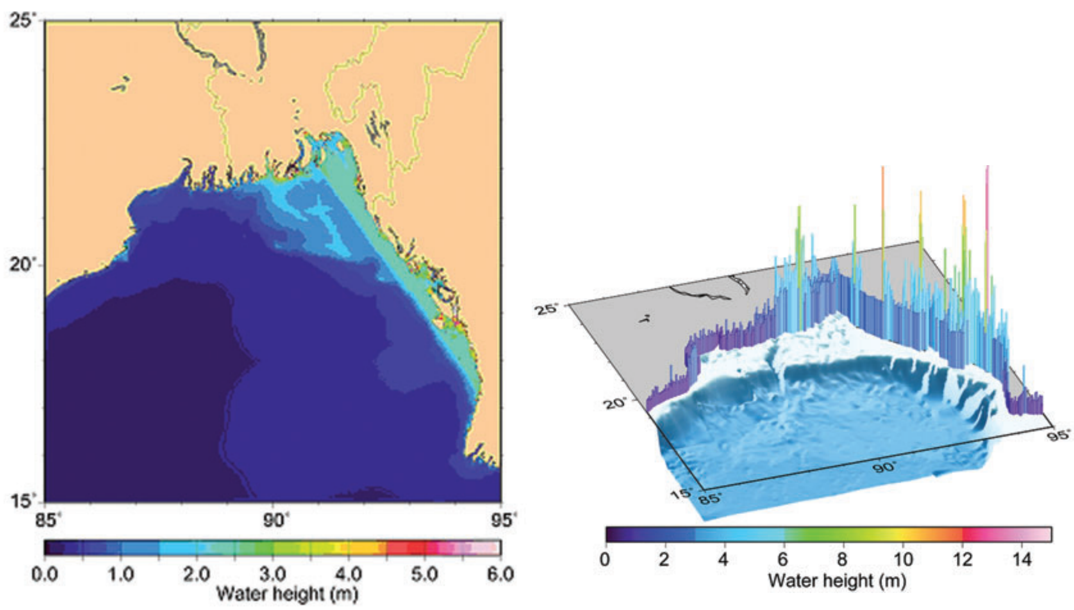

Figure 3. Maximum heights of the calculated tsunami off shore (top) and along the coasts (bottom) of Bangladesh and Myanmar.

CONCLUSION:

Tsunami propagation snapshots based on the parameters as mentioned above indicate that the tsunami wavefront is originally along the fault strike, or roughly in N-S direction, but has been rotated clockwise to reach the southern coast of Bangladesh. The maximum tsunami heights along the Bangladesh coast are computed as about 5 m on a coast gird , although more detailed computation would be needed for hazard assessments

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Geomorphological evidence of great Holocene earthquakes off western Myanmar

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ABSTRACT

Geomorphological evidence of repeated large earthquake that have occurred from subduction zone of the Rakhine Trench in the last 3000 years was found along the western coast of Myanmar. Holocene marine terraces divided into at least four levels were identified, and radiocarbon-dated from uplifted coral and oyster reef to 1395 - 740 BC, 150 BC-AD 60, AD 680-980 and AD 1430-1860 in descending order. The lowest terrace indicates 3-5 m coseismic uplift associated with the 1762 Bengal earthquake. The height and ages of higher terraces suggests that large earthquake as well as the 1762 event accompanied with uplift of 3-5 m has recurred with interval of 900 years. To evaluate northward rupture extent of such earthquake, it is necessary to obtain geomorphological data along the coast of southeastern Bangladesh.

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INTRODUCTION

The rupture of 2004 Sumatra-Andaman earthquake was initiated off Sumatra Island and extended to the Andaman Islands along the Sunda Trench (Ammon et al. 2005). After the 2004 shock, it is expected that another giant earthquake would occur along the Arakan Trench, the northward continuation of rupture area of the 2004 earthquake (Cummins, 2007). In such case, tsunami would influence to the coast of Bangladesh. Evaluation of the potential for earthquakes similar to the 2004 event to occur along the Arakan Trench is therefore important both scientifically and socially. Recently Cummins (2007) proposed models of such tsunami source associated with the 1762 Bengal earthquake (M >7.5) which is the largest earthquake caused along the Arakan Trench in written history. However Cummins's model is based on only a few historical records, and no geological and geomorphological evidence. To obtain exact evidence of the 1762 earthquake and older pre-historical earthquakes, we conducted paleoseismological survey along the Rakhine Coast, western Myanmar during 2006-2008. In this survey, we found several steps of marine terraces that are strong evidence of repeated coseismic uplift. This paper reports the summary of the survey results and tentative result of one day visit in the Cox Bazar coast, southeastern Bangladesh at January 2009.

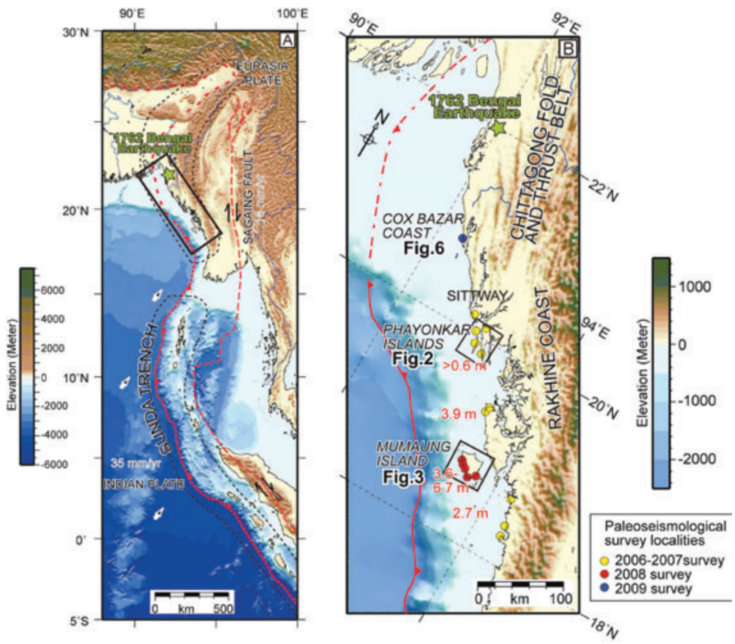

Fig. 1 Tectonics of around the Sunda Trench and the Arakan Trench, and Locality of survey sites, revised from Aung et al. (2009). (A): Topographic map showing three tectonic and seismic segments, Sunda trench, Rakhine trench, Chittagong fold and thrust belt. Area of black rectangle was enlarged in B. (B): Map showing locations of our paleoseismological surveys conducted in 2006-2009. Numbers in red color are reported coastal uplift due to the 1762 Bengal earthquake [Halsted, 1843; Mallet, 1878].

METHODS

Coastal paleoseismology is a unique method to reveal offshore paleoseismicity before starting instrumental observation. Vertical crustal movement associated with past earthquakes can be identified from height and age of paleo-shoreline. Emerged shoreline topography such as wave-cut-bench or -notch is one of the best indicators of paleo-shoreline, and is an important evidence of abrupt sea level fall which is generally caused by coseismic uplift. Marine terrace is composed of such topography, and characterized by almost flat but slightly seaward inclined surface. If coseismic uplift has repeatedly occurred and accumulated, step shaped topography would be formed. In other words, if several stepped marine terraces are found, it indicates an evidence of repeated coseismic uplift event.

Terrace classification by stereoscopic air-photo interpretation is first step to identify each paleo-earthquake. Based on the terrace classification, location of field survey is determined. Making topographic profiles by measuring height referred to present mean sea level is next step in paleo-seismological survey. Height differences between each terrace indicate total amount of vertical crustal movement associated with a cycle of inter-plate earthquake, which is almost equal to minimum amount of coseismic uplift. Collecting samples for dating from each terrace is the most important to reconstruct history of earthquake. Especially fossil of in situ marine shell or coral and its radiocarbon age is the best indicator of the position of paleo-sea-level and timing of its emergence.

RESULTS AND INTERPRETATION

Phayonkar Islands

We surveyed in the Phayonkar Islands (British name is Baronga Islands; northern part of Rakhine coast; Figs. 1 and 2) at four sites of A-D in 2006 and 2007 surveys, and its results have already been reported by Aung et al. (2009). In these sites, we identified at least three levels of Holocene marine terraces, but partly it can be divided into four levels based on air-photo interpretation (Fig. 2). Height of them were measured to the upper terrace >10 m, middle terrace ~5 m and the lower terrace 1-2 m above mean sea level. The observed height of lowest terrace is similar to the reported and computed uplift amounts from the fault model of the 1762 Bengal earthquake (Halsted, 1841, Mallet, 1878, Cummins, 2007; Fig. 1). We collected radiocarbon samples form each terrace. Although most of the samples were reworked coral, we obtained in situ coral from some sites of the lower terrace (Fig. 2). Ages of them are upper terrace 1395 - 740 BC, middle terrace AD 805-1220 and lower terrace AD 1585-1810 respectively. The time interval between lower terrace and the middle terrace is 365 - 1005 years, while that between middle and upper terraces ranges 1455 - 2515 years. The longer time span and higher elevation difference between middle and upper terraces may indicate missing event(s) or variability.

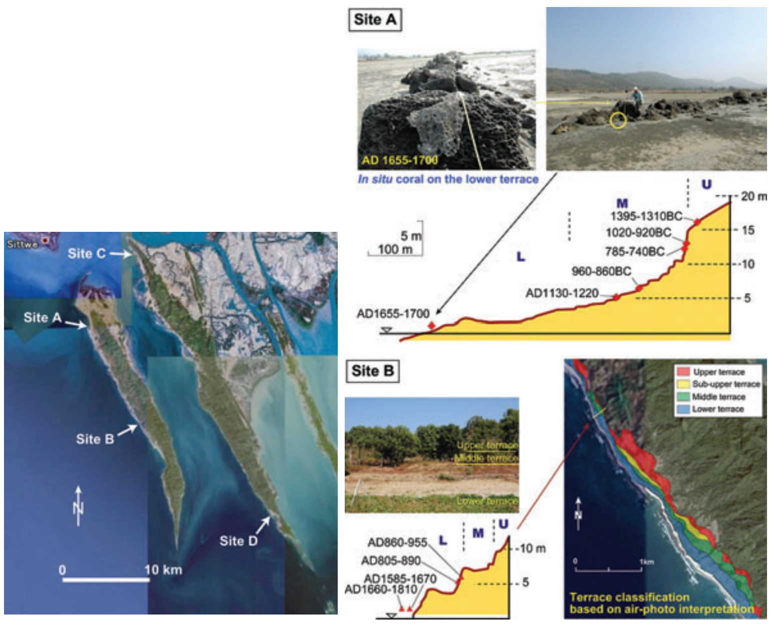

Fig. 2 Locality of survey sites in the Phayonkar Islands (Left), and survey results at Site A and Site B, containing photos, topographic profiles with 14C ages and terrace classification map (Right).

Mumaung Island

In 2008 survey, based on air-photo interpretation, we identified Holocene marine terraces divided into at least four (partly six) steps that named L1-4 terraces in descending order in the Mumaung Island (British name is Cheduba Island; southern part of Rakhine coast; Figs. 1, 3). At five sites in the island, we made topographic profiles along six lines (Fig. 4). The height of each steps are measured to be L1: 15-18m, L2: 12-14 m, L3: 7-10 m and L4: 3-5 m above mean sea level. In situ coral and oyster reef were found on the L2, L3 and L4 terraces (Fig. 5), and were radiocarbon-dated to be L2: 150 BC-AD 60, L3: AD 680-980, and L4: AD 1430-1860 respectively. These ages suggest that the L3 and L4 terraces can be correlated to the middle and lower terraces in the Phayonkar Islands respectively. We assign the lowest terrace to the 1762 earthquake. The L2 terrace is obviously younger than the upper terrace in the Phayonkar Islands, and it thus suggests the missing event between the upper and middle terraces. Although reliable sample could not be obtained from the L1 terrace, it is probably correlated with the upper terrace in the Phayonkar Islands. Age data shows almost equal time interval as ca. 900 years between each terrace.

Amount of uplift of the 1762 event is estimated to be 3-5 m in minimum from the height of paleoshoreline indicated by oyster reef, which is consistent with reports of Halsted (1841) and Mallet (1878). However net uplift amount would be larger because eyewitness accounts during our surveys and comparison of old topographic map with the current topography imply that the coast is currently subsiding. As the height differences between each terrace shows 4-6 m, pre-1762 emergence events were accompanied with almost same amount of uplift as the 1762 earthquake.

Older terrace named H (H1 and H2) terrace is intermittently distributed above the L1 terrace. No age sample was obtained yet, but it is probably pre-Holocene age, judging from distribution pattern and denudated surface.

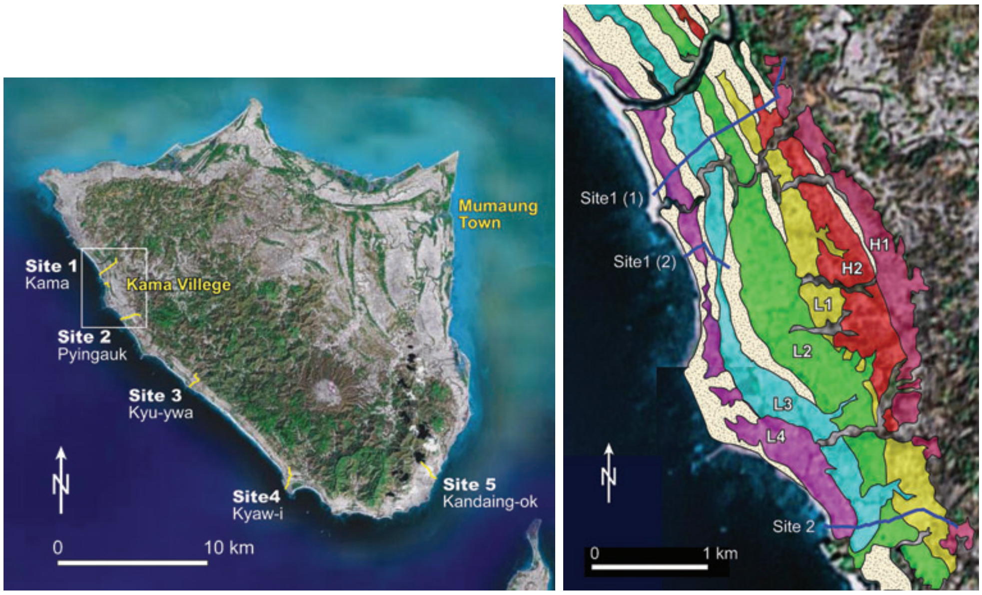

Fig. 3 Locality of survey sites in the Mumaung Island (Left), and terrace classification map at Site 1 and 2, based on air-photo interpretation (Right).

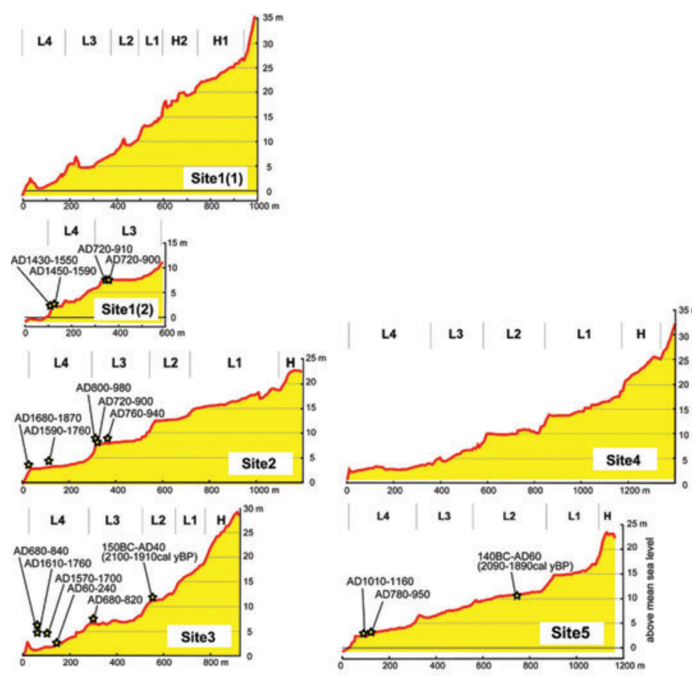

Fig. 4 Topgraphic profiles with 14C ages in the Mumaung Island. Stars on the profile denote the position of collected samples.

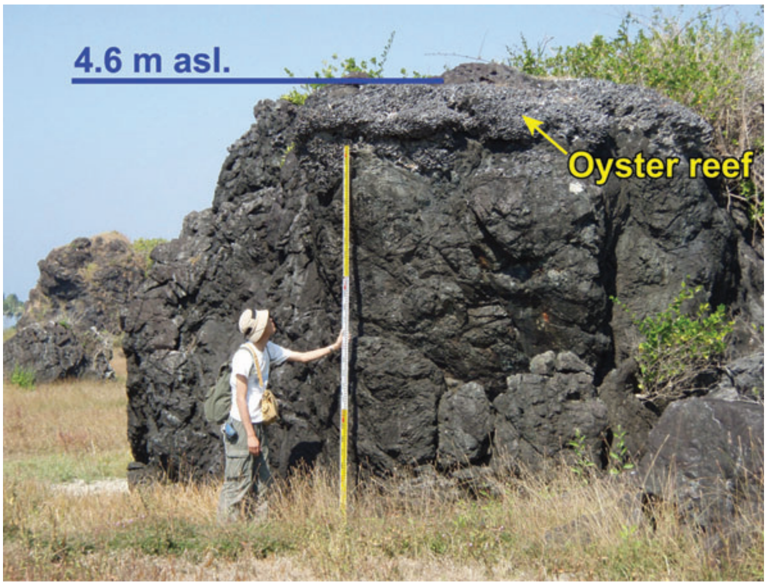

Fig. 5 Photo of uplifted oyster reef observed on the L4 terrace at Site 3 in the Mumaung Island.

Results of brief survey along the Cox Bazar coast

Shishikura, the first author of this paper, conducted brief field survey along the Cox Bazar coast on 19th January 2009. The coast is located at northward continuation from Phayonkar Islands, and is situated in inferred source area of the 1762 earthquake (Cummins, 1762; Fig. 1). Shishikura has moved and seen coastal topography from Cox Bazar to Teknaf, and confirmed existence of marine terrace which are divided into at least three (partly four) levels. He measured the height and made a topographic profile at a site near Teknaf (Fig. 6). It indicates upper terrace > 10 m, middle terrace 6-7 m and lower terrace ~2 m above mean sea level. Although no age samples were obtained yet, three levels may be correlated with the terraces in Phayonkar Islands respectively, and thus the lower terrace was probably emerged during the 1762 earthquake.

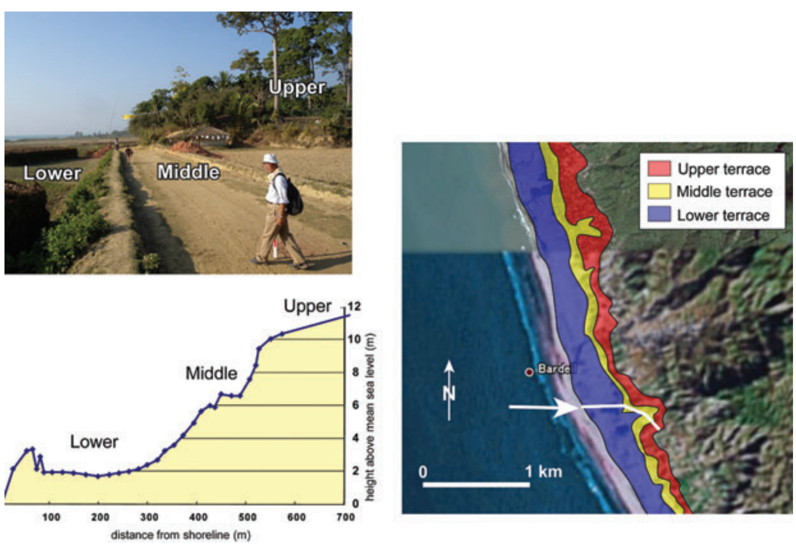

Fig. 6 Tentative result of field survey near Teknaf. Photo of Holocene marine terraces (Left upper). Topographic profile measured by using hand level (Left lower). Terrace classification map (Right).

Discussion and Conclusions

The results of our survey propose strong evidence of coseismic crustal deformation associated with repeated large earthquake caused from subduction zone of the Arakan Trench. Based on the distribution and height of the lowest terrace dated to AD 1430-1860, it is inferred that large slip of plate interface rupture has propagated between the Mumaung Island, the Phayonkar Islands and probably the Cox Bazar coast during the 1762 Bengal earthquake. Our data provides substantial parameters to evaluate the potential source of large tsunami for the Rakhine coast off western Myanmar. To clarify actual rupture extent around southeastern Bangladesh, it is very important to obtain age data of marine terrace along the Cox Bazar coast and to detect evidence of coseismic subsidence around Chittagong from coastal deposit by using sedimentlogical method.

Several steps of marine terrace and their ages suggest that the large earthquake as well as the 1762 event accompanied with uplift of 3-5 m has recurred with interval of ca. 900 years. The time since the last earthquake, ~250 years, is much shorter than the average interval, hence the chance of next earthquakes in the near future may be considered as low. However, two types of earthquake which involve variable rupture extent and different recurrence interval are recently being identified in many other subduction zones (e.g. Chile Trench; Cisternas et al. 2005, Sagami Trough; Shishikura, 2003). Therefore the next earthquake without distinct crustal movement whose magnitude is enough to be preserved geomorphologically could happen sooner or later than would be expected from the average interval deduced from marine terrace.

ACKNOWLEDGEMENTS

Gratitude is extended to Michio Morino of OYO International Corporation and Reshad Md. Ekram Ali of Geological Survey of Bangladesh for helping field survey along the Cox Bazar coast, and Maksud Kamal of CDMP for giving opportunity of the field survey.

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A SIMULATION ANALYSIS OF POSSIBLE TSUNAMI AFFECTING THE ISTANBUL COAST, TURKEY

Fumio Kaneko*

ABSTRACT

Istanbul City has been said to be attacked by a disastrous earthquake in the near future. Its seismic source will be along the North Anatolian Fault (NAF). Recently not only its seismic ground motion but also tsunami waves should become the target for the city's measures against earthquake disaster. Formerly, since NAF is strike slip type, only small tsunami has been thought to be generated. However, recent historical tsunami catalogue study has clearly showed the big tsunamis affected Istanbul coast.

According to the historical earthquake and tsunami catalogue, the dates of past tsunamis are mostly correlating to those of past earthquakes with magnitude M>7. Therefore, not only the seismic faults (NAF) but also the landslides along the cliffs generated and following by the movement of NAF can be considered. Other tsunami sources cannot be realistic there.

More than 50 cases of tsunami sources are considered for tsunami simulation analysis. They are due to NAF movement, landslides along the cliffs and their combinations. The results of tsunami simulations are compared with historical records of tsunamis. The estimated tsunami height due to NAF segments with small vertical movement cannot reach the past tsunami heights a little bit. On the other hand, the estimated tsunami heights due to submarine landslides are not so big but sharp at a local area. Though the tsunami heights due to the combinations with NAF cannot reach fully, but can mostly explain the past records of tsunami.

Further, recently a big tsunami trace has been discovered at the construction point of railway station for the new lines across under the Bosporus strait. That was the past port in the southern coast of old Istanbul city. This makes the past big tsunamis attacked Istanbul coast at around every half a millennium. This corresponds to the tsunami catalogue, unfortunately the detailed historical records are not always found sufficiently.

Nowadays, the coastlines along the Istanbul city have been improved by roads and quays, rather than older ages.Then, tsunami disasters will be expected a little bit smaller than the historical days. Instead, the urbanization has made more vulnerable and wider in these days. The Istanbul Metropolitan Municipality (IMM) Government has started the measures against tsunamis as well as ground motion based on the above analysis.

Consequently, the above hybrid analysis for submarine landslide induced tsunami will be improved and to be used for another cases in the world. And when analyzing tsunamis and their disasters in the future, naturally, identification of tsunami source, detailed bathymetrical topography, altitudes along coast and advanced tsunami simulation programs are necessary. But significantly, more than those, the investigation and verification based on the past historical tsunami records and traces, deposits due to tsunamis are extremely effective, especially in the case of less detailed information on tsunami sources and past earthquakes like Bengal Bay and so on.

Keywords: Tsunami, Istanbul, Marmara Sea, historical catalogue, tsunami traces, landslide induced tsunami, topography/bathymetry analysis, landslide simulation

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INTRODUCTION

In the Marmara Sea, locating off coast of Istanbul, large disastrous earthquakes have been generated from east to west at around every 250 years in the past. Since the latest event was on 1754 in front of Istanbul, and the near eastern portion of North Anatolian Fault (NAF) was the 1999 Izmit earthquake, Istanbul city has been in the imminent situation for the coming one in the near future to measure against it.

Until recently, since NAF in the Marmara Sea is strike-slip type fault moving horizontally, it is assumed that it will generate small tsunamis. However, after the information of historical tsunami catalogue which reported the large tsunami disasters at Istanbul, tsunami analysis has started.

For the reason of tsunami other than NAF, the steep slope spreading in the midst of the sea of Marmara, which have been produced by the pull-apart activity of NAF with relative depth more than 1000m, can be the candidate (Sari et al., 2006). Actually, dating results of several soil samples showed correspondence of the ages of the past large earthquakes (McHough, et al., 2006).

Assuming NAF, submarine landslides, and their combinations as tsunami sources, simulated results are compared with historical records. And then application to the future tsunami disaster management measures is described.

HISTORY OF EARTHQUAKES AND TSUNAMIS IN MARMARA SEA

As well as the earthquake catalogues (Ambraseys. 2002 etc.), recently, tsunami catalogues for Istanbul shore has been established (Altinok, 2006 etc.) around the Marmara Sea. Until then Istanbul has less aware to tsunami disaster. According to the catalogues compared with earthquake catalogue that has more than 70 events in the Sea of Marmara with magnitude 7 or more along the North Anatolian Fault, over 40 events can be confirmed during these twenty centuries. On the other hand, out of 30 to 40 tsunami events are captured in these twenty centuries (Fig. 1 and Fig. 2), 30 events are confirmed as a reality. Most of tsunami events can be corresponding to the past large earthquakes. For missing records possibility in older days, more events can be estimated in the future.

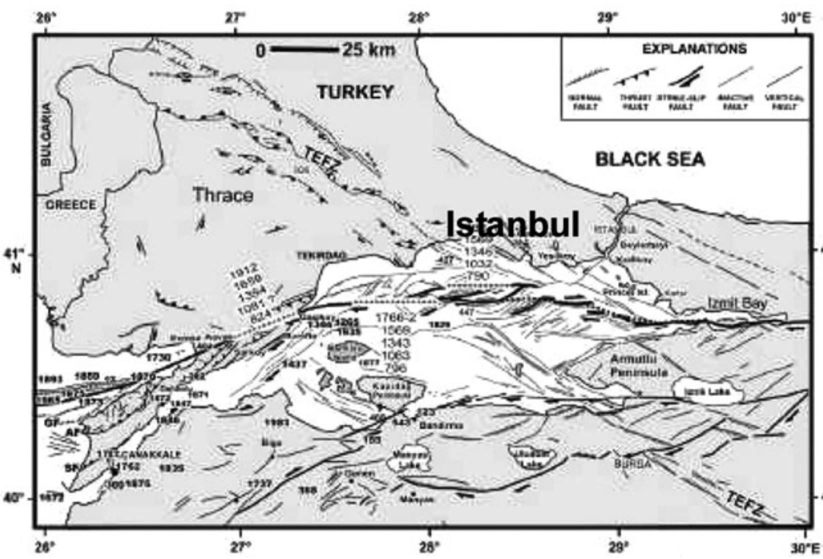


Fig. 1 Historical Tsunamis distribution in the Marmara Sea (after Altinok, 2006)

Among the historical tsunami events, only three in these 500 years can be list up as quantitative. The most remarkable one was the 1509 earthquake tsunami that caused 6m run up height at Yenikapi port and Aksaray town, and also Galata town were flooded (Fig. 3). This is the maximum run up height record in Istanbul. Especially at Yenikapi port, the construction has been undergoing and the precious tsunami deposits were found, such as quays were cut twice in Yenikapi port and several old ships were sunk, shown in Fig. 4 and Fig. 5 (Perincek et al., 2007). This clarified after dating study that Istanbul has been attacked by large tsunamis at around every half a millennium, for instance 5 - 7 th century, 10 -11 th century, and 1509.

Next one was the 1894 earthquake tsunami that caused 4 to 4.5 m run up height at Golden Horn bay for the article that told the wave over the Azapkapi Bridge (Fig. 6 and Fig. 7), and the last example was the 1912 earthquake tsunami that caused 2.7m run up height at Yesilkoy shore (Fig. 8).

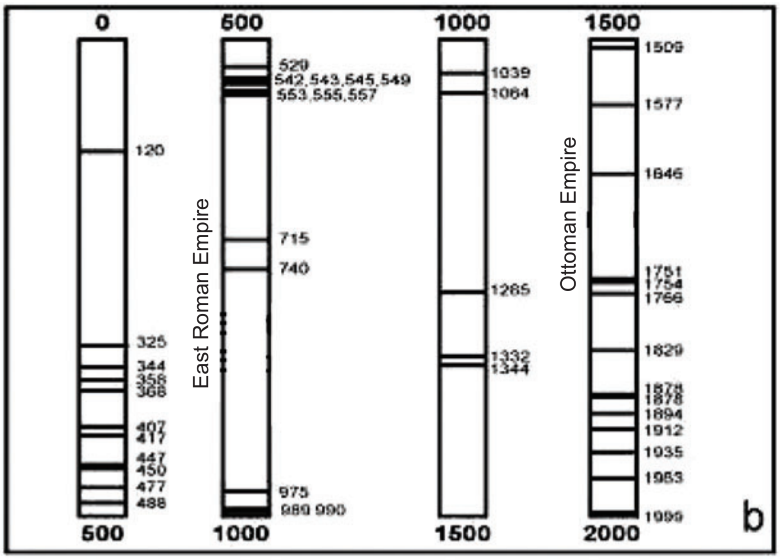
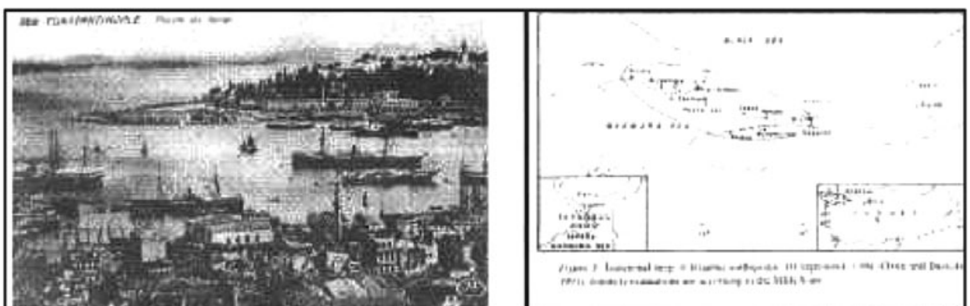


Fig. 2 Historical Tsunamis (time domain) in the Marmara Sea (after Altinok, 2006)

These records and traces have still some uncertainty but should be the target for the simulation and disaster management. And they can provide the verification and new findings for the tsunami study in Istanbul. Further this kind of tsunami deposit study must be necessary for another portion of Istanbul shore for higher resolution and provision of certificate for tsunami disaster management.



Altinok and Ersoy, 2000

10 SEPTEMBER 1509 ISTANBUL EARTHQUAKE

It occurred in the Marmara Sea, and was felt over a very large area, causing damage from Bolu to Edirne, and possibly as far as Mt. Athos. Maximum damage occurred in İstanbul (Ambraseys and Finkel, 1995).

loss of lives : 4000-5000
injures : 10000
households : 1000 (İstanbul)
I_0 = XI, (MSK), Magnitude ≈ 8.0 (Öztin and Bayülke, 1991)
Tsunami wave height ≥ 6.0m
M_S = 7.2 (Ambraseys, 2002a)
Waves overtopped the walls in Yenikapi and Aksaray was flooded. Sea inundated the area behind the city walls of Istanbul and Galata, and invaded the streets (Orgun, 1941).
The walls of Izmit Castle on the shore were damaged beyond repair, the quay walls of the shipyard collapsed and waves flooded the dockyard and the lower districts of the city (Oztin and Bayulke, 1991).

Fig. 3 Historical Tsunami record for the 1509 event (Altinok, 2006)

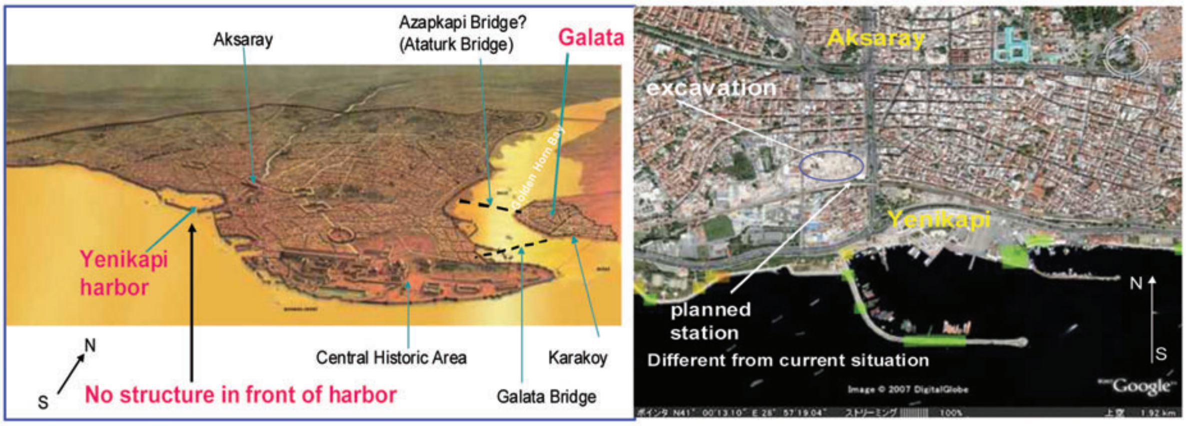


Fig. 4 Yenikapi port in Constantinople (Byzantium) at 6 th Century and current situation

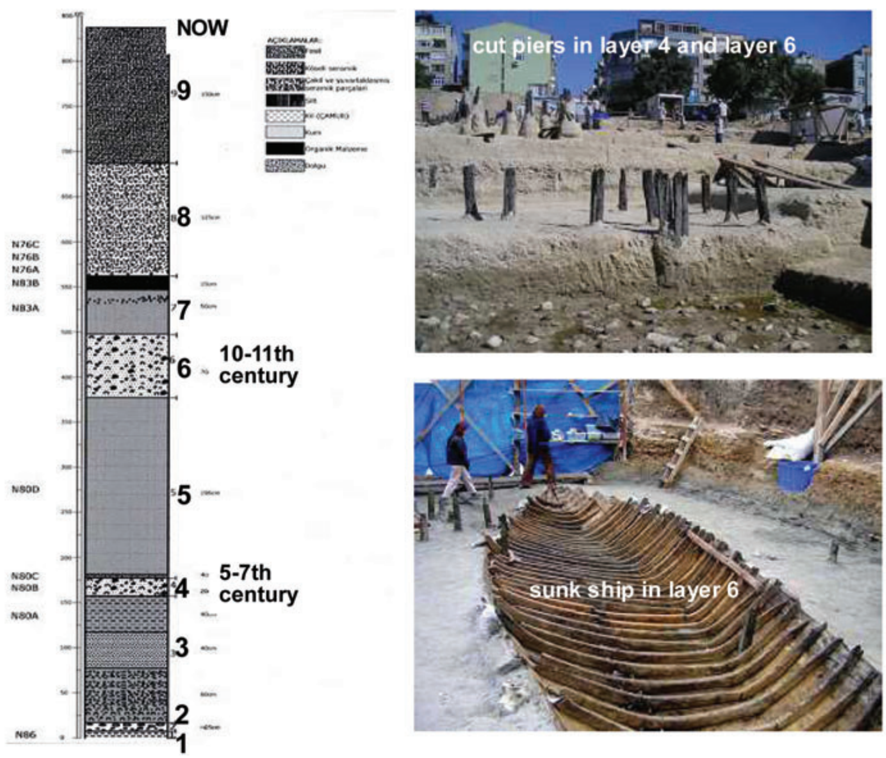


Fig. 5 Tsunami Trace at Yenikapi port (after Perincek et al., 2007)

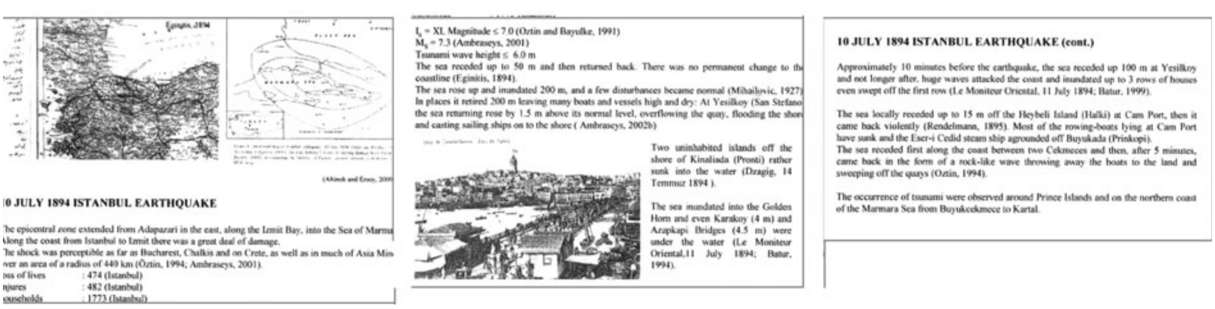


Fig. 6 Historical Tsunami record for the 1894 event (Altinok, 2006

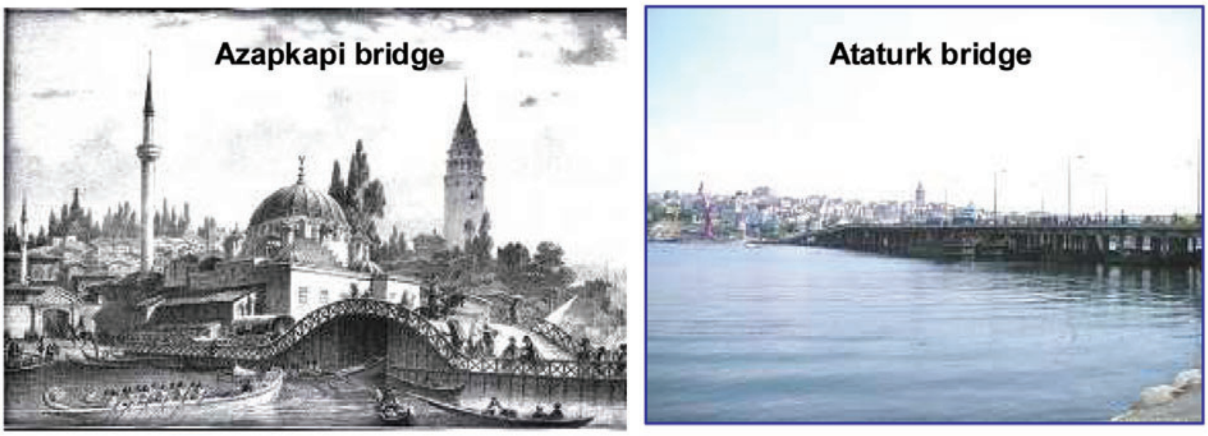
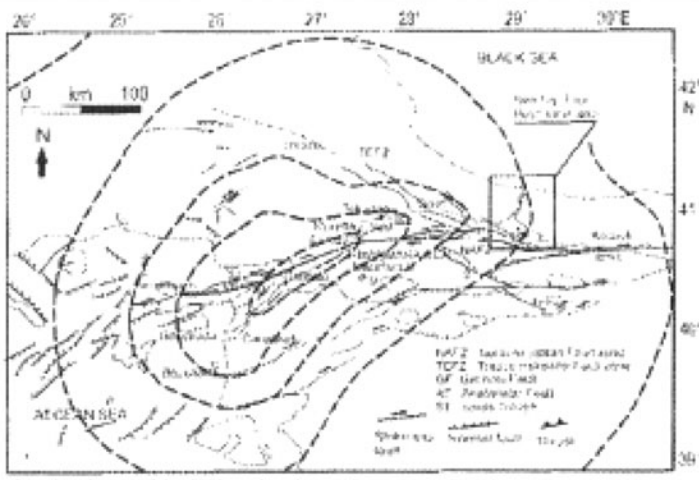


Fig. 7 Azapkapi bridge in older times and current Ataturk bridge in Golden Horn bay



Isoseismal map of the 1912 earthquake (Ambraseys and Finkel, 1987). NAF: North Anatolian Fault, TEF: Thrace-Eskişehir Fault, WMT: Western Marmara (Tekirdağ) Trough, ST: Saros Trough. A simplified tectonic setting of the Marmara Sea region (Yaltirak et al., 2000) were superimposed (Altinok et al., 2003a).

The sea at Yesilkoy has lifted the boats up to a height of 2.7m. A high water occurred as the consequence of the earthquake in the Bosphorus, which is shallow and narrow water passage between the Marmara and the Black Sea. Its average length is 31 km with an average width of 1.6 km. Its average depth is 36 m, with a maximum of 110 m. The high water demolished Hidiv Pasha's yacht named "Mahrussa", anchored off Pasabahce (Altinok et al., 2003a).

Fig. 8 Historical Tsunami record for the 1912 event (Altinok, 2006)

METHODOLOGY FOR SUBMARINE LANDSLIDES INDUCED TSUNAMI SOURCE IDENTIFICATION

The Sea of Marmara is consisted of pull-apart basins surrounded by steep and high slopes with relative height of more than 1,000m maximum. These topographies have been produced according to the right lateral movementby the North Anatolian fault. If some portion of slopes will slip to bottom of basin, tsunami can be produced.

It is known that more than half of past tsunamis are tectonic origin, but almost one third were landslide induced. However, there has been so far less number of examples for submarine landslide induced tsunami simulations, such as Fine et al. (2003) by theoretical and experimental, Kvalstad et al. (2005) by an analytical attempt to the large off Norwegian slope in the North Sea, rather than those generated by active faults. Yalciner et al. (2002) tried to analyze the submarine landslides in from of Istanbul using the Two-Layered methodology developed by Imamura et al., 1995, but it had several problems for its process in geotechnical and topographical settings.

In order to solve these problems, an analytical and hybrid methodology for setting tsunami sources was attempted based on the combination of topographical analysis, response and stability analysis and three dimensional landslide simulations at Marmara Sea in front of Istanbul, Turkey.

For instance, the first step will be how to identify vulnerable slopes with their extent, shape and depth by topographical analysis using the existing detailed bathymetry data. According to this, vulnerable slopes which slipped or may slip will be detected. Next, these vulnerable slopes will be studied on their stability during earthquakes by response analysis and stability analysis. The final step will be how these vulnerable slopes may slip and move by three dimensional landslide simulation. For this, several assumptions such as geotechnical properties, moving velocity during slip etc. in time series should be necessary, because there is not such exact information in this area. After then, tsunami simulation will be conducted with the movement of slopes as the tsunami source and the results will be compared with the past events by using the sources with combination of the simulated results due to active faults movement.

ANALYZED RESULTS

Topographical Analysis

Fortunately the precise bathymetry data (20m grids) in Marmara Sea bottom is available, shown in Fig. 9 (TUBITAK/IFREMER, 2005). Using the data, the topographic analysis was conducted for identification of vulnerable slopes that may generate disastrous tsunamis. Some criteria were given by existing information, for example scale of slopes (Hebert et al., 2005), past activities of active faults (IMM, 2007) etc. Though the analysis was based on what used for on land slopes, the situation at submarine was taken into consideration such as sea water resistance, weathering by sea water and active movements by the North Anatolian Fault etc. Soil samplings with dating tests at sea bottom surface certificate the trace of the past events of slope failure, and past tsunami records might suggest the possibility of generating tsunami by submarine landslides during or just after the earthquakes (McHugh et al., 2006, etc.) . Consequently, the 10 vulnerable slopes are identified, including 3 past events debris sites for verification of methodology.

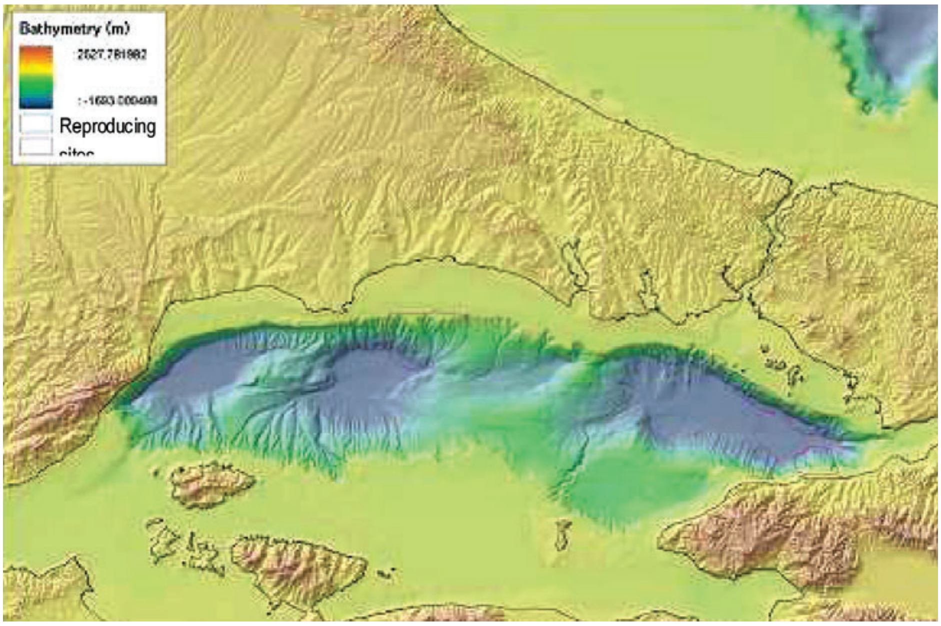


Fig. 9 Bathymetry and Topography around the Marmara Sea including Istanbul (IMM, 2007)

Stability Of Vulnerable Submarine Slopes For Generating Tsunami In Marmara Sea

Based on the active fault information along the North Anatolian Fault in Marmara Sea and assumed geological features, the one dimensional quasi-linear response analysis (Yoshida et al., 2004) was conducted for giving ground acceleration at the vulnerable slopes during the earthquakes due to the active faults movement of the NAF. Though geotechnical information was less so far, soil model with geotechnical properties at the vulnerable slopes are assumed from the geological/geotechnical and geophysical investigation results in Istanbul municipality area and used. Next the circle sliding stability analysis by Limit Equilibrium Method was executed. This method is popularly used in civil engineering field. The results provided not only the safety of the slopes but also the limit seismic motion amplitudes and the estimation of friction angle of the vulnerable slopes in Marmara Sea in front of Istanbul, Turkey. This result provided the possibility of landslides during or just after the active fault movement.

Landslide Simulation For Tsunami Source Identification

Tsunami simulation method requires three dimensional changes of topography shape in time series. Regarding to the submarine landslide case, the sea bottom bathymetry change along time is necessary. For this purpose, the three dimensional landslide simulation technique was adopted. Several dynamic soil properties are estimated after some try and error process (Lang et al., 1998, etc.). First the three slopes that might be slipped due to the past earthquakes are analyzed. After estimating the shape before slip and simulated during slip and calculated until corresponding to the current shape. Then, the shapes during slip along time should be used for the tsunami source and trying a tsunami simulation. After verifying the past cases, the 7 vulnerable slopes are simulated when they start to slip. Thus, all the vulnerable slopes in Marmara Sea that may generate disastrous tsunamis are simulated for the source for tsunami simulation. The key factor should be the dynamic friction coefficients of slip mass and moving velocity of the slip mass. Though still this simulation methodology for submarine landslides should be refined using numerical tests, verification by actual examples, it must be effective for tsunami simulation for submarine landslides rather than empirical trials so far. Fig. 10 and Fig. 11 show an example of landslide simulation

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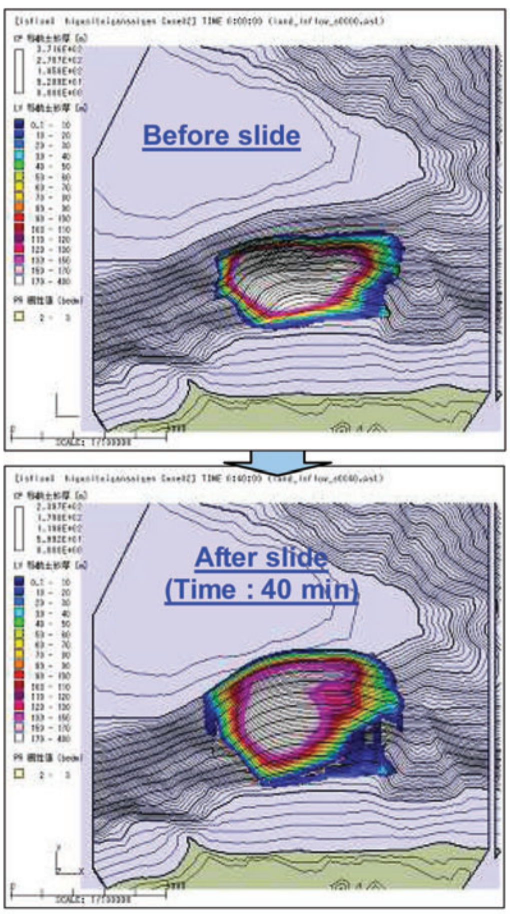


Fig. 10 Example of Landslide Simulation

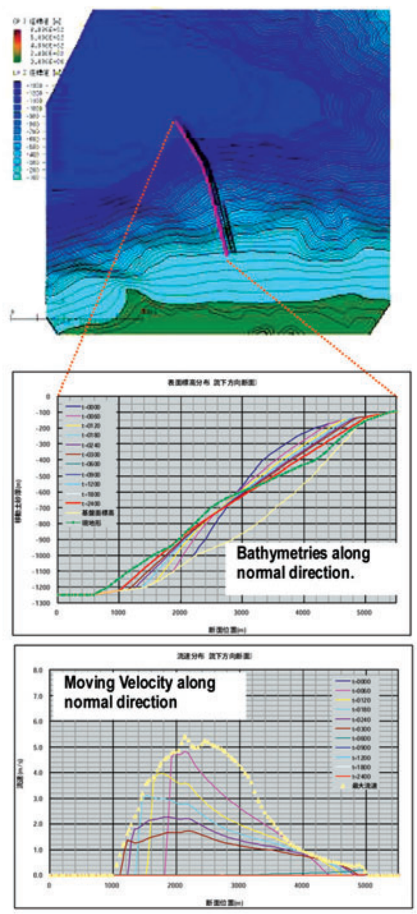


Fig. 11 An Example of before and after slip shape by landslide simulation

Tsunami Simulation

Based on above analytical tsunami sources, tsunami simulations were conducted. Used tsunami sources for active faults are shown in Fig. 12 based on the study by IMM (2007), and those of landslides are shown in Fig. 13. For active faults, some vertical movement of 15 degrees was used based on the assumption by Muller et al., 2005. The using program is N2 by Dr. Imamura and NAMIDAMCE by METU (Imamura et al., 2006). Bathymetry data is derived from 20m grids all around Marmara Sea by TUBITAK/IFREMER (2005), and finally 50m grids are used for the nearest regions of the coast. Fortunately, tide variation is less during years/days, such as less than 50cm. Friction coefficient of sea bottom is set and also for land surface they are set estimated from building density (Kotani et al., 1999).

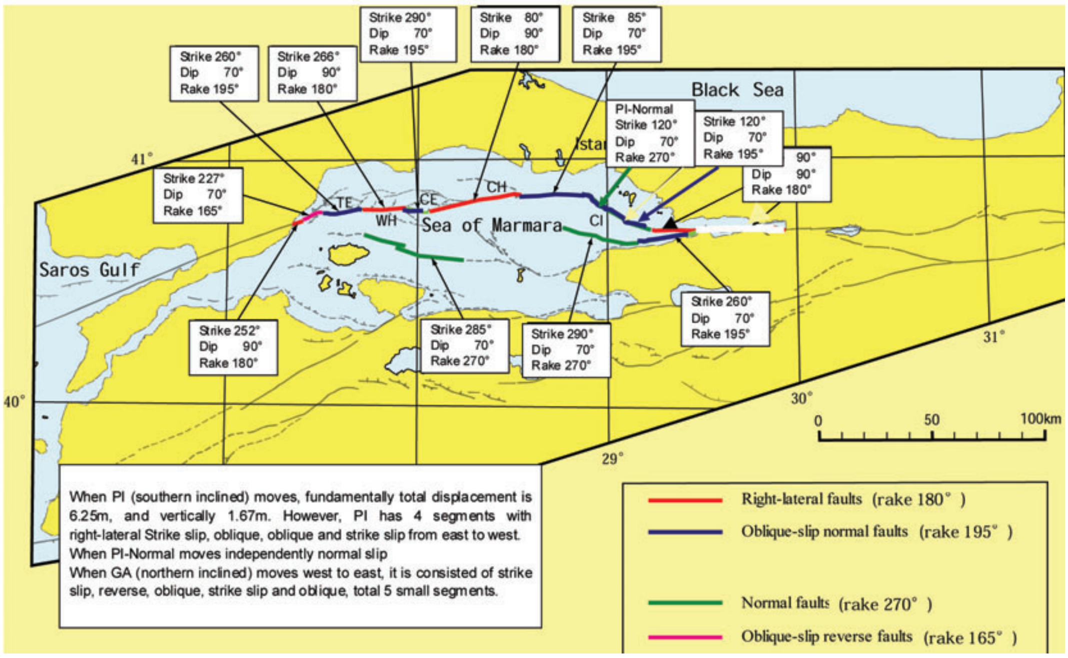


Fig. 12 Used Tsunami Sources for Active Faults along NAF in Marmara Sea (IMM, 2007)

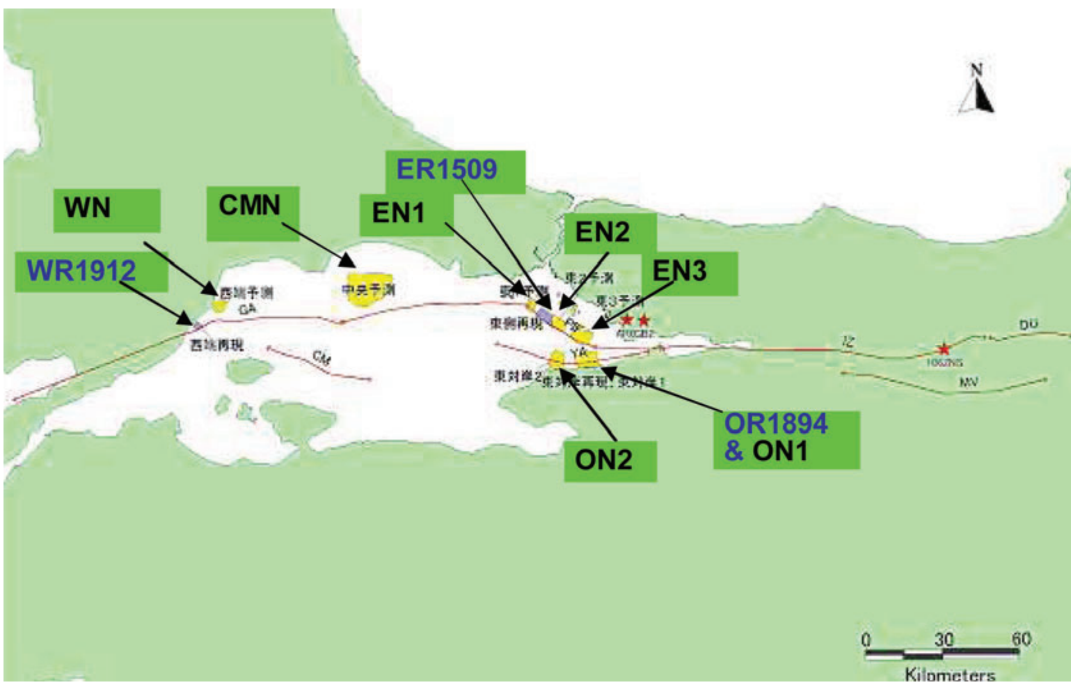


Fig. 13 Tsunami Sources for Submarine Landslides in Marmara Sea

COMPARISON BETWEEN SIMULATED RESULTS AND PAST EVENTS

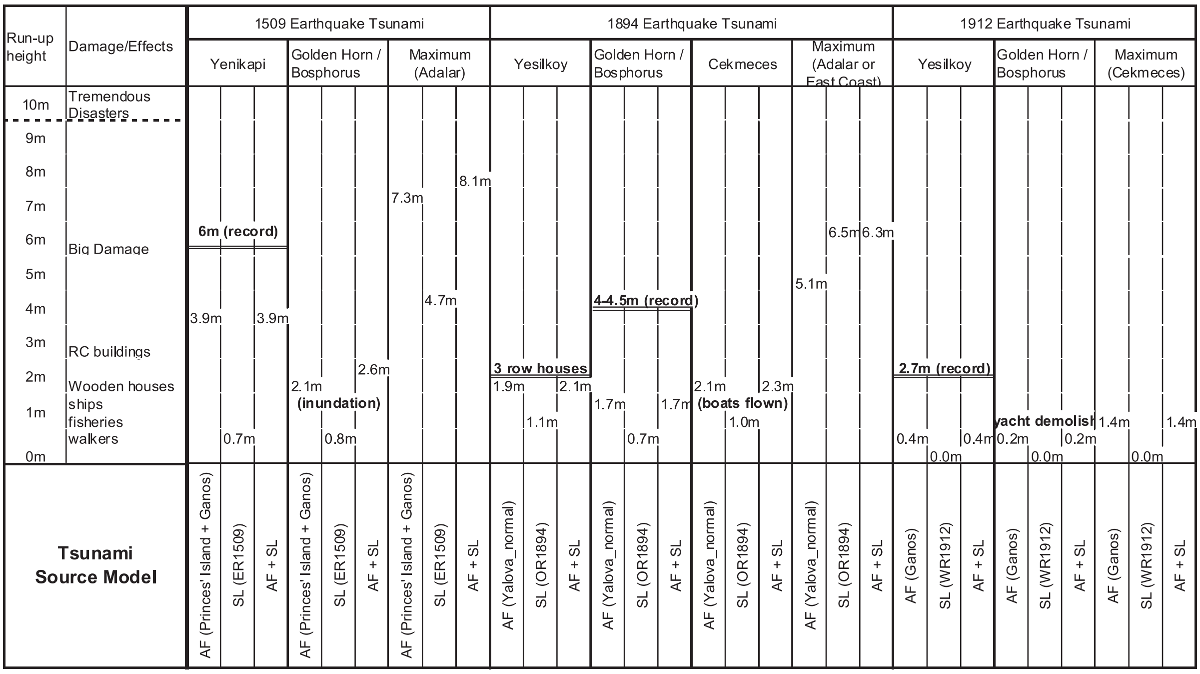
The three target past events are, as mentioned above, what poses quantitative tsunami records; the 1509, the 1894 and the 1912 events. The summary is shown in Table 1.

For the 1509 event, the simulated results provided sufficient height at Golden Horn bay comparing with the record. And without record, the simulation showed the remarkable height at eastern part of Istanbul city. However, the simulation provided less height than the past events at Yenilkapi port. One of the reasons for this difference, as shown in Fig. 4, bathymetry and on land topography has been quite changed. In front of the port were reclaimed and more than 3m height road along the coast line was built. Therefore another simulation using the bathymetry data at the time of 1509 will be effective.

For the 1894 event, the simulated results provided sufficient tsunami height at Yesilkoy town and Cekmeces lake. However, the simulated results gave less height than the past events at Golden Horn bay. A possible reason will be, as shown in Fig. 7, the different heights of Azpkapi bridge, 4-6m at central part and 2-3m at edge portion. If not the central portion, simulation has well matched the record.

For the 1912 event, the simulated results provided less than the past event records. We need to confirm both the tsunami sources and the historical records again.

TABLE 1 COMPARISON BETWEEN SIMULATED RESULTS AND PART EVENT RECORDS



DISCUSSION

Totally, the simulated results including the combination of active faults and submarine landslides cannot always catch up with perfectly the run up heights due to the past tsunami events in Istanbul. However, mostly the results should provide sufficient tsunami heights for the inundated shore areas in the past events.

At most cases, the contribution of submarine landslide induced tsunamis looked not so big. However, the contribution should change due to the time lag between fault movement and landslide movement, and the combined results are sensitive and sharply at each point. The maximum contribution will be sum of maximums from active fault and landslide induced. Actually, in the case of Papua New Guinea on 1998, the landslide would be generated after 20 minutes of the fault movement.

As mentioned above, the historical records are essential for the tsunami simulation. And even there are still less historical records, though the great efforts in Istanbul have just started by Dr. Altinok with difficulties on older languages. Sometimes further verifications are necessary on the records. More studies can be suggested on this subject with more contributors and with seismological or topographical knowledge. Another possibilities of researching historical events are topographical survey, tsunami deposits investigation at younger formation with dating tests etc. These efforts should be developed as well as historical records study.

Further the study on submarine landslides induced tsunamis has been small amount so far. This time one proposal for simulation analysis methodology was proposed. However, still there exist several unknown factors such as soil properties, slipping velocities interaction between slipping mud and sea water etc. further study on this subject is one of the problems for tsunami researchers in the world. And still it should be insisted that there are various evidences of large submarine landslides in Marmara Sea, the study at Istanbul should be continues and developed.

For the tsunami simulation, the program itself has been already established, then, more detailed input data such as bathymetry, and consideration of historical time such as no fill or reclaimed land at the time should be necessary.

Now the Istanbul Metropolitan Municipality government has started the preparedness effort towards tsunami as well as seismic ground motion for the approaching large earthquake. The simulated results are the base for the efforts, and especially, the simulated results suggested not only European side coast, but more significantly eastern coast and islands off eastern coast will affected much.

Finally, these simulations are not only by program or detailed data but also historical facts are essential for more precise simulation and for ultimately disaster management with reducing risks.

ACKNOWLEDGEMENT

The author would like to express his great thanks to Mr. A. Bas (IMM) for giving the opportunity to release the project result. Also especially to Dr. M. Erdik and Dr. E. Durukal for their important suggestions and guidance for analysis, to Dr. A. Yalciner for his efforts on tsunami simulation, to Dr. Y. Altinok and Dr. D. Perincek for their guidance on historical tsunamis. Further, to Dr S Hori for his efforts on landslide simulation, and Mr. M. Nemoto on his tsunami simulation in the study team.

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TSUNAMI SIMULATION ALONG PENINSULAR MALAYSIA AND SOUTHERN THAILAND USING A NESTED-GRID MODEL: A CASE STUDY OF INDONESIA TSUNAMI 2004

Dr. Md. Fazlul Karim*

ABSTRACT

A one-way nested tsunami computation model is developed and applied to compute the response of the 2004 Indonesian tsunami along the coastal belts of Penang Island in Peninsular Malaysia and Phuket Island in Southern Thailand. In this study, a one-way nested finite difference scheme is used to solve the depth averaged shallow water equations in Cartesian coordinates. Two nested models with fine mesh numerical schemes (inner models) for the west coast of Malaysia covering 5º10´-5º35´N and 100º-100º30´E and the Southern Thailand covering the region between 7.4˚ N to 8.10˚ N and 98˚ E to 98.4˚ E to record fine orographical details of the region of Penang and Phuket Islands have been nested into a coarse mesh scheme (outer model) enclosing 2º-14ºN and 90º-100º30´E. The fine mesh schemes incorporate the Penang and Phuket Islands more accurately as the grid size is considered small. In a one-way nested grid model, information (velocity components and sea surface elevation) from the coarse mesh scheme could enter and affect the fine mesh scheme through the interface between them in each time step of the solution process, while disturbances from the fine mesh do not feed back to the coarse one. The outer scheme is thus running completely independent in each time step of the solution process. A simulation experiment shows that the performance of the inner schemes of the one-way nested model is superior in accuracy compared to that of outer scheme. Different aspects of tsunami along the coastal belts of Penang and Phuket Islands have been computed through outer and inner schemes and the results are found to be satisfactory.

Key words: Nested model, Penang Island, Phuket Island, Indonesian Tsunami 2004.

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INTRODUCTION

The tsunami associated with the earthquake of 26 December 2004 hit the southern Thailand and west coasts of Malaysia; both the regions are designated as Peninsular. That event had a profound impact along the coastlines of Phuket in Thailand and Penang in Malaysia and indicated that both the regions were in vulnerable positions for tsunami surge due to a seismic zone at Sumatra. According to Ishii et al. (2005), the rupture of sea bed along the fault line spreads over 1300 km-long aftershock zone by propagating northward at ~ 2.8 km s-1 for ~ 8 min. As the Indian Ocean has several seismic sources, recurrence of tsunamis on the scale of 2004 event can be anticipated in future. So, it is necessary that tsunamis are studied in detail and prediction models are developed for simulating propagation, and estimating surge amplitude and run-up along these coastal belts.

Tsunami models have been developed by various investigators after occurrence of 2004 Indonesian event. Most of the past studies for the event of 2004 along the coastal belt of southern Thailand are based on field surveys. The most notable contributions are Matsutomi et al (2005), Satake et al. (2005) and Tsuji et al. (2006).

Kowalik et al. (2005) developed a spherical polar shallow water model, with a very fine mesh resolution, to simulate the 2004 Indonesian tsunami throughout the globe between 80ºS and 69ºN latitudes. A nonlinear polar coordinate shallow water model has been developed by Roy et al. (2007) to compute tsunamis due to 2004 Indonesian event along North Sumatra and Penang Island. Karim et al. (2006) developed a linear Cartesian coordinate shallow water model for tsunami computation along the west coast of Thailand and Malaysia. Karim et al. (2007) also investigated the effect of the different orientations of the source of 2004 Indonesian tsunami along the coastal belts of Penang Island.

Nested grid models are new widely used to increase the resolution of numerical model (Wang et al. 2006). The specification of lateral boundary conditions to nested grid domain(s) is critical for a realistic simulation of oceanic and atmospheric phenomena being modeled and is an area that has received considerable attention over the past three decades (Walko et al. 1995). Most of the past attempts to develop nesting approaches (either one-way or two-way) have been only for storm surge modelling. The most notable contributions are Johns et al. (1985), Roy et al. (1995), Jones and Davis (1998). The grid nesting could be implemented by one-way or two-way. In a one-way nested grid model, information (velocity components and sea surface elevation) from the coarse mesh could enter and affect the fine mesh through the interface between them, while disturbances from the fine mesh do not feed back to the coarse one. Because it is simpler and requires less computer time (Koch and McQueen, 1987; Yu and Zhang, 2002), the one-way approach is used in most nested ocean and atmosphere models (e. g. Davis and Flather, 1987, Johns et al. 1985, Roy 1995).

The west coast of Peninsular Malaysia and Southern Thailand has high bending, very irregular in shape and many off-shore islands. Proper incorporation of coastline and island boundaries in a numerical scheme is essential for accurate estimation of water levels due to tsunami. For that purpose a numerical scheme consisting of very fine mesh is required along the coastal belt, whereas this is unnecessary away from the coast. Consideration of very fine mesh over the whole analysis area involves, unnecessarily, more memory and more CPU time in the solution process and invites problem of numerical instability. A nested grid system is especially suitable for incorporation of coastline and island boundaries which require a fine resolution. A nested numerical scheme (inner scheme with fine resolution) within the parent model (outer scheme with coarse resolution) can record fine orographical detail in the regions of interest and this is particularly important for these regions.

In this study, in the light of the rupture process and the curvilinear nature of west coast of Peninsular Malaysia and Southern Thailand, a one-way nested numerical scheme is used to compute the response of 2004 Indonesian tsunami along the coastal belts of both the regions.

NUMERICAL MODEL

Depth averaged shallow water equations

In Cartesian coordinates, the following governing equations, including the depth-averaged continuity equation and momentum equations are used in the present model. The depth-averaged shallow water equations are

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\left[(\zeta + h)u\right] + \frac{\partial}{\partial y}\left[(\zeta + h)v\right] = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial \zeta}{\partial x} - \frac{F_x}{\rho\,(\zeta + h)} \qquad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -g\frac{\partial \zeta}{\partial y} - \frac{F_y}{\rho\,(\zeta + h)} \qquad (3)$$

where ζ is the sea surface elevation above the undisturbed sea level; *h* the depth of undisturbed water; υ, ν the *x*- and *y*- components of the depth-mean current; *f* the Coriolis parameter; *Fx, Fy* the components of bottom friction; *g* the gravity acceleration; *Cf* the friction coefficient; ρ the water density.

The parameterization of the bottom stress is done by the depth averaged velocity components:

$$F_x = \rho\ C_f\ u\ \left(u^2 + v^2\right)^{1/2} \quad \text{and} \quad F_y = \rho\ C_f\ v\ \left(u^2 + v^2\right)^{1/2}$$

The origin of the system of coordinates is located on the undisturbed sea surface.

BOUNDARY CONDITIONS OF OUTER MODEL

Other than the west coast of Peninsular Malaysia, the boundaries are considered as straight lines in the open sea. The southern and northern open sea boundaries lie parallel to *x*-axis and the western open sea boundary lies parallel to *y*-axis. The radiation boundary conditions for the southern, northern and western open sea boundaries, due to Johns et al. (1981), are

$u - (g/h)^{1/2}\zeta = 0$	at the west open boundary; parallel to *y*-axis	(5)
$v + (g/h)^{1/2}\zeta = 0$	at the south open boundary; along *x*-axis	(6)
$v - (g/h)^{1/2}\zeta = 0$	at the north open boundary; parallel *x*-axis	(7)

This type of boundary condition allows the disturbance, generated within the model area, to go out through the open boundary. The coastal belts of the main land and islands are the closed boundaries where the normal components of the current are taken as zero.

ONE - WAY NESTING

There is an economical way to improve the resolution of a numerical model by nesting a fine mesh within a coarse mesh, since the nested model can save computer time and memory compared with a model having the same fine resolution throughout the wide model domain (Koch and McQueen, 1987). In a one-way nested grid model, information from the coarse mesh could enter and affect the fine mesh through the interface between them, while disturbances from the fine mesh do not feed back to the coarse one. In other words, the coarse scheme is entirely independent of the fine mesh scheme

Figure 1: Outer model domain including west coast of Thailand, Peninsular Malaysia and source zone west of North Sumatra.

The outer and inner model domains are shown in Figs. 1 and 2(a-b) respectively. The outer scheme area includes the region where the source of 2004 Indonesian tsunami is located and the inner scheme area covers the Phuket Island in Southern Thailand and Penang Island in peninsular Malaysia. Since the deep ocean has not been included in the fine grid scheme area the time step can be considerably large and this can save some computer time. The ratio of the coarse grid size, $(1/30)^0$ (about 4 km), to the fine grid size, $(1/120)^0$ (about 0.8 km), is an integer (5). The time step for each scheme is taken as 10 *s*, and this ensures the stability of the numerical scheme.

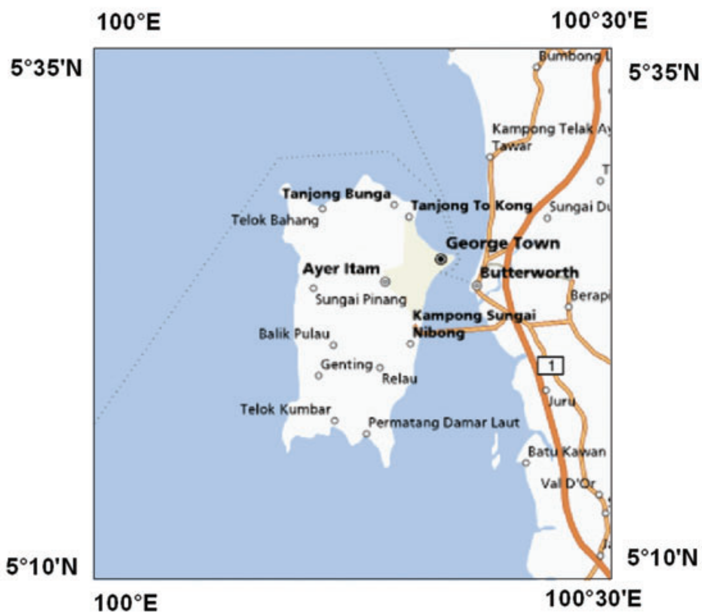

Figure 2a: Inner model domain covering Penang Island

Figure 2b: Inner model domain covering Phuket Island

Both the schemes (outer and inner) have the same dynamical equations (1) – (3) with different boundary conditions. For the outer scheme the boundary conditions (5) – (7) are used in each time step of the solution process. The interface conditions, typically including the open boundary conditions of the fine mesh, are of great importance for the one-way nested model in maintaining stability. In this model, each interface is a matching of an open boundary grid line of the inner scheme with the appropriate grid line of the outer scheme. The velocity components *u, v* and elevation ζ computed by $(1/30)^0$ resolution along the matching grid line of outer scheme in each time step are used as the boundary values of $(1/20)^0$ resolution along the matching boundary grid line of the inner schemes. The high resolution inner schemes is thus depends on the dynamics of the coarse outer scheme but the coarse one is not influenced by the fine resolution scheme. This has the advantage that the models can be run successively starting with the coarse resolution scheme. The coupling of the coarser and finer schemes is done according to Johns et al. (1985), who maintained the one way interaction between the parent (outer) and nested schemes of the model. This implies that the outer scheme drives the nested (inner) scheme but the response in the nested scheme does not affect the outer scheme of the model.

INITIAL CONDITION (TSUNAMI SOURCE GENERATION IN OUTER SCHEME)

Based on rupture parameters estimated by several authors discussed in introduction, a reasonable tsunami source has been designed for the 12/26/2004 event, in terms of magnitude and timing of sea surface displacement. We consider the source, extended along the fault line between 92–97˚E and 2–13.5˚N; this zone is a rectangular area having length ~ 1200 km and width ~ 300 km. This rectangular zone has been divided into 42×4 segments. We designate the segments by *Sij* where $i = 1, 2, \ldots, 42$; $j = 1, 2, 3, 4$. Starting from S11 at the southwest corner of the rectangular source zone we activate the whole source in 45 time steps (in 450 seconds) in the following way:

Time step	segm ent activated				
1	S_{11}				
2	S_{21}	S_{12}			
3	S_{31}	S_{22}	S_{13}		
4	S_{41}	S_{32}	S_{23}	S_{14}	
………………………………					
k	S_{k1}	$S_{k-1\ 2}$	$S_{k-2\ 3}$	$S_{k-3\ 4}$	k = 4, 5,…..,42
………………………………					
42	$S_{42\ 1}$	$S_{41\ 2}$	$S_{40\ 3}$	$S_{39\ 4}$	
43		$S_{42\ 2}$	$S_{41\ 3}$	$S_{40\ 4}$	
44			$S_{42\ 3}$	$S_{41\ 4}$	
45				$S_{42\ 4}$	

Thus the source has been activated gradually from south to north and from west to east. According to the estimation of Kowalik et al. (2005), the tsunami source is extended along the fault zone from south-east to north-west with the sea bed uplift of 507 cm to subsidence of 474 cm from west to east. Ammon et al. (2005) also suggest that the maximum uplift to subsidence of sea bed within ± 5m. Tanioka et al. (2006) computed the rupture zone and suggest that the subsidence to uplift of the rupture zone is within -3m to 8m. Based on the above information we consider the source, extended along the fault line between 92–97˚E and 2–13.5˚N with maximum rise of 5 m and maximum fall of 4.75 m of the sea surface from west to east. For the corresponding instantaneous version, the same extent and intensity is assigned as the initial condition. The initial sea surface elevations and the velocity components are taken as zero everywhere.

RESULTS AND DISCUSSION

Results obtained from Outer Scheme

The governing equations (1)-(3) along with the boundary conditions (5)-(7) are solved by using a finite difference scheme. Wave propagation of the source is computed and water levels along the coastal belts of Penang Island are estimated.

Propagation of Tsunami towards Phuket and Penang Island

Results from the numerical simulation of propagation of tsunami towards the west coast of Peninsular Malaysia are shown in Figs. 3 and 4 in the form of contour of sea surface elevation. The disturbance pattern of the sea surface is presented at two different instants of time. At 1.5 hr after the generation of the initial tsunami wave at the source, the sea surface disturbance is found to be proceeding towards Penang island in Peninsular Malaysia after flooding the Phuket region (Fig. 3) and finally at 4 hr the tsunami surge is hitting the north and west coasts of Penang Island (Fig. 4).

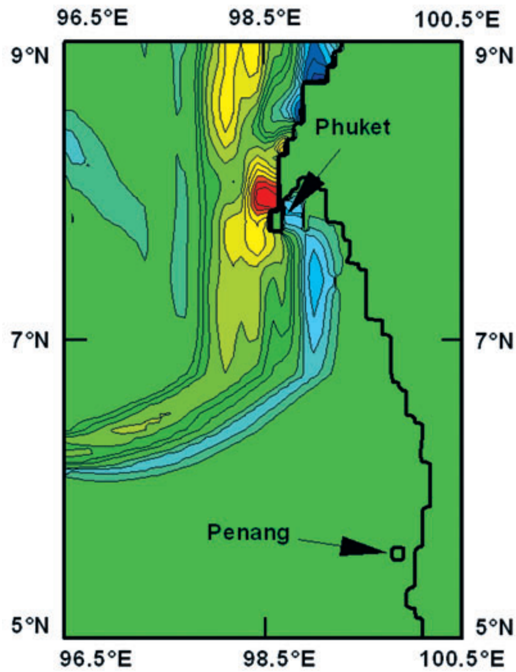

Figure 3: Propagation of tsunami at 1.5 hr.

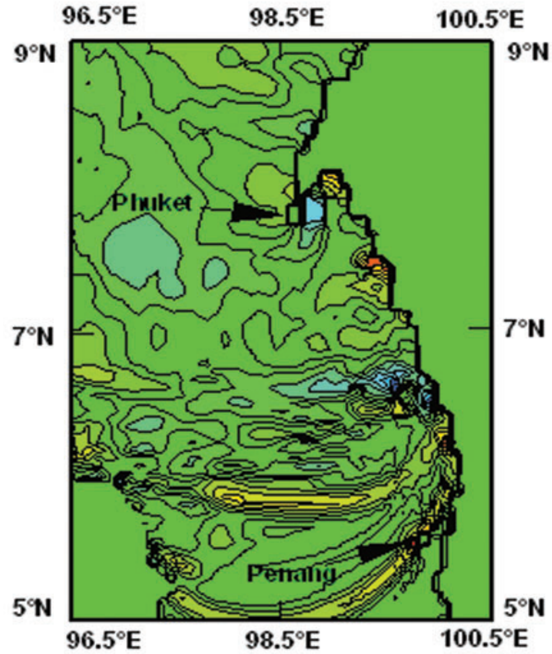

Figure 4: Propagation of tsunami at 4 hr.

Arrival Time of Tsunami

The arrival time plays an important role in prediction and early warning systems of tsunami. In Fig 5, the tsunami arrival time is shown in the form of contour plot in minutes; time of +0.1 m sea level rise at each grid point is considered as the arrival tsunami at that point. It is seen that after initiating the source, the disturbance propagates gradually towards the Coast of Phuket Island in Southern Thailand. Then, the disturbance continues propagating towards Penang Island and reaches the north-west coast at approximately 220 minutes. The propagation slows down at Malacca Straits because of very shallow water along this strait and this is consistent with the fact that a long wave speed reduces in shallow water. Computed result shows earlier arrival of tsunami than that of observation available in USGS website

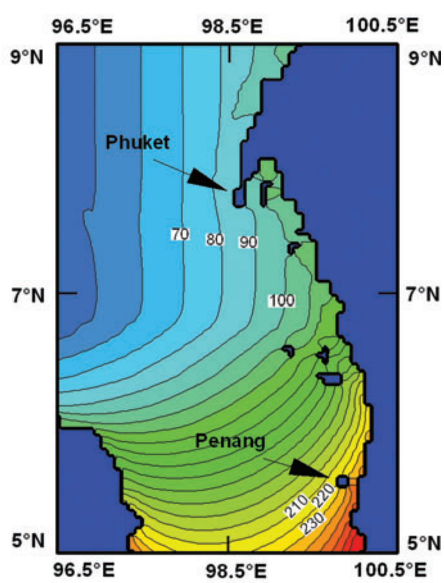

Figure 5: Contour showing tsunami propagation time in minutes; sea level rise of 0.1 m is considered as the arrival of tsunami.

RESULTS OBTAINED FROM INNER NESTED SCHEME

Computed Time Series of Water Levels at the coastal belts of Phuket and Penang Island

The computed water levels at several locations of the coastal belts of Phuket and Penang Islands are stored at an interval of 30 seconds.

Figure 6(i) depicts the time series of water levels at two locations on north-west and east coasts of Phuket in southern Thailand. At north-west coast of Phuket, the time series begins with a depression of -4.2 m and the maximum water level is about 8.6 m and the water level continues to oscillate for several hours. At east coast of Phuket, it begins with a depression of -2.5 m and the maximum water level reaches up to about 4.4 m .

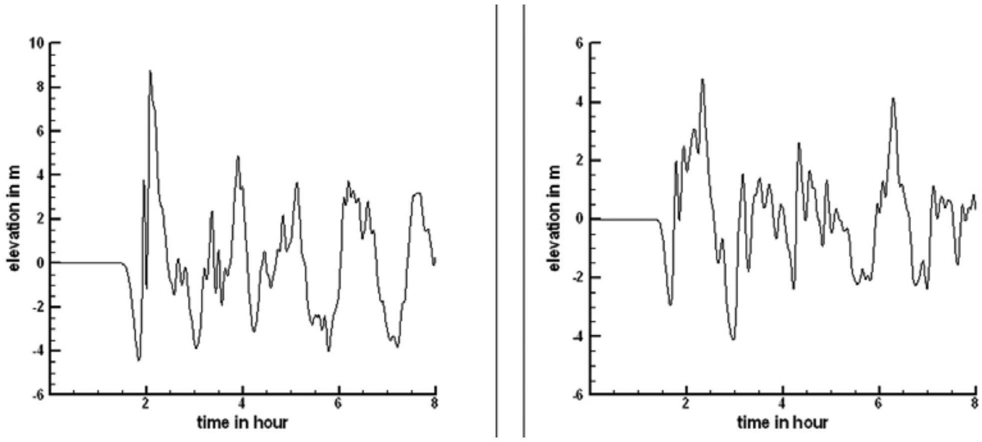

Figure 6(i): Time series of computed elevation at coastal locations of Phuket Island: (a) North-west (b) East coast

Figure 6 (ii) shows the time series of water levels at Batu Ferringhi (north-west coast) and at Pasir Panjang (south coast) of Penang Island. At Batu Ferringhi, the maximum elevation is approximately 3.4 m. The water level shows oscillatory behavior and the oscillation continues for several hours. At Pasir Panjang, the result shows the same pattern as that of Batu Ferringhi but with different maximum elevation of 2.2 m

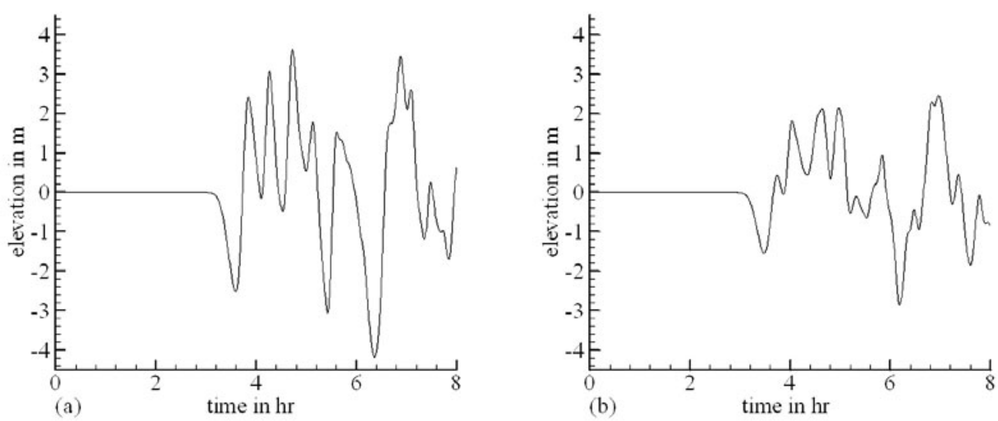

Figure 6(ii): Time series of computed elevation at two coastal locations of Penang Island (a) Batu Ferringhi (North-west) (b) South Penang

Estimation of Maximum Water Level along the coasts and Corresponding Time

Figure 7 shows the maximum water level contours along the coastal belts of Phuket and Penang Islands. The water level near Phuket is increasing from south to north; ranging from 1.5 m to 12 m (Fig. 7a). The water level is increasing very fast when it reaches near the shoreline. We compare the computed maximum surge levels with that available in the USGS website (www.drgeorgepc.com/Tsunami 2004/Indonesia.html). In this website address it is reported that wave height reached 7 to 11 m surrounding Phuket Island. Thus, comparison with USGS website is quite good. The maximum water level at Penang Island varies from 2 m to 4.5 m (Figure 7b). The computed water levels indicate that the north and west coasts of Penang Island is vulnerable for stronger surges.

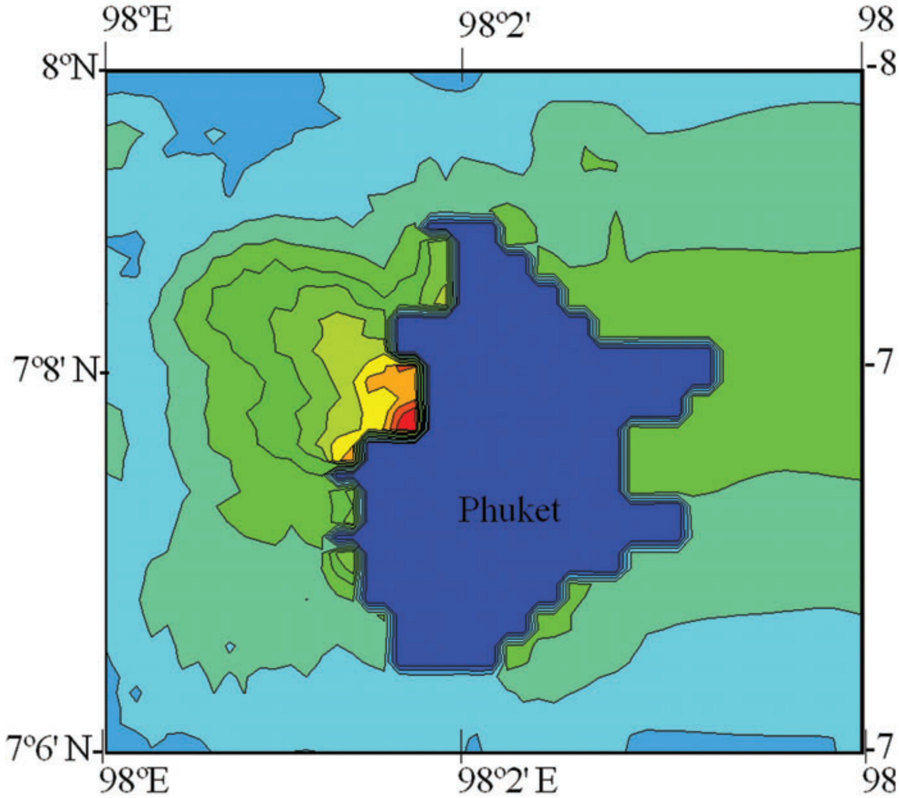

Figure 7a: Contour of maximum water levels around the Phuket Island associated with the Indonesian tsunami 2004

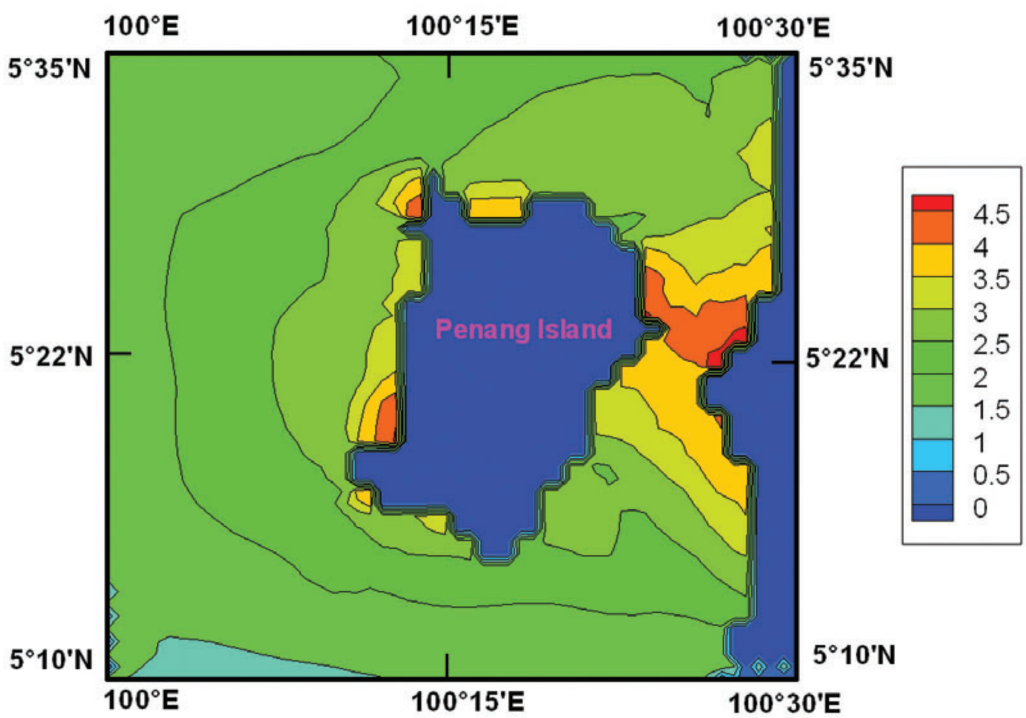

Figure 7b: Contour of maximum water levels around the Penang Island associated with the Indonesian tsunami 2004

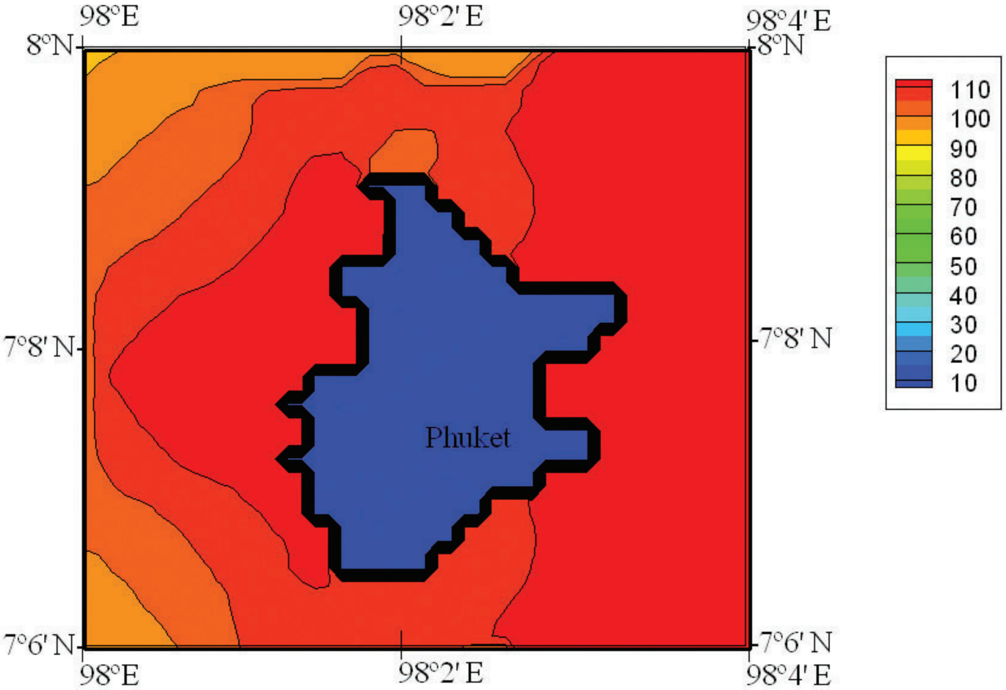

Figure 8a: Contour of times, in minutes, of attaining maximum water levels around the Phuket Island associated with the Indonesian tsunami 2004

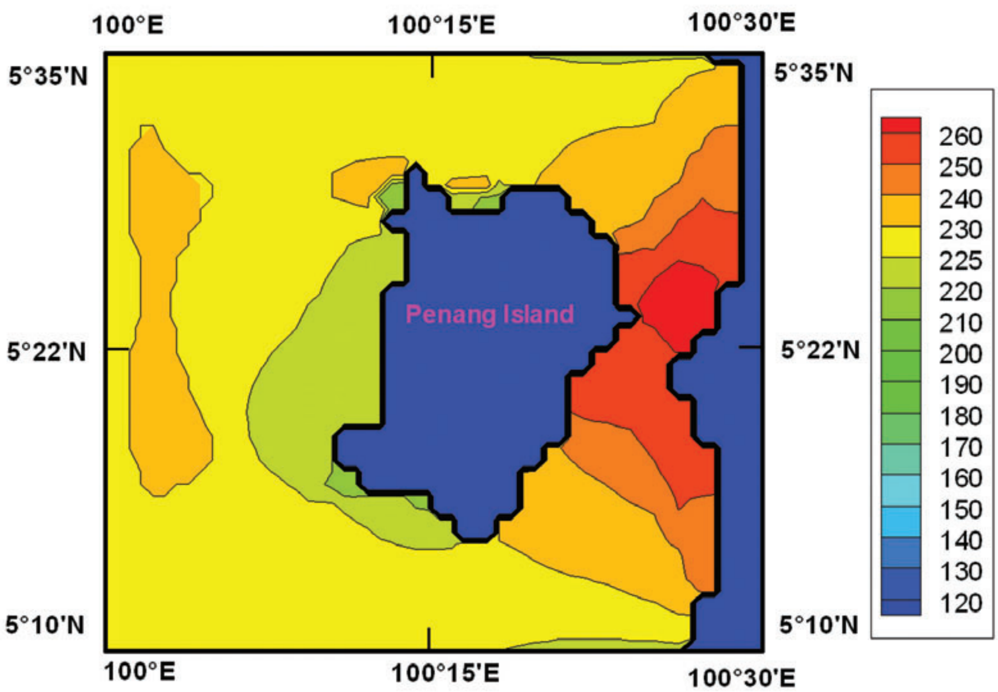

Figure 8b: Contour of times, in minutes, of attaining maximum water levels around the Penang Island associated with the Indonesian tsunami 2004

The numerical simulation of the travel time of tsunami at every grid point, as the time of attaining +0.1 m sea level rise, is presented in Fig. 8 in the form of time contours. It is seen that the arrival time of tsunami surge along the along the coastal belts of Phuket (north to south) is between 100 and 110 min (Fig. 8a) and the same is between 250 and 260 min for the Penang Island (Fig. 8b). The USGS website [(http://staff.aist.go.jp/kenji.satake/Sumatra-E.html) (Tsunami travel time in hours for the entire Indian Ocean)] confirms the fact that tsunami reaches at Phuket within 2 hours and in Penang within 4 hr 30 min. Hence the computed travel times are in good agreement with those of USGS observations.

CONCLUSIONS

In this study a one-way nested tsunami computation model is developed and applied to compute the 2004 Indonesian tsunami along the coastal belts of Peninsular Malaysia and Southern Thailand. In the one-way nested technique, it has been possible for more reasonable values for the open boundaries of the inner scheme to be supplied from the coarse mesh scheme. The computed water levels and arrival time of tsunami along the coastal belts of both the regions are in good agreement with data of observations. This nested model may be applied to compute the tsunami phenomena to any localized coastal region where a tsunami hazards exist.

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INDIAN OCEAN TSUNAMI-ENABLED COASTAL SEA LEVEL STATIONS: SPECIFICATIONS AND COMMUNICATIONS

Bernard Kilonsky, Mark Merrifield*

ABSTRACT

During the First Session of the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS-I), Perth, 3-5 August 2005, intersession technical working groups were established to work on specific aspects of the IOTWS and given the task of studying the optimal configuration of the instrumental networks. To ensure the rapid implementation of such a system, the recommendations of the United Nations Educational, Scientific, and Cultural Organization's (UNESCO) Intergovernmental Oceanographic Commission (IOC) to upgrade the near real-time Global Sea Level Observing System (GLOSS) sea level stations in the central and western Indian Ocean, and to install new near real-time GLOSS stations in the eastern Indian Ocean where early detection was of the highest priority were forwarded by the sea level working group (WG2). It was recommended: that these systems make use of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorology Satellite (Meteosat); the Japanese Meteorological Agency (JMA) MTSAT and the Japanese National Warning Center; the World Meteorological Organization's (WMO) Global Telecommunications System (GTS), and the Pacific Tsunami Warning Center (PTWC) for the transmission and evaluation of the tide gauge data for tsunami warning and monitoring. Subsequent ICG/IOTWS meetings furthered plans for the development of these systems in the Indian Ocean. This report addresses the operational specifications recommended by the ICG/IOTWS WG2 for the development of sustainable tsunami-enabled coastal sea level stations, and explores communication schemes available for transmitting the sea level data to those responsible for tsunami monitoring and warning.

Key words: Tsunami, sea level, tide gauge data

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HISTORICAL PERSPECTIVE

In the early 1970s, Klaus Wyrtki the director of the University of Hawaii Sea Level Center (UHSLC), recognized the importance of in situ sea level observations for the study of basin wide ocean dynamics, and specifically their usefulness in research into the ENSO phenomena. At that time, the only coordinated international program for the collection of sea level was the Permanent Service for Mean Sea Level (PSMSL) which collected monthly averaged sea level values from national agencies. However, there were significant gaps in the coverage of some of the most important sites, particularly those located on small open ocean islands which for economic and scale reasons had problems establishing and maintaining the in situ sites. As research advanced, it was apparent that to rectify this situation, the program had to assume the task of establishing these sites, and processing the collected data to research quality standards. Thus, the sea level observing system at the University of Hawaii was born. At the very beginning of the data collection program, the program determined that the processed information and data should not only be in the public domain, but also should be distributed free of charge to interested users. This policy of free and open data exchange has always been followed and promoted by the UHSLC, and has become the standard recommendation for IOC GLOSS sea level sites. The processes of data collection, processing, management, and distribution have been refined through the decades with participation in various research efforts, with the advances in technology and knowledge transferred to other users via direct contact and in the GLOSS program. In addition, while the UHSCL cannot legally directly distribute data for operational warning programs, data from supported sites have traditionally been used for storm surge and tsunami monitoring and warning starting with the first satellite transmitting UHSLC sites in the early 1980s. While the decision to install satellite lins was made primarily to improve the rate of data return from these remote sites and to facilitate maintenance planning by having immediate feedback on the status of the stations, the use of the real-time schema has proven critical to tsunami and storm surge efforts.

Since the destructive 2004 Indian Ocean tsunami, UHSLC personnel have chaired sea level working groups and participated in workshops to help define standards for data collection and transmission and have worked with the geostationary metrological satellite system operators to gain access to more frequent transmission windows. The first task that the ICG/IOTWS WG2 performed was to review current coastal sea level station operational standards and develop a recommend standard for the IOTWS sites. To this end, the IOC/GLOSS Manuals I-IV on Sea Level Measurement and Interpretation were reviewed for information on data collection and transmission standards, data display standards, and instrumentation. Also, the December 2004 and the March 2005 Indian Ocean tsunamis that were observed at 11 near real time in situ sea level gauges in the western Indian Ocean along with historical records from the Indian and Pacific Oceans were used to help produce recommendations for the finalization of the technical design of the IOTWS coastal sea level stations In addition to the examination of existing tsunami records, travel time maps were examined and along with the following criteria used to develop locations for the basin-wide coastal tsunami system. The standard at the top of the criteria list was sustainability. If we could not expect the station to be supported for an extended period, then the site was not considered suitable for the core basin-wide system. Next was the location of the sites relative to tsunamigenic zones, and their usefulness in monitoring the progress of a tsunami, and the location relative to tsunami warning forecast points and to the population at risk. Finally, the presence of an existing gauge was considered to be an important consideration as many were already close to fulfilling the proposed operational sampling standards and could be used to develop and sustain the Indian Ocean tsunami climatology.

These exercises re-emphasized the importance of locating sites in harbors where the stations are considered very sustainable and their data can be used for both the determination of the level of the tsunami threat and to support the termination of a local tsunami evacuation. It also helped the WG2 determine that some of the standards developed at meetings prior to the formation of the ICG/IOTWS were valid and could be used in the Indian Ocean system.

STATION DATA COLLECTION AND TRANSMISSION STANDARDS

The [Indo-Tsunami IOC] International Coordination Meeting for the development of a Tsunami Warning and Mitigation System for the Indian Ocean within a global framework, Paris, 8 March 2005, defined recommended data sampling and message transmission requirements for tsunami monitoring in the basin-wide Indian Ocean Tsunami Warning System. The specifications, which included 1 minute sampling and a 15 minute transmission cycle via geostationary meteorological satellites with immediate retransmission via WMO's GTS to JMA, PTWC, and other appropriate warning centers and were developed in consultation with existing tsunami warning center scientists and technicians from PTWC and JMA and with JMA and EUMETSAT geostationary operators. These are the guidelines the WG2 reviewed and recommended and that the IOC/GLOSS partners have been following in establishing and/or enabling sea level stations for the core basin-wide IOTWS. Additional station requirements were developed at subsequent WG2 meetings and include the following considerations: independent power and communications, fault-tolerant redundant sensors, local logging and readout of data, a warning center event trigger, establishing system of surveying benchmarks, and locating the gauges in protected areas such as harbors.

To help develop a basin-wide IOTWS, UNESCO/IOC also recommended following the example of the Pacific system and taking advantage of existing multi-purpose coastal sea level stations and data communications. In particular, it was felt that the tide gauges in the GLOSS core network could be made suitable for tsunami monitoring. The majority of these stations required faster sampling rates (1 2 minutes) and better near real time transmission of data (15 minute or more frequent cycles) via satellite. While the WG2 knew additional stations for tsunami monitoring were required, particularly near the subduction fault in the eastern basin, the group considered the GLOSS network to be well positioned to provide basic basin wide coverage for the IOTWS. A reliance on the GLOSS multiple use water level stations also was thought to maximize the likelihood of maintenance and the continuous operation of the sea level measurement network. These stations, while designed for long-term sea level monitoring, could be configured for a basin-wide tsunami monitoring system. The sea level data acquired through these sites were considered very sustainable as they are used in climate, oceanographic and coastal sea level research, and for other purposes. The stations would report in such a way as to provide sea level data, which meet IOC/GLOSS guidelines for the region, to an operational tsunami-warning center. Initially, these centers were to be PTWC and JMA on an interim basis. The WG2 recommended that each nation assess their needs in terms of early warning requirements. In many cases, this was expected to involve additional gauges and variations on the sampling and transmission requirements. The WG2 recommended and the ICG/IOTWS concurred that all data collected at these stations be freely available to any interested user, without restriction, through GLOSS data centers at the University of Hawaii and at the Permanent Service for Mean Sea Level. These newly established GLOSS stations provide high frequency, sea level data transmitted via the EUMETSAT Meteosat and the JMA MTSAT systems. The sea level data messages are then available for immediate retransmission to the PTWC and the JMA using WMO's GTS facilities, and can be used by these and other warning centers to help confirm the existence of a major tsunami or to cancel a tsunami watch or warning. The stations will be maintained until appropriate national agencies have established their own capability for the operation and maintenance of the stations and developed their own systems for forwarding data via the GTS suitable for tsunami monitoring to PTWC or other duly designated national and international tsunami warning center. In many cases, it is anticipated that these GLOSS stations will transition into permanent national stations. It should be noted here that all of the satellite tsunami enabled sites are currently supplying information for tsunami and storm surge monitoring and warning via the GTS, and that the program is working on developing a capability to utilize to BGAN system for more rapid transmission of data from UHSLC sites.

SEA LEVEL DATA GTS MESSAGE FORMATS

A number of tide gauge and sea level data in text format have been used and distributed on the GTS. The lack of a standard traditional alphanumeric code form for tide gauge and sea level observations in WMO Manual on Codes (WMO No. 386, Part A – Alphanumeric Codes) has resulted in multiple formats being used in different systems. Furthermore the specifications of code figures are not described formally in WMO or IOC handbooks. Data collection systems operated via geostationary meteorological satellites are widely used for the collection of in situ sea level data from Data Collection Platforms (DCPs) and distributed via the Regional Telecommunication Hubs (RTH) on the GTS. Detailed information of the DCP tidal information and data format were prepared and supplied to the WG2 by the Japan Meteorological Agency.

The lack of station information and the inconsistency of representing the station identification in the GTS sea level message have made it very difficult for data processing centers to capture and decode the sea level data in real time. DCP identification numbers are provided in some reports and where no DCP numbers are given the station reports can only be identified by the bulletin header TTAAii CCCC which is intended for communication and message switching purposes at RTH centers on the GTS. The problem is that the same bulletin header cannot be used for other sensors at the same station or other stations. Only stations from one particular network are using WMO numbers as identification and their station details can be found in WMO Publication No. 9, Volume A, Observing Stations. It is recommended by the WG2 that the metadata of the station information for all sea level and tide stations should be managed by an operational system such as the catalogue in WMO Publication No. 9, Volume A and the procedures for its updates carried out and maintained consistently by a responsible agency.

The WG2 also studied the WMO Table Driven Code Form (TDCF) FM 94 BUFR and FM 95 CREX. Discussions with the code experts indicated that the use of CREX (Character form for the Representation and EXchange of data) as the data representation for tide data should be considered as it is both flexible and human readable. This has the added advantage that it can be easily converted into BUFR which has become the standard WMO practice. The template was first developed in 1977 by the WMO CBS Task Team on CREX and has been modified for implementation in its current form. An example of the current CREX template D06025 for the reporting of tide elevation series described in WMO TDCF was developed and recommended. Templates for other forms of tide reports are also available in the code form. If meteorological parameters are reported at the tide station, the WG2 recommended that sequence D06021 should be used. Examples are given in Appendices I-III.

DISTRIBUTION OF SEA LEVEL DATA ON GTS

As stated previously, meteorological bulletins transmitted on the GTS are given specific headers TTAAii CCCC called abbreviated headers. The standard data designators are given in Manual on Global Telecommunication System (WMO Publication No. 386, Part II, Attachment II-5). The operational information service in WMO requires that details of the bulletins be published in WMO Publication No. 9, Volume C1 – Catalogue of Meteorological Bulletins. The Catalogue will contain the list of meteorological bulletins being transmitted for global, inter-regional and regional exchange. Each bulletin is uniquely identified by an abbreviated header and it is described in the Catalogue with details of the code form, time group, contents and remarks. However, bulletin details of the sea level and tidal reports are mostly non-existent in the Catalogue making it very difficult for users of the GTS to search for relevant bulletins that might be of use to their region. The WG2 has obtained the relevant information of the sea level station database from PTWC.

Because some RTH centers have experienced difficulties in obtaining the sea level and tide bulletins on the GTS, the WG2 recommended that all IOTWS members are reminded of the commitment to the free and open exchange of real time sea level data routinely on the GTS and the agreement to provide the historical data and metadata for designated IOTWS sites in their country. Individual IOTWS centers can then receive the GTS message from their respective national meteorological centers (NMCs). The WG2 also considered it to be essential that the operational exchange of in situ sea level data messages on the GTS be monitored routinely, focusing primarily on the availability of reports, including timeliness, and their quality. Some of the anticipated problems that would need to be addressed in monitoring the reports on the GTS include: absence of a report, late reports, errors in the magnitude of one or more parameters, garbled messages, and coding mistakes. This monitoring is expected to be a function of the basin-wide IOTWS centers. The WG2 recognized that WMO is also conducting Annual Global Monitoring (AGM) every year and Special MTN Monitoring (SMM) every quarter for certain types of observations as part of the operation of the World Weather Watch (WWW) Program. As, the results and analyses are published to its members, the WG2 felt that it is also possible that WMO can assist in the monitoring of sea level data in their routine monitoring exercises.

FINAL SUMMARY

To help develop a basin wide warning system, the ICG/IOTWS WG2 developed basic operational standards for the establishment and/or upgrade of coastal tsunami enabled sea level stations. The WG2 also recommended that as suggested by IOC the ICG/IOTWS follow the example of the Pacific system and take advantage of existing multi-purpose coastal sea level stations and data communications. Data from the December 2004 and the March 2005 Indian Ocean tsunamis were used to help produce recommendations for the finalization of the technical design of the coastal in situ sea level element of IOTWS. These specifications include a 1 minute sampling scheme with a 15 minute transmission cycle via geostationary meteorological satellite with immediate retransmission via WMO's GTS to JMA, PTWC, and other appropriate warning centers. Additional station requirements include the following: independent power and communications, fault-tolerant redundant sensors, local logging and readout of data, a warning center event trigger, establishing system of surveying benchmarks, and locating the gauges in protected areas such as harbors. Given this, The WG2 encouraged the establishment of eastern Indian Ocean real-time GLOSS sites in conjunction with the upgrade of the existing central and western Indian Ocean real-time GLOSS sites. The process of developing GTS message headers and formats for sea level was initiated with the co-chair of the CBS Expert Team on Global Telecommunication System and WMO Information System GTS-WIS Operations and Implementation (ET-OI). Current recommendations include creating new sequences for use in reporting tide data in CREX code form, and the development of more rapid transmission schemes for those sites closest to the tsunamigenic zones. The WG2 endorsed the commitment of the IOTWS nations to the free and open exchange of real time sea level data on the GTS and the agreement to provide the historical data and metadata for the designated IOTWS sites in their country. In conclusion, the WG2 helped define and develop a system of coastal sea level stations that enabled PTWC and JMA to begin to provide basic basin-wide tsunami monitoring and advisories to the Indian Ocean nations and that allows other centers to start increasing the in situ sea level data stream necessary for basin-wide tsunami monitoring.

ACKNOWLEDGMENTS

The staff and operators of the geostationary meteorological satellites, the existing warning centers, and WMO provided invaluable advice and services that have enabled the development of the operational standards and the implementation of the system. The engineers and technicians from POL and the UHSLC have help design and install the sea level stations that meet the operational standards of the ICG/IOTWS for core coastal sea level sites. One of the authors, Bernard Kilonsky, was the chair of the first intersession meeting of the WG2. He carried as the vice-chair for coastal sea level through the next two ICG/IOTWS meetings. They and all of the many ICG country representatives who attended the session and intersession WG2 meetings deserve special recognition. Finally, without the support of the IOC, there would be no ICG/IOTWS, and without the enthusiasm and expertise of all, the work of the WG2 would not have proved successful.

Establishment of Rimes End-to-End Early Warning System for Tsunamis in the Indian Ocean and Southeast Asia

Patchanok Srivihok, Dwijendra K.Das, Muriel E. Naguit and Elouie Lepiten*

ABSTRACT

The occurrence of 2004 Indian Ocean tsunami enhances the necessary of a tsunami early warning system for countries in the region. This paper presents the current status of the Regional Integrated Multi-Hazard Early Warning System facilitated by the Asian Disaster Preparedness Center (ADPC) in establishing End-to-end Early Warning System for tsunamis in the Indian Ocean and Southeast Asia .Details of sub-systems namely, Seismic Subsystem, Sea Level Subsystem, Deep Ocean subsystem and Tsunami modeling and forecasting, are discussed.

Key words: geohazards, tsunami, mitigation

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INTRODUCTION

The catastrophic Indian Ocean tsunami of 26 December 2004 united governments and peoples in addressing its unprecedented impacts. The devastating event, a rare occurrence in the Indian Ocean region, brought to the fore the lack of knowledge of and awareness about the hazard and, consequently, the lack of response capabilities, particularly of first responders and authorities who dealt with the large-scale emergency. Countries in the region were of a consensus that a tsunami early warning system is needed to prepare communities and authorities to respond to the azard, and minimize loss of lives and destruction of property.

In the second Intergovernmental Coordination Group (ICG) meeting, the working group on system for interoperable advisory and warning centers recommended the appropriated structure for the Indian Ocean region as consisting of a system of systems, where countries receive advisories through bilateral agreement with Intergovernmental Oceanographic Commission (IOC) accredited tsunami watch providers in the region. Noting the exclusion of Southeast Asia in the first UNESCO/IOC International Coordination Meeting in Paris. Countries in the Southeast Asia expressed the need for a tsunami early warning system in the region and agreed to establish the system that the initial stage would include countries most in need of assistance.

The Regional Integrated Multi-Hazard Early Warning Systems (RIMES) facilitated by the Asian Disaster Preparedness Center (ADPC) is the regional cooperation across Asia and Africa in the early warning of tsunami within a multi-hazard framework. End-to-end Early Warning System for Tsunamis in the Indian Ocean and Southeast is established to serve as a regional watch provider or focal point for a multi-nodal tsunami early warning arrangement in the region.

OBJECTIVES OF THE SYSTEM

The immediate objectives are:

1. Establish regional capabilities to observe and evaluate tsunamigenic seismic activity and anomalous sea level conditions, predict and detect the generation and propagation of tsunamis and their inundation of vulnerable locations, provide participating countries with tsunami warning information
2. Strengthen national capacities in early warning, risk communication, and emergency response
3. Enhance local capacities to assess disaster risks, respond to warnings, and undertake local risk reduction measures
4. Facilitate regional exchanges of information, best practices and lessons learned for cross-country learning and to guide replication
5. Undertake research in all aspects and elements of the end-to-end early warning system to improve system performance and recipient response.

SYSTEM COMPONENT

Seismic Subsystem

Seismic waves naturally travel much faster than tsunami waves and the analysis of seismic wave can provide an early indication of a potentially tsunamigenic earthquake if an appropriate seismic monitoring network is in place to capture and record the generated waves. Digital broadband seismographs enable the detection and characterization (type of faulting, amount of energy release, and stress field responsible for the quake) of earthquakes from the high frequencies of nearby earthquakes, to the low, rolling motion of distant earthquakes, capturing all three axes of ground motion. The existing global broadband seismographic network has a big gap in the Indian Ocean and Southeast Asia (Fig.1).

The proposed network of seismographs would help fill the real-time seismic data gap in the region. In order to fill geographically gaps in coverage of the proposed Real-Time Seismic network particularly in areas near seismogenic sources, a total of 15 stations are proposed to be upgraded or established by RIME in 5 Southeast Asian countries namely Philippines, Bangladesh, Myanmar, Vietnam and Laos. Real-time data communication from the stations to the data processing center would be through satellite link. Real-time seismic data would be contributed to the global Seismographic Network, and enabling RIMES to access data from other network globally e.g. GSN/FDSN stations. During the present phase, 4 primary broadband seismic stations as shown in Fig. 2 are in process of installation. Those stations are listed as below:

1) SZP (120 27.30E 17 33.12N) at Santa, Ilocos Sur, Philippines

2) DLV (108 28.89E 11 57.91N) at Dalat, Central Vietnam

3) SLV (103 54.30E 21 20.03N) at Sonla, North Vietnam

4) SIM (092 53.11E 20 07.99N) at Sittwe, Myanmar

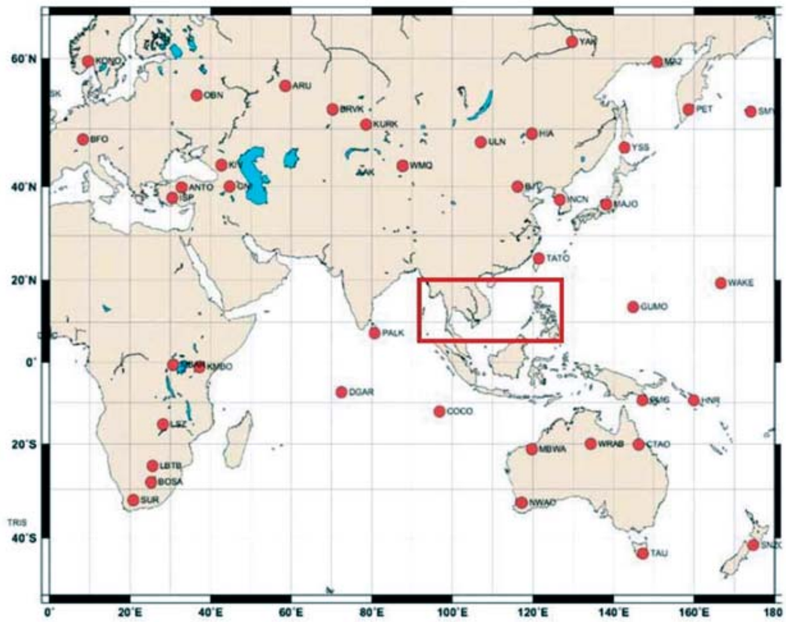

Fig 1: Broadband seismic stations contributing data to the Pacific Tsunami Warning Center

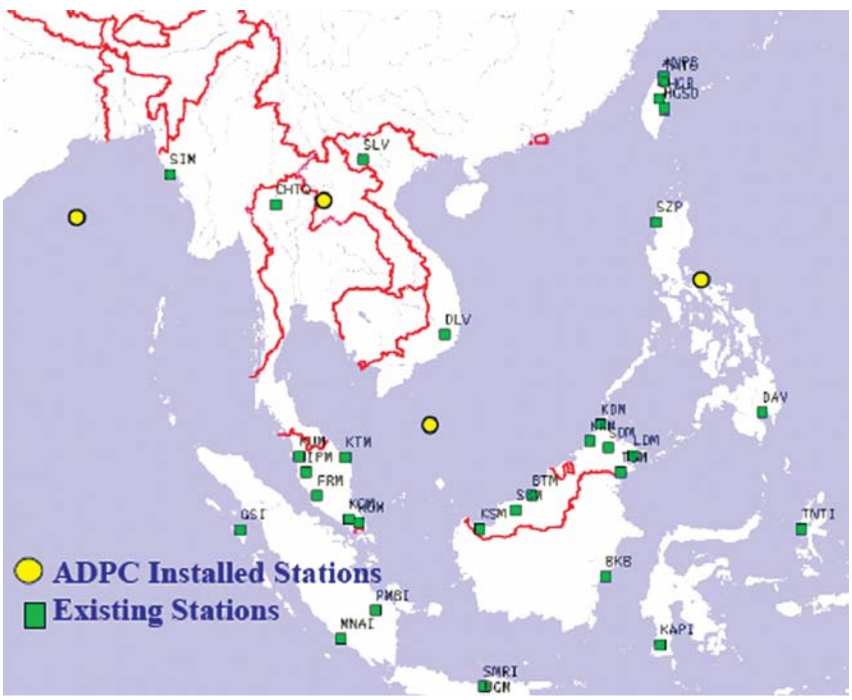

Fig 2: RIMES primary broadband seismic station

Data will be acquired and processed using the "Antelope Seismic Software". Access by participating countries to processed data from the data center would be through broadband internet, or by satellite downlink in countries where internet facilities are poor.

Presently, Antelope system has been installed as the primary seismic data processing system and Seiscomp 2.6 is being set as the secondary system. Presently, Antelope system can connect and import real-time seismic wave form from other networks namely IRIS, GSN and GEOFON. The sub programs inside the system have been configured according to ADPC virtual seismic network. ADPC local network covering the South China Sea can be able to locate earthquake with magnitude greater than 1.0, regional network covering East Africa to Western Pacific Ocean can be able to locate earthquake with magnitude greater than 4.5 whereas the tele-seismic network covering the whole globe can be able to locate earthquake with magnitude greater than 6.0. The integrated alarm system with Antelope was already configured to send alarm via email and SMS. It is still under development of working website to display real-time earthquake detection.

Sea Level Subsystem

Sea level gauges, to be strategically located close to tsunami sources and in areas that would provide sufficient lead-time for response, are useful in confirming the existence and non-existence of tsunami waves following an earthquake, monitor its progress, estimate the severity of the hazard along the coast, and provides a basis for declaring that the hazard is over. The proposed network of sea level stations would help to fill real-time sea level data gap in the region. RIMES has engaged the University of Hawaii Sea Level Center for the survey of sites for an installation of sea level stations in collaboration with national partner. During the present phase, 5 tidal gauges as shown in Fig. 3 were installed and the near-real time tide data is transmitted through Global Telecommunication System (GTS). Those stations are namely:

1) SIT (92 54E 20 9N) at Sittwee, Myanmar

2) KOTA (98 25E 7 49N) at Koh Taphao Noi, Thailand

3) QUIN (109 15.26E 13 46.51N) at Qui Nhon, Vietnam

4) VTAU (107 15.264E 10 20.41N) at Vung Tau, Vietnam

5) SUBI (120 17E 14 49N) at Subic Bay, Philippines

Deep Ocean subsystem

Deep-ocean pressure sensors detect the early passage of a tsunami before it reaches shallow waters and causes destruction along the coast. Presently, RIMES has developed program to receive real-time data from NOAA's National Data Buoy Center (NOAA/NDBC) website, the Deep-ocean level data will be incorporated used to update tsunami prediction. When closet DART can detect the first tsunami wave, the model prediction will be compared to the observed wave and the update of tsunami forecast can be performed.

Fig 3: RIMES facilitated tidal gauges

Tsunami modeling and forecasting

In terms of tsunami modelling, TUNAMI model (Tohoku University's Numerical Analysis Model for Investigation of Tsunami) developed by Disaster Control Research Center, Tohoku University is selected to simulate tsunami generation, propagation and inundation. The agreement of model use was created between Disaster Control Research Center and ADPC in April 2008.

To apply tsunami propagation model in the early warning system, 2-minute girded global bathymetry data (ETOPO2) from NOAA's National Geophysical Data Center (NOAA/NGDC) was inputted to the model by covering area from Latitude S 42.2833 to N 27.48337 / Longitude 15.1169 to 128.2834 for simulating tsunami propagation in the Indian Ocean, and Latitude S 12.6167 to N 27.6833 / Longitude 95.0833 to 132.85001 for simulating tsunami propagation in the South China Sea. Graphical User Interface (GUI) has been developed to integrate many options which are-

1) Earthquake parameters entering module
2) Tsunami propagation computing and database development module
3) Database accessing module

System is designed for automatic and manual entering of earthquake parameters (magnitude, location of epicenter and focal depth) and automatically determine character of potential source (reasonable faulting parameters) which used for computing tsunami generation. After simulation by tsunami propagation model, user can save results into the pre-computed database which will be accessed during operation. Currently, pre-computed simulations are being generated starting from two potential tsunamigenic seismic sources on Manila trench and Java-Sumatra trench. In this system earthquake in the sea with comparatively high magnitude from 6.5-9.0 will be considered as the potential earthquake to generate tsunami.

The information contained in pre-computed tsunami simulation are directivity map of tsunami propagation maximum wave height, tsunami travel time and wave time series at forecast points at key coastal sites, including sea level observation station location as shown by Fig.4. Additionally, application programs were developed to receive and monitor real-time deep ocean level from DART buoys as shown by Fig.5 and realtime sea level from tide gauges as shown by Fig.6. Real-time data stream from deepocean sensors will allow model-based interpretation and data analysis for comprehensive and accurate far-field tsunami forecast. Tide Tool program developed by the Pacific Tsunami Warning Center (PTWC) has been installed to monitor near real-time sea level from tide gauges used for final confirmation of tsunami arrival on the coast.

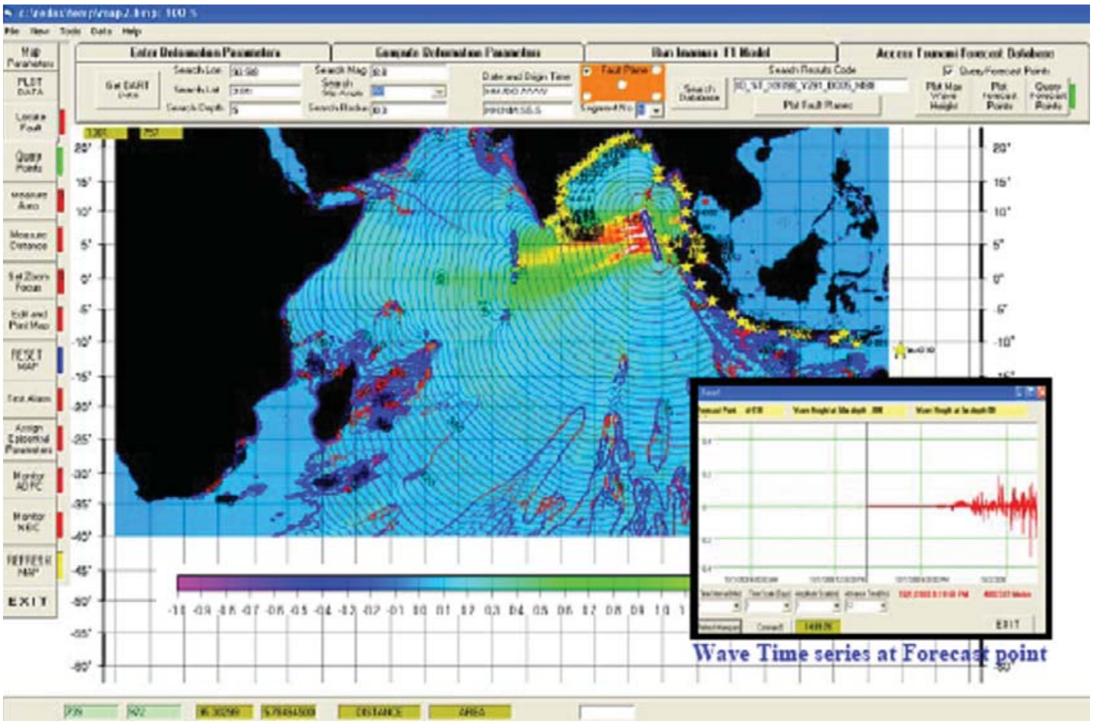

Fig 4: RIMES pre-computed tsunami simulation

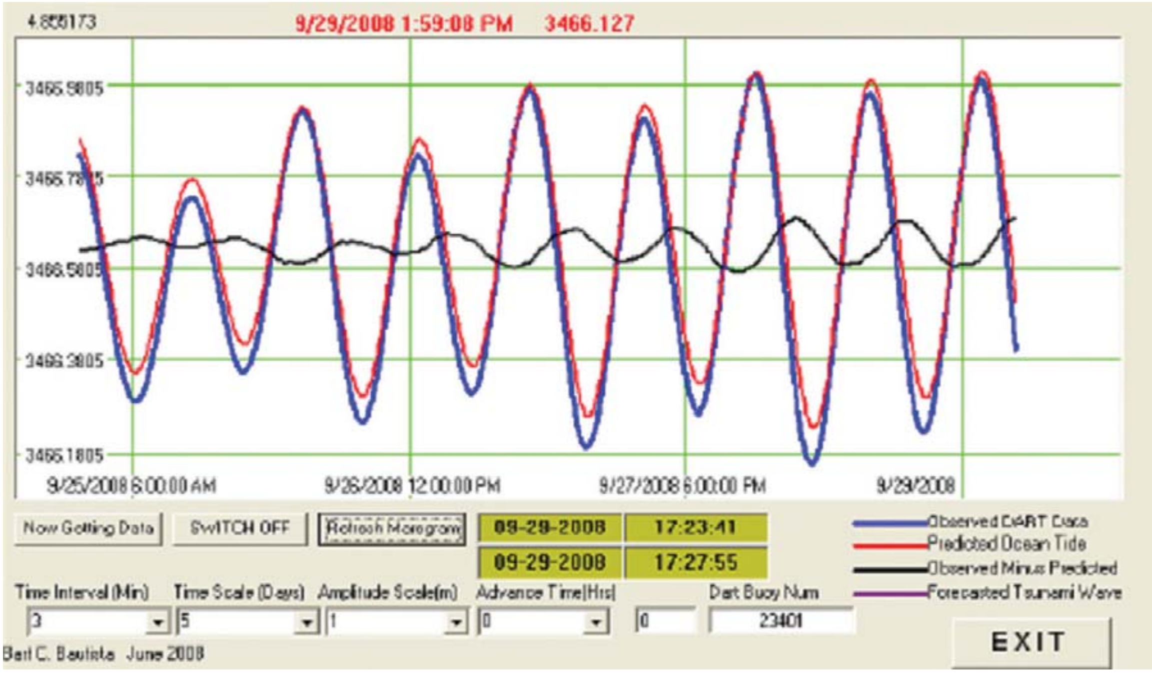

Fig 5: Application programs for monitor real-time deep ocean level from DART buoys

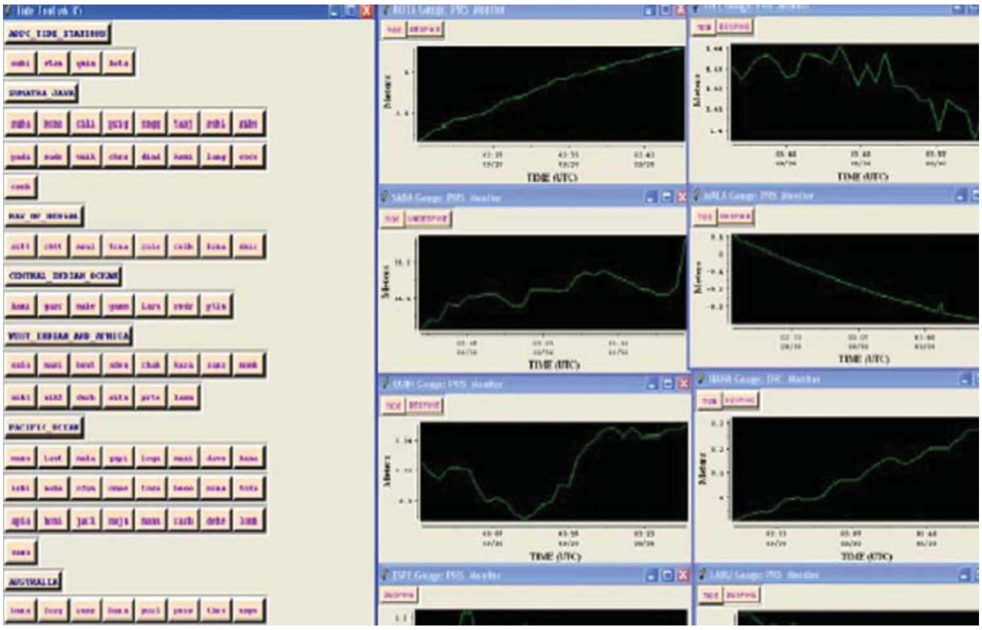

Fig 6: Application programs for monitor near real-time tide data

PROVISION OF TSUNAMI WARNING INFORMATION

To achieve final target of the system in provision of tsunami warning information, two communication servers (one as back-up) will perform the electronic distribution of reviewed data and exchange of information with national contacts. An appropriate number of hotline numbers will be installed in the center. The center shall consider distribution of messages across existing information infrastructure in the region, such as the GTS, electronic mail, fax or voice messages; group SMS or MMS shall be exploited depending on availability and efficiency of delivering information to national contacts, and in consideration of communication resources of these centers. Earthquake information, tsunami forecasts and warning shall be formulated accordingly as events occur within the region utilizing the UNESCO/IOC standard format. All information from the center shall be broadcast in text form to national contacts of all member states. If possible, maps showing location of event, and forecast and actual tsunami propagation will be delivered as well to national contacts of member states. Time values are in Universal Coordinated Time (UCT). During normal times, periodic system

CONCLUSION

RIMES End-to-end Early Warning System for Tsunamis in the Indian Ocean and Southeast Asia is under development and composed of Seismic Subsystem, Sea Level Subsystem, Deep Ocean subsystem and Tsunami modeling and forecasting subsystem. For Seismic Subsystem, seismic wave data from other networks globally e.g. IRIS, GSN and GEOFON and RIMES primary stations being installed are cooperatively used to processed and detect earthquake events. Detail of tsunami events can be displayed by the most likely case of pre-computed tsunami simulation and Deep-ocean level data and Sea level gauges are used for confirming the existence and non-existence of tsunami waves following an earthquake monitor its progress, estimate the severity of the hazard along the coast, and provides a basis for declaring that the hazard is over. Processed earthquake and tsunami information will be reviewed before exchange to the national contacts through the available communication channels.

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Role of Ccop as a Regional Organization for Tsunami Risk Reduction and Hazard Mitigation in Southeast Asia

Niran Chaimanee*

ABSTRACT

The East and Southeast Asia region, much of it situated on the 'Pacific Rim', has always been vulnerable to geohazards such as earthquakes and volcanic eruptions often culminating in extensive economic damage and human tragedy. The Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) is the main Southeast and East Asia Geoscience inter-government agency that play the major role on prevention and mitigation on geohazards impacts in order to reduce the risk of communities within the region. Flooding and landslides have also taken a heavy toll and for these reasons CCOP, in its determination to remain an organisation relevant to the needs of society, has devoted an ever increasing effort to its programme on Geohazards in recent years. All of this was to be thrown into stark perspective by the tragic events consequent upon the 2004 tsunami that struck the coastlines of several CCOP Member Countries on 26 December, 2004. The worldwide response to the tragedy, in which more than a quarter of a million people died, was immediate and overwhelming in the provision of emergency aid but the event had posed some fundamental questions that needed serious discussion and a quick but carefully considered response. The more effective integration of disaster risk consideration into sustainable development policies, planning and programming at all level, with special emphasis on disaster prevention, mitigation,preparedness and vulnerability reduction. The Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) has initiated a number of activities in the region in relation to geohazards and most recently the 26 December 2004 tsunami disaster. The CCOP-DMR project on Tsunami Risk Mitigation Measures with Focus on Land use and Rehabilitation was conducted by Norwegian Geotechnical Institute and The Royal Thai Department of Mineral Resources (DMR) under the supporting of the Norwegian Ministry of Foreign Affairs. The elements of this project are Determine causes and consequences of Dec. 2004 event, Establish future earthquake and tsunami-generating scenarios and their return periods (hazard), Model future tsunamis and their inundation levels, Assess future risk to human life and acceptance criteria, Recommend risk mitigation measures and Ensure local involvement and dissemination of results. The CCOP has accelerated the program on disseminating knowledge about tsunami and other geo-hazards as well as risk information to the public with the present project on Tsunami Risk Assessment and Mitigation in South and Southeast Asia phase II. In this respect, how to live in geo-hazard risk areas with least danger or most safety is very much important to the local people and visitors mainly in Indonesia and the Philippines. With adequate knowledge on geohazards, the people can be aware of dangers and damages from its impacts, and prepare themselves ready for prevention and mitigation to avoid great impacts and lessen of live and property losses in the future.

Key words: geohazards, tsunami, mitigation, risk

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INTRODUCTION

The 26 December 2004 tsunami caused of the order 220,000 casualties and devastated large areas along the coastlines of Indonesia, Thailand, Malaysia, Myanmar, Sri Lanka, India, the Maldives and even some parts of the east African coast. The tsunami was initiated by a gigantic magnitude 9.3 earthquake caused by propagating stress release on the subduction zone created by the steadily ongoing NE movement of the Indo-Australian plate in under the Burma/Sunda plate (along the Sunda arc) (Fig. 1).

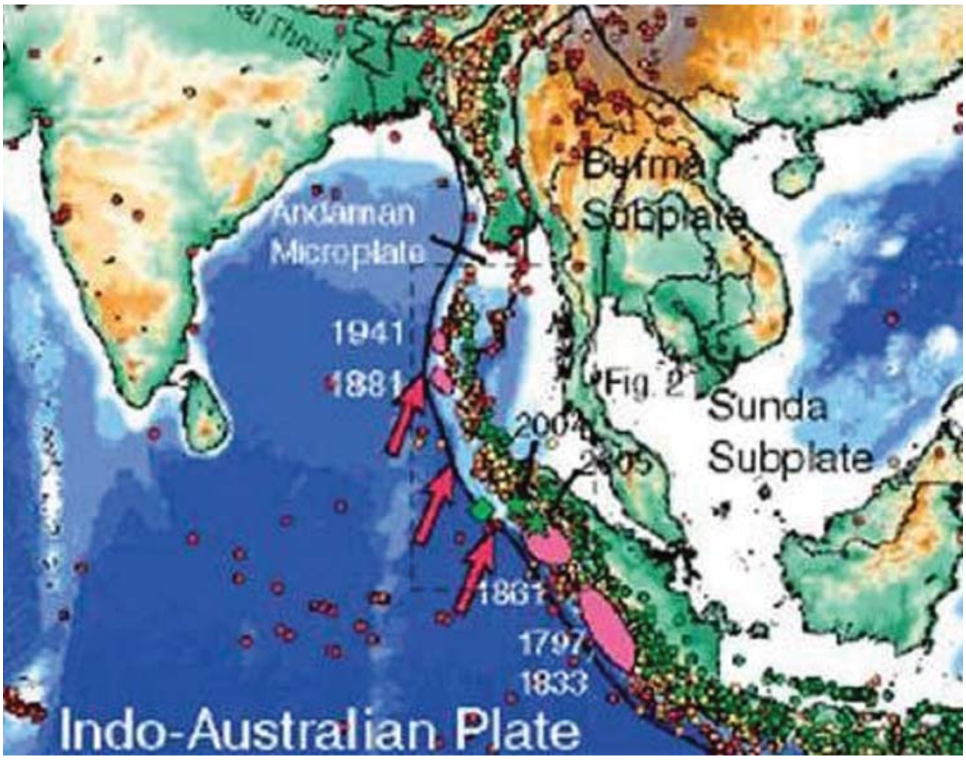

Fig 1: Seismicity in the Northeast Indian Ocean Region during 1900 to 2005. (red dots are earthquake epicenters with magnitude M> 6, green star are 2004 and 2005 tsunami-generated earthquakes) (Source: Lay et al 2005 ref. in CCOP, 2006 a)

The 26 December, 2004 Indian Ocean Tsunami tragically caught many ordinary people unawares, along with researchers, scientist and government officials. As is often the way with such phenomena, it was largely the ordinary people who suffered most. Suffering and loss of life resulted, in part at least, from the local people's general lack of collective memory of tsunami, of tsunami precursors and of appropriate response to such precursors. Locals and tourists apparently followed the receding water, collecting fish and leaving them very exposed to the incoming wave. Where such collective memory of tsunami does exist, appropriate evasive action was apparently taken. Thus, there is anecdotal evidence that the Sentinel Island, a low coral island in the Andaman Islands, retreated from the shore well before the waves hit. Likewise, Sea Gypsies around Phuket on peninsular Thailand appear to have a group memory of tsunami, though it is unclear weather this memory led to appropriate evasive action or is a post-hoc memory of giant wave phenomena.

Subsequent to the 26 December 2004, Tsunami disaster, the Department of Mineral Resources of Thailand (DMR) in cooperation with CCOP organized an international seminar on Tsunami in response to the role of geoscience in the post tsunami rehabilitation and reconstruction, long term planning, tsunami mitigation, early warning and creating of public awareness. The seminar was supported by the DMR, the British Geological Survey (BGS), TNO – National Geological Survey of the Netherlands, and the National Institute for Advanced Industrial Science and Technology/ Geological Survey of Japan (GSJ/AIST).

The main objectives of the seminar are to discuss geoscience actions for post tsunami rehabilitation and reconstruction, tsunami mitigation and early warning system, creating public awareness of tsunami hazards and to discuss how the international communities can assist the affected countries to become ready for future tsunamis. A total of 679 participated in this seminar, among which 612 are from Thailand and 67 foreign experts from other countries, namely Canada, Finland, Germany, India, Indonesia, Japan, Korea, Malaysia, Netherlands, Norway, Papua New Guinea, Poland, Sri Lanka, the United Kingdom and the United States of America. The total of 61 agencies/organizations were represented; 25 from Thailand and 36 from other countries.

The specific outcome from this seminar were shared information and ideas in international Geoscience forum, Identification of key goals and next steps, Opportunities for collaboration in region and A resolution for describing a for future actions for both International and Interagency.

CCOP RESPONSE FOR TSUNAMI 2004

Upon the approval of the 45th Steering Committee Meeting in Phuket, Thailand on 31 March to 2 April 2005, implementation of the Norwegian government supported project on "Tsunami Risk Reduction Measures with Focus on Land-use and Rehabilitation" commenced in June 2005. This project is an 8-month fast track study in consideration of the urgent needs for reconstruction works to commence. The main purpose of this project is to establish practical guidelines for land use and rehabilitation of the devastated areas, considering the risk of future earthquake and tsunami events. The results of the study will also form a platform giving conceptual results that can be used in other parts of the tsunami affected regions around the Indian Ocean.

The project is conducted by the Norwegian Geotechnical Institute (NGI), the project's technical executing organization (TEO) in close cooperation with the Department of Mineral Resources (DMR), Thailand and the Technical Secretariat. Thailand was selected as the case-study country and the technical report and the recommendation summary for decision maker were reproduced and distributed within the Royal Thai Government Agencies and the public all over the region (fig. 2)

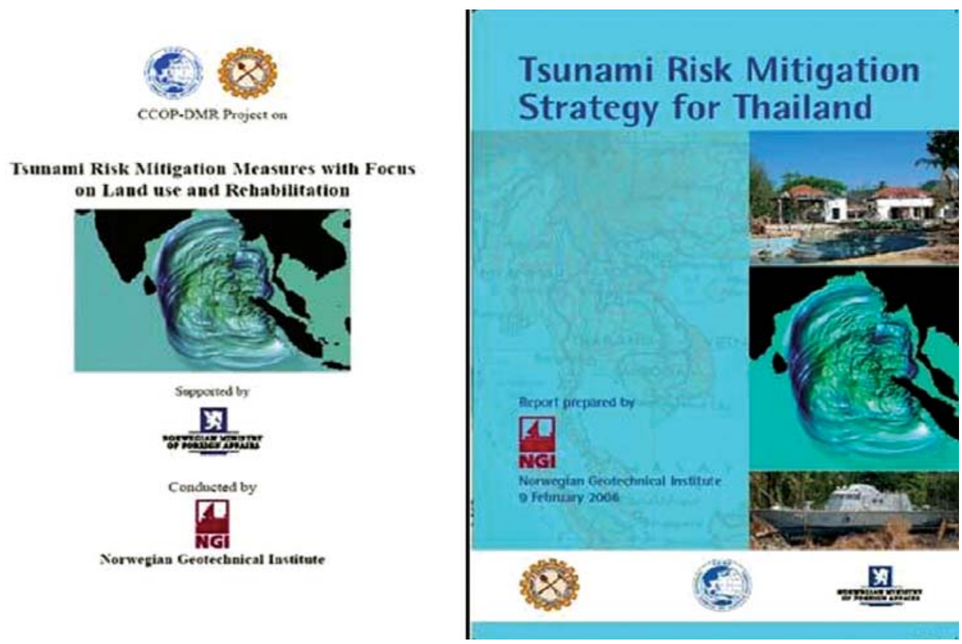

Fig 2: Technical report and Summary report that were distributed throughout the region

RISK ASSESSMENT AND MITIGATION MEASURES

Risk assessment

The study presented in this report was launched in May 2005 to assist the authorities in Thailand with development of plans for how to deal with the future tsunami risk in a short term as well as in a long term perspective. The earthquake caused vertical seabed movements of up to about 4-5 m over a total area of size about 1200 km by 300 km. Along the most affected part of the west coast of Thailand, the generated tsunami led to an inundation or flooding level from about +5.0 m to + 10-12 m above mean sea level. These inundation levels have been confirmed by numerical simulations presented in this report.

The Sunda arc is an active fault zone with frequent earthquakes. The number of earthquakes generally increase 10-fold for every unit decrease in magnitude (such as from 7 to 6). Based on a detailed study of earthquake statistics as well as plate tectonics, the following main conclusions are drawn:

1. The 26 December 2004 earthquake was a megathrust event that has released a lot of the energy accumulated along the northern part of the Sunda arc subduction zone as a result of the steadily ongoing plate movements. Such megathrust events are periodic in nature and it is conservatively concluded that it will take at least 3-400 years before an event of similar magnitude and consequences will occur again (Fig. 3).

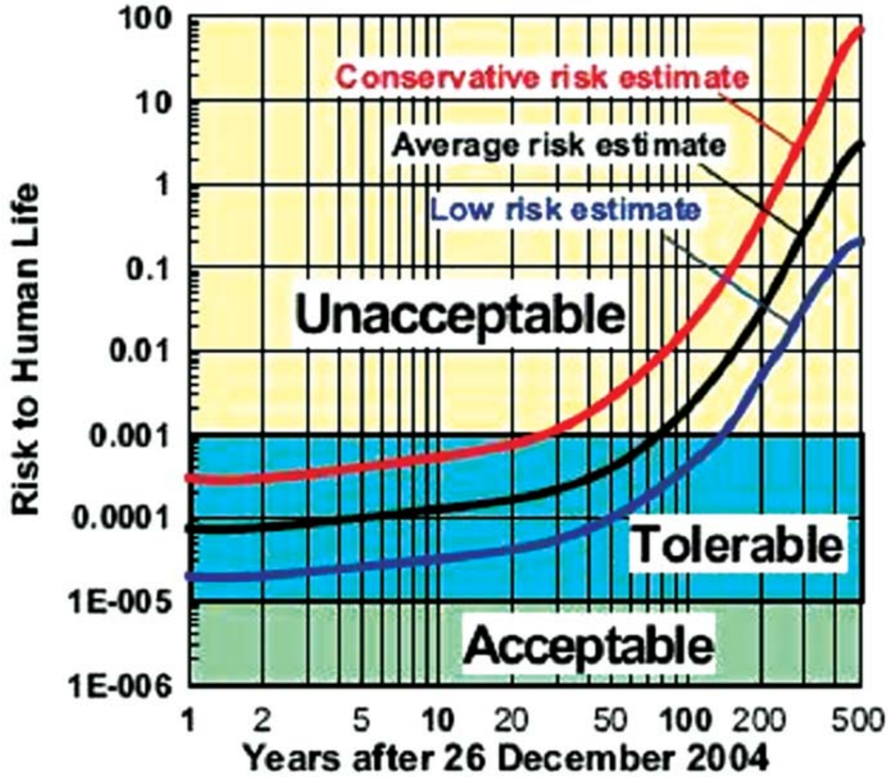

Fig 3: Estimated risk of human fatalities due to future tsunami assuming no mitigation measures are implemented in Thailand (CCOP, 2006b)

2. Within the next 50-100 years the largest credible earthquake to be prepared for along the part of the Sunda arc that could cause a tsunami hitting the coasts of Thailand, is a of magnitude 8.5 earthquake. The return period of an M 8.5 earthquake event is presently of the order of 200 years, but with less periodicity than the mega thrust events.

3. An M 8.5 earthquake could cause a tsunami which at the most gives an inundation or flooding level 1.5 to 2.0 m above sea level along the west coast of Thailand. If this occurs at normal high tide it would correspond to a water level of +2.5 to +3.0 m above mean sea level.

4. For an M 8.5 earthquake and tsunami scenario, the potential risk to human life and property in Thailand will be small and can be regarded as tolerable. The main reason for the small risk is that land areas behind the beachfront generally lie above level +3 m along most of the west coast of Thailand, and thus will not be affected by the potential tsunami.

5. After about 100-200 years the potential for earthquakes larger than M 8.5 will increase gradually. The same applies to the possibility of generating larger tsunamis than for the M 8.5 earthquake scenario. This implies that as time passes by the tsunami risk will gradually increase from tolerable to highly unacceptable.

Mitigation measures recommendation

Tsunami risk is defined as the product of tsunami hazard, defined as yearly probability of occurrence of a tsunami, times its consequence in terms of economic loss and/or loss of human life. We can not influence the earthquake and tsunami hazard but we can mitigate their consequences.

Although the tsunami risk in Thailand is found acceptable for Thailand in the next 100-200 years, it should be the duty and responsibility of the present day society to react to the more long term unacceptable risks. If no risk mitigation measures are planned and implemented in the reasonably near future it is likely that the long term tsunami risk will be forgotten within the next 50 years or so. The main reason is that no significant tsunamis are likely to occur within such a time frame, and the collective memory of the society in relation to natural hazards with long return period has repeatedly been proven to be short. It is therefore recommended that the authorities in Thailand already now plan for implementation of some mitigation measures that can reduce the exposure to and consequences of severe tsunamis to future generations.

The recommended measures include the following main elements:

1. Implementing new requirements to land-use planning and establishment of new building codes to reduce exposure to and/or consequences of future tsunamis.

2. Establishing escape routes that are well marked and easily accessible and which lead to areas or places that are safe from tsunami (Fig. 4). Such safe areas may be artificially elevated land areas or buildings or structures accessible to all. They should be possible to reach within a distance of about 500 m.

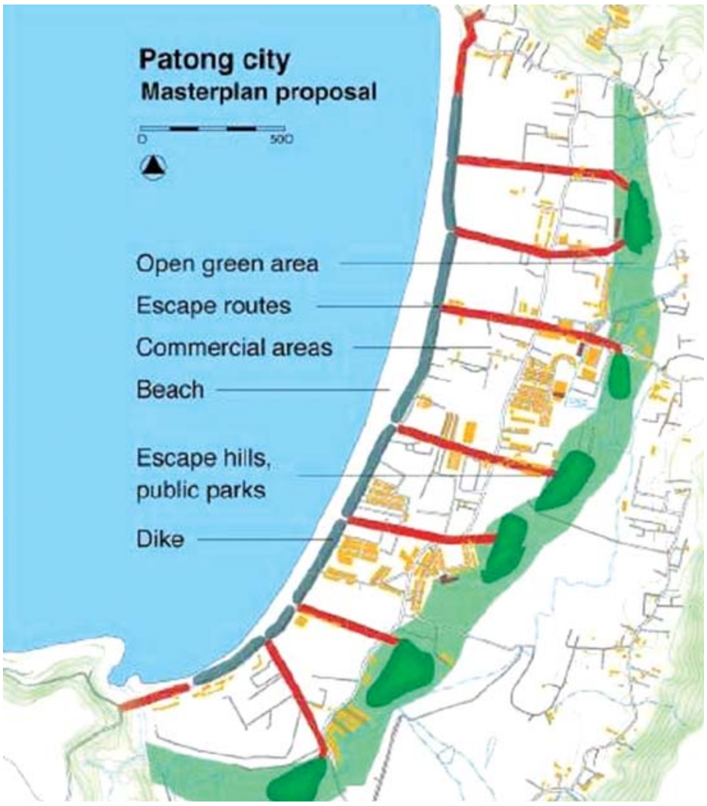

Fig 4: Mitigation Master plan for Patong, Phuket was introduced as the example for populated tourist area (CCOP, 2006a)

3. Constructing artificial walls or dikes to limit the impact and inundation level of tsunamis. This may have particular merit for Patong City and Ban Nam Khem fishing village, but locally also for other areas.

4. Raising the ground level (vertical land reclamation) where buildings are to be constructed in the future. This may be a particularly attractive option for the further development of the Bang Niang tourist resort areas, to some extent also in Nam Khem fishing village.

5. Ensuring that future buildings will not be damaged and that sleeping areas are at a level which is safe from tsunamis. This in consideration of to what extent measures 3 or 4 have been implemented to limit the tsunami inundation level.

LESSON LEARN ON THE CCOP'S COORDINATION PROJECT

The results of the study and recommendations given have been very positively received by the intended target groups. The study has already an impact on the Department of Mineral Resources and other Thai authorities on how Thailand has dealt with the consequences of the tsunami so far. The results of this project were used as the key analysis factor for the 2 projects of DMR: the Ban Nam Khem Coastal Protection Project and the Post Tsunami Land use Planning of Andaman Sea Coast, Southern Thailand Project.

Establishment of the Local Advisory Panel is also believed to have contributed to ensuring a local anchoring of the results of the study. Input from the Advisory Panel was also useful and helped focusing on mitigation measures that are considered practical and viable for implementation. The results of the three case study areas will be implied for the revision of mitigation measures as well as the evacuation plans. Involvement of the Local Advisory Panel ensured local ownership of the project and the results.

Workshops and dissemination seminar arranged for participants from other countries and related international organizations in the region have helped seed ideas on how these countries may take on similar tsunami risk assessments and mitigation studies as done in this project for Thailand (Fig. 5).

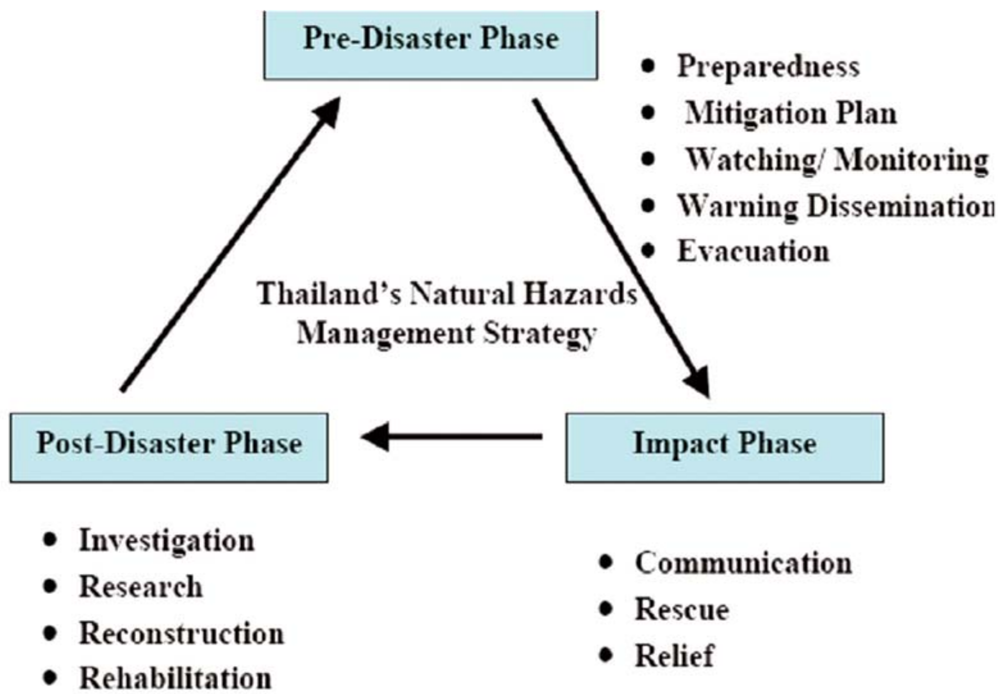

Fig 5: Hazards Management Strategy Framework for Thailand that was formulated after 2004 tsunami event and applied for concern government agencies (DMR, 2006)

From feedback received, there is little doubt that Thai authorities have already made use of the results, and that it will also impact on how they will plan implementation of mitigation measures. In the implementation phase, their main challenge will be to maintain focus, ensure local anchoring, financing, and overcome some local obstacles in relation to land ownership and interests of various affected groups.

The project will also help all countries in the region to focus on the main issues at stake when it comes to dealing with future tsunami risks. The project report was widely distributed through direct information. Accessibility of the report made possible through CCOP and DMR's home pages. And dedicated action taken on dissemination of the project results in the international dissemination seminar to all local and international agencies and bodies involved in similar work, including key international organizations such UNESCO-IOC, ADPC, UNISDR. Countries in regions other than the Indian Ocean region can also benefit from the Project.

The sustainability of the Project can be further enhanced by carrying out similar risk assessment and mitigation studies for other countries that are exposed to earthquake and tsunami risks that presently have yet to conduct such a study. As a result of the project, and subsequent to the discussions at the international dissemination seminar, there has been second phase of CCOP's tsunami project implementing for other South and Southeast Asia countries during 2008-2009.

The countries found of most interest to focus on for a Phase 2 study are Indonesia, the Philippines, Sri Lanka and Vietnam. This is based on a preliminary screening study discussing the needs of different countries, and meetings in Bangkok with invited representatives from Indonesia, the Philippines, Sri Lanka, Vietnam and

Thailand. In addition it will collaborate with and draw upon resources within the Asian Disaster Preparedness Centre (ADPC). The ADPC is presently undertaking a project dealing with establishment of systems for a local tsunami warning centre for member countries Myanmar, Cambodia, Vietnam, Sri Lanka, Thailand, Bangladesh, China, Lao PDR, Maldives and the Philippines. They are already in the process of installing tidal gages and seismic stations at selected locations. The final output and outcome is expected to be distribute for the public before the end of 2009.

5. CONCLUSIONS

The successful completion of this fast track study on the "tsunami and extreme weather risk reduction measures with focus on land use and rehabilitation" has proven that all parties involved were able to take appropriate and fast action immediately after the Dec 26 2004 tsunami that had caused so many casualties and so much economic destruction. It is appropriate that this project has been expeditiously completed so that the results can be used by the authorities to better prepare and plan for similar calamity, which is now not a question of if but when it will happen, and to minimize the loss of lives and assets when such an event occurs in the future.

To make the hazards study effective, purposeful and sustainable, it has incorporated the needs and views of the local people through the Local Advisory Panel. The CCOP activities have also maintained the close cooperation and communication with the local and national authorities, carried out some training that contributed to technology transfer, and ensured wide dissemination of the results to the stake holders locally and internationally through holding the dissemination seminar at the end of the project. All these have proven to be vital to contributing to the complete success of the project.

It was part of the CCOP vision that the results from CCOP's activities should be of general use to other countries within the region that may be exposed to future natural hazards. Although no other site specific studies have been carried out, it is fair to assume that a similar medium term design event for the whole region would be similar or much more severe than in particular area.

Finally, the CCOP has accelerated the program on disseminating knowledge about tsunami and other geo-hazards as well as risk information to the public. In this respect, how to live in geo-hazard risk areas with least danger or most safety is very much important to the local people and visitors. With adequate knowledge on geohazards, the people can be aware of dangers and damages from its impacts, and prepare themselves ready for prevention and mitigation to avoid great impacts and lessen of live and property losses in the future.

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Spatial Distribution of Existing Cyclone Shelters for Tsunami and Storm Surge Preparedness

Ahmadul Hassan[1], Raquib Ahsan[2], Bhuiya Md. Tamim Al Hossain[1], Mohammad Ragib Ahsan[1]

ABSTRACT

The coastal area of Bangladesh is prone to various natural hazards like, cyclones, tsunamis etc. For providing safe haven facilities to the vulnerable population of that area, government and non-governmental organizations are building cyclone shelters along the coast. Many of these shelters are in a bad condition due to poor maintenance. The overall objective of this study on 'Spatial Distribution of Existing Cyclone Shelters for Tsunami and Storm Surge Preparedness' was to update available information on existing cyclone shelters and to check whether these shelters could withstand natural hazards like, tsunamis, cyclones and earthquakes. Under the study, the present operational condition of cyclone shelters with their surroundings and the structural vulnerability of the shelters under different hazard conditions were assessed for cyclone shelter management during cyclone and earthquake induced tsunami. Firstly, secondary information were collected through pragmatic literature review from previous studies including the study on Multipurpose Cyclone Shelter Programme (MCSP), the Cyclone Shelter Preparatory Study (CSPS), the study on Cyclone Shelter Management Information System (CYSMIS), the LGED survey of cyclone shelters, etc. The information was used in identifying the spatial distribution of shelters and their existing management perspectives. Shelter related information was collected through extensive field survey using an in-depth questionnaire. Using a GPS device, the spatial locations of shelters were collected along with their dimensional photographs, which were then attributed into a database. The collected information was used for creating a spatial map and for preparing cyclone shelter attributes using RS and GIS tools. Consequently, modeling and analysis of the shelter structures were conducted to assess the structural condition of the shelters in cyclone, tsunami and earthquake situations. Considering the geometrical complexity of different types of cyclone shelters, three dimensional Finite Element Method based models were generated using the structural design software ETABS. To assist the software based modeling, field-testing of shelters was carried out in cooperation with BUET. In this regard, the Schmidt Hammer Test and Windsor Pin Test were done for assessing the actual concrete strength of the shelters. The results of the tests were incorporated in the modeling. Based on the 3D FEM model, the vulnerability of individual shelters was assessed using tsunami and cyclone inundation risk maps.

BACKGROUND

Bangladesh is one of the most disaster prone countries in the world. Almost every year, natural hazards like floods, cyclones, droughts, earthquakes, tornadoes, etc. frequently affect the country. Out of all these, tropical cyclones cause huge damage to the coastal infrastructure, wealth and social livelihood. Historically, major cyclones hit the coastal area of the country in 1970, 1991, and 2007.

The coastal area of Bangladesh as defined by the Integrated Coastal Zone Management Plan (ICZMP) of the Water Resources Planning Organisation (WARPO), comprises 19 districts, located in the southern part of Bangladesh and influenced by the Bay of Bengal (PDO-ICZMP, 2005). Out of the 19 districts, 16 have cyclone shelters. The districts that were considered for updating cyclone shelter information were Bagerhat, Barguna, Barisal, Bhola, Chandpur, Chittagong, Cox's Bazaar, Feni, Jhalokati, Khulna, Lakshmipur, Noakhali, Patuakhali, Pirojpur, and Satkhira. These districts fall within the latitude of N- 21˚ to N- 23˚30' and the longitude of E- 90˚ to E- 91˚30'. These districts are not equally vulnerable to cyclone and tsunami induced storm surges. The vulnerability of different districts has been defined by the Multipurpose Cyclone Shelter Programme (1993) and recently the risk map has been updated by CDMP.

The coast of Bangladesh is approximately 710 km long around the Bay of Bengal between the Indian and Myanmar borders. The coastal zone is mainly low-lying with 62% of the land having an elevation of less than 3 metres and 86% having an elevation of less than 5 metres. Waves, tides, river flow, sediment movement, plants and animals interact constantly to shape the coastline. This results in a very dynamic coastal topography and land pattern. The coastal zone comprises several ecosystems having an important conservation value. The Sundarbans, which is the world's largest uninterrupted stretch of mangrove ecosystem (6017 km2 area) and a world heritage site, is among these important ecosystems (IWM & CEGIS, 2007). The Sundarbans provide a habitat for an abundance of plant species as well as an array of fish and wildlife.

According to the Population Census 2001, the total population of the coastal area is about 28 million, which is about 22% of the total population of Bangladesh. Considering the total land area, the average population density is about 792 people per sq.km (IWM & CEGIS, 2007). The estimated population (2009) of the 16 coastal districts is about 35.6 million of which 48.8% are women.

About 11,915 km2 of the coastal area is protected by coastal polders. There are 123 polders, which were constructed in the late sixties to protect the land from tidal and monsoon flooding as well as saline water and to increase crop production. Most of the large islands are protected by coastal embankments.

After the devastating cyclone of 1970, which caused a death toll of about 470,000 people, the Government, donors, NGOs and various humanitarian organizations started building cyclone shelters for providing safe haven facilities for the coastal population. The majority of the coastal population is poor with little financial capability for building sufficiently strong houses that could withstand cyclones or tsunamis. It was only after the 1970 cyclone that cyclone shelters started to be built. In terms of shelter management, there was a lack of proper coordination before the 1991 cyclone, but based on various studies more focus was eventually given to the matter. Over the years, construction of cyclone shelters has continued in the coastal area of Bangladesh. But there are still not enough shelters for providing safe haven facilities to the coastal population. Furthermore, as the shelters were built by various organizations and were of different designs, there are differences in the capacity of these shelters to withstand different hazard conditions. Thus, it has become necessary to assess the current condition of the shelters and their vulnerability to various hazard conditions for ensuring the safety and protection of the coastal people.

In order to establish effective shelter management, the most important issues are the spatial location of the shelters, and the structural condition and vulnerability of the shelters during different disasters. GIS is a very useful tool for locating and analysing the locations of shelters and for making the needs and problems visible to decision makers. This paper describes the updating of the spatial locations of cyclone shelters for shelter management in preparing for tsunami and cyclone induced storm surge.

Spatial Location of Cyclone Shelters

Cyclone shelters are being constructed for over 30 years in the coastal area of Bangladesh. The spatial location of these shelters is very important for assessing the future needs of shelters and also for shelter management issues.

Approach

Based on initial literature review and the methodology developed for spatial location information collection and preparation of spatial distribution maps (figure 1), secondary data were first collected from relevant sources like MoFDM, DMB, MCSP, DRRO, UNO, LGED, CYSMIS study etc. These data were used for developing a list of existing cyclone shelters and their related information. A questionnaire was then developed in consultation with experts and local stakeholders for collecting information on existing cyclone shelters. The questionnaire was synchronized based on available secondary information and additional data needed for shelter management. The questionnaire combined a range of information like location, coordinates, shelter descriptionand type, construction agency and period, funding, details of structural elements, capacity and number of people taking shelter, facilities at the shelters etc. Primary data on cyclone shelters were collected through a field survey using the questionnaire. During primary data collection the spatial location of each shelter was recorded by GPS and pictures of the shelters were taken. After data collection from the field, data entry was carried out and all collected information was stored in an MS Access database.

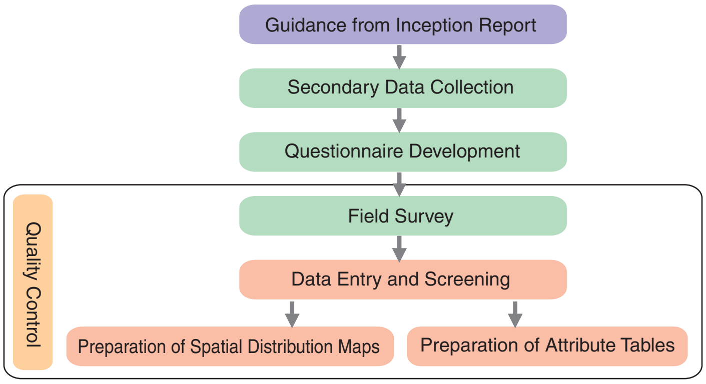


Figure 1: Methodology for preparation of spatial distribution maps and attributes

Based on the information collected during the survey, upazila-wise spatial distribution maps were prepared using a GIS tool (ArcGIS). The maps were prepared using the Bangladesh Transverse Mercator (BTM) projection system and JICA suggested parameters. Base maps were prepared that included roads, rivers, embankments, administrative boundaries (upazila and union), settlement and forests using the National Water Resources Database (NWRD) and recent available satellite images (mainly IRS panchromatic images of 2002-2004). Using all these information, spatial distribution maps and attributes of cyclone shelters were prepared. The quality of field survey and data collection, data entry and screening and preparation of maps and attribute tables was ensured through a quality control process.

Survey Results

The survey results are presented in the spatial distribution maps, a sample of which is shown in Figure 2. The spatial distribution map of each upazila is presented showing cyclone shelters along with the upazila headquarters, administrative boundaries (district, upazila, union), road networks, rivers, embankments, settlements and forests. The maps include legends along with the north direction and scale. The shelters shown in the maps are mainly separated into two broad categories, Shelter and Shelter-cum-Killa.

Figure 2: Spatial distribution map of Kala Para upazila, Patuakhali district

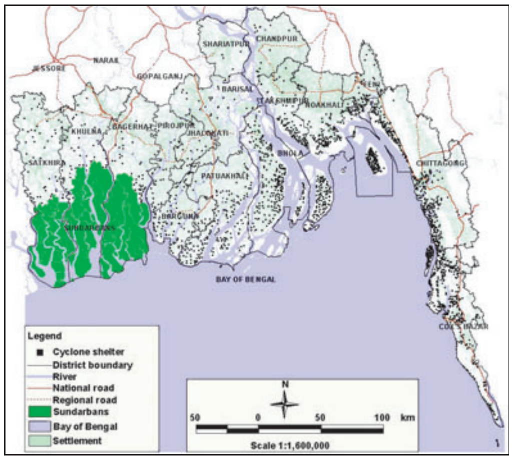


Figure 3: Spatial locations of cyclone shelters in the coastal area.

Each of these categories are classified into three groups (usable, moderately usable and unusable) based on the condition of the shelters. There are also a number of missing shelters, which were washed away by erosion or dismantled.

Figure 3 shows a map of the coastal area indicating the locations of all existing cyclone shelters. There are a total of 2,591 usable cyclone shelters located in the coastal districts.

Result Analysis

During the field investigation a total of 3,865 structures were surveyed. Among these 67% (2,591 Nos.) are usable, 7% (262 Nos.) are not usable, 2% (88 Nos.) are washed away/destroyed/dismantled and 24% (924 Nos) are open ground floor structures/schools which are constructed by Primary Education Development Programme-II (PEDP-II). Though in the worst case people take shelter in PEDP-II structures, but these structures are not suitable as shelter. Figure 4 shows the distribution of shelters based on their current conditions.

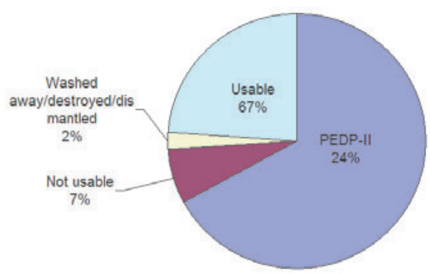


Figure 4: Distribution of shelters based on condition

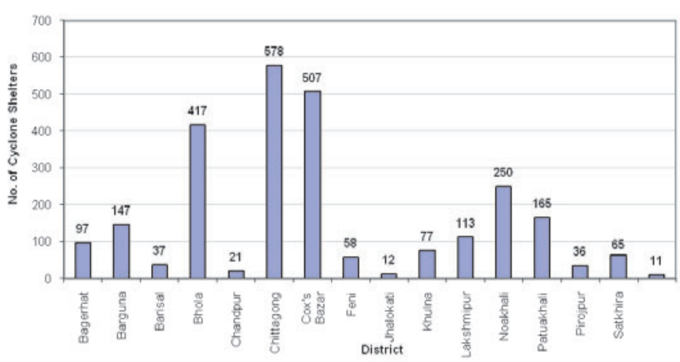
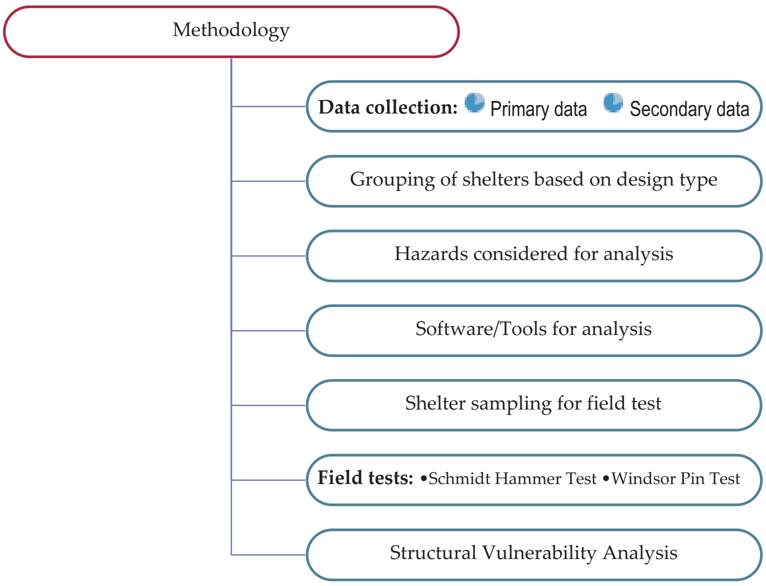


Figure 5: District-wise distribution of cyclone shelters

The district-wise summary of cyclone shelters is given in Figure 5. The figure shows that the districts of Chittagong, Cox's Bazaar and Bhola have the highest number of shelters, while the districts of Jhalokati, Barisal and Shariatpur have the lowest number of shelters.

Structural Vulnerability of Cyclone Shelters

The cyclone shelters are used for protecting the lives of coastal people with shelter during cyclone or tsunami induced storm surges. So, the structural strength of the shelters in disaster situations like cyclone, tsunami and earthquake is of great importance.



Approach

The structural strength of cyclone shelters was assessed through several steps such as (a) Grouping of cyclone shelters based on similar design type; (b) Field strength tests of cyclone shelters and (c) Analysis of the structural strength of the shelters using suitable analysis tools under different hazard conditions like cyclone, tsunami and earthquake and (d) Vulnerability analysis of shelters using spatial location, design type and hazard risk maps.

Based on the structural dimensions, construction and funding agencies and period of construction, the cyclone shelters were grouped into thirteen major design types. As a part of the study, field tests were carried out. The Schmidt Hammer Test and the James Windsor Pin Test were conducted for assessing the concrete strength of the structures. Based on the test results, the concrete strength was assumed for structural analysis. Analyses were conducted using linear 3D Finite Element Method (FEM) based ETABS (version 8.5) software, for assessing the structural strength of the shelters. Structural analyses were conducted for all 13 types of shelters and for tsunami, cyclone and earthquake induced forces. After the FEM analysis the results were combined with the spatial locations of the shelters. With the help of recently developed inundation risk maps under the study titled "Use existing data on available digital elevation models to prepare useable tsunami and storm surge inundation risk maps for the entire coastal region" (IWM, 2008), structural vulnerability analysis was carried out. The analysis was conducted using GIS tools by combining inundation risk maps for cyclone and tsunami, design type of the shelters and shelter capacity to withstand storm surge, wind and earthquake forces.

Field Tests

Field testing of cyclone shelters included two tests, the Schmidt Hammer Test and the Windsor Pin Test. A total of thirteen shelters were selected for the field test. The Schmidt Hammer Test was carried out for 13 shelters, while the Windsor Pin Test was conducted for 7 shelters.

The Windsor Pin Test was conducted to cross check the results of the Schmidt Hammer Test. The test results are presented in tables 1 and 2. The results show that the concrete strength of the structures varies from 1,240 pound/sq. inch (psi) to 5,970 psi. Based on these results, the concrete strength of different types of structures was assumed for conducting the FEM analysis.

Table 1: Schmidt Hammer Test Results

Design Type	Concrete Strength (psi)		
	Spot-1	Spot-2	Spot-3
Type 1 (BDRCS)	**5550**	**5340**	**3270**
Type 2 (BRAC)	**4360**	**5110**	**4180**
Type 3 (LGED -II)	**2920**	**2400**	**3880**
Type 4 (EU)	**4110**	**3120**	**3200**
Type 5 (German)	**3270**	**2950**	**2880**
Type 6 (Grameen Bank)	**1690**	**1240**	**3060**
Type 8 (JICA -II), site 1	**5040**	**4990**	**5260**
Type 8 (JICA -II), site 2	**4720**	**4740**	**5300**
Type 9 (LGED -I)	**3450**	**2520**	**3270**
Type 10 (PWD)	**3600**	**3490**	**2500**
Type 11 (Saudi)	**2990**	**3270**	**2840**
Type 12 (Union Parishad)	**3920**	**3820**	**3140**
Caritas	**2590**	**5970**	**3860**

Table 2: Windsor Pin Test Results

Design Type	Concrete Strength (psi)
Type 2 (BRAC)	**2760**
Type 4 (EU)	**2740**
Type 6 (Grameen Bank)	**2520**
Type 8 (JICA -II), site 1	**3050**
Type 8 (JICA -II), site 2	**2930**
Type 9 (LGED -I)	**2440**
Type 11 (Saudi)	**2810**

Finite Element Method Analysis of the Structures

Linear 3D FEM analyses were conducted for assessing the capacity of the shelters to withstand cyclone, tsunami and earthquake. A wide spectrum of FEM software and tools are available for such analyses. In the present study, ETABS (version 8.5) was used for this purpose. The material property was considered as linear elastic. Loading on the structures like, dead load, live load, wind load, earthquake load and storm surge load were calculated based on the guidelines of the Bangladesh National Building Code (BNBC, 1993). The American Concrete Institute Code (ACI 318-99) was also consulted to complement BNBC. Besides these, UBC 97, IBC 2000, Federal Emergency Management Agency Coastal Construction Manual (FEMA CCM, 2000) and Design Guidelines for tsunami vertical evacuation sites of the Washington State Department of Natural Resources (Yeh et al., 2005) were followed to assess the hydrodynamic and impact forces due to tsunami. MCSP proposed maximum flow velocity was utilized in calculating hydrodynamic forces for cyclonic storms.

In the finite element modeling of the cyclone shelter buildings, beams and columns were modeled as frame elements, slabs as plate elements and shear walls as membrane elements. Based on the information available, some assumptions were made in analyzing the structures. Dead load, live load, wind load and earthquake load were calculated as per BNBC. Regarding the grade of steel reinforcement, it was assumed that 40-grade steel had been used. The detailing was assumed to be as per the Intermediate Moment Resisting Frame (IMRF). Soil condition was assumed to be S3. Wind exposure category was considered as C. While determining adequacy of column sections, it was assumed that they contained 3% longitudinal reinforcement. The dead loads used are, 150 pcf (Reinforced concrete), 120 pcf (Brickwork), 25 psf (Floor finish) and 70 psf (Partition wall); while Live loads were taken as 100 psf, as per the BNBC and MCSP suggestions.

The Equivalent Strut Model was used to consider the effects of infill masonry walls. The masonry infill panel is represented by an equivalent diagonal strut of width, and net thickness, teff. The equivalent strut width depends on the relative flexural stiffness of the infill to that of the columns of the confining frame. The relative infill-to-frame stiffness is evaluated as (Stafford-Smith and Carter, 1969):

$$\lambda_1 H = H[(E_m t \sin\theta)/(4E_c I_{col} h_w)]^{1/4}$$

Where, H is the height of the story, E_m is the modulus of elasticity of the masonry work, t is the thickness of masonry wall, θ is the angle of the diagonal with the horizontal, E_c is the modulus of the elasticity of concrete, I_{col} is the moment of inertia of column section and h_w is the height of the masonry work.

The equivalent strut width is given by,

$$a = 0.175D(\lambda_1 H)^{-0.4}$$

Where, D is the diagonal length of wall. In the FEM model the strut is modeled using frame elements.

There are several forces associated with tsunami, such as, hydrostatic forces, buoyant forces, hydrodynamic forces, surge forces, impact forces and breaking wave forces. According to FEMA CCM, Hydrodynamic force (drag force), F_d is calculated as,

$$F_d = \frac{1}{2}\rho C_d A u_p^2$$

Where C_d is the drag coefficient, and A is the projected area of the body on the plane normal to the flow direction. The FEMA CCM recommends $C_d = 2.0$ for square or rectangular columns and 1.2 for round columns. FEMA CCM provides the following estimate of flood velocity u in the surge depth d_s:

$$u = 2\sqrt{g d_s}$$

Impact loads are those that result from debris such as driftwood, small boats, portions of houses, etc., or any object transported by floodwaters, striking against buildings and structures or parts thereof. According to FEMA CCM and ASCE 7 the generalized expression for impact force, F_I acting at the still water level is:

$$F_I = m\frac{du_b}{dt} = m\frac{u_I}{\Delta_t}$$

Where u_b is the velocity of the impacting body, u_I is its approach velocity that is assumed equal to the flow velocity, m is the mass of the body, Δ_t is the impact duration that is equal to the time between the initial contact of the body with the building and the maximum impact force. The City and County of Honolulu Building Code Δ_t (CCH, 2000) recommends $\Delta_t = 0.1$ second for reinforced concrete.

Forces due to cyclone are mainly storm surge force and wind force. Calculations of storm surge load due to cyclone are similar to that of tsunami load. In this case, the flood velocity is much less compared to tsunami. According to MCSP the maximum flood velocity of storm surge can be taken as 2.5 m/s.

For wind loading, the BNBC recommended basic wind speed of 260 km/h for cyclone of a 50-year return period in the coastal area was used. Apart from that, other parameters used in wind load calculation are: Exposure category = C and Structure Importance coefficient $C_I = 1.25$.

For earthquake resistant structural design, it is essential that a specific design code is followed. For the analysis and design check, the Equivalent Static Force Method and the Dynamic Response Method of BNBC were followed. BNBC requires that the Dynamic Response Method must be used for structures having a stiffness, weight or geometric vertical irregularity. In all shelters, there is an open ground story causing vertical stiffness irregularity. So, the Dynamic Response Method, particularly the Response Spectrum Analysis, was used for analysing these structures. However, in order to perform Response Spectrum Analysis, the Equivalent Static Force Method is needed to calculate the base shear. The main considerations for calculating earthquake load are: $C_I = 1.25$ and Response modification co-efficient, $R = 8.0$. For Response Spectrum Analysis, normalized response spectrum for soil type S_3 and 5% damping ratio, as per BNBC, was used.

3D FEM model of all thirteen types of shelters was built in ETABS 8.5. All types of structures were analyzed for different load combinations as per BNBC and for different storm surge heights.

FEM Analysis Results

From the structural analysis using ETABS, three types of structures, namely - Type 3 (LGED-II), Type 2 (BRAC) and Type 13 (PEDP-II), were found unable to meet code requirements even under dead and live loads.

These structures need to be strengthened irrespective of their locations and hazard potential. Most of the other types of shelters, in general, can withstand storm surge inundation of about 20 ft (± 5 ft, depending on the structure type) even for severe cyclones. However, for tsunami, due to its excessive flood velocity, few structures can sustain a tsunami height of more than 6 ft.

In the earthquake analysis conducted for the structures, it was found that Type 11 (Saudi), Type 1 (BDRCS), Type 8 (JICA-II), Type 6 (Grameen Bank) and Type 4 (EU) structures have adequate capacity to resist earthquakes. Only one column of Type 7 (JICA-I) shelter is inadequate under earthquake loading. Other types of shelters located in Seismic Zone-II are not capable of resisting earthquake forces.

Structural Vulnerability Analysis

Utilizing the inundation risk maps generated by the Institute of Water Modelling (IWM), for cyclone and tsunami induced storm surge, a structural vulnerability analysis was conducted. GIS techniques were used for identifying spatial distribution of shelters vulnerable under different hazard conditions. Spatial distribution maps have been produced for tsunami and cyclonic storms. A sample map showing the distribution of shelters is presented in Figure 7.

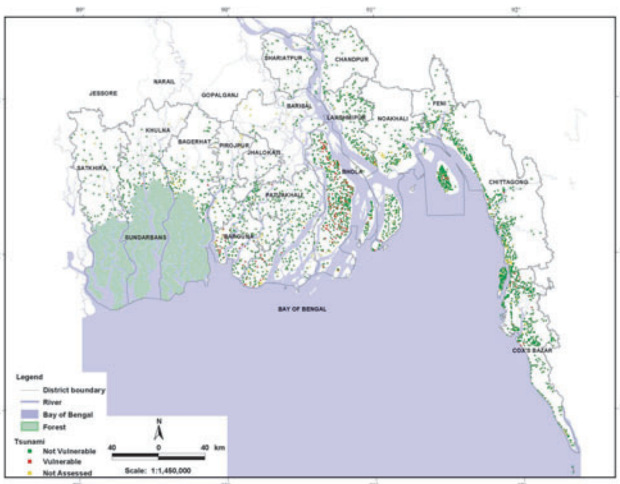


Figure 7: Cyclone Shelter Vulnerability Map: Tsunami

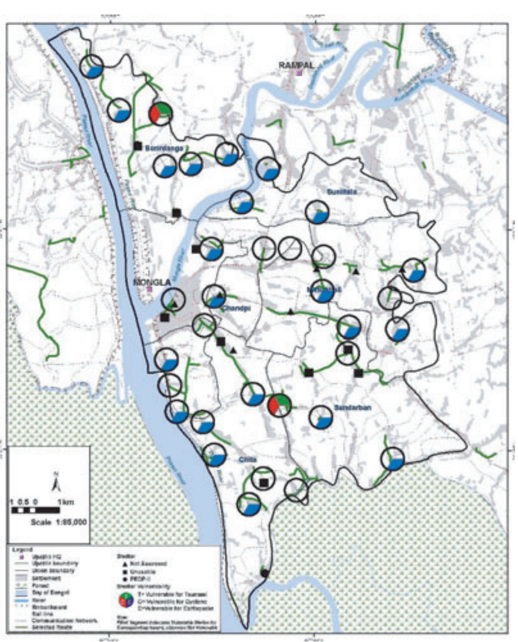


Figure 8: Shelter Vulnerability and Evacuation Route Map

From the analysis, it has been found that 66 (2.6%) shelters are vulnerable to tsunami and 196 (7.6%) shelters are vulnerable to cyclone, while a large portion of shelters are vulnerable to earthquake. From the vulnerability analysis it has been found that the most vulnerable districts to hazards like tsunami or cyclone, are Bhola, Patuakhali, Barguna, Chittagong and Lakshmipur. Using the shelter vulnerability information, shelter vulnerability and evacuation route map has been developed. Figure 8 shows a shelter vulnerability and evacuation route map of Mongla upazila of Bagerhat district.

CONCLUSION

The study demonstrates usage of GIS and GPS tools in locating the shelters and visualizing the spatial distribution of safe haven facilities against tsunami and cyclone induced storm surge in the coastal area of Bangladesh.

Over the periods, government, donor agencies and NGOs constructed 2,941 cyclone shelters to provide safe haven to the disaster affected people. Among these shelters 2,591 are usable. Construction of shelters is dynamic in nature as various agencies are constructing shelters in the coastal areas, but the potential affected people remained uninformed where to go during emergencies. Therefore, it is imperative to have the technology to update the cyclone shelter information along with delineate the catchment area of the respective shelters and informing the people where they will take shelter. Alongside, a strong legislation should be there to follow the Bangladesh National Building Code (BNBC) in constructing shelters in future.

In this paper, it is also identified that, many of the shelters are vulnerable against cyclonic wind and storm surge (196 nos., 7.6%) and surge from tsunami (66 nos., 2.6%). This vulnerability is mainly due to design fault, as they did not follow BNBC properly. As a result, about 8% of shelters are not safe enough to provide shelter to the coastal population.

It is very important to note that, a 'S' mark should be painted on the roof-top in distantly visible manner, so that, the shelters could be easily located through remote sensing tool. Categorization of formal and informal shelters is another debatable issue which should be resolved by generalization of shelters.

ACKNOWLEDGEMENT

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Structural Strength Analysis of Infrastructure in the Coastal Region of Bangladesh

Md. Anwar Hossain Bhuiyan[1], Raquib Ahsan[2] and Manjur Murhsed Zahid Ahmed [3]

ABSTRACT

The coast of Bangladesh is known as zone of vulnerabilities as well as opportunities. The coastal region of Bangladesh is always vulnerable to natural hazards like floods, cyclones, storm surge, tsunami and others. The frequency and intensity of natural disasters like floods, cyclones, storm-surges and tidal bores are very high in Bangladesh.

There are many infrastructures like schools, college, hospitals, district headquarters, fire services, CPP offices, Red Crescent offices and other emergency response and control buildings in the coastal region of Bangladesh. These buildings can be used as shelter during the events of tsunami and storm surge. In order to evacuate people safely to such buildings, it is necessary to analyze the structural strength and also to establish the methodology to evaluate the structural safety of the refuge buildings against tsunami and storm surge loads.

The main objectives of the study are to carry out structural strength analysis of infrastructures in the coastal region of Bangladesh and to determine the adaptation capacity of the vulnerable infrastructures for tsunami and storm surge events.

The detail information of different category of infrastructure has been collected by field survey under the present study. The structural members in ground floor of existing buildings have been investigated because the tsunami/surge forces are greatest at these levels and these members carry the greatest loads. Failure of any of these members could lead to progressive collapse of significant portion or whole of the building.

Three dimensional (3D) Finite Element Method (FEM) models of the selected coastal structures have been generated in the present study using structural design tool named ETABS (version 9.0.4). The model result shows that the flood velocity for Tsunami is much higher compared to that of storm surge. In case of Tsunami, for only 1 m inundation flood velocity becomes about 7 m/s, whereas the maximum velocity in case of storm surge is around 2.5 m/s. Due to higher flood velocity, Tsunami exerts greater hydrodynamic and impact forces on a structure. Thus from the analyses of the model results it is found that all the selected structures are inadequate to resist Tsunami forces even for 1 m inundation.

The model result also shows that the Primary School building and the High School building are adequate against cyclonic load along with storm surge. On the other hand the College building and the Madrasha building are inadequate since these buildings are designed without satisfying very basic requirements of the code.

Keywords: Infrastructure, Hydraulic Load, Tsunami, Storm Surge and Structural Design Tool.

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INTRODUCTION

The coastal region of Bangladesh is densely populated and about 28% of the population lives in coastal zone (Coastal Zone Policy, 2005). The population is expected to increase from 36.8 million in 2001 to 43.9 million in 2015 and to 60.8 million by 2050 (PDO-ICZM, 2005).

The coast of Bangladesh is known as zone of vulnerabilities as well as opportunities. The coastal region of Bangladesh is always vulnerable to natural hazards like floods, cyclones, storm surge, tsunami and others. The frequency and intensity of natural disasters like floods, cyclones, storm-surges and tidal bores are very high in Bangladesh. Its flat deltaic topography with very low elevation makes it more vulnerable to tsunami and storm surge. About 62% of the land's elevation in the coastal region is up to 3 metres and 86% up to 5 meters from mean sea level.

There are many infrastructures like schools, college, hospitals, district headquarters, fire services, CPP offices, Red Crescent offices and other emergency response and control buildings in the coastal region of Bangladesh. These buildings can be used as shelter during the events of tsunami and storm surge. In order to evacuate people safely to such buildings, it is necessary to analyze the structural strength and also to establish the methodology to evaluate the structural safety of the refuge buildings against tsunami and storm surge loads.

Study area is the costal region of Bangladesh. Infrastructures like School/Hospital/Emergency Response and Control Buildings in the coastal region of Bangladesh have been considered in this study.

The main objectives of the study are to carry out structural strength analysis of infrastructures in the coastal region of Bangladesh and to determine the adaptation capacity of the vulnerable infrastructures for tsunami and storm surge events.

VULNERABLE INFRASTRUCTURE

The categories of infrastructure considering various occupancies are: Educational institution buildings (such as college, school, madrasha), hospital, fire service, CPP office, Red crescent office and emergency response buildings.

The detail information concerning location, type of structure, size, number of story, year of construction , present condition etc. for each category of structure have been collected by field survey from 245 unions under 46 upazilas of 13 districts located in high risk area (depth of inundation > 1.0m) in coastal region. The total numbers of surveyed infrastructure are 4707 nos. (i.e. college-100 nos, school-3130 nos, madrasha-449 nos, hospital/ FWC-99 nos, DC office-9 nos, fire service-11 nos and red crescent office-7 nos).

The surveyed infrastructures include pucca (898 nos), semi pucca (387 nos), RCC frame (2661 nos), brick wall (99 nos) and tin shed (622 nos) type construction. The number of one story, two story and three story structures are 2726, 1522 and 419 nos respectively.

GENERAL REQUIREMENT

In coastal areas the buildings or structures should be designed to resist the effects of coastal floodwaters and tsunami/surge.

In the present study, structural members in ground floor of existing buildings have been investigated because the tsunami/ surge forces are greatest at these levels, and these members carry the greatest loads. Failure of any of these members could lead to progressive collapse of significant portion or whole of the building.

DESIGN CODES

In general, Bangladesh National Building Code, 1993 has been followed for selection/computation of loads and analysis of structural members.

The Washington Division of Geology and Earth Resources has prepared Open File Report 2005-4, November 2005, titled "Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Site" (52-AB-NR-200051) by Harry Yah - Oregon State University, Ian Robertson - University of Hawaii and Jane Preuss - Plant West Partners.

The following design codes as mentioned in aforementioned design guideline with respect to computation of tsunami loads have been used for this study:

1. The City and Country of Honolulu Building Code (CHH)

2. The Federal Emergency Management Agency Coastal Construction Manual (FEMA CCM)

3. The ASCE 7-98 (ASCE 7) authored by the American Society of Civil Engineers Committee 7 (ASCE 7).

DESIGN LOADS

Load on buildings include, dead load, live load, wind load, hydraulic (storm surge/tsunami) load. The dead load, live load and wind loads as specified in the Bangladesh National Building Code, 1993 have used in structural strength analysis.

STORM SURGE/TSUNAMI LOAD

The following loads are relevant:

- Hydrostatic Forces.
- Buoyant Forces
- Hydrodynamic Forces
- Surge Forces
- Impact Forces
- Breaking Wave Forces

TSUNAMI AND STORM SURGE INUNDATION DEPTH DATA

Tsunami and storm surge inundation risk maps have been prepared under a separate study entitle "Prepare Spatial Distribution Maps of the Tsunami and Storm Surge Vulnerable School/Hospital/Emergency Response and Control Buildings-Draft Report, December 2008". The numbers of infrastructures under each category of inundation depth have been shown in that report for tsunami and surge vulnerability.

TSUNAMI/ SURGE DESIGN CODE EQUATIONS

Design Flood Velocity

FEMA CCM and CCH provide the following estimate of the flood velocity u in the surge depth ds, based on Dames and Moore (1980):

$$u = 2\sqrt{gd_s}$$

Hydrodynamic Force

Both CCH and FEMA CCM provide the following expression for hydrodynamic force (drag force) Fd:

$$F_d = \frac{1}{2} \rho C_d A u_p^2$$

Where:

C_d = drag coefficient, and

A = projected area of the body on the plane normal to the flow direction.

The CCH recommends:

C_d = 1.0 for circular piles, 2.0 for square piles and 1.5 for wall sections.

The FEMA CCM recommends:

C_d = 2.0 for square or rectangular piles and 1.2 for round piles.

Surge Force

The CCH adopted the following equation (Dames & Moore, 1980) for surge force Fs.

$$F_s = 4.5 \rho g h^2$$

where, h = surge height. The resultant force acts at a distance approximately h above the base of the wall. This equation is applicable for walls with heights equal to or greater than $3h$. Walls whose heights are less than $3h$ require surge forces to be calculated using appropriate combination of hydrostatic and hydrodynamic force equations for the given situation.

Impact Force

The CCH, FEMA CCM and ASCE 7 contained similar equations that resulted in the following generalized expression for impact force FI acting at the still water level:

$$F_I = m \frac{du_b}{dt} = m \frac{u_I}{\Delta t}$$

where,

u_b = velocity of the impacting body,

u_I = approach velocity of the impacting body that is assumed equal to the flow velocity,

m = mass of the body,

Δ_t = impact duration that is equal to the time between the initial contact of the body with the building and the maximum impact force.

The CCH recommends Δ_t values for wood construction as 1.0 second, steel construction as 0.5 second, and reinforced concrete as 0.1 second. The FEMA CCM provides the Dt values shown in Table 1 below.

Table 1: The Impact Duration Dt Recommended By Fema Ccm

Type of construction	Duration (t) of Impact (sec)	
	Wall	Pile
Wood	0.7 - 1.1	0.5 - 1.0
Steel	NA	0.2 - 0.4
Reinforced Concrete	0.2 - 0.4	0.3 - 0.6
Concrete Masonry	0.3 - 0.6	0.3 - 0.6

Breaking Wave Forces

Breaking Wave Loads on Vertical Piling and Columns

The ASCE 7 and FEMA CCM provide the following expression for the breaking-wave force Fbrkp:

$$F_{brkp} = \frac{1}{2} \rho g C_{db} D H_b^2$$

where,

C_{db} = shape coefficient (ASCE 7 and FEMA CCM recommended C_{db} values of 2.25 for

square or rectangular piles and 1.75 for round piles),

D = pile diameter, and

H_b = breaking wave height (FEMA CCM recommends that H_b = 0.78 ds in which ds is the design still-water flood depth).

The codes indicate that the potential for scour around structural foundations must be considered, but provide there is no guidance on how this scour can be estimated or how footings can be designed to withstand the effects of scour.

ALLOWABLE STRESSES

The allowable stresses in concrete and reinforcement has been followed according to Bangladesh National Building Code, 1993.

SELECTED STRUCTURES FOR ANALYSIS

Four typical structures, each one for primary school, high school, college and madrasha have been collected from Facilities Department and Upazila Office as shown in Table 2 below.

TABLE 2: INFORMATION ON COLLECTED STRUCTURES

Srl.	Type of structure	Type of construction	No. of story	Source of collection
1	Primary school	RCC frame	One story building with provision of 2 story	Patuakhali Sadar Upazila Office
2	High school	-do-	One story	Facilities Department, Patuakhali
3	College	-do-	Three story	-do-
4	Madrasha	-do-	One story	-do-

ANALYSIS OF STRUCTURES

Assessment of structural strength of a building requires modeling and analysis of the structure of the building to determine the stress and load levels it can sustain for different modes of loading. The most convenient method of modeling a building structure is to develop numerical model in Finite Element Method (FEM). Three dimensional (3D) FEM models of the selected coastal structures have been generated in the present study using structural design software package ETABS (version 9.0.4).

SOFTWARE SELECTION CRITERIA

Linear 3D FEM analyses of the selected buildings have been conducted in order to assess the capacity of the structures to withstand loading caused by tsunami and cyclone along with storm surge. A wide spectrum of FEM software and tools are available for such analyses. In the present study, ETABS (Version 9.0.4) has been used for this purpose. ETABS has been chosen for its user friendly features in analyzing building structures (Computers and Structures, Inc., 2005). The special features of ETABS are mentioned below:

- User friendly graphical user interface for generating story-wise building models
- Availability of necessary elements for developing FEM model of a building
- Provision for changing orientation of frame elements
- Automatic consideration of rigid end zones of frame elements
- Automatic calculation of member self-weight
- Automatic calculation of member sectional properties
- Integrated design features
- Consideration of moment magnification for slender columns

FINITE ELEMENT MODELS OF THE BUILDINGS

Frame elements have been used to model the columns and plate/shell elements have been used to model the slabs. The frame elements are typical two-noded elements in space having six degrees of freedom per node - three translations and three rotations in three mutually perpendicular axes system. The plate/shell elements are of rectangular (or quadrilateral) and triangular shape. The quadrilateral element has four nodes at its four corners. Each node has six degrees of freedom - three translations and three rotations in a 3D space configuration. At base level, the columns are assumed to be held fixed. 3D views of the Finite Element Models of the selected structures.

Masonry infill model

Equivalent strut model has been used to consider the effect of infill masonry walls. The masonry infill panel has been represented by an equivalent diagonal strut of width, a and thickness, t. The equivalent strut width, a depends on the relative flexural stiffness of the infill to that of the columns of the confining frame. The relative infill-to-frame stiffness is evaluated using equation (Stafford-Smith and Carter, 1969):

$$\lambda_1 H = H[(E_m t \sin\theta)/(4E_c I_{col} h_w)]^{1/4}$$

Where, H is the height of the story, Em is modulus of elasticity of the masonry work, t is the thickness of masonry wall, θ is the angle of the diagonal with the horizontal, E_c is modulus of elasticity of concrete, I_{col} is the moment of inertia of column section and h_w is the height of the masonry work. The equivalent strut width is given by,

α =0 .175Δ(1H)-0.4

Where, D is the diagonal length of the wall. In the FEM model strut is modeled using frame elements.

Geometric configuration and material properties

Detail geometric configuration and material properties of the structures are required to develop their finite element models. Information regarding their geometric configuration has been collected from secondary sources. Information regarding the existing concrete properties has been gathered through field testing like Rebound Hammer test and Windsor Pin test. It was found that in general concrete property was satisfactory in the tested structures. For the developed models the 28 day cylinder strength of concrete was assumed to be 20 N/mm2 (3000 psi). It was difficult to collect adequate samples of reinforcement for testing their tensile strength. Hence it is conservatively assumed that 40 grade steel was used as reinforcement in the selected structures.

SPECIAL CONSIDERATIONS FOR LOADING

All the selected structures have been analyzed separately for tsunami loading and loading due to cyclone along with storm surge. In both the cases Dead Load and Live Load were considered as per BNBC. Since these schools and colleges may be used as shelters during cyclone or tsunami, according to the guideline of Multipurpose Cyclone Shelter Programme, 1993, live load on the floors and roof is assumed to be 4.8 kN/m2 (100 psf). For both tsunami and storm surge, three cases of inundation have been considered in this study: a surge height of 1m, 2m and 3m. Among the selected structures the primary school, the high school and the madrasha are one storied. So there is no scope of considering surge height of more than 3m. It is later shown in the present report that the college building is inadequate against a surge height of 3m both in the case of Tsunami and Cyclone. Since for such inundation no floor is submerged, buoyant forces do not act on the structures.

The lateral loads have been applied in the shorter direction of the buildings which is more critical. For tsunami loading hydrodynamic and impact forces on the columns of a structure have been estimated . Flood flow velocity has been estimated by the relation of tsunami flow velocity with inundation depth as provided by Dames and Moore (1980)

A relationship between the maximum wind speed and the surge level has been developed based on the information. The surge height can roughly be said that increases with increased wind speed. The relationship can be expressed as:

Surge Height (m) = 0.16 x Wind Speed (m/s) - 3.98

There can be an error of ±2m.

ANALYZED CASES

All the four types of structures have been analyzed for each of the following loading conditions and checked for their adequacy:

1. a) 0.75 (1.4DL + 1.7LL + 1.87T) for ds = 1m.
   b) 0.75 (1.4DL + 1.7LL - 1.87T) for ds = 1m.
2. a) 0.75 (1.4DL + 1.7LL + 1.87T) for ds = 2m.
   b) 0.75 (1.4DL + 1.7LL - 1.87T) for ds = 2m.
3. a) 0.75 (1.4DL + 1.7LL + 1.87T) for ds = 3m.
   b) 0.75 (1.4DL + 1.7LL - 1.87T) for ds = 3m.
4. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 1m and Vb = 260 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 1m and Vb = 260 km/h.
5. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 2m and Vb = 260 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 2m and Vb = 260 km/h.
6. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 3m and Vb = 260 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 3m and Vb = 260 km/h.
7. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 1m and Vb = 210 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 1m and Vb = 210 km/h.
8. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 2m and Vb = 210 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 2m and Vb = 210 km/h.
9. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 3m and Vb = 210 km/h.
   b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 3m and Vb = 210 km/h.
10. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 1m and Vb = 178 km/h.
    b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 1m and Vb = 178 km/h.
11. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 2m and Vb = 178 km/h.
    b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 2m and Vb = 178 km/h.
12. a) 0.75(1.4DL + 1.7LL + 1.7WL + 1.7S) for ds = 3m and Vb = 178 km/h.
    b) 0.75(1.4DL + 1.7LL - 1.7WL - 1.7S) for ds = 3m and Vb = 178 km/h.

Where,

DL: Dead Load (both self-weight and super-imposed)

LL: Live Load

T: Tsunami Load (hydrodynamic and impact forces are combined.)

WL: Wind Load

S: Surge Load (hydrodynamic and impact forces are combined)

ds: Depth of Submergence

Vb: Basic Wind Speed

Here +/- implies two opposite directions. All these above cases have further been analyzed for two different conditions: One before breaking of the ground story infill walls and the other after breaking of the ground story infill walls. Thus, in total, 144 different cases have been analyzed and checked with the design.

RESULTS OF ANALYSIS

For each of the different 144 conditions mentioned in the previous section each of the four different types of selected structures has been analyzed and the developed stresses have been compared with the allowable stresses.

Capacity of the individual members of an RC structure depends both on the concrete section and the amount and location of the steel reinforcement. In the following paragraphs the results of the analyses and adequacy of each of the selected structure types are explained.

The Primary School building can sustain the loads due to cyclone with basic wind speed of 260 km/h and surge height of 3 m without any structural members failing. However, a number of columns require more reinforcement than provided for Tsunami load of only 1m surge height.

The High School building can sustain the loads due to cyclone with basic wind speed of 260 km/h and surge height of 3 m without any structural members failing. However, a number of columns require more reinforcement than provided for Tsunami load of 1 m surge height.

A number of columns of the College building require more reinforcement than provided even for dead and live loads and thus fail to sustain any Tsunami or Cyclone loading

The Madrasha building under usual live load condition can sustain a 3m storm surge along with wind load of 260 km/h. A number of columns of the Madrasha building, however, fails to withstand any Tsunami loading.

CONCLUSIONS

Flood velocity for Tsunami is much higher compared to that of storm surge. In case of Tsunami, for only 1 m inundation flood velocity becomes about 7 m/s whereas the maximum velocity in case of storm surge is around 2.5 m/s. Due to higher flood velocity, Tsunami exerts greater hydrodynamic and impact forces on a structure. Thus from the above analyses it is found that all the selected structures are inadequate to resist Tsunami forces even for 1 m inundation.

The Primary School building, the High School building and the Madrasha building are adequate against cyclonic load along with storm surge. On the other hand, the College building is inadequate since the building fails to satisfy very basic loading combinations of the code.

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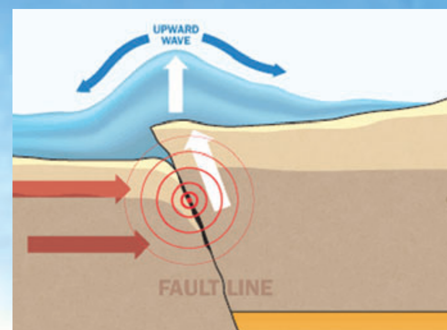

Disaster Management Vision of the Government of Bangladesh

To reduce the risk of people, specially the poor and the disadvantaged from the effects of natural environmental and human induced hazards to a managable and acceptable humanitarian level and to have in place an efficient emergency response management system

UNDP Bangladesh

DFID Department for International Development

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