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Numerical Simulation based modeling of 2004 Andaman-Sumatra Tsunami to understand the tsunami hazard along the coastline of Mainland India

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Abstract: *Natural hazards affect the progress towards sustainable development. Increasing effects ofnatural hazards viz. earthquakes, tsunamis, floods, landslides around the world has a directsocial, economic and environmental impact. The people living in the coastal areas of thetropics are exposed to various types of natural hazards of which the most devastating onesinclude high energy events such as earthquakes and tsunamis. The lithosphere of the Earth iscomposed of seven major and minor tectonic plates colliding, subducting or rifting apart withrespect to one another. This phenomenon has resulted in several tectonic plate boundariesaround the globe. The plate boundaries marked by subduction zones have produced numerousmega-earthquakes and associated transoceanic tsunamis. In the domain of the Indian sub-continent, the ongoing collision between the Indian plate and the Eurasian plate has resulted in the formation of the Himalayas in the north, and asubduction zone in the southwest along the Sumatra-Andaman trench. In the last fewdecades, Indian sub-continent experienced several devastating earthquakes with Mw >7.5.These events are viz. the 2001 Bhuj earthquake (Mw7.6) in Stable Continental Region (SCR)of Western India; 2005 Muzaffarabad earthquake (Mw7.6) in Kashmir; 2015 Gorkhaearthquake (Mw7.8) along the active plate-boundary along Himalaya; and 2004 Sumatra-Andaman earthquake (Mw9.3) and associated transoceanic tsunami in the Indian oceandirectly affected the people and their property. The Indian Ocean Tsunami (IOT) directlyaffected the coastlines of Indian Mainland, Sri Lanka, Thailand, Indonesia, Maldives andSomalia, killing about 280,000 people. The whole coastline of India faces the danger oftsunamis from the tsunamigenic subduction zones lying close to the Indian Subcontinentwhich include the Arakan subduction zone and Andaman-Sumatra subduction zone. Thenumerical study of tsunami provides an insight of the assessment of the level of risk to whichthe coastal regions are exposed.*

In the present study attempts have been made to know about the effects of probable tsunamison the Indian coastline considering the arrival time, wave height and directivity of tsunami waves as well as the inundation of the waves inland at the coasts of Andaman andmainland India. Keeping these in mind, modeling is carried out for 2004 Sumatra-Andamantsunami is generated as well as validated. Modeling is likean art which can be applied to generate past events. Numerical Modeling based on Non-linearShallow Water (NSW) help to know about the wave height and directivity of tsunami wavesbased on which time required to reach the tsunami waves at a particular location can beestimated. Tsunami height observed along the south eastern coast of Mainland India ranges between 2 to 3 m for 2004 tsunami. It took around 120 minutes to reach the coastline of Mainland India and hit the coastal structures. If a transoceanic tsunamioccurs in Indian Ocean having epicenter near Andaman Island, it will cause completedevastation of south eastern coast of Mainland India. This study will helps in formulation and design of mitigation measures with the early warning systems, which may eventually lead toless loss of life and damages to the property.

Keywords: *Modeling, Indian Ocean Tsunami, Andaman, Tsunami Height, Tsunami Directivity*

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I. Introduction

Natural hazard is a series of calamitous events that leads to quashing of lives in millions and mass destruction of properties, worth billions. These events are earthquakes, tsunamis, typhoons etc., which just takes only few minutes or hours to create such devastation that can affect countries at all fronts. It leads to socio-economic breakdown and environmental degradation in that region. Thus, these catastrophic events require extensive research to figure out its nature, how it gets generated, its affect spatially-temporally and mitigation factors, which need to be considered. In the last few decades, Indian sub-continent experienced several catastrophic events, viz. the 2001 Bhuj earthquake (Mw 7.6); 2005 Muzaffarabad earthquake (Mw 7.6); 2004 Sumatra-Andaman earthquake (Mw 9.3) and 2015 Gorkha earthquake (Mw 7.8). In all these Sumatra-Andaman (2004) was the most catastrophic, as it was associated with a mega-earthquake along Sumatra-Andaman Subduction Zone that generated a transoceanic tsunami in the Indian Ocean (Lay et al., 2005; Satake and Atwater, 2007; Sieh et al., 2008 and Malik et al., 2015). The convergence rate of Indian plate relative to the Sunda plate is ~40 mm/yr, while that of Australian plate is ~50 mm/yr along the northern part of Sumatra region (Subarya et al., 2006). These ongoing thrusting results in the several major and minor earthquakes in inter and intra-plate regions of the southeast Asia (Bilham et al., 2005; Lay et al., 2005; Rajendran et al. 2013., Malik et al., 2015).

The present study is focused on the earthquakes and associated tsunamis occurred in the Indian Ocean due to the presence of major subduction zones: Sumatra- Andaman and Arakan-Andaman. This event was second largest magnitude earthquake in the Sumatra region with the magnitude of Mw 9.3 (Bilham et al., 2005). In Indian Ocean there are chances of occurrence of many large magnitude earthquakes which are capable of generating tsunamis in the future (Singh et al., 2012). Some of the studies in the northern Bay of Bengal have shown the possibility of a giant tsunamigenic earthquake in the Arakan region. The offshore tsunami wave height of around 2.5 m occurred due to Arakan Earthquake of 1762 (Cummins 2007). Based on the hypothesis of development of stress in the Arakan Subduction Zone, an earthquake of magnitude 8.5 and 9.0 with recurrence interval of 100 and 500 years can be expected in future (Socquet et al., 2006). Malik et al. (2011) demonstrated geological evidence of two major paleoseismic events those occurred during AD 1600 accompanied by subsidence of ~ 1 m, and uplift as well as a tsunami event during AD 1700. Further, paleoseismic studies conducted in the west coast of South Andaman Island reported stratigraphic evidences of three paleoearthquakes and associated transoceanic tsunamis during past 1000 years (Malik et al., 2011; 2015). Based on this stratigraphic evidences the authors suggest a recurrence interval of 300-500 years due to mega-subduction zone earthquakes and associated tsunamis in the Sumatra-Andaman subduction zone (Malik et al., 2015). Whereas, paleoseismic and paleotsunami studies, as well as combined regional database from Andaman & Nicobar suggests that a comparable transoceanic event similar to 2004 occurred during 800–1100 year ago, and another occurred around AD 1450 (Rajendran et al., 2013).

Since, we got from the previous studies that tectonic governs the hazards in the coastal areas. Therefore, it is very important to comprehend the earthquakes and associated tsunamis and furthermore carry out a very significant task in characterizing the nature of tsunami i.e., whether it’s a near source or a far source. It means whether the areas affected are close to earthquake’s epicenter or not. Consequently, this study has been divided into different objectives to attain all those information and provide a hazard assessment as discussed above. Thus, the objectives, which are needed to be fulfilled, are:

(a) Simulation of tsunamigenic waves to generate the wave height and
(b) Simulation of tsunamigenic waves to generate the travel time maps
(c) Interpretation of generated results to know the severity of impact at desired locations

In this study, we carried out the numerical modeling for the case of 2004 tsunamigenic earthquake and then validated with available observed data. Numerical modeling found helpful to simulate the tsunami wave height at different locations and arrival time for waves to reach at desired locations. Finally the outcomes talks about the severity of tsunami waves in sense of its effect along the adjoining areas of Indian Ocean. Furthermore tsunami hazard assessment is discussed to draw out the mitigation measures for future tsunamis in the Indian Ocean to protect the adjoining areas of the Indian Ocean.

II. Tectonic Settings

The Andaman trench marks the active subduction zone, where the northeast moving Indian plate subducts below the Eurasian plate in an oblique mode. The chain of Island are on a small tectonic plate, which are often referred as the Burma-microplate (Dasgupta and Mukhopadhyay 1993; Ortiz and Bilham 2003). Back-arc extension is basically accommodated at the Andaman Back-Arc Spreading Center (ABSC) at ~10^o (Diehl et al., 2013). Hence, this tectonic setting has resulted in the development of thrust and strike-slip faults (Ortiz and Bilham, 2003; Curray, 2005). The West Andaman Fault (WAF) is one of the prominent right lateral strike-slip fault systems, which has continued all along the Islands starting from Burma microplate in the north to Sumatra in the south. The volcanic ridges are comprised of active volcanoes of Barren (Ba) Islands and Narcondam (Na) Islands as well as the sea mounds and basins where Barren Island is an active volcano erupted in 1994–1995, 2005–2006, and 2008–2009, and the activity at Narcondam is not clearly known (Pal et al., 2007). Additionally, the Central Andaman Basin (CAB) is characterized by extension and normal faulting along the spreading center having dextral strike-slip in the transform segments. The fore-arc basin has two major faults: Eastern Margin Fault (EMF) and Diligen Fault (DF). A detailed tectonic study by Kumar et al. (1996) along the Burma arc region shows the dextral strike-slip and comparatively less seismic activity than the southern segments.

According to Newcomb and McCann (1987), the two great Sumatran paleo-earthquakes in 1797 (Mw 8.2) and 1833 (Mw 8.7) generated very large tsunamis on the islands and mainland coast. Newcomb and McCann (1987) also identified great interplate earthquakes 1833 (Mw 8.7) and 1861 (Mw 8.5). A large earthquake with a magnitude and source area similar to the 2005 Nias-Simeulue earthquake occurred in 1861 (Bilham et al., 2005; Lay et al., 2005). The 1907 event produced a more destructive tsunami on the western coast of Simeulue than occurred in 2004 Sumatra-Andaman tsunami (Newcomb and McCann, 1987; Briggs et al., 2006). An earthquake Mw~7.7 in 1935 was produced by a narrow 70-km long section of the megathrust near the equator (Natawidjaja et al., 2004). North of Sumatra towards Andaman Island, an earthquake in 1941 (Mw 7.9) reportedly known to have occurred and generated tsunami (Bilham et al., 2005; Lay et al., 2005). The other significant events are 1762 (M 7.5) Arakan earthquake (Cummins, 2007); the Great-Nicobar earthquake (1847, Ms ~7.5), Car Nicobar earthquake (1881, Ms 7.9); South Andaman earthquake (1941, Ms 7.7) and the most recent is 2004 Sumatra-Andaman earthquake (Mw 9.3), (Bilham, 2005; Malik et al., 2015). In the southern part of this subduction zone, several ruptures related to major earthquakes and tsunami have been reported and studied during the events in 1797 (M 8.8), 1833 (M 8.7), 1861 (M 8.5) (McCloskey et al., 2007, Newcomb and McCann, 1987, Ortiz and Bilham., 2003 and Choi et al., 2006). The coseismic land-level change caused by 2004 tsunamigenic Sumatra–Andaman earthquake was dramatic: it resulted into subsidence and uplift at several locations along the coasts of Andaman and Nicobar Islands (Malik and Murty, 2005). The Port Blair (east coast) subsidence by ~1m, whereas, the west coastline by ~0.5m (Malik and Murty, 2005). It has been reported that southern islands likewise Great Nicobar subsided by ~3m and Car Nicobar by ~2.0m (Malik and Murty, 2005).

III. Methodology

This study incorporates the numerical modeling based on computational simulation of Non-linear Cartesian Shallow Wave equation, provides the wave height and travel time information of the tsunamigenic waves. However, every modeling needs to be validated to know its functionality and robustness. Therefore, to corroborate the modeling techniques, data of 2004 Sumatra-Andaman earthquake is used. December 26th, 2004 earthquake is the most recent catastrophic event in the Indian Ocean. Due to its severity it has been very keenly recorded and extensively studied.

In this study Nami-Dance software used to carry out the Numerical Modeling. Nami Dance is a computational tool developed by Andrey Zaytsev, Ahmet Yalciner, Anton Chernov, Efim Pelinovsky and Andrey Kurkin which is basically used for tsunami modeling. This software provides direct simulation and efficient visualization of tsunamis for assessment, understanding and investigation of tsunami generation and propagation mechanisms. Nami-Dance software used for the generation of model which is a computational tool based on the C++ programming. This software generate the tsunami model in real time by means of implementing the solution of a non-linear form of the long wave equations. There are several solutions of long wave equations for tsunamis. In general the explicit numerical solutions of Nonlinear Shallow Water (NSW) equations is preferable for the use since it uses reasonable computer time and the memory. Overall it gives the results in acceptable error limit. Nami-Dance software uses finite difference computational method to solve both linear and nonlinear forms of depth-averaged shallow water equations associated with the long wave problems. Tsunami propagation in a uniform flat bathymetry with a Gaussian hump as an initial free surface profile similar to was used to be simulate in the Nami-Dance software (Yoon et al. 2007).

Since the vertical motion of water particles has a negligible effects on the present distribution, so it's not considered in the theory of long waves. Using the necessary dynamic and kinematic conditions and including the bottom friction terms, the fundamental equations of Nami-Dance, which are given Equation are obtained and these equations are discretized by following the staggered leapfrog scheme.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M\sqrt{M^2 + N^2} = 0 \qquad (2)$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}} N\sqrt{M^2 + N^2} = 0 \qquad (3)$$

$\mathrm{M} = \mathrm{u}\,(\mathrm{h} + \eta) = \mathrm{uD}(4)$

$\mathrm{N} = \mathrm{v}\,(\mathrm{h} + \eta) = \mathrm{vD}(5)$

Where x and y are the horizontal axes, t is time, h is undisturbed flow depth, η is the vertical displacement above the undisturbed water surface, M and N are the discharge fluxes in x and y directions respectively, u and v are the particle velocities in x and y directions respectively, n is the Manning's roughness coefficient, g is the acceleration due to gravity and D is the total water depth given by h+ η. The last terms correspond to bottom friction and expressed as $\boldsymbol{\tau_x}$ and $\boldsymbol{\tau_y}$ in the x and y directions respectively.

$$\frac{\tau_x}{\rho} = \frac{1}{2g}\frac{f}{D^2} M \sqrt{M^2 + N^2} \quad (6)$$

$$\frac{\tau_y}{\rho} = \frac{1}{2g}\frac{f}{D^2} N \sqrt{M^2 + N^2} \quad (7)$$

To simulate the 2004 tsunami we divided whole rupture length into five segments (A1-A5) as shown in the following Table. The bathymetry data was downloaded from GEBCO, which comes from the database of British Oceanography Data Centre, and the topography data is the SRTM that is incorporated from USGS earth explorer. The GEBCO data is of 1 arc minute and SRTM data is of 30 arc second resolution global topography. Both of the datasets are then merged with the help of Global Mapper v15.0. This simulation generated series of outputs. Initially, source file was generated from every rupture parameters and bathymetry-topography datasets. These source files are the initial wave generated during earthquake, and these were used for tsunami simulation along with the gauge points along the coast of Mainland India, Andaman and Nicobar Islands, Myanmar and Indonesia. However, the outputs we were concerned were the wave heights, directivity and time charts for each rupture.

Table 1: Fault parameters used for Tsunami Simulation for 2004 Tsunami

Moment Magnitude	9.3				
Fault Segment	A1	A2	A3	A4	A5
Longitude	95.10E	93.90E	93.41E	92.10E	92.00E
Latitude	2.50N	4.33E	5.80N	9.10N	10.50N
Fault Length	220	150	390	150	350
Fault Width	150	150	150	95	95
Focal Depth	30	30	30	30	30
Dip Angle	12	12	12	12	12
Strike Angle	323	348	338	356	10
Rake Angle	90	90	90	90	90
Displacement	18	23	12	12	12

IV. Result and Discussion

Validation of 2004 tsunami was carried out by regenerating the conditions having rupture fault length of 1100 km and 150 km width, with a strike of 329˚, dip angle of 8˚, displacement 11 m and focal depth of 25 km as per data taken from Centroid Moment Tensor (CMT). This data is easily available and can downloaded for any date of earthquake *(http://www.globalcmt.org/CMTsearch.html)*.However, due to change in strike of Sumatra-Andaman trench, the rupture length of 1100 km was sub-divided into 5 segments (Table1). These parameters were used as an input along with the high-resolution bathymetry and topography data. The extracted values such as wave heights and travel time from the computation are in concurrence with the observed values from the altimetric satellite Jason-I and tide gauges at coastal and island stations (Singh et al., 2012).

Table 2: Run up height comparison between the obtained values and the observed values

Station location	Maximum wave height Observed (m)	Maximum wave height Computed (m)
Chennai	3.2	2.46
Kalpakkam	2.0	1.73
Kundakullam	0.40	0.59
Port Blair	3.5	3.2
Paradip	3.2	2.6
Visakhapatnam	2.9	2.37

Table 3: Travel-Time comparison between the obtained values and the observed values (Merrifield et al., 2005; Nagarajan et al., 2006)

Station location	Travel time Observed	Travel time Computed
Chennai	2 hr 34 min	1 hr 54 min
Kalpakkam	1 hr 34 min	1 hr 56 min
Kundakullam	3 hr 20min	3 hr 14 min
Port Blair	0 hr 15 min	0 hr 10 min
Paradip	2 hr 28 min	2 hr 4 min
Visakhapatnam	2 hr 36 min	1 hr 41 min

It depicts to somewhat the similar scenarios that existed during the 2004 tsunami at various coast of Indian subcontinent and Southeast Asia. The directivity and time chart results suggest the analogous energy propagation of tsunamigenic waves i.e., encompassing around the Indonesia, Thailand, Andaman and Nicobar, Sri Lanka and south-east Indian coast, as they were near the epicenter, causing severe destruction. We computed the maximum wave height of the tsunami waves 2.46 m at Chennai, while observed height was 3.2 m. Similarly at Visakhapatnam, our computed height is 2.37 m while observed one is 2.9 m. This clearly indicated that values that we computed are close enough to the values observed. At Chennai and Kundukullam, computed travel time is 120 minutes and 180 minutes, which is also got matched with the travel time observed at these locations. Tsunami waves hit the Port Blair in just 10 minutes with maximum height upto 3.2 m based on the computation data. Directivity map in Figure 1, shows that tsunami originated at Sumatra and moved in westward directions. Countries other than India, like Myanmar, Bangladesh and Thailand affected a lot as a result of impactful nature of tsunami waves.

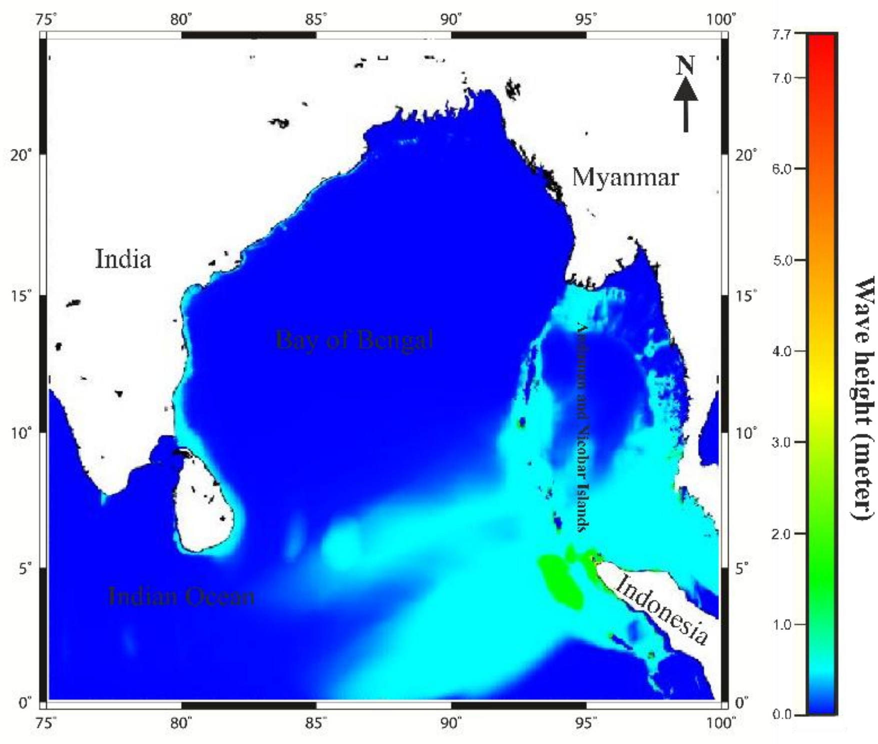

Figure 1: Directivity of the tsunami waves caused by the December 26th 2004, Indian Ocean Tsunami

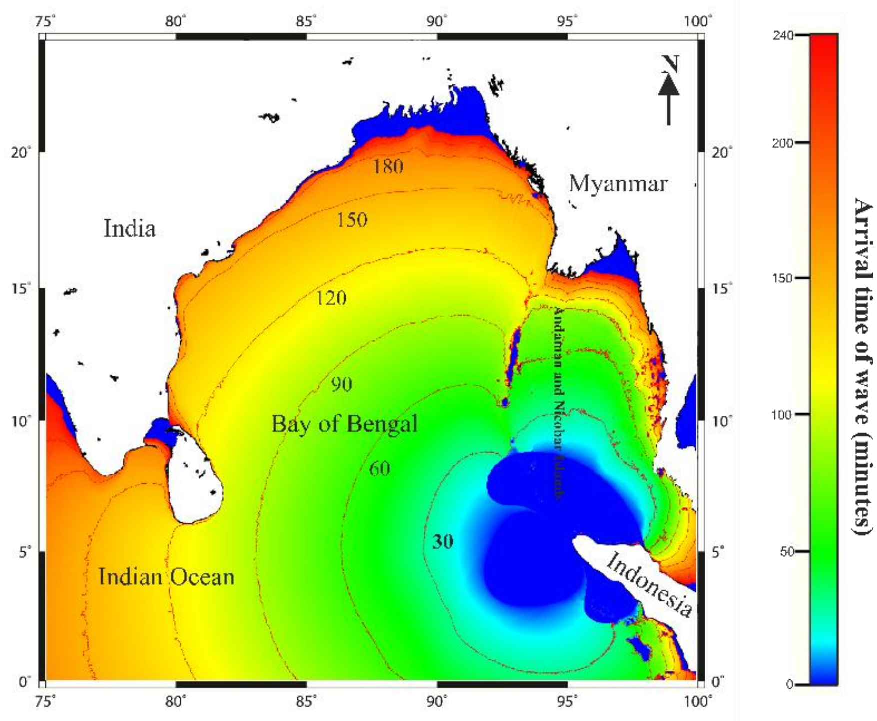

Figure 2: Time chart for arrival of first wave caused by the December 26th 2004, Indian Ocean Tsunami

V. Conclusion

Exponential growth in the Indian population and infrastructure development in the last few decade as well as extreme lack of understanding on hazards in seismically vulnerable areas has increased the level of risk of both life and the property. Hence, it has become very necessary to study and identify the hazard posed by natural processes, and to find the ways to mitigate these risks in the country. Of course, it is very difficult to accurately predict the timing of tsunami arrivals and their devastating nature even with installed monitoring systems. However, the modeling based present study on the tsunami simulation helped us to know about the tsunami wave height and tsunami directivity at Andaman Islands and along the east coast of Mainland India. Which further gives an idea about the energy of the tsunami waves on shoreline of southeastern coast of Mainland India. Through these studies we analysed the impact and the nature of tsunamigenic waves in terms of wave height and directivity of the wave near coastal areas. Tsunami height observed along the south eastern coast of Mainland India ranges between 2 to 3 m for 2004 tsunami. If a transoceanic tsunami occurs in Indian Ocean having epicenter near Andaman Island, it will cause major devastation of south eastern coast of Mainland India. This study will help in formulation and design of mitigation measures with the early warning systems, which may eventually lead to less loss of life and damages to the property.

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