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Numerical modelling of tsunami wave to assess the possible impacts along western coasts of India

BABITA DANI, VAIBHAVA SRIVASTAVA, A. P. SINGH[#] and R. BHATLA[!,*@]

Department of Geology, Institute of Science, Banaras Hindu University, Varanasi, India

[#]*National Centre for Seismology, Ministry of Earth Sciences (MoES), New Delhi – 110 003, India*

[!]*Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India*

[*]*DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India*

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[@]e mail : rbhatla@bhu.ac.in

सार — **सुनामी** TUNAMIN2 **कोड का उपयोग करके भारत के पश्चिमी तटों के लिए सुनामी लहरों का संख्यात्मक मॉडलिंग तैयार किया गया है। इस अध्ययन में, पूर्व प्रकाशित साहित्य से भ्रंश प्राचलों पर विचार किया गया है। बाथमीट्री डेटा और सुनामी बनने के संभावित स्थान** ETOPO2 (**ग्लोबल रिलीफ मॉडल**) **और महासागरों के सामान्य बाथमीट्रिक चार्ट** (GEBCO) **उपग्रह डेटा से प्राप्त किए गए हैं। सुनामी के आगे बढ़ने के लिए भूमि स्थलाकृति डेटा शटल रेडार टोपोग्राफिक मिशन** (SRTM) **का उपयोग किया जाता है। वर्तमान अनुकरण में** 6 **घंटे** (360 **मिनट**) **का समय लगता है। विभिन्न स्थानों पर आयाम के साथ संभावित आगमन समय का अनुमान लगाया गया है। इस शोध पत्र में अलग-अलग परिदृश्यों के रूप में झुकाव और स्ट्राइक कोणों को बदलकर भारत के पश्चिमी तटों की ओर उत्पन्न सुनामी तरंगों की दिशा में परिवर्तनों का भी विश्लेषण किया गया है। गुजरात तट के विभिन्न हिस्सों में समय श्रृंखला और ऊंचाई तथा सुनामी तरंगों के प्रति घंटा यात्रा-समय चार्ट पर भी चर्चा की गई है। भूकंप और प्रारंभिक सुनामी तरंग उत्पन्न होने के बाद, यह कच्छ की खाड़ी** (**गुजरात**) **के सभी स्थानों पर लगभग** 2 **घंटे से** 5.30 **घंटे में** 1 **से** 2.5 **मीटर के आयाम के साथ, मुंबई में लगभग** 4.45 **घंटे में** 2 **मीटर के आयाम के साथ, गोवा में लगभग** 3.08 **घंटे में** 1 **मीटर आयाम के साथ, कारवार** (**कर्नाटक**) **में लगभग** 3.12 **घंटे में और मैंगलोर में लगभग** 3.36 **घंटे में प्रत्येक का आयाम** 1 **मीटर के साथ पहुंच गया। मकरान सबडक्शन जोन** (MSZ) **के साथ** 1945 **के सुनामी युक्त भूकंप के अनुमानित सुनामी चरणों की प्रामाणिकता की उपलब्ध रिपोर्टों और प्रकाशित साहित्य से पुष्टि की जाती है।**

ABSTRACT. Numerical modelling of tsunami waves has been made for the western coasts of India using TUNAMIN2 code. In this study, the fault parameters are considered from earlier published literatures. Bathymetry data and possible tsunami generation locations have been obtained from the ETOPO2 (Global Relief Model) and General Bathymetric Chart of the Oceans (GEBCO) satellite data. For tsunami run-up the land topography data Shuttle Radar Topographic Mission (SRTM) is used. The present simulation consists of a duration of 6 hours (360 min). Possible arrival times with amplitude at various locations have been estimated. The paper also analyses the changes in the directivity of the generated tsunami waves towards the western coasts of India by changing the dip and strike angles as different scenarios. Time series and height along the different parts of Gujarat coast and hourly travel-time chart of the tsunami waves are also discussed. After the earthquake and initial tsunami wave generation, it reached all the locations along the Gulf of Kachchh (Gujarat) in nearly 2 hrs to 5.30 hrs with amplitudes from 1 to 2.5 m, Mumbai in around 4.45 hrs with amplitude of 2 m, Goa in around 3.08 hrs with amplitude 1 m, Karwar (Karnataka) in around 3.12 hrs and Mangalore in around 3.36 hrs with amplitudes 1 m each. The authenticity of the estimated tsunami phases of the 1945 tsunami genic earthquake along the Makran Subduction Zone (MSZ) are corroborated with the available reports and published literatures.

Key words – Tsunami Modelling, MSZ, Tsunami travel time, Wave heights, Run-up, Western coasts of India.

1. Introduction

Tsunamis are known for the most devastating natural hazard to the coastal environment ever. Highly populated areas near coastal lengths are the main source of economic support, helping trade and business. They are also at a high risk of getting affected by these natural hazards, *viz*., sea-level rise, tsunamis, cyclones and inland inundation etc. Thus, affecting directly or indirectly the trade, export-import business and the coastal environment. Bernard (2016) believed that about 85% of all tsunamis are generated by an earthquake. Tsunami waves generated because of earthquakes under the water and other causes, can have hazardous impacts on the environments of coastal belts. The effects of a tsunami on a coastline could be devastating most of the time (Patel *et al*., 2016). Recent tsunamis in the Pacific and the Indian Ocean have proven the vulnerability of coastal areas to such extreme events. Few literatures also support the fact that destructive tsunamis could occur in the Indian Ocean in the future also (Jordan, 2008; Rastogi, 2006). Along the eastern coast of India, some deadliest tsunamis have been recorded as on 26 December, 2004, which devastated the groundwater regime on many islands of Andaman and Nicobar and the Indian mainland (Singh, 2008). This tsunami generated was due to an earthquake of magnitude 9.3 with larger impacts in Sri Lanka, Thailand, India, Somalia and other nations (Narayan *et al*., 2005; Singh *et al*., 2012). After the earthquake of 26 June, 1941, the strongest ever recorded earthquake is the 26 December, 2004, in the Andaman and Nicobar Islands, which generated a destructive tsunami. Two other earthquakes on 23 August, 1936 (7.3 Mw) and 17 May, 1955 (7.25 Mw), could not produce any significant tsunami (Murty *et al*., 1999). Warek (2013) worked on a tsunami generation, propagation and inundation hydrodynamic computational model (TUNAMI N2) by using 8 earthquake scenarios along the New Britain Trench and Ramu-Markham fault zone in the south-eastern region of Papua New Guinea. Bhaskaran *et al*. (2005) described that the countries in the vicinity of the East Indian Ocean faced the most dreadful tsunami in reported history. They suggest that modern-day technology could avoid or aid in minimizing the loss of life and property. Pararas-Carayannis (2005) studied earthquakes from 1900 to 1980, a total of 348 events were documented in the areas surrounded by 7.0 N to 22.0 N and 88.0 E to 100 E. The earthquake magnitudes were in the range from 3.3 to 8.5, but only five of them had magnitudes around 7.1 and produced tsunamis (Bapat, 1982) Bhaskaran *et al*. (2005) studied the past records of tsunamis which says that most of the damaging tsunamis in the world are generated by earthquakes during the last 55 years: some of the most devastating are (*i*) 1952 - Kamchatka Peninsula: 18-19 meters high (more than 2000 deaths); (*ii*) 1960 - Chile: 25 meters high (more than 500 deaths) and (*iii*) 1964- Alaska: 67 meters (more than 100 deaths reported). We have also witnessed many more of these types of catastrophic natural hazards in the past, such as the 27th November 1945 Makran earthquake (Mw 8.1) and tsunami; Papua New Guinea, 1998 (Mw 7.8); 2004 Indian Ocean Tsunami - a mega thrust event (Mw 9.1-9.3) and the Japan Tsunami, 2011 (Mw 9.1) which is also a mega thrust event. These deadliest tsunami events (specially the December 2004 Andaman earthquake and tsunami) have compelled scientists all over the world to think seriously and have started doing research in the field of tsunami modelling. With the help of modeling, tsunami wave propagation, its travel time, inundation and run-up could be analyzed for past and future tsunamis also. The past and recent literature reviews also suggest the same and many have been reported in the form of research works. Some of them are discussed below.

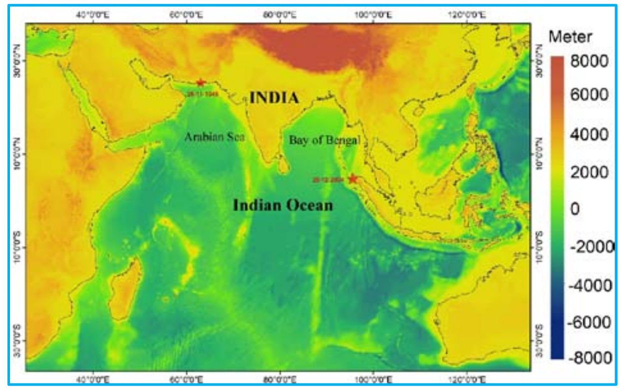


Fig. 1. Tsunamigenic sources in western and eastern coast (Makran Subduction Zone (MSZ) and Andaman-Sumatra Subduction Zone (ASSZ) respectively)

For India, there are two tsunami genic sources (Earthquake) namely the Makran Subduction Zone (MSZ) in the Arabian Sea and the Andaman-Sumatra Sub-duction Zone (ASSZ) in the Eastern Indian Ocean (represented in Fig. 1). It is obvious that the east coast of India is impacted by the tsunami generated along ASSZ and west coast from MSZ in the past and recent years, as stated in the literature review also. The west coast of India is badly impacted by a tsunami genic earthquake along the MSZ. On 27th of November 1945, a tsunami occurred by an earthquake (8.1 Mw) in the MSZ, which is one of the extremely devastating tsunamis in the Arabian Sea (Patel *et al*., 2016). One more earthquake (7.7 Mw) along the southern Pakistan on 24th September, 2013 generated a tsunami of a height of 1m which remained unnoticed as it occurred at low tide (Hoffmann *et al*., 2014). Hoffmann et al., 2013, in their study divided the MSZ into two segments (eastern and western), which has variation in seismicity. This variation in seismicity has also been mentioned by Rashidi *et al*., 2020 that the eastern Makran is an active seismic zone, as evident from the recorded tsunamis in 1945 (8.1 Mw) and 2013 (7.7 Mw). These two segments of the MSZ can generate earthquakes that can produce tsunamis affecting the west coast of India. The seismicity of the Makran region is comparably low as in the neighboring regions, which have been devastated frequently by large earthquakes (Quittmeyer and Jacob, 1979). Some parts of the Makran region are unruptured for a long period and could generate large earthquakes in the near future. Tectonic setting of MSZ, past records of earthquakes and tsunamis in the region and a recent event (September, 2013) shows that the tectonic activity is occurring. In the eastern segment of the MSZ, large earthquakes occur infrequently. Rashidi *et al*., 2020 reviewed and revaluated recent activities on the deterministic and probabilistic tsunami hazards in the MSZ. Heidarzadeh *et al*., 2008 has also studied tsunami hazard in the MSZ by employing numerical modeling. They evaluated the hazard by simulating five scenarios based on historical records. The results show a runup of 12-15 m on land. The study also reveals that the MSZ can generate a massive tsunami with considerable heights at locations far from the epicenter. Therefore, the more recent earthquake of 28 November, 1945 is an example which teaches us a lesson that this subduction zone could produce large destructive earthquakes in the near future also (Mokhtari and Farahbod, 2005; Pararas-Carayannis, 2005, 2006). Tsunamis generated through MSZ could travel into the Arabian sea and would cause destruction along the west coast of India and the Lakshadweep Islands. The wave height is around 11.5 m that struck the Kutch region of Gujarat, along the west coast of India, which was reported over estimated. This tsunami was also responsible for massive loss of life and devastation along the coasts of Pakistan, Iran and Oman. Its waves destroyed many villages and caused damage to port facilities. (Jaiswal *et al*., 2009; Shahid, 2005). By using a numerical model, Neetu *et al*., 2011, analyzed the reasons why the high waves persisted for so long along the coastlines. The reason behind that is the trapping of tsunami energy along the shorelines (with ~300 km stretches of continental shelf). Murty *et al*., 2022, also studied the 2004 Indian Ocean tsunami case and computed wave heights and associated coastal inundation patterns using a finite-element-based Advanced CIRCulation (ADCIRC) model (widely used for the simulation of storm surges). Simulation results match well with the available real-time recorded data. ADCIRC could be efficiently used for near real-time predictions because of its computational efficiency and accuracy. They suggested that the topographic studies on tsunami genic shelves make the preparedness measures more effective. Lodhi *et al*., 2021, estimated the extent of run up and inundation at Gwadar, Pasni and Ormara by collecting information from eyewitnesses and newsletters. The most affected cities were Pasni and Ormara because of the 1945 Makran earthquake and tsunami. They reported different arrival times of waves suggesting the tsunami arrived due to earthquake and underwater landslides both. The coast of Gujarat has also been prone to many disasters in the past. It alone has a long coastline of about 1600 km and has massive capital and infrastructure investments in its coastal regions which are at stake. Hence, massive destruction and loss of life has occurred here. The tsunami reached near Mumbai at Bombay Harbor, Versova (Andheri), Haji Ali (Mahalaxmi), Juhu (Ville Parle) and Danda (Khar). Around fifteen people died at Versova (Andheri, Mumbai), Haji Ali (Mahalaxmi, Mumbai), Danda and Juhu (Patel *et al*., 2016). These observations are useful in understanding that western coastal areas of India are highly vulnerable to these catastrophic natural hazards which may have severe impacts on coastal environments in the future also. Since, few studies have been done on modelling of tsunami waves and environmental impacts thereof, the present study deals with the modelling of tsunami wave amplitude, height along some locations, its travel time, inundation and run-up into the land and to study possible impacts on the coastal environment. This has been made for some of the locations along western coastal areas of India from the possible tsunami genic source using TUNAMI-N2 code.

2. Data and methodology

Data have been collected through published literature for input in modeling. The data includes the location of the fault plane, slip magnitude, fault length and width, strike, dip, rake and depth. Then maximum possible assumptions have been made to see the worst scenario of the tsunami and its impact. Bathymetry data and possible tsunami generation locations have been obtained from the ETOPO2 and GEBCO satellite data. For tsunami run-up and amplitudes, the land topography data was taken from Shuttle Radar Topographic Mission (SRTM). Bathymetry data is converted into grid files using SURFER as the first step. The fault parameters (represented in Table 1) considered are latitude (25.204° N), longitude (63.420° E), depth (10 km), strike (250°), rake (90°), dip (15°), slip (10 m) and length (200 km) and width (100 km) of fault. We have also generated different scenarios for the same location with varying strike and dip angles, which would be helpful to understand the severe impact along some of the western coasts of India. The present study is based on “Tsunami Numerical Simulation with the Staggered Leap Frog Scheme” of Dr. Fumihiko Imamura, Prof. of Tsunami Engineering (Tohoku University) prepared in June 1995 for the TIME project. Tsunami wave numerical modelling is done to understand tsunami cases that have already occurred in the past and can also be useful in predicting the effects of any future tsunami. Basic numerical modelling has been done using TUNAMI N2. It is a numerical model (numerical code), which can efficiently simulate the propagation of tsunami waves. It uses a fixed computational grid (computational domain should include the origin of the tsunami and the area of study), involves a wave friction factor and lets the wave reach towards the initial coastline. Maximum wave

TABLE 1

Fault parameters used for modelling of tsunami wave (Makran Source)

Longitude	63.4200 E
Latitude	25.2040 N
Depth (km)	10
Strike	2500
Rake	900
Dip	150
Slip (m)	10
Length (km)	200
Width (km)	100

height predicts its maximum run-up inland along the coastlines. The model includes a main module and three sub-modules, namely bathymetry, fault and stability. The bathymetry sub module stores all the coordinate data of the entire computational domain. 'Fault module' generates the initial wave. The stability sub-module check the stability of the prepared grids and the 'Main module' computes the propagation of the tsunami wave. This model provides fine grid data which is especially important while dealing with the run-up and inundation characteristics of a coastal area. Hence, this model has been chosen to simulate the propagation, directivity, travel times and amplitude of the tsunami along the western coasts of India under the present study. Besides that, TUNAMI N2 is more widely and globally accepted for simulation of tsunami. Modeling of tsunami wave generation, its propagation and travel times and runup in the form of directivity of tsunami waves has been made for some of the western coastal areas of India from the possible Tsunami genic source (Makran Subduction Zone) using TUNAMI-N2 code. For that, it needs the initial wave due to the fault as well as the prepared grid and coastal/land topography data. The basic steps of the program can be seen from the flowchart given below (*Source*: Imamura *et al.*, 2006).

Input
(Dimension parameters)
↓
Input
(Spatial grid size and time step)
↓
Input (gauges file)
Gauge.dat (Coordinates of the gauges)
↓
Input fault data (initial wave)

Output file of faultwave.f (fault*.grd)
↓
Input (outsec and tend)
(Time interval for output and Total time of simulation)
↓
Input (bathymetry file)
(bathymetry.grd file in ASCII format)
↓
Conservation of mass
(NLMASS subroutine)
↓
Conservation of momentum
(NLMMT subroutine)
↓
Check of area for computation
↓
Time > Total time — No (return to Conservation of mass)
↓Yes
OUTPUT
(Point, Propagation, Runup, Total output)

A programme made for run up height and time of arrival of the tsunami in the MATLAB environment and various tsunami phases map such as tsunami wave generation at time t = 0, travel time, directivity of tsunami waves, amplitude of tsunami waves at few locations and different scenarios with varying strike and dip angles were made and represented in the results section and are discussed in detail.

3. Results and discussion

After setting the tsunami model grid using ocean bathymetry and land topography, calibration of the tsunami source is done in the simulation procedure. The first stage in the modelling of tsunami waves is the calculation of the initial deformation of the sea floor due to an earthquake. Here from the Makran coast of Pakistan, initial (t = 0) tsunami generation map is shown in Fig. 2. Once the tsunami source (initial condition) is known, the generation, propagation, directivity, travel times and amplitudes of tsunami waves can be modelled by numerical simulation. Then, the initial wave at t = 0 for simulation has been computed by the fault parameters for modelling at individual locations and 6 scenarios (tabulated in Table 2) have been created which is assumed to have different fault parameters. For evaluation of the impact of tsunami along the Western coasts of India, numerical simulation was made for each source with varying possible range of strike and dip angles, while

TABLE 2

Different scenarios with varying strike and dip angles

Scenario	Lat.	Long.	Depth (km)	Strike	Rake	Dip	Slip (m)	Length (km)	Width (km)
a	25.204°N	63.420°E	10	270°	90°	5°	15	200	100
b	25.204°N	63.420°E	10	260°	90°	15°	15	200	100
c	25.204°N	63.420°E	10	280°	90°	15°	15	200	100
d	25.204°N	63.420°E	10	280°	90°	10°	15	200	100
e	25.204°N	63.420°E	10	270°	90°	10°	15	200	100
f	25.204°N	63.420°E	10	270°	90°	5°	15	200	100

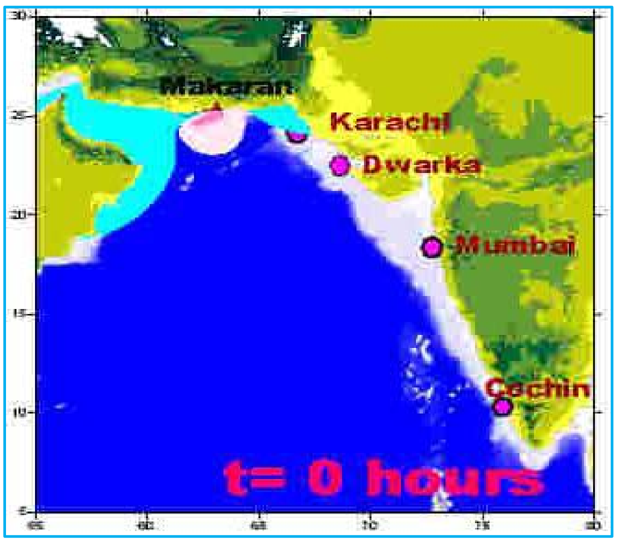
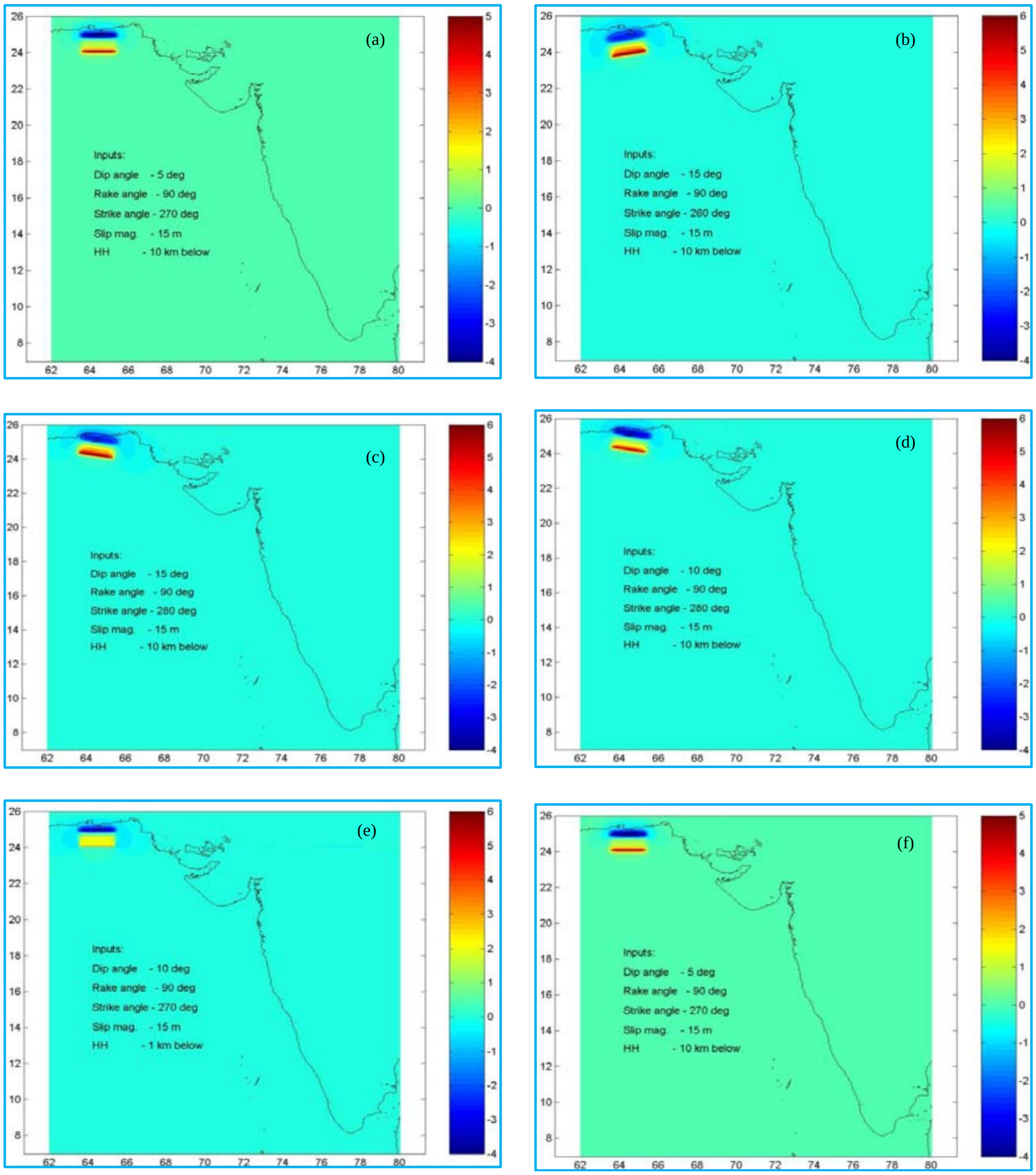


Fig. 2. Initial tsunami wave generation at time t=0

other parameters, such as latitude and longitude of fault; length and width of the fault; rake angles; and depth, were kept constant as shown in Figs. 3 (a-f) and in Table 2. Deformation of the seafloor due to earthquakes creates initial disturbance of the ocean's surface. The initial tsunami wave elevation and depression for all the 6 scenarios are modelled and these are shown in Figs. 3 (a-f). Both the positive and negative amplitudes of the initial wave are nearly same for all the 6 scenarios. It is the first most important step in the modelling of tsunami wave, its generation, propagation, directivity and then runup and inundation on the land (Singh *et al*., 2012). A large volume of water will be assumed to be displaced and eventually generate a large tsunami because of an earthquake occurring (at a shallow subduction zone) or an earthquake having a larger vertical angle of deformation. Initial deformations using varied strike and dip angles have been made, keeping all other fault parameters constant. In Figs. 3 (a-f) different scenarios have been generated to see the impacts with varying possible ranges of strike and dip angles, while other parameters such as latitude and longitude of fault; length and width of the fault; rake angles; and depth, were kept constant. After knowing the tsunami source, the modelling of the propagation of the tsunami waves can be done. The model results depict that the tsunami energy dissipates to varying degrees towards the western coasts of India. The scenario 2, *i.e*., Fig. 3 (b) directs the tsunami waves towards the western coastline of India directly (Jaiswal *et al*., 2009). The strike angle is 260° and the dip angle is 15° with other constant parameters have been used to generate the initial tsunami wave generation with directivity towards western coast.

Figs. 4 and 6 shows that the 1945 Makran event affected the entire western coast of India including Gujarat, Maharashtra, Goa, Karnataka and Mangalore considered in the present study. The directivity of tsunami waves is a crucial information while dealing with hazard reduction. It is affected mainly by the tsunami genic source characteristics. These characteristics include directivity of tsunami waves due to the alignment of source fault (Kajiura, 1970; Ben-Menahem and Rosenman, 1972) and parameters such as dip and strike angle or slip amount.

The role of bottom friction is also an important asset in this regard; over 3-km deep ridge, elevation is insignificant; hence, the waves can travel a large distance without losing their energy. The directivity maps are presented in Fig. 4. Due to this effect (according to the theory of directivity), maximum energy propagates into the Indian Ocean and some of it affects the western coast of India. As it can be observed from the figure that the source parameters used here to simulate tsunami can generate waves with maximum directivity towards the western Indian coasts.



Figs. 3(a-f). Different scenarios of tsunami wave generation with varying strike and dip angle

This could result in large destruction along the entire western coasts, which are utmost important source of economic assets for India. Few coasts, such as Mandvi, Mundra, Kandla, Lakhpat, Jakhau, Okha, Navlakhi, Dwarka of Gujarat and Mumbai, Goa are the important business ports of India upon which much of the economy rely. Since, most of the ports are situated along these coastal belts from where export-import business is done, these are at a high risk of impacts from tsunami. Therefore, it is also clear from the tsunami wave amplitude and time taken by the tsunami waves to reach the coasts (Figs. 4 & 6 and Table 3) can have a high capability of affecting the entire western coasts of India with serious impacts.

The Figs. 5 (a-d) depicts the water levels (in meters) at different selected locations bordering the western Indian coastline with respect to time. A total of 6 hrs simulations have been done for all the locations to see the water levels and the impacts thereof. The tsunami heights over different locations of Gujarat (India) with respect to time is considered in the present study. The water elevations

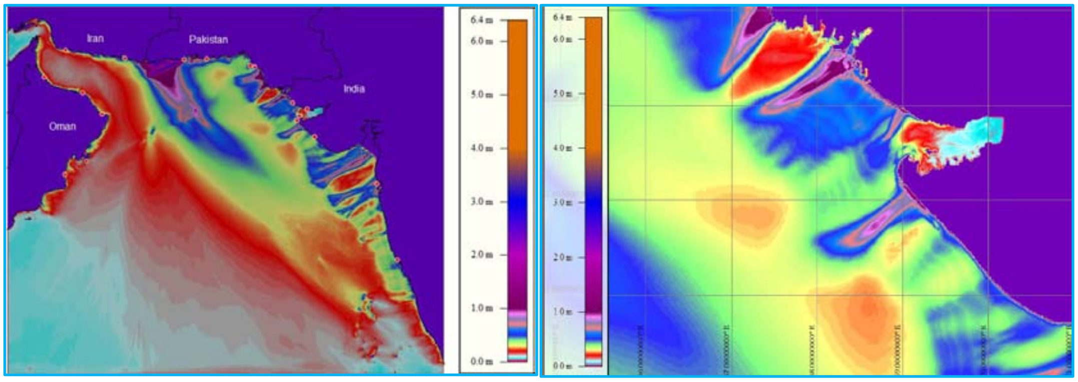
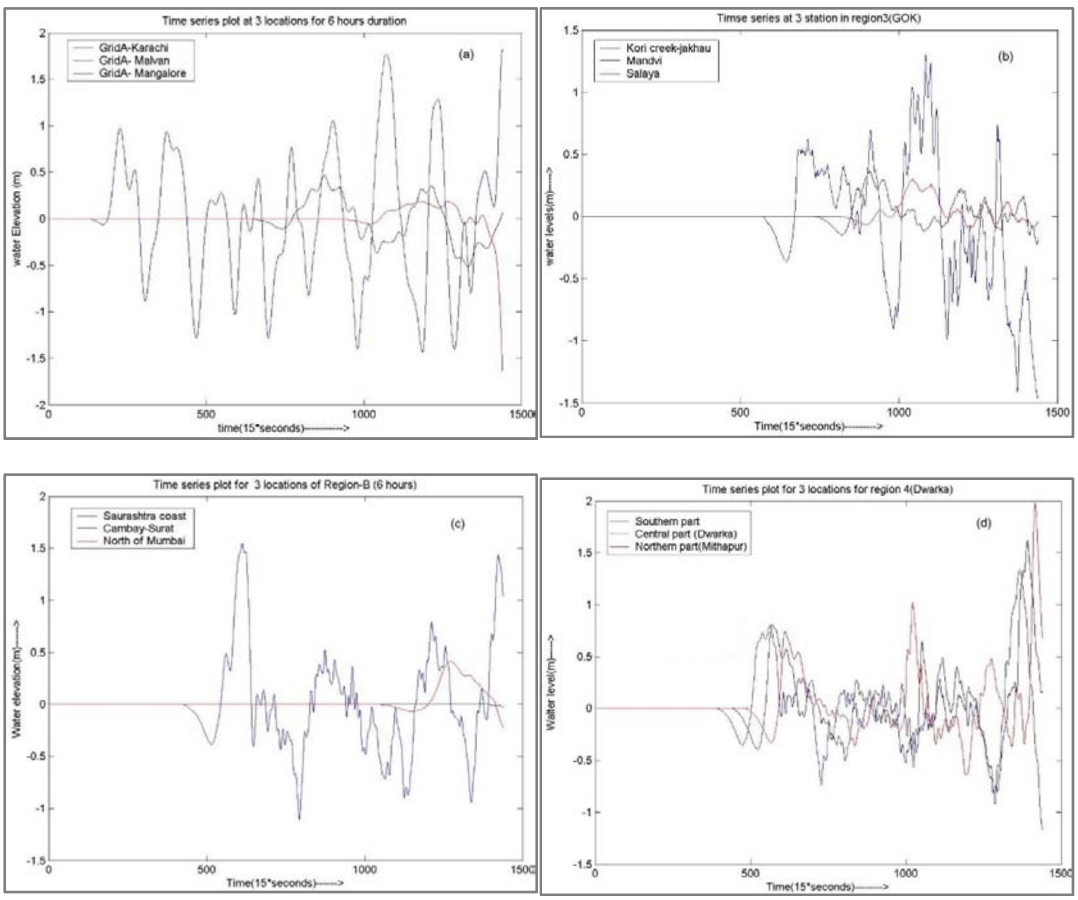


Fig. 4. Directivity map for M8 in the central part of the Makran earthquake, Strike of 250 degrees of the fault directed the tsunami towards western India



Figs. 5(a-d). Time series plot with water levels (heights) along different locations in Gujarat

represent the height of waves on the offshore areas (at respective locations). Fig. 5 (a) shows the water elevations at 3 locations (Karachi, Malvan and Mangalore) with respect to time within the initial disturbance domain (grid-A). Here, waves have higher amplitudes and heights along Karachi. The waves reached Karachi (Pakistan) in around 2 hrs after the initial deformation with water elevation (~1 m). It may rise in height up to 2 m in 6 hrs, which can be devastating. Literature also shows that the waves destroyed many villages and caused large scale destruction to the port facilities. Around 4,000 people died because of the earthquake and tsunami together (Shahid, 2005, Jaiswal *et al*., 2009). At Malvan (Maharashtra) and Mangalore, the waves reached a level of about 1 m each from the mean sea level in nearly 3 and 4 hrs, respectively. The water level rises abruptly, initially with

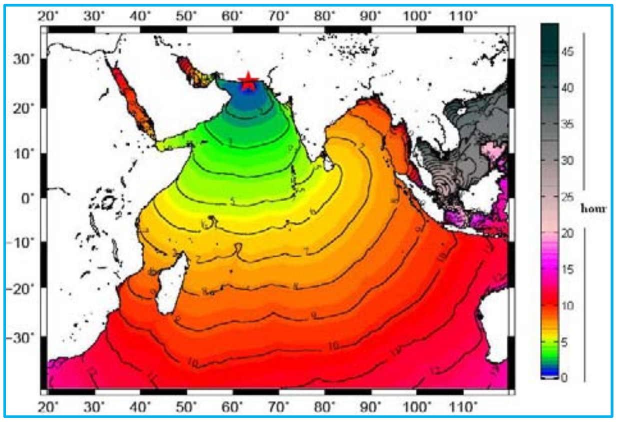


Fig. 6. Hourly travel-time chart of the tsunami wave that resulted from the Makran Earthquake

more height at the nearest location (*i.e*., at Karachi) to the epicentre and then to the distant place. More damage would be expected near Karachi and Malvan and fewer in the Mangalore. Moreover, it can be stated that emergency warnings can be generated to evacuate (for acquiring minimal loss) for the location far from the epicentre. Coming to Fig. 5 (b), it depicts the water elevations at another 3 locations (grid-C) in the Gulf of Kachchh (GOK) region (Kori creek-Jakhau, Mandvi and Salaya) with increasing time. Here, waves have higher amplitudes and heights along Kori creek-Jakhau, which is closer to the epicentre as compared to the other two. Also, Jakhau (is a populated port) is situated at the creeks in the GOK so the waves got trapped in it causing fatalities and damage. As the water elevates up to a level of around 0.8 meters in nearly 2.5 hrs when the first wave reaches land. It may rise in height up to 2.5 m in about 3 hrs, which can be more devastating. It can be seen from the figure that the waves reached Mandvi (is a very important business port in Gujarat with a high population) in around 3 hrs after the initial deformation with water elevation (~0.7 m) and may cause serious destruction. At Salaya, the waves reached a level of about 1.2 m from the mean sea level in around 3 hrs. More damage would be expected in the coastal areas near Jakhau and Mandvi (both holds economic importance for Gujarat). If more damage (in terms of life and financial) occurs, it will take more time to recover from the impact of the tsunami.

Fig. 5(c) shows the rise in wave heights at 3 locations (Saurashtra coast, Cambay-Surat and North of Mumbai) with respect to time within grid-B. The waves reached Gujarat and North of Mumbai in around 2 and 4 hrs after the arrival of the first wave with water elevations of up to 1.5 to 2 m (inland) respectively. Less or fewer damage may occur at Surat as the waves arrive here after 3 hrs with a low height of water (~1 m). More damage would be expected near Saurashtra coast and Mumbai. Mumbai is the business capital of India and has massive capital and infrastructural investments and is highly populated. This could be a reason that an immediate evacuation is not an option and losses would be maximum. Emergency preparedness and mitigation plans are required for these types of places where immediate evacuation or relocation is next to impossible. At Dwarka (GOK, Gujarat) 3 locations (grid-D) were selected for the study and are shown in Fig. 5 (d). These locations are the Southern part, Central part (Dwarka) and the Northern part (Mithapur). The figure explains the high fluctuations in water heights along all the three locations. Here, waves have higher amplitudes and heights along all the locations. The first wave reached nearly in 1.5 to 2 hrs at all places with higher wave amplitude and heights. Water elevations at these locations are around 1-1.5 m each when the first wave arrives. Also, Dwarka at the coastline along GOK facing Arabian Sea so the waves directly hit the coast and would cause maximum fatalities and destruction. The waves may rise in height up to 2 m in about 2 hrs, which could be more devastating. More damage would be expected in the selected areas in Dwarka (holding economic importance as it has a tourism business) which cannot be recovered immediately after loss.

The hourly travel time chart of the tsunami wave is shown in Fig. 6, depicting travel times in hours (contour intervals are of one hour) and this travel time chart is constructed for the first wave which has arisen due to the initial deformation. Better understanding of the first wave (travel time) provides supplementary time to evacuate people in case of an emergency. Results depicts that the tsunami waves reached near the coastal areas of Gujarat in nearly 2 hours 45 minutes to 5 hours 30 minutes after the earthquake and to Mumbai (4.45 hrs), Goa (3.08 hrs), Karwar (Karnataka) and Mangalore (3.36 hrs) in nearly 3 hours to 4 hours 45 minutes. So, the highly vulnerable coastal areas need to be provided with safety protection while planning for preparedness. The tsunami wave arrives at the western coast of India along the Gulf of Kachchh in around 2.45 to 5.30 hrs, Okha in about 2.35 hrs, Dwarka in around 2.10 hrs, Nava Bandar in around 3 hrs, Gulf of Khambhat in around 5.30 hrs, Mumbai in about 4.45 hrs, Goa in about 3.08 hrs, Karwar (Karnataka) in around 3.12 hrs and Mangalore in about 3.36 hrs. The distance from the epicentre to the Gujarat coast is less, but the arrival time of the first tsunami wave is nearly 2 to 5.30 hrs. This is because when the waves encounter the shore their energy dissipates and the waves slow down with an increase in wave height. Similarly, the arrival time of the first tsunami wave at Mumbai is more than Goa because the distance from the epicentre to Mumbai is less than Goa. It could be that Mumbai's offshore areas are shallower (that is why the amplitude is more than Goa, *i.e*., 2 meters given in Table 3) than Goa's

TABLE 3

Estimated possible arrival time with amplitude at various places

Place	Arrival Time (in hrs)	Amplitude (meter)
Lakhpat	2.45	1.2
Koteshwar	2.55	1.5
Jakhau	3.02	2.5
Mandvi	3.10	0.7
Mundra	3.20	2.0
Kandla	3.30	2.0
Okha	2.35	2.0
Salaya	3.05	1.2
Sikka	3.15	1.2
Bedi	4.02	1.5
Navlakhi	4.45	1.5
Dwarka	2.10	2.0
Veraval	2.52	1.0
Nava Bandar	3.02	1.2
Gulf of Khambhat	5.30	1.5
Suvali	5.30	0.4
Mumbai	4.45	2.0
Goa	3.08	1.0
Karwar (Karnataka)	3.12	1.0
Mangalore	3.36	1.0

and also due to the direction of tsunami wave propagation. Most of the energy (tsunami's) moves vertically to the strike angle of the fault and hence determines the directivity of the tsunami waves (Ben-Menahem and Rosenman, 1972; Jaiswal *et al.*, 2009; Singh *et al.*, 2012; Patel *et al.*, 2013, 2016). As a result of this effect, much of the energy propagates in the direction towards the western coast of India. It is seen that the simulated time of arrival of tsunami waves at all the locations around the coastal belts of Gujarat and Maharashtra, Goa, Karnataka and Mangalore match well with the existing data sources and literature reported.

The model results are as similar as the reported damage. Results tabulated in Table 3 shows maximum amplitude along all the coasts of Gujarat (maximum at Jakhau (2.5m); Mundra, Kandla, Okha and Dwarka (2m all); Koteshwar, Bedi, Gulf of Khambhat and Navlakhi (1.5m all) and Mumbai (2m). The outcome of the scenarios examined in the present study is that the patterns of far-field maximum amplitudes predicted by the simulations are like those observed in the 1945 Makran Earthquake. The waves at the shallower depth locations like Jakhau, Mundra, Kandla, Okha, Dwarka and Mumbai reach with more time and with more wave amplitude. Talking about the important ports of Gujarat (in Gulf of Kachchh), *viz*., Jakhau, Mandvi, Mundra, Kandla, Okha, Navlakhi and Dwarka are highly vulnerable to natural hazards like tsunami in this study. Because these ports have massive capital and infrastructure investments upon which a large population rely for their livelihood. This may be a high-risk factor that if any emergency condition arises due to tsunami, it is next to impossible to evacuate people and relocate port facilities (infrastructures) immediately. This is because the travel time of tsunami waves to arrive at the coasts (Gujarat and Mumbai specially) from the source (MSZ) is very less. As it can be seen from the Table 1 that the waves reached these ports in a very less time, *i.e.*, around 2 hrs at Dwarka to 4.45 hrs at Mumbai etc. Apart from the Infrastructure and capital investments the Gujarat state also has biodiversity rich places of importance, such as the Marine National Park and Sanctuary of Gulf ofKachchh, Banni grassland and Gir Forest National Park and Wildlife Sanctuary (Gulf of Khambhat). From these tourist sites also, Gujarat gains its economy, which will be at stake if a much larger tsunami occurs soon. The Gulf of Kachchh and Gulf of Khambhat are at very high risk of be severely impacted by any tsunami like conditions and financial losses will also being much higher (Jaiswal *et al*., 2009; Singh *et al*., 2008).

4. Conclusion

The run-up height of tsunami waves, arrival time (travel times), directivity and amplitude were studied along the western coasts of India. The effect of different fault parameters by varying strike and dip angles were also studied. The resultsof the model depict the heightening in amplitude in shallow water and especially near land and islands. Based on the tsunami simulation result, it can be concluded that tsunamis could reach along the western coasts ~2 hrs to 5.30 hrs after the initial tsunami wave generated with heights from 1 m upto 2.5 m along the MSZ. The most affected coasts of Gujarat are Jakhau, Mundra, Kandla, Okha and Dwarka. Here, the tsunami wave amplitudes are high, *i.e.*, 2 meters, with different arrival times varying from 2 hrs to 0330 hrs. Similarly, in Mumbai waves reached in 0445 hrs but the wave amplitude is only 2 meters. This states that the amplitude should increase inland due to shallower depth. The travel times and maximum heights are derived from the tsunami simulation in the present study. The depth of a tsunamigenic source can affect the height of tsunami waves and travel times of the tsunami waves. Also, the geomorphology of the coastal areas plays a crucial role in increasing the height of tsunami. It has been found that applying different strike and dip angle at the tsunami source location has resulted in the varying direction of wave propagation and with different heights of tsunami at the selected locations for the present study.

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