Effect of Murray ridge on the tsunami propagation from Makran subduction zone

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Summary

The aseismic Murray ridge (MR) is a continuation of the Owen fracture zone which marks the boundary between the Indian and Arabian plates. Due to large variation in morphology and structure within this NE–SW trending ridge in the Arabian Sea a large variation of the bathymetry from few hundred metres to about 4000 m is seen. Observed seismicity on the ridge system is predominantly strike-slip. Tsunamis generated in the Makran subduction zone (MSZ) will propagate through the MR system due to its proximity. As the tsunami speed depends on the depth of the ocean, bathymetry plays a vital role on tsunami propagation. In this paper, the effect of tsunami propagation through the MR system is carried out with the existing bathymetry and comparing the results by removing the bathymetry. To study this phenomenon the 1945 Makran tsunami and worst possible tsunamigenic earthquakes from eastern and western MSZ are considered. The directivity of tsunami propagation with the ridge system is seen to change after crossing the MR towards the southeast direction for tsunamis generated in the eastern MSZ. For tsunami generated in the western MSZ there is no change in its directivity and is almost same as without the ridge with propagation being towards the open sea. Hence the MR not only affects the amplitude of the tsunamis but also the directionality and the arrival times.

Key words: Tsunamis; Guided waves; Wave propagation; Indian Ocean.

1 INTRODUCTION

The deadliest tsunamigenic earthquake prior to 2004 December 26 in Indian Ocean is the earthquake of 1945 November 27 along the Makran subduction zone (MSZ). This region is seismically active and has had several historical tsunamigenic earthquakes (Quittmeyer & Jacob 1979; Murty & Rafiq 1991; Heidarzadeh et al. 2008). It has resulted from the convergence between the Eurasian and Arabian plates in the Northern Arabian Sea with nearly E–W trend from the Strait of Hormoz to near Karachi in Pakistan. Complex tectonic areas form the boundaries for MSZ. The most conspicuous feature is the division of the MSZ into two segments, namely the eastern and the western segments by the Sistan Suture zone (Minshull et al. 1992). Seismological studies by Byrne et al. (1992) showed that the eastern Makran had experienced large thrust earthquakes and continue to experience small to moderate size thrust earthquakes whilst the western Makran has no established historical records of any large earthquake nor the modern instrumentation has recorded any great earthquake from this region. The segmentation is more apparent with absence of moderate sized shallow interplate seismicity as most of the seismicity in this region is attributed to the down going slab with normal faulting focal mechanisms. The eastern segment is seen to be more stressed than the western segment as evident from the seismicity patterns. The western Makran if locked does not rule out the possibility of a major earthquake occurring in this region. The $b$-value is used as one of the precursors to identify the plausible high stress regions, as decreasing $b$-value for earthquakes located within a seismogenic volume under consideration is found to correlate with increasing effective stress levels prior to major shocks (Kanamori 1981; Wiemer & Wys set al. 2011). However, to draw conclusive inference about the western segment is locked or aseismic at this moment is not possible since the data from this region is very sparse. Also one of the major differences between the western and eastern Makran is the absence of coastal earthquakes in the western Makran and the seismicity that has been used for this study is concentrated on the land covered region.

Due to rifting of India and Madagascar during the late cretaceous, the Western continental margin of India and the associated seafloor were formed and one of the important aseismic ridges is the MR (Rajaram et al. 2009). This NE–SW trending volcanic ridge was discovered during the John Murray cruise in 1933. It lies in the close proximity of the MSZ extending to about 750 km from the northern Owen Fracture Zone in the southwest to the triple junction offshore Karachi in the northeast and marks the boundary between the Indian and Arabian plates (White 1984; Edwards et al. 2000).
Effect of Murray ridge on tsunami propagation

The MR System comprises of northern and southern MR and the Dalrymple Trough. The northern and southern MR differs significantly in morphology. Southern MR is relatively at low depth of less than 1000 m and northern MR is at higher depth of 2000 m. The Dalrymple Trough is the deepest seafloor in the Arabian Sea with a depth as deep as 4400 m and the topographic high of the MR is located at the southeast of Dalrymple Trough (Gaedicke et al. 2002).

As the tsunami speed depends on the depth of the ocean, bathymetry plays a vital role on tsunami propagation. Tsunami waves tend to become concentrated above undersea ridges because of refraction and acts as a wave guide which lead to enhanced tsunami wave heights. Ridges can act as a wave guides for long ocean waves. Tsunami wave directionality mainly depends on focusing of source region and the waveguide structure. Southwest Indian Ridge and the Mid-Atlantic Ridge acted as waveguides for tsunami energy propagation into the Atlantic Ocean whereas Southeast Indian Ridge, Pacific Antarctic Ridge and East Pacific Rise acted as wave guide for waves to enter Pacific (Titov et al. 2005).

Buchwald (1968) considered uniform ridge of arbitrary cross-section and have shown that an infinite number of modes of wave propagation along the ridge is possible. Groesen et al. (2008) have studied the near coast tsunami waveguiding with the synthetic bathymetry ridge models using shallow water and a linear dispersive variational Boussinesq model. To examine the bathymetric effect, Satake (1988) applied ray tracing of seismic surface waves on the spherical Earth to study tsunami propagation in the entire Pacific Ocean and the Japan Sea.

Active fault system associated with giant landslides at the Owen Fracture zone can generate tsunamis in the NW Indian Ocean (Fournier et al. 2011; Rodriguez et al. 2012; Rodriguez et al. 2013).

The Haiti earthquake of 2010 triggered independent twin tsunamis in Gulf of Gonave and along Haiti’s south coast due to landslides with a runup of 3 m (Fritz et al. 2013). Papua New Guinea earthquake on 1998 July 17 of magnitude 7.0 caused a large undersea landslide, which intern caused a tsunami that hit

Figure 1. Bathymetry profile along the Murray ridge.

Figure 2. (a) With Murray ridge bathymetry. (b) Without Murray ridge bathymetry.
Table 1. Fault parameters used for tsunami simulations from Makran subduction zone.

<table>
<thead>
<tr>
<th>Fault parameters</th>
<th>Scenario-I</th>
<th>Scenario-II</th>
<th>Scenario-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>1945 Makran tsunamigenic earthquake</td>
<td>Possible tsunamigenic earthquake from eastern</td>
<td>Possible tsunamigenic earthquake from western</td>
<td></td>
</tr>
<tr>
<td>(Byrne et al. 1992)</td>
<td>Makran</td>
<td>Makran</td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td>63.48°E</td>
<td>66.3°E</td>
<td>61.16°E</td>
</tr>
<tr>
<td>Latitude</td>
<td>25.15°N</td>
<td>25.20°N</td>
<td>24.59°N</td>
</tr>
<tr>
<td>Magnitude</td>
<td>8.1 ( M_w )</td>
<td>9 ( M_w )</td>
<td>9 ( M_w )</td>
</tr>
<tr>
<td>Fault length</td>
<td>150 km</td>
<td>366 km</td>
<td>366 km</td>
</tr>
<tr>
<td>Fault width</td>
<td>70 km</td>
<td>183 km</td>
<td>183 km</td>
</tr>
<tr>
<td>Slip</td>
<td>7 m</td>
<td>11 m</td>
<td>11 m</td>
</tr>
<tr>
<td>Strike</td>
<td>246°</td>
<td>256°</td>
<td>278°</td>
</tr>
<tr>
<td>Dip</td>
<td>7°</td>
<td>7°</td>
<td>7°</td>
</tr>
<tr>
<td>Rake</td>
<td>89°</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>Focal depth</td>
<td>27 km</td>
<td>25 km</td>
<td>25 km</td>
</tr>
</tbody>
</table>

Table 3. Fault parameters used for tsunami simulations from Makran subduction zone.

Figure 3. (a) Tide gauge locations along the west coast of India (b). Gauge locations taken along L, M and N profiles across the Murray ridge.

As the tsunami waves approached the Carlsberg ridge within the Arabian Sea during the 2004 Sumatra tsunami the energy got focussed towards the Horn of Africa causing damage to life and property in Somalia and Socotra Islands in Yemen (Fritz & Borrero 2006; Fritz et al. 2006; Fritz & Okal 2008; Ramalanjaona 2011). This also brings out the effect of ridge system on tsunami propagation.

Okal et al. (2006) compared the distant tsunami hazard in terms of runup heights for the 2004 Indian Ocean tsunami and the 1945...
Makran tsunami along the Arabian Sea coast primarily at some locations along the Oman coast and found them to be of comparable magnitude. Fritz et al. (2010) measured high water marks and inundation at these locations for the strongest tropical cyclone Gonu in 2007 in Arabian Sea which matched well with the 2004 Indian Ocean tsunami.

Topographic features of the oceanic ridges not only affect the amplitude of the tsunamis but also the directionality and the arrival time. Yeh et al. (1995) modelled 1994 Shikotan tsunami originating near northern Japan and showed that the Hawaiian Ridge serves as a wave guide for tsunamis propagating from the west there by increasing the amplitudes of tsunamis in Hawaii. Tsunami scattering index for the Pacific Ocean shows that the major scattering features in the north pacific are the Emperor Seamount chain, the Hawaiian Ridge and the Hawaiian Islands (Mofjeld et al. 2004). Tsunami propagation along the bottom ridges in the Pacific Ocean area is presented by Marchuk (2009). Neetu et al. (2011) experimented with bathymetry along the Makran coast by removing the bathymetric irregularities to observe tsunami wave localization due to the narrowing of the shelf.

The anomalous bathymetry of MR can cause the focussing or defocusing of the tsunami waves coming from MSZ. To demonstrate the propagation over the MR the 1945 Makran tsunamigenic earthquake of magnitude 8.1 which occurred in the eastern segment (Epicentre: 25.1°N and 63.48°E) is considered. This tsunamigenic earthquake generated a large destructive tsunami causing large scale damage to the life and property at Baluchistan, Pakistan, Iran, and northern India. Due to this tsunami the cable link between Karachi and Muscat got destroyed (Omar 2005).
The 1929 Grand Banks landslide generated tsunami causing sequence of breaks in the submarine telegraph cables from North America to Europe (Fine et al. 2005). The 1945 tsunamigenic earthquake might have triggered a submarine landslide as evidenced by break in the submarine cables and the delay in the arrival of tsunami waves (Ambraseys & Melville 1982; Byrne et al. 1992). This event caused the eruption of mud volcanoes and created several temporary islands (Sondhi 1947). 1958 Lituya Bay landslide tsunami generated the highest run up of 524 m causing total destruction to the nearby forest (Cranford 2000; Clague et al. 2003; Fritz et al. 2009). A submarine landslide triggered by an earthquake in Papua New Guinea produced a tsunami that killed several thousands of people (Bardet et al. 2003; Clague et al. 2003).

The Makran tsunami effects were observed along the Indian coast as far as Mumbai (1100 km away) and Karwar (1500 km away) and a 2 m runup observed at Mumbai (Pendse 1948; Ambraseys & Melville 1982; Murty & Bapat 1999). Okal & Synolakis (2008) modelled different scenarios of tsunamigenic earthquakes in the MSZ and studied the tsunami propagation. In this paper, tsunami propagation over the MR with and without its bathymetry is modelled and the effect of MR on the tsunami directivity, arrival times and wave heights presented.

2 MODEL AND DATA

TUNAMI N2 (Imamura 1996) code is originally authored by Professor Nobuo Shuto and Fumihiko Imamura of the Disaster Control Research Center in Tohoku University (Japan). It involves linear theory in deep sea, shallow water theory in shallow sea and runup on land with constant grids of increasing resolutions. The TUNAMI N2 model and its application procedure is described in detail in the IOC manual number 35 (Goto et al. 1997). The equations are solved using the leap-frog scheme of finite differences. Boundary conditions of free transmission at open sea and perfect reflection on land is applied.

The initial seafloor displacement at the source is obtained using closed form analytical expressions for the initial displacement and strains due to shear and tensile faults in a half space for both point and finite rectangular sources (Mansinha & Smylie 1971; Okada 1992).

The resultant tsunami waves are determined by the quantum of the deformation of the seafloor. Initial wave (static tsunami source) generated at the source is almost equal to the seafloor displacement. More the vertical displacement, greater will be the size of the waves. The source parameters, which include coordinates of the epicentre, fault length, fault width, slip, strike, dip, rake and focal depth, are provided as input to get the initial seafloor displacement.

The TUNAMI N2 code is extremely used to understand the tsunami propagation, arrival times, runup and inundation extents. Tsunami modelling is done by using the TUNAMI N2 software all around the globe. Using the results of this code we can obtain arrival times from source to different locations, directivity (direction of maximum tsunami wave height), runup and inundation maps. Tsunami modelling results obtained using TUNAMI-N2 code have been validated with the observations from the 2004 December
Figure 7. Directivity map for the three scenarios with and without MR.
tsunami (Goto & Ogawa 1982; Shuto & Goto 1988; Imamura & Shuto 1989; Shuto et al., 1990; Goto et al. 1997). Srivastava et al. (2011a) computed the tsunami wave heights at Nagapattinum and the results validated using the observations made along the Nagapattinum coast by Chadha et al. (2005). This code is used by several researchers to simulate the Pacific, Indian and Atlantic tsunamis (Zahibo et al. 2003; Yalciner et al. 2005; Tinti et al. 2006; Jaiswal et al. 2009; Srivastava et al. 2011a,b). Tsunami modelling from the MSZ is quantified by Swaroopa Rani (2010) and a change in the directivity at the MR seen. Krishna (2013) used the TUNAMI N2 code to quantify the tsunami hazard at nuclear installations along the west coast of India.

Fine bathymetry and topography data serves as the key input for tsunami modelling. Online available bathymetry data from General Bathymetric Chart of the Oceans (GEBCO), 1 arcmin (1834 m) resolution and topography data from the Shuttle Radar Topography Mission (SRTM), 3 arcsec (93 m) resolution are used to quantify the tsunami propagation, runup and inundation modelling. A set of four nested grids A, B, C and D, where A grid has coarse resolution, covering the entire MSZ and the west coast of India and the D grid has fine resolution of 93 m and covers the study region where runup and inundation are quantified. In this code topography of land is taken as negative and ocean bathymetry is considered as positive value. Fig. 1 shows the bathymetry along the MR. The tsunami modelling using the bathymetry with natural MR system (Fig. 2a) is carried out for the three sets of fault parameters as given in Table 1. For the same set of fault parameters the effect of MR system on tsunami propagation is studied by removing the existing bathymetry of MR system and surrounding irregularities and making it to be a constant value of 3400 m which happens to be the average value of the surrounding bathymetry (Fig. 2b). Apart from tsunami propagation in open Ocean/Sea the runup and inundation extents at Mumbai along the west coast is also quantified.

In this study the 1945 November 27 tsunami and worst possible tsunamigenic earthquake scenarios from MSZ is modelled. The maximum possible length of MSZ over which fault rupture may develop is considered for the worst possible scenarios. The rupture parameters used to model the simulation of 1945 Makran earthquake is taken from Byrne et al. (1992) and realistic rupture parameters for worst possible scenarios from the east and west MSZ used (Table 1). Tsunami simulation is carried out for 8 hr and the results discussed in the following section.

3 ANALYSIS AND RESULTS

The tide gauge locations along the west coast of India, Pakistan and two gauge locations along the coast of Oman (to study the western Makran tsunami) are shown in Fig. 3(a).

Three profiles L, M and N across the MR with four gauge locations on each profile are considered (Fig. 3b). Mumbai, which is
about 1000 km away from MSZ is considered as the study region to see the effect of tsunami propagation and runup analysis (Fig. 4). First the initial seafloor displacement at the source for the three scenarios is computed and plotted in Fig. 5. From the figure we see that the displacement at the source ranges from 2 to 3 m. Maximum wave heights plots along the gauge locations L, M and N profiles are given in Fig. 6. The directivity for three scenarios I, II and III computed and the results plotted in Fig. 7.

Scenario-I
The initial displacement at the source for scenario-I is seen to be around 2.5 m. With MR bathymetry the directivity of tsunami is slightly deviating after crossing the MR with increased wave heights in the open Ocean. Without MR the directivity is towards open Ocean with reduced wave heights (Fig. 7). In Fig. 6 with MR, it is clearly observed that the waves got amplified at M2 and N2 locations. The maximum wave heights is much higher with MR when compared to the without MR along the west coast (Fig. 8). However there is no significant change in the wave heights further away from the MSZ. With MR the estimated wave heights with gauge locations along the Mumbai coast is ranging from 0.2 to 0.45 m and without MR is 0.2 to 0.4 m. From Fig. 9 we observe that the tsunami takes a longer time to reach different locations along the Mumbai with the MR. The maximum inundation with MR is 389 m and without MR it is 330 m. The maximum runup height with MR at Bandra west is about 0.45 m which is higher than without MR (Fig. 10). Neetu et al. (2011) have presented the tide gauge recordings at Mumbai and Karachi for the 1945 Makran tsunami. Our computations at these locations for scenario-I (1945 Makran tsunami) are seen to match well with the observations (Fig. 11). Fig. 12 depicts the tsunami travel time (in hr) contours for scenario-I with MR and without MR. The tsunami travel time difference between these shows that the time difference is more in open ocean where as it is less along the continental shelf.

Scenario-II
With MR the directivity is focussed towards Karachi coast after crossing the MR with decreased wave heights in the open ocean. Without MR the directivity is towards open Ocean with increased wave heights in open ocean (Fig. 7). The wave heights along M and N profile are amplified at M2 and N2 gauge locations with MR bathymetry (Fig. 5). However, at M3 and L3 locations the wave heights are more without the ridge but are not amplified. The plot of maximum wave heights shows that wave heights are increased with MR bathymetry when compared to without MR. Also the arrival times at different locations is computed (Fig. 8). The runup with MR is ranging from 0.5 to 2.4 m and without MR it is 0.5 to 2.2 m (Fig. 10). With MR maximum inundation is around 1262 m and without MR it is 1295 m and tsunami arrival times are less without MR bathymetry. The runup heights in Karachi is matching well with the results of Heidarzadeh et al. (2009) for the worst case scenarios.

Scenario-III
For scenario III the tsunami wave energy is more concentrated towards Oman. Increased wave heights are observed in the open Ocean with MR bathymetry and reduced wave heights are observed without MR (Fig. 7). The wave heights along M and N profile are amplified at M2 and N2 gauge locations with MR bathymetry (Fig. 6). The estimated maximum wave heights at different location along the west coast are higher with MR when compared to without MR (Fig. 8). The wave heights observed are high at Muscat and Al Khuwaymah along the coast of Oman and are tabulated in Table 2. The estimated run up along the Mumbai coast with MR is ranging from 0.4 to 1.38 m and without MR it is 0.4 to 1.28 m (Fig. 10). The maximum inundation along Mumbai coast with MR is 875 m and without MR is 842 m.

4 DISCUSSION AND CONCLUSIONS
In this paper tsunami propagation from the MSZ across the MR is studied in detail. Three profiles across the MR are considered and the wave heights at different locations along the profile quantified. Without MR, in all scenarios tsunami waves travel faster as no ridge is present and reaches the coast earlier without amplification. With the presence of the MR the tsunami waves for all scenarios are seen to slow down at the MR due to shallow depth thereby taking longer time to reach the coast. Due to shoaling effect the tsunami waves amplified above MR and propagated through the open ocean leading to the late arrival of tsunami waves with increased wave heights along the west coast of India.
Figure 10. Runup along the Mumbai coast for the three scenarios with and without MR.
The profile taken at the western end across the MR, where the bathymetry is flat there is no significant difference of the tsunami heights with or without the MR. However, for the other two scenarios, that is the 1945 Makran tsunami which lies in the center and another scenario from the eastern end results reveal that there is an increase in the wave height at these locations. Wave guiding nature is observed and focussing of tsunami waves towards Karachi and Achu locations (Table 2).

Our studies reveal that detailed bathymetry and topography has important effects on the runup and inundation results. Future improvements require very fine bathymetry in the open Ocean, along the continental shelf and slope regions through which tsunami propagate towards coastal cities. Mapping features like oceanic ridges and seamounts contribute greatly in understanding the tsunami propagation and runup analysis.

Table 2. Maximum wave heights at locations close to epicentre.

<table>
<thead>
<tr>
<th>Gauge location</th>
<th>Scenario-I</th>
<th>Scenario-II</th>
<th>Scenario-III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With MR</td>
<td>Without MR</td>
<td>With MR</td>
</tr>
<tr>
<td>Karachi</td>
<td>0.441</td>
<td>0.427</td>
<td>2.609</td>
</tr>
<tr>
<td>Achu</td>
<td>0.559</td>
<td>0.507</td>
<td>3.431</td>
</tr>
<tr>
<td>Muscat</td>
<td>0.450</td>
<td>0.449</td>
<td>0.742</td>
</tr>
<tr>
<td>Al Khuwaymah</td>
<td>0.523</td>
<td>0.689</td>
<td>1.188</td>
</tr>
</tbody>
</table>

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