Tsunami Simulation along the South West Coast of India: Lakshadweep Islands acting as wave-barricade

Shila Saha* and Kirti Srivastava
CSIR-National Geophysical Research Institute, Hyderabad, India.
* [E-mail: sheela.saha@gmail.com]

In the Arabian sea, the 1945 Makran Earthquake is the last grave due to Tsunamigenic earthquake that occurred in the month of November as it originated along the Makran Subduction Zone (MSZ). In this study, the effect of the propagation of Tsunami wave from MSZ and its impact all along the south west coastal area of India and the protection that Lakshadweep Islands are providing is studied. Tsunami studies are carried out with the existing bathymetry of the Indian Ocean and then this is compared with the results attained by removing the Lakshadweep Islands for two scenarios, one is 1945 Makran Tsunami and a large possible Tsunamigenic earthquake from the eastern part of Makran. With the presence the Lakshadweep Islands, Tsunami waves are amplified in the vicinity of the Lakshadweep; which in turn increases the arrival time of Tsunami waves at the southern part of the western coast of India. In the absence of Lakshadweep Islands in our simulation, the Tsunami wave arrival times and wave amplitudes becomes less at the Indian mainland near Mangalore and the wave height tends to increase towards the south western part of India. Hence the conclusion is that, Lakshadweep acts as a wave barricade for the south west coast of India.

[Keywords: Tsunamigenic earthquake; Makran subduction zone; Lakshadweep ridge; Wave barricade; Bathymetry]

Introduction

The best known Tsunami in Makran region is the one which was generated by the great earthquake of 27th November 1945 off Pakistan's Makran coast in the Northern part of Arabian sea, which killed several thousands of people1. The Makran Subduction Zone is a convergence plate boundary where the Arabian plate is constantly moving northward relative to the Eurasian plate at a rate of about 40-50 mm /yr2,3,4. The plate movement in the northward direction and subduction of the Oman's oceanic lithosphere beneath the Iranian micro-plate has dragged tertiary marine sediments which results in the formation of the Makran coastal area. This region is exceedingly folded and has heavily faulted mountain ridges which is equidistant from the present shoreline5,6. According to George Pararas-Carayannis7, the continental convergence has deformed and folded the western boundary, which in turn created fractures in the micro plate. Great faults, large grabens, the subduction zone and the active orogenesis have resulted in faulted and folded mountain ranges along the coastal region of Makran Subduction Zone. These are associated with thrust earthquakes, which causes local Tsunamis. The distribution of MSZ into two parts, namely the eastern and western parts by the Sistan Sutur zone is the most noticeable characteristic of the Makran Subduction Zone8. A study of the b value and fractal dimension9 inferred that eastern segment of Makran Subduction Zone is more stressed than the western segment. The eastern boundary of Makran Subduction Zone is formed by the major transparessional strike-slip system, the Ornach-Nal fault system and the western boundary of the Makran Subduction zone is formed by the Zendan-Minab fault system. Makran Subduction Zone has a low dip angle unlike the other world’s subduction zones and there is no trench also10,11. Makran is a large sedimentary prism accreted during the Cenozoic era12 forming a wedge which thickened seaward. Many active mud volcanoes are also present all along the Makran Subduction Zone.

The Chagos - Laccadive Ridge is an important volcanic ridge and oceanic plateau which extends between the Northern and the Central Indian Ocean. Figure 1 shows the Makran Subduction Zone with Lakshadweep Islands' Bathymetry. The Lakshadweep Islands are the above-water parts of the Chagos-Laccadive Ridge13. The coral atolls, on the surface, show reliable differences between their eastern and western sides. Most of the flat dish-shaped lagoons in Lakshadweep are confined to the western sides of the Islands (Fig 2a). The Islands of the Lakshadweep group are irregularly scattered in the Arabian Sea, and are away from Kozhikode by about 200 km to 400 km.
The Ridge rises from the deep sea from a depth of 2000 to 2700 m in Lakshadweep sea and 1000 m in Arabian sea and also the inhabited Islands have 3 m to 4 m elevation\textsuperscript{14,15,16}. The speed of Tsunami depends on the ocean depth and we know the average depth of Indian Ocean is about 4500 m, so on Tsunami wave dissemination bathymetry plays a very critical role. Because of the location of epicenter at a subduction zone and its large magnitude, the focal mechanism for 1945 Makran earthquake have been assumed as a thrust faulting by a number of authors\textsuperscript{2,3}. According to a large number of authors the 1945 Makran Tsunami is the first Tsunami in the Makran Subduction Zone region which is instrumentally recorded. Only for this particular earthquake, we have available information regarding earthquake magnitude and run-up heights in different coastal areas. Heidarzadeh and Kijko\textsuperscript{17} studied the Tsunami hazard associated with the Makran Subduction Zone using deterministic and probabilistic methods. According to\textsuperscript{18} remarkable aspect of the 1945 Makran Tsunami is that, it's main waves were significantly delayed with respect to the

Fig. 1 — Makran Subduction Zone With Lakshadweep Islands

Fig. 2 — (a) Southern part of India with Lakshadweep Islands Bathymetry (b) Southern part of India without Lakshadweep Islands Bathymetry (c) Selected gauge locations along Lakshadweep Islands.
earthquake along the eastern Makran coast and this has been described in some detail. A recent study\textsuperscript{19} shows that the Tsunami propagation changes its direction towards the Indian coast after crossing the Murray ridge. Propagation of Tsunamis from MSZ into Arabian sea and its effect on the Androth Island of Lakshadweep is studied in detail\textsuperscript{20}. In the present paper Tsunamis from the MSZ is studied to see if Lakshadweep is acting like a wave barricade for south west coast of India.

Materials and Methods

TUNAMI N2 code which was initially developed\textsuperscript{21} and further modified\textsuperscript{22} has been used to model the propagation of Tsunami waves. In our study, we have tried to model a possibly large Tsunamigenic earthquake from the Makran subduction zone and calculated the approximate Tsunami wave arrival time along the Lakshadweep and the western coast of India. The initial condition is computed using Mansinha and Smylie\textsuperscript{23} method which computes the deformation at the source. The boundary conditions are free transmission in the open sea and perfect reflector for land boundaries. The bathymetry data which we have used in our study are taken from GEBCO (the General Bathymetric Chart of the Oceans) 1 arc minute (1834 m) and the topography data is taken from SRTM (Shuttle Radar Topography Mission) 3 arc sec (93 m). It uses the data which is formatted into three columns X-coordinate (longitude), Y-coordinate (latitude) and Z-coordinate (land elevations as (-)ive and ocean depths as (+)ve) and converted into evenly spaced grids by using surfer software. This program uses nesting of grids with accurate bathymetry and topography data to simulate the Tsunami i.e. A, B, C and D grids. In our study, we have considered grid spacing of all the 4 grids in 1: 3 ratio, i.e. A and B grids to model the linear effects in deep sea which are of 81 arc seconds and 27 arc seconds and C and D constant grids to model the non-linear effects of the Tsunami which are of 9 arc seconds and 3 arc seconds.

In the present study we have selected the gauge locations at the water depth of 3 m to 7 m to observe the impact of Tsunami wave height. To get the estimation of Tsunami wave height at the coastal region, Green’s law is applied to the estimated height at the forecast point towards the sea of the coastal area. Green’s law says that the numerical value of the Tsunami height at the coastal area is calculated by the fourth root of the sea depth ratio at the forecast point. As for “h” value, the sea depth at the coast, 1 m is assumed, but actually measured value would be more appropriate, if it is available. From Green’s law Tsunami’s height is in proportion to a fourth root of water depth's change and is in inverse proportion to a square root of the expanse of wave front. When Tsunami gets close to coast, the later contribution can be neglected. h is assumed to be equal to 1 meter and the following equation can be obtained\textsuperscript{24,25,26}.

\[
H = \frac{4}{\sqrt{h}} H_1 \rightarrow \frac{4}{h_1} H_1
\]

where,

- \(H_1\) is the Tsunami wave height at the location
- \(h_1\) is the water depth at the location
- \(H\) is the Tsunami height at the forecast.

Using equation (1) the run-up heights on land is computed.

Results

For two different scenarios the Tsunami wave propagation from the Makran Subduction Zone is modelled, one is the scenario for the 1945 Makran earthquake and the other is a large earthquake scenario considering the Tsunamigenic earthquake from the eastern Makran part. The source characteristics used in the Tsunami simulation of the two scenarios are given in the Table 1. The Tsunami simulation code is run for 9 hours and the estimated results are discussed below.

There is a dependency of the Tsunami wave parameters on the earthquake fault parameters because the gravity wave generated by the known motion of the solid bottom has to propagate in the highly incompressible liquid, so the fault parameters play a vital role in estimating deformation at the ocean bottom reflected above the ocean surface as

<table>
<thead>
<tr>
<th>Earthquake Fault Parameters</th>
<th>Case-I</th>
<th>Case-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Fault</td>
<td>1945 Makran tsunamigenic earthquake</td>
<td>A large earthquake scenario from Eastern Makran</td>
</tr>
<tr>
<td>Longitude</td>
<td>63.48°E</td>
<td>65.72°E</td>
</tr>
<tr>
<td>Latitude</td>
<td>25.15°N</td>
<td>25.22°N</td>
</tr>
<tr>
<td>Magnitude</td>
<td>8.1 Mw</td>
<td>9 Mw</td>
</tr>
<tr>
<td>Fault Length</td>
<td>150 km</td>
<td>366 km</td>
</tr>
<tr>
<td>Fault Width</td>
<td>70 km</td>
<td>183 km</td>
</tr>
<tr>
<td>Slip</td>
<td>7 m</td>
<td>11 m</td>
</tr>
<tr>
<td>Strike Angle</td>
<td>246°</td>
<td>250°</td>
</tr>
<tr>
<td>Rake</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>Dip Angle</td>
<td>7°</td>
<td>7°</td>
</tr>
<tr>
<td>Focal Depth</td>
<td>20 km</td>
<td>20 km</td>
</tr>
</tbody>
</table>
seafloor upliftment. The earthquake focus should be at shallow depths to uplift the ocean floor vertically. Mansinha and Smilye and Okada gave analytical expressions for the seafloor deformation due to an earthquake. The ocean bottom deformation gives rise to static sea floor upliftment which forms the initial conditions required for simulations of Tsunami propagation and inundation (Fig. 3). A thorough structure of bathymetry and topography plays an important role on the results of run-up and inundation.

In this study an attempt is made to find out actually how much protection the western part of India is getting in the presence of the Lakshadweep ridge if a Tsunamigenic earthquake occurs at the Makran Subduction Zone. Figure 2 (b) shows the Southern part of India without Lakshadweep Islands.

**Case I**

For 1945 Tsunamigenic earthquake form Makran, the initial deformation of sea floor at $t = 0$ sec, is seen to be around "3.2 m" which has been shown in Figure 3(a). The directivity of the Tsunami wave propagation is shown in Figure 4. From the Figure 4 it is clear that with the presence of Lakshadweep Islands the

---

Fig. 3 — (a) Sea floor deformation at time $t=0$ sec for 1945 Makran Tsunami (b) Sea floor deformation at time $t=0$ sec for a large earthquake scenario from the eastern Makran part.

Fig. 4 — Directivity map for the two cases with and without Lakshadweep
Tsunami wave is getting amplified with the Island and the directivity is almost towards the western part of India and because of the amplification of the wave, the wave heights increased towards the Indian coastal city near Mangalore. But without the presence of Lakshadweep Islands the Tsunami directivity is towards the open ocean region with less arrival time towards the coastal cities south of Panjim and an increase in the wave heights towards the southern part of Western Coast of India after Ponani (which lies to the south of Kozhikode). To show the amplification of wave with the Islands we have considered few locations on and around Lakshadweep Islands which has been shown in Fig. 2 (c). The locations (B1, B2, B2, B6) and (C1, C2, C6) are chosen along the Lakshadweep Islands and the locations (A1, A2, A6) and (D1, D2, D6) are taken on either side of the Lakshadweep Islands. With the presence of Lakshadweep Island the amplification of wave is very clear at some locations along Lakshadweep Island i.e. at B2, C2, C3 and C4 locations in Figure 5.

There is no additional impact of the Tsunami along western coast of Indian cities like Mumbai, Ratnagiri and Panjim even if Lakshadweep is present or not.

Fig. 5 — Approximate maximum wave heights at different tide gauge locations along the Lakshadweep Ridge for 1945 Makran Tsunami and a possible large earthquake scenario.
The change in the wave height is observed from Mangalore city onwards and towards its south. With the presence of Lakshadweep Islands the maximum wave height is observed in Mangalore and wave height goes on decreasing towards the southern part of Mangalore (Fig. 6).

**Case II**

A possible Tsunamigenic earthquake from the Eastern Makran region has been considered for a large earthquake scenario. The initial deformation at the source at \( t = 0 \) sec is observed around "4 m" (Fig. 3(b)). The directivity of Tsunami wave is towards the Indian coastal city of Mangalore. Without Lakshadweep Islands the Tsunami wave directivity is towards the open Ocean/Sea. Amplification of the wave is noticeable at the locations B2, C2, C3 and C4 (Fig. 5). In this case also the maximum Tsunami wave height is at Mangalore with the presence of Lakshadweep Islands when compared to without Lakshadweep Islands.

The Tsunami waves arrival time at different locations along the Western coast of India is shown in Fig 6. The impact on the Tsunami wave arrival time along the Western coast of India with or without Lakshadweep ridge is distinguishable only from the coastal city of Mangalore (Fig. 6). Up to Ratnagiri and Panjim there is no change in the arrival time and wave height, even if the Lakshadweep Ridge is present or not. The estimated run-up height and wave arrival time near Kochi city is shown in Fig 7. The wave arrival time at the different selected locations near Kochi city along the west coast of India is less without Lakshadweep Islands. It is clear that with the presence of Lakshadweep Islands the run-up heights at Chellam is 2.6 m, which is obviously shorter as compared to without the presence of Lakshadweep Islands which is 2.9 m (Fig. 7). From this we can conclude that with the presence of Lakshadweep Islands, the wave height is more near the vicinity of the mainland of Lakshadweep Islands. As we move towards south, the wave height will be less but without Lakshadweep Islands the wave height will be more towards the Southern part of the Indian west coast.

**Discussion and Concluding remarks**

A number of studies indicate the possibility of repetition of modest to large earthquakes in the Makran Subduction Zone. In this paper the propagation of Tsunami from the Makran Subduction Zone and its impact along the western coast of India is studied with and without considering the bathymetry of the Lakshadweep Islands.
We have considered a few locations across the Lakshadweep ridge to see the impact along the Western coast of India and the wave height at different locations are quantified. We have studied two scenarios, one is 1945 Makran earthquake and the other one is a large earthquake scenario from the Eastern Makran part. Tsunami waves are amplified in the vicinity of Lakshadweep Islands which in turn increases the arrival time of Tsunami waves at the Southern part of the western coast of India. Because of Lakshadweep ridge, the wave height is maximum towards the Indian mainland near Mangalore and the wave height tends to be minimum towards the Southern part of Indian coast i.e. Kerala coast. But, if we remove the bathymetry of Lakshadweep Islands, the Tsunami wave arrival times and wave amplitudes becomes less at the Indian mainland near Mangalore but the wave height tends to increase towards the southern part of Indian coast, i.e. Kerala coast. This brings us to the conclusion that because of Lakshadweep Ridge, Southern part of Indian coast i.e. region towards the South of Mangalore would have less run-up and inundation for a Tsunami propagation from Makran region. The inundation extents are seen to be very less which is due to a large continental shelf along the west coast of India.

**Acknowledgement**

The First author wishes to thank DST Women Scientist Scheme - A for funding to do this research work. We wish to thank the Director of CSIR-National Geophysical Research Institute of India, for his kind permission to publish this work.

**References**

14 https://earthobservatory.nasa.gov/IOTD/view.php?id=77647
15 www.unitedstatesofindia.com