CHAPTER 3

TSUNAMI NUMERICAL MODELING

3.1 Introduction

The most common type of tsunami formation is seismic generated source mechanism. The earth is constantly moving on large tectonic plates. When these tectonic plates move past each other, collide or slide under one another, an earthquake results. The earthquake fault types are normal, reverse and strike slip faults. According to the parameters, those geologists define, the type of the fault is determined. Normal faults occur mainly by a block of the fault move downward relative to other fault and the crust is being extended. Whereas, reverse faults is the movement of a block of fault above relative to other fault and the crust is being subducted. A strike slip fault is the slide of the blocks of faults pass to each other. These faults are identified as either right-lateral or left lateral depending on whether the displacement of the far block is to the right or the left when viewed from either side. Reverse faults generate higher magnitude tsunamigenic earthquake.

However the formation of seismic generated tsunami is depending on not only fault types and focal mechanism but also magnitude of an earthquake. It should be noted that not all earthquakes produces tsunami. Generally, underwater earthquakes are triggering the formation of tsunami. The earthquake produces a fluctuation in the mean sea level, which transfer the energy obtained from rupture to the shore as large water column. As a discussed in chapter 2, on the history, earthquakes occurred in land also caused tsunami in the near shore. On December 26/27, 1939, during the Erzincan Earthquake (MS=8.0), in Fatsa the sea receded 50 m and after a while the sea returned 20 m inland from the coast (Parejas et al. 1942). In this thesis, submarine earthquake
generated source mechanisms are focused.

**3.2 Rupture Parameters of Earthquake Tsunami Source Mechanisms**

The fault plane is characterized by $\eta$, its normal vector, and its direction of motion is given by $d$, the slip vector in the fault plane. The slip vector indicates the direction in which the hanging wall (upper side) moves with respect to the footwall (lower side). The slip vector always lies in the fault plane, and is therefore perpendicular to $\eta$. A coordinate system is useful for studying faults. The $X_1$ axis is in the strike direction of the fault, $X_3$ is vertical, and $X_2$ is perpendicular to $X_1$ and $X_3$ (Figure 3.1). $\delta$ represents the dip angle, $\theta$ the strike of the fault, and $\lambda$ the rake (slip) angle of the fault, then the vectors $\eta$ and $d$ can be described in terms of the geographic coordinate system (Rawlinson, 2007).

![Figure 3.1: Focal mechanism of fault (Rawlinson, 2007)](image)

Although the slip angle can vary between 0 to $2\pi$, several basic fault geometries can be defined as in Figure 3.2. The fault type does not give any evidence of its estimated fault dimensions (Konstantinoua et al., 2005).
If a fault is constrained to a rectangular shape, then the distance along strike is the fault length, and the dimension in the dip direction is the fault width. In reality, a fault may be a complicated surface, and an earthquake generated by movement along this surface may ultimately be composed of several sub-events at different places. Complicated seismic events of this type can be treated as a superposition of simpler events, however, so it is useful to understand how seismic waves can be generated by a simple fault with a rectangular geometry (Rawlinson, 2007).

There are eight parameters described a rupture generated source mechanism (Figure 3.3):

i. The dip angle ($\delta$)
ii. Strike angle, the direction of the fault axis from North (Clockwise) ($\theta$)
iii. The rake (slip) angle ($\lambda$)
iv. Length of the fault ($L$)
v. The width of the fault ($W$)
vi. Epicenter coordinates
vii. Vertical displacement of the fault ($D$)
viii. Focal depth ($H$)
Figure 3.3: Rupture Characteristics of Seismic Generated Source Mechanisms.

The red star indicates the epicenter of rupture that used in present study. To evaluate a risk analysis when an earthquake happens, these eight parameters are needed to explain the rupture characteristics of a seismic generated source mechanism. Thus, inputting the parameters needed, the impact of tsunami on the desired shoreline can be forecasted in a short time. However, when an earthquake occurs, only focal depth, epicenter coordinates and magnitude of an earthquake is known. The other parameter may be estimated considering the characteristics of historical data.

The use of surface ruptures as primary data for fault dimension estimation exhibit two important problems. First, field observations of ground breakage may not always express the manifestation of the seismogenic fault reaching the surface of the Earth, but rather secondary ground deformation phenomena (like superficial cracks, liquefaction, landslides, etc.). Second, surface rupture lengths usually fail to estimate the actual length of the seismogenic fault by a factor that is inversely proportional to the magnitude of the earthquake (Wells and Coppersmith, 1994).
The bathymetry topography database for tsunami modeling is developed from GEBCO 30 sec. The bound coordinates are selected 55° - 76° E longitudes and 10° – 30° N latitudes. The rupture parameters, as provided by Byrne et al. (1992), were used to model the source of 1945 earthquake and finite difference model. In this study, the most significant tsunamigenic earthquake in recent times was that of 28 November 1945, 21:56 UTC (03:26 IST) with a magnitude of 8.3 (Mw), used for numerical modeling.

For the assumed 3-meter uplift, the magnitude of an earthquake the scalar moment required rupturing fault plane can be calculated by

\[ M_w = 2/3((\log_{10} M_0 - 9.1) \] (1)

Where \( M_0 \) is the scalar moment of the earthquake evaluated as

\[ M_0 = \mu DLW \] (2)

and \( \mu \) is the rigidity of earth mantle, D is the dislocation (slip) and L is the length of the fault plane and W is the width of the fault plane. The rigidity, \( \mu = 3.0 \times 10^{10} \) N/m², is taken for this calculation.

**Table 3.1: The rupture parameter of 1945 Makran earthquake provided by Byrne et al. (1992)**

<table>
<thead>
<tr>
<th>Epicenter of Earthquake</th>
<th>Fault length (km)</th>
<th>Fault width (km)</th>
<th>Strike angle °</th>
<th>Rake angle °</th>
<th>Dip angle °</th>
<th>Slip magnitude (m)</th>
<th>Focal depth (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>Longitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>246</td>
<td>90</td>
<td>7</td>
<td>7</td>
<td>15</td>
</tr>
</tbody>
</table>

The Makran subduction zone is potentially capable of producing major earthquakes, up to magnitude \( M_w 8.7-9.2 \) (Smith et al., 2013). Past assumptions may have significantly
underestimated the earthquake and tsunami hazard in this region. Earthquakes similar in magnitude to the 2004 Sumatra earthquake could occur in an area beneath the Arabian Sea at the Makran subduction zone, according to recent research published in Geophysical Research Letters. These results have important earthquake and tsunami hazard implications, particularly for the adjacent coastlines of Pakistan, Iran, Oman, and India, as the Makran has not been previously considered a likely candidate for a Mw>9 earthquake (Smith et al., 2013). The research was carried out by scientists from the University of Southampton based at the National Oceanography Centre Southampton (NOCS), and the Pacific Geoscience Centre, Natural Resources Canada.

On basis of above research here we considered magnitude of Makran earthquake M\textsubscript{w} 8.3 for tsunami impact assessment along the Western cost of India. We selected seven potential sources (sources I, II, III, IV, V, VI and VII) to assess tsunami impact along the Western coast of India. The simulation were performed for each potential source (I, II, III, IV, V, VI, VII) for varying plausible range of strike angles , while other parameters such as dip and rake angles, and failure depth, were maintained constant. The characteristics of the leading wave (depression or elevation) depend directly on the orientation (strike angle) of the rupture when the other rupture parameters are same (Narcisse Zahibo et al., 2011). The impact is assessed in terms of arrival time of first wave, maximum positive and negative water elevation, time histories along the Western coast of India. In our applications the difference in strike angle in each source alternative resulted with minor differences in the time histories. The rupture parameters of Makran earthquake are given in table 3.2.
Table 3.2: The rupture parameter of 1945 Makran earthquake

<table>
<thead>
<tr>
<th>Source</th>
<th>Epicenter of Earthquake</th>
<th>Fault length (km)</th>
<th>Fault width (km)</th>
<th>Strike angle °</th>
<th>Rake angle °</th>
<th>Dip angle °</th>
<th>Slip magnitude (m)</th>
<th>Focal depth (km)</th>
<th>Seismic Moment (N m)</th>
<th>Uplift (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source-I</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>190</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-II</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>200</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-III</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>210</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-IV</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>220</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-V</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>230</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-VI</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>240</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
<tr>
<td>Source-VII</td>
<td>25.15° N 63.48° E</td>
<td>200</td>
<td>100</td>
<td>250</td>
<td>90</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>4.2x10(^{21})</td>
<td>3</td>
</tr>
</tbody>
</table>

3.3 Tsunami Numerical Modeling

Tsunami as a long wave travel faster than short waves but there is an upper limit. For gravity-induced waves of small amplitude, the maximum speed is:

\[
C = \sqrt{gh}
\]  

(3)

Where \( g \) represents the acceleration due to gravity (about 9.8 m/sec\(^2\) at sea level) and \( h \) is the local water depth measured from at the floor of the ocean up to the free surface.

This criterion is especially pertinent for tsunami, which have very long wavelengths. Tsunami waves move with a high speed at ocean and it is barely noticeable. When the wave approaches shoreline the depth decreases, in front of the wave slows down. However, wave energy does not break and converts the length to the wave height. Moreover, when the following second wave compresses the front wave, since fluids are incompressible, it reflects the horizontal force vertically up. Then huge volume of water hits the shore. A wave that was barely noticeable in open sea can become very large and destructive in near shore. For that reason, the mathematical and numerical background of the wave should be carefully studied to understand tsunami
propagation. In the theoretical part, the equations affect the tsunami propagation in open sea and near shore are examined. In the numerical background part, the solution of these equations using a finite difference numerical method is examined.

3.3.1 Theoretical Background

Tsunami propagation can be described by shallow water wave equation. Linear form of shallow water wave theory can be used at open sea. In the theory, there is relatively small effects of non-linear processes, dispersion and friction in the open ocean, as well as the Coriolis effect. The numerical code that was used in this thesis can solve nonlinear wave equation in Cartesian or spherical coordinate systems taking into account dispersion, friction and Coriolis effect. However, the effect of these terms becomes important when tsunami wave approaches to the shoreline. When water depth decreases less than 50 m the linear form of shallow water wave equations can take its place with nonlinear form of shallow water equations. Shallow water theory is emphasized since it creates the major impact on shore. The vertical motion of water particles has no effect on the pressure distribution. It is a good approximation that the pressure is hydrostatic. In this thesis, Coriolis effect is neglected because tsunami travel distance remains insignificant in relations to the earth’s complete rotation time. The governing equations in tsunami numerical modeling are non-linear form of shallow water equations with friction term. The formulas are solved in Cartesian coordinate system. Based upon these approximations and neglecting the vertical acceleration, the equations of mass conservation and momentum in the three dimensional problem Imamura et.al (2006) are given:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0
\] (4)
where, $x$ and $y$ are horizontal axes, $z$ the vertical axis, $t$ time, $h$ the still water depth, $\eta$ the vertical displacement of water surface above the still water surface, $u$, $v$ and $w$ are water particle velocities in $x$, $y$ and $z$ directions, respectively, $g$ the gravitational acceleration, $D$ is the total water depth given by $h+\eta$, $M$ and $N$ are the discharge fluxes in the $x$ and $y$ directions which are given. The last terms correspond to bottom friction.

It is generally expressed as $\tau_x$ and $\tau_y$ in the $x$ and $y$ directions,

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

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

In Eq.9 and Eq.10, $\rho$ is fluid density and $f$ is the friction coefficient. It is preferred to use Manning’s roughness coefficient $n$, which is 0.018 for smooth earth (Chow 1959) and expressed in Eq.11.

$$n = \sqrt{\frac{fD^{1/3}}{2g}}$$

A horizontal eddy viscosity that is assumed constant in space, the shear stress on a surface wave is neglected. The equation of momentum in the $z$ direction with the dynamic conditions at a surface yields the hydrostatic pressure ($p$). The dynamic and kinetic boundary conditions at surface and bottom are given as follows:

$$p=0 \quad \text{at } z=\eta$$
3.3.2 Numerical Background

The finite difference method is used to solve Eq.4, Eq.5 and Eq.6 numerically. The finite difference method based upon the Taylor expansion series is shown in Eq.15 (Imamura et al. 2006).

\[
\eta(x,t + \Delta t) = \eta(x,t) + \Delta t \frac{\partial \eta(x,t)}{\partial t} + \frac{\Delta t^2}{2} \frac{\partial^2 \eta(x,t)}{\partial t^2} + \frac{\Delta t^3}{2} \frac{\partial^3 \eta(x,t)}{\partial t^3} + \ldots \]  

(15)

where \( \Delta t \) is the grid interval. The staggered leapfrog scheme is used by applying central difference method (Eq.16) with the staggered numerical points for water level and discharges. \( O(\Delta t) \) is truncation error.

\[
\frac{\partial \eta(x,t)}{\partial t} = \frac{\eta(x,t + \frac{\Delta t}{2}) - \eta(x,t - \frac{\Delta t}{2})}{\Delta t} + O(\Delta t^2) \ldots \]  

(16)

Imamura and Goto (1988) investigated the truncation errors in three kinds of typical scheme for long wave’s simulations and showed that in term of numerical accuracy the staggered leapfrog scheme is the best among them. Eq.4 and Eq.5 are simplified to one-dimensional form in order to show the application to Eq. 15 and 16 and given in below.

\[
\frac{1}{\Delta t} (\eta^{n+1} - \eta^n) + \frac{1}{\Delta x} (M^{n+1}_{i+1/2} - M^{n+1}_{i-1/2}) + O(\Delta x^2) = 0 \ldots \]  

(17)

\[
\frac{1}{\Delta t} (M^{n+1}_{i+1/2} - M^{n-1}_{i-1/2}) + g \left( \frac{D_{i+1}^n + D_i^n}{2} \right) \frac{1}{\Delta x} (\eta^{n+1}_i - \eta^n_i) + O(\Delta x^2) = 0 \ldots \]  

(18)

Where \( \Delta x \) and \( \Delta t \) are the grid size in x direction and in time t and \( D_i^n = \eta_i^n + h_i \). The point schematics for the numerical scheme are illustrated in Figure 3.4 (Imamura et al. 2006).
The difference should be taken in the direction of the flow. This is the reason why this scheme is called the upwind difference. Although the leapfrog scheme has the truncation error of the order of $\Delta x^2$, as long as the convection term concerns, its order become large as $\Delta x$.

In numerical simulations, a numerical result is unexpectedly diverged depending on grid size and time step, which is caused by instability in numerical simulations. A stable numerical scheme is one for which errors from any sources (round-off, truncation and so on) are not permitted to grow in the sequence of numerical procedures as the calculation proceeds from one marching step to the next. The finite method provides stable results as long as it satisfies Eq. 19.

$$C(\text{celerity}) < \frac{\Delta x}{\Delta t}$$  \hspace{1cm} (19)

In designing numerical computations for long waves, it is recommended to set an open sea boundary. For the continuation of computation at the boundary of a region of different grid length and for stability of numerical computation, Eq.20 should be satisfied.

$$\frac{\Delta x}{\Delta t} \geq \sqrt{2gh_{max}}$$  \hspace{1cm} (20)
Where $\Delta x$ and $\Delta t$ are the temporal and spatial grid lengths, respectively and the ratio defines numerical speed, and $h_{\text{max}}$ is the maximum still water depth in a computation region. The numerical speed must be equal and greater than actual speed. In the leapfrog scheme, grid points are alternatively located for velocity and water level. The wave profile deforms, depending upon the spatial grid length and the travel distance. The smaller the grid length and the shorter the travel distance is, the truer the solution becomes.

### 3.4 Computational Tool

NAMI DANCE used for simulation and efficient visualization of tsunami, understanding and investigation of tsunami generation and propagation mechanisms. NAMI DANCE simulates, animates and visualizes generation, propagation, coastal amplification and inundation of tsunami given arbitrary shaped bathymetry under the input wave and current conditions. NAMI DANCE is developed in collaboration with Ocean Engineering Research Center, Middle East Technical University, Turkey and Institute of Applied Physics, Russian Academy of Science, Russia especially for tsunami modeling. NAMI DANCE has been, tested and verified parallel to TUNAMI-N2 in the international workshops (NAMI DANCE Manual 2010).

NAMI-DANCE is developed by using C++ programming language by following leapfrog scheme numerical solution procedures for faster simulation and better visualizations. The model creates the initial wave from different sources and generates the sea state at specific time intervals of tsunami during simulation. NAMI DANCE also computes the distributions of current velocities and their directions at selected time intervals, relative damage levels according to drag and impact forces, and it also prepares 3D plots of sea state at selected time intervals from different camera and light positions, and animates the tsunami propagation from source to target for.
visualization (Zaytsev et al. (2008)). NAMI DANCE is used for modeling of tsunami in several oceans and seas (Yalciner et al. 2007). The accuracy and the success of the models need higher accuracy of bathymetry. The bathymetry processing for simulations is given in the following.

3.5 Data Processing

Developing a bathymetric data is the basic step of tsunami modeling because tsunami propagation is affected by ocean bottom thus plays a great role in determining the wave height distributions in coastlines. It is necessary to note that high-resolution bathymetry maps are a crucial component in tsunami wave simulations.

Bathymetric data are the principal datasets required for the model to capture the generation, propagation and inundation of the tsunami wave from the source to the land. The bathymetry topography database for tsunami modeling is developed from GEBCO 30 sec. The bound coordinates are selected 55° - 76° E longitudes and 10° – 30° N latitudes.

3.6 Tsunami Forecast Points

20 locations are selected whether the region has touristic, industrial and geopolitical importance along the coast of India, Oman, Iran and Pakistan. The coordinates of the points satisfies the sea depth less than 10 m to better examine tsunami effect. The forecast points’ locations Kutch, Okha, Dwarka, Porbandar, Mumbai, Goa, Duqm, Masirah, Sur, Muscat, Suhar, Jask, Chabahar, Pasni, Ormara, Karachi are illustrated in Figure 3.5 and given in Table 3.3.
Table 3.3: Locations and Depth of Forecast Points

<table>
<thead>
<tr>
<th>Name of gauge point</th>
<th>Depth of gauge point (m)</th>
<th>Latitude (ºN)</th>
<th>Longitude (ºE)</th>
<th>Name of gauge point</th>
<th>Depth of gauge point (m)</th>
<th>Latitude (ºN)</th>
<th>Longitude (ºE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kutch, India</td>
<td>0.84</td>
<td>23.1158</td>
<td>68.7153</td>
<td>Muscat, Oman</td>
<td>37.52</td>
<td>23.5919</td>
<td>58.61</td>
</tr>
<tr>
<td>Okha, India</td>
<td>0.17</td>
<td>22.4826</td>
<td>69.0647</td>
<td>Sohar, Oman</td>
<td>1.98</td>
<td>24.3535</td>
<td>56.7543</td>
</tr>
<tr>
<td>Dwarka, India</td>
<td>5.99</td>
<td>22.2528</td>
<td>68.9445</td>
<td>Pasni, Pakistan</td>
<td>2.96</td>
<td>25.2022</td>
<td>63.4809</td>
</tr>
<tr>
<td>Porbandar, India</td>
<td>0.24</td>
<td>21.457</td>
<td>69.7793</td>
<td>Karachi, Pakistan</td>
<td>1.33</td>
<td>24.8351</td>
<td>66.9055</td>
</tr>
<tr>
<td>Mumbai, India</td>
<td>0.71</td>
<td>19.1829</td>
<td>72.7854</td>
<td>Karachi, Pakistan</td>
<td>0.6</td>
<td>24.9143</td>
<td>66.6777</td>
</tr>
<tr>
<td>Goa, India</td>
<td>0.47</td>
<td>15.5088</td>
<td>73.7597</td>
<td>Ormara, Pakistan</td>
<td>2.24</td>
<td>25.2489</td>
<td>64.5757</td>
</tr>
<tr>
<td>Duqm, Oman</td>
<td>1.58</td>
<td>19.6358</td>
<td>57.7365</td>
<td>Jask, Iran</td>
<td>1.1</td>
<td>25.6574</td>
<td>57.7906</td>
</tr>
<tr>
<td>Masirah, Oman</td>
<td>2.66</td>
<td>20.2889</td>
<td>58.7791</td>
<td>Chabahar, Iran</td>
<td>1.5</td>
<td>25.2713</td>
<td>60.6573</td>
</tr>
<tr>
<td>Sur, Oman</td>
<td>3.74</td>
<td>22.57</td>
<td>59.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.7 Results and Discussions

Discussion of modeling result is carried out in two stages: (a) first stage consists of the validation of the work and also the obtained results converted into GIS/CAD based application for better visualization and spatial analysis; (b) In second stage different scenario are generate by varying strike angle is discussed in next chapter 4.

There are different estimates about the location of earthquake epicenter. Heck (1947) reported the epicenter at 25.00º N and 61.50ºE. According to Pendse (1946), the epicenter was at 24.20ºN and 62.60ºE, about 120 km away from Pasni. Ambraseys and
Melville (1982) reported the epicenter at 25.02°N and 63.47°E. By recalculating the seismic parameters of the 1945 earthquake, Byrne et al. (1992) suggested the epicenter was at 25.15°N and 63.48°E, that used in the present study.

Run-up values estimated from historic reports are important for hazard assessment, thus we searched various references to find reliable information about the tsunami run-up heights along the different Makran coasts. Pendse (1946) reported: Pasni, an important trading centre along the Makran Coast and distant about 75 miles from the epicenter, was overwhelmed by the wave, there being serious loss of life and property. The height of this wave has been estimated variously from 40 ft (12 m) to 50 ft (15 m). Serious loss of life and property was also caused at Ormara (about 130 miles away from the epicenter) and in several coastal villages. Large quantities of fish were washed inland on the coast. Also, based on his report, the run-up heights observed in Karachi and Mumbai were of approximately 4.5 ft (1.4 m) and 6.5 ft (2 m), respectively.

Volcanic activity was reported by Pendse (1946) during the 1945 Makran earthquake. He reported the formation of two uncharted islets in the approximate position of 25°7’ N and 64°15’ E. Berninghausen (1966) reported that wave heights were about 40–50 ft (12–15 m) at both Pasni and Ormara, and 6.5 and 4.5 ft in Mumbai and Karachi, respectively. Ambraseys and Melville (1982) reported that the tsunami wave height was of approximately 4–5m in Pasni, about 1.5m in Karachi, and 2m in Mumbai. Also, they reported that the tsunami caused extensive flooding of low-lying areas in Iranian coastline, but no details were presented.

According to Murty and Bapat (1999), the tsunami was also observed at Muscat and Gwadar, and reached a height of about 11m in Kutch. The run-up height was
reported to have been about 40–50 ft (12–15 m) by Snead (1966). According to Snead (1966), two small rocky islands were formed off the Makran coast as a result of the 1945 earthquake. Based on Page et al. (1979), the 1945 tsunami reached a height of about 7–10m along parts of the Makran coast. Also, they reported that four mudvolcanoes, rising 8–30m above the Arabian Sea, were formed as a result of the earthquake. There was a time lag of about 2–3 h between the first and second tsunami waves. The second wave was larger than the first (Pendse, 1946; Ambraseys and Melville, 1982).

Page et al. (1979) reported that the uplift of the ocean floor due to the 1945 earthquake was about 2m. Also, Ambraseys and Melville (1982) reported 2m uplift and 1.5m subsidence following the 1945 event. Figure 3.6 presents a schematic view of the areas affected by the 1945 Makran tsunami and the reported run-up values in the different coasts.

![Figure 3.6: Areas affected by the Makran tsunami of 1945 in the MSZ and reported run-up heights along the various coasts](image-url)
3.7.1 Validation of the tsunami simulation results

Tsunami snapshots show that the 1945 event affected all the neighbouring countries including Iran, Oman, Pakistan, and India. However, the tsunami wave height along the southern coast of Pakistan is far larger than that along the other coasts. The initial wave amplitudes (elevation and depression) for source was computed using Okada’s (1985) method, the water elevation in the source is about 3 m, and the depression is about 1 m. The results of initial tsunami generation based on the fault parameters given by Byrne et al. (1992) are shown in Figure 3.7.

![Initial sea floor deformation at time t = 0 min](image)

Figure 3.7: Initial sea floor deformation at time t = 0 min

Tsunami snapshots (Figure 3.8) show that the 1945 Makran event affected all the neighbouring countries including Iran, Oman, Pakistan, and India. Tsunami snapshots (Figure 3.8 (a), 3.8 (b), 3.8 (c), 3.8 (d), 3.8 (e) and 3.8 (f)) shows the
estimated wave propagation at $t=0$, 30, 60, 90, 120 and 150 minutes after the tsunamigenic earthquake, respectively. Along the southern coast of Pakistan, the tsunami wave reaches Pasni in about 5-15 min, Ormara in about 60 min and Karachi in about 110 min. While along the southern coast of Iran, the tsunami wave reaches Chabahar in about 30-35 min and Jask in about 70-75 min. After the earthquake, the tsunami wave reaches the coast of Oman, namely at Muscat, in about 40 min, Sur in about 30-40 min, Masirah in about 60-70 min, Sohar in about 80 min and Duqm in about 130 min. Furthermore, the tsunami wave reaches the western coast of India along the Gulf of Kachchh in about 240 min, Okha in about 185 min, Dwarka in about 150 min, Porbandar in about 155 min, Mumbai in about 300 min and Goa in about 215 min. It is also observed that the distance from epicentre to Mumbai is less than Goa, but the arrival time of the first tsunami wave at the Mumbai is more than Goa. It could be due to the fact that Mumbai offshore is shallower that Goa and also due to the directivity of tsunami wave propagation. It is well known that most of the tsunami’s energy travels perpendicular to the strike of the fault which is due to directivity (Ben-Menahem & Rosenman 1972; Singh et al. 2012). Due to this effect, most of the tsunami energy propagates in the direction shown in figure 3.9.

![Figure 3.8: Results of the tsunami generation (a) and propagation modeling (b, c, d, e and f).](image-url)
Figure 3.8: Results of the tsunami generation (a) and propagation modeling (b, c, d, e and f).
Figure 3.8: Results of the tsunami generation (a) and propagation modeling (b, c, d, e and f).
The tsunami travel time contour map showing the location of the leading wave front at 30 minutes intervals is given in figure 3.10. The closely spaced contour along are indicates that the bathymetrical features slow down the tsunami wave propagation. The ocean depth suddenly changed from deep (>2000 m) to shallower depth (<225 m). It should be noted from figure 3.11 that the bathymetric features act as a natural barrier to slow down tsunami waves at shallower depths (<225 m) by refractions and diffractions of sea-waves. Several researchers reported that the delay in the tsunami arrival from MSZ was probably due to a submarine landslide generated by the earthquake (Bilham et al. 2007; Neetu 2011).
Figure 3.10: Tsunami travel time contour map.

Figure 3.11: Bathymetry map in and around the study region.
Figure 3.12 (a-d) shows the maximum calculated tsunami run-up along the neighbouring countries including Iran, Oman, Pakistan, and India for a tsunami simulation of 360 min. The maximum calculated tsunami run-up were about 0.7-1.1m along coast of Oman (0.5 near Muscat, 0.1 near Sur), 0.7-1.35m along the western coast of India, 0.5-2.3m along the southern coast of Iran and 1.2-5.8m along the southern coast of Pakistan are shown in Figure 3.12 (a-d), respectively. The tsunami run-up along the southern coast of Pakistan is far larger than that along the other coasts may be due to directivity of the tsunami. The time series for tsunami forecast points along Pakistan, India, Iran and Oman are presented in Figure 3.13(a-d), respectively. The tsunami run-up and its arrival time at various tide gauge stations are listed in Table 3.4.
Figure 3.12(a): Maximum calculated tsunami run-up along Oman for a tsunami simulation of 360 min

Figure 3.12(b): Maximum calculated tsunami run-up along Iran for a tsunami simulation of 360 min
Figure 3.12(c): Maximum calculated tsunami run-up along India for a tsunami simulation of 360 min

Figure 3.12(d): Maximum calculated tsunami run-up along Pakistan for a tsunami simulation of 360 min
Figure 3.13 (a): Time series of the calculated tsunami run-up at several locations along the coast of India
Figure 3.13(b): Time series of the calculated tsunami run-up at several locations along the coast of Oman
Figure 3.13(c): Time series of the calculated tsunami run-up at several locations along the coast of Pakistan

Figure 3.13(d): Time series of the calculated tsunami run-up at several locations along the coast of Iran
### Table 3.4: The maximum tsunami run-up and its arrival time at various forecast points

<table>
<thead>
<tr>
<th>Name of gauge point</th>
<th>Depth of gauge point (m)</th>
<th>Latitude (ºN)</th>
<th>Longitude (ºE)</th>
<th>Time first wave (min)</th>
<th>Time max. wave (min)</th>
<th>+Amplitude (m)</th>
<th>-Amplitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kutch, India</td>
<td>0.84</td>
<td>23.1158</td>
<td>68.7153</td>
<td>206.433</td>
<td>211.7</td>
<td>1.21</td>
<td>-0.76</td>
</tr>
<tr>
<td>Okha, India</td>
<td>0.17</td>
<td>22.4826</td>
<td>69.0647</td>
<td>187.467</td>
<td>192.3</td>
<td>0.56</td>
<td>-0.4</td>
</tr>
<tr>
<td>Dwarka, India</td>
<td>5.99</td>
<td>22.2528</td>
<td>68.9445</td>
<td>146.1</td>
<td>151.467</td>
<td>0.71</td>
<td>-1.13</td>
</tr>
<tr>
<td>Porbandar, India</td>
<td>0.24</td>
<td>21.4570</td>
<td>69.7793</td>
<td>159</td>
<td>164.467</td>
<td>1.13</td>
<td>-0.43</td>
</tr>
<tr>
<td>Mumbai, India</td>
<td>0.71</td>
<td>19.1829</td>
<td>72.7854</td>
<td>299.367</td>
<td>305.2</td>
<td>0.96</td>
<td>-0.43</td>
</tr>
<tr>
<td>Goa, India</td>
<td>0.47</td>
<td>15.5088</td>
<td>73.7597</td>
<td>222.967</td>
<td>227.767</td>
<td>1.01</td>
<td>-0.56</td>
</tr>
<tr>
<td>Duqm, Oman</td>
<td>1.58</td>
<td>19.6358</td>
<td>57.7365</td>
<td>117.5</td>
<td>130.167</td>
<td>0.56</td>
<td>-0.46</td>
</tr>
<tr>
<td>Masirah, Oman</td>
<td>2.66</td>
<td>20.2889</td>
<td>58.7791</td>
<td>61.333</td>
<td>63.9</td>
<td>0.28</td>
<td>-0.26</td>
</tr>
<tr>
<td>Sur, Oman</td>
<td>3.74</td>
<td>22.5700</td>
<td>59.5300</td>
<td>38.033</td>
<td>42.6</td>
<td>1.16</td>
<td>-1.3</td>
</tr>
<tr>
<td>Muscat, Oman</td>
<td>37.52</td>
<td>23.5919</td>
<td>58.6100</td>
<td>38.9</td>
<td>42.433</td>
<td>0.53</td>
<td>-0.33</td>
</tr>
<tr>
<td>Sohar, Oman</td>
<td>1.98</td>
<td>24.3535</td>
<td>56.7543</td>
<td>78.333</td>
<td>82.067</td>
<td>0.46</td>
<td>-0.42</td>
</tr>
<tr>
<td>Pasni, Pakistan</td>
<td>2.96</td>
<td>25.2022</td>
<td>63.4809</td>
<td>0</td>
<td>7.133</td>
<td>1.25</td>
<td>-1.65</td>
</tr>
<tr>
<td>Karachi, Pakistan</td>
<td>1.33</td>
<td>24.8351</td>
<td>66.9055</td>
<td>120.733</td>
<td>135.333</td>
<td>0.88</td>
<td>-1.33</td>
</tr>
<tr>
<td>Karachi, Pakistan</td>
<td>0.60</td>
<td>24.9143</td>
<td>66.6777</td>
<td>97.2</td>
<td>252.467</td>
<td>1.55</td>
<td>-0.6</td>
</tr>
<tr>
<td>Ormara, Pakistan</td>
<td>2.24</td>
<td>25.2489</td>
<td>64.5757</td>
<td>60.6</td>
<td>67.333</td>
<td>1.02</td>
<td>-1.19</td>
</tr>
<tr>
<td>Jask, Iran</td>
<td>1.10</td>
<td>25.6574</td>
<td>57.7906</td>
<td>71.333</td>
<td>75.167</td>
<td>0.54</td>
<td>-0.48</td>
</tr>
<tr>
<td>Chabahar, Iran</td>
<td>1.50</td>
<td>25.2713</td>
<td>60.6373</td>
<td>32.567</td>
<td>38.233</td>
<td>1.33</td>
<td>-0.92</td>
</tr>
</tbody>
</table>
It is observed from Figure 5.8 that the maximum run-up heights due to the 1945 tsunami in Pasni, Raan of Kutch, Gulf of Kutch, and Mumbai are about 5-6, 1.5, 0.75, and 1.1 m, respectively. The simulated run-up height is in agreement with the earlier published data. In the near field, i.e., Pasni, the simulated run-up height is in agreement with the observed run-up during the 1945 event reported by Page et al. (1979) and Ambraseys and Melville (1982). However, it is smaller than the run-up height of about 12–15m reported by Pendse (1946), Berninghausen (1966), and Snead (1966). It could be limitation of tsunami model.

The first tsunami wave approaches the coast within 299.36 minutes at Mumbai, 222.96 minutes at Goa. The distance from epicentre to Mumbai is less compare to Goa, but the arrival time of first tsunami wave is more, which is due to the effect of directivity. It could be concluded from Figure 5d that most of the tsunami’s energy travels perpendicular to the strike of the fault which is due to the effect of directivity (Okal and Talandier, 1991).

The first tsunami wave approaches the coast within 187.46 minutes at Okha, 146.1 minutes at Dwarka and 159 minutes at Porbandar. The maximum runup at Okha is approximately 0.56m and estimated arrival time is 192.3 minutes, at Dwarka is approximately 0.71m and estimated arrival time is 151.46 minutes, at Porbandar is approximately 1.13m and estimated arrival time is 164.46 minutes.

3.10 Conclusions
The NAMI-DANCE numerical model has successfully simulated the propagation of tsunami event of 28th November 1945. The simulated results are qualitatively reliable with the reported damage. Our model gives maximum amplitude along the creeks at the coast of
Gujarat. So the most vulnerable areas of the coast need to be provided greater protection when planning for preparedness. Tide gauges should be installed where the tsunami amplitude is bigger. For a tsunami generated from MSZ, which propagates across the Arabian Sea or Indian Ocean, there is half an hour to 1 h arrival time for more accurate and reliable warning for Gujarat Coast and western coast of India. Any large earthquake in the world can be located in 7–15 min using seismic body waves recorded on the global seismic network. For accurate estimation of earthquake size, a few tens of minutes may be needed until surface waves are recorded around the globe. Because there is only half an hour to 1 h time before tsunami arrival at the Gujarat coast and western coast of India, it is very important to actually confirm the tsunami generation. The calculated 2.0 hr tsunami travel time to Indian coast is in good agreement with earlier reports. For this purpose, sea level monitoring systems, located on western coasts and offshore of India, are necessary. The seismic and sea level data need to be shared in real-time, using satellite communication.

An effective tsunami early warning system is achieved when all the persons in vulnerable western coastal communities are prepared and respond appropriately, and in a timely manner, upon recognizing that a potentially destructive tsunami is approaching. Timely tsunami warnings issued by a recognized tsunami warning center are essential. When these warning messages are received by the designated government agency, tsunami emergency response plans must already be in place in coastal communities so that standard and efficient actions are immediately taken for evacuation, if necessary.