

Numerical Modeling of Tsunami Inundation for Potential Earthquake at Makran Subduction Zone

(A case study for Gwadar Coastal Area)



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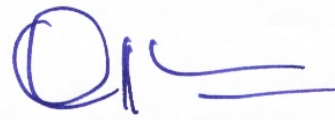
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PREFACE

Makran Subduction Zone is unique region in the world due to its geological and seismological characteristics. Shallow angle of dip and rate of subduction are interesting and distinctive features of this zone. This area has observed Tsunamigenic events as a result of major shock Magnitude 8.4 in October 1945 which caused about 4000 casualties along the Makran coast. Since then a long silence poses a potential threat of major tsunamigenic disaster for the coastal dwellers in that region.

The source is very close to Pakistan's coast line and the tsunami waves may take hardly 20 to 25 minutes to reach the coast line. Present report delineates the possible threat of tsunami in the coastal areas of Pakistan. Different parameters like arrival time, wave height and maximum amplitude of tsunami waves are imperative for hazard estimation, evacuation and emergency response in the region. All these parameters have been detailed in this study to mitigate hazard and avoid any loss of life due to such catastrophic event if occurs in future. This study could be helpful and may provide a scientific reason for decision makers in the process of future disaster mitigation planning.



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Summary

According to the historical seismic importance of Makran Subduction Zone (MKZ), it has the potential for future large earthquakes and tsunami. This study is based on numerical modeling of tsunami propagation by taking Gwadar coast as focal area which has geographical and economical importance for Pakistan and had been extensively affected by tsunami generated in 1945 Makran earthquake. Simulation for tsunami propagation and inundation at Gwadar coast was carried out at moment magnitude M_w 8.5; 5.26 m rupture slip due to this earthquake and fixing the source area within Makran Subduction Zone i.e. 120 km away from the coastline. The results show maximum flow depth of 5m and maximum inundation up to 1.46 km on Gwadar coast. Numerical simulation reveals that any future Makran Subduction Zone earthquake with M_w 8.5 can generate a destructive tsunami.

Key Words: Makran Subduction Zone, Gwadar coastal area, Maximum flow depth, Maximum inundation, Numerical modeling

1. Introduction

Numerical modeling of tsunami is very important for understanding past events and simulating future ones. The use of numerical modeling to determine the potential run-ups and inundation from a local or distant tsunami is recognized as useful and important tool, since data from past events is usually insufficient. The tsunami of 1945 from Makran earthquake has left perspective, the need for assessing tsunami hazard in vulnerable coastal areas of Pakistan. The size of a tsunami generated by a subduction zone earthquake depends on a number of factors including the magnitude, source geometry and location of the event. The magnitude and source geometry of the earthquake determine the surface deformation, which, in turn, evaluates the overall size and length scale of the tsunami. Representative source geometry can be calculated via an empirical formula that takes fault length, width, slip and moment magnitude into account. In the present study, we used ComMIT software (*Community Model Interface for Tsunami*) as a research tool, which is an internet-enabled interface to the community tsunami model developed by the NOAA Center for Tsunami Research (NCTR).

Inundation modeling was done for the Gwadar coastal area in order to assess the potential and find out the impact of tsunami from any future Makran Subduction Zone earthquake. The focus of this initial study is to model maximum wave heights at the shoreline of Gwadar coastal area.

2. Tsunamigenic Source Threatening Pakistan

In south of Pakistan we have Makran Subduction Zone which is the source of 1945 Makran earthquake. In Makran Subduction Zone, the denser micro oceanic Arabian Plate is going to be subducted underneath the less dense large continental Eurasian Plate. This subduction results thrust faulting in the area, which is the major source of generating the Tsunamigenic events. Although this subduction zone is not much larger but on the basis of historic records we cannot ignore its tsunami producing potential.

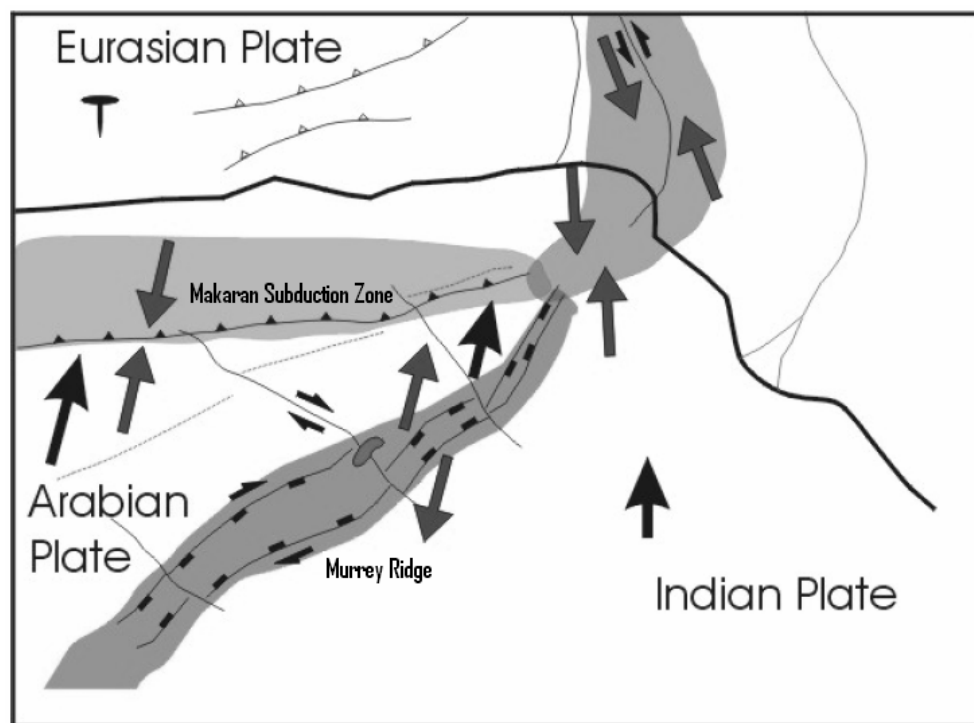


Figure-1: Makran Subduction Zone where Arabian Plate is subducted into Eurasian Plate.

2.1. Focal Mechanism Solution at Makran Subduction Zone

The source mechanism solutions of Makran Subduction Zone shows that thrust faulting is more dominant with strike slip component, which is a characteristic of subduction zone as shown below in Figure 2. The earthquake mechanism (focal mechanism) shows that the part of the sea is going downward opposite to the coast line. If the Tsunamigenic earthquake occurs, the sea will retrieve first and then after some time high tide will approach the Makran coast.

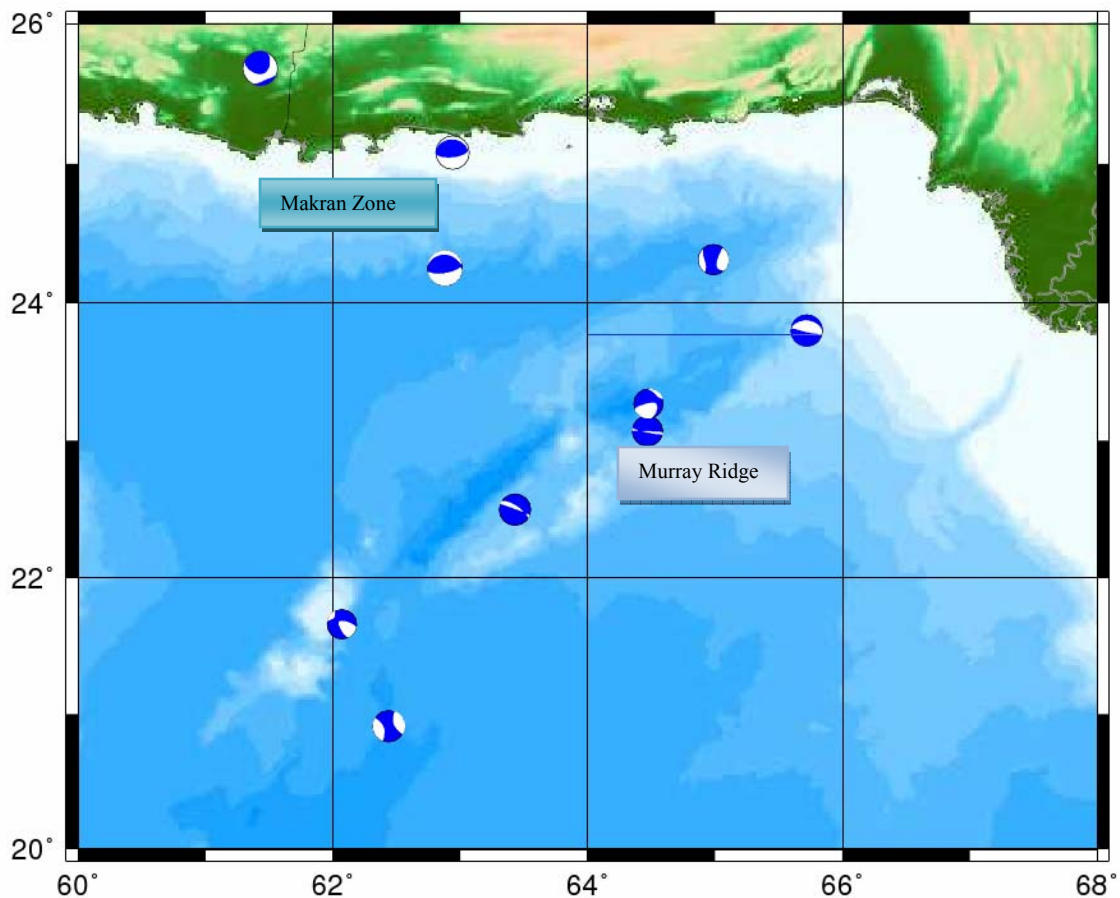


Figure- 2: Focal Mechanism solutions of Earthquakes in Arabian Sea

3. Numerical Modeling of source area in Makran Subduction Zone

Numerical modeling is useful in creating the tsunami generation in deep or coastal waters, wave propagation to the impact zone and inundation along the study area. We used [MOST](#) (Method of Splitting Tsunami) model, developed by Titov of PMEL and Synolakis of University of Southern California along with ComMIT (Community Model Interface for Tsunami) interface for tsunami generation, wave propagation to the impact zone and inundation along the study area. To reproduce the correct wave dynamics during the [inundation computations](#) high resolution bathymetric and topographic grids are needed. In this study we have selected source area which lies in the Makran Subduction Zone.

3.1. Model Grids

In order to assess the tsunami impact along the Gwadar coastal area, we have selected three Grids A, B and C in which C is subset of B and B is subset of A. The size and resolution of three grids are also defined in Table 1.

Table-1

Most Stage	Resolution
Grid A (Outer)	1 arc minute (~1800m)
Grid B (Intermediate)	6 arc seconds (~180m)
Grid C (Inner)	2 arc seconds (60m)

ComMIT Grids; A, B and C selected around Gwadar coastal area within Makran source shown in Figure 3 by considering two important factors:

- Ideally grids should have ratio 1:6 (1:10 maximum)
- Boundaries should not intersect

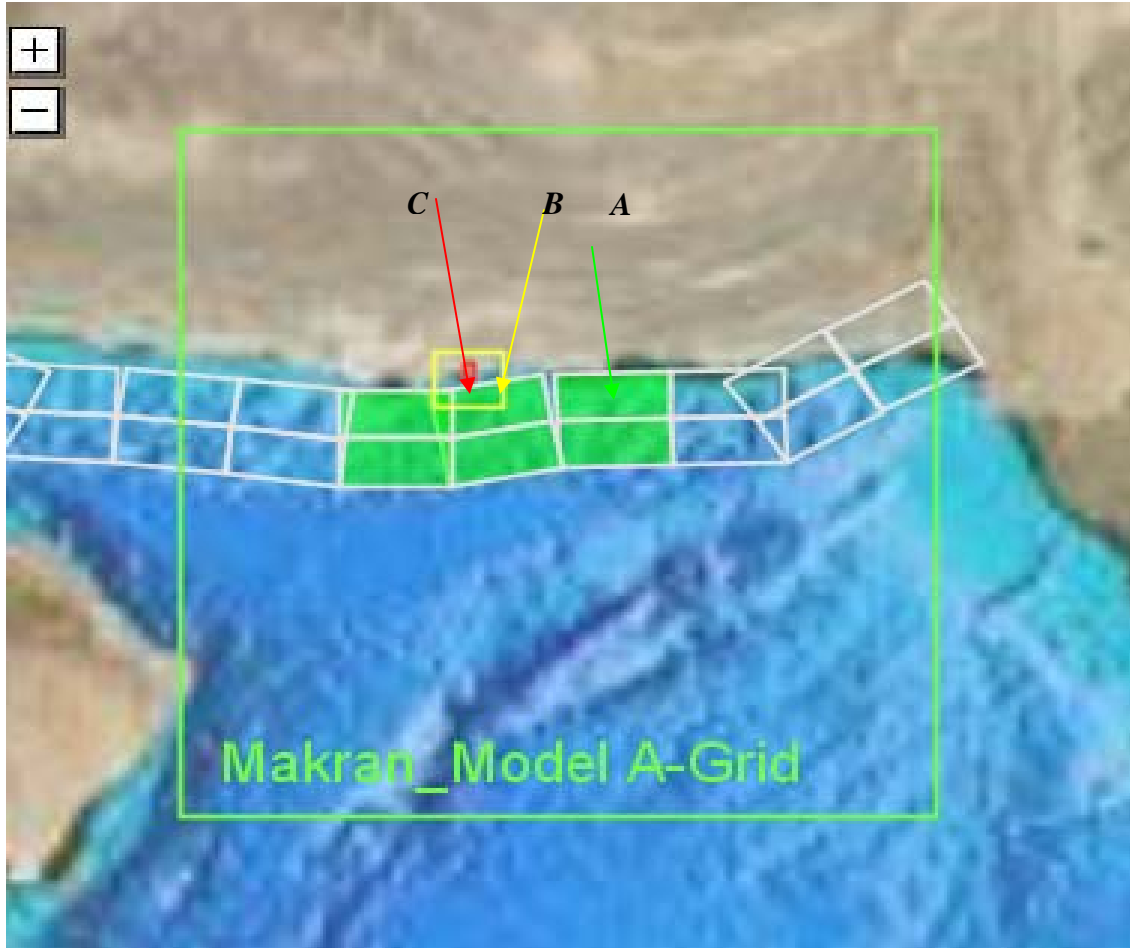


Figure-3: Grids of selected source area (Gwadar)

3.2 Bathymetry Data

The bathymetry data used in this model is 2- arc minute global relief data (ETOPO2) produced by the NOAA National Geophysical Data Center, obtained from web source: <http://sift.pmel.noaa.gov/grid/>.

ETOPO2 dataset, which was generated from digital data bases of seafloor and land elevations on a 2-minute latitude/longitude grid. The ETOPO2v2 dataset is compiled from several sources; most bathymetry comes from the Smith & Sandwell satellite radar altimetry dataset. Topography is from the CGIAR SRTM 90m digital elevation model produced by the CGIAR Consortium for Spatial Information. CGIAR's dataset is a processed version of the Shuttle Radar Topography Mission (SRTM) data created by NASA.

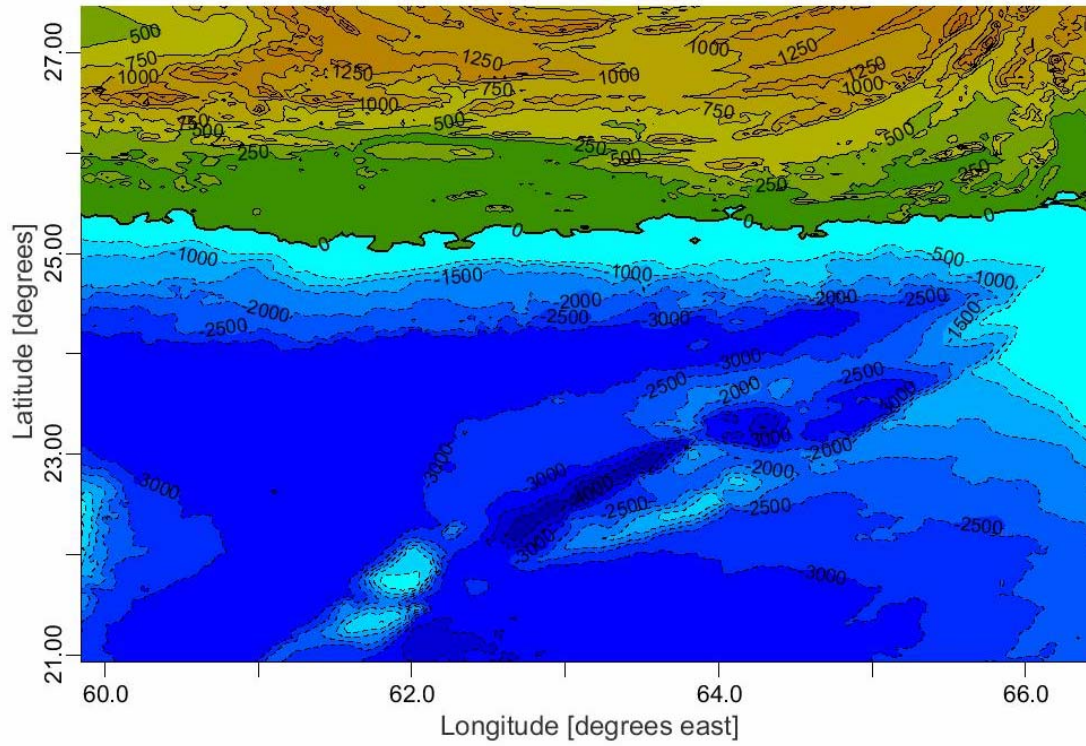


Figure-4: Depth in meters of the Arabian Sea in front of Makran coast Grid A of fig 3.

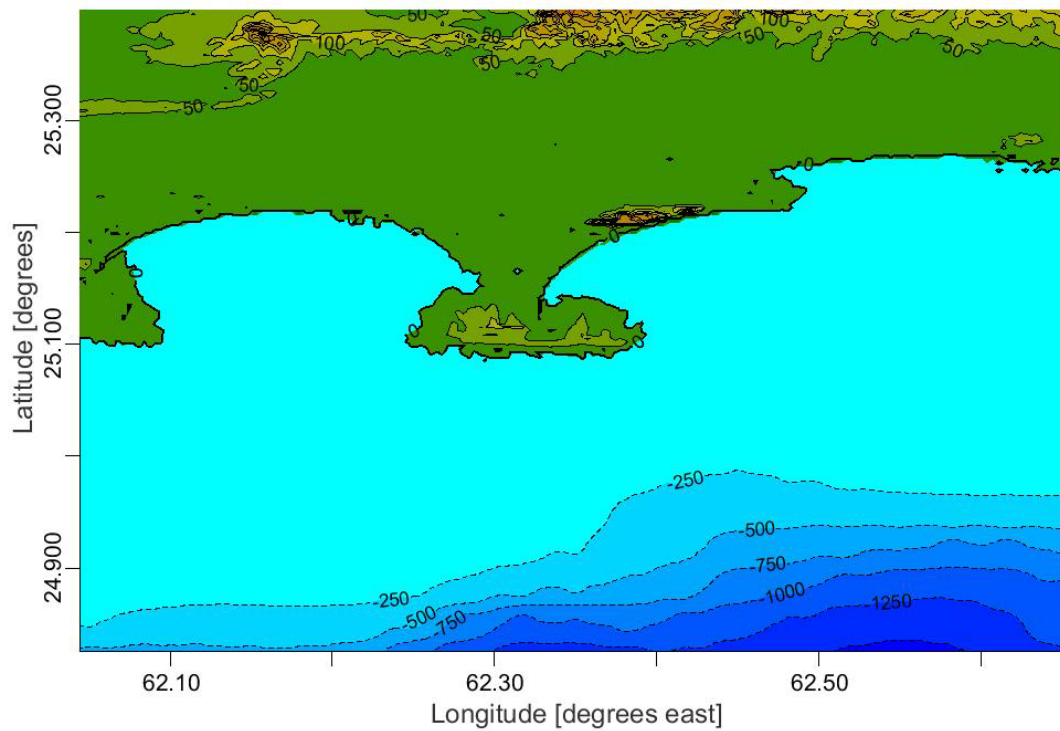


Figure-5: Depth in meters of Sea water close to Makran coast, Grid B of fig-3.

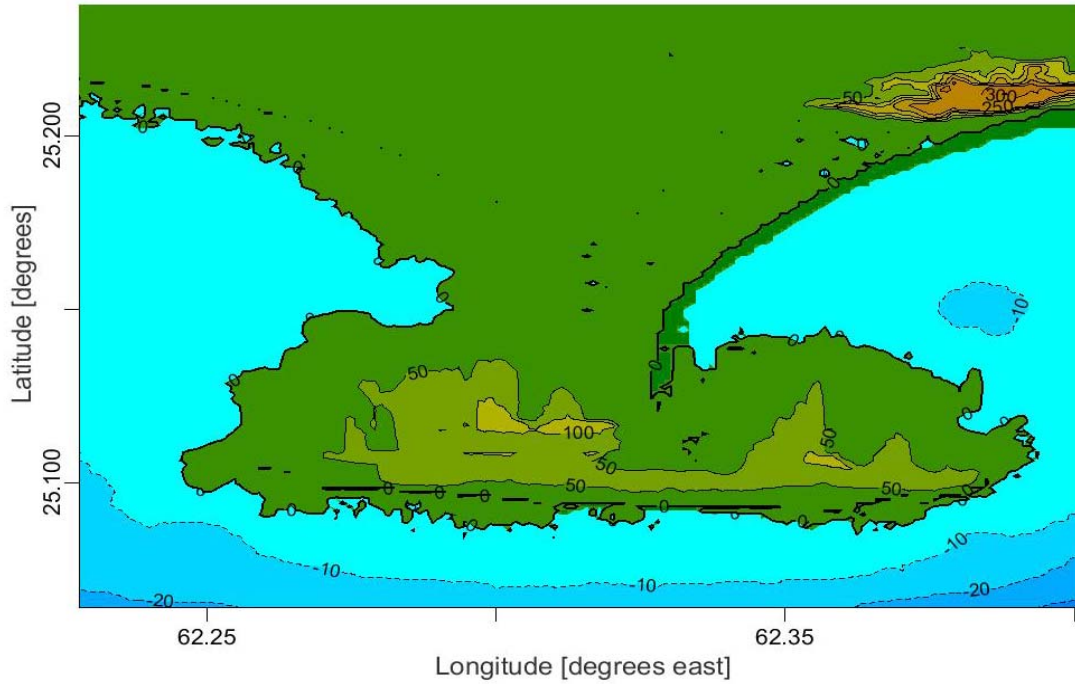


Figure-6: Depth in meters of Sea water close to Makran coast, Grid C of fig-3.

The model was designed to compute shoreline wetting (wave run-up) and drying (wave retreat) in its finest grid C (Gwadar coast).

3.3. Magnitude and Estimated Slip at Source

We selected 06 unit sources with time step of length 1.35sec by using CFL (Courant-Friedrich-Lewy) condition

$$\Delta t \leq \min \Delta x_i / |u_i| + \sqrt{g h_i}$$

The results were tested by fixing Magnitude at 8.5 and the fault supposed to be moved up to ~5.26m. The tsunami source is very close to the Makran coast so 6000 second (100 minutes) total run time was selected. The first tsunami waves may strike to Gwadar in 22 minutes.

Table-2: Parameters on which inundation was computed by using ComMIT Technique.

Total Magnitude		8.5	Mw	
Name	% Mag	Slip (m)	0.0050	Minimum amp of input offshore wave (m)
Mksza4	16.7	5.26	5.0	Minimum Depth of offshore (m)
Mkszb4	16.7	5.26	0.1	Dry land depth of inundation (m)
Mksza5	16.7	5.26	0.0009	Friction coefficient (n**2)
Mkszb5	16.7	5.26	✓	Let A- Grid and B- Grid run up
Mksza6	16.7	5.26	90.0	Max. eta before blow-up (m)
Mkszb6	16.7	5.26	1.35	Time Step (sec)
			6000	Total number of time steps in run
			1	Time steps between A- Grid computations
			1	Time steps between B- Grid computations
			30	Time steps between output steps
			1	Save output every n-th grid point
Add/Del		Jump	Current Site	

3.4. Shallow Water Wave Propagation

In order to estimate the Tsunami propagation in Arabian Sea and inundation along Gwadar coastal areas, shallow water wave equations (V.V Titov and Synolakis, 1995, 1996, 1997) for simulating the event was used. We apply the Numerical model “MOST” (Method of Splitting Tsunami) developed by NOAA/PMEL to implement non-linear shallow water ocean model. Wave propagation is accomplished with a numerical dispersion scheme. The model equations for shallow water wave propagation are;

$$h_t + (uh)_x + (vh)_y = 0$$

$$u_t + uu_x + vu_y + gh_x = gd_x$$

$$v_t + uv_x + vv_y + gh_y = gd_y$$

$$d(x,y,z) = d_0(x,y,t), t \leq t_0$$

$$d(x,y,t) = d_0(x,y,t_0), t \leq t_0$$

where $h = \eta(x,y,t) + d(x,y,t)$ is the amplitude, $d(x,y,t)$ is the undisturbed water depth, $u(x,y,t)$, $v(x,y,t)$ are the depth-averaged velocities in the x and y directions respectively, g is the acceleration of gravity.

In this model, a set of nonlinear shallow water equations with bottom friction term are discretized by the leap-frog finite difference scheme. This model is useful to simulate tsunami propagation and inundation on a dry land.

4. Computational Analysis and Results

Based on the numerical model results, the spatial distribution of estimated tsunami height and its inundation is estimated for the case of Gwadar coastal area from any future expected Makran Subduction Zone earthquake. The maximum wave amplitude on MOST output Model is shown in the fig below.

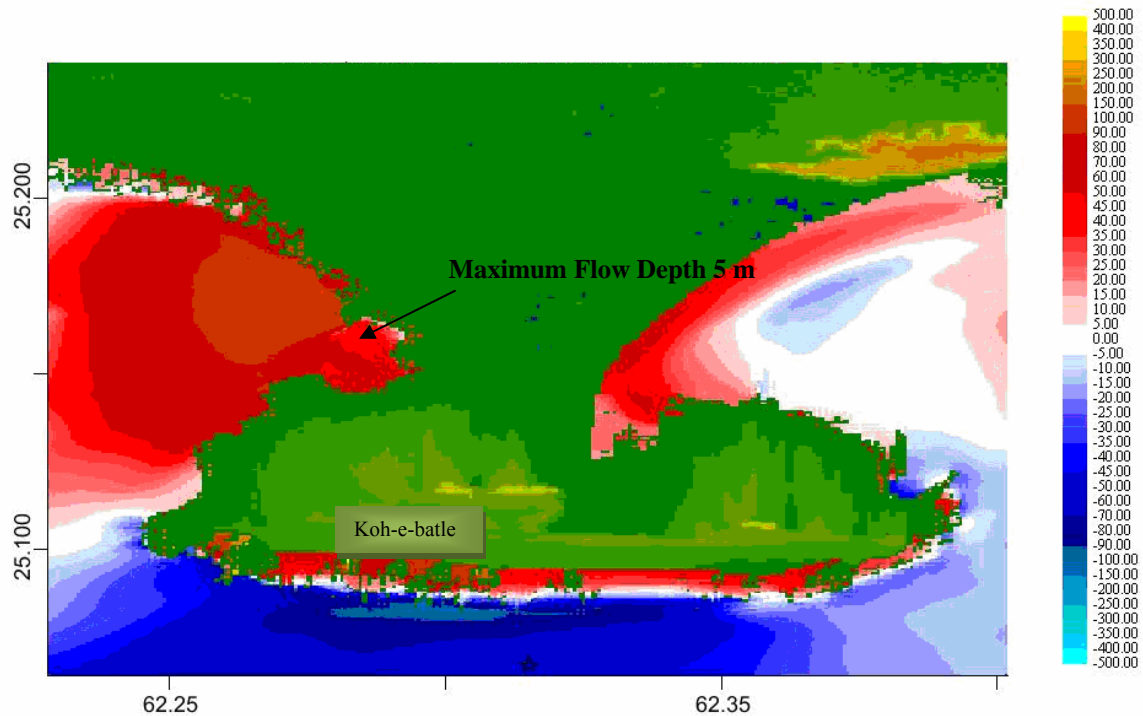


Figure-7: Maximum Wave Amplitude MOST Output Model

4.1. Maximum Inundation

Maximum inundation results for MOST Model with the use of ComMIT technique are shown below in the Figure 8. The maximum inundation is approximately 1.46km and maximum flow depth of 5m. The figures describe the distribution of maximum inundation depths on the land, which is measured from the local ground to the surface of surging water. For these areas,

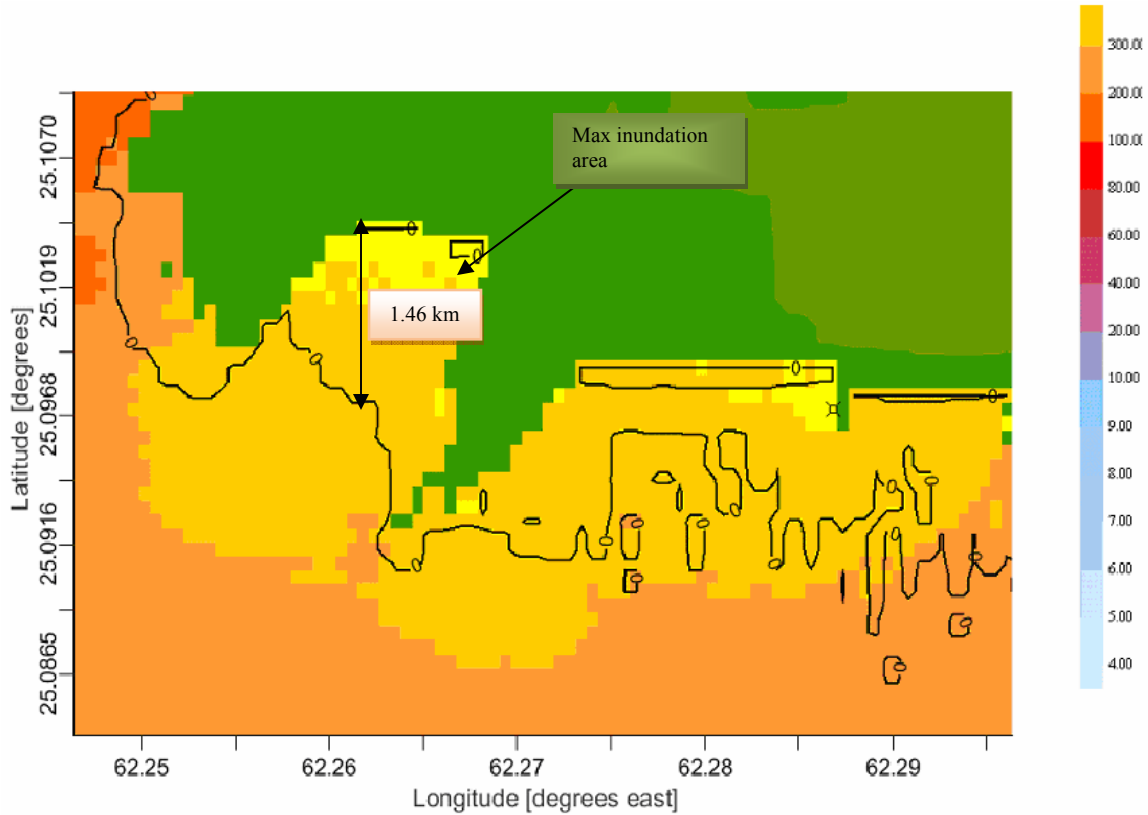


Figure-8: Maximum Inundation Results

Figure-8: shows inundation in the Gawadar area with maximum inundation 1.46 km as mentioned in the figure.

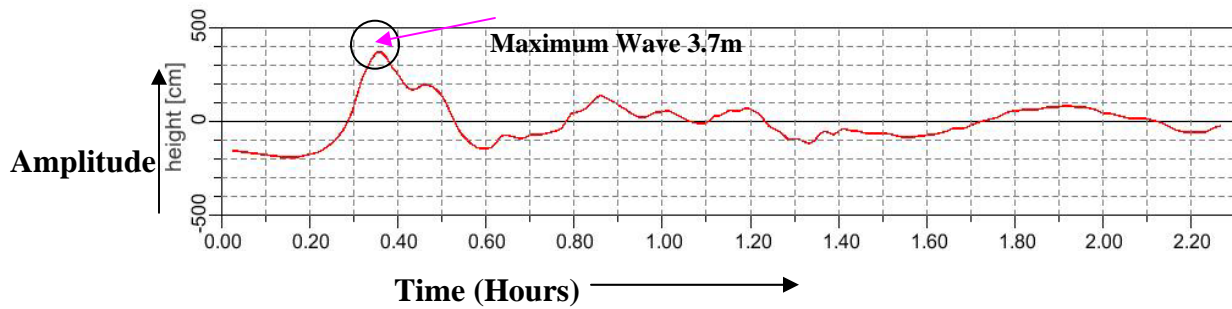


Figure-9: Graph 1, Maximum Wave at Gwadar

The maximum run up at Gwadar is approximately 3.7 m and estimated time of arrival is 22 minutes to reach Gwadar coast for an earthquake of magnitude Mw 8.5 if occurred in Makran subduction zone. The maximum possible time duration for tsunami existence is 2 hours and 30 minutes approximately, wave height approaches to minimum.

4.2 Results of Tsunami impacts along the Gwadar Coast

Inundation was also tested for Gwadar coastal area as shown below in figure 7. The Inundation map at Gwadar area shows that the inundations mainly occur at the left corner of Gwadar coast.

5. Conclusions

- Tsunami energy is concentrated along the Makran Zone (shallow area)
 - Maximum flow depth could be **5 meters**.
 - Maximum inundation distance at Gwadar \approx **1.46 km**
 - Maximum Run-up of wave at Gwadar: 3.7 meters and estimated arrival time 22 Minutes.
 - Results may be more refined by using more accurate Bathymetry and topography data [international bathymetry data was used which is only up to 10 m. It is worth mentioning here that for the purpose of Navigation, below 10 m data is useless].
 - High resolution bathymetry data with topography is important for inundation mapping.
- ✓ This technique (used by PMD) could provide propagation and Inundation Mapping for entire coastal belt of Pakistan.
 - ✓ This technique (**ComMIT**) provided benchmarked and validated numerical modeling methods for Makran coast.
 - ✓ PMD can develop numerical modeling for tsunami source generation, wave propagation and coastal inundation for whole Makran coast.

1-These results indicates the numerical modeling of trans-Oceanic propagation to estimate the potential tsunami hazard.

2) Regional Damage Mapping: GIS analysis with world population database to find out the impacted region and exposed population against tsunami.

3) Local damage estimation efforts: numerical modeling of coastal inundation with use of fragility functions to quantify the damage. This method changes its focus from regional to local scale as the possible affected area is detected.

Models can be initialized with potential worst case scenarios for the tsunami sources or for the waves just offshore to determine corresponding worst case scenarios for **run-up and inundation**. Models can also be initialized with smaller sources to understand the **severity of the hazard** for the less extreme but more frequent events. This information could become the basis for creating tsunami **evacuation maps and procedures**. Such modeling is proposed to be carried out for entire coast length of Pakistan to **identify the areas at risk**.

Detecting local damage in the impacted area requires the integrated approach of inundation modeling with local bathymetry/topography grid and fragility functions to convert the estimated potential tsunami hazard into the qualitative estimation of damaged houses or casualties.

One more factor we cannot ignore, the repulsion of waves from the coast of Oman and may travel back toward Makran coast of Pakistan.

Numerical Results:

We summarize the numerical results obtained from ComMIT software. Tsunami propagation within the Gawadar coast is modeled. The results of numerical simulation demonstrate the water movement that generates the receding and rushing waves.

1. At $t=0$ min wave height is 0 m which is initial condition i.e. time of just occurrence of earthquake Mw 8.5.
2. At $t=12$ min, retrieval of sea water up 1 m from generation of tsunami.
3. After $t=16$ min, depression of water may go to 4m
4. At $t=22$ min, the first wave arrives at the coast with maximum run up 3.7 m.
5. The maximum inundation is approximately 1.46km Figure 8 describes the distribution of maximum inundation depths on the land, which is measured from the local ground to the surface of surging water.

6. The maximum run up at Gwadar is approximately 3.7 m and estimated time of arrival is 22 minutes to reach Gwadar coast for an earthquake Mw 8.5 produced a tsunami.
7. The maximum possible time interval for tsunami is measured from the graph 1 is 2 hours and 30 minutes approximately at which wave height approaches to minimum level.
8. Maximum flow depth could be **5 meters** as shown in figure 7.
9. Along the coast, multiple and significant tsunami run-up with the periods of 2-30 hours resulted because of the reflections and energy entrapment of the tsunami.
10. The numerical results of tsunami propagation show that most of the wave energy is trapped in the Gawadar peninsula and then propagated mostly towards narrow beam as waves become more steeper This is because the strait to the Arabian sea was narrow and Gawadar is wide open to Arabian Sea. The simulation suggests that, besides the Makran coasts, significant tsunami run-up is received at Gawadar
11. The results indicate that the smaller the flow velocity in the shallow water region, the smaller the wave height of the rushing wave.
12. Results may be more refined by using more accurate Bathymetry and topography data [international bathymetry data was used which is only up to 10 m. It is worth mentioning here that for the purpose of Navigation, below 10 m data is useless].

The results of numerical simulation demonstrate the water movement that generates the receding and rushing waves. The results indicate that the smaller the flow velocity in the shallow water region, the smaller the wave height of the rushing wave.

There are 3 sides of Gawadar peninsula attacked by the tsunami. One is wide open in front of Arabian Sea which experiences direct attack of tsunami from any Makran Source. The water flowing into the open flat peninsula side where waves get quickly dispersed during the propagation to the shore before 20 minutes of occurrence of earthquake and it can not cause significant impact as compared to the narrow part of peninsula because of tsunami attack from two sides which cause waves become more steeper and rising amplitude of the wave and result significant inundation on this narrow part and it can experience significant disaster.

The narrow part of peninsula can have impact of the receding and rushing waves.

The receding wave covers the entire coast over 2 and half hours after the impact. The positive wave follows with a height of more than 3.5 m, reaching the coastal area. It runs up over the Plains and passes the Gawadar area a distance of over 1.46 km. The time history of the simulated tsunami shows multiple waves, riding on the main slow water-level fluctuations. The simulated wave heights at Gawadar correspond well with the results of Makran earthquake 1945 at which estimated the run-up of 3.5 m from the geological inference of the tsunami deposits.

Acknowledgement

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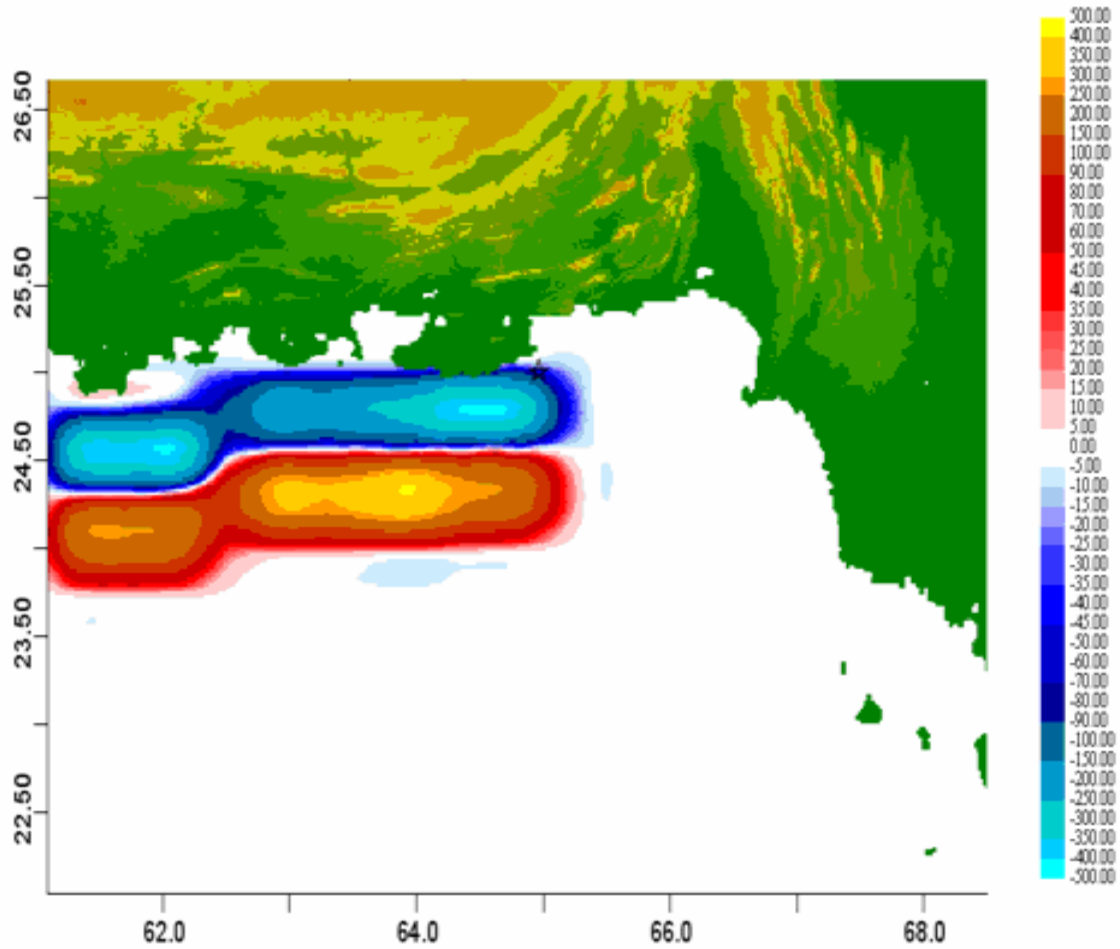
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Web sources:

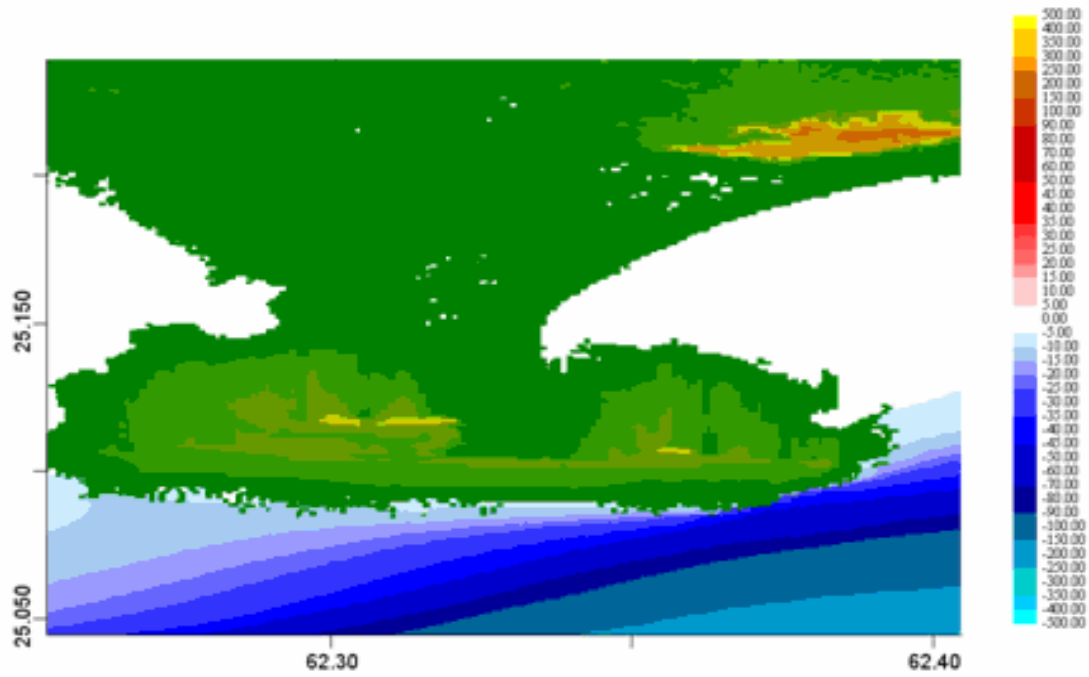
1. <http://nctr.pmel.noaa.gov/ComMIT/>
2. <http://sift.pmel.noaa.gov/grid/>
3. <http://www.globalcmt.org/CMTsearch.html>
4. <http://srtm.csi.cgiar.org/>

Annex-1

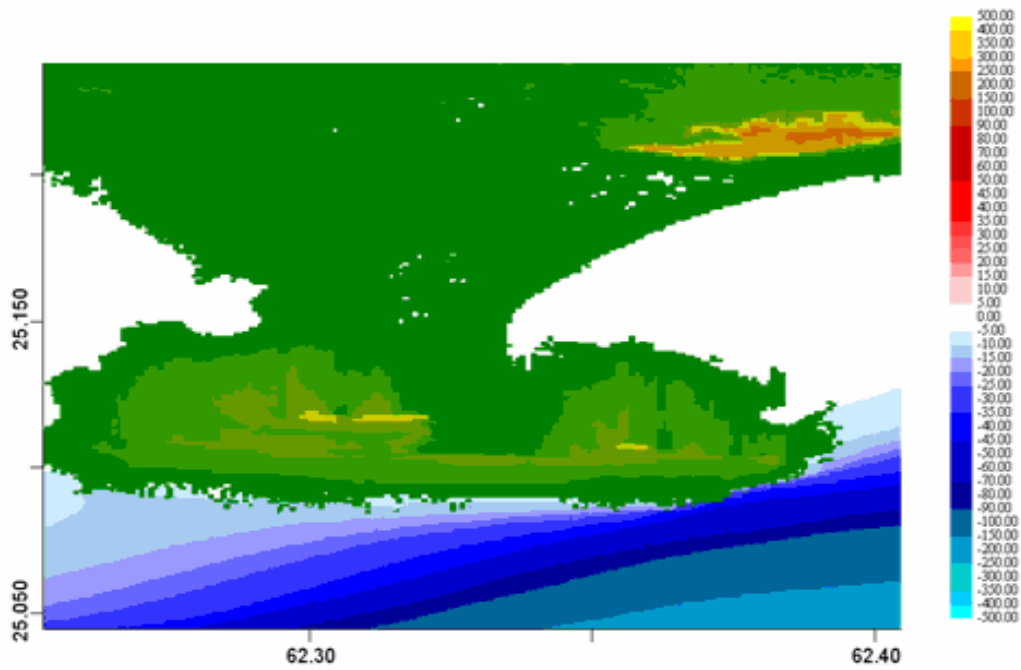
Time steps for Tsunami propagation, flow depth and inundation



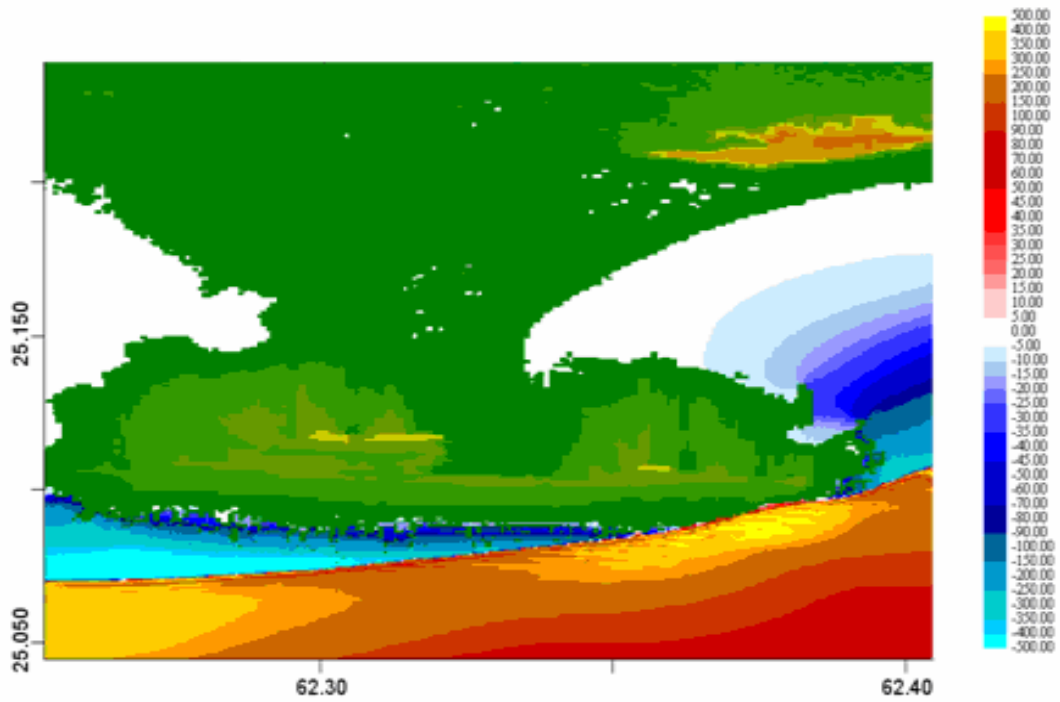
At $t=0$ min wave height is 0 m which is our initial condition
i.e. time of just occurrence of earthquake.



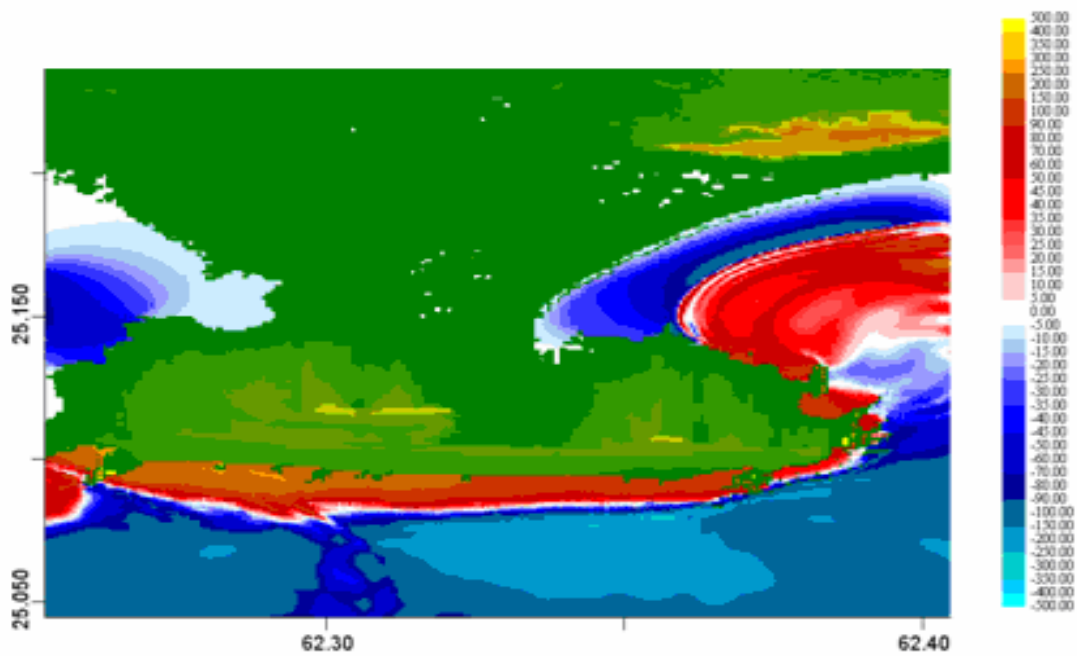
Retrieval of sea water up 1 m after 12 Minutes from generation of tsunami



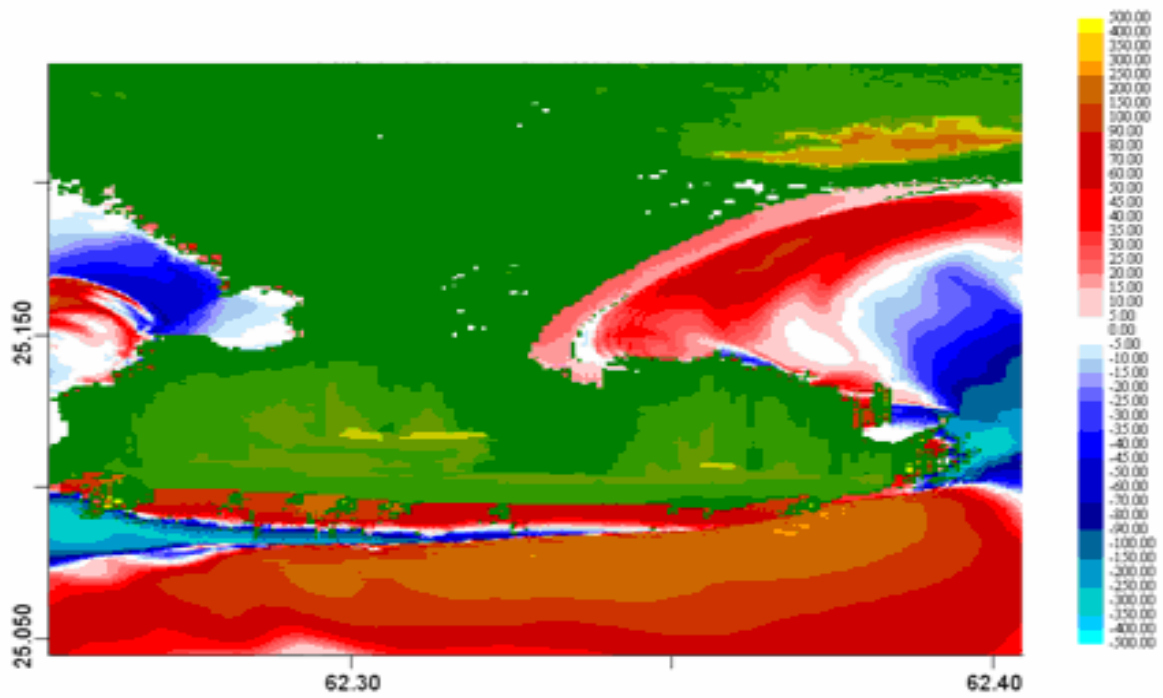
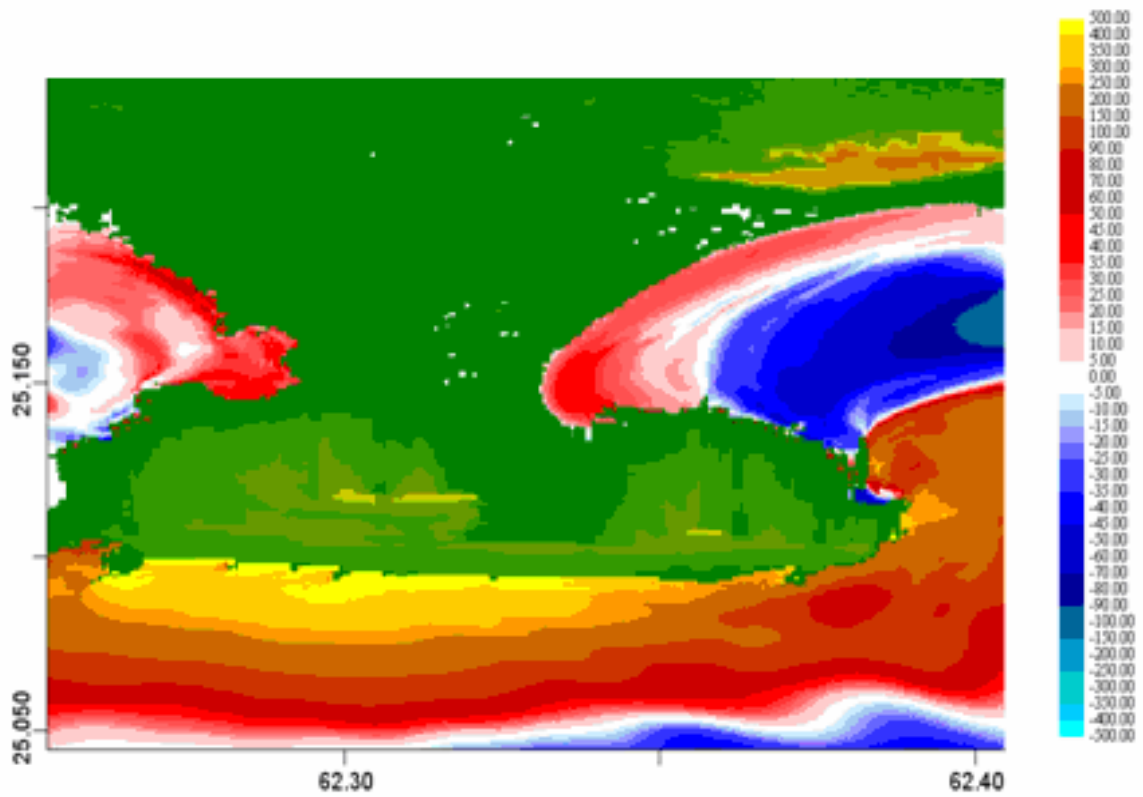
After 16 min depression of water may go to 4m

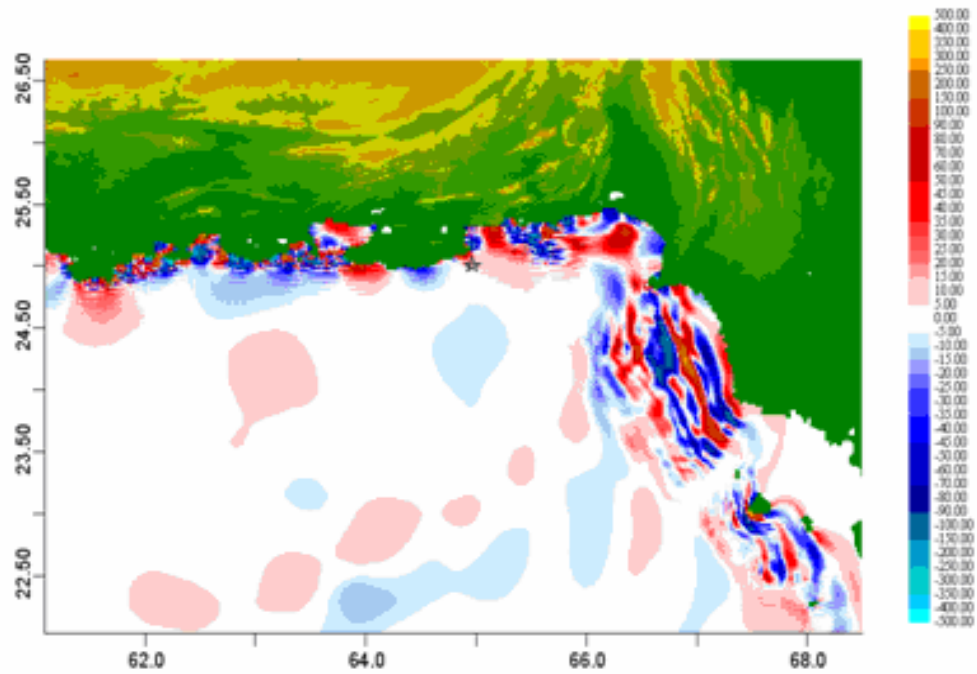


After $t=20$ min water flows into the land



At $t=22$ min coast receives maximum wave of 3.7 m





Possible inundation for Karachi which is minimum

