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TSUNAMI PROPAGATION IN ARABIAN SEA AND ITS EFFECT ON DWARKA CITY OF GUJARAT, INDIA

Vikram M. Patel[1] , H. S. Patel[2] and A. P. Singh[3]
[1]Ganpat University, Ganpat Vidyanagar, Mehsana, Gujarat, India
[2]Department of Applied Mechanics, L. D. College of Engineering., Ahmedabad, Gujarat, India
[3]Institute of Seismological Research, Gandhinagar, Gujarat, India

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In Western Coast of Gujarat destructive tsunamis have been generated from large earthquakes along the Makran Coast, Chagos Ridge and Kutch Region in the past. Although the historical record is incomplete, it is believed that such Tsunamis were destructive on the coasts of India, Pakistan, Iran, Oman and Sri Lanka and possibly had significant effects on Islands. The most significant tsunamigenic earthquake in recent times was that of 28 November 194521:56 UTC (03:26 IST) with a magnitude of 8.1 (Mw). In this paper an attempt is made for a numerical simulation of the tsunami generation from the Makran Subduction Zone, and its propagation into the Arabian Sea and its effect on the Dwarka city of Gujarat, India, through the use of a numerical model. It is observed from the results that the simulated arrival time of tsunami waves at the Dwarka is in good agreement with the available data sources. In this study more importance has been given to the run up height of tsunami waves, arrival time and inundation map. Also effect of different fault parameters on basic data is also studied.

Keywords: tsunami, Arabian Sea, Makran subduction zone (MSZ), Western Coast of Gujarat, run up height

1. Introduction

Tsunamis are water waves generated by the disturbance caused by submarine earthquakes. Landslides, explosive volcanism and meteorite impact with the ocean may be cause of tsunamis.

[1] Ph.D. Student
[2] Professor
[3] Scientist

Correspondence to: Vikram. M. Patel, Ganpat University, Ganpat Vidyanagar, Mehsana-384002, Gujarat, India, E-mail: vmpatel001@yahoo.com

Among these, submarine earthquakes are the major cause for tsunami generation. With reference to eastern coast & southern coast, western coast of India is having very less numbers of tsunami recorded in the past. Because of it, very less work has been done on tsunamigenic sources and possible tsunami hazard from earthquakes in the Arabian Sea and Western coast of India particularly Dwarka. Due to unavailability of data, Government and people in this region are not so active for protective measures.

Five of the great earthquakes in Makran may have ruptured the plate boundary in four different rupture segments of lengths of about 200 km each in 1483 (58–60°E), 1851 and also 1864 (61–63°E), 1945 (63–65°E), and 1765 (65–67°E) (Byrne & Sykes, 1992) (Figure 1 and 2). Out of all these earthquakes only the 1945 earthquake is known to have caused a large tsunami, followed by a large aftershock in 1947 immediately to the south. The western Makran zone has no clear record of historic great earthquakes. Absence of frequent earthquakes indicates either that seismic subduction occurs or that the plate boundary is currently locked and experiences great earthquakes with long repeat periods (Dimri, 2007).

One of the most deadly tsunamis ever recorded in the Arabian Sea occurred with its epicenter located in the offshore of Pansi in the northern Arabian Sea, about 100 km south of Churi (Baluchistan), Pakistan , at 21.56 UTC (03.26 IST) on November 28, 1945. More than 4000 people lost their life along the Makran coast of Pakistan by both the earthquake and tsunami. The tsunami was responsible for great loss of life and destruction along the coasts of India, Pakistan, Iran. The earthquake’s Richter Magnitude (Ms) was 7.8 (Pendse, 1948) & the Moment Magnitude (Mw) was revaluated to be 8.1 (Byrne et al, 1992).

The sesimotectonics of the MSZ, historical earthquakes in the region, and the recent earthquake of October 8, 2005 are indicative of the active tectonic collision process that is taking place along the entire southern and southeastern boundary of the Eurasian plate as it collides with the Indian plate and adjacent micro plates. Tectonic stress transference to other, stress loaded tectonic regions could trigger tsunamigenic earthquakes in the Northern Arabian Sea in the future.

Dwarka, which is important historical & religious place of India, is not being studied by any researcher. In last few years on western coast of India particularly in Dwarka population is going on increase. Hence, the accurate modeling of tsunami hazard from the earthquake and early warning system of tsunamis for a coastal community is of great importance in this area.

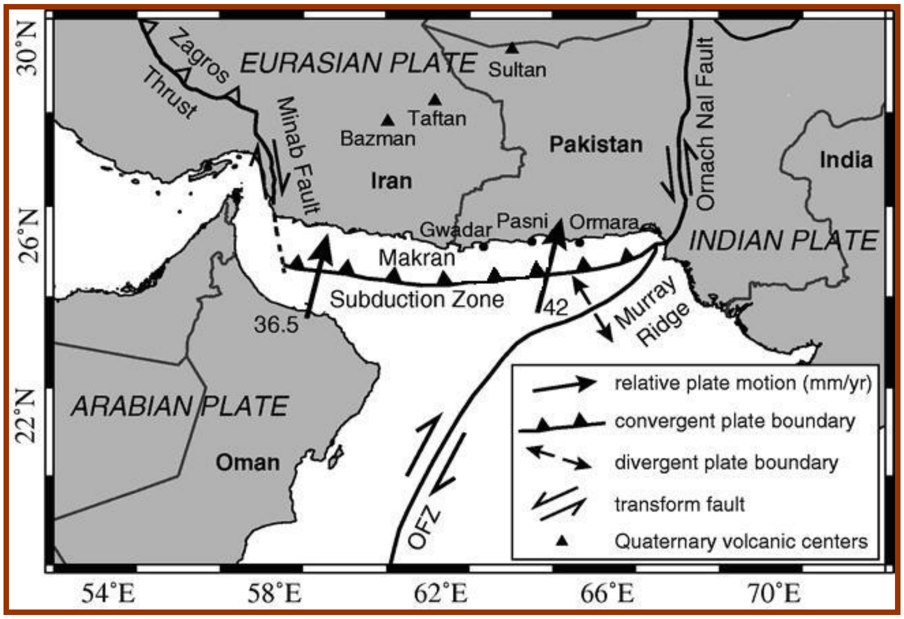

Figure 1. Makran subduction zone (MSZ)

Figure 2. Major earthquakes in MSZ

2. Numerical Modeling

Numerical modeling of tsunamis is commonly carried out to better understand events that have occurred either during or before historical times. Numerical modeling can also help to predict the effects of a future tsunami.

The present study uses the finite difference code of TUNAMI – N2 to predict wave propagation (Imamura, 2005). The rupture parameters, as provided by Jaiswal et. al. (2008) was used for the source of 1945 earthquake for validation of program. Along with this some another probable parameters have been taken for the study. Static displacement on the surface of an elastic half space due to elastic dislocation was computed on the basis of equations provided by Mansinha et. al. (1971).

Tsunamis which are mainly generated by the movement of sea bottom due to earthquakes belong to long waves. In the theory of such waves, the vertical acceleration of water particles are negligible compared to the gravitational acceleration except for an oceanic propagation of tsunami [Kajiura, 1963]. Consequently, the vertical motion of water particles has no effect on the pressure distribution. It is a good approximation that the pressure is hydrostatic.

Based upon these approximations and neglecting the vertical acceleration, the following two dimensional equations (this is called the shallow water theory) were used. 2D continuity equation is as:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

And, 2-D mass momentum Equation:

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{\tau_x}{\rho} = A\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{\tau_y}{\rho} = A\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right) \tag{3}$$

where D is the total water depth given by h+η, τ_x and τ_y the bottom frictions in the x and y directions, A the horizontal eddy viscosity which is assumed to be constant in space, the shear stress on a surface wave is neglected. M and N are the discharge fluxes in the x- and y-directions.

3. Methodology

The bathymetric grid was built from General Bathymetric Chart of the Ocean (GEBCO) 30 second database and updated with the help of latest hydrograph charts of Gujarat Maritime Board (GMB). Shuttle Radar Topography Mission (SRTM) data has been used to accurately map the land heights (topography). In this study four nested domains, namely A,B,C, and D are used. The increased resolution is essential in order to simulated as best as possible the travel time and tsunami amplitude of the waves. For grids A and B, the model is run in the linear mode which, although not good enough for run-up estimates, but it is good enough for travel time estimates. Another reason for increasing resolution is to diminish numerical dispersion into shallower water (Shuto et.al., 1985, 1986). Therefore each tsunami wavelength should be covered by at least 20 grid points. Ramming and Kowalik (1980) found that 10 grid points per wave length is sufficient if we are willing to accept 2% error in the phase velocity. Still another reason is that numerical stability considerations require that the finite differences time step be such that $\Delta t \leq [\Delta x / \sqrt{(2gh)}]$, where Δx is the space discretization size, g the gravitational acceleration, and h is the maximum depth in the given grid. As the wave propagates into shallower waters h decreases and by decreasing Δx we can maintain a constant Δt (Goto and Ogawa 1992).

The initial displacement is generated in the exterior domain (A), and it is interpolated into the higher resolution grids B, C and D. The end result is an initial sea surface profile that extends smoothly from the exterior, lower resolution, domain into the higher resolution domains. The tsunami propagation states at every 1-min interval are simulated. In this study, model outer domain has a horizontal resolution of 2700 m over the Arabian Sea including the Indian sub-continent (7–26N and 62–80E). The simulation is carried out for duration of 360 min. and the Sea states at 0, 30, 60, 90, 120, 150 and 180 min. in the Arabian Sea are presented in (Figure 3-a to e). The wave amplitude varies with the forward motion of the tsunami waves. Boundary conditions play a significant factor in the separation of the land and ocean boundary.

In order to validate quantitatively the simulation and it is compared to the only available measurements of the 1945 Makran tsunami. The results obtained are configured with the available reports of 1945 Makran Tsunami (Pendse, 1948) and also with results of Indian Seismological Research Centre Team of Gandhinagar. (R.K.Jaiswal et.al., Nat Hazards 2008).

4. Analysis and Results

Model runs of eighty six earthquake events were simulated for a far source generated tsunami caused by an offshore earthquake. Table 1 shows the time of arrival of maximum amplitude of water waves and wave run up height at Okha, Mandvi, Dwarka and Porbandar for different fault models of MSZ.

5. Inundation Mapping

The elevation data sets are the most important input for inundation mapping in tsunami prone areas. Preparation of a vulnerability map could inform coastal community and others about susceptibility to inundation corresponding to various wave-heights. The Gujarat state has important installations like ports, jetties, industries along the coast, and also other socio-economical perspective, which can be affected by tsunami trigged due to such events, and hence the determination of possible inundation areas is important.

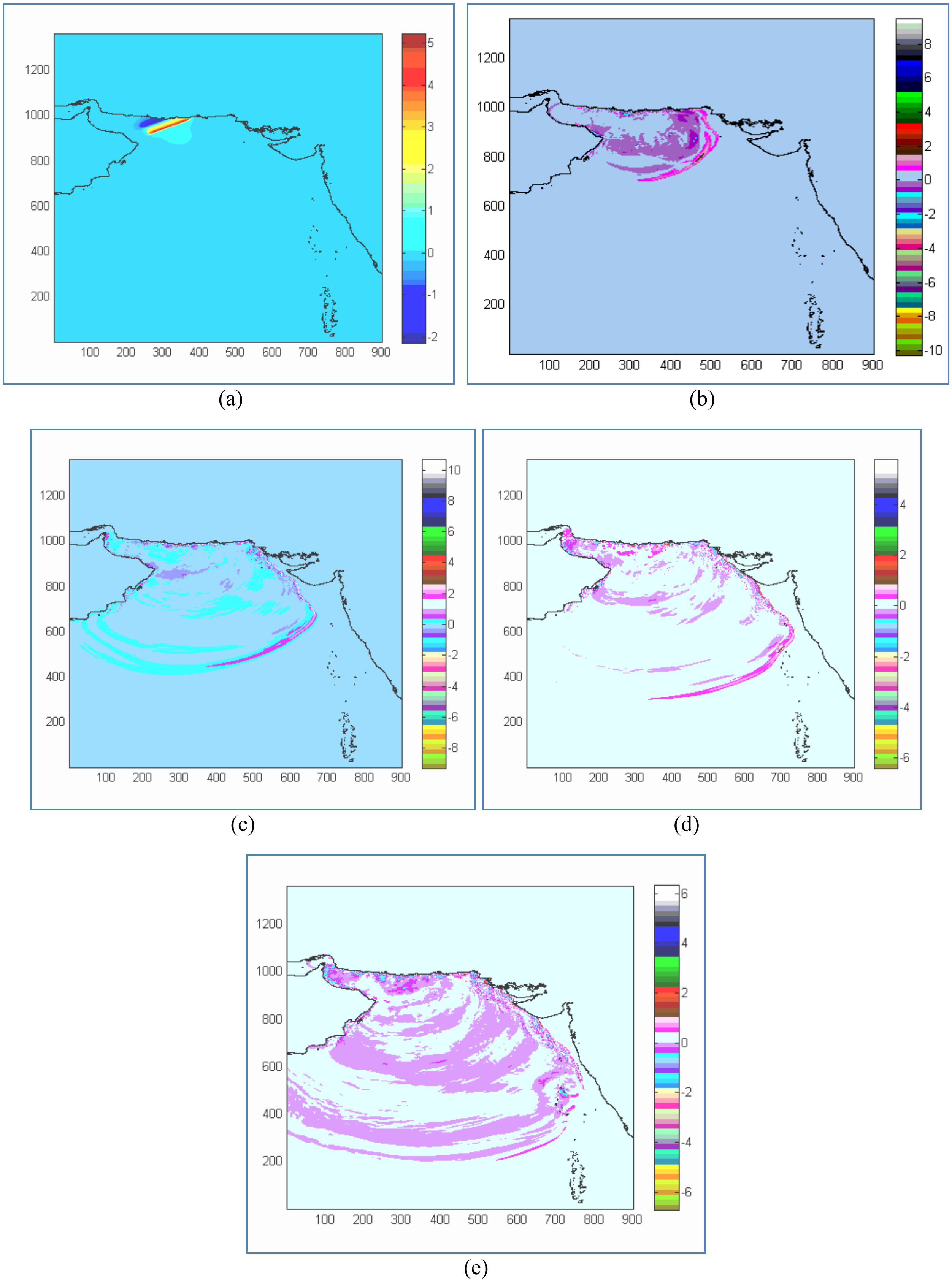

Figure 3. Propagation of the waves after: a) 0 min.; b) 60 min.; c) 120min.; d) 150 min.; and e) 180 min.

Table 1. Run up height and time of arrival for different models of earthquakes in Dwarka

Sr. No.	Length (km)	Width (km)	Dip (km)	Depth to Top (Focus)	Strike	Rake	Slip	Depth of water (m)	Long. - x	Lat. - y	Arr. Time	Run-up ht.
1	200	100	15	-10	90	250	10	68	60.99	25.09	183	1.14
2	200	100	15	-10	90	250	8	68	60.99	25.09	183	0.93
3	200	100	15	-10	90	250	12	68	60.99	25.09	183	1.36
4	250	100	15	-10	90	250	10	68	60.99	25.09	184	1.29
5	300	100	15	-10	90	250	10	68	60.99	25.09	185	1.65
6	150	100	15	-10	90	250	10	68	60.99	25.09	182	1.09
7	200	50	15	-10	90	250	10	68	60.99	25.09	203	0.71
8	200	75	15	-10	90	250	10	68	60.99	25.09	183	0.86
9	200	100	15	-10	90	240	10	68	60.99	25.09	183	0.86
10	200	100	15	-10	90	260	10	68	60.99	25.09	185	0.98
11	200	100	15	-10	90	230	10	68	60.99	25.09	179	1.28
12	200	100	15	-10	90	270	10	68	60.99	25.09	187	0.76
13	200	100	20	-10	90	250	10	68	60.99	25.09	184	1.3
14	200	100	25	-10	90	250	10	68	60.99	25.09	184	1.44
15	200	100	10	-10	90	250	10	68	60.99	25.09	183	0.98
16	200	100	15	-5	90	250	10	68	60.99	25.09	184	1
17	200	100	15	-15	90	250	10	68	60.99	25.09	183	1.23
18	350	100	15	-10	90	250	12	68	60.99	25.09	185	1.65
19	300	100	15	-10	90	240	12	68	60.99	25.09	183	1.86
20	200	100	15	-10	90	250	10	52	62.23	25	172	1.16
21	200	100	15	-10	90	250	8	52	62.23	25	172	0.94
22	200	100	15	-10	90	250	12	52	62.23	25	172	1.38
23	250	100	15	-10	90	250	10	52	62.23	25	172	1.22
24	300	100	15	-10	90	250	10	52	62.23	25	174	1.59
25	350	100	15	-10	90	250	10	52	62.23	25	174	1.79
26	150	100	15	-10	90	250	10	52	62.23	25	171	1.06
27	200	50	15	-10	90	250	10	52	62.23	25	194	0.78
28	200	75	15	-10	90	250	10	52	62.23	25	171	0.87
29	200	100	15	-10	90	240	10	52	62.23	25	171	1.32
30	200	100	15	-10	90	260	10	52	62.23	25	174	0.94
31	200	100	15	-10	90	230	10	52	62.23	25	167	1.43
32	200	100	15	-10	90	270	10	52	62.23	25	179	0.67
33	200	100	20	-10	90	250	10	52	62.23	25	172	1.3
34	200	100	25	-10	90	250	10	52	62.23	25	172	1.42
35	200	100	10	-10	90	250	10	52	62.23	25	171	1.02
36	200	100	15	-5	90	250	10	52	62.23	25	172	0.98
37	200	100	15	-15	90	250	10	52	62.23	25	171	1.26
38	350	100	15	-10	90	250	12	52	62.23	25	174	1.79
39	300	100	15	-10	90	240	12	52	62.23	25	171	2.07
40	200	100	15	-10	90	250	10	27	63.48	25.05	169	1.16
41	200	100	15	-10	90	250	8	27	63.48	25.05	161	0.94
42	200	100	15	-10	90	250	12	27	63.48	25.05	161	1.38
43	250	100	15	-10	90	250	10	27	63.48	25.05	163	1.37
44	300	100	15	-10	90	250	10	27	63.48	25.05	165	1.85
45	150	100	15	-10	90	250	10	27	63.48	25.05	160	1.06
46	200	50	15	-10	90	250	10	27	63.48	25.05	160	0.73
47	200	75	15	-10	90	250	10	27	63.48	25.05	161	0.88
48	200	100	15	-10	90	240	10	27	63.48	25.05	161	0.88
49	200	100	15	-10	90	260	10	27	63.48	25.05	163	0.92
50	200	100	15	-10	90	230	10	27	63.48	25.05	157	1.37

Table 1 (Cont.). Run up height and time of arrival for different models of earthquakes in Dwarka

Sr. No.	Length (km)	Width (km)	Dip (km)	Depth to Top (Focus)	Strike	Rake	Slip	Depth of water (m)	Long. - x	Lat. - y	Arr. Time	Run-up ht.
51	200	100	15	-10	90	270	10	27	63.48	25.05	164	0.51
52	200	100	20	-10	90	250	10	27	63.48	25.05	162	1.3
53	200	100	25	-10	90	250	10	27	63.48	25.05	162	1.42
54	200	100	10	-10	90	250	10	27	63.48	25.05	161	1.01
55	200	100	15	-5	90	250	10	27	63.48	25.05	161	0.98
56	200	100	15	-15	90	250	10	27	63.48	25.05	161	1.26
57	350	100	15	-10	90	250	12	27	63.48	25.05	174	1.94
58	300	100	15	-10	90	240	12	27	63.48	25.05	171	2.25
59	350	100	15	-10	90	240	12	27	63.48	25.05	162	2.3
60	350	100	15	-10	90	230	12	27	63.48	25.05	182	3.28
61	300	100	15	-10	90	240	10	128	61.61	25.045	177	1.62
62	200	75	20	-10	90	240	10	128	61.61	25.045	175	1.23
63	200	100	15	-10	90	250	12	128	61.61	25.045	178	1.38
64	200	100	15	-10	90	250	10	128	61.61	25.045	178	1.15
65	300	100	15	-10	90	250	10	128	61.61	25.045	179	1.46
66	200	100	15	-15	90	250	10	128	61.61	25.045	166	1.34
67	300	100	15	-10	90	240	10	29	62.855	25.025	166	1.85
68	200	75	20	-10	90	240	10	29	62.855	25.025	164	1.42
69	200	100	15	-10	90	250	12	29	62.855	25.025	166	1.45
70	200	100	15	-10	90	250	10	29	62.855	25.025	166	1.22
71	300	100	15	-10	90	250	10	29	62.855	25.025	169	1.56
72	200	100	15	-15	90	250	10	29	62.855	25.025	166	1.34
73	300	100	15	-10	90	240	10	234	63.48	24.968	160	1.76
74	200	75	20	-10	90	240	10	234	63.48	24.968	158	1.31
75	200	100	15	-10	90	250	12	234	63.48	24.968	160	1.41
76	200	100	15	-10	90	250	10	234	63.48	24.968	160	1.19
77	300	100	15	-10	90	250	10	234	63.48	24.968	160	1.41
78	200	100	15	-15	90	250	10	234	63.48	24.968	160	1.29
79	300	100	15	-10	90	240	10	168	60.99	25.041	182	1.53
80	200	75	20	-10	90	240	10	168	60.99	25.041	141	1.25
81	200	100	15	-10	90	250	12	168	60.99	25.041	183	1.38
82	200	100	15	-10	90	250	10	168	60.99	25.041	182	1.15
83	300	100	15	-10	90	250	10	168	60.99	25.041	145	1.36
84	200	100	15	-15	90	250	10	168	60.99	25.041	143	1.23
85	200	100	15	-10	90	250	10	243	60.863	25.09	184	1.12
86	200	100	15	-10	90	250	10	23	63.607	25.05	202	0.64

Inundation model is prepared for coastal parts of Gujarat belt on the basis of existing topographic and bathymetric (water depth) data sets. For preparation of the inundation map, high resolution of SRTM data set has been used. Surfer 8.0 software is used to plot elevation data. The different colors in Figure 4 present various elevations as 0–10 m are shown, over the parts of Gujarat state. This figure shows that Rann of Kutch region has very low elevations, and therefore inundation would be more due to tsunamigenic conditions than other costal parts of Gujarat.

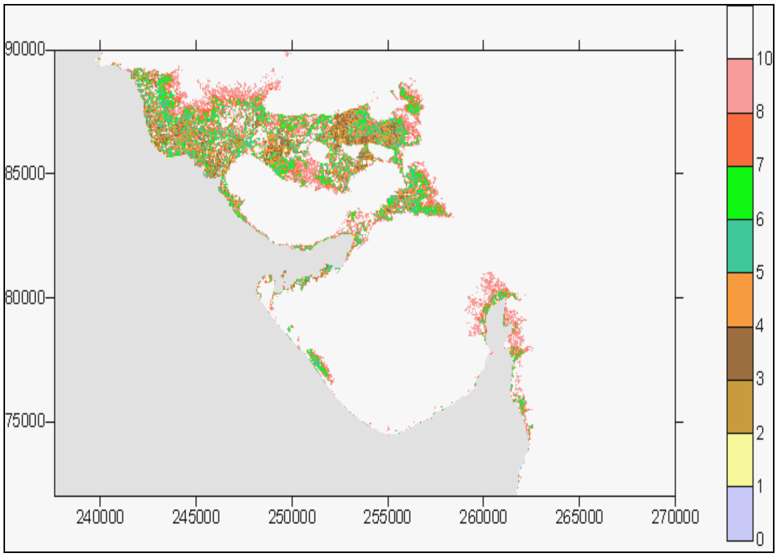

Figure 4. Inundation map of Gujarat

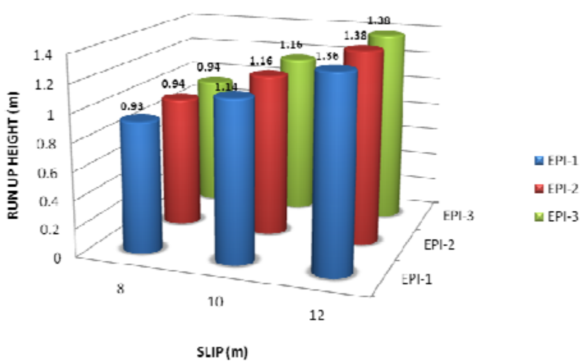

Figure 5. Comparison of slip variation

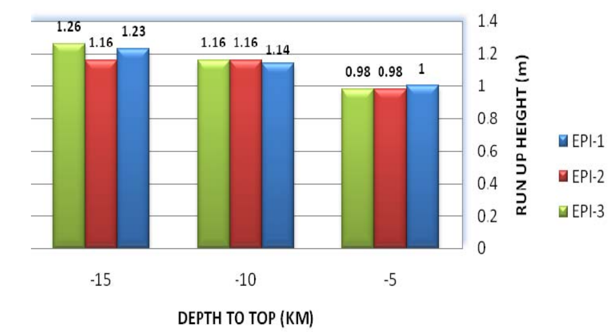

Figure 6. Comparison of depth to top (focus) variation

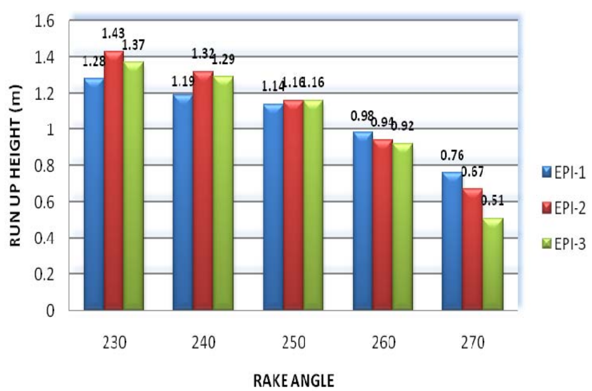

Figure 7. Comparison of rake variation in Dwarka

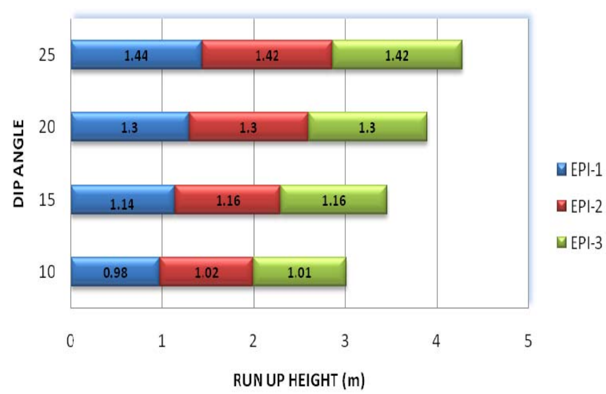

Figure 8. Comparison of dip variation in Dwarka

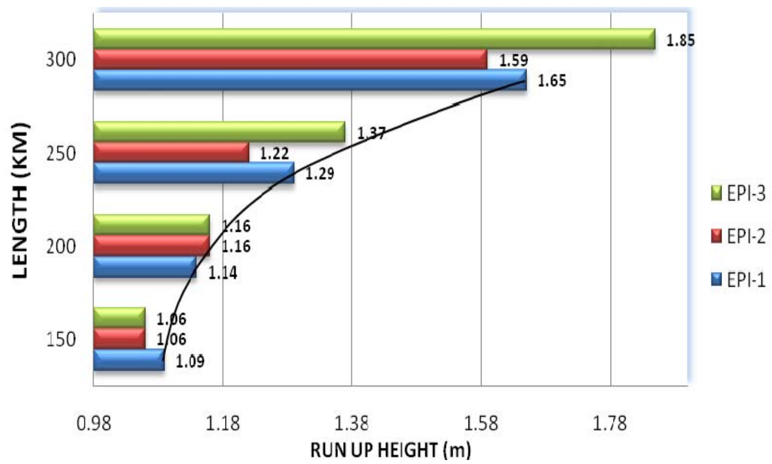

Figure 9. Comparison of length variation in Dwarka

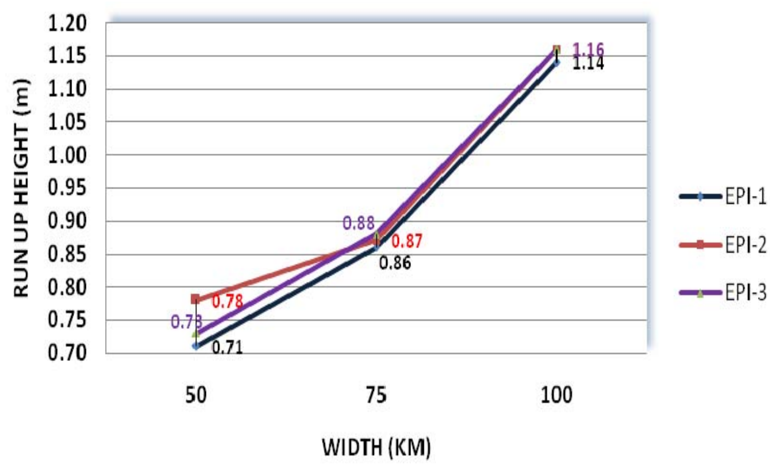

Figure 10. Comparison of width variation in Dwarka

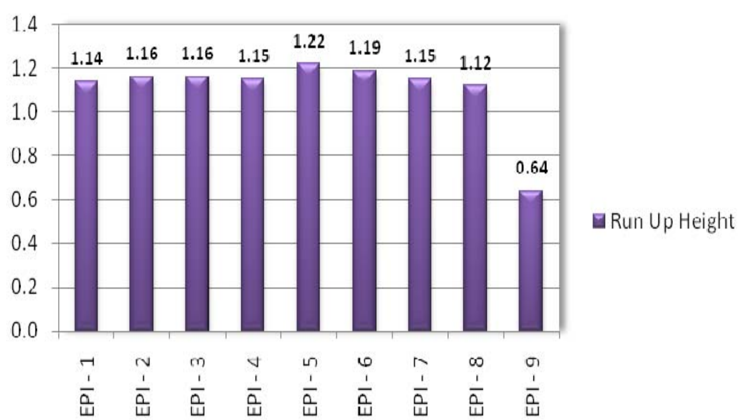

Figure 11. Comparison of run-up height with different epicenter in Dwarka

4. Discussion and Conclusions

Eastern and Western parts of the Makran Subduction Zone of southern Pakistan are potential zones for great earthquakes that can generate tsunamis affecting west coast of India. The eastern part of the Makran zone has produced the 1945 Mw 8.0 earthquake that generated the last major tsunami in the Arabian Sea. Some sectors of the Makran zone are un-ruptured for a long time and can produce large earthquakes in near future.

The basic grids have been prepared with the help of surfer 8.0, Global Mapper 9.0 and MatLab R2009a. Basic Numerical Modeling has been done in TunamiN2. A programme made for run up height and time of arrival of tsunami in MatLab environment.

The following conclusions can be drawn from this study:

1. The Numerical modeling is an appropriate tool and can be used for scientific studies aimed at revealing the physical processes of tsunami generation, propagation and inundation and to establish seismic criteria for issuing tsunami warnings in the event of an actual tsunami.
2. When distance between Epi Center and Location increases time of arrival of tsunami increases and run up height decreases.
3. When width, length and dip angle increases time of arrival of tsunami decreases and run up height increases.
4. Arrival time is decreasing while increasing depth of water.
5. At 250˚ orientation of failure plane whole MSZ is having same effect at Dwarka, below which eastern Makran is more effective and above it western Makran is more effective.
6. When Depth to Top (Focus) increases, effect of tsunami increases.
7. Because there is only 150 to 180 minutes time before tsunami arrival at the Dwarka, it is very important to actually confirm the tsunami generation by earthquake parameters as earliest as possible.

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