Evaluating the Tsunami Hazard in the Persian Gulf and its Possible Effects on Coastal Regions

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Abstract:
Due to the placement of several ports, harbors, oil fields, and associated structures in the Persian Gulf, the study of tsunami hazard in this region is of vital importance for authorities. Indeed, the Persian Gulf coastlines are under threat of tsunamis which are generated in the Indian Ocean and travel across the Strait of Hormoz to strike these shorelines. One of the most tsunamigenic sources in the Indian Ocean is Makran Subduction zone in the northwest of Indian Ocean near the coastlines of Iran, Oman, Pakistan, and India. In fact, it is believed that a tsunami generated in the Makran zone has the potential to hit the Persian Gulf shorelines. Therefore, in this paper the effect of tsunami generated in the Makran zone on the coastlines of Persian Gulf is discussed. Considering different scenarios for large earthquake occurrence in the Makran zone, the propagation of possible tsunami into the Persian Gulf was modeled. In this regard, the nonlinear shallow-water theory was used to model the tsunami propagation on the coastlines. The shallow water equations are solved numerically by means of a finite difference method. Also, for selected sites in the Persian Gulf the time histories of the tsunami waves are presented.

Introduction:
Tsunamis are gravity water waves and usually occur following a large and relatively shallow underwater earthquake in coastal areas. They are generated by a sudden vertical motion of the ocean bottom due to earthquakes, landslides, volcano eruptions and asteroid impacts. But, the most common cause is submarine earthquakes. Tsunamis usually are associated with great loss of life and property. Although the majority of the reported tsunamis are from the countries of the Pacific Ocean basin, the occurrence of recent tsunamis in the Indian Ocean showed that the risk of tsunami is high in this region. The recent Indian Ocean tsunamis which totally took the lives of more than 230000 [1] people in coastal areas and left about 1.5 million homeless [2] has brought the need to assess tsunami hazards in the vulnerable coastlines bordering the Indian Ocean.
Two main tsunamigenic sources that can trigger tsunami generating earthquakes in the Indian Ocean basin include the Indonesian subduction zone and the Makran subduction zone [3]. The Indonesian subduction zone has produced three large earthquakes followed by devastating waves in the recent two years. These earthquakes and associated tsunamis include the 26 December 2004 tragedy, the 28 March 2005, and 17 July 2006 events in the Indian Ocean which took the lives of about 225000, 1000, and 401 people in coastal zones on this ocean respectively [4&5].
The other important tsunamigenic zone in the Indian Ocean basin is Makran subduction zone (MSZ) located off the southern coasts of Iran and Pakistan in the north-western Indian Ocean. In this region the Oman oceanic lithosphere slips below the Iranian micro-plate at the estimated rate of

about 19 mm/yr [6]. The last major historical earthquake and tsunami in the MSZ occurred on 28 November 1945 at 21:56 local time.

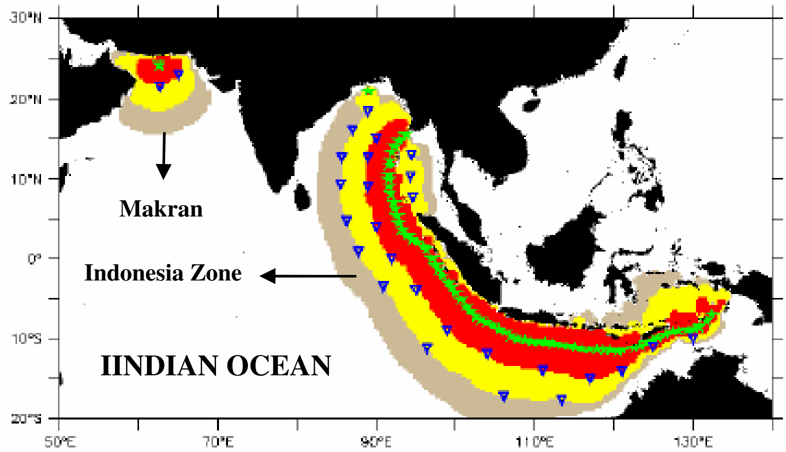


Figure 1: Two tsunamigenic sources in the Indian Ocean [3]

The epicenter of the earthquake was located at latitude 24.50 ºN and longitude 63.00 ºE, about 87.1 kilometers from the south west of Churi, Pakistan. The magnitude of the earthquake was evaluated to be 8.1 [7]. In fact, this was the last major tsunami-generating earthquake in the Makran zone. The destructive tsunami killed more than 4,000 people and caused great loss of life and devastation along the coasts of Western India, Iran, Oman and Pakistan [7].

The main purpose of this paper is to assess the impact of tsunamis generated in the MSZ on the ports, harbors, and associated structures located in the Persian Gulf. Persian Gulf is located in southwestern Asia, between the Arabian Peninsula on the southwest and Iran on the northeast. The gulf extends northwest 970 km from the Strait of Hormuz to the Shatt al Arab, a river formed by the confluence of the Tigris and Euphrates Rivers. The gulf is connected to the Arabian Sea by the Strait of Hormuz and the Gulf of Oman. The Persian Gulf varies in width from 47 to 370 km. The area is 230,000 square km and the greatest depth is 102 m [8]. The chief islands in the gulf are Qeshm and Bahrain. The United Arab Emirates, Saudi Arabia, Qatar, and Kuwait are on the south-western shore; Iraq is on the northern tip; and Iran is on the northeastern shore. The general map of the Persian Gulf is shown in Figure 2.

Figure (2): General map of the Persian Gulf [8]

As can be seen, the Persian Gulf coastlines are relatively populated and principal ports and oil fields are placed in the littoral countries of the Persian Gulf including Iran, Iraq, Kuwait, Saudi Arabia, Qatar, Bahrain, and United Arabic Emirates. Hence, possible tsunami waves may produce great destruction and loss of life in the Persian Gulf basin. From hydrodynamical point of view since the average Persian Gulf water depth is about 50 m (the greatest depth is 102 m [8]), the tsunami generation potential of Persian Gulf is extremely low. However, the Persian Gulf coastlines are under threat of tsunamis which are generated in the Indian Ocean and travel across the Strait of Hormoz to strike these shorelines. In fact, in this study it is intended to study the propagation of Indian Ocean tsunami into the Persian Gulf.

Tsunami Source Modeling:

It was mentioned that in this study the MSZ is considered as the tsunami source. Since the deformation of ocean floor is responsible for tsunami generation, it is necessary to calculate the ocean floor deformation due to earthquake occurrence. After earthquake occurrence the earth's crust experiences vertical movement in the form of uplift and subsidence at the location of subduction zone. The resulted seafloor deformation provides the initial condition for the tsunami propagation and runup modeling. Here, as the initial condition for tsunami source analysis, an earthquake with moment magnitude of 8.2 is used. The epicenter of the selected earthquake is placed in the western part of the MSZ at longitude 60.00^o E and latitude 24.50^o N.

Earthquakes typically have rupture durations of minutes, which can be considered as instantaneous when compared to the time scale of the subsequent tsunamis. Kajiura (1970) suggested that for tsunami modeling the initial surface wave be treated as identical to the vertical component of the seafloor deformation due to faulting [9]. Here, the algorithm of Mansinha and Smylie (1971) [10] is used to calculate the seafloor deformation based on input seismic parameters that include the strike, dip, and slip angles, the amount of slip, and the dimensions and location of the fault.

In this study, empirical relations presented by Wells and Coppersmith (1994) [11] are used to related the moment magnitude of the underwater earthquake to the fault parameters. These equations include ($\mathrm{Log(u)} = -4.80 + 0.69\mathrm{M}$), ($\mathrm{Log(L)} = -3.22 + 0.69\mathrm{M}$), and ($\mathrm{Log(W)} = -1.01 + 0.32\mathrm{M}$) where u is the displacement on the fault surface, L and W are fault length and width respectively and M is the earthquake magnitude. Using the mentioned equation, for earthquake having magnitude of 8.2 the rapture length and width would be estimated as 274 and 41 km respectively. Also, the fault displacement is 7.2 m. The other rapture parameters including dip, slip, and strike angles are selected as 10, 100, and 270 degrees respectively. The focal depth of the earthquake is selected as 20 km. The results of tsunami generation analysis are presented in Figures 3 and 4.

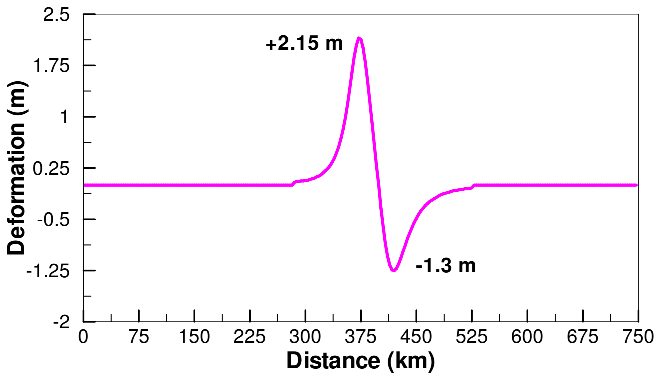


Figure (3): Deformation of the ocean floor deformation

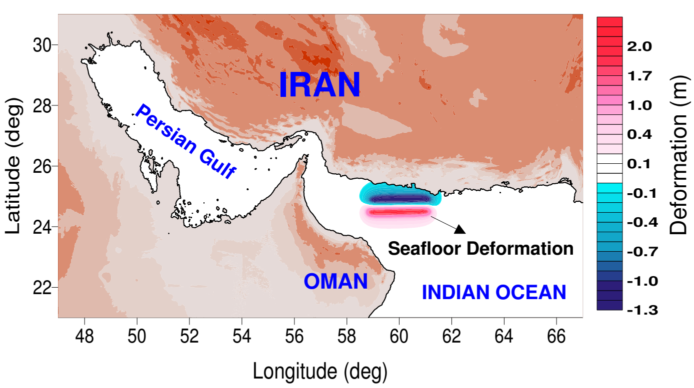


Figure (4): 2D view of seafloor

Tsunami Propagation Modeling:

Since tsunami wavelengths (hundred of kilometers) are much larger than the ocean depth (a few kilometers), tsunamis are considered as shallow water waves, following the long wave theory. In the long wave theory the vertical acceleration of water particles is negligible compared to the gravitational acceleration, and the hydrostatic pressure approximation is used. It may be added that under the assumption of long wave theory, the hydrodynamic equations describing the conservation of mass (equation 1) and momentum (equation 2) can be depth averaged [11].

$$\frac{\partial(\eta + h)}{\partial t} + \nabla[v(\eta + h)] = 0 \quad (1)$$

$$\frac{\partial v}{\partial t} + (v\nabla)v = -g\nabla\eta + \sum f \quad (2)$$

where h is the sea depth and η the water elevation above mean sea level, v is the depth-averaged horizontal velocity vector, g is the gravity acceleration, and f represents bottom friction and Coriolis forces. The above system is completed by suitable boundary conditions that are of pure wave reflection on the solid boundary and of full wave transmission on the open sea:

$v.n=2(c_1 - c_0)$ on the open sea (3)

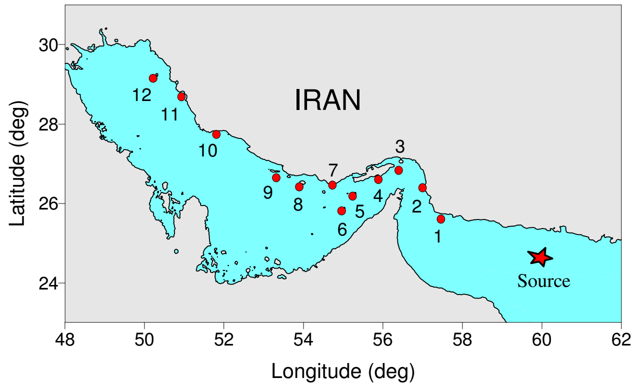
$v.n=0$ on the solid boundary (4)

where $c_0 = \sqrt{gh}$ is the phase velocity of the linear wave and $c_1 = \sqrt{g(h+\eta)}$ is the local phase velocity (non-linear waves). Due to close distance of about 150 km between the Makran subduction zone and Iranian coastal regions, there is the threat of near-field tsunamis in southern coasts of Iran. In the case of near-field tsunamis, that is, those whose propagation distance is less than 1000 km, the model of plane Earth with no rotation is applied and the Cartesian coordinates can be used. In other words, the coriolis forces and the Earth's curvature can be neglected.

In this study, the governing equations are solved by the finite difference technique with leap-frog scheme. The bathymetry of the region was obtained from the British Oceanographic Data Center with 2000 m grid size. The time step is selected as 5 s to satisfy the stability condition. The total number of grid points in the study area is 349554 (782 × 447). Along the depth of 20 m contour line the vertical wall boundary condition is assumed. In our study, waveform and height can be predicted at any location in the calculation area. To facilitate wave height prediction, a number of reference locations are selected to record time histories of tsunami waves. The longitude and latitude of the selected reference locations are listed in Table 1. In addition, figure 5 shows the calculation area along with the reference locations. Figures 6, 7 and 8 present time histories of wave height in the shown reference locations. Figures 9 and 10 show snapshots of the water surface at times t = 1, and 5 hours.

Table (1): Longitude and latitude of the selected reference locations

Location No.	Country Name	Location Name	Longitude (deg)	Latitude (deg)
1	IRAN	Jask	57.76	25.61
2		Sirik	56.97	26.52
3		Larak	56.40	26.81
4		Hengam-e qadim	55.90	26.60
5		Tunb	55.37	26.24
6		Abu Musa	55.08	25.84
7		Bandar-e Lengeh	54.88	26.38
8		Halah	54.00	26.45
9		Qort	53.29	26.75
10		Tonbak	52.17	27.67
11		Bushehr	50.69	28.71
12		Kharg	50.29	29.18



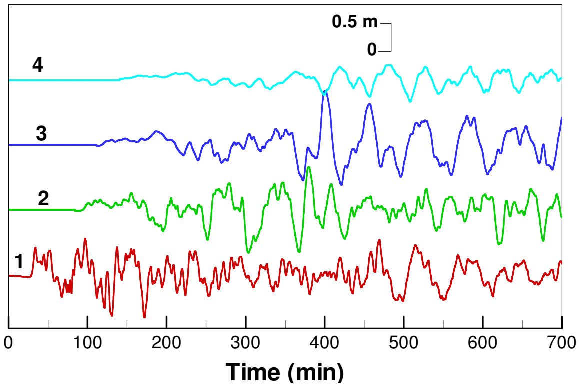
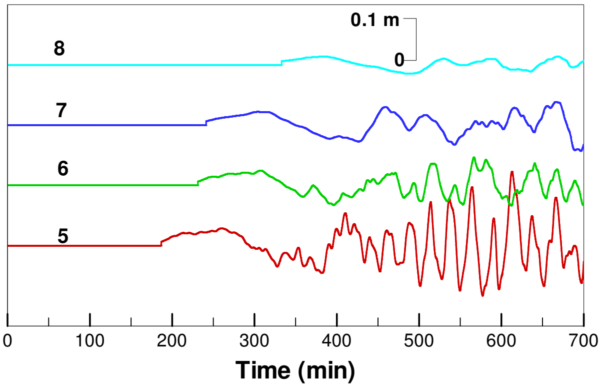


Figure (5): Calculation area along with the reference sites **Figure (6): Wave height time history for Sites No. 1 to 4**



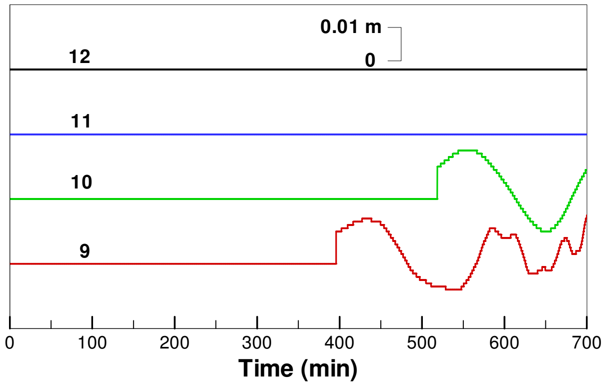
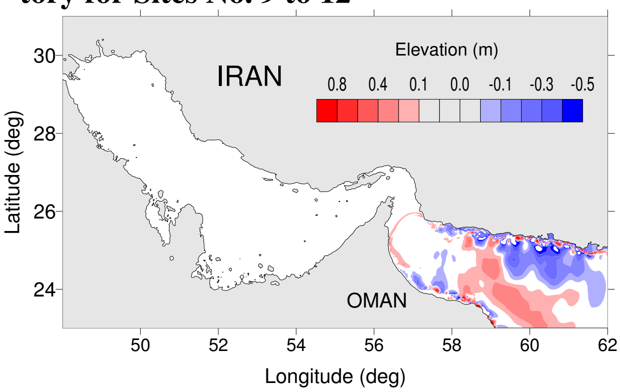


Figure (7): Wave height time history for Sites No. 5 to 8 **Figure (8): Wave height time history for Sites No. 9 to 12**



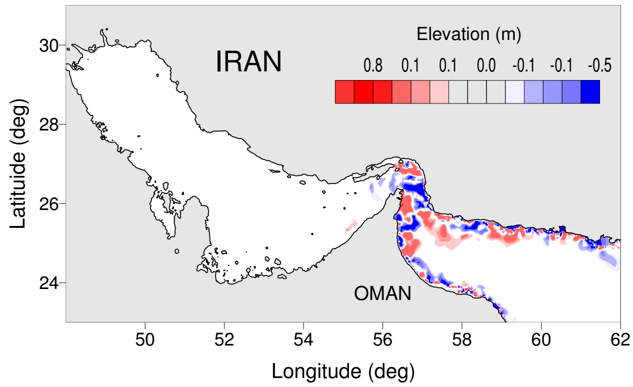


Figure (9): Snapshot at times t =1 hour **Figure (10): Snapshot at times t = 5 hour**

Discussion and Conclusion:

Numerical simulations of tsunami generation and propagation are presented to assess the hazard of Indian Ocean tsunamis in the Persian Gulf. A numerical model based on finite difference technique with leap-frog scheme was employed to model tsunami propagation. Using this model the wave-form and height time histories in the selected reference locations are presented. The propagation modeling was performed for the case of magnitude 8.2 earthquake at the at latitude 24.50 ºN and longitude 60.00 ºE.

Results of this study based on the above-mentioned tsunami source, show that for areas near to the strait of Hormoz the hazard of tsunami can not be neglected. Figure 6 shows that possible tsunami waves can reach the height of about 50 cm near Jask. Also, as can be seen in figures 7 and 8, as tsu-nami enters the shallow waters of the Persian Gulf the wave speed reduces highly and consequently losses a great part of its energy. Figure 8 shows that after about 12 hours, no wave is recorded in

Kahrg and Bushehr. In addition, the wave heights at the locations number 7, 8, 9 and 10 are very small. Considering figures 6, 7 and 8, it can be concluded that except for areas near to the strait of Hormoz, the hazard of tsunami waves in the other parts of the Persian Gulf is very low.

The wave height and wave time histories presented in this study can be used for tsunami hazard assessment in the Persian Gulf and also for locating safe areas for development of new ports, harbors and related structures in the Persian Gulf. However, authors believe that more studies should be done to investigate the tsunami hazard in the Persian Gulf.

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