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Tsunami Hazard Assessment on Qatar Coastline from Makran Earthquakes Considering Tidal Effect and Coastal Landslides Scenarios

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Abstract

To assist the analysis of tsunami hazards for Qatar coastal areas were using numerical model. By Tsunamis waves created from submarine earthquakes of magnitude of (M_w) 8.6 and 9.0 in Richard scale along the Makran Subduction Zone (MSZ) as well as coastal landslides with soil volume of 1.25 to 2.0 km^3 along Iranian coast inside the Arabian Gulf is considered. TUNAMI-N2KISR model (Al-Salem) was applied in this study to predict the tsunami propagation and magnitude of Tsunami induced wave heights. The model adopts to solve shallow water equations describing nonlinear long-wave theory. The model also incorporate tidal effect inside the Arabian Gulf as a tsunami travel time from Makran Subduction to Qatar coastline takes more than 9 hours with the tidal range of about 1.6 m during Spring Tide event. For coastal landslides, tsunami generation was simulated using a two-layer numerical model, developed by solving nonlinear long-wave equations. Two-layer model was used to determine initial wave deformation generated by a landslide case. Then TUNAMI-N2KISR was use to simulate tsunami wave propagation. Tsunami waves from landslide scenario arrived after 2.5 - 3 hr with maximum tsunami amplitudes along coasts of Ras laffan-Qatar were 0.8 to 1.0 m. Incorporation of ocean tide is found to impose some small effect on tsunami amplitude at Qatar coastline and nearby areas for the Mw 9.0 earthquake due to small tidal range in this area. In addition, it is found that the tsunami arrival time has become shorter.

Keywords

Tsunami Hazards, Makran Subduction Zone (MSZ), Subaerial Landslide, Qatar Coastline, Ocean Tide

1. Introduction

Countries along the Arabian Gulf are the main oil and natural gas suppliers to the world. This represents approximately 30% of oil traded worldwide making the Arabian Gulf one of the world's major crude oil and gas exporting ports. Most of the population and coastal facilities of the countries surrounding the Arabian Gulf are located along the coastline. Most populations of these countries depend greatly on the continuous operation of their ports, power and desalination plants, where located within a few meters from the coastline. Qatar's coastal infrastructure, oil, gas industry and water desalination plants are located in an area less than 5 - 10 m above mean sea level, as shown in Figure 1, making them vulnerable to pressures from the sea, such as flooding caused by tsunamis waves. Al-Doha would be one of the largest cities in Qatar and having Qatar international Airport located on Qatar coastline. Major City were located on Qatar Coastline which are (Mesaieed, Al-Wakrah, ADaayen, AlKhor, Ras Laffan Industrial city, Ad-Dahirah and Abu-AlDhalouf). Al-Doha city region consisting of major valuable industrial facilities such as (Qatar Petrochemical company,

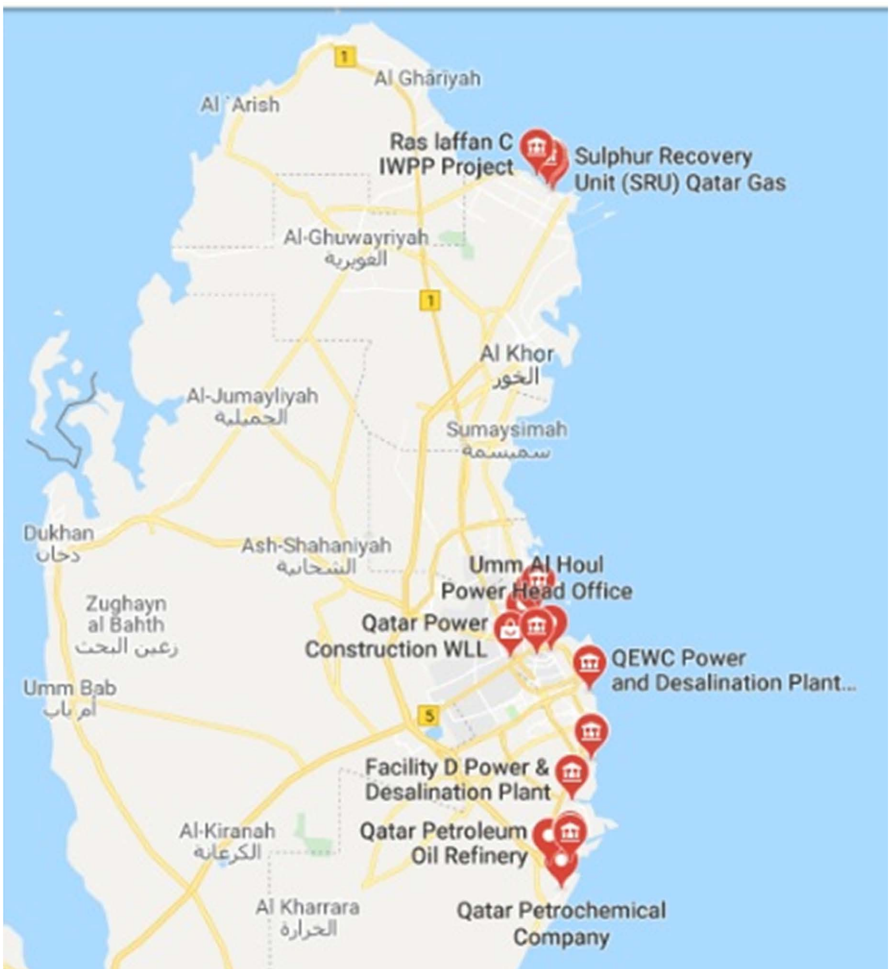

Figure 1. Qatar's coastal infrastructure, oil, gas industry, power and water desalination Plants.

Qatar Petroleum oil refinery, MP power, Facility D Power & Desalination Plant and Umm Al Houl Power (IWPP). These facilities are located at Coastline or very near. Also Ras Laffan consists of valuable industrial facilities such as (Qatar power plant and Recovery Unit Qatar GAS). Qatar power plant is a fuel–oil power plant with a design capacity of 1025 M_w and produces 60 MIGD potable water to cater the drinking water requirement of Qatar. Recovery Unit in Qatar QatarGAS Ras Laffan Liquefied Natural Gas Company Limited was founded in 1993 and consists of two trains, Trains 1 and 2, each of which can produce 3.3 mtpa of LNG. The LNG facility has capabilities for receiving and treating intake gas, stabilizing condensate, liquefying gas, and loading sulfur.

The significant tsunami recorded in the Arabian Gulf region is very low compared to other areas along the Indian Ocean's (Mokhtari [1]). A few studies were conducted on Investigation of the dangers and impacts associated with potential tsunami events in the Arabian Gulf. Nevertheless, the low potential of the tsunami hazards to coastal communities, such an investigation is very important. The Qatari authorities should conduct a thorough evaluation of these potential threats in order to proactively develop and implement emergency preparedness strategies to effectively manage the occurrence of natural hazards in their coastal areas. The Framework outlines the primary constituents of disaster preparedness. Warning systems encompass a comprehensive array of robust communication systems, including advanced technology, well-developed infrastructure, and proficient personnel. These systems are to be designed to efficiently communicate warnings to individuals who are at risk. Plan the creation of disaster preparedness strategies that emphasize viability, commitment, and resource assurance. Information systems refer to the utilization of efficient and dependable systems for the purpose of collecting and disseminating information among various stakeholders. This includes the exchange of crucial data such as predictions, warnings, appropriate capacities, role allocation, and available resources. The response mechanisms encompass a range of established and well-known procedures utilized by disaster response agencies and individuals affected by disasters. These mechanisms may involve many activities such as evacuation protocols, provision of shelters, deployment of search and rescue teams, evaluation of needs, activation of emergency lifeline services, as well as the establishment of receiving centers and shelters to accommodate displaced individuals. Education and training initiatives encompass a range of activities, including training courses, workshops, and extension programs, which are specifically designed to cater to at-risk communities and disaster responders. The distribution of information related to risk and the execution of appropriate measures via public information and educational frameworks. The purpose of these guidelines is to facilitate the comprehension of tsunami dangers, exposure, and susceptibility among coastal communities in Qatar, as well as to mitigate the ensuing risk through the implementation of land use planning, site planning, and building design strategies.

2. Tsunami Sources

Tsunamigenic sources of Makran submarine earthquakes and subaerial landslides are considered to be a potential tsunami threat to Qatar coastline. This section identifies possible tsunamigenic sources in terms of submarine earthquake based on historical events.

2.1. Makran Subduction Zone

This study aims to evaluate tsunami hazards along the coastal areas of Qatar using numerical modeling from potential local and regional sources. Tsunamigenic sources considered in this study were Makran submarine earthquakes. Makran Submarine earthquakes were identified to be possible in the Makran Subduction Zone (Al-Salem [2]). **Figure 2** display the sea surface deformation scenarios after submarine earthquake. To set up earthquake scenarios in this study, the Makran submarine Zone was considered to generate a tsunami waves in two cases, as shown in **Table 1**. Case E1 M_w 8.6 a scenario analysis suggested by (Heidarzadeh [3] [4]) and also proposed tsunami sources from significant earthquakes of up to M_w 9.0 as in Case E2. The relation between fault geometry of earthquake location and earthquake magnitude; it gives a smaller rupture area, but a higher slip and ensures the worst-case scenarios as suggested in (Wells and Coppersmith [5]).

2.2. Subaerial Landslides Generate Tsunamis.

Terrestrial landslide is another tsunami source that should be considered in this region. In some cases, tsunamis were generated by both earthquake and landslide at the same time. The landslide in (Shoaei and Ghayoumian [6]) was

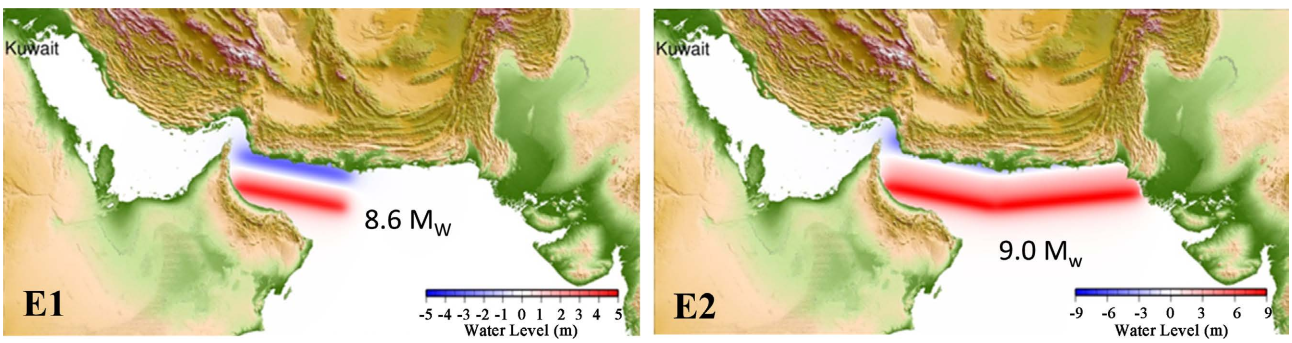

Figure 2. Initial sea surface deformation for cases E1 and E2 (Source Al-Salem 2017).

Table 1. Earthquake fault parameters for the selected cases in Makran Subduction zone.

Case	M_w	Length (km)	Width (km)	Slip (m)	Depth (km)	Strike	Dip	Rake
E1	8.6	500	100	13	25	280	7	90
E2	9	500	150	25	25	265	7	90
		400	150	25	25	280	7	90

*Source: Al-Salem 2017.

estimated volume of approximately 20 km^3. A possible tsunami event by 1008 AD in the Gulf at Siraf, Iran was identified and focusing on the impacts of tsunami on Arabian Peninsula (Jordan [7]). Based on the possible landslide-generated tsunami by 1008 AD in the Gulf at Siraf, four possible areas for terrestrial landslides (Location A to D) were identified at the Iranian coastline where the land elevations are higher than 500 m and are close to the sea side as shown in **Figure 3**. Although future detailed investigation is needed to verify the volumes, for simplicity of future comparison, the landslide volume was preliminarily set (width: 10 km and thickness: 5 m) based on previous studies for other areas around the world. Terrestrial landslide parameters in this study are shown in **Table 2**.

3. Technical Approach

3.1. TUNAMI-N2KISR Model

The Tohoku University developed a numerical model that was used to simulate the spread of the tsunami. The TUNAMI (Numerical Analysis Model for Investigation of Near-field Tsunamis) code was developed by Tohoku University (IUGG/IOC TIME Project 1997). The Kuwait Institute for Scientific Research (AL-Salem [2]) modified the model, which is detailed at http://www.hceatkuwait.net. To solve

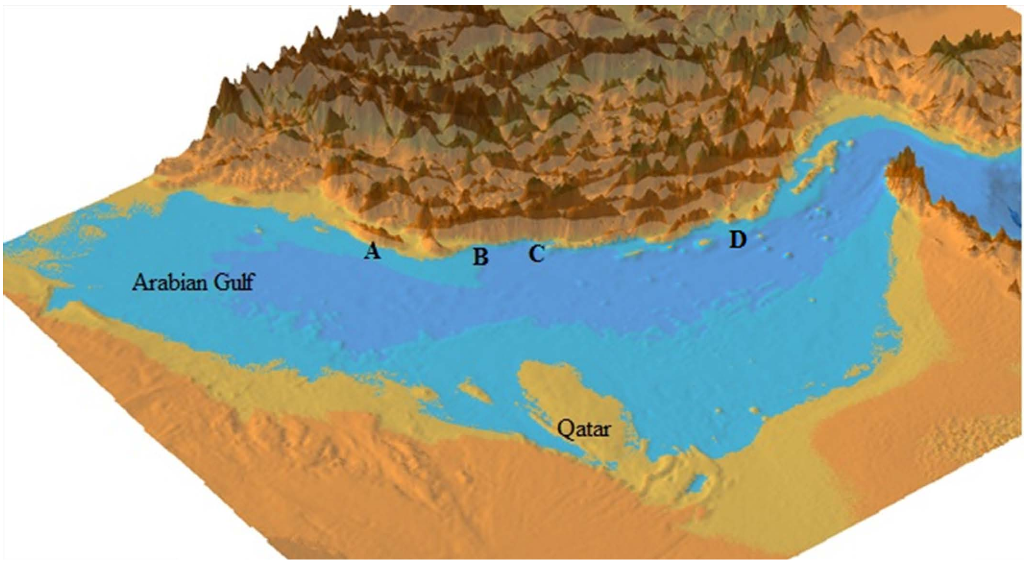

Figure 3. Locations of terrestrial landslide in the Arabian gulf region (Source: Al-Salem 2017).

Table 2. Terrestrial landslide parameters for the assumed scenarios inside the Arabian Gulf.

Loc.	Latitude	Longitude	Volume (km^3)	Length (km)	Width (km)	Thickness (m)
A	28.39˚	51.21˚	2	40	10	5
B	27.71˚	52.34˚	2	40	10	5
C	27.55˚	52.58˚	1.25	25	10	5
D	26.74˚	54.17˚	1.25	25	10	5

*Source AL-Salem 2017.

shallow water equations defining nonlinear long wave theory, the model uses a staggered leap-frog method (Imamura [8] and [9]). Following the fault parameters for each instance as previously given in **Table 1**, the simulation was carried out. To guarantee that the greatest tsunami amplitude would be reached, the simulation time was set to 20 hours. According to **Figure 4**, the tsunami waveforms are calculated for key ports or cities along Qatar's coastline.

3.2. Ocean KTide 2D Water Level Prediction Model

Because the source of Makran Subduction Zone is far from Qatar, it was estimated that tsunami wave has to travel approximately 7 - 10 h from the source to Qatar. TUNAMI-N2 KISR model was updated to be able to incorporate ocean tide on tsunami propagation in the Arabian Gulf (AL-Salem [2]). KTide model is 2D water level variations using 2D harmonic analysis of tide (from predefined validated set of harmonic constituents).

KTide model was developed and coupled with TUnami model by [AL-Salem [10] and http://www.hceatkuwait.net/request/HCA-Manual.pdf. Calculation 2D tidal level is a water level prediction from mean sea level (MSL), and the tidal level was used to update stepwise water depth or bathymetry data at hourly interval. It means that still water depth was updated according to the tidal change at hourly interval in the tsunami simulation before solving the nonlinear equations of mass and momentum conservation.

3.3. Two-Layer Model

In addition to tsunami caused by earthquakes, the Iranian coastline is susceptible to tsunami caused by underwater and subaerial landslides. A two-layer numerical model was created by solving nonlinear long wave equations within two interacting layers with suitable kinematic and dynamic boundary conditions at the seabed, interface, and water surface (Imamura and Imteaz [11]). This model was used to simulate the generation of tsunami caused by landslides.

4. Results and Discussion

Tsunamis generated by both submarine earthquakes from the Makran Subduction Zone and subaerial landslides inside the Arabian Gulf were simulated and investigated. The results of numerical tsunami simulation presented in this section are the potential tsunami threat along the Qatar coastline and also was investigated for maximum tsunami amplitude. Tsunami waveforms are computed at selected locations of major cities, ports and industrial facilities at Qatar Coastline as shown in **Figure 4**.

4.1. Earthquake Induced Tsunami Scenarios from the Makran Subduction

The input fault parameters in **Table 1** were used to calculate initial sea surface deformation. The generation of earthquake-generated tsunamis was simulated

Mesaieed	565388 mE	2771276 mN	3.2m
Al-Wakrah	566152 mE	2784164 mN	5.0m
Doha airport	566361 mE	2796494 mN	5.4m
Doha city	560000 mE	2806384 mN	2.1m
Sumaysimah	554264 mE	2828640 mN	2.4m
Al-Dhakira	560860 mE	2846238 mN	2.2m
Ras Laffan	556616 mE	2868753 mN	4.5m
Abu Al-Dhalouf	521954 mE	2901716 mN	9.5m

Figure 4. Selected locations of major cities, ports and industrial facilities at Qatar Coastline.

from the initial sea surface deformation as shown in **Figure 2** for Case E1 (M_w 8.6) with a rupture length of 500 m, Case E2 (M_w 9.0) with a rupture length of 900 m. Uplift areas are shown in red, and subsidence areas are shown in blue. Maximum uplift is approximately 5, and 9 m for Cases E1 and E2, respectively.

From the numerical simulation results, the Makran Subduction Zone earthquake with a M_w of 8.6 in Case E1 could cause a tsunami amplitude of approximately 0.2 m along the coasts of Al-Doha city (Qatar) after 9 hr from earth quake generation as shown in **Figure 5**, where a M_w 9.0 earthquake of Case E2 could cause tsunami amplitudes of up to 0.6 m along the coasts of the Al-Doha city Qatar after 8.5 hr from earth quake generation, up to 0.6 m along the coasts of Ras Laffan Qatar at 8 hr from earth quake generation as shown in **Figure 5**. The numerical simulation results in **Figure 5** suggested that earthquake-generated tsunamis in the Makran Subduction Zone for Cases E1 and E2 were about (0.2 - 0.6 m). **Figure 6** shows simulated snapshots of tsunami propagation to Al-Doha Qatar at 2 hr and 9 hr for case E1 and 2 hr and 8.5 hr for case E2 from start earth quack time in Makran Subduction Zone.

4.2. Effect of Ocean tide on Tsunami Propagation

The effect of ocean tide in the Arabian Gulf was incorporated to numerical tsunami simulation considering the complex tidal characteristics. The travel time of a tsunami wave from the Makran Subduction Zone to Al-Doha Qatar is 8.5 h for

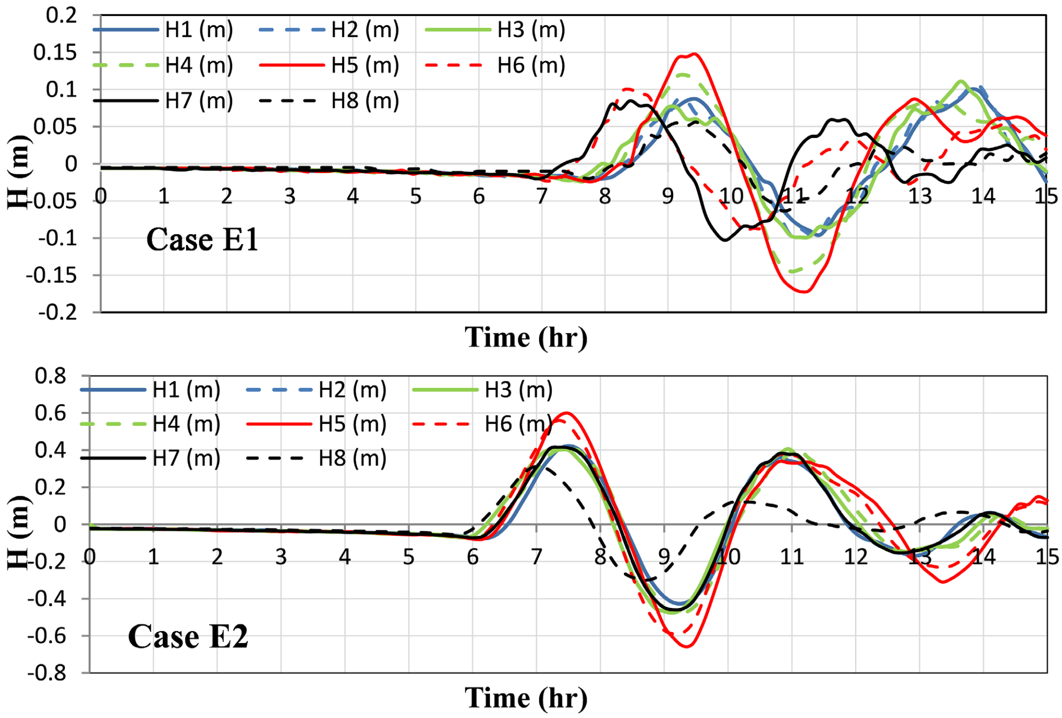

Figure 5. Simulated tsunami waveforms for cases E1 and E2 at Selected cities along Qatar coastline.

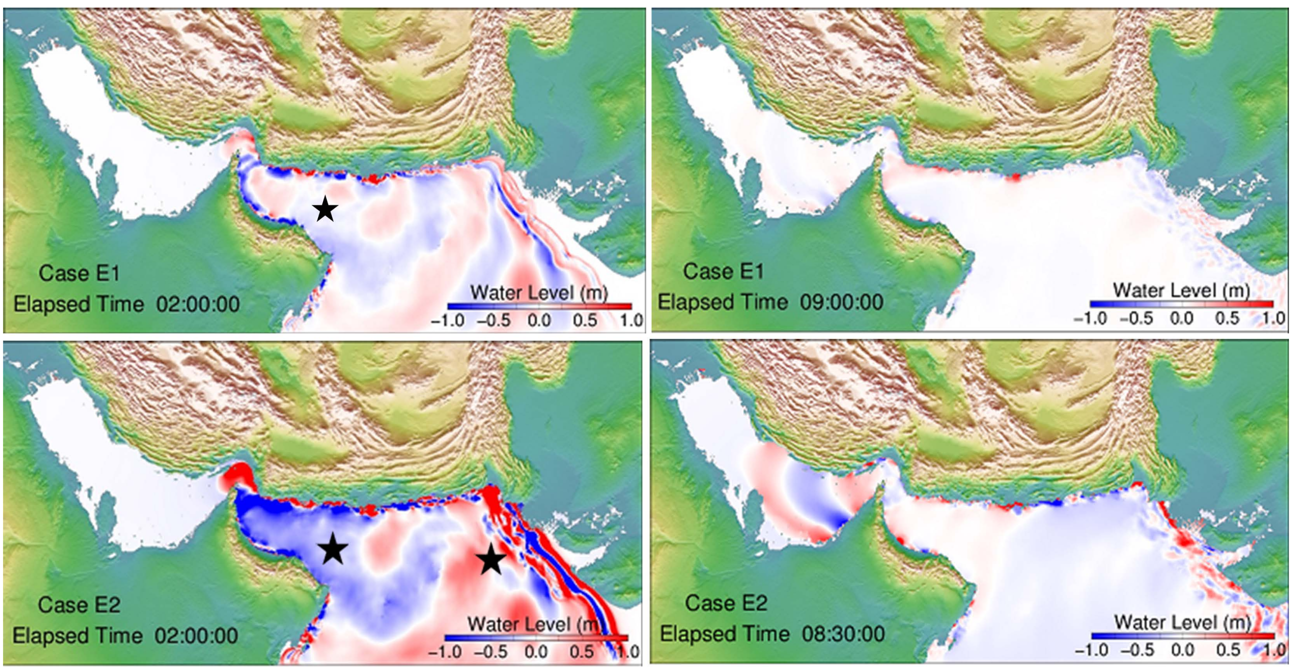

Figure 6. Tsunami waveforms propagation at 2 and 9 hr for Case E1 and 2 and 8.5 hr for Case E2 (★ : Epicenter-Location).

Case E2. Therefore, this tidal change should have a significant effect on tsunami propagation. Figure 7 shows the tide level at offshore of Al-Doha during Feb 12, 2020, where tide type is Spring tide and the highest tide level is during 7 to 9 am where the same time of the maximum tsunami wave reach Al-Doha coastline from Case E2 having tidal range of about 1.6 m. In general, tidal wave is much

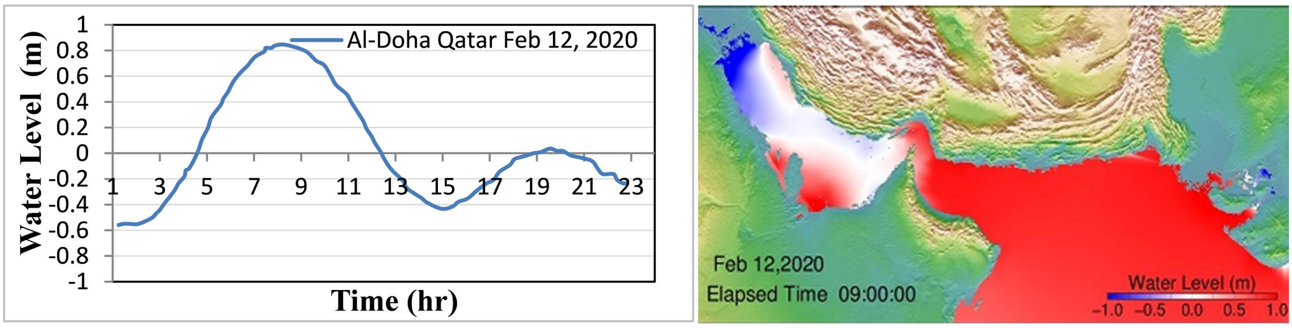

Figure 7. Tidal level at Al-Doha Qatar coastline for 24 hr from mean sea Level as 1D and at 9:00 Am as in 2D for Arabian Gulf and Gulf of Oman from KTide model.

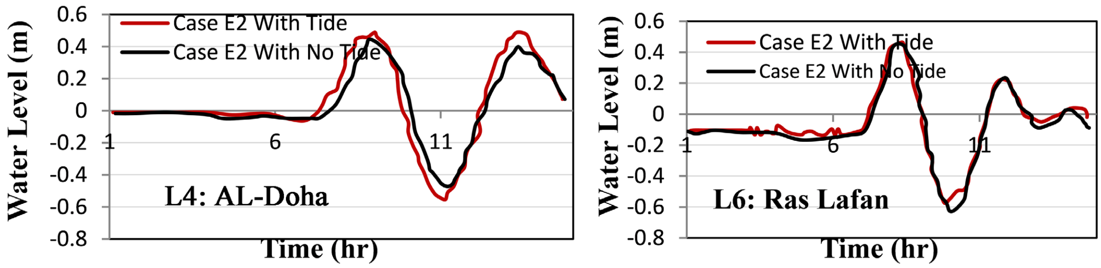

Figure 8. Comparison of Tsunami waveforms with the effect of ocean tide at Al-Doha and Ras laffan Qatar for Case E2.

smaller than tsunami wave, so this small tidal wave does have small significant effect on tsunami propagation. For Case E2 with the effect of ocean tide, tsunami propagation is shown in Figure 8. The tsunami propagation with the effect of ocean tide demonstrated small significant differences compared for Case E2 with and without the effect of ocean tide. As shown in Figure 8, both waveforms for Al-Doha city and Ras Laffan are somewhat with the same arrival time of 8.5 - 9 h, but the effect of ocean tide could impose higher tsunami amplitude in the first and second peak at AL-Doha Location. So the effect of ocean tide could generate little higher tsunami amplitude at all vital places along the Qatar coastline. It is found that there is minimum effect due to low tidal range around Qatar coastline.

4.3. Tsunami Scenarios from Landslide Sources

Based on the landslide sources as given in Table 2 and Figure 3, the two-layer model was used for tsunami generation and implemented with TUNAMI-N2KISR model to simulate tsunami propagation. The tsunami wave started to propagate from the opposite coast of Qatar coastline and Tsunami waves arrived after 2.5 - 3 hr. The maximum tsunami amplitudes along the Qatar coasts were 0.8 to 1.0 m for the Ras laffan and Abu AlDhalouf at Qatar Coast for Source B and C, Where Al-Doha coast receives tsunami amplitudes of 0.4 - 0.5 m (Source B and C) as well as the nearby areas as shown in Figure 9.

These results suggest that the distribution of the maximum tsunami amplitude after 3 h for Source B and C as shown in Figure 3 with a landslide volume of 2 km^3 and 1.25 km^3 was concentrated on the north coast of Qatar, where the

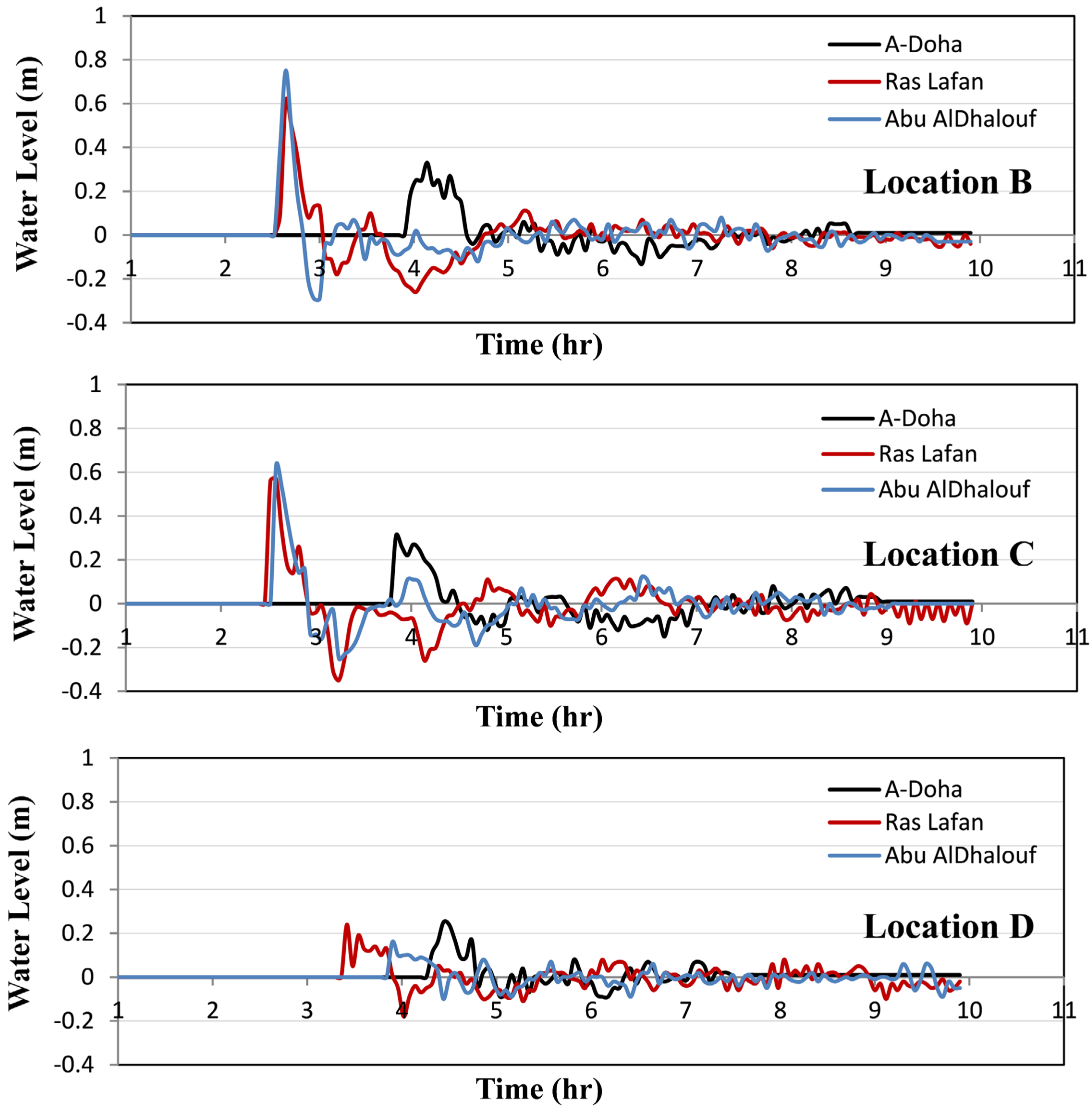

Figure 9. Simulated landslide generated tsunami waveforms from source locations B, C and D at selected cities along Qatar coastline.

Al-Doha side coast receives comparatively smaller amplitude of tsunami waves. For landslide Sources A,B,C and D, the simulated snapshots of tsunami propagation at 1 hr, 2 hr, and 3 hr are shown in **Figure 10** to demonstrate tsunami hazards along the Qatar coastline.

Figure 11 shows the tsunami propagation toward Qatar Coastline in 3D forms for Location B and for more result 2D/3D animation http://www.hceatkuwait.net/Q8TSUnami/Q8main.aspx. The tsunami propagation from Source D shows minimum impacts along the Qatar coasts.

5. Conclusion

Possibility of Tsunami waves around Qatar coast is studied for Makran earthquake and for landslides in the Iranian coast. Even low tsunami risks can impose a potential threat to Qatar coastline, since the coastal area is more populated

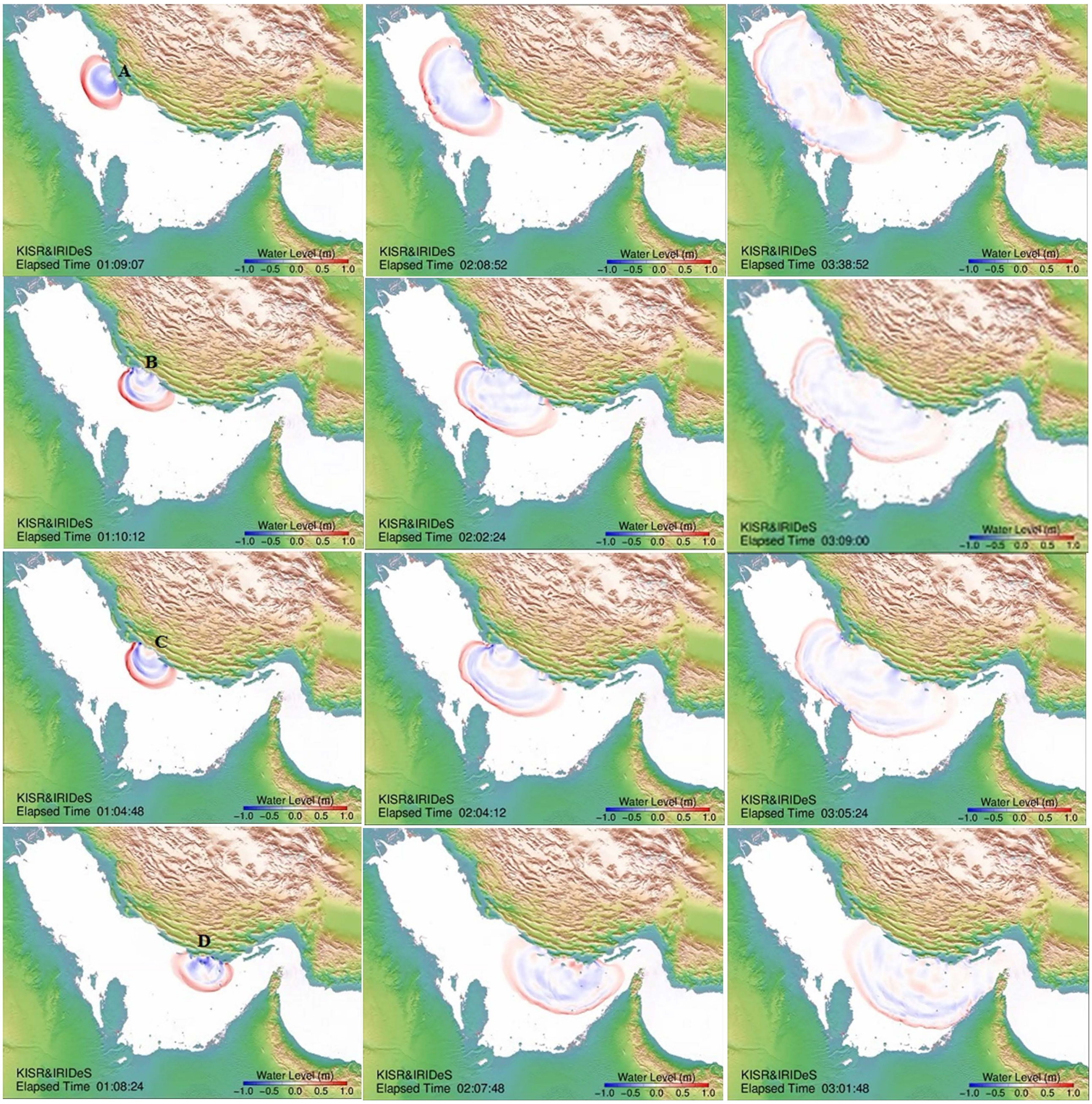

Figure 10. Tsunami wave propagation from sources A, B, C and D at 1 h, 2 h, and 3 h along Qatar coastline.

with human life and infrastructures. This study identified one major tectonic fault in Makran Subduction Zone, which is situated outside the Arabian Gulf, which may potentially cause an earthquake generated tsunami. Tsunamis generated by earthquakes of M_w 8.6 - 9.0 at the Makran Subduction Zone were modeled and investigated. This study strongly suggests that only a tsunami generated by a M_w 9.0 earthquake at the Makran Subduction Zone could have a significant impact on the Qatar coastline. The simulated maximum tsunami amplitudes were approximately 0.8 - 1.0 m at the north side of Qatar coast and decreased to approximately 0.5 m in Al-Doha coast and nearby, where tsunami wave it takes

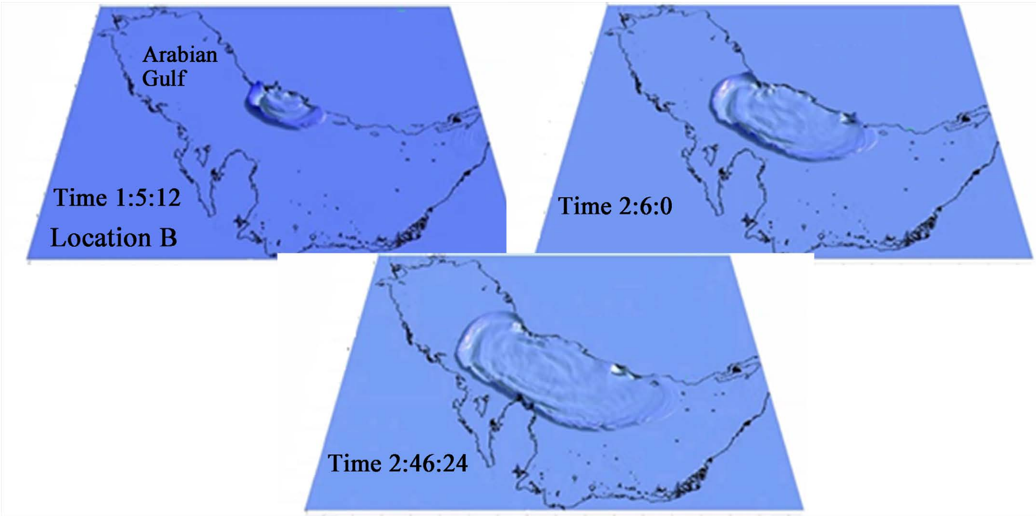

Figure 11. Tsunami propagation from sources location B at 1 h, 2 h, and 3 h along the Qatar coastline in 3D wave form.

9 hr to reach Qatar coast. This study illustrated the effect of incorporating ocean tide on the modification of Tsunami wave propagation, change in Tsunami wave amplitude and Tsunami wave arrival time. It is found that the effect is small effect on tsunami amplitude at Qatar coastline and nearby areas for the M_w 9.0 earthquake due to small tidal range area. However, it is found that the tsunami arrival time became shorter, when incorporating the tidal effect.

The investigation of landslide-generated tsunami using assumptions for landslide volumes based on topographic slope and landslide records. The landslide volumes used in this study varies between 1.25 and 2.0 km^3 were applied in the two-layer model. The landslide sources along the Iranian coast used in this study could cause only localized impacts. The landslide simulation result produce maximum tsunami amplitude of up to 1 m in certain areas along Qatar coastline and arriving wave time to Qatar coastline about 3 hr from the starting of landslide at Iranian coastline. Though the tsunami amplitude expected about 1.0 m, it can cause significant damage to coastal structures, since most of the coastal infrastructures are very close to high water line. Hence the result of this study can be used for needed strategy for resilience and risk management during such disaster.

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Authors' Contributions

Data curation: Khaled AL-Salem and Mohammad Al-Sarawi.

Formal analysis: Khaled AL-Salem and Mohammad Al-Sarawi.

Roles/Writing—original draft; Writing—review & editing: Khaled AL-Salem and Mohammad Al-Sarawi.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author or at http://hceatkuwait.net/Q8TSUnami/Q8main.aspx.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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