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Tsunami Risk Assessment for the Red Sea and Generating Initial Tsunami Levels for Various Return Period Conditions

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ABSTRACT
Earthquake swarms are frequent in the Red Sea but most of the earthquakes are weak (ranging in magnitude Mw from 0.3 to 3.5). However, sometimes earthquakes with moderate strength occur in the Red Sea such as the 1977 event with Mw 6.6. These earthquakes can generate tsunamis affecting coastal cities and ships cruising in the Red Sea. Some major developments are taking place recently within the Red Sea and adjacent to its coastlines. Tsunami risk should be assessed for such major developments. In this paper a) tsunami risk for the Red Sea has been assessed b) a list of major earthquakes since 1977 has been provided c) earthquake magnitudes (Mw) for various return periods (100, 1000 and 10000 years) have been provided and d) initial tsunami levels for these return periods and the 1977 event have been generated using the MIKE21 Toolbox of DHI. These initial tsunami levels can be used to drive a tsunami model for deriving tsunami levels and forward velocities at various locations within the Red Sea. Structural design considerations and tsunami risk reduction measures are also discussed in this paper. The methodology described in this paper for tsunami risk assessment and generating initial tsunami levels in the Red Sea could also be applied to other sites around the world.

Key words: Tsunami, Natural Hazards, Red Sea, Numerical Modelling, Port Development, Royal HaskoningDHV

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1. INTRODUCTION

Formation of tsunamis

“Tsunami” is a Japanese word written with two Chinese characters. “Tsu” means “harbour/port” and “nami” means “wave” and, therefore, “tsunami” means “harbour/port wave” in Japanese. The naming comes from the fact that tsunamis seem to appear suddenly and become very violent in shallow areas, attacking low-lying areas that are actively used and densely populated, such as port areas [1].

A tsunami (also known as a seismic sea wave) is a series of water waves (similar to shallow water waves) in a water body caused by the abrupt displacement of a large volume of water initially resembling a rapidly rising tide. A tsunami can be generated by underwater earthquakes, landslides, fault breaks (ruptures), volcanic eruptions and other underwater explosions (such as the detonation of nuclear devices), glacier calving, impact of objects from outer space (such as meteorites, asteroids, comets) and other disturbances in water. Ninety (90) percent or more of historical tsunamis in the world have been generated by earthquakes in the sea and coastal regions. Generally larger and shallower hypocentre earthquakes cause larger tsunamis [1].

Propagation of tsunamis

Tsunami wave periods range from minutes to hours (typically 5 to 60 minutes) and having a wavelength much longer than sea waves and can travel long distances across the oceans. Their behaviour is similar to shallow water waves (because their wavelength is >> water depth) which means that the speed (v) is calculated as the square root of the product of the water depth (h) and the acceleration due to gravity (g) i.e. $v = \sqrt{(gh)}$. Consequently, tsunamis travel very fast in deep oceans. For example, if the water depth is 5000m, the speed will be more than 200m/s or about 800km/hour.

A tsunami wave is normally not very high in deep water but when it approaches the coastline, the wave will begin to steepen due to shoaling effects and, depending on the size of the incoming wave, can reach a height of more than 10m.

Damages from tsunamis

Tsunamis can cause significant damage to coastal facilities such as seaports, oil terminals and jetties during their construction and operation. Significant loss of life and damage to properties, ecosystems and marine facilities can occur due to tsunamis. Typical examples of such coastal and marine structures and facilities are flood and coast protection structures, revetments, seawalls, quay walls, dikes, retaining structures, piers, breakwaters, port and dry dock buildings and facilities, ferry terminals, wharf, dolphin, barges, gates, warehouses, boats, small ships and larger vessels including cargos, oil tankers, bulk carriers and passenger carriers. Damage due to collision among boats, small ships or larger vessels is common during a tsunami.

Furthermore, such natural hazards put lives and properties in coastal areas at great risks through flooding and submergence of low-lying areas. Very high tides during a tsunami may damage installations, dwellings, transportation and communication systems, trees etc. and cause fires resulting in considerable loss of life, damage to properties and ecosystems. Destruction of transportation or communication infrastructures hampers clean-up and rescue efforts. High tides during a tsunami may cause floods and submergence of low-lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property. The resulting floods, standing water and coastal inundation pollute drinking water sources and spread diseases leading to outbreak of epidemics. Tsunamis also cause secondary damage from floating debris, drifting trees and vessels, sediment erosion and deposition and spreading of fire.

As reported in [2], the 1960 Valdivia earthquake (M_w 9.5), 1964 Alaska earthquake (M_w 9.2), 2004 Indian Ocean earthquake (M_w 9.2) and 2011 Tōhoku earthquake (M_w 9.0) are recent examples of powerful megathrust earthquakes that generated tsunamis (known as teletsunamis or distant tsunamis) that can cross entire oceans. The 2004 Indian Ocean tsunami was among the deadliest natural disaster in human history with at least 230,000 people killed or missing in 14 countries bordering the Indian Ocean. The 2011 tsunami in Japan resulted to 15,894 deaths, 6,152 injured and 2,562 people missing. The 2011 tsunami damaged many buildings, dams, bridges, nuclear power stations and many other infrastructures. The World Bank's estimated economic cost due to the 2011 tsunami was US$235 billion, making it the costliest natural disaster in world history. As reported in [3], deaths from the 1945 earthquake in the Makran Subduction Zone that generated tsunamis along the coastlines of Iran and Pakistan were reported to be as many as 4,000 people. Furthermore, the tsunami caused catastrophic damage to properties and other coastal facilities.

Types of faults and properties of tsunamigenic earthquakes

Dip-slip faults are the faults which move along the direction of the dip plane and are described as either normal or reverse or thrust faults, depending on their motion. Strike-slip faults are the faults which move horizontally and are classified as either right-lateral or left-lateral.

An earthquake induced tsunami is generated by a seafloor deformation associated with submarine and near-coast earthquakes with shallow depth (<50 km), large magnitude ($M > 6.5$) and dip–slip mechanism [4]. Strike–slip fault motion produces a small vertical deformation of the sea floor, and consequently the induced tsunamis are usually of smaller height [4].

The present study

Initially the tsunami risk in the Red Sea has been assessed and a list of major earthquakes has been provided. Earthquake magnitudes (Mw) for various return periods have been reviewed. Usually, 1 in 100 year tsunami conditions are used for designing marine structures and facilities whereas 1 in 1,000 year conditions are used for rescue and emergency planning purposes. Some high-profile major developments need 1 in 10,000 year conditions as well. Therefore, initial tsunami levels for 100-, 1000- and 10000-year return periods have been generated using the MIKE21 Toolbox of DHI [5]. Initial tsunami levels were also generated for the 1977 event. These initial tsunami levels can be used to drive a tsunami model for deriving tsunami levels and forward velocities at various locations within the Red Sea. Structural design considerations and tsunami risk reduction measures are also discussed in this paper.

Steps and software generally used in a tsunami modelling study are illustrated in Figure 1 [6]. Definitions of tsunami water level and wave height generally used are illustrated in Figure 2 [6]. A tsunami wave height refers to the vertical distance from trough to peak of a tsunami wave. A tsunami level (also called a tsunami height) is referred to the height of the water column above the Mean Sea Level (MSL). Any tsunami level (or tsunami height) in this paper refers to a level above the MSL.

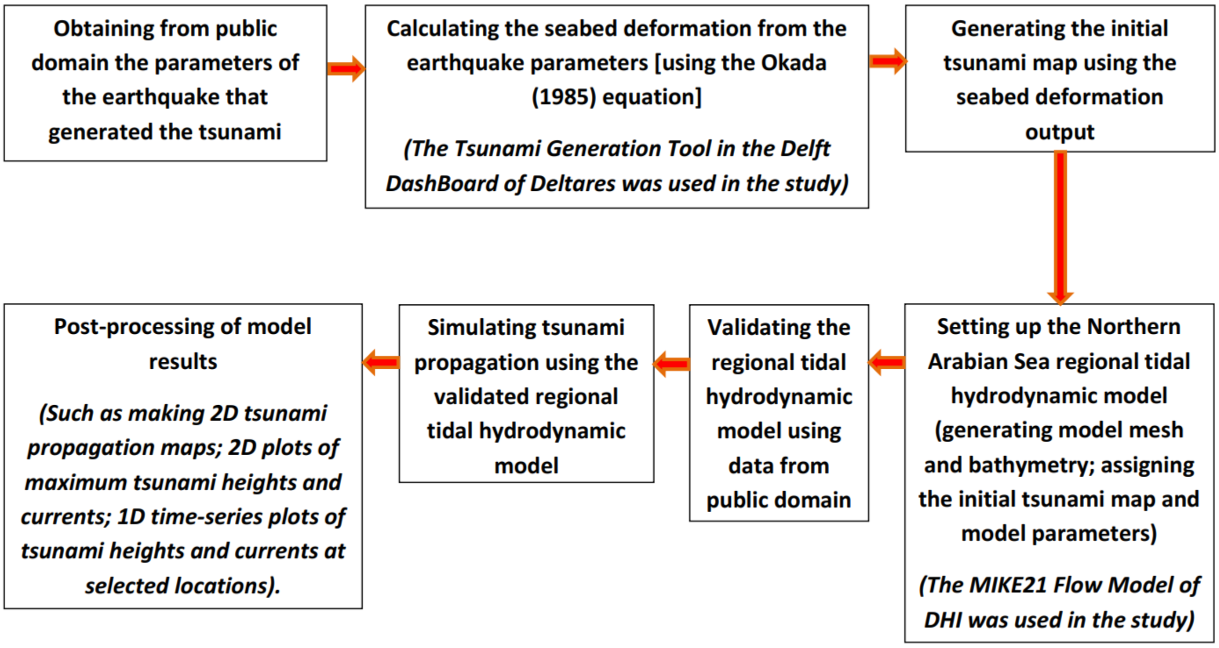

Fig. 1 Steps and software generally used in a tsunami modelling study [6]

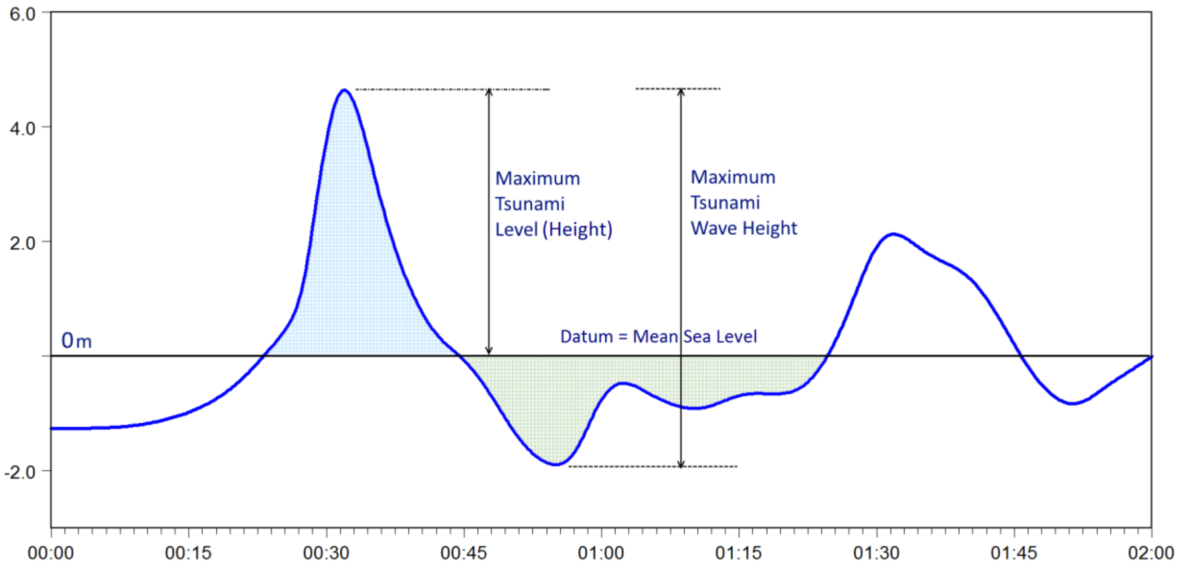

Fig. 2 Definitions of tsunami water level and wave height [6]

2. PLATE TECTONICS AND EARTHQUAKES IN THE RED SEA

The Red Sea

The Red Sea is situated in the Middle East in between Egypt and Saudi Arabia. It is connected to the Mediterranean Sea by the Gulf of Suez and the Suez Canal at its north-west. It is connected to the Arabian Sea by the Gulf of Aden at its south-east. The Red Sea is surrounded by desert and hence it is one of the warmest seas in the world. The Red Sea water is very salty, and high in nutrients and plankton (tiny plants and animals). The name of the Red Sea is derived from the colour changes observed in its waters from an intense blue green to occasionally a reddish brown upon algae dying off.

The plate tectonics of the Red Sea

The Red Sea rift was formed by the divergence between the African and the Arabian Tectonic Plates as shown in Figure 3 [7]. It extends from the Dead Sea Transform fault system, and ends at an intersection with the Aden Ridge and the East African Rift, forming the Afar Triple Junction in the Afar Depression of the Horn of Africa [7]. Figure 3 shows that the African and the Arabian Tectonic Plates are moving apart at the rates of 7 mm/year at the southern part of the Red Sea and 17 mm/year at its middle part.

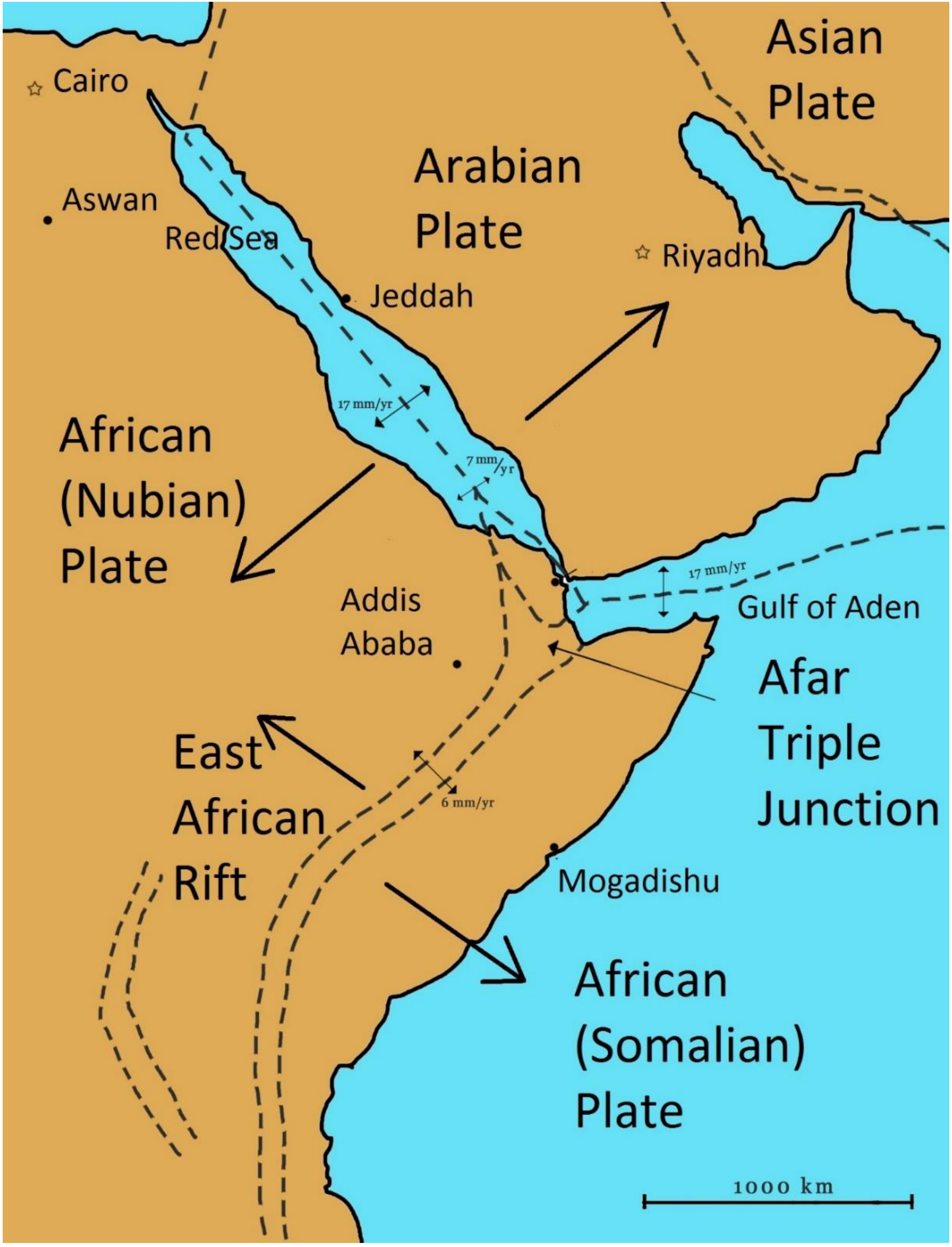

Fig. 3 Plate tectonics of the Red Sea [7]

The Red Sea lies in a fault between the Arabian Plate and the Nubian (Africa) Plate [8] which are moving apart. These two plates meet with the Somalian Plate in the south [9]. Earthquakes occur in the Red Sea due to the motion among these three plates.

The northern part of the southern Red Sea is dominated by normal faults striking perpendicular to the direction of extension whereas in the south there is left lateral strike-slip activity as well as normal faulting [10].

Major earthquakes in the Red Sea

The major earthquakes in the Red Sea since 1977 (as in Table 1) were obtained from the Global CMT Catalog Search (https://www.globalcmt.org/CMTsearch.html) [11, 12].

Table -1 Major historical earthquakes in the Red Sea since 1977 [11, 12]

Date/month/year	Magnitude	Latitude (°N)	Longitude (°N)	Depth (km)	Strike (°N)	Dip (°)	Slip (°)
28/12/1977	6.6	15.97	40.32	10.1	106	66	-171
17/01/1978	5.4	17.51	40.49	15.0	282	90	180
14/01/1980 (1)	6.0	17.12	40.53	15.0	24	76	-9
14/01/1980 (2)	5.7	16.99	40.12	15.0	301	90	180
10/12/1988	5.6	16.56	41.10	15.0	339	74	-17
12/03/1993 (1)	5.3	19.39	38.34	15.0	148	31	-83
12/03/1993 (2)	5.0	19.76	38.68	15.0	321	45	-90
13/03/1993	5.6	19.42	38.55	15.0	144	40	-84
14/03/1993	4.9	19.65	38.74	15.0	301	45	-90
16/03/1993	5.3	19.18	38.61	15.0	127	38	-114
22/03/1993	5.0	19.43	38.59	15.0	315	45	-90
23/03/1993	5.2	19.85	38.39	16.3	313	45	-90
02/11/1996	5.3	19.13	38.94	15.0	153	20	-68
25/05/2001	5.2	18.21	40.07	15.0	303	36	-128
02/07/2006	4.7	19.09	39.28	12.0	329	29	-93
01/01/2009	5.0	17.11	40.58	12.0	328	26	-61
05/02/2009	4.9	19.03	39.26	12.0	106	49	-127
09/08/2010	5.0	18.72	39.46	17.5	329	29	-59
08/07/2013	5.5	16.81	40.86	13.8	108	80	-171
23/12/2013	5.2	19.08	39.22	12.0	125	38	-105
10/07/2014	4.7	17.70	40.25	13.5	132	42	-98
25/06/2015	5.1	17.23	40.57	12.0	338	49	-59
06/03/2016 (1)	4.8	17.54	40.48	12.0	341	45	-51
06/03/2016 (2)	5.0	17.56	40.39	12.0	323	42	-76
07/03/2016	4.9	17.68	40.28	12.0	128	40	-107
06/03/2019 (1)	5.1	17.62	40.29	12.3	133	40	-143
06/03/2019 (2)	5.1	17.97	40.07	12.0	169	37	-68
08/03/2019	5.1	18.02	39.85	15.6	354	14	-123
11/09/2019	4.8	16.62	40.05	18.0	75	25	94
16/06/2020	5.3	27.13	34.64	12.0	217	85	-4
27/11/2020	4.7	17.91	40.07	12.0	134	33	-102

Tsunami Risk Assessment

The probability of occurrence of a tsunami is very low but if it occurs it can be devastating. Therefore, an adequate level of tsunami risk assessment is essential for any major coastal project. The first step in assessing the tsunami hazard is to carry out a statistical analysis of the historical tsunami events in a certain region. This is not an easy task because large tsunamis are rare which makes a robust statistical analysis almost impossible.

Initially a seismic risk assessment should be carried out to a) identify the major fault lines in the region b) assess the risks to the site from tsunamis and c) determine the most critical tsunamigenic earthquake affecting the site. Published literature and papers can be obtained from the public domain to identify historic tsunamis to assess the risks and to obtain earthquake parameters required for tsunami modelling.

Earthquake Return Periods for the Red Sea

Earthquake magnitudes (Mw) for various return periods were obtained from Hamouda (2011) [13], El-Quliti et al. (2016) [14] and Abdelfattah et al. (2022) [15] and are provided in Table 2. Values from the three sources are broadly similar although values from Hamouda (2011) [11] are slightly higher. Therefore, values from Hamouda (2011) [13] provided in Table 3 were selected to use in the present study to represent the worst-case scenario.

Table -2 Earthquake magnitudes Mw obtained for various return periods from different authors

Return periods	Earthquake magnitude (Mw)		
	Hamouda (2011) [13]	El-Quliti et al. (2016) [14]	Abdelfattah et al. (2022) [15]*
1 in 100 years	6.3	6.1	6.1
1 in 1,000 years	7.0	6.7	6.7
1 in 10,000 years	7.1	7.0	6.8

*upper values extracted

Table -3 Earthquake magnitudes Mw selected for the present study for various return periods from Hamouda (2011) [13]

Return periods	Earthquake magnitude (Mw)
1 in 100 years	6.3
1 in 1,000 years	7.0
1 in 10,000 years	7.1

Generating Initial Tsunami Levels for the Red Sea

It is assumed that the initial sea surface rise or fall is the same as the final seafloor deformation after the earthquake. This is a reasonable assumption because the duration of an earthquake is generally short, and the size of the rupture area is much larger than the water depth. Consequently, there is not enough time for the water above the deformed seafloor to drain out. The seismic rupture is much faster than water wave propagation.

Initial tsunami levels were generated for the earthquake magnitudes in Table 3 using the MIKE21 Toolbox developed by DHI [5]. The Crustal dip-slip fault mechanisms from [16] was used. Square grid size of 1km x 1km was used for the domain to generate the initial tsunami levels. Table 4 provides the earthquake parameters used in generating the initial tsunami levels. Depth, dip angle and rake angle for the return period earthquakes were obtained as average from the historic earthquakes of Mw ≥ 5 listed in Table 1. Latitude and longitude are for an assumed location (epicentre) on the Faultline. The strike angle is the actual heading of the Faultline at that location. The tool calculates the length, width and slip (seabed deformation) based on a given Mw. The actual parameters were used for the 1977 event.

The two Lamé coefficients (shear modulus and lambda) describe physical characteristics of the earth's crust. Shear Modulus, μ (or rigidity) is the measure of how an elastic body deforms due to forces parallel to one of its surfaces. Lambda (l) has no physical meaning but can be derived from shear stress and Poisson ratio. The values for shear modulus and lambda depend on the depth of the rupture and can be taken from the four-layer half-space model of the earth (Wang et al., 2003) [17]. Shear modulus of 39.7 GPa and lambda of 32.1 GPa were used in the tool.

Table -4 Earthquake parameters used in generating the initial tsunami levels

Earthquakes	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Depth (km)	Slip (m)	Strike (°N)	Dip (°)	Slip/Rake (°)
1 in 100 year	21.4151	37.8966	18.9	10.1	14.0	0.51	350	49	-86
1 in 1,000 year	21.4151	37.8966	49.0	17.0	14.0	1.91	350	49	-86
1 in 10,000 year	21.4151	37.8966	56.1	18.3	14.0	2.30	350	49	-86
1977 event	15.97	40.32	28.4	12.6	10.1	0.90	106	66	-171

The initial sea surface elevation generated for the four cases (as in Table 4) are summarised in Table 5 and illustrated in Figures 4 to 7. It should be noted that the maximum initial tsunami level and its location for a given Mw will vary due to the distribution of the length, width and dislocation (slip) of the fault.

Table -5 Maximum rise and fall in the sea surface elevation (m)

No.	Earthquake conditions	Maximum rise or fall in sea surface elevation	
		Rise (m)	Fall (m)
1	1 in 100 year (Mw = 6.3)	0	0.07
2	1 in 1,000 year (Mw = 7.0)	0	0.50
3	1 in 10,000 year (Mw = 7.1)	0.05	0.65
4	1977 event (Mw = 6.6)	0.04	0.07

The 1 in 100 year earthquake magnitude (Mw 6.3) is smaller than the threshold Mw of 6.5 for generating a significant tsunami. Therefore, no major rise or fall in the sea surface elevation was found for this condition. The 1 in 1000 year and 1 in 10000 earthquake magnitudes (Mw 7.0 and 7.1 respectively) are higher than the threshold value of Mw 6.5. Therefore, reasonable falls in the sea surface elevation were found (0.5m fall for 1 in 1000 year and 0.65m fall for 1 in 10000 year). The 1977 earthquake magnitude (Mw 6.6) is close to the threshold Mw of 6.5. Therefore, no major rise or fall in the sea surface elevation was found for this event.

Sensitivity tests were carried out using Crustal strike-slip (Wells and Coppersmith, 1994) [16] and Subduction zone dip-slip (Papazachos et al., 2004) [18] for all the four cases in Table 5. Changes in sea surface elevation were found to be smaller for all the four cases than those reported in Table 5.

The two plates that are moving apart in the Red Sea will not produce a large seabed deformation. This is more the effect when two plates meet. Small earthquake magnitude (Mw) with a small slip and a negative slip angle will not produce higher changes in the seabed [19].

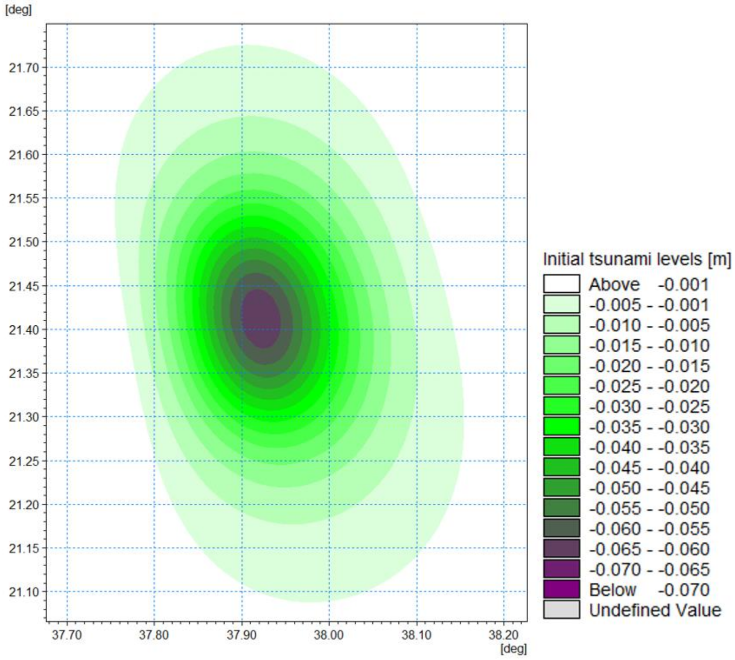

Fig. 4 Initial tsunami levels for 1 in 100-year return period (Mw = 6.3)

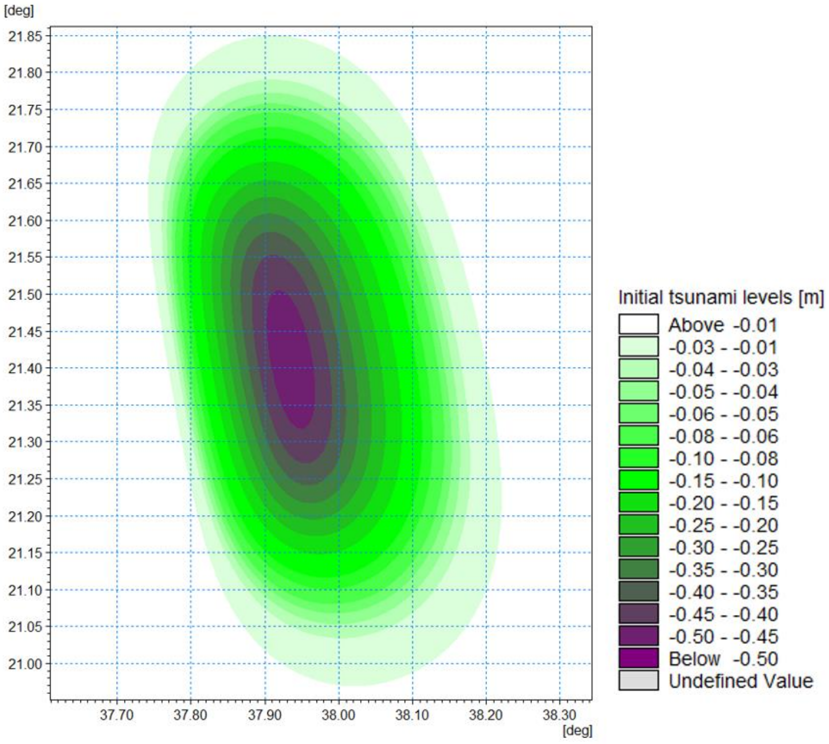

Fig. 5 Initial tsunami levels for 1 in 1,000 year return period (Mw = 7.0)

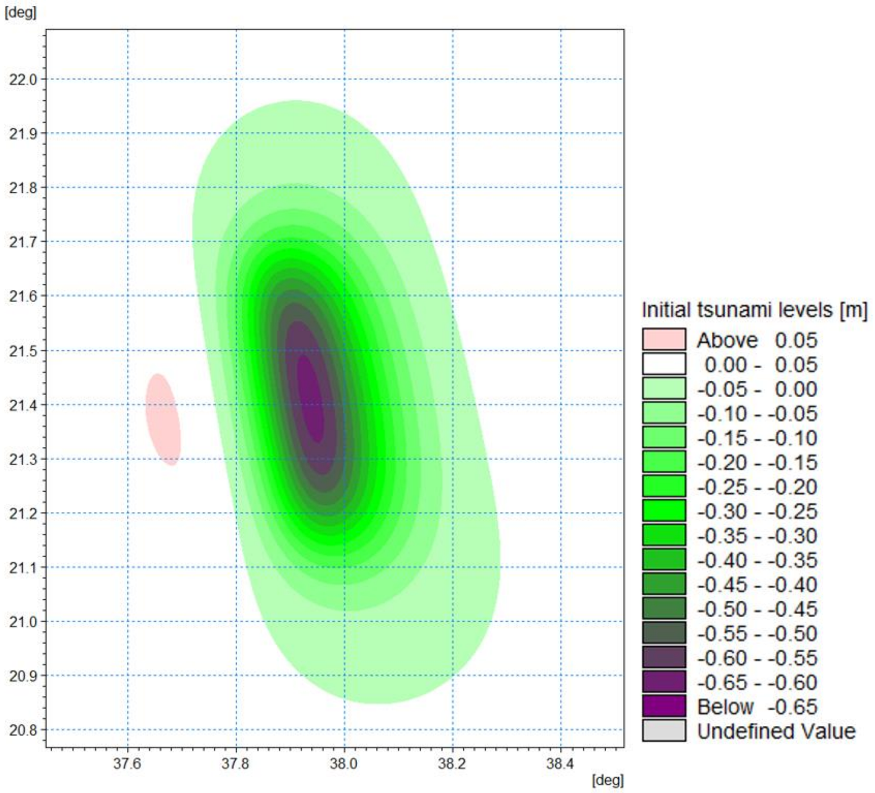

Fig. 6 Initial tsunami levels for 1 in 10,000 year return period (Mw = 7.1)

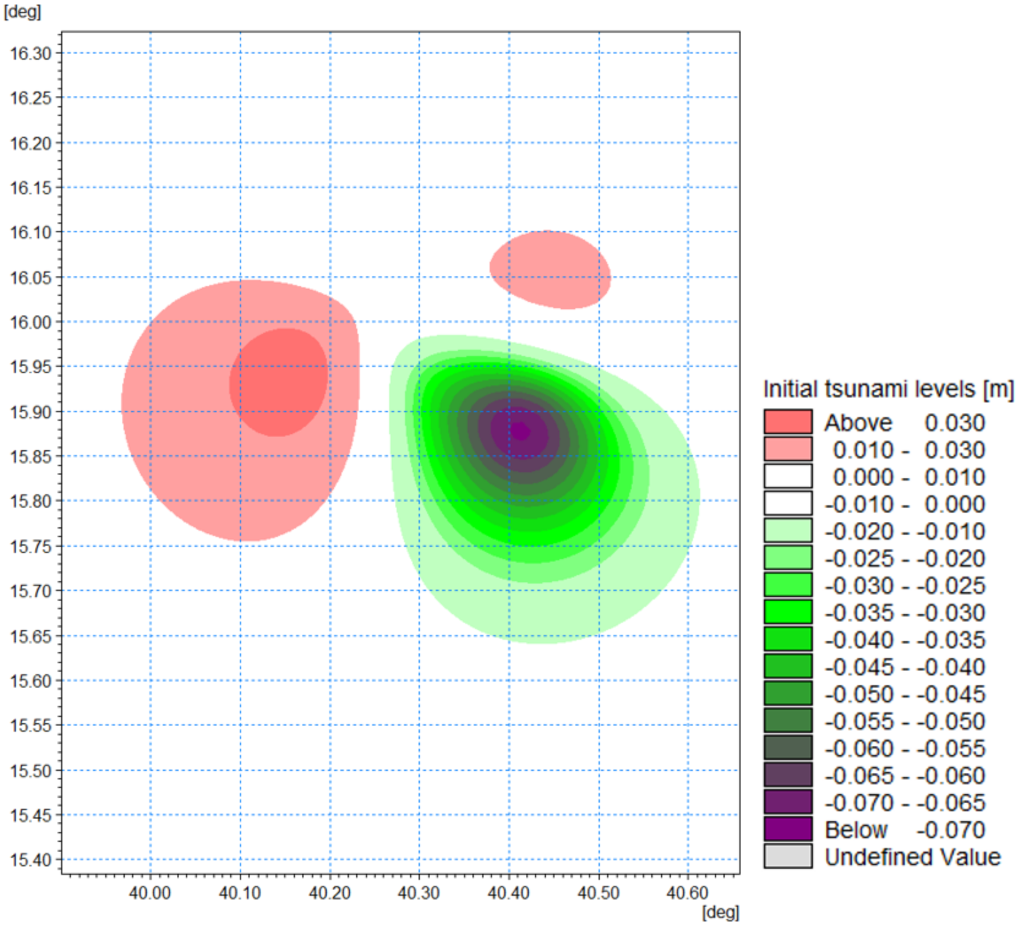

Fig. 7 Initial tsunami levels for the 1977 earthquake (Mw = 6.6)

3. RECOMMENDED DESIGN CONSIDERATIONS

The potential impact of a tsunami event on the design of coastal and marine facilities may be summarised as follows:

1) Shoaling results in an increase in water levels and stronger currents inshore and the measures will be required to protect structures from scouring of the foreshore and seabed and limit damage to the crest if heavy overtopping occurs;
2) The foreshore will be subjected to flooding as the tsunami waves and surge approach; and
3) Facilities located on the landward slope are at risk from tsunami wave run-up and surge.

4. TSUNAMI RISK REDUCTION MEASURES

Damage due to a tsunami depends on the strength and proximity of the tsunami as well as local bathymetry and topography and location of people, structures and facilities.

It is almost impossible to fully protect people and settlements from major tsunami events. However, various soft and hard measures (independently or in combination) could be adopted to reduce fatalities and damage to key infrastructure.

Some potential measures to reduce the risk of damage from major tsunami events are highlighted below:

1) Detection, early warning systems and real-time observation systems are of great importance to save lives and reduce damage;
2) Appropriate awareness and understanding among the general public will reduce death toll;
3) Mitigation plans and evacuation and rescue preparedness by responsible authorities will reduce damage and death toll;
4) Tsunami risk assessment, flood risk and inundation hazard maps;
5) Tsunami shelters are of great use for people to flee;
6) Developing artificial forest such as mangroves and casuarinas of appropriate width behind the shoreline will reduce tsunami wave energy;
7) Maintaining natural sand dunes;
8) Regulations for development in the coastal zone;
9) Saline embankments to prevent salt-water entering into fertile lands;
10) Raising ground levels of important structures and facilities such as warehouses, terminals and quays will reduce risk to these being flooded; and
11) Constructing tsunami defence structures such seawalls, dikes, gates, nearshore breakwaters and offshore barriers will reduce risk and damage. However, these structures are huge and are very expensive.

For major coastal infrastructure, the adoption of appropriate design parameters, a proper assessment of structural loads, forces and stability in combination with a detailed understanding of tsunami processes will reduce the level of damage resulting from these events. Furthermore, physical modelling of major coastal and marine structures and mooring systems to investigate their stability under severe conditions will be helpful to reduce damage due to tsunamis.

Risks Reduction from Mudslides and Landslides

High tides during a tsunami may cause floods and submergence of low-lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property. Landslides and mudslides are downhill earth movements that can move slowly and cause damage gradually. These can also move rapidly destroying property and taking lives suddenly and unexpectedly. They typically carry heavy debris like trees and boulders which can cause severe damage along with injury or death. Faster movement of mudslides makes these deadly.

There is nothing one can do to prevent a mudslide or a landslide. However, one can always be prepared and take necessary steps to lessen the impact of a mudslide or prevent one altogether. Some guidelines are briefly mentioned below:

1) Carrying out risk assessment;
2) Creating public awareness and practicing an evacuation plan;
3) Staying up to date on storm/rainfall/tsunami warnings during times of increased risk;
4) Watching for any visible signs such as cracks on land, debris flows or trees tilting or boulders knocking;
5) Staying alert and awake;
6) Moving out of the path of the landslide or debris flow; and
7) Some erosion control measures might be helpful (such as installing barrier walls, improving drainage system and planting trees with deep and extensive root systems).

5. SUMMARY AND FINDINGS

An earthquake magnitude (Mw) of greater than 6.5 is required to generate a major tsunami but most of the earthquakes in the Red Sea are weaker than this threshold Mw of 6.5. Only the 1977 earthquake magnitude (of Mw 6.6) was higher than 6.5 over the last 45 years. Therefore, the tsunami risk in the Red Sea is not significant. However, tsunami risk assessment should be carried out for any major development within the Red Sea and at its adjacent coastlines to avoid any potential loss of lives and damage to properties. Tsunamis are rare and coastal projects do not always take them into account. However, for major projects the risks should be assessed.

The 1 in 100 year, 1 in 1000 year and 1 in 10000 year earthquake magnitudes Mw were respectively 6.3, 7.0 and 7.1 and the corresponding falls in the sea surface elevation were 0.07m, 0.50m and 0.65m respectively. The 1977 earthquake magnitude Mw was 6.6 and the fall in the sea surface elevation was 0.07m.

Sensitivity tests carried out using Crustal strike-slip and Subduction zone dip-slip produced smaller changes in sea surface elevation. Small earthquake magnitude (Mw) with a small slip and a negative slip angle will not produce higher changes in the seabed as the two plates are moving apart in the Red Sea.

The initial tsunami levels are on the Faultline at offshore and must the transferred to a project site by a two-dimensional model to generate tsunami levels and forward velocities required for designing marine structures and facilities.

Damage due to a tsunami depends on the strength and proximity of the tsunami as well as local bathymetry and topography and location of people, structures and facilities. It is almost impossible to fully protect people and settlements from major tsunami events. However, various soft and hard measures (independently or in combination) could be adopted to reduce fatalities and damage to key infrastructure.

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