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Numerical Modelling of Potential Subsea Landslide Generated Tsunami in the Owen Ridge (Arabian Sea)

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ABSTRACT

The Owen Ridge is a prominent submarine relief located 300 to 400 km away from the coast of Oman. Literature search suggests large landslide along the Owen Ridge that could have occurred in the past. Numerical modelling of a potential tsunami from landslide along the Owen Ridge was carried out in the present study. The MIKE21 Flow Model FM developed by DHI was used to simulate this tsunami. Sample results from the modelling study are presented in this paper for illustration purposes. The model could be used to simulate any tsunami generated within the Arabian Sea. The methodology described in this paper for modelling the tsunami in the Owen Ridge could also be applied to simulate this type of events at other sites around the world.

Key words: Tsunami, Owen Ridge, Natural Hazards, Earthquakes, Seismicity, Landslide, Numerical Modelling, Arabian Sea, Port Development, RHDHV

INTRODUCTION

The Owen Fracture Zone (OFZ)is a transform fault in the northwest Indian Ocean that separates the Arabian and African Plates from the Indian Plate. It starts at the meeting point of the Carlsberg Ridgeand the Sheba Ridge at south and goes north-northeast to the Makran Subduction Zone in the north [1]. Slip rate along the Owen Fracture Zone is at 2 mm per year (the slowest rate on Earth) [2].

Owen Fracture Zone is named after HMS Owen that identified the 'fracture line' in April/May 1963 [3]. The Owen Fracture Zone and the Dalrymple Trough north of it (named after HMS Dalrymple surveyed the area together with HMS Owen) form the modern boundary between the Arabian and Indian Plates [4].

The 800 km long the Owen Fracture Zone runs along the Owen Ridge which is divided into two segments. The Southern Owen Ridge, 300 km long and 50 km wide, is a near-linear structure that drops steeply 2,000 m on its eastern side. The Central Owen ridge, 220 km long and 50 km wide, in contrast, is more uneven and reaches a maximum height of 1,700 m. The Qalhat Seamount and Murray Ridge are located at the northern end of the Owen Fracture Zone [5]. All the above information was obtained from [6].

The Owen Ridge is a prominent submarine relief located 300 to 400 km away from the coast of Oman. It is mentioned that a number of mass failures have been mapped in detail along the ridge. Although the slide mass could be considerably large (up to ~45 km^3) and when occur they may cause large tsunamis but the recurrence interval of such an event is estimated as in the order of 10^5–10^6 years [7]. Nevertheless, there is a significant risk from subsea landslide generated tsunami along the Owen Ridge.

The potential hazard of the slide event to Oman was assessed by [8] through numerical simulations of tsunami generation and propagation from one of the biggest landslides (40 km^3 in volume and 140m layer thickness at initial stage). The slide event was modelled by [8] using a separate model that treated the slide as a viscous fluid with its own velocity with dynamic viscosity (i.e. visco-plastic fluid or also called a Bingham plastic fluid) without including the slide mechanism. This modelling approach or an approach that includes the generation mechanism of the slide requires a complex modelling tool which is beyond the scope of the present study.

The aim of the present study is to introduce the slide in a numerical model as initial condition resembling the tsunami signal after t = 10 minutes in the simulation performed by [8]. After forming an initial amplitude of ~5m, after 10 minutes an outward radiating wave from its origin (17.3333^0 N, 60.0^0 E) is observed with two peaks and troughs. The water ahead of slide direction is pushed away, creating a leading positive wave in the slide direction towards the Oman coast. The wave height after 10 minutes is estimated to be ~2m and the trough approximately -1.5m. After some testing with the orientation of the initial wave pattern the best result for the central Omani coastline is adopted for the simulation (mimicking a slide direction of 280 degrees north).Given the relatively large wave length (L), at initial stage (~200 km), this wave can be considered as a long wave and its propagation can be modelled with software that is used in the present study.

Setting up a large tidal hydrodynamic model is essential to simulate propagation of a tsunami. Royal HaskoningDHV has set upa regional tidal hydrodynamic modelcovering the Arabian Sea to support their work in the region. The model has been used on several occasions to assess tsunamis within this region.

The MIKE21 Flow Model FM developed by DHI [9] has been used in the present study. The initial tsunami waves for a potential tsunami from landslide along the Owen Ridge were generated based on the work by [8].Sample results of tsunami levels and arrival time from the modelling study are presented in this paper for illustration purposes. Structural design considerations and tsunami risk reduction measures (including mudslides and landslides) are also discussed. The model could be used to simulate the passage of a tsunami anywhere within the Arabian Sea. The methodology described in this paper for modelling the tsunami generated at the Owen Ridge could also be applied to simulate this type of events at other sites around the world. The flowchart in Figure 1[adapted from (10)] illustrates the steps and the software used in the present study.

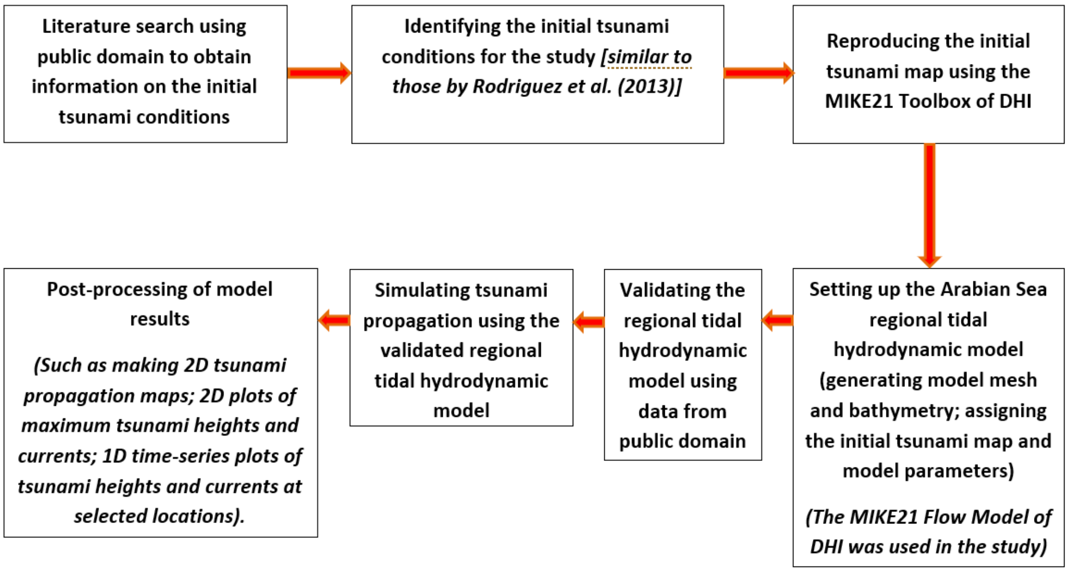


Fig. 1 Steps and software used in the tsunami modelling study [adapted from (10)]

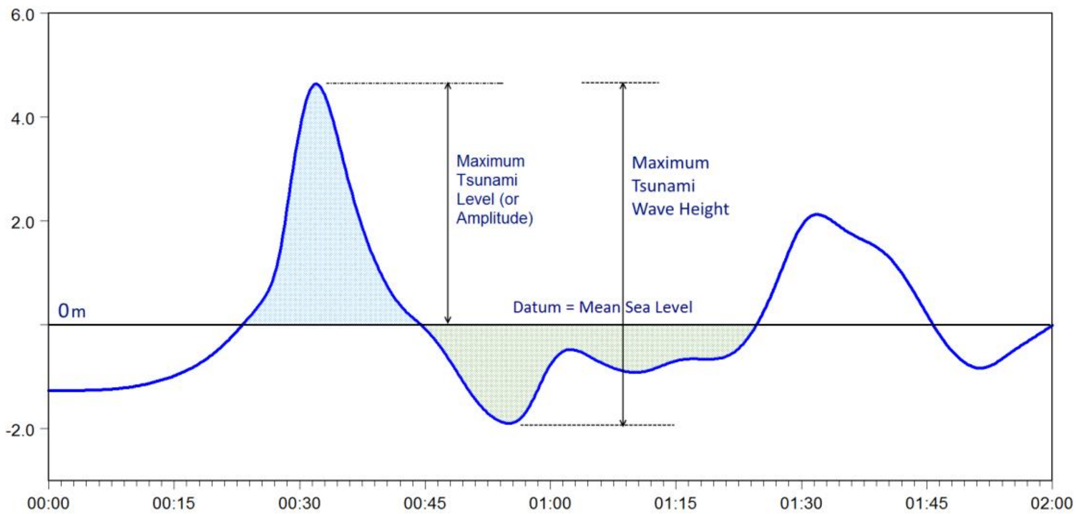


Fig. 2 General definition of tsunami level and tsunami wave height [11]

The general definition of tsunami level and wave height is illustrated in Figure 2 [11]. A tsunami wave height refers to the vertical distance from trough to peak of a tsunami wave. A tsunami level (also called amplitude) is referred to the height of the water column above the datum. Usually Mean Sea Level (MSL) or Chart Datum (CD) are used as datum in tsunami modelling. Chart Datum was used in the present study and, therefore, any tsunami level (or tsunami amplitude) in this paper refers to a level above/below the Chart Datum.

Regional Tidal ModelSet Up by Royal HaskoningDHV

Royal HaskoningDHV has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Arabian Sea using the MIKE21 Flow Model FM software of DHI [9].

The regional model covers the coastlines of six countries i.e. Yemen, Oman, UAE, Iran, Pakistan and India (see Figure 3). The model bathymetry (as shown in Figure 3) was obtained from the C-Map Global Database [12]. This regional tidal model was used in the study to simulate the tsunami propagation.

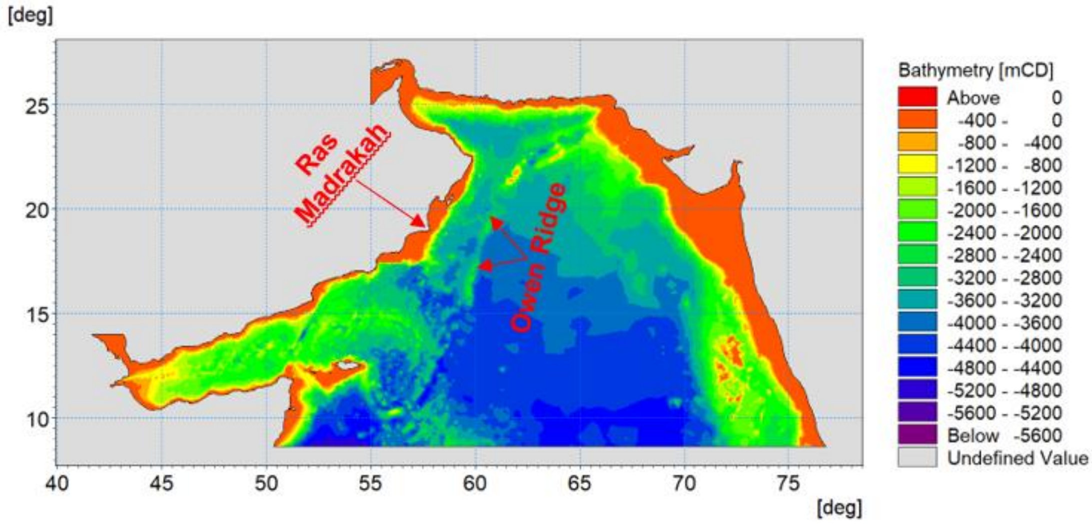


Fig. 3 The regional model domain and bathymetry

Model Mesh and Bathymetry

A flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. Attention was given to the shallow areas particularly around the Owen Ridge.

Typically, 20-30 grids (ideally 40 grids) per wave length are required to correctly resolve the physical processes of tsunami propagation. Shallower waters have shorter wave lengths. Therefore, smaller grid sizes are required for shallower waters.

The mesh size distribution was generally as below:

- 50m grid size at 1m depth
- 150m grid size at 10m depth
- 500m grid size at 100m depth
- 1500m grid size at 1000m depth
- 3000m grid size for the remaining deeper areas

The bathymetry of the model domain was obtained from the C-Map Database [12]. Figure 3shows the model domain and bathymetry.

Model Parameters

Some other major model parameters are given below:

- Minimum time step = 0.01s
- Maximum time step = 15s
- Critical Courant-Friedrich-Lévy (CFL) number = 0.8
- Run duration = 3 hours
- Higher order numerical scheme used
- Coriolis force = varying in domain

The MIKE21 Flow Model uses a variable time step between the minimum and maximum time steps assigned in the model. The time step interval must be selected so that the CFL number is less than 1 in order to secure the stability of the numerical scheme using an explicit scheme in the MIKE21 Flow Model. However, the calculation of the CFL number is only an estimate and, therefore, a reduced value of 0.8 was assigned in the model.

Initial Tsunami Levels

The seabed landslide after t =10 minutes in the simulation performed by [8] was reproduced in the study.The initial rise in sea surface due to the seabed landslide is illustrated in Figure 4. The maximum rise in sea surface is 1.9m.

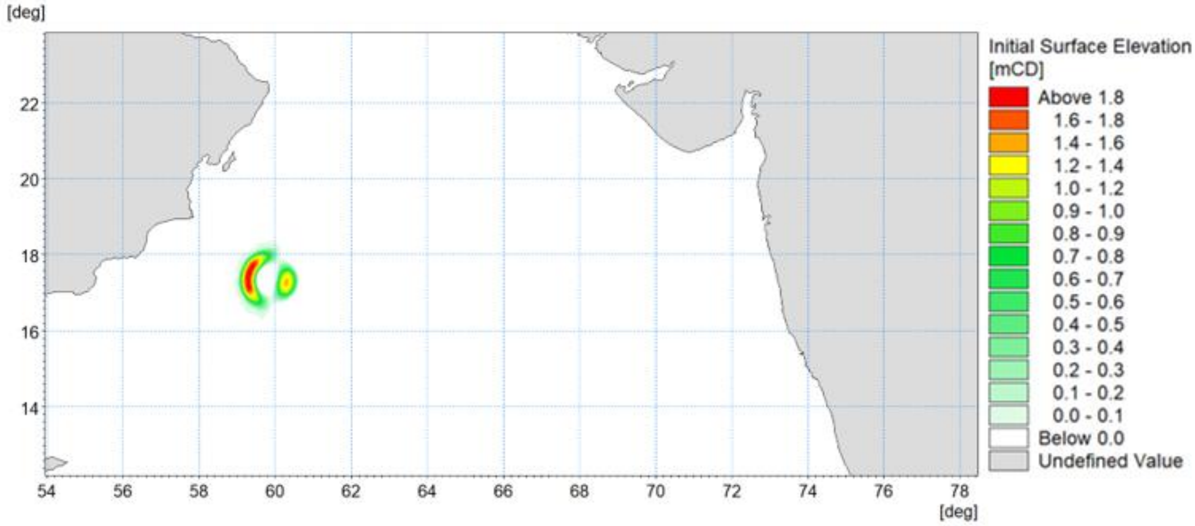


Fig. 4 Initial tsunami levels

Model Validation

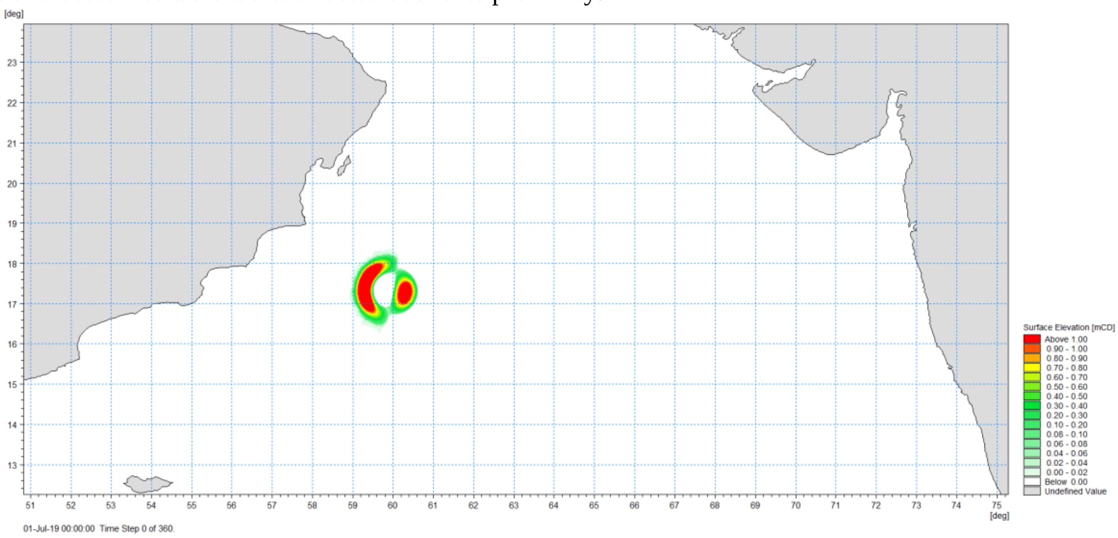
Tsunami levels and arrival times were extracted from the model results at Ras Madrakah headland and at the Masirah Bay (between Ras Madrakah and Masirah Island). These results are compared with those from [8] in Table 1. A good agreement was found both in tsunami levels and travel time.Therefore, it is concluded that the present model can predict the tsunami levels and arrival time anywhere within the model domain with an acceptable level of confidence.

Table -1 Model validation results

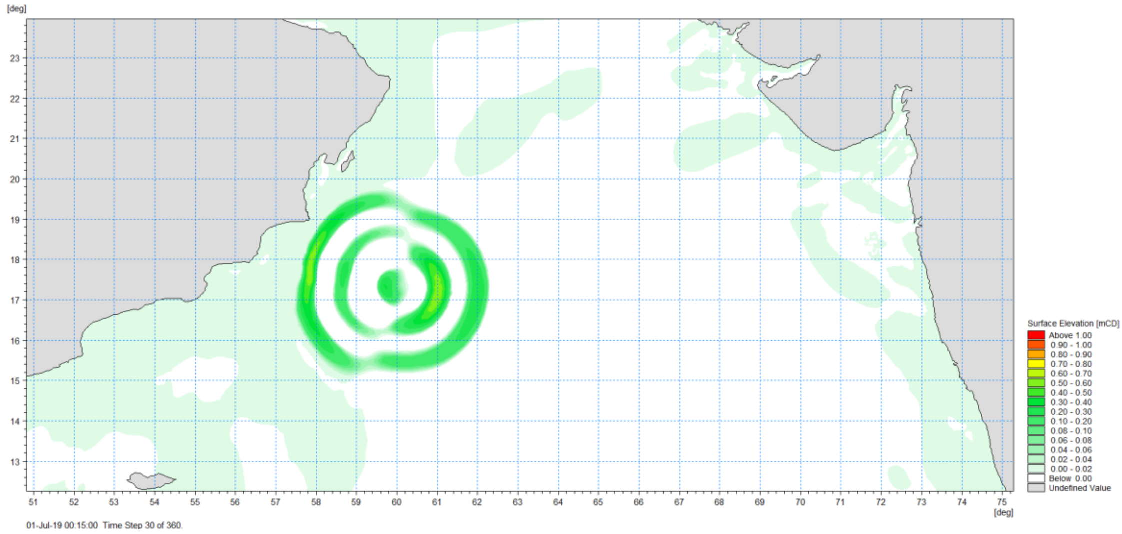
Sources	Initial tsunami level	Tsunami level at Masirah Bay	Tsunami arrival time at Ras Madrakah
Present Study	1.9m	Up to 1.5m	37 minutes
[8]	≈ 2m	≈ 1m	35 minutes

Model Results and Discussion

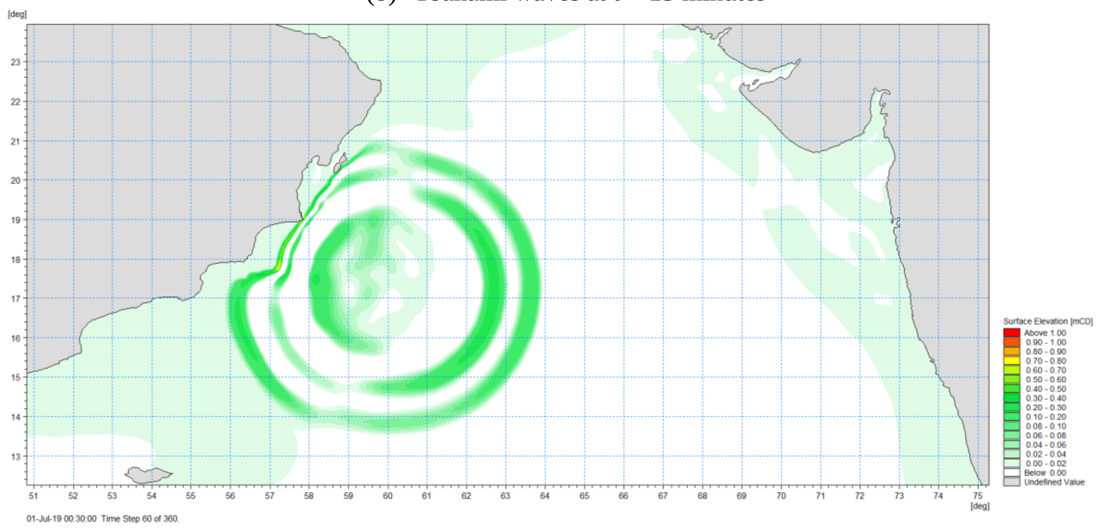
The propagation of tsunami waves over time was extracted from the model results as shown in Figure 5. The model results suggest that the coastlines at central Oman feel the tsunami signals within about half an hour.The nearby islands, headlands and coastlines were worst affected due to its proximity.



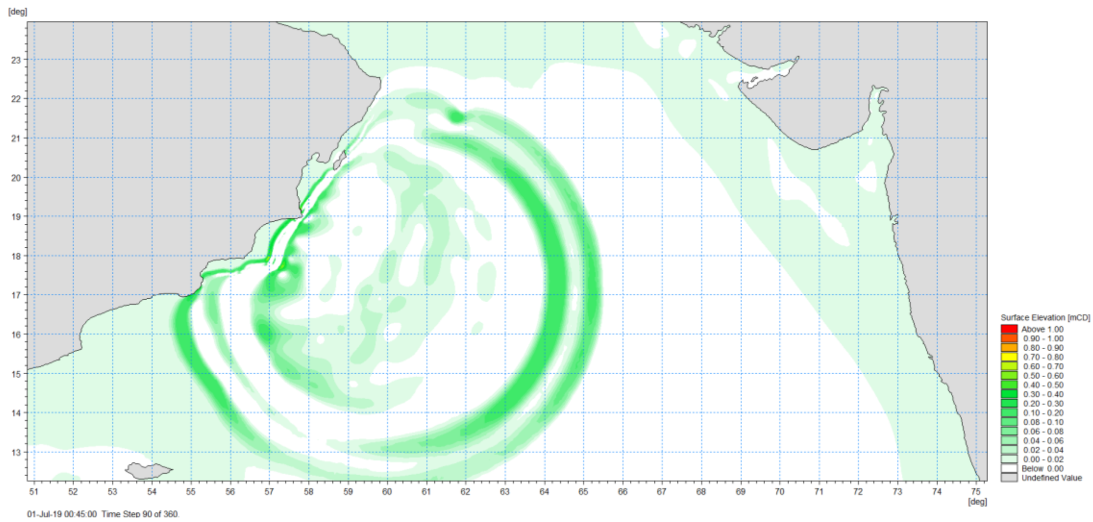
(a) Tsunami waves at t = 0 minutes



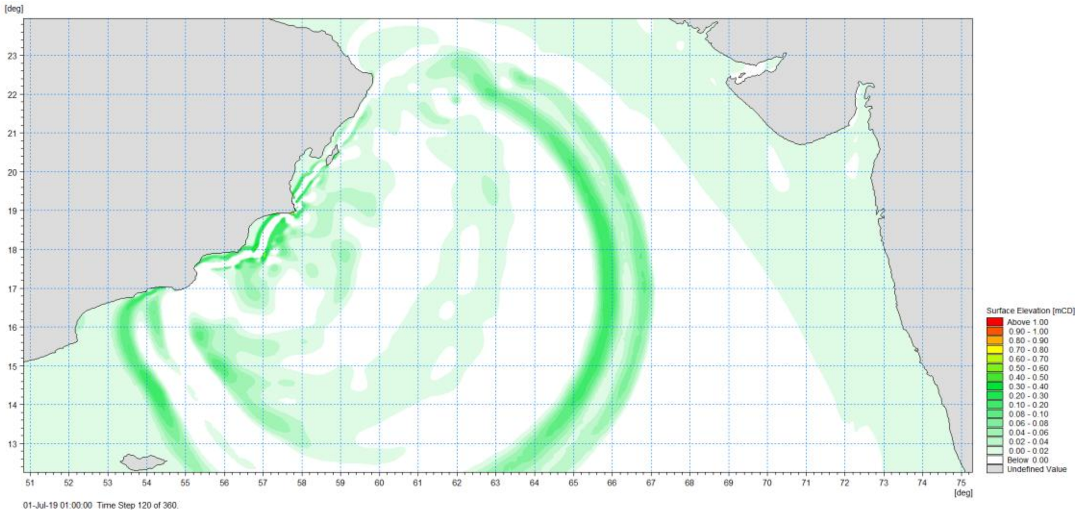
(b) Tsunami waves at t = 15 minutes



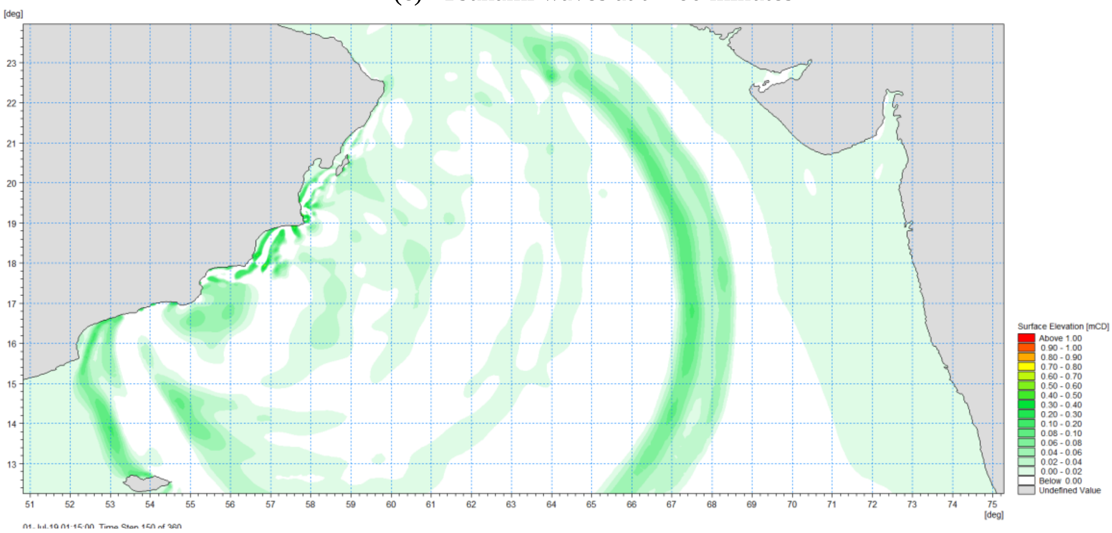
(c) Tsunami waves at t = 30 minutes



(d) Tsunami waves at t = 45 minutes



(e) Tsunami waves at t = 60 minutes



(f) Tsunami waves at t = 90 minutes

Fig. 5 Propagation of tsunami waves over time

Statistical analysis was carried out using MIKE21 Toolbox [13] to derive maximum tsunami levels over the entire model domain during the full duration of the tsunami as shown in Figure 6. The central Omani coastline was affected the most with the maximum value of about 1.5m at Ras Madrakah (see Figure 7).The location of Ras Madrakah is shown in Figure 3. It takes about two hours for the tsunami to calm down as illustrated by Figure 7.

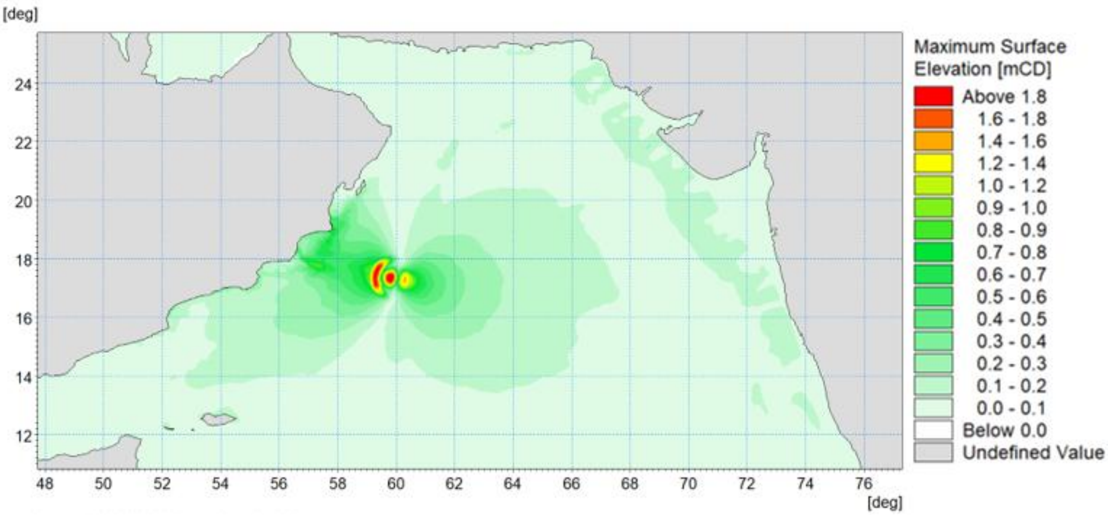


Fig. 6 Maximum tsunami levels

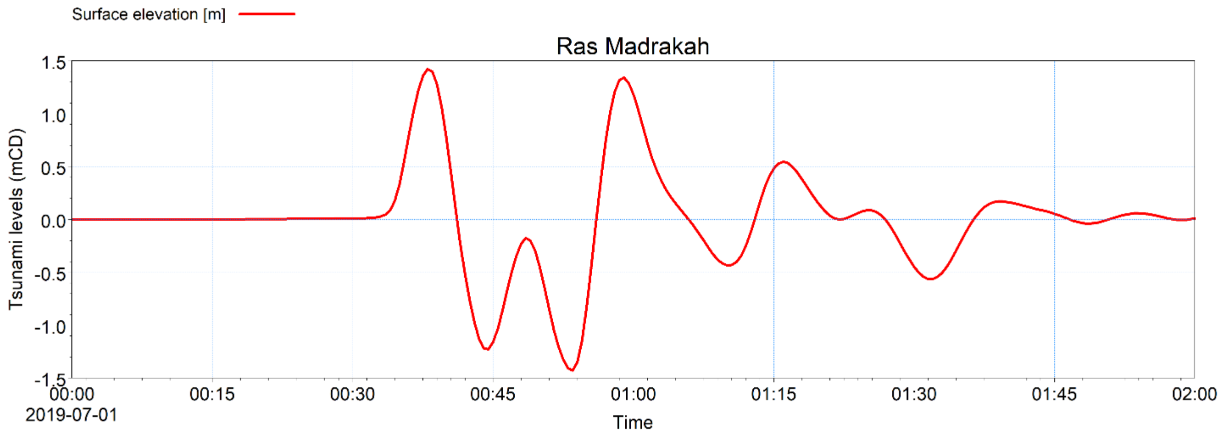


Fig. 7 Time-series of tsunami levels at Ras Madrakah

Maximum current speeds were also extracted from the model results and are shown in Figure 8. Higher currents were found at Ras Madrakah and its neighbourhoods at north and south. The maximum current speed at Ras Madrakah was about 1.2 m/s (see Figure 9). Localized current speeds of up to 2.3 m/s were found within bay north of Ras Madrakah.

It should be noted that the values of the tsunami levels and current speeds and areas affected will vary depending on the landslide location. The above values are an approximation for the location of the landslide shown in Figure 4.

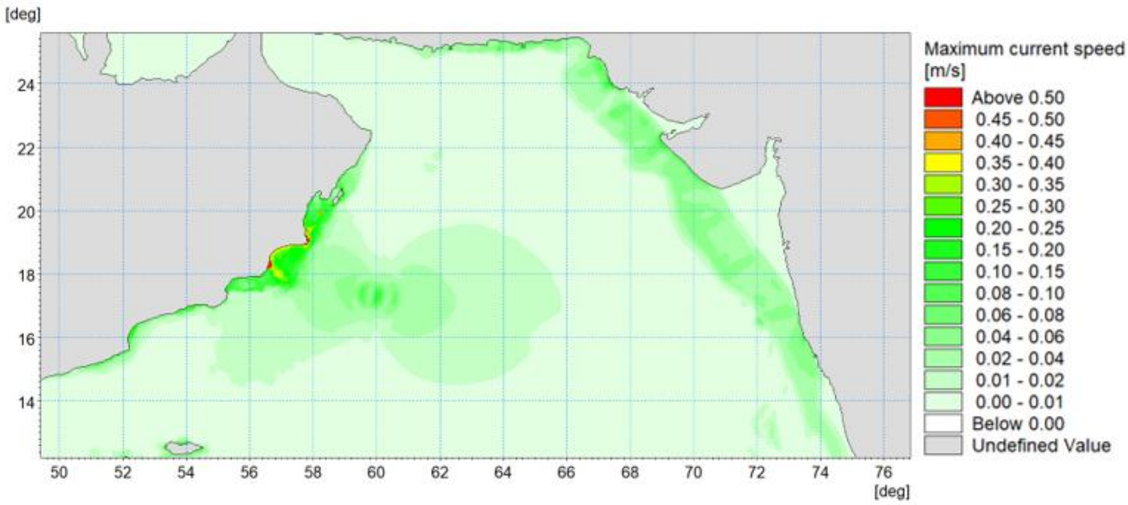


Fig. 8 Maximum tsunami current speeds

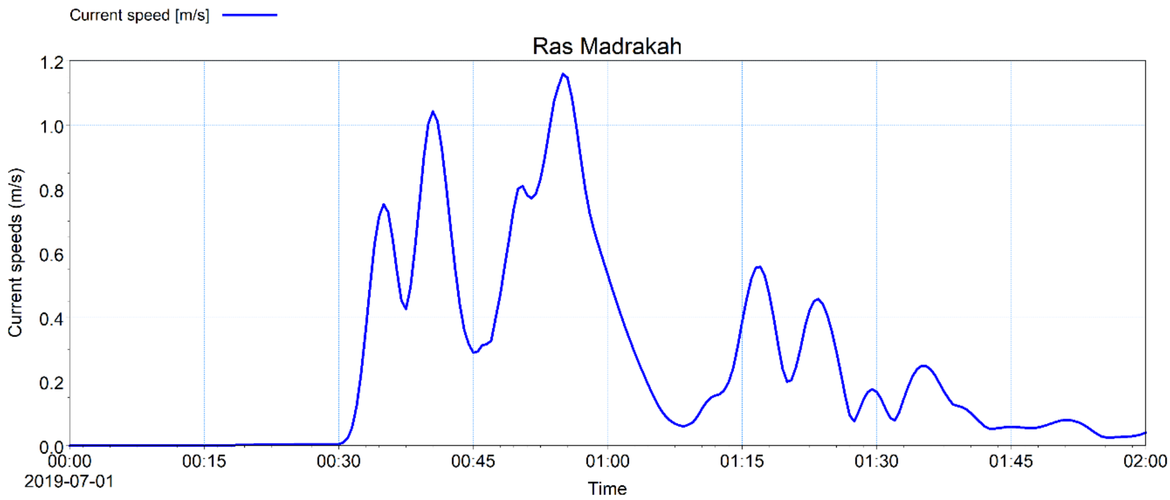


Fig. 9 Time-series of tsunami current speeds at Ras Madrakah

The model showed rapid rise in sea level and then receding it leaving a drying beach and foreshore. In contrast, for an earthquake generated tsunami, the sea level recedes first followed by a rapid rise in sea level.

A relatively higher rise in sea surface elevation was found in the shallower water depths. Rise in water level at shallow waters is higher than that in deeper waters as expected due to shoaling effects.

SUMMARY OF FINDINGS

Numerical modelling of the tsunami generated by a potential landslide along the Owen Ridge was carried out in this study. This paper illustrates how a tidal hydrodynamic modelcan be used to simulate the impacts of a tsunami on coastal developments, facilities and communities.

Findings from the tsunami modelling study are summarised below:

a) The coastlines at central Oman feel the tsunami signals within about half an hour. The nearby islands, headlands and coastlines were worst affected due to its proximity.
b) Ras Madrakah was severely affected due to its close proximity with a tsunami level of up to 1.5m.
c) Maximum current speed at Ras Madrakah was about 1.2 m/s. Stronger currents of up to 2.3 m/s were found at bay north of Ras Madrakah.
d) The model showed rapid rise in sea level and then receding it leaving a drying beach and foreshore. In contrast, for an earthquake generated tsunami, the sea level recedes first followed by a rapid rise in sea level.
e) A relatively higher rise in sea surface elevation was found in the shallower water depths. Rise in water level at shallow waters is higher than that in deeper waters as expected due to shoaling effects.

It should be noted that the values of the tsunami levels and current speeds and areas affected will vary depending on the landslide location.The methodology described in this paper for modelling the landslide tsunami along the Owen Ridge could also be applied to other sites around the world that are affected by this type of events.

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