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Numerical Modelling of the Tsunami Generated by the 1762 Major Earthquake in the Arakan Subduction Zone (Bay of Bengal)

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ABSTRACT
A major earthquake (Mw 8.8) occurred in the Arakan subduction zone on 2 April 1762 generating a tsunami. In this paper initial tsunami levels from the 1762 earthquake have been generated using the MIKE21 Toolbox. Then numerical modelling of tsunami propagation has been carried out using the MIKE21 Flow Model. Sample results from the tsunami modelling study are presented in the paper. The model could be used to simulate any tsunami generated anywhere within the Bay of Bengal. The methodology described in this paper for generating initial tsunami levels and tsunami propagation in the Bay of Bengal could also be applied to this type of events at other sites around the world.

Key words: Tsunami, Natural Hazards, ArakanSubduction Zone, 1762 Earthquake, Bay of Bengal, Numerical Modelling, Port Development, Royal HaskoningDHV

1. INTRODUCTION

1.1 The Arakan Subduction Zone

The ArakanSubduction Zone (ASZ) is situated in the north-eastern part of the Bay of Bengal along the Bangladesh-Myanmar coastline as shown in Figure 1 (Geoscience Australia, 2015). This is the northern extension of the Andaman-Sunda Trench.

1.2 Past Major Tsunamigenic Earthquakes in the Arakan Subduction Zone

Gupta and Gahalaut (2009) reported that the great tsunamigenic earthquakes have not occurred in the region (Aung et al., 2006, 2008). The only reliable evidence of a great earthquake in the region is the 2 April 1762 Arakan earthquake.
As reported in Gupta and Gahalaut (2009), great earthquakes are not common in the region (Aung et al., 2008). In fact, after the 1762 earthquake, no great earthquake has occurred in the region; the last great earthquake prior to 1762 possibly occurred more than 800 years before 1762 (Aung et al., 2008).
Gupta and Gahalaut (2009) found the following:

a) The northern Bay of Bengal does not have a tectonic environment conducive for the occurrence of a megathrust tsunamigenic earthquake.
b) The region is characterised by oblique plate motion leading to strike-slip dominated earthquakes with low tsunami generating potential.
c) The deformation front associated with the plate boundary between India and Sunda plates in the northern Bay of Bengal is either landward of the coast or under shallow water in the Arakan region and, therefore, even a large oblique slip during a future great earthquake is unlikely to displace large amounts of water to create a significant tsunami.
d) Convincing evidence that the 1762 Arakan earthquake generated a large tsunami is lacking. They concluded that this earthquake did not generate a giant or even a major tsunami.
e) No large tsunami has affected the region in the past 2000 years.
f) While a great earthquake could occur in the Arakan region, the physiographic situation may not lead to generation of a large tsunami.

1.3 The 1762 ArakanEarthquake, Tsunami and Damage

The text in this section was obtained from Wikipedia (2021).

The Earthquake

The 1762 Arakan earthquake occurred at about 17:00 local time on 2 April 1762. The epicentre was at 22.0°N, 92.0°E (see Figure 2). The epicentre was somewhere on the coast from Chittagong (Bangladesh) to Arakan in Myanmar (Mondal et al. 2018). It had an estimated magnitude (Mw) of as high as 8.8 on the moment magnitude scale and a maximum estimated intensity of XI (*Extreme*) on the Mercalli intensity scale. It triggered a local tsunami in the Bay of Bengal and caused at least 200 deaths. The earthquake was associated with major areas of both uplift and subsidence. It is also associated with a change in course of the Brahmaputra River to from east of Dhaka (Old Brahmaputra River) to 150 kilometres to the west via the Jamuna River (Al Jazeera, 2017).

The earthquake lasted for about four minutes at Chittagong. The epicentre is not well-constrained and likely locations have varied from near Chittagong to along the Arakan coast. The extent of the rupture is uncertain but may have been as much as 700 km along the plate interface. This is based both on the extent of uplift, which was recorded along the coast of Myanmar from Foul Island to Ramree Island, and the area of subsidence around Chittagong, further north. The 700 km extent combined with an estimated displacement of 10m gives a maximum estimated magnitude of Mw 8.8 on the moment magnitude scale (Cummins, 2007). Other workers have pointed out that neither the subsidence, which could be due to lateral spreading, nor the uplift, which is not unequivocally linked to the 1762 earthquake, necessarily provide a reasonable estimate for the size of this event and prefer to regard this as a magnitude Mw 7.0–8.0 earthquake (Kundu and Gahalaut, 2012).

Studies of uplifted marine terraces along the Myanmar coast have found evidence for three uplifts, the most recent of which is interpreted to be from the 1762 earthquake. The Saint Martin's Island has been uplifted by 2.0-2.5 m during that earthquake (Mondal et al. 2018). A repeat period of about 500 – 700 years has been suggested for earthquakes similar to that in 1762(Mondal et al. 2018).

The Tsunami

A tsunami was reported along the north-eastern coast of the Bay of Bengal and at Dhaka and Kolkata (NGDC, 2012a). This is regarded as a local tsunami, as no effects were recorded on the western side of the bay (Kundu and Gahalaut, 2012).

Damages

In Chittagong, it was reported that no buildings or walls built of brick had escaped either destruction or serious damage. The East India Company's factory inside the fort was so badly damaged that it could no longer be safely used (Verelst, 1764). An area of about 160 km^2 permanently subsided beneath the sea along the coast near Chittagong. At Bar Chara, just north of Cox's Bazar, the land sank and 200 people were killed. Chittagong was said to have "suffered severely" with soil liquefaction effects such as sand volcanoes and ground fissures (NGDC, 2012b).

The above text was obtained from Wikipedia (2021).

1.4 Previous Numerical Modelling Studies on the 1762 EarthquakeGenerated Tsunami

Cummins (2007) carried out numerical modelling of the tsunami generated by the 1762 earthquake. As reported in Gupta and Gahalaut (2009), Cummins (2007) considered a worst-case scenario in which he simulated the rupture of the 1762 earthquake and the tsunami caused by this earthquake. He assumed the deformation front well into the sea, which is about 70km west of the structurally mapped deformation front, and thrust motion of 10m on the earthquake rupture. He simulated a prominent tsunami with wave heights of about 1.5–2.5 m in the coastal Arakan region, about 1 m in the open sea, and more than 0.5 m in the coastal Indian region.

Gupta and Gahalaut (2009) carried out simulation of the 1762 tsunami. Following Cummins (2007), they assumed a rupture length and width of 700km and 125km, respectively, with a north-east dip of about 20°. They placed this rupture along the structurally mapped front and assumed uniform oblique slip of 10m.Such a rupture model produces uplift near the south-west edge and subsidence near the north-west edge, which is consistent with the available qualitative observations of co-seismic subsidence at Chittagong and uplift at Chedooba, Foul, and Ramree (Gupta and Gahalaut, 2009).

Srivastava (2016) also carried out numerical modelling of the tsunami generated by the 1762 earthquake.

The parameters used by Cummins (2007), Srivastava (2016) and Gupta and Gahalaut (2009) are summarised in Table 1.

Table -1 Earthquake parameters used by Cummins (2007), Srivastava (2016) and Gupta and Gahalaut (2009)

Cummins (2007)	Srivastava (2016)	Gupta and Gahalaut (2009)
• Mw = 8.8 • Fault length = 700km • Fault width = 125 km • Slip = 10m • Strike angle = 323°N (calculated)	• Fault length = 600km • Fault width = 125 km • Focal depth = 30km • Slip = 10m • Strike angle = 315°N • Dip angle = 8° • Rake angle = 110°	• Fault length = 700km • Fault width = 125 km • Dip angle = 20° • Slip = 10m

1.5 The Present Study

In this paper initial tsunami levels from the 1762 earthquake were generated using parameters from Cummins (2007) and Srivastava (2016) using the MIKE21 Toolbox developed by DHI. Then numerical modelling of tsunami propagation has been carried out using the MIKE21 Flow Model developed by DHI. Sample results from the modelling study are presented in the paper.

The general definition of tsunami level and tsunami wave height is illustrated in Figure 3. The flowchart in Figure 4 illustrates the steps and the software involved in a typical tsunami modelling study.

2. SELECTION OF THE 1762 EARTHQUAKE PARAMETERS FOR THE PRESENT STUDY

The selected fault parameters for the 1762 earthquake are summarised in Table 2. The Mw, coordinates of the middle point of the fault area, fault length, width, slip and strike angle (calculated) were obtained from Cummins (2007). Focal depth, dip angle and rake angle were not available in Cummins (2007) and, therefore, these were obtained from Srivastava (2016).

Table 2 – Selected fault parameters for the 2 April 1762 earthquake used in the present study

Mw	Latitude (°N)	Longitude (°E)	Length (km)	Width (km)	Depth (km)	Slip (m)	Strike (°N)	Dip (°)	Rake (°)
8.8	20.0826	93.1667	700	125	30	10	323	8	110

3. GENERATION OF INITIAL TSUNAMI LEVELS

It is assumed that the initial sea surface rise 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 parameters in Table2using the MIKE21 Toolbox developed by DHI (DHI, 2021a). Square grid size of 2kmx2km was used for the domain to generate the initial tsunami levels. Figure 5 shows the initial tsunami levels generated using earthquake parameters from Table 2.

The maximum initial tsunami levels along the Bangladeshi coastline was 3.3m. 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.

4. NUMERICAL MODELLING OF THE TSUNAMI

4.1 The Tsunami Model

The MIKE21 Flow Model FM developed by DHI (DHI, 2021b) was used to simulate the tsunami. The modelling system is based on the numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds Averaged Navier-Stokes (RANS) equations. Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

4.2 Tsunami Model Domain, Mesh and Bathymetry

Royal HaskoningDHV (RHDHV) has developed a regional tidal hydrodynamic model based on the MIKE21 Flow Model. The model covers the Bay of Bengal as shown in Figure 6. This model was used to hindcast the tsunami in the study.

A flexible (triangular) mesh was used with variable mesh size distribution of required resolution and smooth transition to obtain accuracy in the model results. Particular attention was given to the study site and around the fault line. A smaller mesh size was also maintained in the areas where seabed slope is steep. Generally, 20-30 grids per wave length are recommended for simulating a tsunami, however, about 40 grids per wave length was used in the study to obtain higher accuracy in model results.

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 was obtained from the C-Map Database (C-Map, 2014). Figure 6shows the model bathymetry with respect to the Chart Datum (CD).

4.3 Tsunami Model Parameters

Some major model parameters are given below:

- Time step = 15s;
- Run duration = 3 hours;
- Higher order numerical scheme used; and
- Coriolis force = varying in domain.

4.4 Model Validation

Maximum tsunami level of about 2.5 m -3.5m were extracted at the fault area from the colour plots in Cummins (2007) and Srivastava (2016). In the present study the maximum tsunami level was found as 3.3m close to the fault area.

A good agreement was found in the maximum tsunami level both in the present study and the previous studies. Therefore, it is concluded that the present model can predict the tsunami levels and arrival time of the 1762 tsunami at anywhere within the model domain with an acceptable level of confidence.

4.5 Model Results

Propagation of tsunami waves over time is shown in Figure 7. Figure 8illustrates the maximum tsunami levels during the entire passage of the tsunami. The maximum tsunami level was found as 3.3m close to the fault area. Figure 9 shows the time-series of tsunami levels at selected locations. These locations were shown in Figure 6. Peak tsunami levels and its arrival time at the selected locations are summarized in Table 3.

Table 3 – Peak tsunami levels and arrival time at the selected locations

Locations	Peak tsunami levels (m)	Arrival time of the peak level (minutes)
Chittagong	2.64	31
Cox's Bazar	2.28	0

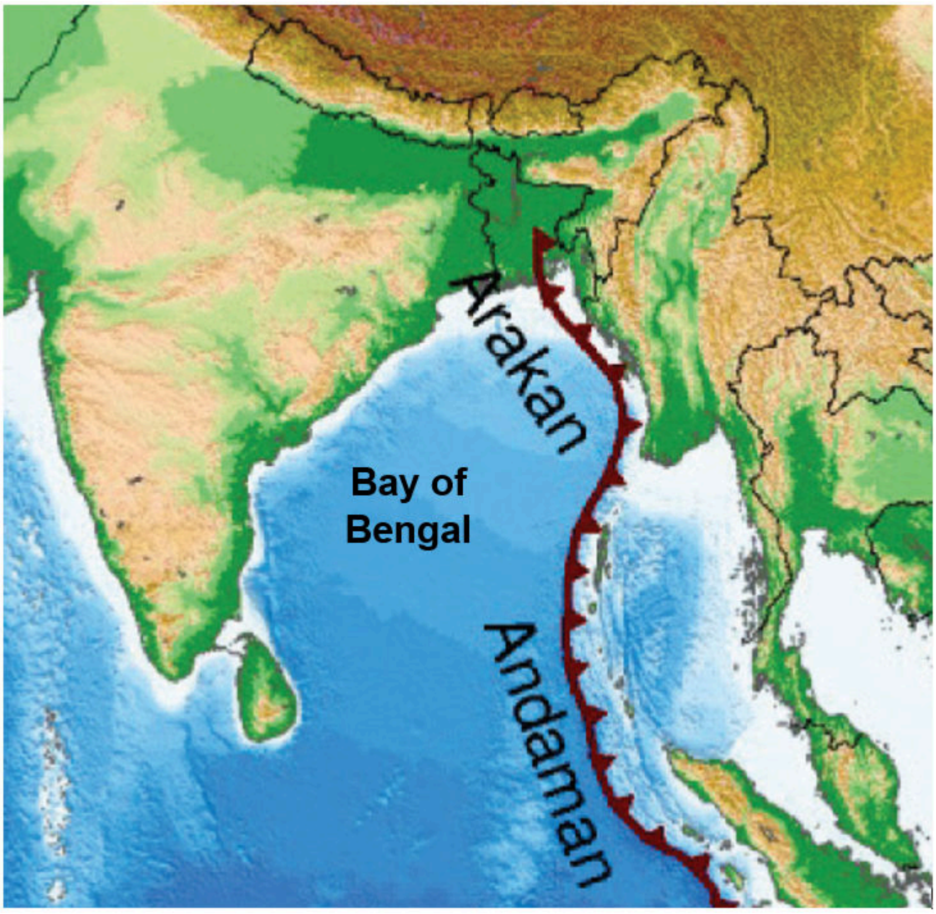


Fig. 1 Location of the ArakanSubduction Zone [Source –Geoscience Australia, 2015]

Fig. 2 Location of the 1762 Earthquake (Wikipedia, 2021)

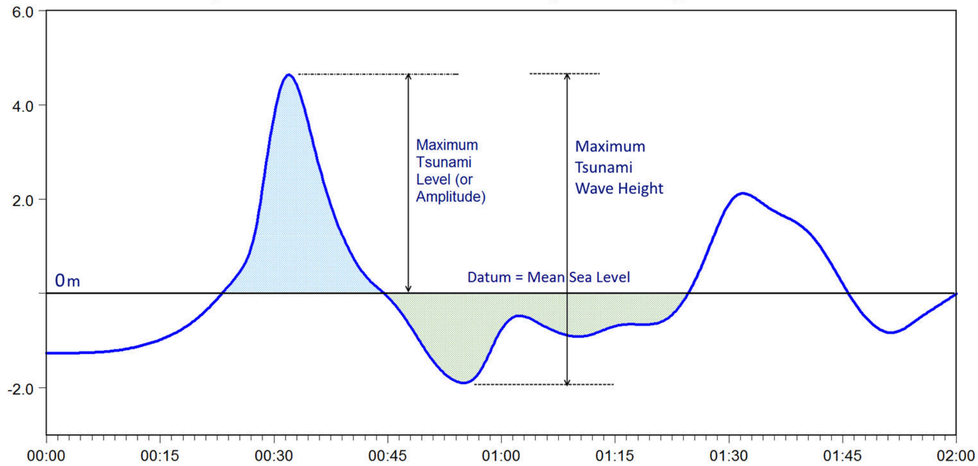


Fig. 3 General definition of tsunami level and tsunami wave height

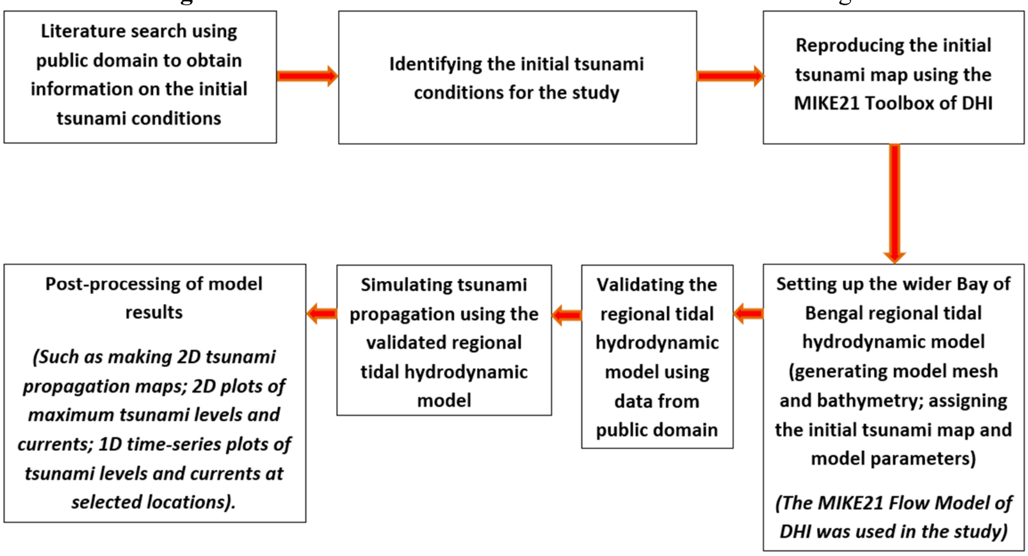


Fig. 4 Steps and software used in a typical tsunami modelling study

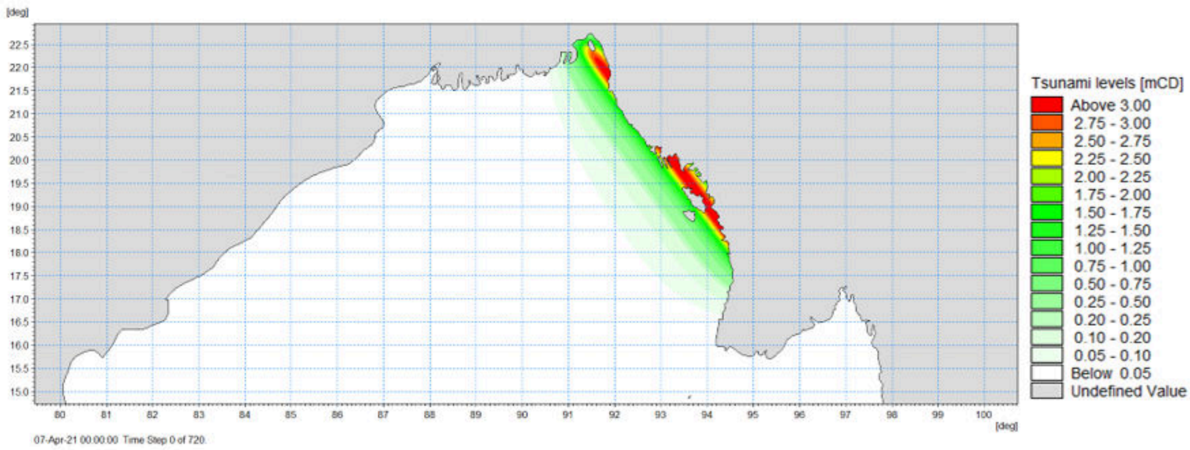


Fig. 5 Initial tsunami levels (mCD)

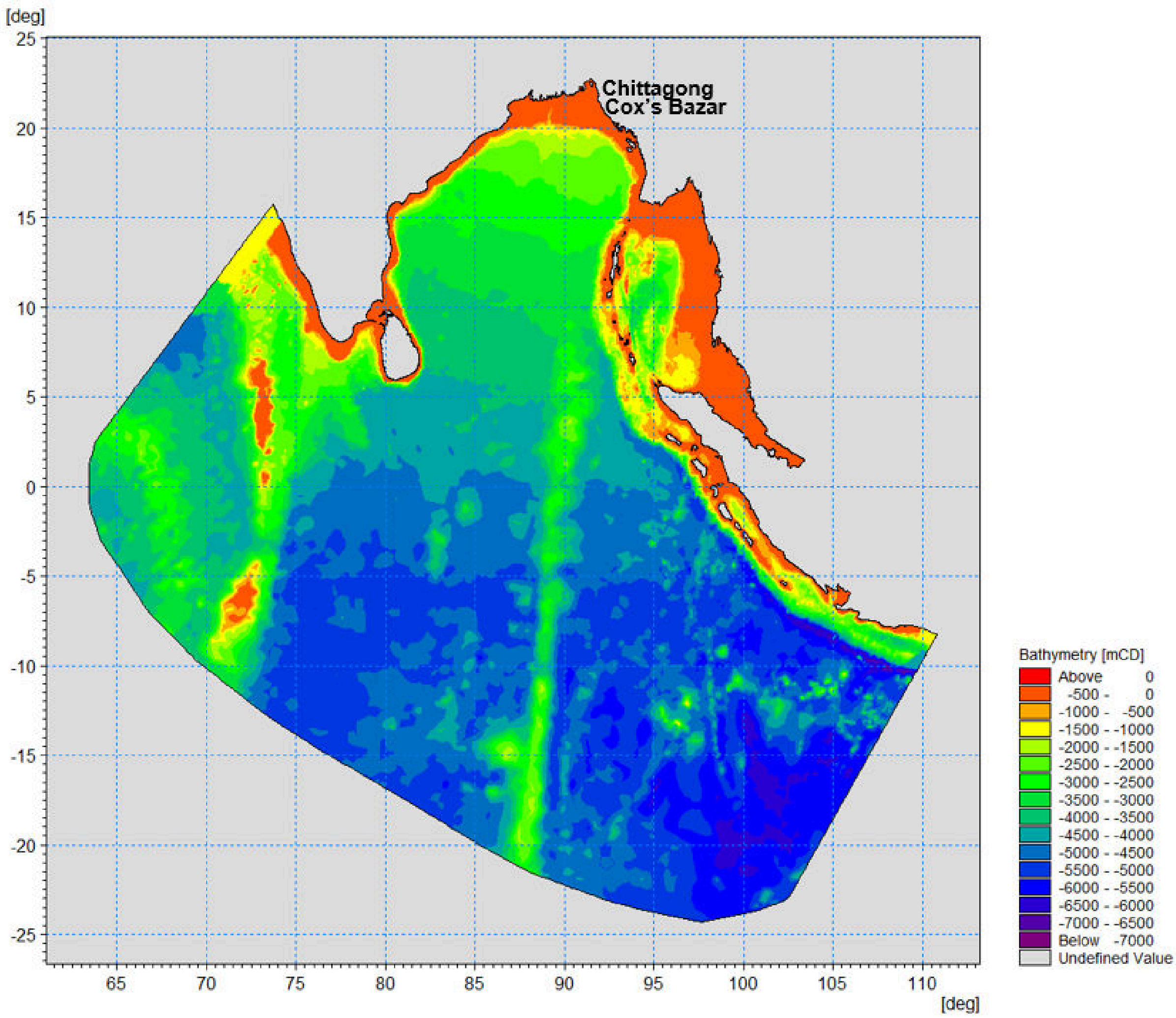
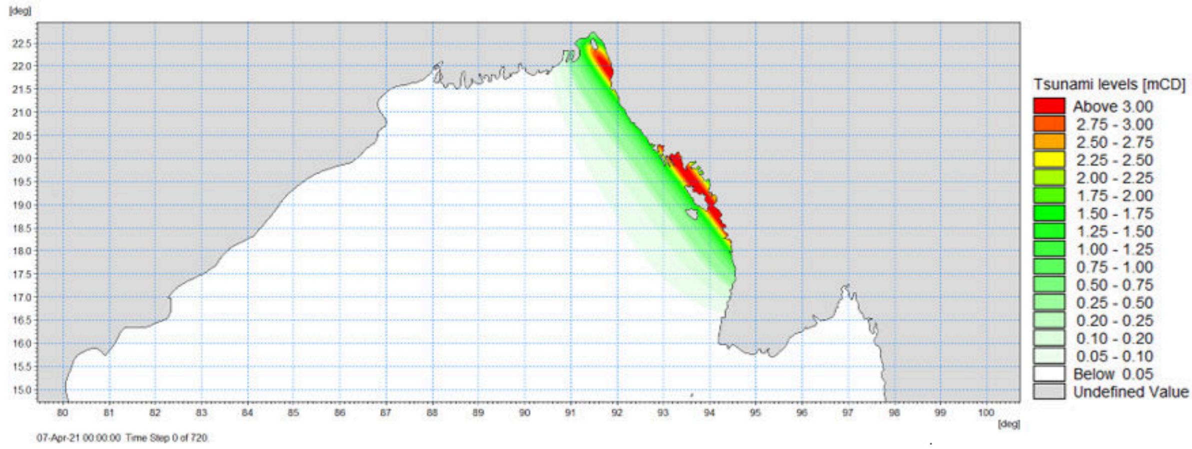
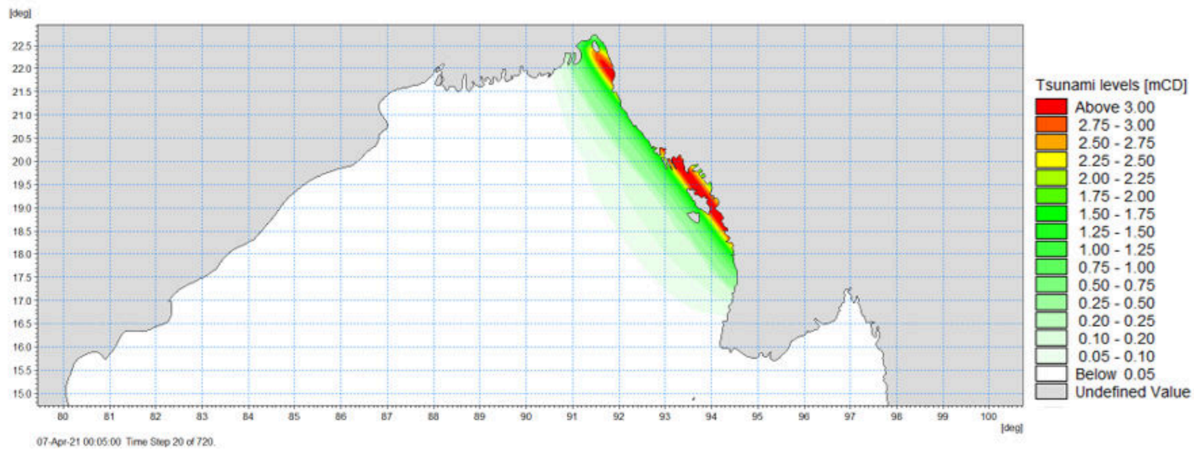


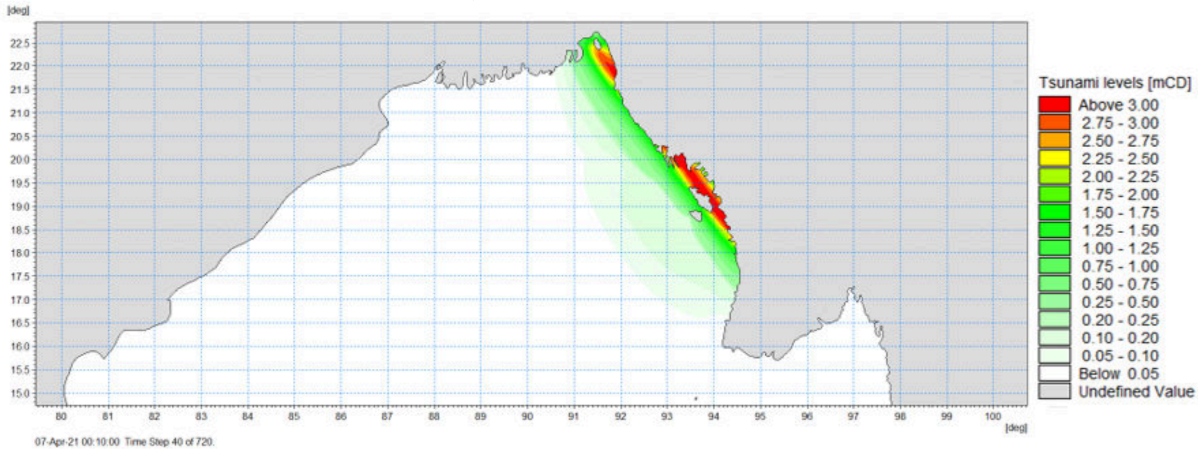
Fig. 6 Model domain and bathymetry (mCD)



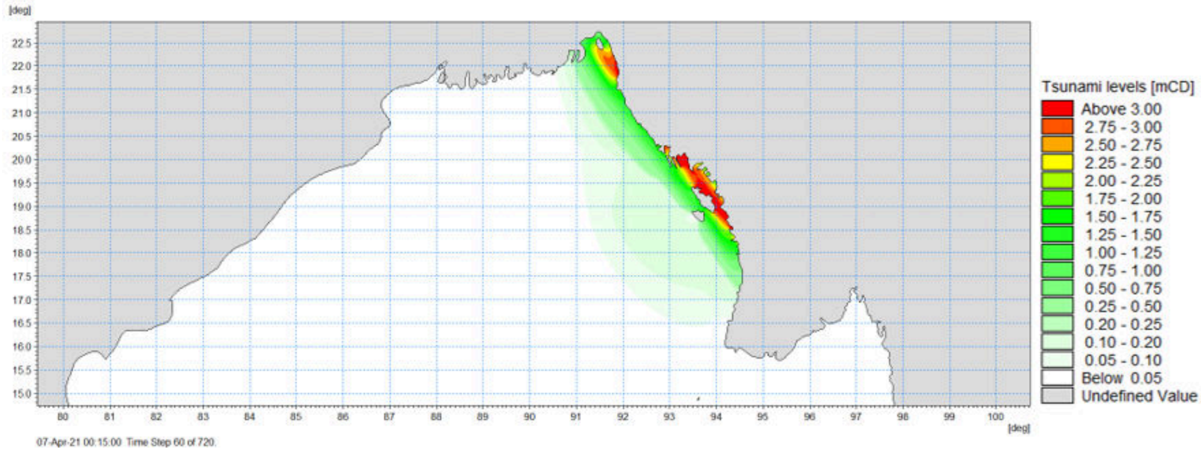
a) Tsunami waves at time = 0 (initial tsunami levels)



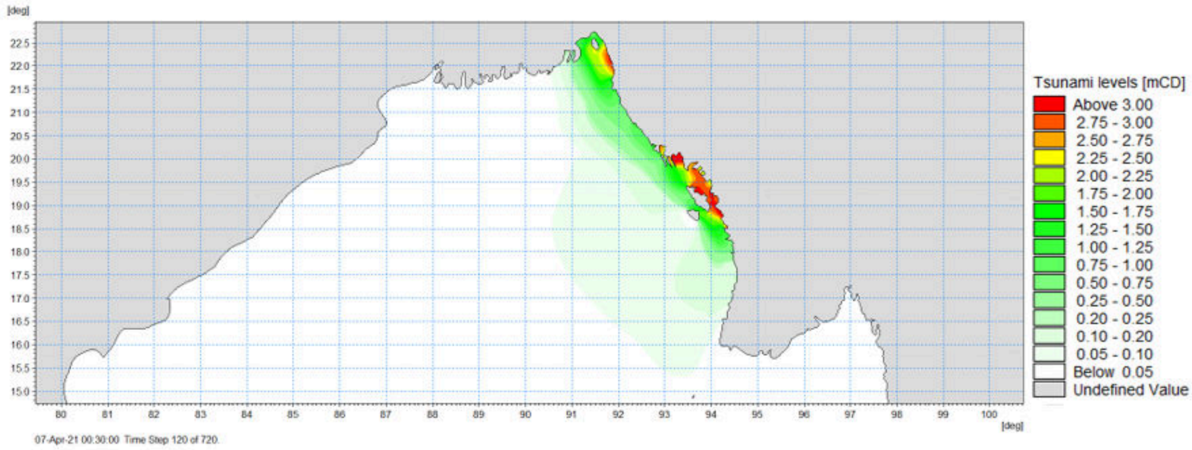
b) Tsunami waves at time = 5 minutes



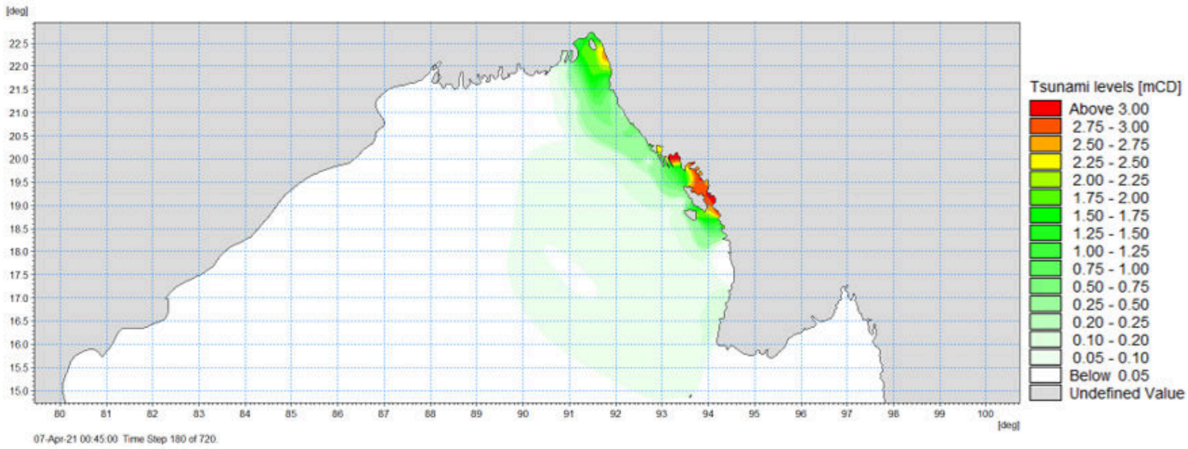
c) Tsunami waves at time = 10 minutes



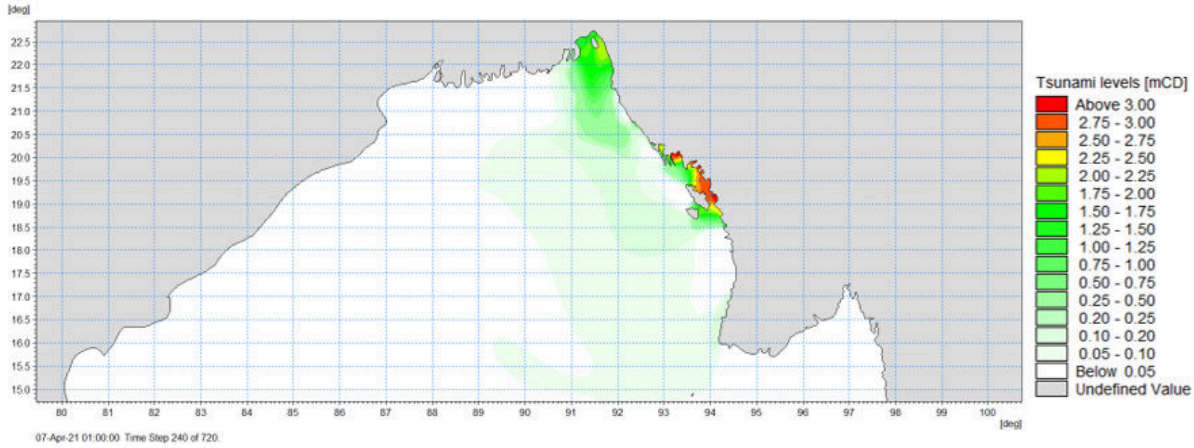
d) Tsunami waves at time = 15 minutes



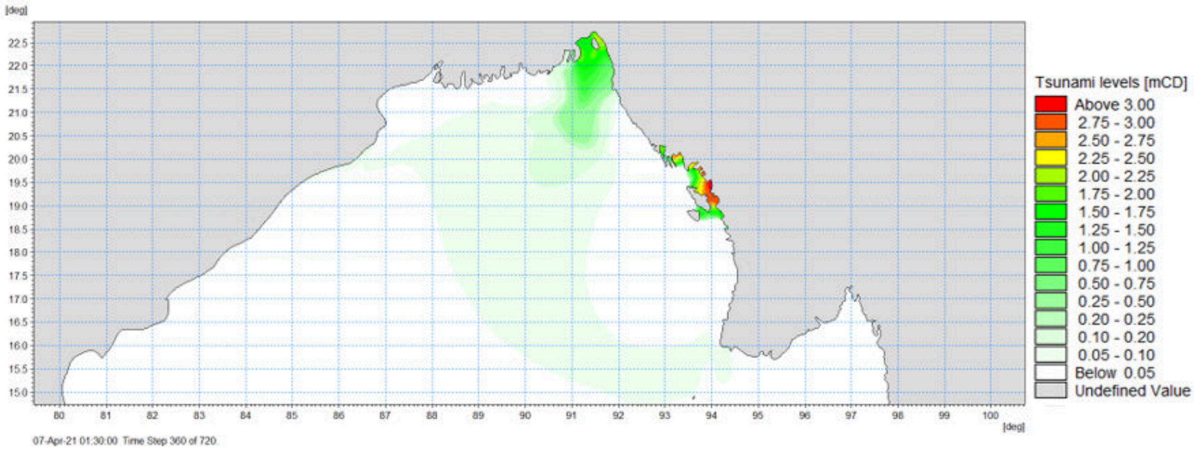
e) Tsunami waves at time = 30 minutes



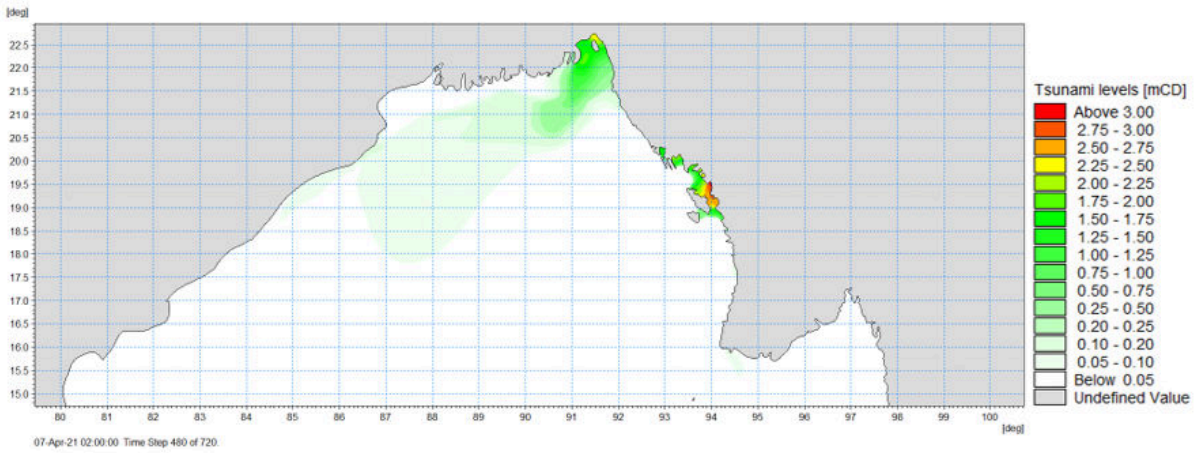
f) Tsunami waves at time = 45 minutes



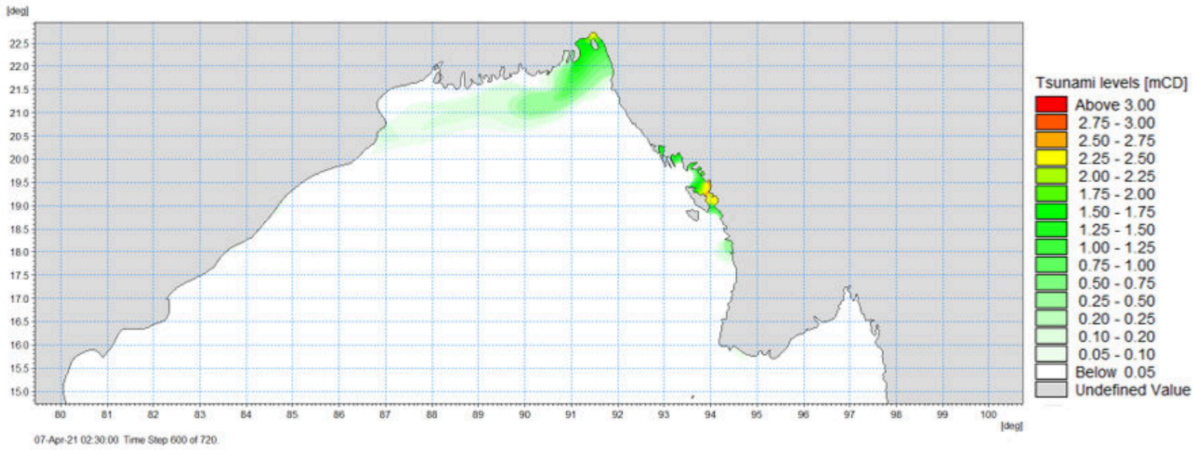
g) Tsunami waves at time = 1 hour



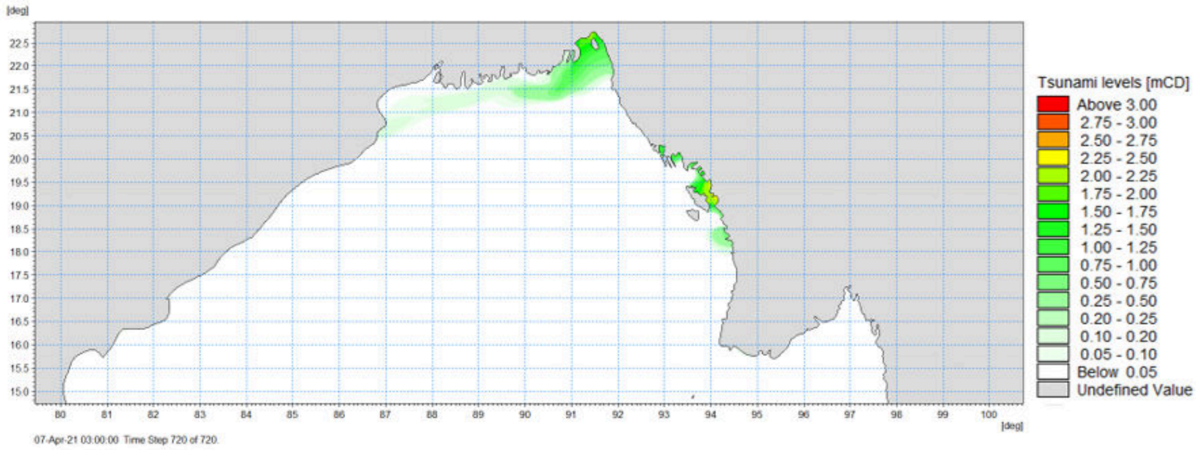
h) Tsunami waves at time = 1 hour 30 minutes



i) Tsunami waves at time = 2 hours



j) Tsunami waves at time = 2 hours 30 minutes



k) Tsunami waves at time = 3 hours

Fig. 7 Tsunami wave propagation over time

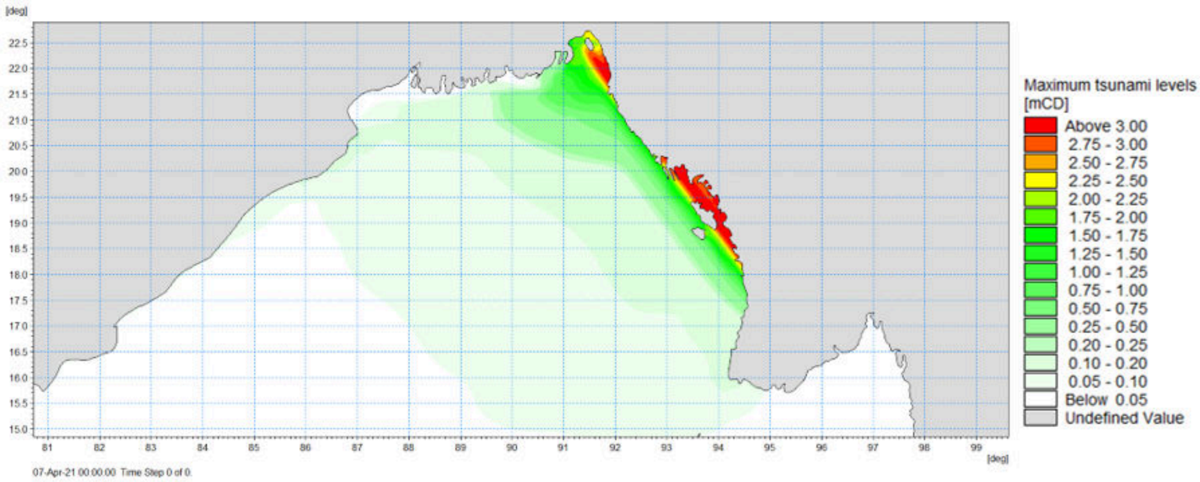


Fig. 8 Maximum tsunami levels (mCD)

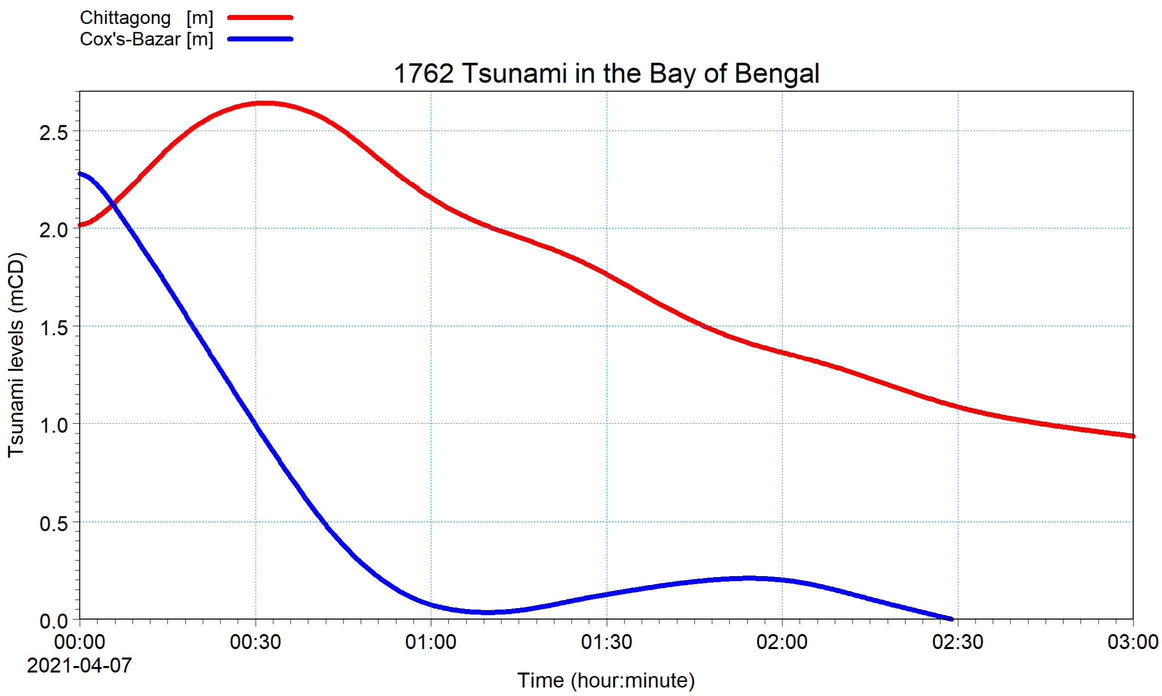


Fig. 9 Tsunami levels at Chittagong and Cox's-Bazar (of Bangladesh)

5. LIMITATIONS ON THE MODEL RESULTS

Model results presented in this paper are for illustration purposes only. These should not be used for any practical project work for which use of local survey bathymetry data and detailed local calibration are essential.

6. SUMMARY AND FINDINGS

Literature search suggests a repeat period of about 500 – 700 years for earthquakes similar to that in 1762.
Maximum initial tsunami levels of 3.3m was found near the fault area. Maximum tsunami levels of 2.64m and 2.28m were found at Chittagong and Cox's Bazar (in Bangladesh) respectively.
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 sub-faults.

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