Numerical Modelling of the 2004 Indian Ocean Tsunami by Royal HaskoningDHV

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Abstract: A tsunami can cause significant loss of life and damage to properties, ecosystems and marine structures and facilities. Tsunami modelling results are used for deriving robust design conditions for coastal and marine structures and facilities. The results are also used for emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop rescue and mitigation measures and plan clean-up operations. Royal HaskoningDHV (RHDHV) has set up a regional tidal hydrodynamic model covering the Bay of Bengal and its surroundings including Indonesia to provide data to address the above issues. The 2004 Boxing Day earthquake in the Sunda Trench generated a tsunami along the coastlines of Indonesia, Sri Lanka, India and other countries killing as many as 230,000–280,000 people in 14 countries. *Furthermore, the tsunami caused catastrophic damage* to properties and other coastal facilities. The tsunami modelling in the present study was carried out for this 2004 event. The MIKE21 Flow Model FM of DHI was used to simulate this tsunami event and sample results from the modelling are presented in this paper for illustration purposes. The model could be used to simulate any tsunami generated within the Bay of Bengal and its surroundings. The methodology described in this paper for modelling the 2004 tsunami in the Sunda Trench could also be applied to simulate this type of events at other sites around the world.

Keywords: Tsunami, Sunda Trench, Earthquakes, Seismicity, Numerical Modelling, Tsunami Hazards, Bay of Bengal, Port Development.

1. INTRODUCTION

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. 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 (PIANC, 2010). Wave periods of a tsunami 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. tsunamis travel very fast in the deep oceans.

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. A tsunami can cause significant damage to coastal facilities such as sea ports, 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.

As reported in Wikipedia (2019a), 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.

Setting up a large tidal hydrodynamic model is essential to simulate propagation of a tsunami. Given the above risks, Royal HaskoningDHV has set up a regional tidal hydrodynamic model covering the Bay of Bengal and its surroundings including Indonesia to support their work in the region. The model has been used on several occasions to assess tsunamis within this region particularly the 2004 event. The flowchart in Figure 1 illustrates the steps and the software used in the tsunami modelling study.

2. TSUNAMIS IN THE SUNDA TRENCH

As reported in Wikipedia (2019b), the Sunda Trench, earlier known as and sometimes still indicated as the Java Trench, is an oceanic trench located in the Indian Ocean near Sumatra, formed where the Australian-Capricorn plates subduct under a part of the Eurasian Plate. It is 3,200km long. Its maximum depth of 7,725m (at 10°19'S, 109°58'E, about 320 km south of

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Yogyakarta) is the deepest point in the Indian Ocean. The trench stretches from the Lesser Sunda Islands past Java, around the southern coast of Sumatra on to the Andaman Islands, and forms the boundary between Indo-Australian Plate and Eurasian plate (more specifically, Sunda Plate). The trench is considered to be part of the Pacific Ring of Fire as well as one of a ring of oceanic trenches around the northern edges of the Australian Plate. For about half of its length, off Sumatra, it is divided into two parallel troughs by an underwater ridge, and much of the trench is at least partially filled with sediments. Mappings after the 2004 Indian Ocean earthquake of the plate boundary showed resemblance to suspension bridge cables, with peaks and sags, indicative of asperity and locked faults, instead of the traditional wedge shape expected. The subduction of the Indo-Australian Plate beneath a bloc of the Eurasian Plate is associated with numerous earthquakes. Several of these earthquakes are notable for their size, associated tsunamis, and/or the number of fatalities they caused. Some of the major earthquakes in the Sunda Trench are listed in Table 1. The above information was obtained from Wikipedia (2019b).

Table 1 – Some of the major earthquakes in the SundaTrench [Wikipedia (2019b)]

No.	Segments	Year	Names of	Magnitudes
			earthquakes	(M _w)
1	Sumatra	1797	Sumatra	~8.4
	Segment		earthquake	
2	"	1833	u	8.8-9.2
3	"	1861	u	~8.5
4	u	1935	u	7.7
5	u	2000	u	7.9
6	u	2002	u	7.3
7	u	2004	Indian Ocean	9.1-9.3
			earthquake	
8	u	2005	Nias-Simeulue	8.6
			earthquake	
9	u	2007	Sumatra	8.5, 7.9, 7.0
			earthquake	
10	u	2009	u	7.9
11	"	2010	Mentawai	7.7
			earthquake	
12	u	2018	Sulawesi	7.4
			earthquake	
13	Java	1917	Bali earthquake	6.6
	Segment			
14	u	1994	Java earthquake	7.8
15	"	2006	Pangandaran	7.7
			earthquake	
16	u	2009	West Java	7.0
			earthquake	

3. THE 2004 EVENT

The 2004 Indian Ocean Earthquake (also known as the Sumatra–Andaman or the Boxing Day Earthquake) occurred at 00:58:53 UTC on 26 December 2004 with its epicenter off the west coast of Sumatra (between Simeulue and mainland Sumatra) in Indonesia (see Figure 2). The undersea megathrust earthquake with a moment magnitude (M_w) of 9.0–9.3 was caused when the Indian Plate was sub-ducted by the Burma Plate. It was the third-largest earthquake ever recorded on a

seismograph and had the longest duration of faulting ever observed (between 8.3 and 10 minutes). The earthquake caused the entire planet to vibrate as much as 1 centimeter (0.4 inches) and triggered other earthquakes as far away as Alaska. The earthquake generated numerous aftershocks off the Andaman Islands, the Nicobar Islands and the region of the original epicenter. [Source – Wikipedia (2019a)].

4. FAULTING MECHANISM OF THE 2004 EARTHQUAKE

The megathrust earthquake was unusually large in extent having an estimated 1,600km of fault surface slipped (or ruptured) about 15m along the subduction zone where the Indian Plate slided (or sub-ducted) under the overriding Burma Plate. The slip did not happen instantaneously rather it took place in two phases over several minutes. The first phase involved a rupture of about 400km long and 100km wide and 30km beneath the seabed (the largest rupture ever known caused by an earthquake). The rupture proceeded at about 2.8km/s beginning off the coast of Aceh and proceeding north-westerly over about 100 seconds. After a pause of about another 100 seconds, the rupture continued northwards towards the Andaman and Nicobar Islands. However, the northern rupture occurred more slowly than in the south, at about 2.1 km/s, continuing north for another five minutes to a plate boundary where the fault type changed from subduction to strike-slip (the two plates slide past one another in opposite directions). [Source -Wikipedia (2019a)].

5. MAGNITUDE (MW) OF THE 2004 EARTHQUAKE

The estimated magnitudes of the 2004 earthquake reported by various authors are provided in Table 2. These suggest the magnitude (M_w) of the 2004 Indian Ocean Earthquake was in the range 9.0-9.3.

Table 2 -	Estimated	magnitudes	(M_w)	of	the	2004
earthquake						

Magnitudes (M _w)	Sources					
9.0-9.3	Koshimura et al. (2009) and Geist et al. (2007).					
9.1-9.3	Grilli et al. (2007) and Wikipedia (2019a). Also					
	reported by Poisson et al. (2011) from Ammon et al.					
	(2005), Park et al. (2005) and Stein & Okal (2005).					
9.1	PIANC Report 112 (2010) and Aon Benfield (2015).					
9.2	Tony Song et al. (2005), USGS (2007) and					
	Nieuwenhuis et al. (2008). Also, by Kanamori (2006)					
	as reported in Wikipedia (2019a).					
9.1-9.2	Banerjee et al. (2005) as reported by Tsai et al.					
	(2005).					
9.3	Okal et al. (2006). Also reported by Tsai et al. (2005)					
	from Stein and Okal (2005).					

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6. THE 2004 EARTHQUAKE PARAMETERS

Slip (vertical displacement of seabed during an earthquake) is never uniform over the entire fault length although sometimes an averaged uniform slip can be used for simplification. Use of an averaged uniform slip will lead to significantly lower initial tsunami levels. Ideally the entire fault length should be divided into several segments (say 3 or more) and separate slips assigned to each segment to generate the initial tsunami conditions. For the present study, the entire fault length was divided into five segments. The earthquake parameters for these segments were obtained from Grilli et al. (2007) and are summarized in Table 3.

Table 3: Earthquake parameters used in the presentstudy [obtained from Grilli et al. (2007)]

Parameters	Segme	Segmen	Segmen	Segmen	Segmen
	nt 1	t 2	t 3	t 4	t 5
Latitude	3.83	5.22	7.41	9.70	11.70
(ºN)					
Longitude	94.57	93.90	93.21	92.60	92.87
(ºE)					
Length (km)	220	150	390	150	350
Width (km)	130	130	120	95	95
Slip (m)	18	23	12	12	12
Depth (km)	25	25	25	25	25
Strike angle,	323	348	338	356	10
φ (º)					
Rake (or	90	90	90	90	90
slip) angle, λ					
(⁰)					
Dip angle, δ	12	12	12	12	12
(<u>°</u>)					
M ₀ (Joules)	1.85 ×	1.58 ×	2.05 ×	0.61 ×	1.46 ×
	1022	1022	1022	1022	1022
Maximum	-3.27;	-3.84;	-2.33;	-2.08;	-2.31;
vertical	+7.02	+8.59	+4.72	+4.49	+4.60
subsidence					
and uplift of					
seafloor, η₀					
(m)					

The total seismic moment of all five segments in Grilli et al. (2007) is M_0 = 7.55 × 10²² Joules or moment magnitude M_w = 9.25.

Besides the earthquake parameters in Table 3, two Lame coefficients were also used in the present study that describe physical characteristics of the earth's crust. The Shear Module (μ) or rigidity is the measure of how an elastic body deforms due to forces parallel to one of its surfaces. A value of 39.7 Giga Pascal (GPa) for the Shear Module was used in the study. The other coefficient Lambda (λ) has no physical meaning but can be derived from shear stress and Poisson ratio. A value of 32.1 Giga Pascal (GPa) for the Lambda was used in the study. The values for shear modulus and lambda depend on the depth of the rupture and were taken from the four-layer half-space model of the earth (Wang et al., 2003) as given in the MIKE21 Toolbox (DHI, 2019a).

7. DAMAGES DUE TO THE 2004 TSUNAMI

The 2004 earthquake triggered a series of devastating tsunamis along the coasts of most landmasses bordering the Indian Ocean. It was one of the deadliest natural disasters in recorded history and the deadliest of the 21st century so far. Indonesia suffered the most, followed by Sri Lanka, India, and Thailand. The tsunami inundated coastal communities with levels reached a height of 24 m when coming ashore along large stretches of the coastline, rising to 30 m in some areas when traveling inland killing 230,000–280,000 people in 14 countries. The estimated damage by the event was US\$15 billion (2004) and the worldwide community donated more than US\$14 billion (2004) in humanitarian aid. [Source – Wikipedia (2019a)].

The 2004 earthquake has also caused an enormous environmental impact on ecosystems such as mangroves, coral reefs, forests, coastal wetlands, vegetation, sand dunes and rock formations, animal and plant biodiversity and groundwater. The earthquake threatened the environment even further through the spread of solid and liquid wastes and industrial chemicals, water pollution and the destruction of sewage collectors and treatment plants. The earthquake damaged the freshwater supplies and the soil by saltwater infiltration and a deposit of a salt layer over arable land. [Source – Wikipedia (2019a)].

8. TSUNAMI RISK ASSESSMENT

The probability of occurrence of a large tsunami is 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.

9. BAY OF BENGAL REGIONAL TIDAL MODEL SET UP BY RHDHV

Royal HaskoningDHV has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM software of DHI (2019b). The model is based on the numerical solution of the two/threedimensional shallow water incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure.

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Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia and Indonesia (see Figure 3). The model has one open boundary along south-east, south and southwest. Unstructured flexible mesh was used in the study. The model bathymetry shown in Figure 3 was obtained from the C-Map Global Database (C-Map, 2014). This regional tidal model was used in the study to simulate the 2004 tsunami.

10. NUMERICAL MODELLING OF THE 2004 TSUNAMI

10.1 The Model

Royal HaskoningDHV has set up a two-dimensional Regional Tsunami Model for the Northern Indian Ocean covering the Bay of Bengal and its surrounding coastlines using the MIKE21/3 Flow Model FM software developed by DHI (2019b). The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia and Indonesia. The model area and bathymetry are shown in Figure 3.

The modelling system is based on the numerical solution of the two-dimensional shallow water equations - the depth-integrated incompressible Reynolds averaged Navier-Stokes equations. Thus, the model consists of continuity, momentum, temperature, salinity and density equations. An unstructured flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. The model can be used to simulate the propagation of tsunami waves and to predict their level and forward velocity within the Bay of Bengal and its surrounding areas.

The higher order numerical scheme was used in the study to improve accuracy in model results. Standard "Flood and Dry" were included in the model to consider flooding and drying processes. Barotropic density type and Smagorinsky eddy viscosity type were used. Coriolis forcing was included in the model as varying in domain. A constant bed resistance as Manning's number (n = $1/44 \text{ m}^{1/3}/\text{s}$) was used throughout the model domain.

10.2 Model Domain, Mesh and Bathymetry

Royal HaskoningDHV has set up a Regional Tidal Model covering the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM. This model was used in the study to hindcast the 2004 tsunami. 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 and around the Sunda Trench.

Typically, 20-30 grids (ideally 40 grids) per wave length are required to correctly resolve the physical processes of tsunami propagation. Shallower waters

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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 [C-Map, 2014]. Figure 3 shows the model domain and bathymetry.

10.3 Model Parameters

Tsunami levels refer to rise/fall of sea surface above/below a reference sea level. Usually Mean Sea Level (MSL) or Chart Datum (CD) are used as a reference sea level in tsunami modelling. The calculated rise in the sea surface can then be applied to a range of water levels/water depths. A constant water level (above CD) was maintained over the entire model domain. Therefore, any surface elevation above/below this level predicted by the model indicates rise/fall in sea surface due to the tsunami.

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 = 8 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.

The order of the numerical schemes that are used in the numerical calculations for time integration and for space discretization can be specified in the MIKE21 Flow Model to control the simulation time and accuracy. A lower order scheme (first order) is faster but less accurate whereas a higher order scheme is slower but in general produces results that are significantly more accurate than the lower order scheme. Therefore, the higher order numerical scheme

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was used in the study both for time integration and for space discretization.

10.4 Initial Tsunami Levels

The MIKE21 Toolbox of DHI (2019a) was used to generate the initial seabed deformation due to the 2004 earthquake. The tool uses the Okada (1985) equation to calculate the seabed deformation due to shear and tensile faults.

For the present study, the entire fault length was divided into five segments with variable slips assigned to each segment. The resulting seabed deformation is shown in Figure 4. A maximum rise of the seabed by about 10m was calculated with a maximum fall of the seabed by about 6m.

It is assumed that the changes in the sea surface are equal to the changes in the seabed. The initial sea surface elevation due to the 2004 earthquake is shown in Figure 5.

The general definition of tsunami level and wave height is illustrated in Figure 6. 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.

10.5 Model Validation

The maximum tsunami levels and tsunami arrival time at various locations were extracted from the model results and are provided in Tables 4 and 5. Observed tsunami levels and arrival time at these locations (as in Tables 4 and 5) were obtained from Wikipedia (2019a).

Table 4 - Modelled and observed tsunami levels atvarious locations

Locations	Observed levels	Modelled levels	
	(m)	(m)	
	[Wikipedia	(present study)	
	(2019a)]		
West Coast of Aceh	15.0-24.0	14.2-23.0	
(Indonesia)			
Banda Aceh Coast	6.0-12.0	7.5-11.5	
(Indonesia)			
North Coast of Weh	3.0-6.0	3.5-5.0	
Island (Indonesia)			
Port Blair (Andaman and	3.0	4.5	
Nicobar Islands)			
Andhra Pradesh (India)	2.2	1.8	
Galle Coast (Sri Lanka)	4.8	3.8	
Dawei (Myanmar)	0.9-2.9	0.8-2.2	

Table 5 – Modelled and observed tsunami arrival timeat various locations

Locations	Observed	Modelled	Modelled
	arrival time	arrival time	arrival time
	[Wikipedia	[NOAA	(present
	(2019a)]	(2004)]	study)
West Coast of	15-20 mins	-	25 mins
Banda Aceh			
(Indonesia)			
East Coast of India	90-120 mins	1 hr 55 mins	2 hrs 30
			mins
East Coast of Sri	90-120 mins	1 hr 45 mins	1 hr 55
Lanka			mins
Dawei (Myanmar)	2.0-5.5 hours	3.0 hours	2 hrs 50
			mins

A good agreement was found both in the modelled and observed tsunami levels and arrival time at various locations within the model domain. Therefore, it is concluded that the present model can predict the tsunami levels and current speeds anywhere within the model domain with an acceptable level of confidence.

10.6 Model Results and Discussions

The propagation of tsunami waves over time was extracted from model results as illustrated in Figure 7. Andaman and Nicobar Islands were quickly affected (within 5 minutes) due to the proximity to the epicenter. West Coast of Banda Aceh (Indonesia) and the south Coast of Weh Island (Indonesia) were also affected relatively quickly (within half an hour). It took about two hours for the tsunami to reach to Sri Lanka and Myanmar and about two and a half hours to reach to Indian east coast. Further details on tsunami arrival time at key locations are provided in Table 6.

Figures 8, 9 and 10 illustrate the maximum sea surface elevation during the entire passage of the tsunami around Aceh, Sri Lanka and India-Bangladesh-Myanmar respectively. The coastal areas east of the epicenter (west coast of Aceh) were the worst affected due to their proximity to the fault. 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. Further details on maximum tsunami levels at key locations are provided in Table 6.

Figures 11, 12 and 13 illustrate the maximum current speeds during the entire passage of the tsunami around Aceh, Sri Lanka and India-Bangladesh-Myanmar respectively. The coastal areas east of the epicenter (west coast of Aceh) were the worst affected due to their proximity to the fault. Further details on maximum tsunami speeds at key locations are provided in Table 6.

Time-series of tsunami levels (Figure 14) and current speeds (Figure 15) were extracted at selected locations of Indonesia, Andaman Islands, Myanmar, Sri Lanka and India. The coordinates of these output locations and tsunami arrival time, maximum tsunami level and maximum current speeds are provided in Table 6. Here, the arrival time is the time when the first high water arrives.

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Table 6 - Maximum levels, maximum speeds andarrival time of the tsunami at selected locations

Locations	Latitude (°N)	Longitude (°E)	Arrival time (hrs:mins)	Levels (m)	Speeds (m/s)
West Coast of Banda Aceh (Indonesia)	5.456	95.242	0:33	22.8	4.2
South Coast of Weh Island (Indonesia)	5.774	95.302	0:28	6.0	1.4
Port Blair (Andaman and Nicobar Islands)	11.623	92.755	0:05	4.5	0.5
Andhra Pradesh (India)	14.910	80.072	2:54	1.6	0.5
Nagapattnam (India)	10.851	79.854	4:17	2.5	1.4
Panama (Sri Lanka)	6.677	81.788	2:45	5.5	1.9
Dawei (Myanmar)	13.896	98.079	3:00	2.2	0.4

The model correctly reproduced the tsunami phenomena observed on site with the sea initially receding and leaving a drying beach and foreshore followed by a rapid rise in the level of the sea. The nearby Aceh province in Indonesia was worst affected due to its proximity. The highest level of 22.8m was found at west coast of Banda Aceh (Indonesia) after 33 minutes. The highest current speed of 4.2m/s was also found in this location. It took more than 8 hours for the sea state at this location to come back to normal condition.

11. FINDINGS AND CONCLUSIONS

Numerical modelling of the tsunami generated by the 2004 earthquake in the Sunda Trench was carried out in this study. This paper illustrates how a tidal hydrodynamic model can 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) Movements on the Sunda Trench resulted in a maximum rise of the seabed by about 10m and a maximum fall of the seabed by about 6m. It is assumed that the changes in the sea surface are equal to the changes in the seabed.
- b) The coastal areas west of Aceh province in Indonesia were the worst affected due to their proximity to the fault with maximum tsunami level up to 22.8m and maximum current speed up to 4.2 m/s predicted. It took only about half an hour for the tsunami to arrive to these areas.
- c) 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.

The methodology described in this paper for modelling the 2004 tsunami in the Sunda Trench could also be applied to other sites around the world that are affected by this type of events.

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FIGURES Obtaining from public domain the parameters of the earthquake that generated the tsunami	Calculating the seabed defor earthquake parameters [u (1985) equatio (The Tsunami Generation To Toolbox of DHI was used	mation from the sing the Okada n] ol in the MIKE21 in the study)	Generating the initial tsunami map using the seabed deformation output		
Post-processing of model results (Such as making 2D tsunami propagation maps; 2D plots of maximum tsunami heights and currents; 1D time-series plots of	Simulating tsunami propagation using the validated regional tidal hydrodynamic model	Validating the regional tidal hydrodynamic model using data from public domain	Setting up the Bay of Bengal regional tidal hydrodynamic model (generating model mesh and bathymetry; assigning the initial tsunami map and		

Figure 1: Steps and software used in the tsunami modelling study

tsunami heights and currents at selected locations).

model parameters)

(The MIKE21 Flow Model of DHI was used in the study)

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Figure 5 - Initial sea surface elevation (mCD) due to the 2004 earthquake

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Figure 6: General definition of tsunami level and wave height



(a) Tsunami waves at t = 0 minutes



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100

110 [deg]

90





-20

70

80





⁽d) Tsunami waves at t = 1 hour 30 minutes





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Above 1.0 0.8 - 1.0 0.7 - 0.8

> 0.6 - 0.7 0.5 - 0.6 0.4 - 0.5 0.3 - 0.4

0.2 - 0.3 0.1 - 0.2 0.0 - 0.1 -0.2 - 0.0

-0.4 - -0.2 -0.6 - -0.4 -0.8 - -0.6

-1.0 - -0.8 Below -1.0 **Undefined Value**











Figure 7 – Propagation of the 2004 tsunami waves



Figure 8: Maximum sea surface elevation near Aceh





Figure 9: Maximum sea surface elevation near Sri Lanka



Figure 10: Maximum sea surface elevation near India, Bangladesh and Myanmar













^{01/06/2018 00:00:00} Time Step 0 of 0.





Figure 14: Time-series of tsunami level



Figure 15: Time-series of tsunami current speeds

Time

2018-06-01