TSUNAMI HAZARDS IN SRI LANKA: ASSESSMENT OF EXPOSURE LEVELS OF THE SOUTHERN COAST

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Degree of Master of Science

Department of Civil Engineering

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science

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DECLARATION

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ABSTRACT

TSUNAMI HAZARDS IN SRI LANKA: ASSESSMENT OF EXPOSURE LEVELS OF SOUTHERN COAST

In Sri Lanka, monsoonal floods, droughts, cyclones and landslides are the common and well-known natural hazards and almost every year the country experiences one or more of these hazards. Tsunamis have not been frequent in the history of Sri Lanka but the Indian Ocean tsunami in 2004, subsequent tsunami alerts issued in the country and historical accounts of tsunami events in the past have clearly highlighted the exposure of Sri Lanka to tsunami hazards. Tsunamis are generated by a variety of causes and undersea earthquakes have been identified as the most common cause for tsunami generation. Considering the location of Sri Lanka and the undersea earthquake prone regions in the world, it is evident that the country is exposed to potential tsunami events generated at the Sunda Trench located to the east and the Makran Fault located to the north-west. The Indian Ocean Tsunami was caused by an earthquake occurred in the Sunda Trench. The Indian Ocean Tsunami caused widespread damages in coastal areas of the country and the exposure of many coastal areas to tsunami hazards became evident form the damages experienced. The southern area of the country was significantly affected by the in 2004 and the 03 main populated/urban areas along the southern coastline-Galle, Matara and Hambantota-were considered for the assessment of the levels of exposure.

Numerical models are widely used to simulate tsunami events in order to assess the exposure of coastal areas to tsunami hazards. The numerical model MOST with the user interface ComMIT, developed by the National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce was used to simulate the selected earthquakes at Sunda Trench and Makran Fault in this study. The tsunami wave height in coastal waters and the tsunami arrival times were obtained by numerical modelling were considered to assess the level of exposure. Sunda Trench was divided into 4 regions, extending from north to south along the trench, for the purpose of this study. The upper (northern) part of the trench was considered as Region 1, and the middle section were divided in to two regions, Region 2 and Region 3. The lower part was considered as Region 4. Based on the results of the study, it can be concluded that the southern coast is at a high risk due to the earthquakes generated in Regions 2 and 3 of the Sunda Trench. A high level of exposure was evident due to earthquakes of magnitudes higher than 9.0 Richter Scale. No significant level of exposure was evident due to tsunamis generated at the Makran Fault. An early warning system would be very effective in mitigating adverse impacts due to tsunamis and such a system can be based on a large database developed from the results of tsunami simulations similar to the ones carried out in the study. Further improvements of the results of such simulations can be made by considering higher resolution bathymetric information obtained by surveys, together with relevant overland topographic data to assess the inundation characteristics of tsunamis in coastal areas.

Key words: Makran Fault, Sunda Trench, Wave Height

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LIST OF ABBREVIATIONS

ComMIT	Community Model Interface for Tsunami
CTWP	Caribbean Tsunami Warning Program
DEM	Digital Elevation Model
GA	Geoscience Australia
GITEWS	German-Indonesian Tsunami Early Warning System
GUI	Graphical User Interface
IOC	Intergovernmental Oceanographic Center
IOT	Indian Ocean Tsunami
IOTIC	Indian Ocean Tsunami Information Centre
INCOIS	Indian National Center for Ocean Information Services
ITEWC	Indian Tsunami Early Warning Centre
ITIC	International Tsunami Information Center
JATWC	Joint Australian Tsunami Warning Center
JRC	Joint Research Centre
MF	Makran Fault
MOST	Method of Splitting Tsunamis
NCEI	National Centers for Environmental Information
NCTR	NOAA Center for Tsunami Research
NEAMTWS	North East Atlantic and Mediterranean Tsunami Warning System
NOAA	National Oceanic and Atmospheric Administration
NSW	Non-linear Shallow Water
PTWC	Pacific Tsunami Warning Center
RIMES	Regional Integrated Multi-Hazard Early Warning System
ST	Sunda Trench
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTC	Universal Time Coordinate
WDS	World Data Services

CHAPTER 1 : INTRODUCTION

1.1 Background

Monsoonal floods, droughts, cyclones and landslides are the common and well-known natural hazards in Sri Lanka. Almost every year the country experiences one or more of these hazards. Based on meteorological forecasts, relevant warnings are usually issued for the public to enable them to evacuate to safer locations. Even though property damages occur, loss of human lives can be minimized due to the availability of proper early warning mechanisms for these natural hazards.

Prior to 2004, tsunamis were not known to most of the Sri Lankans. Therefore, impacts due to the 2004 Indian Ocean Tsunami (IOT) were devastating as no warning was issued and no evacuation measures were in place.

The IOT was generated by a devastating earthquake of magnitude 9.1 on 26 December 2004, off the west coast of northern Sumatra. It occurred at the boundary of the Indian Tectonic Plate and the Burma Micro Plate due to the thrust faulting at the interface. The location of the epicenter was 3.316^0 N and 95.854^0 E, at a depth of 30 km. In few minutes, it released the energy that was stored through centuries from ongoing subduction of the Indian Plate underneath the superseding Burma Micro Plate. The IOT is the third largest seismic activity in the world since 1900 (Hayes, et al., 2017).

Several countries bordering the Indian Ocean were severely affected by the IOT. In Sri Lanka, 13 out of 14 Districts along the coastal belt were affected by the IOT (**Figure 1.1**) and more than 30,000 lives lost.

The extent of damage varied along the coastline and details as per the Department of Census and Statistics are given in **Table 1.1**.

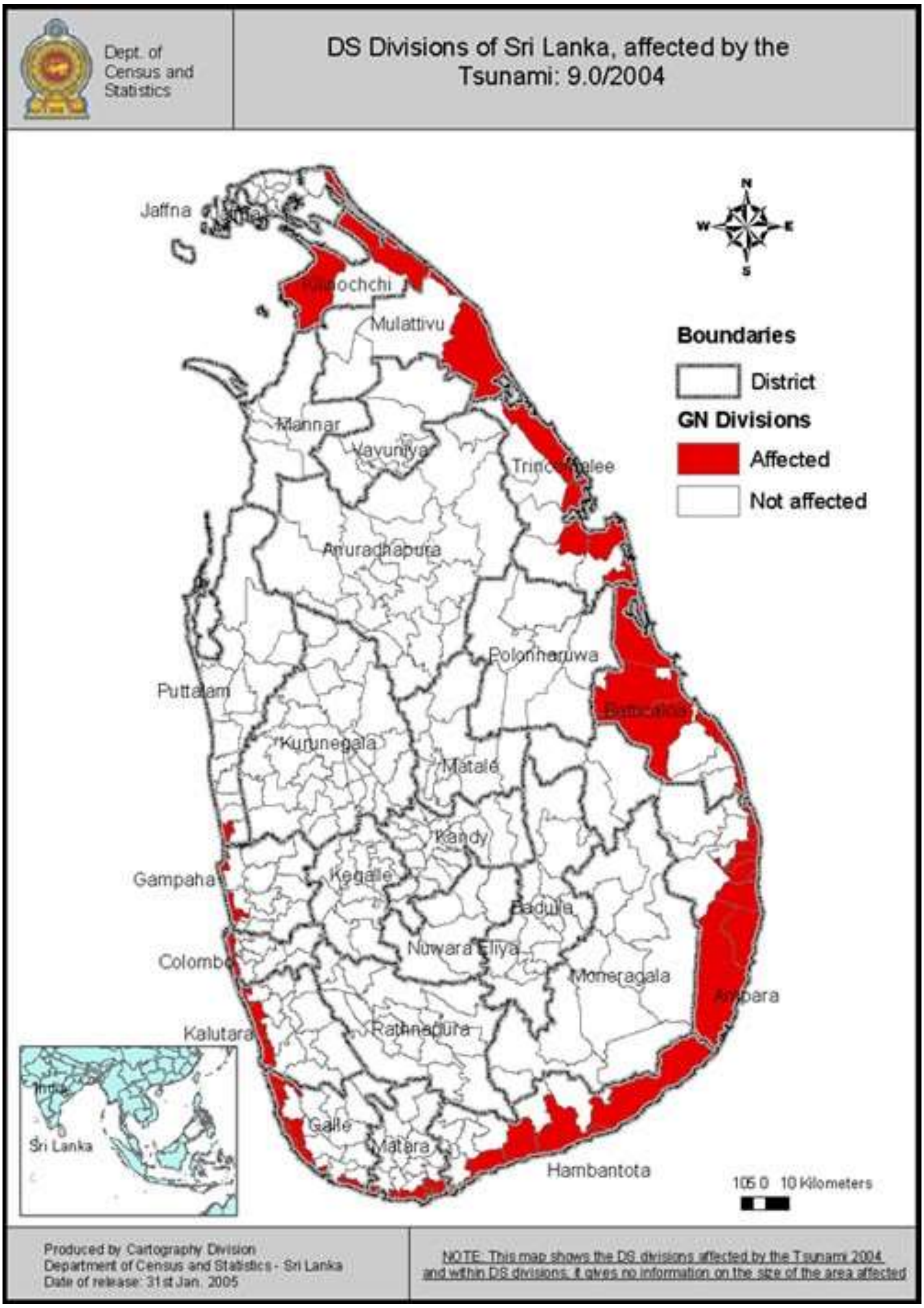


Figure 1.1: Coastal Areas affected by the IOT
(Source: Department of Census and Statistics, Sri Lanka)

Table 1.1: Details on the Extent of Damage by the IOT
(Source: Department of Census and Statistics, Sri Lanka)

District	No of reported deaths	No of reported displaced people	No of destroyed houses	No of damaged houses
Gampaha	6	1449	292	307
Colombo	79	31239	4170	2521
Kalutara	256	27713	3100	3668
Galle	4214	128077	5408	5628
Matara	1342	13305	7188	5659
Hambantota	4500	17723	2303	1744
Ampara	10436	75172	29097	-
Batticaloa	2840	61912	15939	5665
Trincomalee	1078	81643	5974	10394
Mullativu	3000	22557	10585	5270
Jaffna	2640	39907	12000	1114
Killinochchi	560	1603	3400	4250
Puttalam	4	66	23	72

As per **Table 1.1**, the highest number of deaths was reported from the Ampara District on the eastern coast of the country with more than 10,000 deaths were reported in the District. Also the third highest number of displaced people, exceeding 75,000, was reported from the same District. Further, the maximum property damage was also reported from Ampara District with more than 29,000 houses completely damaged. In the Galle District on the southern coast, despite the comparatively low number of reported deaths (4,214), more than 100,000 displaced people was reported. It is evident as per the information given in **Figure 1.1** and **Table 1.1** that the eastern coastal areas were the most affected by the IOT. However, the areas along the southern, south-western as well as the western coastline were also significantly affected by the IOT. Only the western and north-western coastal areas were not affected by the IOT. The widespread exposure of the coastal areas of the country to tsunami hazard is evident form these considerations.

1.2 Exposure of Sri Lanka to Tsunami Hazards

After the IOT in 2004, tsunamis are now considered as a natural hazard in Sri Lanka. The historical studies conducted after the IOT in 2004 revealed that several accounts of sea inundations were reported in historical texts which indicate the possibility of tsunami events in Sri Lanka in the past.

It is reported that several times during ancient times, some regions of the country were inundated due to an overflow of the ocean (Geiger, 1912). It is of the view that such an event occurred 2,200 years ago when the King Kelanitissa ruled Maya Rata in which whole villages were inundated around Kelaniya, which was 25 miles away from the coast (Geiger, 1912). According to (Suraweera, 2000), an extent including 100 harbor towns and 970 fishing villages were inundated by the ocean waves.

Administrative chronicles of Portuguese who governed coastal areas area of the country (1954-1612) state that a seismic activity hit the Colombo City on 14 April 1615. The tremor that occurred at 7.00 p.m. damaged a section of the town wall and 200 housing units. Also, more than 2000 lives were lost (10% of the city population). Another tremor occurred in Batticaloa on 14 June 1814, damaging some property without causing any deaths.

The tsunami created due to the volcano explosion of Krakatoa in Indonesia on 27 August 1833 was sensed in some places on the eastern and southern coastlines of Sri Lanka. It was reported that at 1.30 p.m., the ocean retreated, revealing the ocean bed for 36 m to 126 m from the coastline for several minutes (similar to the IOT in 2004). However, the ocean did not arrive in a tsunami and the normal sea level raised by 4 feet as reported. Only two deaths were recorded and minimum property was damaged as per the records.

In view of the above consideration, it is clearly evident that Sri Lanka is exposed to tsunamis even though the frequency of occurrence is much less than the other natural hazards experienced in the country. As revealed by the literature review in Chapter 2, it is now known that Sri Lanka is potentially exposed to tsunamis generated due to undersea earthquakes in Sunda Trench and Makran Fault. Since the IOT in 2004, several tsunami alerts were issued in Sri Lanka, in response to tsunami events generated at the Sunda Trench, although the country was not affected by such events. The damages caused by the IOT in 2004 were mainly due to the absence of an early warning system and evacuation measures in the coastal areas of the country. An early warning system would have played a vital role reducing the huge death toll in Sri Lanka due to the IOT in 2004.

Tsunamis, as a natural hazard, is a worldwide phenomenon and several international organizations associated with early warning of such hazards. These include the PTWC (Pacific Tsunami Warning Center), CTWP (Caribbean Tsunami Warning Program) NEAMTWS (North East Atlantic and Mediterranean Tsunami Warning System) and INCOIS (Indian National Center for Ocean Information Services). These centers are governed by UNESCO/ IOC (Intergovernmental Oceanographic Center). In addition, a few other organizations such as Japan Meteorological Agency, Australian Government Bureau of Meteorology, Tsunami Early Warning System-Indonesia are also involved with early warning on tsunami hazards. In the event of an undersea earthquake which can cause a tsunami, these organizations issue tsunami warnings for the relevant countries. Sri Lanka is a recipient of such warnings from PTWC or Indian Tsunami Warning Center. However, such warnings are issued for the whole country, and no details are usually issued to identify the exposure levels of the different parts of the country along its coastline. Hence a need exists to develop an early warning system for the country which is based on the exposure levels of different parts of the country to for potential tsunami events likely to affect the country. The need for such a system was evident due to the variation of exposure levels along the coastline of the country resulted from the IOT in 2004. Such a system would enable warnings to be issued only for the areas along the coastline which are likely to be affected, without considering the other areas which are not potentially exposed to the tsunami event generated.

1.3 Objectives

In view of the above considerations, this research study was conducted with the objective given below:

- To assess the level of exposure of the coastal areas of Sri Lanka to potential tsunami events in the Indian Ocean

1.3.1 Specific Objectives

Within the stated objective above, the specific objectives of the study are

- To base the assessment of the level of exposure on tsunami characteristics given below:
    - tsunami arrival time in the coastal waters of the country
    - maximum tsunami (wave) height in the coastal waters in the areas of interest
    - (depending on the availability of information) tsunami inundation characteristics

The southern coastal area was considered in the study. As stated earlier, the southern area of the country was significantly affected by the IOT in 2004. The 03 main populated/urban areas along the southern coastline-Galle, Matara and Hambantota-were considered for the assessment of the levels of exposure.

CHAPTER 2 : LITERATURE REVIEW

A literature review was carried out in which the attention was focused on the causes of tsunami generation, previous studies on the assessment of tsunami exposure levels in Sri Lanka and the methods used in the assessments of exposure levels and the findings of the review are summarized in the chapter.

2.1 Tsunami Generation

Tsunamis are large ocean waves caused by sudden displacement of sea bed/surface. Such displacement could occur due to:

- undersea earthquakes
- undersea volcanic eruptions
- landslides
- meteorite impacts
- nuclear explosions

NOAA's National Centers for Environmental Information (NCEI) and World Data Service (WDS) for Geophysics and the International Tsunami Information Center (ITIC), a UNESCO/IOC-NOAA conglomerate, have workd together to create a map presenting tsunami causes. The data taken from the NCEI Historical Tsunami Database that consists of data on tsunami causing actions all over the world that occurred from 1610 B.C. to A.D. 2016. The tsunami explanations are from the Tsunami Glossary 2016 published by UNESCO. Among the 2,500 events in the NCEI Historical Tsunami Database, more than 1,200 definite tsunami causing events are demonstrated on the map. The map is shown in **Figure 2.1**.

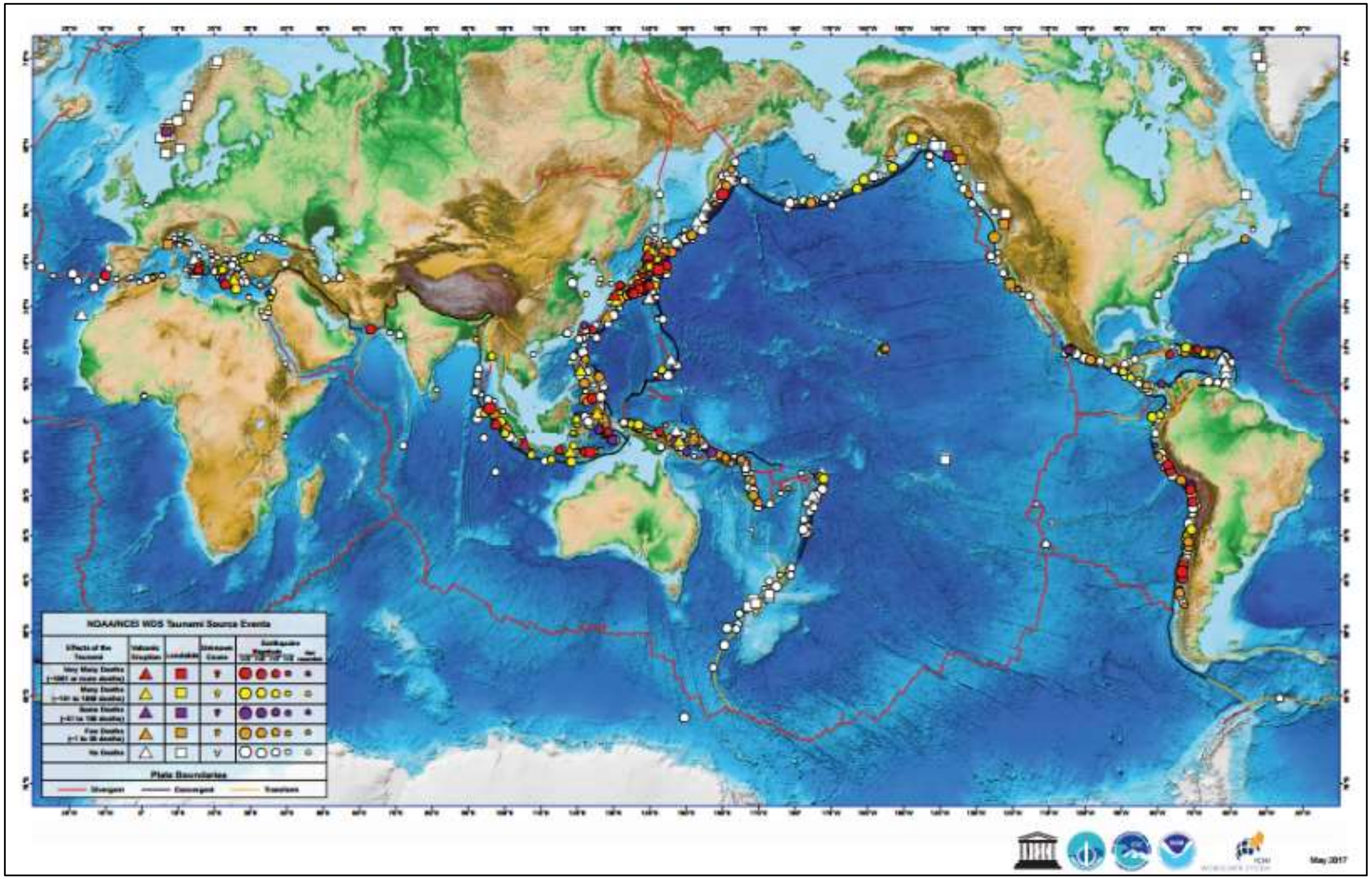


Figure 2.1: Tsunami Sources from 1610 B.C. to A.D. 2016
Source: https://www.ngdc.noaa.gov/hazard/tsu_db.shtml

The global distribution of these confirmed tsunami sources is 70 % in the Pacific Ocean, 15 % in the Mediterranean Sea, 9 % in the Caribbean Sea and Atlantic Ocean and 6 % in the Indian Ocean. As indicated by **Figure 2.2**, most of these confirmed tsunamis were generated by earthquakes (81 %) or earthquakes that caused landslides (6 %). The remaining events were caused by volcanic eruptions (5 %), landslides (4 %), and other causes (4 %).

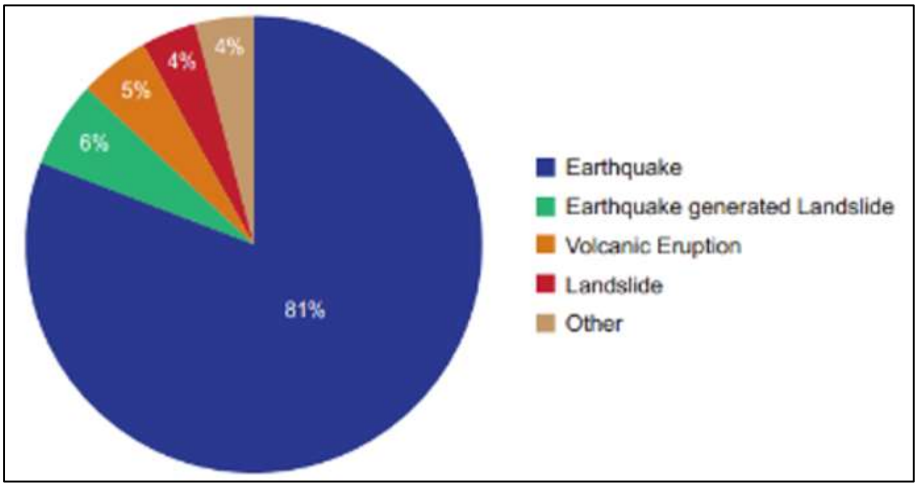


Figure 2.2: Distribution of Tsunamis by Generation Mechanism

A schematic diagram of tsunami generation mechanisms is given in **Figure 2.3**.

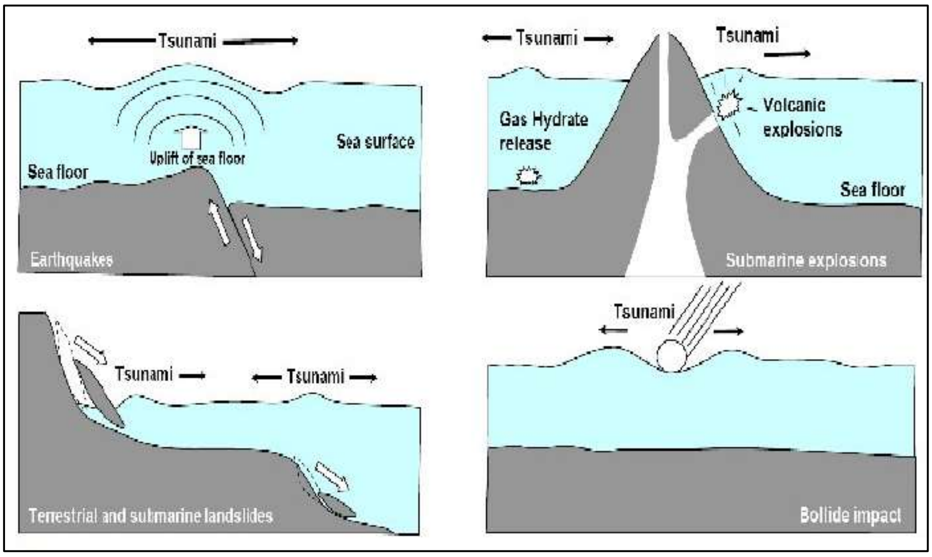


Figure 2.3: Tsunami Generation Mechanisms
Source: https://www.slideshare.net/chius/assessing-tsunami-hazard-for-hong-kong-inqua-2007

2.1.1 Tsunami Generation by Undersea Earthquakes

A submarine seismic activity is the most frequent method of tsunami generation, generally creating the most damaging tsunamis. The earth is continuously moving on outsized tectonic surfaces. Considering the plate tectonics of earth, the most aged part of earth core is made up of two stratums, the Lithosphere and the Asthenosphere. The Lithosphere is fragmented into tectonic plates. The segment where two such surfaces come across is named a plate boundary and plate boundaries are generally linked with geological actions such as earthquakes and the formation of topographic landscapes such as mountains, volcanoes, mid-ocean ridges and oceanic trenches.

Most tsunamis are generated due to earthquakes occurred in a subduction zone, an area where an oceanic surface is being pulled down into the mantle by plate tectonic forces. The resistance among the subducting plate and the superseding plate is massive. This resistance avoids a slow and steady rate of subduction and hence the two stratums become stuck. Due to the downhill movement of the stuck stratum into the mental, a slow alteration of the overriding stratum occurs. Energy can store in the overriding stratum for an extended duration (decades or even centuries) until it surpasses the resisting forces among the two stuck stratums. In the meantime, inland regions of the overriding stratum can get lowered unexpectedly. A tsunami can occur even if the epicenter of the earthquake is near or far to the shoreline.

Tsunamis are infrequent incidents compared to undersea earthquakes and most undersea tremors do not produce tsunamis. It is reported that out of the 1098 undersea tremors that occurred along the west coast of South America (a coast more susceptible to tsunamis) have generated only 20 tsunamis. This low rate of occurrence basically reveals the fact that many tsunamis are minor in amplitude and undetected or the fact that most earthquake induced tsunamis involve a shallow focus seismic event with a surface magnitude greater than 6.5 on the Richter Scale.

2.1.2 Tsunami Generation by Volcano Explosions

An intense volcano explosion can create tremendously damaging tsunami waves in the close vicinity since it moves a large quantity of water. The movement of water occurs due to the slope failure of the volcano. However, these are comparatively rare events. The region ‘Ring of Fire’ is located around the Hawaiian Islands and around 452 volcanoes are located there. Many tsunamis in the Pacific Ocean generate closer to this area.

Hawaiian Islands were damaged by more than 40 tsunamis created due to volcano explosions in the ‘Ring of Fire’ area from 1819. On 26 August 1883, a massive tsunami with wave heights of 135 feet damaged the shoreline areas of Java and Sumatra. It took away the valuable lives of more than 36,000 people. This was due to the eruption and failure of the Krakatoa volcano in Indonesia.

2.1.3 Tsunami Generation by Landslides

Submarine landslides can also create tsunamis with demoralizing local damages restricted to a limited area. When methane gas trapped within the seabed is released, it can create landslides. The damage of the tsunami it creates depends on the quantity of soil, the speed of dropping and the angle. These landslides mainly occur due to earthquakes.

A massive tsunami occurred in Lituya Bay, Alaska in 1958 with wave heights in the order of 30 m. This type of tsunamis has only limited time for the warnings because the cause is close to the coast. However, only two deaths were reported.

The most reasonable mitigation action is to instruct the people to move into the elevated land soon after they feel an earthquake or witness the retreated sea bed. Regular tsunamis with wave heights of more than 30 m occur in Alaska due to landslides. In 1964, the great Prince William Sound earthquake created a tsunami with great destruction and took many lives. Jamaica, a Caribbean island, face many tsunamis due to landslides. In 1692, the tsunami generated due to the Port Royal earthquake damaged the city and caused about 2000 deaths.

2.1.4 Tsunami Generation by Asteroid Impacts

Most of the earth surface (about two thirds) is oceans. An asteroid coming from the outer space can plunge into the ocean creating a large surface displacement of water. Even though these are very infrequent happenings, they can create massive destructive tsunamis. Wave height of such a tsunami is based on the size of the asteroid.

In recent history, no tsunamis were recorded due to asteroid impacts.

2.1.5 Tsunami Generation by Large Explosions

In addition to above causes, tsunamis can be generated due to undersea large explosions (e.g. nuclear) as well and the impact will depend on the magnitude of the explosion.

2.2 Sunda Trench

Considering the location of Sri Lanka and the undersea earthquake prone regions in the world, it is evident that the country is exposed to potential tsunami events generated at the Sunda Trench located to the east and the Makran Fault located to the north-west.

The Sunda Trench is situated close to Sumatra where the Australian Stratum subducts beneath a part of the Eurasian Stratum with a span of 3200 km. It is at the border among Indo Australian Plate and Eurasian Plate and forms a section of the' Pacific Ring of Fire'. Earthquakes generated in recent past at the Sunda Trench are given in **Table 2.1**.

Table 2.1: Earthquake History of Sunda Trench

Date	Moment Magnitude	Location		Time (UTC)	Depth (km)
12/26/2004	9.1	3.30 N	95.78 E	00:58:53	30
03/28/2005	8.7	2.30 N	97.10 E	16:09:36	32
09/12/2007 (1st quake)	8.4	4.52S	101.37 E	11:10:26	34
09/12/2007 (2nd quake)	7.9	2.51 S	100.91 E	23:49:04	10
09/13/2007 (3rd quake)	7.0	2.16 S	99.85 E	03:35:26	10
04/11/2012	8.6	2.29 N	93.08 E	08:38:36	20
08/13/2017	6.4	3.73 S	101.62 E	03:08:00	40

2.3 Makran Fault

The Makran Fault is a subduction region along the northeastern boundary of the Gulf of Oman neighboring to the southwestern shore of Baluchistan of Pakistan and the southeastern shore of Iran. In this area, the ocean crust of the Arabian Plate is being subducted underneath the continental crust of the Eurasian Plate. In the Makran area, the Arabian Plate subducts underneath the Eurasian Plate at a rate of 4c m per year. Earthquakes generated in recent past at Makran Fault are given in **Table 2.2**.

Table 2.2: Earthquake History of Makran Fault

Date	Moment magnitude	Location		Time (UTC)	Depth (km)
05/31/1935	7.7	29.50 N	66.80 E	-	15
11/27/1945	8.1	24.50 N	63.00 E	21:56:00	-
08/05/1947	7.3	-	-	-	-
July 1990	6.1	-	-	-	-
09/24/2013	7.7	27.00 N	65.51 E	11:29:48	20

2.4 Numerical Models of Tsunamis

Numerical models are widely used to simulate tsunami events in order to assess the exposure of coastal areas to tsunami hazards. ComMIT and AVI-NAMI are 2 such models which have been used in several studies related to Sri Lanka as well as other areas in the world.

2.4.1 ComMIT

Tsunami events at the Sunda Trench of magnitudes 7.5, 8.0, 8.5, 9.0, 9.2 and 9.5 were modeled and the maximum wave heights and tsunami arrival times at 10 points located near Matara, Southern Coast of Sri Lanka have been assessed using ComMIT (De Silva, 2010).
Tsunami events at the Sunda Trench of magnitudes 7.8, 8.2 and 9.2 were modeled and the maximum wave heights at 5 points located near the port city of Gallehave been assessed using ComMIT (Samarasekara, 2014).

Both (De Silva, 2010) and (Samarasekara, 2014) have verified the results for the IOT 2004 data for which empirical relations by (Wells & Coppersmith, 1994) have been used to derive the initial conditions of earthquakes.

2.4.2 AVI-NAMI

According to (Ohga, et al., 2010), a tsunami is a sequence of oceanic waves with extended wave length and period compared to wind created waves caused mainly due to subduction earthquakes. When propagating, the rate of energy loss in a wave is inversely proportional to its wave length, thus losing minimum energy, a tsunami wave can travel transoceanic distances in a short time duration. The numerical model AVI-NAMI is used after validating with 2004 tsunami data, for three scenarios selected based on the historical records with 8.8 magnitude. The 1st scenario is located near to the top edge of the fault, 2nd at the middle part and 3rd at the southern part of the fault in the Sunda trench. After analyzing the numerical model results (Ohga, et al., 2010), concluded that 1st and 2nd events have high risk on Sri Lanka with a low risk due to 3rd event. Further, the probability of occurrence of the 2nd event is marginal since much of the accumulated energy is released in 2004 December (Mw = 9.1) and 2005 March (Mw = 8.5) events. By analyzing the historical records, it can be seen that the 2005 event happened at the rupture area of 1861 event (Mw = 8.7). The 3rd event considered in (Ohga, et al., 2010) is at the rupture area of 1833 event (Mw = 8.7) where the 1797 event (Mw = 8.2) took place. Hence (Ohga, et al., 2010) conclude that the southern Sumatra section of the Sunda Trench is a potential zone for a massive seismic activity (by analyzing the repetitive pattern of events) even though no substantial risk to Sri Lanka.

2.5 Indian Ocean Tsunami (IOT) 2004 and related Studies

Subsequent to the IOT in 2004, many studies on the tsunami hazards in Sri Lanka were carried out.

A detailed survey was carried out of a team of investigators from United States and New Zealand and details on many parameters including maximum tsunami heights, maximum run up heights, inundation distances and inundation areas were recorded. The parameters were taken from water marks on the buildings, tress and from eyewitness reports. Changes done to the natural coastal belt by humans had caused severe damages at some locations were also recorded. Based on the result of the survey, the team has produced the detailed map, shown in **Figure 2.4**, of measured maximum tsunami heights around the western, southern and eastern coastal areas (Liu, et al. 2005).

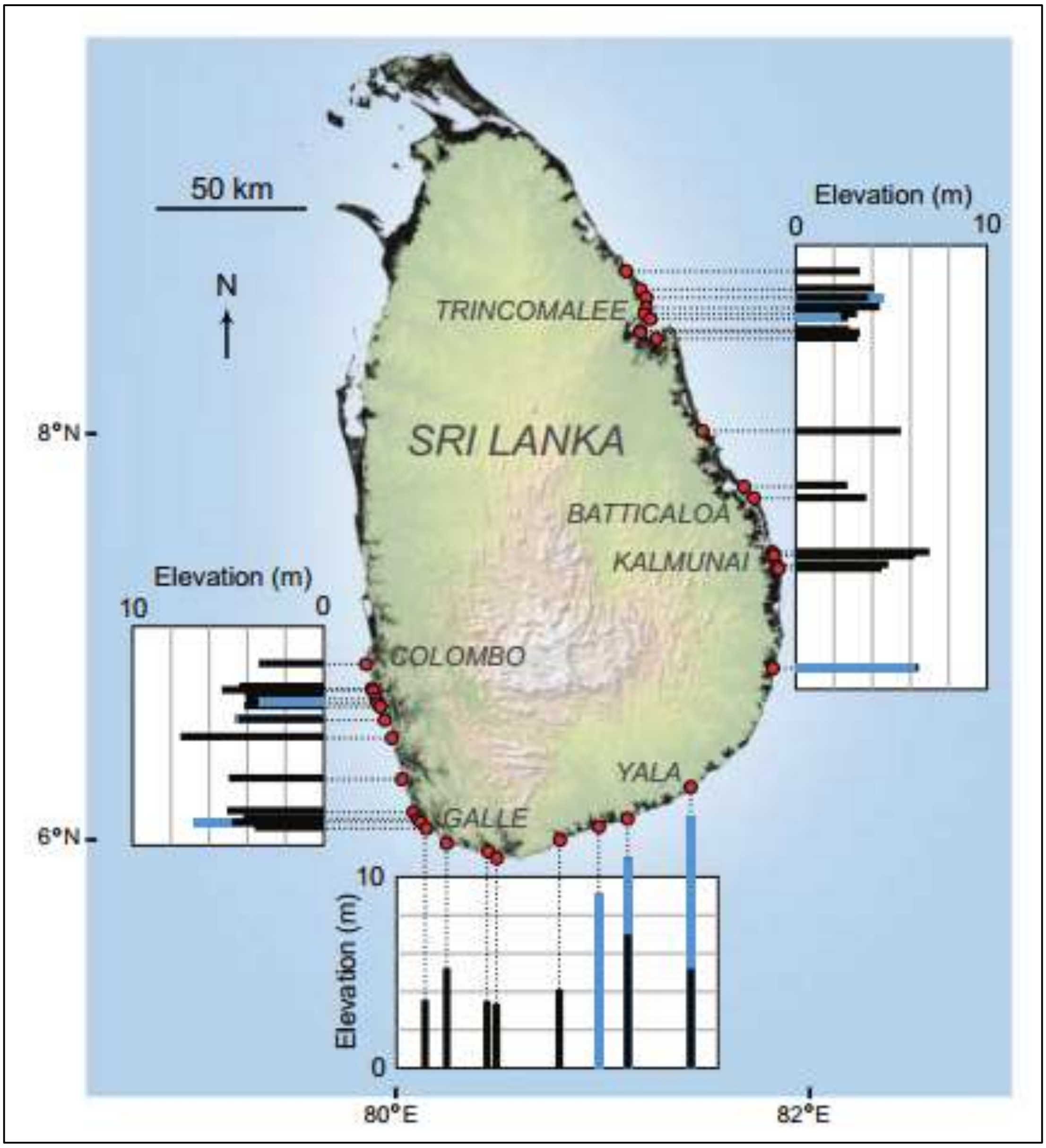


Figure 2.4: Tsunami Heights in Sri Lanka, IOT 2004
Source: Liu et al. (2005)

By considering the historical tsunamis in 1833, 1881, 1941, 1945, 1977 and 1994 along with recent tsunami events in 2004, 2005 and 2007 and the energy accumulated in those subduction zones after these events, (Okal & Synolakis, 2008) have performed simulations using the MOST Code for 8 main scenarios. The scenarios are shown in **Figure 2.5**. In these simulations, (Okal & Synolakis, 2008) have considered possible fault zones in Indian Ocean Basin-Southern Sumatra, North of Andaman (Myanmar), Makran Fault of Baluchistan and Java subduction zone-and analyzed the risk on various coastlines of Indian Basin countries-Sri Lanka, India, Maldives, Madagascar and the Mascarenes, Africa, Australia, Malaysia, Singapore and northern Java and Kerguelen.

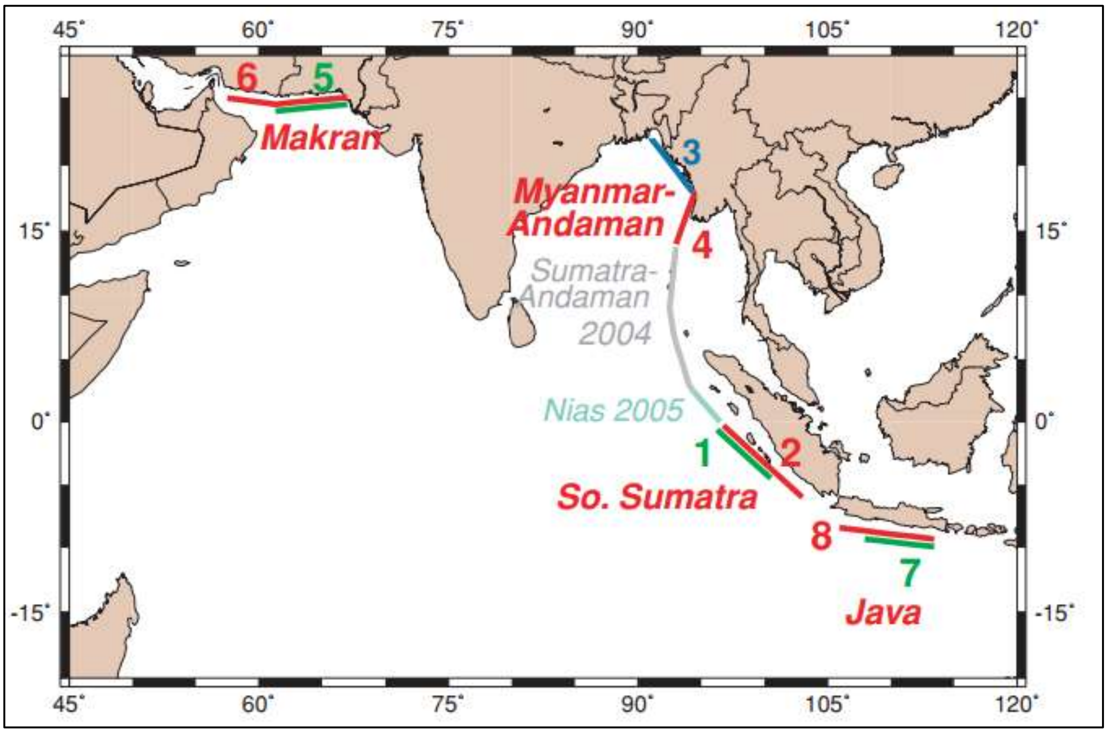


Figure 2.5: Scenarios considered for the Study
Source: Okal and Synolakis, 2008

To provide numerical guidance to the tsunami warning services, a tsunami scenario database, which is called T1, was developed by Joint Australian Tsunami Warning Centre (JATWC) A development for that database (T2) is made and the number of source locations were increased in T2 and the MOST Model used for the numerical simulations. Altogether, four earthquake magnitudes were selected for the analysis (Mw = 7.5, 8.0, 8.5 and 9.0) at each source location. To determine the fault parameters equations (2.3) and (2.4) were used. To provide guidance to tsunamis generated due to earthquake magnitudes other than considered in the study, scaling factor given in equation (2.5) was used. Hence, wave height for 8.1 magnitude can be calculated by multiplying the wave height of simulated 8.0 scenario by the relevant factor (Greenslade, et al., August 2009). But they recommended not to use this scaling factor for magnitudes greater than 9.2 and less than 7.3 since it will produce unrealistic values. (Greenslade, et al., August 2009) evaluated the results using tsunameter observations from 2006 Tonga Event (Mw = 7.9) and 2007 Sumatra Event (Mw = 8.4). Further evaluations were done using tsunameter observations from 2009 Kuril Islands event (Mw=7.4) and 2009 Tonga event (Mw=7.6) (Greenslade, et al., 2011).

(Greenslade, et al., 2014) compared tsunami amplitudes at 10 output points from 8 tsunami forecast systems due to 8 different hypothetical tsunami events. The selected tsunami forecast systems in the study are listed below.

- Joint Australian Tsunami Warning Centre (JATWC)
- Indian Tsunami Early Warning Centre (ITEWC)
- German-Indonesian Tsunami Early Warning System (GITEWS) – Indian Ocean Tsunami Information Centre (IOTIC)
- Regional Integrated Multi-Hazard Early Warning System (RIMES)
- Geoscience Australia (GA)
- European Commission Joint Research Centre (JRC)
- German Research Centre for Earth Sciences (GFZ)
- US National Oceanic and Atmospheric Administration (NOAA) Centre for Tsunami Research (NCTR)

Different elements in each forecast system are given in **Table 2.3**.

The hypothetical earthquake scenarios considered are given in **Table 2.4**.

The locations in the considered study (Greenslade, et al., 2014) are shown in **Figure 2.6**.

Table 2.3: Summary of Key Elements of the Forecast Systems (Greenslade, et al., 2014)

System	Technique	Propagation Code	Simulation Time	Spatial Resolution	Output Time Interval
JATWC	0.5 interval Mw with linear scaling	MOST	24 h	4’	2 min
ITEWC	Unit source	TUNAMI-N2	15 h	2.7’	15 s
GITEWS	0.2 interval Mw	TsunAWI	24 h	200 m -25 km	1 min
RIMES	Unit source	TUNAMI-F1	18 h	2’	6 s
GA	Unit source	Modified Satake (1995)	27 h	1’-2’	0.5 s
JRC	0.25 interval Mw	SWAN-JRC	12 h	Depends on Mw	1.8 min
GFZ	On-the-fly	EasyWave	10 h	2’	15 s
NCTR	Unit source	MOST	30 h	4’	1 min

Table 2.4: Hypothetical Earthquake Scenarios Considered (Greenslade, et al., 2014)

Source region	Epicenter	Magnitude
Makran A	61.6^0 E, 25.3^0 N	7.3
Makran B	61.6^0 E, 25.3^0 N	8.3
Sunda North A	92.2^0 E, 10.5^0 N	7.5
Sunda North B	92.2^0 E, 10.5^0 N	8.2
Sunda Central A	100.0^0 E, 3.0^0 S	7.8
Sunda Central B	100.0^0 E, 3.0^0 S	9.1
Sunda South A	116.0^0 E, 10.5^0 S	8.0
Sunda South B	116.0^0 E, 10.5^0 S	8.7

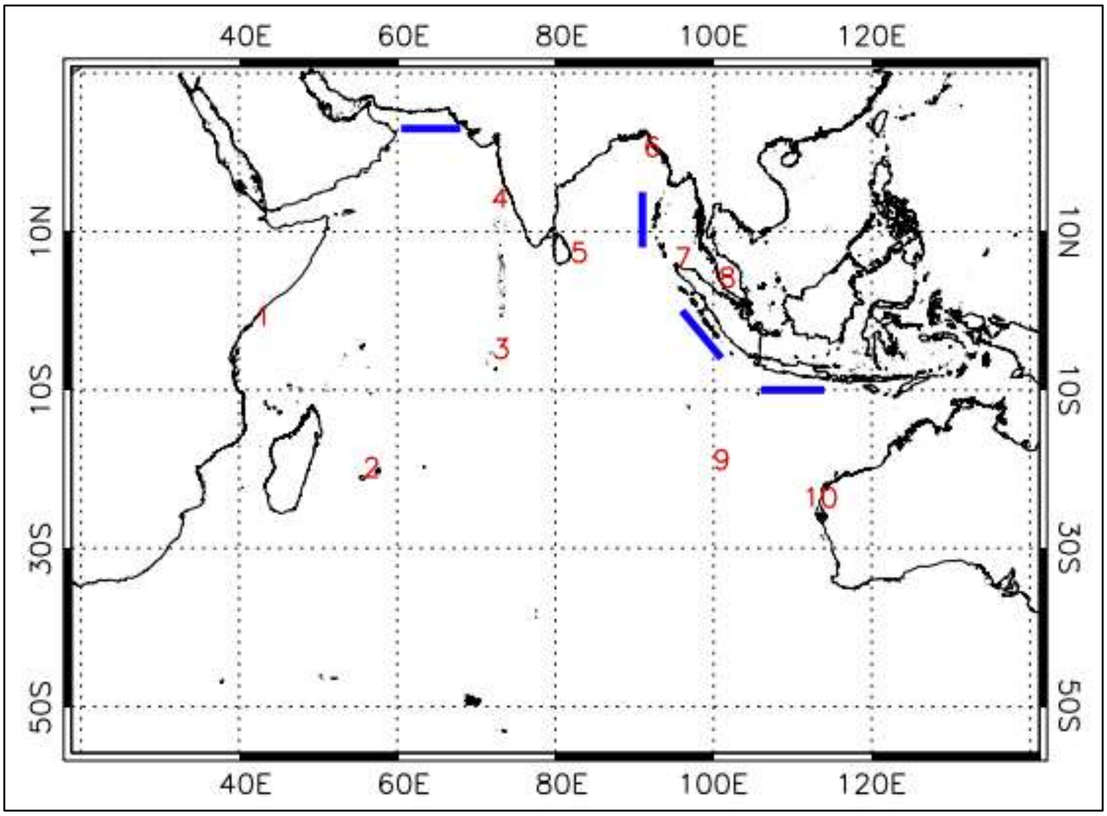


Figure 2.6: Selected Earthquake Locations and Output Data Collection Points (Greenslade, et al., 2014)

(Greenslade, et al., 2014) suggest that variation of the maximum amplitude in each forecast system may be due to differences in

- Initial conditions (source models)
- Bathymetry data set and its resolution
- Wave propagation physics (linear/ non-linear shallow water equations)
- Numerical approximations
- Interpolation between or scaling of pre computed scenarios according to the magnitude

By calculating the coefficient of variation, (Greenslade, et al., 2014) conclude that the variation is partly due to the diverse spans of time series each forecast system has used and the differences in the bathymetry data sets (depth of output locations) they used was not a major factor contributing to the difference in the maximum amplitude at output locations.

By analyzing the past tsunami events and the seismic information (Titov, et al., 2011) have concluded that deep ocean bathymetry and forecast models are equally important as the seismic information in tsunami warning process. Subsequent to the major tsunami events in the history (1964 Alaskan Tsunami and 2004 IOT), the importance of establishing a web-based community computational model was identified. Such a model can be used to develop tsunami inundation maps for diverse earthquakes and real-time tsunami forecasts which are important in constructing tsunami resilient communities in the region. The team utilized the numerical model MOST (Method of Splitting Tsunamis) along with a precomputed propagation data base which include “unit sources” as fault planes with 100 km length, 50 km width, 1 m slip and 7.5 moment magnitude. For the inundation phase also, the model ComMIT uses MOST model with 3 telescoping grids with increasing resolution to model tsunami dynamics and inundation onto dry land. ComMIT requires data on bathymetry and coastal topography, initial and boundary conditions and specific model run information like spatial resolution, time step and length of model run. It works as a Graphical User Interface (GUI) to select input data and to display output parameters like animations and maximum amplitude plots for each nested grid and time series at a user specified location within the grids (Titov, et al., 2011).

CHAPTER 3 : METHODOLOGY

Based on the literature survey, numerical modelling of tsunamis by the model ComMIT was identified as the appropriate methodology for the assessment of exposure levels due to tsunamis. ComMIT has been used by previous researches, (De Silva, 2010) and (Samarasekara, 2014), who have verified the results for the IOT 2004 data for which empirical relations by (Wells & Coppersmith, 1994) have been used to derive the initial conditions of earthquakes.

The steps followed during the research are given in **Figure 3.1**.

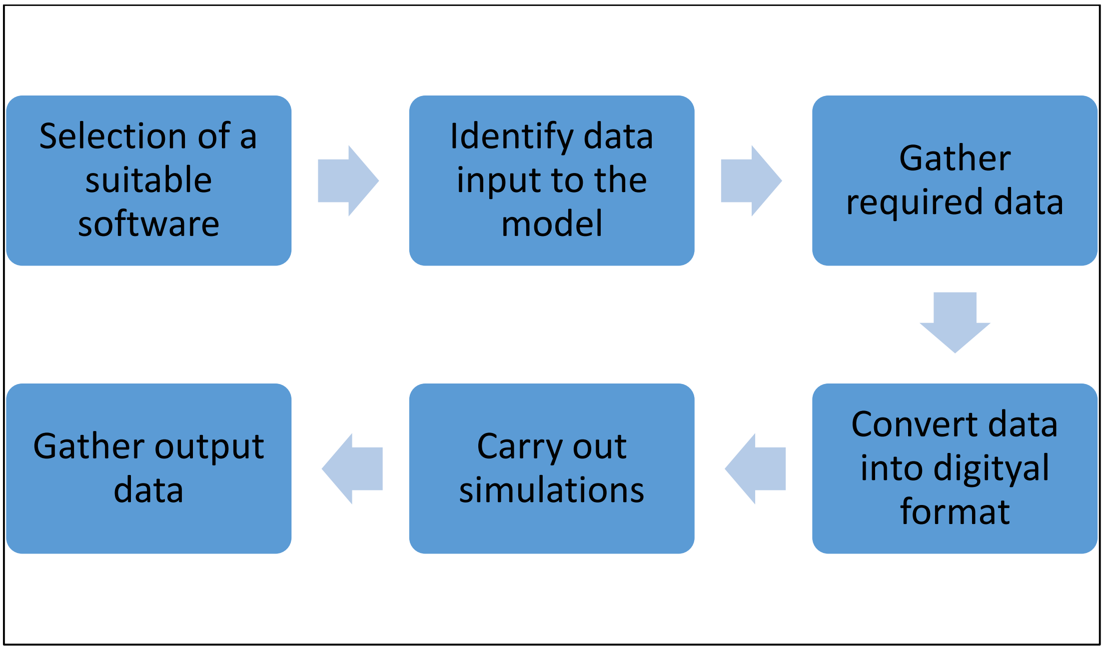


Figure 3.1: Methodology Flow Chart

3.1 Selection of the Numerical Model

Mathematical models can be used to simulate the tsunamis and assess the impacts in coastal areas. ComMIT, AVI-NAMI and WindITDB are among available mathematical models to simulate tsunami events, used in many studies. (Karunathilaka, 2010) has compared these models and selected ComMIT as the most suitable mathematical model. It was confirmed using the multi criteria analysis (Alonso & Lamata, 2006). It is also verified using 2004 IOT data (Samarasekara, 2014).

3.2 Identify the required data inputs to the model

The mathematical model MOST was developed to offer an accurate method to review tsunami performance and to produce long term forecasts. Also, it assists the efforts of Tsunami Warning Centers and other emergency managers in predicting the consequences that a possible tsunami generating seismic activity may have on coastal areas. The model requires earthquake parameters and sea bed characteristics to simulate tsunami events. ComMIT interface is used with the MOST model. Tsunami modelling using MOST, proceeds in 3 phases and an illustration of which is given in **Figure 3.2**.

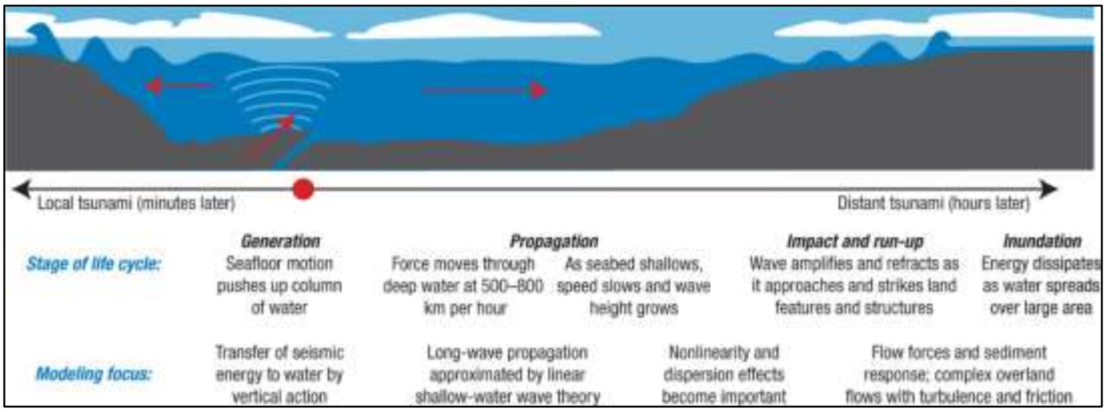


Figure 3.2: Phases of Modelling in MOST

3.2.1 Deformation Phase

The deformation phase produces the preliminary settings for a tsunami by replicating sea bed deviations due to a seismic activity. This computation utilizes input data on the rupture, along a submarine fault and the information is taken in as deformation rectangles and a DEM (Digital Elevation Model) data set.

3.2.2 Propagation Phase

In this phase, the created tsunami propagates across deep Ocean utilizing nonlinear shallow water wave (NSW) equations. The propagation phase models the open oceanic evolution of a tsunami.

3.2.3 Inundation Phase

This phase simulates the coastal tsunami performance together with onshore run-up. This utilize the data from propagation phase, the depth integrated NSW equations calculated on a set of nested DEM grids, and a run-up algorithm to forecast onshore inundating. A nested grid system, similar to that shown in **Figure 3.3**, with progressively higher resoulutions can be used in this phase to improve the accuracy of the outputs.

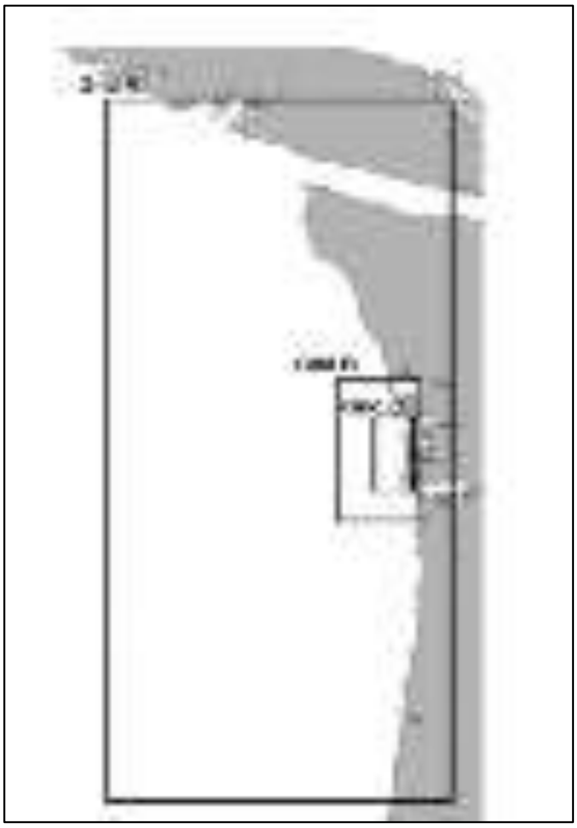


Figure 3.3: Inundation Phase Nested Grids

The output from this phase includes

- amplitude of the wave
- regional speed
- meridional speed for each of the nested NSW calculations

The output can be saved for selected time steps.

3.2.4 Input Parameters

The input parameters for the model are listed below.

- The magnitude and area of the ocean bed interruption, caused due to the earthquake.
- Networked bathymetric information for the deep-sea propagation
- A group of networked Digital Elevation Models (DEM) including bathymetry and topography for utilize in the inundation phase

The MOST model requires four Digital Elevation Models, as given below.

- One bathymetric data set for open ocean tsunami modeling
- A set of three overlapping DEM to compute tsunami onshore run up or inundation

The recommended spatial resolutions are given in **Table 3.1**.

A new model run can be created using the step by step procedure given in the ComMIT Manual, where grids ‘A’ and ‘B’ were selected from the available bathymetry in ComMIT server and grid ‘C’ was added using the manually digitized maps of higher spatial resolution.

Table 3.1: MOST DEM Grids Spatial Resolutions

MOST Modelling Stage	Recommended Resolution	Lowest Required Resolution
Deformation/ Propagation	1 arc minute (~ 1800 m)	4 arc minutes (~ 7300 m)
Inundation		
Grid A	36 arc seconds (~ 1080 m)	2 arc minutes (~ 3600 m)
Grid B	6 arc seconds (~ 180 m)	18 arc seconds (~ 500 m)
Grid C	≤1 arc second (≤ 30 m)	2 arc seconds (60 m)

It was necessary to have a proper naming procedure to identify each model run separately. As the length of the Sunda Trench is approximately 3200 km, to observe the impact of the location of the seismic event, it was decided to divide the Sunda Trench into five regions. The 40-unit sources given in the ComMIT, stretching from Myanmar to Southern Sumatra were considered as the Sunda Trench in this analysis and divided into five regions where each region consists of 8-unit sources in length. The regions selected are listed below and shown in **Figure 3.4**.

1. Region 01 (R1) : io1b - io8b
2. Region 02 (R2) : io9b – io16b
3. Region 03 (R3) : io17b – io24b
4. Region 04 (R4) : io25b – io32b
5. Region 05 (R5) : io33b – io40b

To identify between Sunda Trench and Makran Fault, the first part of the name of the model run name was set as either ST or MF. Then the location of the output data collection point was given. This was selected from Matara, Galle or Hambantota. Next it was the region of the Sunda Trench and last portion was dedicated to the earthquake magnitude. Hence 8.5 magnitude earthquake in Sunda Trench Region 01 where the output is to be taken at Hambantota was named as **ST_Hambantota_R1_8.5**

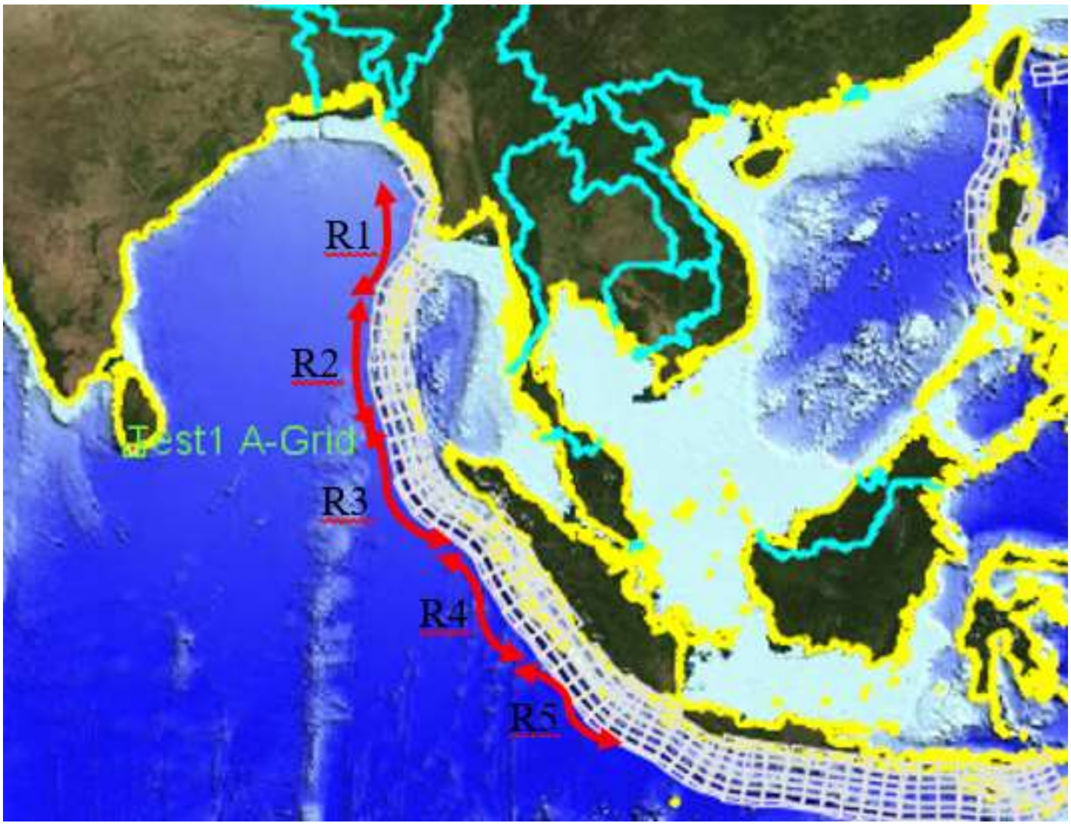


Figure 3.4: Selected Regions in Sunda Trench

3.3 Calculation of the Fault Parameters

Empirical formulas published by (Wells & Coppersmith, 1994) are commonly used to convert the moment magnitude to the fault parameters. For all slip types,

$$\text{Log (L)} = -3.22 + 0.69Mw \qquad (3.1)$$

$$\text{Log (W)} = -1.01 + 0.32Mw \qquad (3.2)$$

Where L is the fault length and W is the fault width in km and Mw is the moment magnitude of the earthquake.

$$Mo = \mu DLW \qquad (3.3)$$

Seismic moment Mo (in Nm) can be calculated by equation (2.3) where μ is the rigidity and D is the average slip (Kanamori, 1972).

For Sunda trench μ is taken as 4.5 x 10^{10} N/m^2

The equation (2.4) expresses the relationship between moment magnitude Mw and Seismic magnitude Mo (in Nm) (Kanamori, 1972).

$$Mw = \frac{2}{3} log_{10} Mo - 6.07 \qquad (3.4)$$

The empirical equations (3.1) to (3.4) were used to calculate the fault parameters. Earthquake magnitudes from 7.5 to 9.5 in 0.1 increment were used for the analysis.

A sample calculation performed for 7.6 earthquake magnitude is illustrated in **Figure 3.5**.

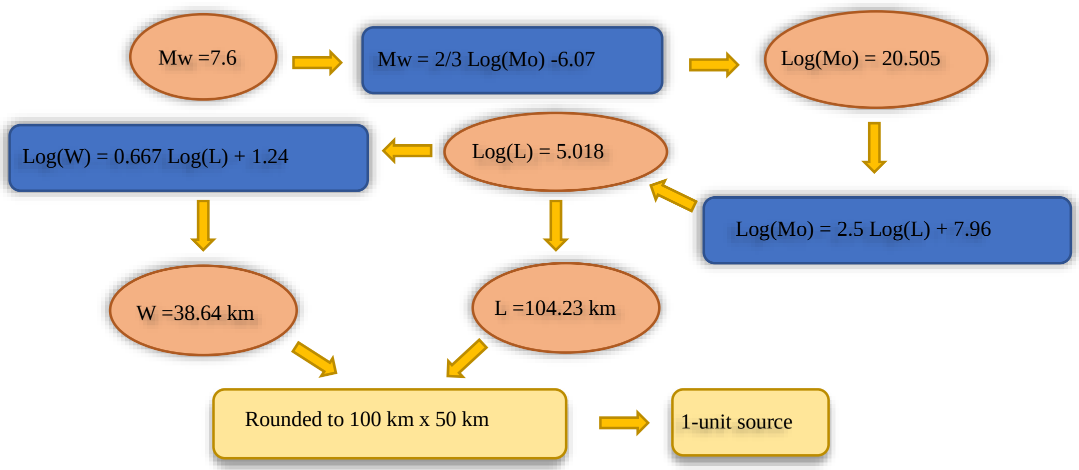


Figure 3.5: Calculation of Fault Parameters

For M_w = 7.6

From Equation (3.1): $\frac{2}{3}$ log(M_o) = M_w + 6.07 =7.6 + 6.07 = 13.67

log(M_o) = 13.67 * 1.5 = 20.505

From Equation (3.2): 2.5log(L) = log (M_o) -7.96 = 20.505 – 7.96 = 12.545

$\log(L) = 12.545/2.5 = 5.018$

$L = 10^{5.018} = 104{,}231.7$ m

From Equation (3.3): $\log(W) = 0.667*5.018 + 1.24 = 4.58701$

$W = 10^{4.5871} = 38{,}637.2$ m

$\mu = 4.5 \times 10^{10}$ N/m^2 for Sunda Trench is commonly considered and, hence, slip value for the calculated length and width is,

From Equation (3.4): $D = M_o / \mu LW = 3.198895*10^{20} / 4.5*10^{10}*104231.7*38637.2$

$D = 1.76515$ m

Each unit source in ComMIT software is of 100 km length and 50 km width and a slip value of 1.0 m and, therefore, when selecting unit sources for 7.6 magnitude, it is required to round off the actual lengths and widths to 100 km multiples and the width into 50 km multiples. Hence for 7.6 magnitude rounded length is 100 km and rounded width is 50 km. When selecting one-unit source, the moment magnitude in ComMIT is given as 7.5007. To convert it into the required magnitude, it is necessary to use a conversion factor. In the ComMIT software, the conversion factor is given as the 'Alpha coefficient' which can be calculated from equation (3.5).

$$F_s = 10^{\,1.5(M1-M2)} \qquad (3.5)$$

where F_s is the conversion factor (Alpha Value), M_1 is the actual moment magnitude and M_2 is the moment magnitude equivalent to the selected number of unit sources. Hence, for the 7.6 moment magnitude, the Alpha Value is

$F_s = 10^{\,1.5(7.6-7.5007)} = 1.4091$

Hence, by selecting one-unit source and giving the Alpha Value as 1.4091, the earthquake magnitude can be set to 7.6. Following the same procedure, the number of unit sources and Alpha Values for other earthquake magnitudes can be calculated. The calculated fault parameters are given in **Table 3.2** and **Table 3.3**.

Table 3.2: Calculated Fault Parameters

Mw	Mo	Calculated Length (m)	Calculated Width (m)	Rounded Length (km)	Rounded Width (km)	Calculated Slip (m)
7.5	2.265E+20	90782.053	35235.951	91	35	1.5732636
7.6	3.199E+20	104231.74	38637.231	104	39	1.7651495
7.7	4.519E+20	119674.05	42366.833	120	42	1.9804391
7.8	6.383E+20	137404.2	46456.448	137	46	2.2219869
7.9	9.016E+20	157761.13	50940.828	158	51	2.4929955
8.0	1.274E+21	181134.01	55858.08	181	56	2.7970581
8.1	1.799E+21	207969.67	61249.987	208	61	3.1382063
8.2	2.541E+21	238781.13	67162.368	239	67	3.5209632
8.3	3.589E+21	274157.42	73645.464	274	74	3.9504038
8.4	5.07E+21	314774.83	80754.364	315	81	4.4322218
8.5	7.161E+21	361409.86	88549.477	361	89	4.9728057
8.6	1.012E+22	414954.04	97097.042	415	97	5.5793228
8.7	1.429E+22	476430.99	106469.69	476	106	6.2598148
8.8	2.018E+22	547015.96	116747.07	547	117	7.0233043
8.9	2.851E+22	628058.36	128016.51	628	128	7.8799142
9.0	4.027E+22	721107.48	140373.78	721	140	8.8410019
9.1	5.689E+22	827942.16	153923.88	828	154	9.9193105
9.2	8.035E+22	950604.79	168781.95	951	169	11.129137
9.3	1.135E+23	1091440.3	185074.25	1091	185	12.486522
9.4	1.603E+23	1253141.2	202939.23	1253	203	14.009463
9.5	2.265E+23	1438798.6	222528.68	1439	223	15.718152

Table 3.3: Fault Parameters in ComMIT

Mw	Rounded Length (km)	Rounded Width (km)	Unit Sources	Magnitude from ComMIT	Alpha Value
7.5	100	50	1x1	7.5007	0.9976
7.6	100	50	1x1	7.5007	1.4091
7.7	100	50	1x1	7.5007	1.9904
7.8	200	50	2x1	7.7014	1.4057
7.9	200	50	2x1	7.7014	1.9856
8	200	50	2x1	7.7014	2.8048
8.1	200	100	2x2	7.9021	1.9808
8.2	200	100	2x2	7.9021	2.7980
8.3	300	100	3x2	8.0195	2.6348
8.4	300	100	3x2	8.0195	3.7218
8.5	400	100	4x2	8.1027	3.9441
8.6	400	100	4x2	8.1027	5.5712
8.7	500	100	5x2	8.1674	6.2936
8.8	600	100	6x2	8.2201	7.4105
8.9	600	150	6x3	8.3375	6.9783
9	700	150	7x3	8.3822	8.4470
9.1	800	150	8x3	8.4208	10.4424
9.2	1000	150	10x3	8.4854	11.8005
9.3	1000	200	10x4	8.5687	12.5012
9.4	1300	200	13x4	8.6447	13.5816
9.5	1500	200	15x4	8.6861	16.6284

The deformation phase calculation uses input information on the rupture along an undersea fault, expressed as a deformation rectangle, and a DEM data set. There are predefined unit sources (deformation rectangles), shown in **Figure 3.6**, to input the earthquake parameters. Each unit source has a fault length of 100 km, fault width of 50 km and a slip value of 1 m generating an equivalent moment magnitude, Mw of 7.5

For each of these unit sources latitude, longitude, strike angle, dip angle and depth have been defined.

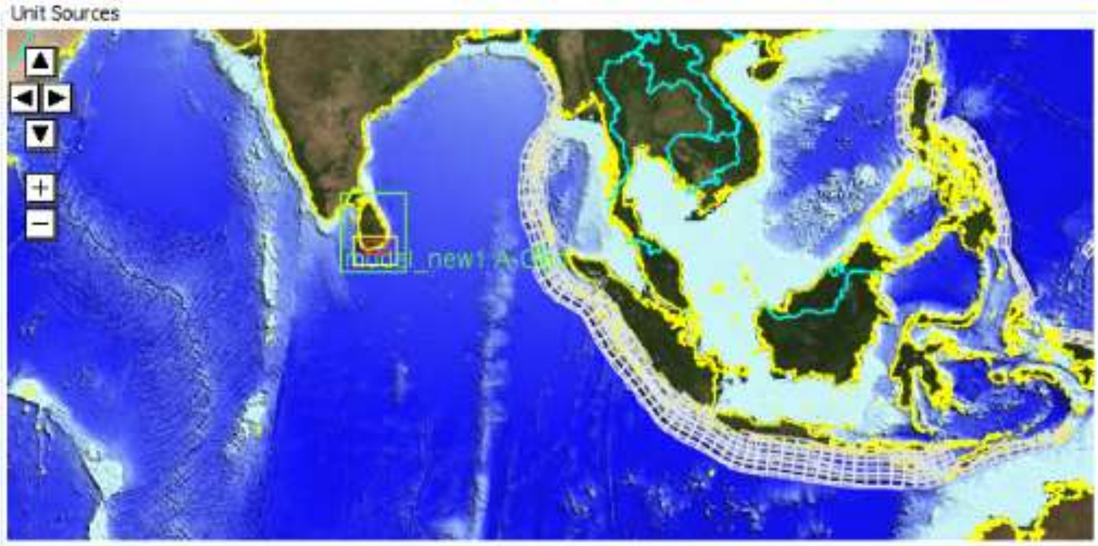


Figure 3.6: Deformation Rectangles (Unit Sources) in ComMIT

The unit sources are shown in rectangles with white colored borders in **Figure 3.6** and each of these sources are identified as per the coding system shown in **Figure 3.7**.

	c	b	a	z	y	x	w
1							
2							
3							
4							
5							

Figure 3.7: Unit Source Identification System

The cells are numbered according to the pattern shown in **Figure 3.7**. The maximum number of cells in the horizontal direction is 7 and is numbered from right to left as w,x,y,z,a,b,c . In the vertical direction, cells are numbered from 1,2,3,4 and onwards.

Also, each cell is identified by the ocean in which it is located. Sunda Trench is in the Indian Ocean and hence the marked cell in **Figure 3.6** can be identified as 'io2a'.

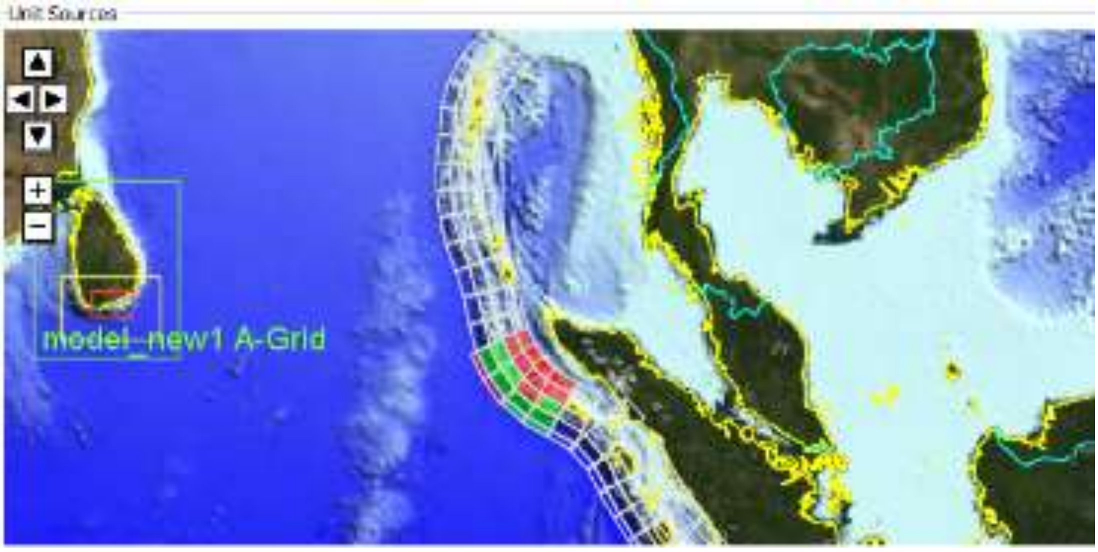


Figure 3.8: Data Input: Deformation (Earthquake) Parameters

In **Figure 3.8**, 20 cells are marked and the total moment magnitude (Mw) is 8.4. Similarly, the unit sources can be marked in the required location to obtain the required moment magnitude. Since there are 20 cells and the same Alpha Value is given for all the cells percentage magnitude of each cell is 5%.

For bathymetric data, Admiralty Charts developed by the United Kingdom Hydrographic Office for the coastal belt of Sri Lanka were used. It was required to digitize the charts so that those data can be fed into ComMIT. The software ArcGIS is used for this purpose. The charts used are shown in **Figure 3.9** and procedure adopted of digitizing the maps is illustrated in **Figure 3.10**.

Figure 3.9: Admiralty Charts used for the Study
Source: Hydrographic Office, Tauntan, Somerset TA1 2DN, United Kingdom

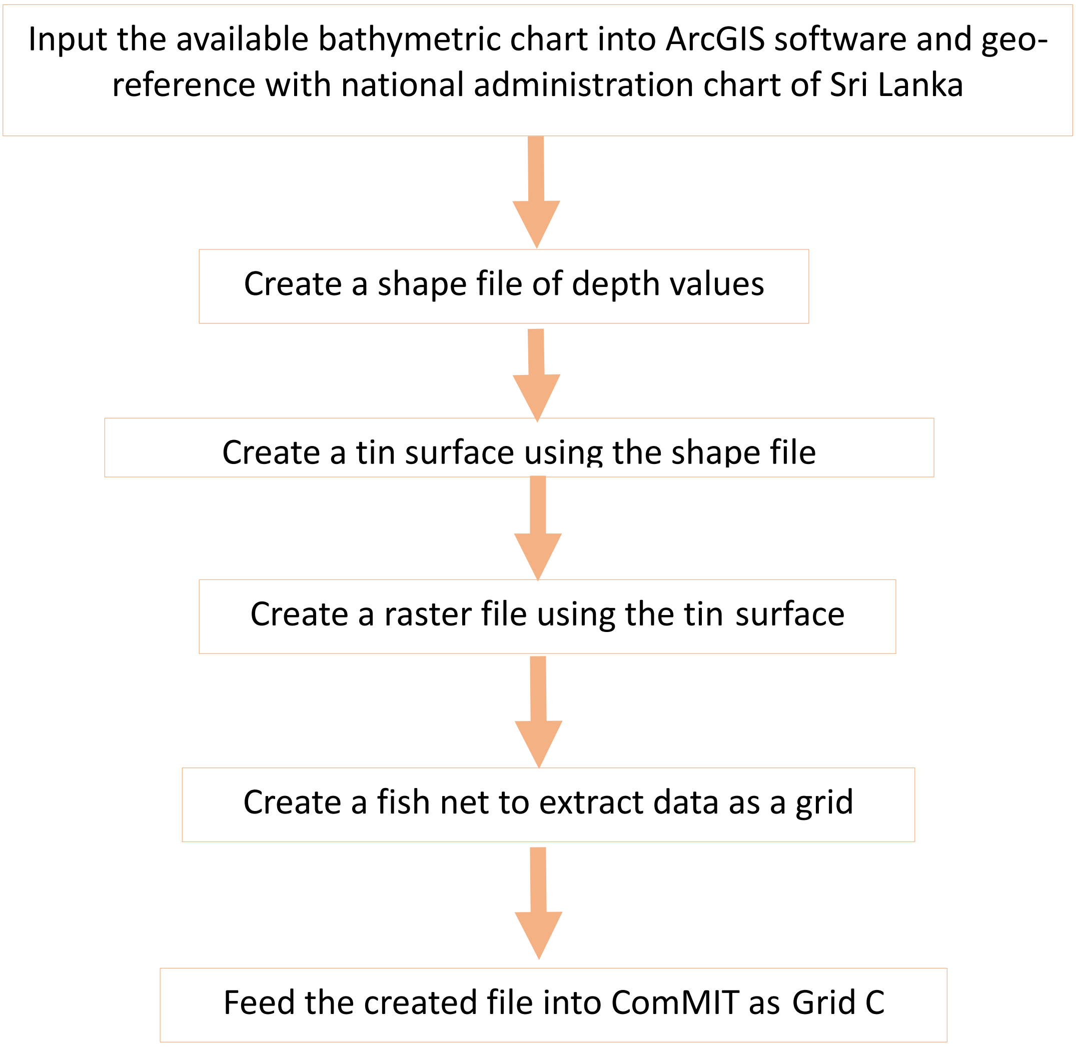
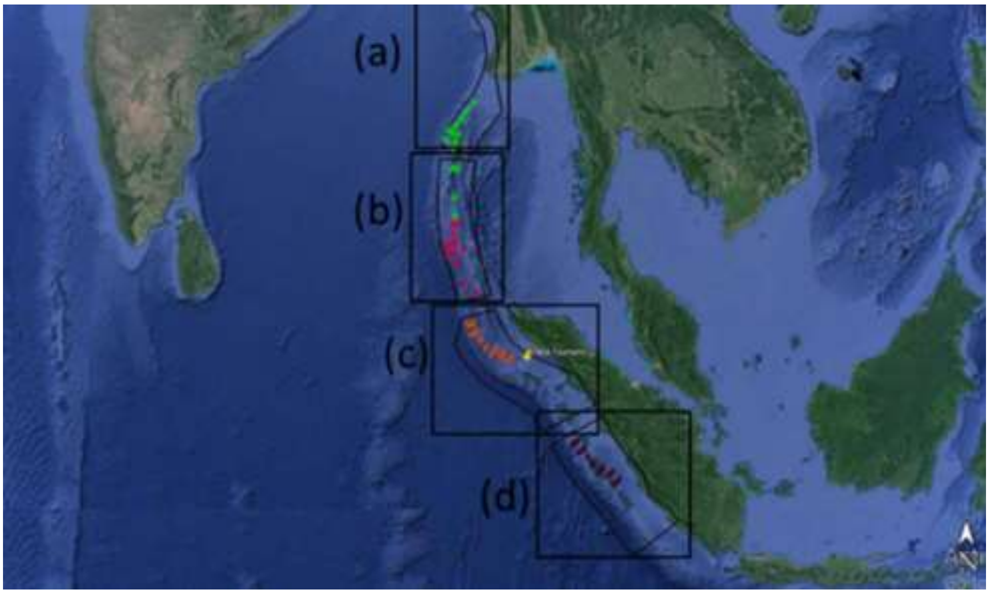


Figure 3.10: Methodology for Converting Bathymetric Data into Digital Format

CHAPTER 4 : RESULTS AND ANALYSIS

4.1 Earthquake Locations and Output Data Collection Points

Numerical simulations using the ComMIT provide the output parameters for each model run. Wave height at a given location and the wave arrival time can be obtained from the simulations. Also, each unit source is defined with a given co-ordinate and, therefore, the epicenter of the selected earthquake also can be determined using the data from the software. The four regions in the Sunda Trench considered in the analysis are given in **Figure 4.1**. For each area, the epicenter of each earthquake considered are shown in **Figure 4.2** to **Figure 4.5**.



((a) – Region 01, (b) – Region 02, (c) – Region 03, (d) – Region 04)

Figure 4.1: Selected Regions in the Sunda Trench

The selected output data collection points along the southern coastal belt in Galle, Matara and Hambantota are shown in **Figure 4.6**. The study area is the southern coastal belt of Sri Lanka and these three locations were selected to represent the most urban areas with high populations in the three districts in southern province. Southern coastal belt was severely damaged during the IOT in 2004 with 10,056 deaths and 14,899 destroyed houses reported.

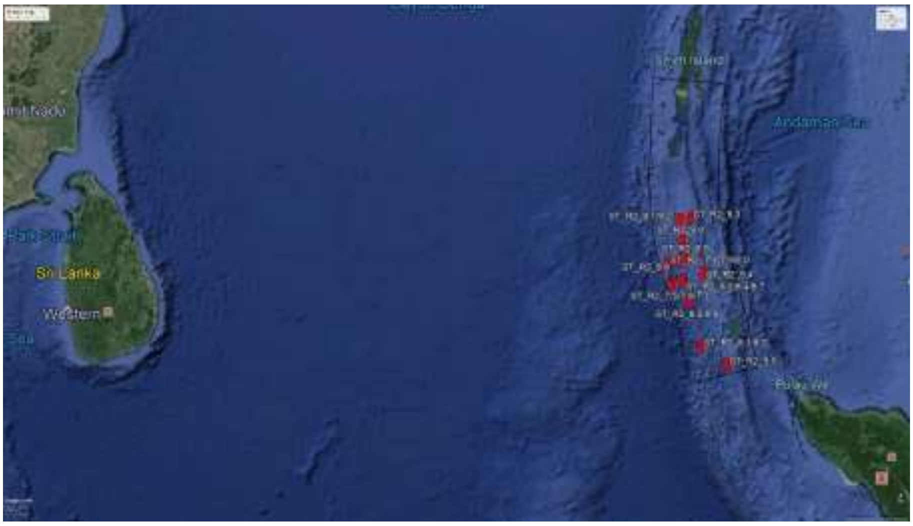


Figure 4.2: Epicenters of Selected Earthquakes: Region 1

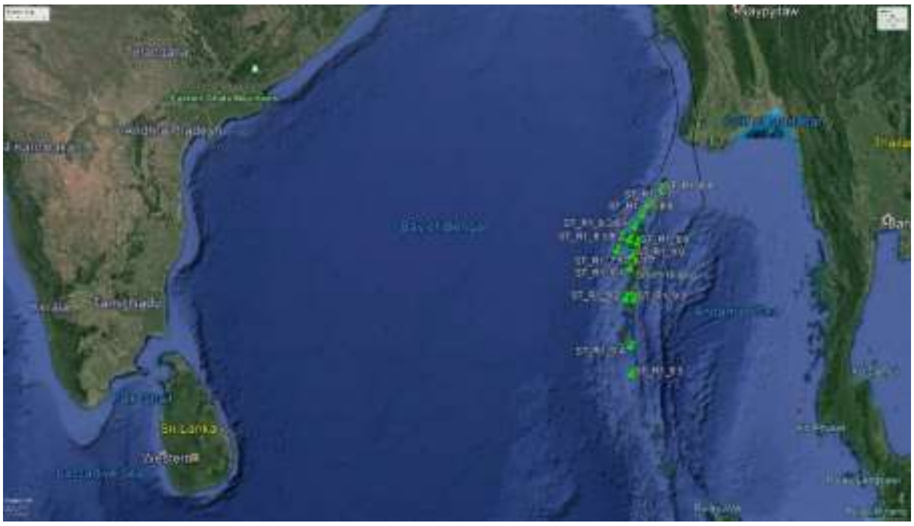


Figure 4.3: Epicenters of Selected Earthquakes: Region 2

Figure 4.4: Epicenters of Selected Earthquakes: Region 3

Figure 4.5: Epicenters of Selected Earthquakes: Region 4

Figure 4.6: Locations of Output Parameters

The co-ordinates of each output location are given in **Table 4.1**.. The selected locations The water depth selected at each location is 3 m.

Table 4.1: Co-ordinates of Locations of Output Parameters

Location	Latitude (^{0} N)	Longitude (^{0} E)	Depth (m)
Matara	5.93961	80.54804	3
Galle	6.02742	80.22960	3
Hambantota	6.11864	81.10208	3

4.2 Earthquake/Tsunami Generation

As stated in the methodology, the assessment of exposure levels due to earthquakes/tsunamis generated at the Sunda Trench is analyzed considering four different regions along trench. The detailed assessments are given below.

4.2.1 Region 01

The epicenters of each earthquake generated in the Region 01 are given in **Table 4.2**. As indicated in the table, a few earthquake magnitudes have the same epicenter. The epicenter depends on the number of unit sources selected in the software and the distribution of the selected unit sources. These epicenters were calculated similar to the calculation of center of gravity. The depth of epicenters also varies with the earthquake magnitude. The depth values vary from 5 km to 15.44 km. Earthquake magnitudes from 8.1 to 8.8 have the same depth of 8.48 km. Further, longitudes are in between 92.2400 ^{0}E and 93.4924 ^{0}E. Latitude values range between 9.4471 ^{0}N and 14.4293 ^{0}N.

The variation of tsunami wave heights in the selected output locations due to earthquakes generated at region 01 are given in Figure 4-3. The wave height variation in all three output locations Matara, Galle and Hambantota trail a similar pattern in region 01. The wave height remain below 50 cm up to the earthquake magnitude of

9.0 and demonstrate a rapid increase thereafter. The wave height remain same in both magnitudes 9.2 and 9.3 in all three locations regardless of the different epicenter depth values of 11.96 km and 15.44 km respectively. Up to 9.0 magnitude all three locations have the similar wave heights, but subsequently Galle and Matara fluctuate closely while Hambantota lags behind. For Galle, the maximum wave height at 9.5 magnitude is 400 cm and for Matara it is 350 cm. For the selected location at Hambantota, the maximum wave height at 9.5 magnitude is approximately 250 cm.

Table 4.2: Earthquake Epicenters in Region 01

Earthquake Magnitude	Longitude (^{0} E)	Latitude (^{0} N)	Depth (Km)
7.5, 7.6, 7.7	92.2400	12.7687	5.00
7.8, 7.9, 8.0	92.3905	13.1413	
8.1, 8.2	92.6023	13.0608	8.48
8.3, 8.4	92.7442	13.4113	
8.5, 8.6	92.9597	13.7228	
8.7	93.1752	14.0343	
8.8	93.4924	14.4293	
8.9	92.8142	12.9803	11.96
9	92.6808	12.6519	
9.1	92.6176	12.2967	
9.2	92.5151	11.4856	
9.3	92.7412	11.4676	15.44
9.4	92.6564	10.2037	
9.5	92.6931	9.4471	

The unit source distribution of Region 01 is not uniform in the Sunda Trench and therefore it was difficult to select the large number of required unit sources for higher magnitudes of more than 9.0. Hence the epicenters of magnitudes from 9.1 to 9.5 are located in Region 02 and the selected unit sources are from both Region 01 and Region 02.

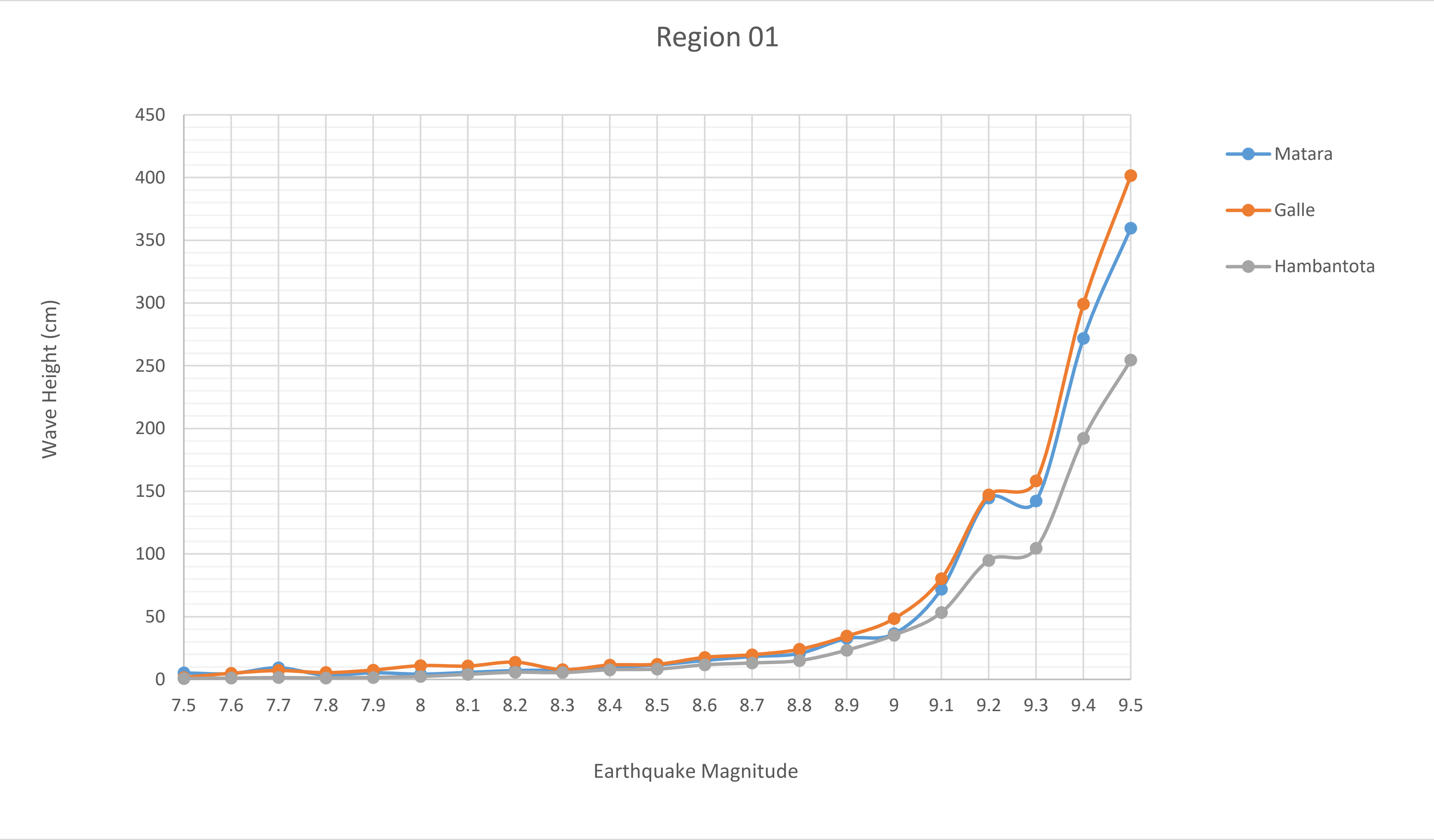


Figure 4.7: Wave Height Variation due to Earthquakes/Tsunamis generated in Region 01

4.2.2 Region 02

The epicenters of the earthquakes at Region 02 are given in **Table 4.3**. In Region 01, earthquake magnitudes of 9.3 to 9.5 were generated at a depth of 15.44 km but in Region 02 higher magnitude earthquakes were generated at a shallower depth compared to Region 01.

Table 4.3: Earthquake Epicenters in Region 02

Earthquake Magnitude	Longitude (^{0} E)	Latitude (^{0} N)	Depth (Km)
7.5, 7.6, 7.7	92.4049	7.7286	5.00
7.8, 7.9, 8.0	92.2851	8.1334	
8.1, 8.2	93.0288	6.4568	8.05
8.3, 8.4, 8.7	92.6169	7.8040	
8.5, 8.6	92.7636	7.3619	
8.8	92.5011	8.1964	
8.9	92.7170	8.2591	11.09
9	92.6051	8.6389	
9.1, 9.2	92.5371	9.0304	11.53
9.3	92.7589	9.0681	14.79
9.4	93.0406	7.9547	14.14
9.5	93.5861	6.0853	

Another important factor in Region 02 earthquakes is that 8.7 magnitude earthquake also generated at the same epicenter of 8.3 and 8.4 magnitude earthquakes. Epicenters of 8.7 and 8.8 earthquakes are not closely located. Further, when earthquake magnitude increases from 8.8 to 8.9, the epicenter depth changes from 8.05 km to 11.09 km.

The variation of tsunami wave heights in the selected output locations due to earthquakes generated at Region 02 are given in **Figure 4.8**. A comparable variation can be seen in between Matara and Galle whereas Hambantota lags behind. In all three locations the variation trend is similar. When considering the output location at Galle, the wave height rapidly increases up to 8.8 magnitude and a sudden drop from 8.8 to 8.9 can be seen. Nevertheless, after 8.9 magnitude, again the wave height progress and reach above 400 cm at 9.5 magnitude.

Even though the wave height variation trend at the Matara output location is similar to the trend of Galle output location, the sudden drop of wave height occurs when the wave height increase from 8.7 to 8.8 where as in Galle that sudden drop is from 8.8 to 8.9. The maximum wave height at Matara is 320 cm when the earthquake magnitude is 9.5.

The wave height variation at Hambantota output location follows a similar pattern to Galle and Matara with lower values. Similar to Galle, the drop of wave height is from 8.8 to 8.9. The maximum wave height at Hambantota reach 250 cm when the earthquake magnitude is 9.5.

The wave height at each output location does not depend only on the earthquake magnitude. It is affected by the epicenter of earthquake as well as the deep ocean propagation pattern of the tsunami wave. To check on the effect of earthquake generation location or the epicenter, each of these earthquakes can be selected using the unit sources so that the epicenter is same for all the magnitudes. Such an analysis can be used to confirm the effect of the epicenter of earthquake on the wave height at the output location.

4.2.3 Region 03

The epicenters of the earthquakes at Region 03 are given in **Table 4.4**. Earthquake epicenters of region 03 are divided among four depth values. From magnitude 7.5 to 8.0, the epicenter is at a depth of 5 km whereas the earthquake of magnitudes from 8.1 to 8.8 generate at a depth of 8.05 km. Earthquake magnitudes 8.9 to 9.2 generate at a depth of 11.09 km. The highest earthquake magnitudes from 9.3 to 9.5 originate at a depth of 14.14 km.

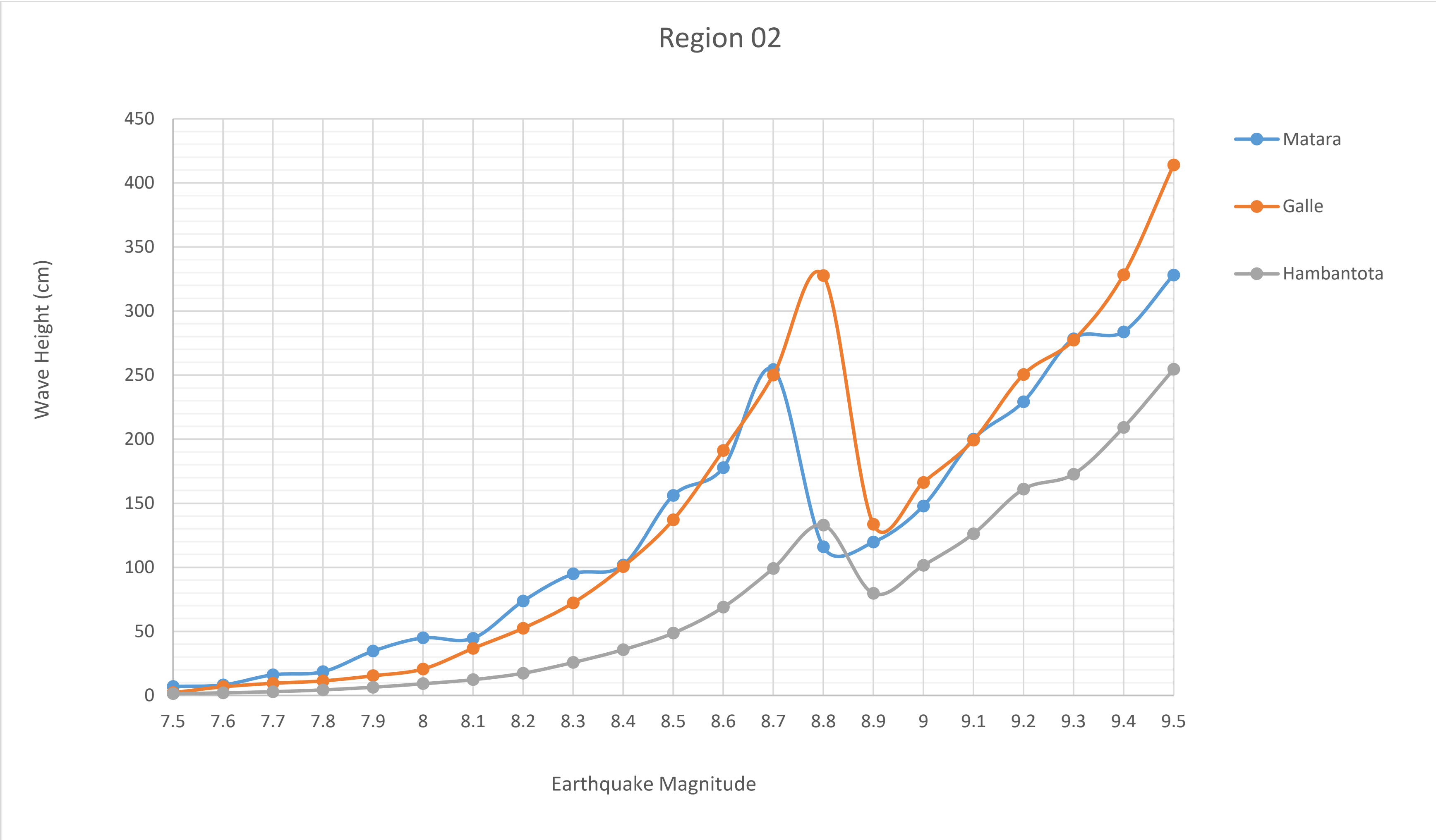


Figure 4.8: Wave Height Variation due to Earthquakes/Tsunamis generated in Region 02

Table 4.4: Earthquake Epicenters in Region 03

Earthquake Magnitude	Longitude (^{0} E)	Latitude (^{0} N)	Depth (Km)
7.5, 7.6, 7.7	93.4228	4.3359	5.00
7.8, 7.9, 8.0	93.2784	4.7173	
8.1, 8.2	93.4869	4.7958	8.05
8.3, 8.4	93.6239	4.4337	
8.5, 8.6	93.8255	4.1021	
8.7	94.0272	3.7705	
8.8	94.2813	3.4963	
8.9	94.4442	3.6469	11.09
9	94.6815	3.3907	
9.1, 9.2	94.9758	3.1813	
9.3	95.1046	3.3621	14.14
9.4, 9.5	94.8275	3.5594	

The variation of tsunami wave heights in the selected output locations due to earthquakes generated at Region 03 are given in **Figure 4.4**. The major dissimilarity of Region 3, compared to Regions 1 and 2 is that the wave heights at Matara output location point are relatively greater than that of Galle. In Regions 1 and 2, a slightly higher wave heights were detected in Galle, compared to Matara.

The maximum wave heights at each output location due to earthquakes at Region 3 are lower than those of Region 1 and 2. In Region 3, the maximum wave height at Galle and Matara is around 270 cm and 170 cm at Hambantota. The wave height at Hambantota gradually increase while in Galle and Matara few peaks and valleys can be identified.

The precise location of the earthquake epicenter is important since it affects the deep ocean wave propagation pattern. Even a slight difference at the epicenter can cause greater difference in wave height at the output location.

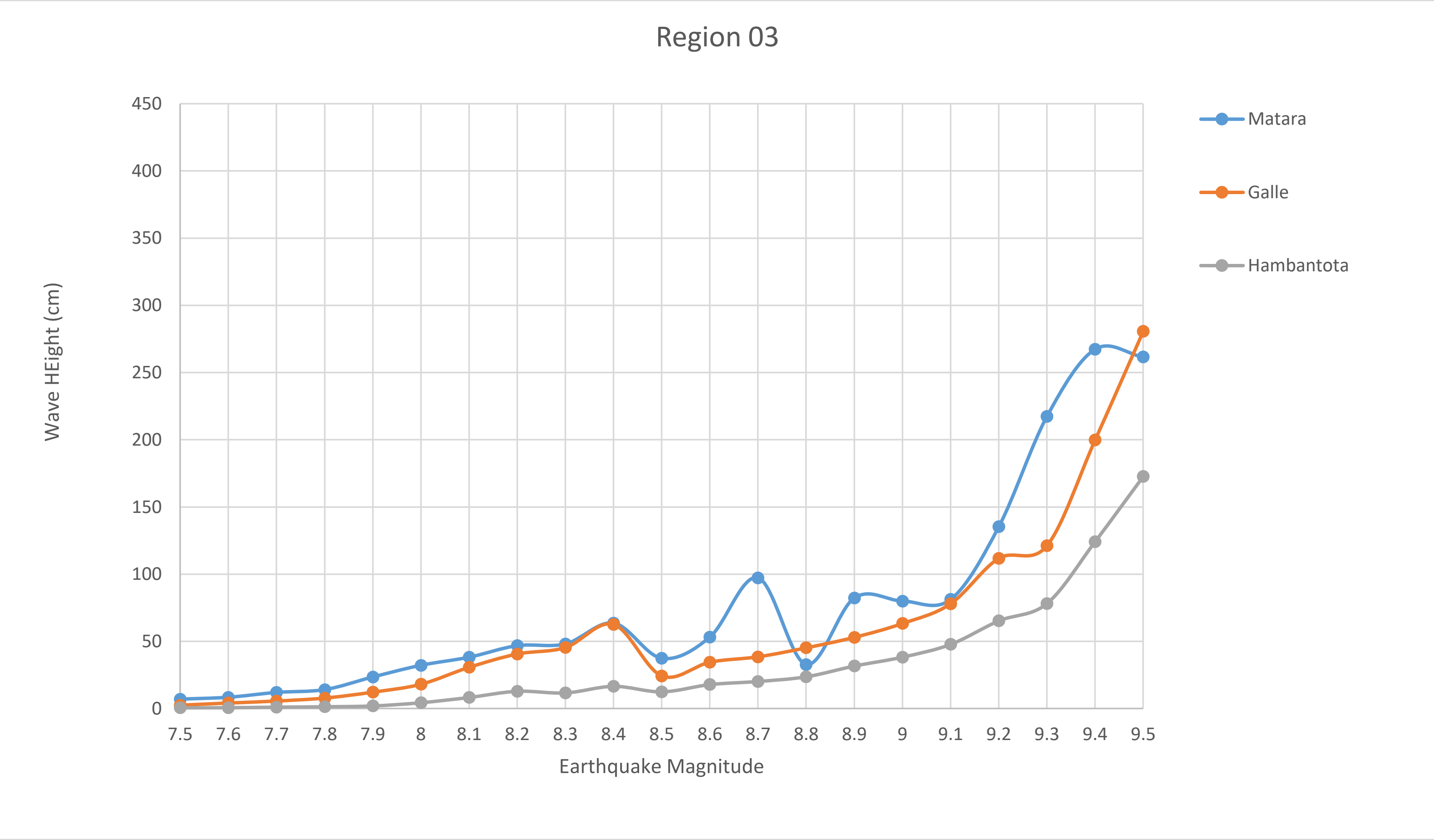


Figure 4.9: Wave Height Variation due to Earthquakes/Tsunamis generated in Region 03

4.2.4 Region 04

The epicenters of the earthquakes at Region 04 are given in **Table 4.5**. The depth variation of Region 4 is similar to that of Region 03. The epicenter depths vary from 5.0 km to 14.14 km in Region 4 similar to Region 3. All epicenters of Region 4 are located below the equator, hence the latitude values are indicated as negative values.

Table 4.5: Earthquake Epicenters in Region 04

Earthquake Magnitude	Longitude (^{0} E)	Latitude (^{0} N)	Depth (Km)
7.5, 7.6, 7.7	98.0538	-0.8764	5.00
7.8, 7.9, 8.0	97.8296	-0.4904	
8.1, 8.2	98.0228	-0.3786	8.05
8.3, 8.4	98.2457	-0.7630	
8.5, 8.6	98.4741	-1.1044	
8.7	98.7025	-1.4459	
8.8	98.9691	-1.7797	
8.9	99.1433	-1.6407	11.09
9	99.4058	-1.9694	
9.1, 9.2	99.7004	-2.3326	
9.3	99.8738	-2.1923	14.14
9.4, 9.5	99.5760	-1.8252	

The variation of tsunami wave heights in the selected output locations due to earthquakes generated at region 04 are given in **Figure 4.10**. The wave heights in all three output locations indicate a similar variation, but wave heights in Hambantota are slightly lower compared to Galle and Matara.

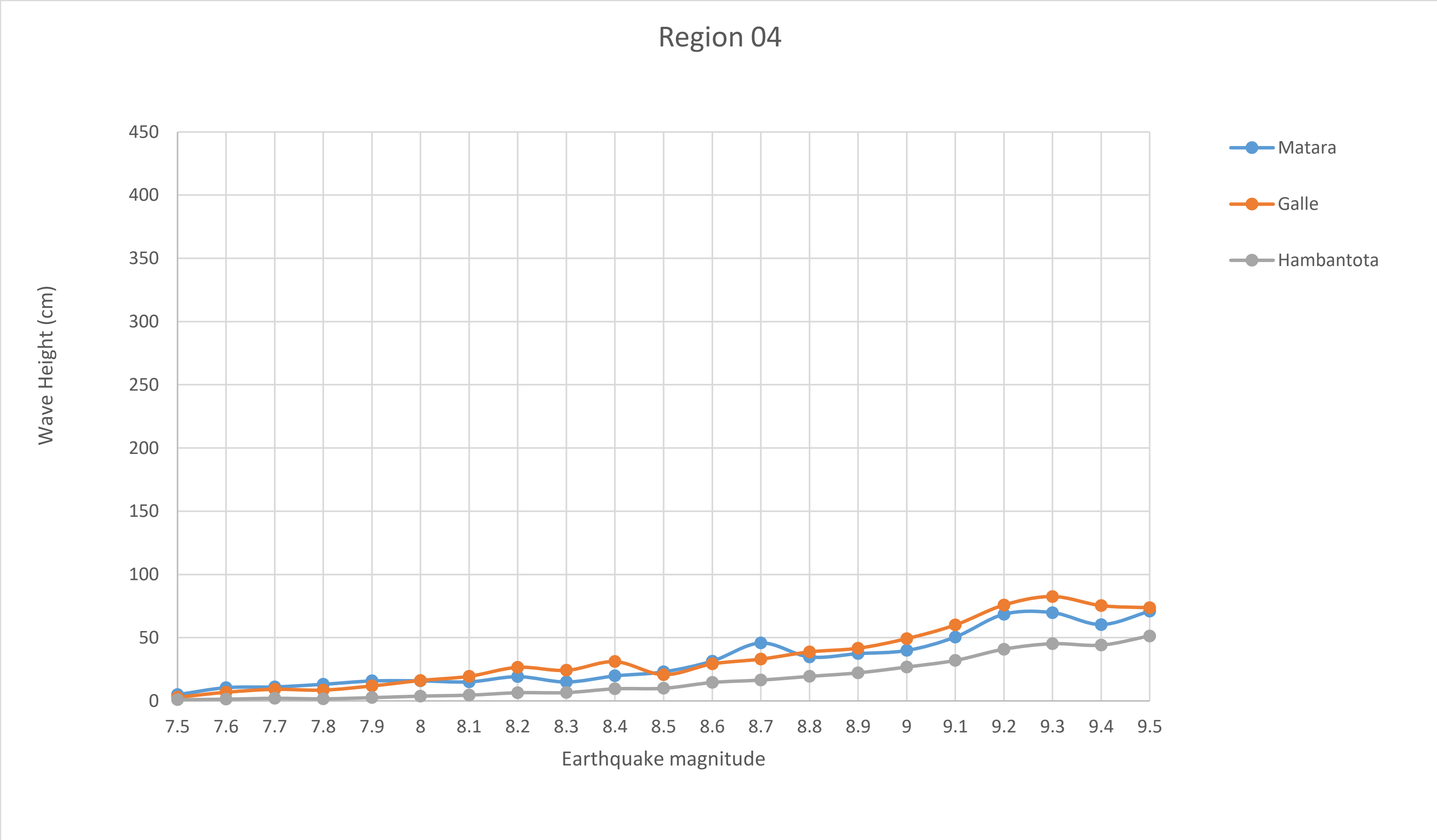


Figure 4.10: Wave Height Variation due to Earthquakes/Tsunamis generated in Region 04

The maximum wave heights for the highest earthquake magnitude of 9.5 in Matara and Galle are close to 70 cm while for Hambantota it is about 50 cm. (All four graphs for each region has the same scale for thevertical axis to indicate the differences in wave height variation.

Analysis of all four regions conclude that the maximum effects are from Region 2 while the lowest impact is from Region 4. Furthermore, Galle and Matara have greater damage compared to Hambantota when tsunami heights are compared in the coastal waters.

4.3 Output Data Collection Points

4.3.1 Matara

The wave height variation is given in **Figure 4.11** for Matara output location due to each region. The magnitudes of wave heights based on the earthquake magnitude in Matara are given in **Table 4.6**. The wave heights are categorized into a few sections for the convenience of analysis. Wave heights less than 100 cm are categorized into one segment and wave heights in between 100 – 150 cm are given in the next segment. The 150 – 200 cm variation is considered in a separate segment while the wave heights higher than 200 cm are compressed to the last segment.

Table 4.6: Wave Height Variation in Matara

<table>
<tr><th rowspan="2">Earthquake Magnitude</th><th colspan="4">Wave Height Variation (cm)</th></tr>
<tr><th>R1</th><th>R2</th><th>R3</th><th>R4</th></tr>
<tr><td>7.5-8.4</td><td rowspan="2">0-100</td><td>0-100</td><td rowspan="2">0-100</td><td rowspan="5">0-100</td></tr>
<tr><td>8.5-9.1</td><td>150-200</td></tr>
<tr><td>9.2</td><td rowspan="2">100-150</td><td rowspan="3">>200</td><td>100-150</td></tr>
<tr><td>9.3</td><td rowspan="2">>200</td></tr>
<tr><td>9.4-9.5</td><td>> 200</td></tr>
</table>

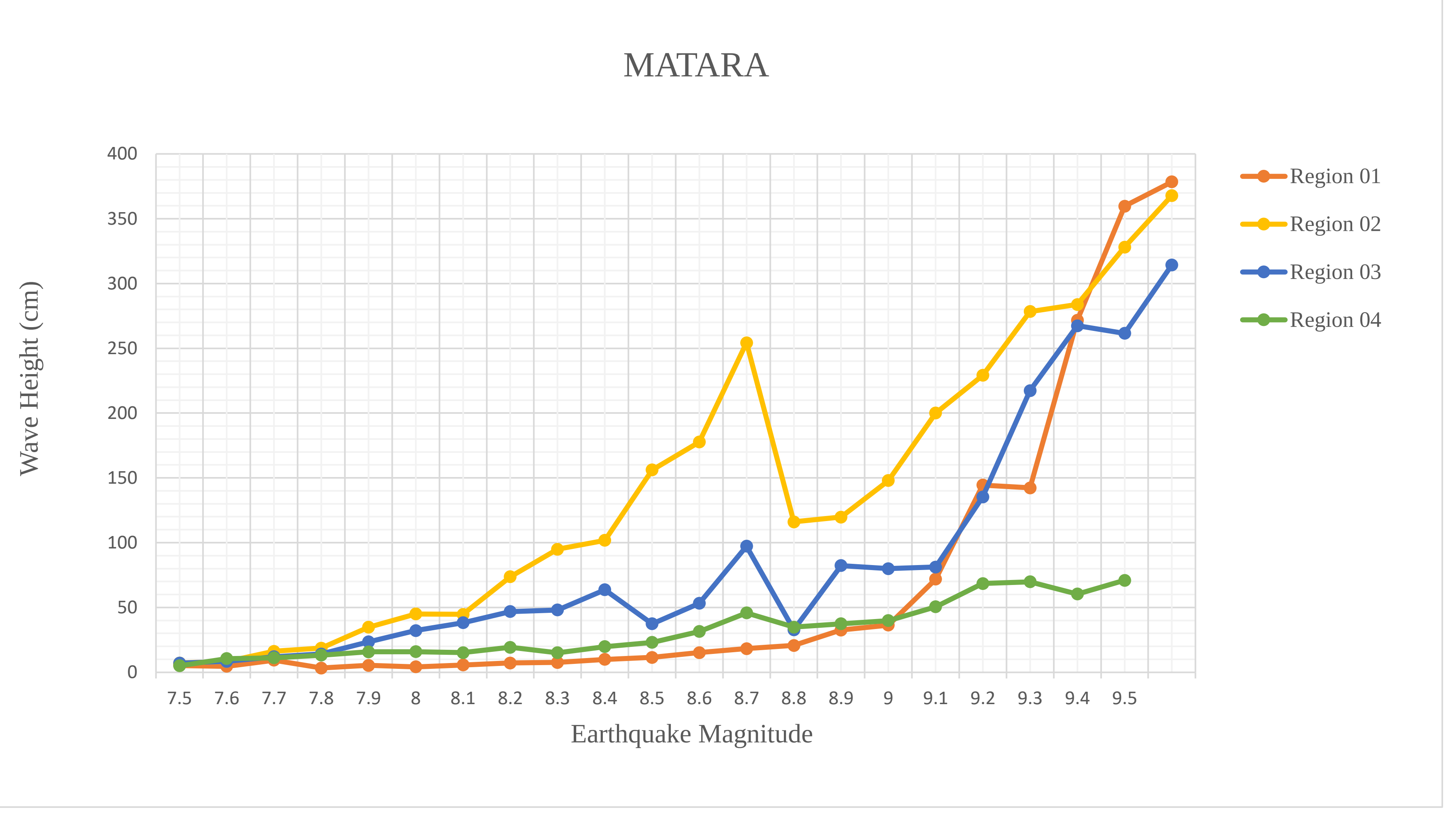


Figure 4.11: Wave Height Variation in Matara

As per the details given in **Table 4.6** , it is evident that the exposure level due to tsunamis from Region 4 is minimum compared to all other regions as even for the highest earthquake magnitude also, the wave height is less than 100 cm. The effect of Region 1 is comparatively higher than that of Region 4, but less than the effect from Region 3. However, the highest impact in Matara is due to Region 2.

As stated earlier, the wave height variation is given in **Figure 4.11** for Matara output location due to each region. Earthquake magnitudes have been selected from each region-Region 01 to Region 04. In each region, earthquake magnitudes from 7.5 to 9.5 in 0.1 increment were considered. As indicated in **Figure 4.11**, the effect from Region 02 is prominent in comparison with other regions. Though the wave height rapidly increases until 8.7 magnitude, a sudden drop of wave height occurs when the magnitude increases from 8.7 to 8.8. Beyond that point, again a similar increase can be observed. Region 03 earthquakes follow the same pattern with a few local variations. Such a pattern is not very prominent for Region 01 and Region 03.

The wave height variation for Galle and Hambantota are given in **Figure 4.12** and **Figure 4.13**. Similar trends in the variation of wave height are evident in these figures.

4.4 Exposure Levels due to Tsunamis generated at Makran Fault

Simulations similar to those for Sunda Trench were also carried out and the results indicated that the exposure levels assessed in terms of the tsunami wave heights in coastal waters at the same output locations are significantly less than those due to tsunamis generated at the Sunda Trench. Earthquake magnitudes up to 8.8 were considered in the simulations and the wave height reaching southern coast were found to be less than 0.2 m with arrival times in the order of 6 hours. Significantly lesser levels of exposure of the southern coast due to the tsunamis generated in the Makran Fault was thus evident from the studies and no further analysis was carried out.

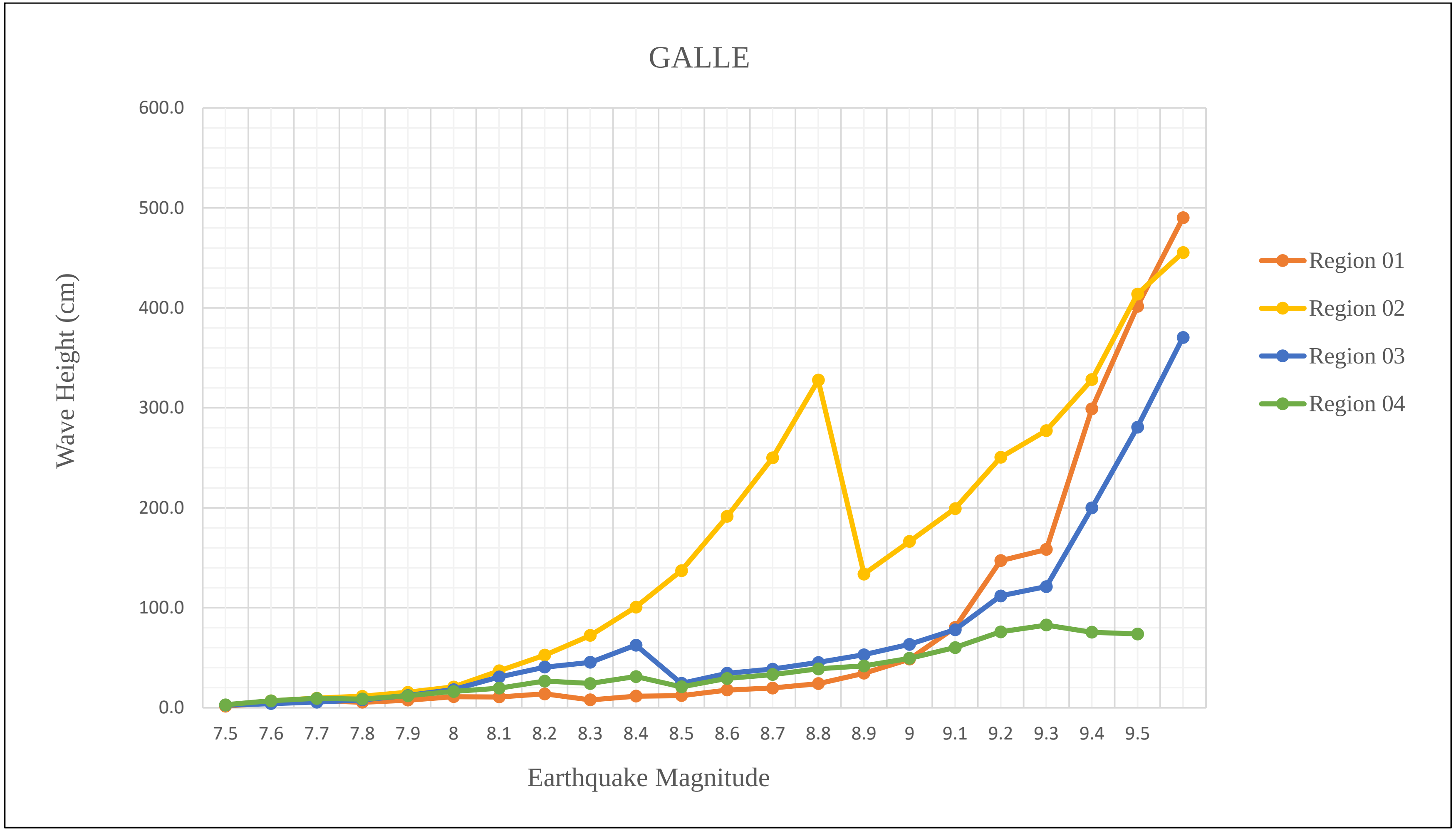


Figure 4.12: Wave Height Variation in Galle

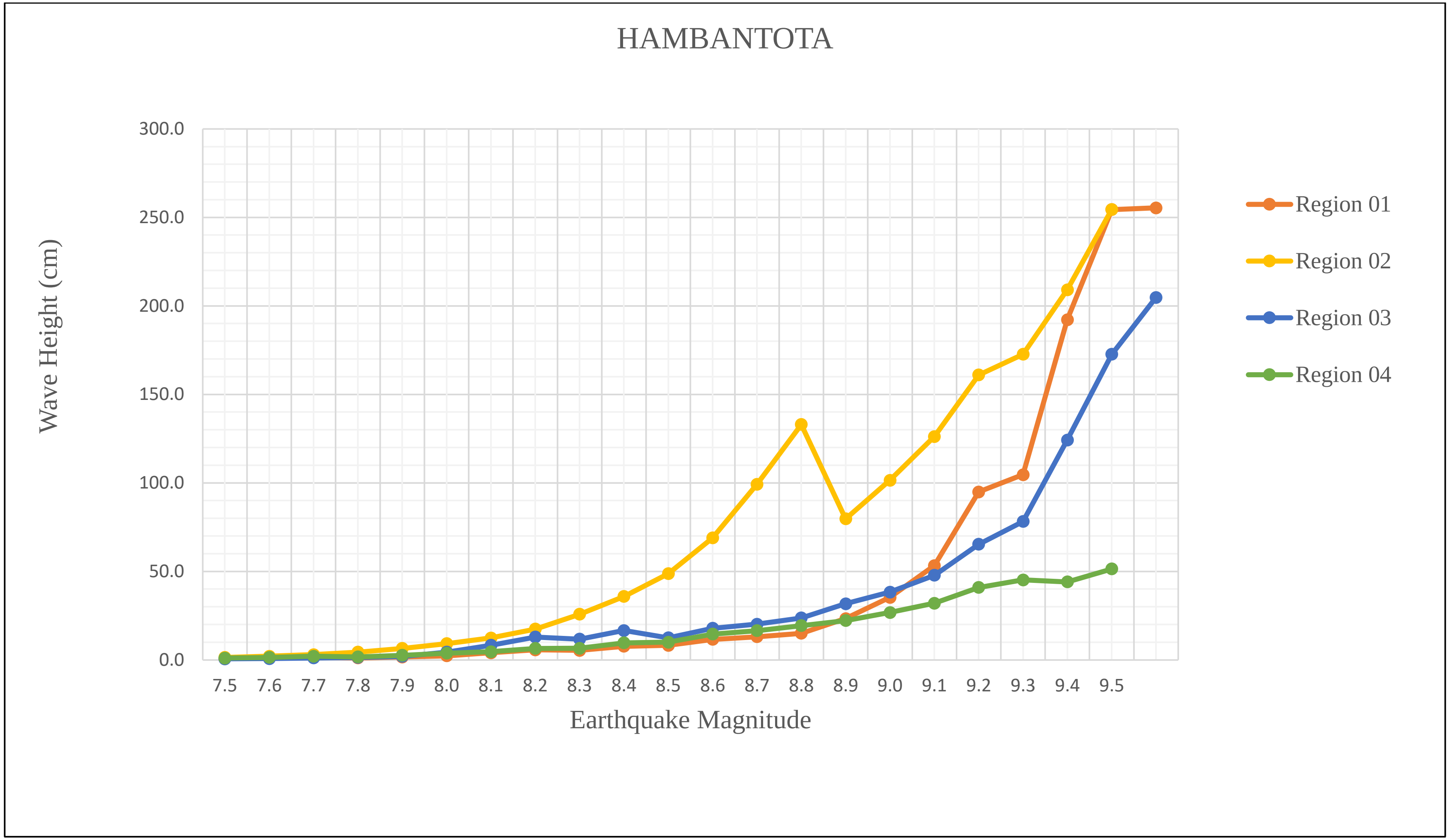


Figure 4.13: Wave Height Variation in Hambantota

CHAPTER 5 : DISCUSSION

5.1 Level of Exposure

Except for a part of the western coastline and the north western coastline, all other parts of the country were affected by the IOT in 2004 indicating the widespread exposure of the country to tsunami hazards. In this study, the attention was focused on assessing the level of exposure of the southern coastline of the country, which was significantly affected by the IOT in 2004.

Sunda Trench was divided into 4 regions, extending from north to south along the trench, for the purpose of this study. The upper (northern) part of the trench was considered as Region 1, and the middle section were divided in to two regions, Region 2 and Region 3. The lower part was considered as Region 4. Based on the results of the study, it can be concluded that the southern coast is at a high risk due to the earthquakes generated in Regions 2 and 3 of the Sunda Trench. A high level of exposure was evident due to earthquakes of magnitudes higher than 9.0 Richter Scale.

No significant level of exposure was evident due to tsunamis generated at the Makran Fault.

5.2 Inundation Extent and Depth

Due to the unavailability of topographic data in the coastal areas with the required resolutions, overland inundations were not simulated in the model studies carried out. The level of exposure was assessed in terms of the tsunami wave height in coastal waters along the coastline.

5.3 Maximum Tsunami Wave Height in Coastal Waters

Under computer simulations carried out in this research, earthquake magnitudes from 7.5 to 9.5 were considered in 0.1 increments. Also, Sunda Trench was divided into four regions and three output data collection points were used. The maximum tsunami wave height for all the simulations were obtained and a summary of results for Matara is given in **Table 5.1**.

Table 5.1: Summary of Wave Height Variation in Matara

<table>
<tr><th rowspan="2">Earthquake Magnitude</th><th colspan="4">Wave Height Variation (cm)</th></tr>
<tr><th>R1</th><th>R2</th><th>R3</th><th>R4</th></tr>
<tr><td>7.5-8.4</td><td rowspan="2">0-100</td><td>0-100</td><td rowspan="2">0-100</td><td rowspan="5">0-100</td></tr>
<tr><td>8.5-9.1</td><td>150-200</td></tr>
<tr><td>9.2</td><td rowspan="2">100-150</td><td rowspan="3">>200</td><td>100-150</td></tr>
<tr><td>9.3</td><td rowspan="2">>200</td></tr>
<tr><td>9.4-9.5</td><td>> 200</td></tr>
</table>

As given in **Table 5.1**, due to earthquakes generated at Region 1 and Region 3, up to 9.1 magnitude, the wave heights are less than 100 cm. But for the earthquakes at Region 2, the wave height exceeds 100 cm at 8.5 magnitude. However due to earthquakes from Region 4, the shallow water wave height does not reach 100 cm even for the highest magnitude of 9.5.

A similar analysis was carried out for Galle and a summary of results is given in **Table 5.2**.

Table 5.2: Summary of Wave Height Variation in Galle

<table>
<tr><th rowspan="2">Earthquake Magnitude</th><th colspan="4">Wave Height Variation (cm)</th></tr>
<tr><th>R1</th><th>R2</th><th>R3</th><th>R4</th></tr>
<tr><td>7.5-8.3</td><td rowspan="2">0-100</td><td>0-100</td><td rowspan="2">0-100</td><td rowspan="6">0-100</td></tr>
<tr><td>8.4-9.1</td><td>100-200</td></tr>
<tr><td>9.2</td><td rowspan="2">100-150</td><td rowspan="4">>200</td><td rowspan="2">100-150</td></tr>
<tr><td>9.3</td></tr>
<tr><td>9.4</td><td rowspan="2">>200</td><td rowspan="2">>200</td></tr>
<tr><td>9.5</td></tr>
</table>

As given in **Table 5.2**, due to earthquakes generated in Region 1 and Region 3, up to 9.1 magnitude, the wave heights are less than 100 cm. But for the earthquakes in Region 2, the wave height exceeds 100 cm at 8.4 magnitude. However due to earthquakes from Region 4, the shallow water wave height does not reach 100 cm even for the highest magnitude of 9.5.

A similar analysis was also carried out for Hambantota a summary of results is given in **Table 5.3**.

Table 5.3: Summary of Wave Height Variation in Hambantota

<table>
<tr><th rowspan="2">Earthquake Magnitude</th><th colspan="4">Wave Height Variation (cm)</th></tr>
<tr><th>R1</th><th>R2</th><th>R3</th><th>R4</th></tr>
<tr><td>7.5-8.9</td><td rowspan="2">0-100</td><td>0-100</td><td rowspan="3">0-100</td><td rowspan="5">0-50</td></tr>
<tr><td>9.0-9.2</td><td rowspan="2">100-200</td></tr>
<tr><td>9.3</td><td rowspan="2">100-200</td></tr>
<tr><td>9.4</td><td rowspan="2">>200</td><td rowspan="2">100-200</td></tr>
<tr><td>9.5</td><td>>200</td></tr>
</table>

As given in **Table 5.3**, due to earthquakes generated in Region 1, up to 9.2 magnitude, the wave heights are less than 100 cm. For Region 3, the wave height exceeds 100 cm at 9.4 magnitude. But for the earthquakes in Region 2, the wave height exceeds 100 cm at 9.0 magnitude. However due to earthquakes from Region 4, the shallow water wave heights are less than 50 cm even for the highest magnitude of 9.5.

5.4 Tsunami Arrival Times

Considering the analysis of tsunami arrival times from each region, the minimum and maximum time durations were obtained irrespective of the output data collection location, which are summarized in **Table 5.4**.

As indicated in **Table 5.4**, tsunami arrival times exceeding 2 hours are evident for tsunamis generated at the Sunda Trench, which can be effectively utilized for early warning of the hazard.

Table 5.4: Tsunami Arrival Time from each Region in the Sunda Trench

	R1	**R2**	**R3**	**R4**
Minimum Arrival Time (hr:min)	02:05	02:06	02:05	02:31
Maximum Arrival Time (hr:min)	03:06	02:41	02:44	03:36

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

Even though there is evidence of tsunamis occurred in the history of Sri Lanka, in the recent past, the Indian Ocean Tsunami in 2004 is the very first experience of a tsunami to Sri Lankans. This tragic natural disaster and subsequent tsunami alerts issued in the country, as well as the historical records, tsunamis are now considered as a natural hazard in the country. Considering the various causes of tsunami generation, it is evident that Sri Lanka is potentially exposed to the tsunamis generated at the Sunda Trench and Makran Fault.

Based on the results of the study carried out, it can be concluded that Sri Lanka is exposed to far-field tsunamis as opposed to near-field tsunamis and the arrival times exceed 2 hours. The area and the locations considered in the study-Galle, Matara and Hambantota-along the southern coastline are exposed to the tsunamis generated at the Sunda Trench and the level of exposure depends on the location of the tsunami generation earthquake and its magnitude.

The results of the study reveal that the southern coastline of Sri Lanka is mainly exposed to tsunamis generated in the Region 2 of the Sunda Trench considered in the study. Though lesser than that for Region 1, the exposure to the tsunamis generated in Regions 2 and 3 of the Sunda Trench was evident from the results. The southern coastline is least exposed to the tsunamis generated in Region 4 of the Sunda Trench.

No significant exposure to the tsunamis generated in the Makran Fault was evident from the study. The tsunami wave The arrival times of tsunamis generated at the Makran Fault weree also much higher and in the order of 6 hours.

An early warning system would be very effective in mitigating adverse impacts due to tsunamis and such a system can be based on a large database developed from the results of tsunami simulations similar to the ones carried out in the study. Further improvements of the results of such simulations can be made by considering higher resolution bathymetric information obtained by surveys, together with relevant overland topographic data to assess the inundation characteristics of tsunamis in coastal areas.

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