ASSESSMENT OF THE CO-BENEFITS OF STRUCTURES IN COASTAL AREAS FOR TSUNAMI MITIGATION AND IMPROVING COMMUNITY RESILIENCE IN SRI LANKA

A Thesis

by

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in Partial Fulfillment

of the Requirements for the Degree

Master of Sustainability Science

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Graduate Program in Sustainability Sciences – Global Leadership Initiative

Graduate School of Frontier Sciences

THE UNIVERSITY OF TOKYO

September, 2016

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ABSTRACT

Tsunami risk along vulnerable coasts is rapidly increasing due to unplanned and rapid coastal development in many countries. Even though a variety of different tsunami countermeasures can be attempted, typically due to budgetary limitations early warning systems are the most common type attempted against far-field tsunamis. However, due to issues related to the poor maintenance of early warning systems, it has been argued that ultimately hard defensive structures can often be far more effective than early warning systems. Some of coastal structures have a variety of other benefits to a given community, aside from coastal development, which are often overlooked in research. . However, to date few researchers have applied multi-functionality of coastal hard infrastructure to reduce the tsunami risk of developing countries, and little research has been done on defining the exact tsunami mitigation benefits and measuring the economic feasibility of such countermeasures.

The engineering resilience of defensive structures needs to be upgraded if they are to withstand a tsunami, though upgraded structures can offer a multitude of co-benefits to a community, and all of these costs and benefits must be financially quantified. Two types of coastal infrastructure along the Southern coast of Sri Lanka were selected as case studies. The authors used a combination of methodologies used in diverse filed of expertise, such as civil engineering, social science and finance. The proposed upgrades to the structures were developed after an extensive literature review. Drawings of coastal structures, information about construction costs, and socio-economic data were collected through field survey and expert interviews with representatives of government agencies, construction companies, and academia. Community willingness to pay (WTP) and the current level tsunami preparedness in the case study area were measured by conducting structured questionnaires with local residents. Using these results the willingness to pay was modeled using logits regression

models. The benefits and drawbacks of an upgraded revetment and a coastal railway embankment were estimated considering housing sector, tourism, fisheries, etc. Both grade crossings and underpasses were considered as crossings of railway embankment. The extent of the inundated area for a variety of tsunamis cases was numerically estimated using ComMIT model (which was developed by pacific Marine Laboratory, National Ocean Atmospheric Association) for different scenarios with and without upgraded structures. Damage to housing was estimated using fragility functions proposed to Sri Lanka. Finally, the drawbacks of upgrading were identified through focus group discussions and field surveys of the area.

Both the upgrades of the coastal revetment and the coastal railway embankment were effective to protect against tsunamis generated by average and higher magnitude earthquakes along the selected fault-line. Revetment had a higher failure probability than that of railway embankment due to tsunami overflow to its proximity to coast. Hence, the tsunami mitigation potential of revetment was lower than that of railway embankment. However structural upgrading was reduced tsunami mitigation co-benefit of revetment and railway embankment. The revetment cannot resist under large tsunamis, but railway embankment can resist under large tsunamis. The expected reduction of damage of revetment is lower than that of railway embankment in lower earthquake magnitudes and vice versa. The tsunami mitigation co-benefit of railway embankment is higher than that of revetment. The results of the questionnaire survey show that the community’s willingness to pay to upgrade the railway embankment was higher than that of revetment due to its negative influence on different sectors, such as tourism, fisheries and the environment. Railway embankment with underpasses gives slightly larger benefits compared to that of railway embankment with grade crossings. Therefore railway embankment with underpasses is recommended to this village.

The railway embankment with underpass is the most suitable tsunami co-beneficial structure to the Dimbuldooa and Wenamulla villages

The results clearly show that the co-benefits of tsunami protection coastal infrastructure are highly sensitive to a number of factors, and slight modifications of the proposed structures can significantly alter the economic benefits or cost of the project. Therefore, conducting a quantitative evaluation is essential when proposing coastal infrastructure upgrade for tsunami disaster mitigation, and the methodology proposed can help disaster risk managers to understand the best solution from a disaster risk prevention and economic development point of view.

Key words: Co-benefit, Tsunami, Coastal Structures, Sri Lanka, WTP, Expected Reduction in damage

(Word Count: 688)

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor, Professor Jun Sasaki, for his guidance and support throughout this project. My gratitude goes to my co-supervisor, Project Associate Professor Miguel Esteban for helping me in the preparation of questionnaire and thesis writing. I would like to thank Project Associate Professor Hirotaka Matsuda for providing knowledge of regression analysis. I would specially like to extend my gratitude to MEXT, GPSS_GLI and Jun Sasaki laboratory to provide financial aid do studies in both Sri Lanka and Japan.

I have relied on the help of many colleagues and counterparts specially Dr. (Mrs.) Retno Utami and Mr. Masaya Watanabe. Thank you for taking time to share your knowledge with me. Big thanks go out to all GPSS students and faculty to providing critical discussions which were very useful in formulating the research. I would also like to thank members of Jun Sasaki laboratory to encourage and motivate me to continue studies.

My gratitude also goes out to the interviewees involved in this project. Professor Samantha Hettiarachchi, Prof. Priyan Dias, Mrs. Chathuri Madusanka, Mr. Chanaka Vinodh and Mr. Pradeep Kodippili, thank you for taking the time to provide me valuable insights into disaster management practice in Sri Lanka. I would also like to thank my friends who help me to organize focus group discussions and who helped me as numerators of the questionnaire.

I am very grateful to have a very supportive Father, Mother, Sister and Brother-in-Law to collect hosing data and arrange meetings with experts. And finally to all my friends in Kashiwa campus to make a pleasant working environment, thank you. Besides the groups and individuals mentioned, I recognize that there are still many others who have helped my research in varies ways. I would like to thank all of them too.

DEDICATION

I dedicate this thesis to my beloved parents

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LIST OF TERMINOLOGY: ABBREVIATIONS

CECB – Central Engineering Consultancy Bureau

CGIAR - Consultative Group for International Agricultural Research

ComMIT – Community Model Interface for Tsunami

CSI - Consortium for Spatial Information

DMC – Disaster Management Center

EWS – Early Warning System

GEBCO – General Bathymetric Chart of the Oceans

ICG – Intergovernmental Co-ordination Group

IOC – Intergovernmental Oceanographic Commission

IOT – Indian Ocean Tsunami

IOTWS – Indian Ocean Tsunami Early Warning System

JMA – Japanese Meteorological Organization

LHI-SL – Lanka Hydraulic Institute – Sri Lanka

LR – Likelihood Ratio

MLIT – Ministry of Land Infrastructure Tourism

MOST – Method of Splitting Tsunami

MSL – Mean Sea Level

NOAA – National Oceanic Atmospheric Administration

PMEL – Pacific Marine Laboratory

SLR – Sri Lankan Rupee

UNESCO – United Nations Educational Scientific and Cultural Organization

WTP – Willingness to Pay

1 INTRODUCTION

1.1 Background

Tsunami risks around the world are increasing due to population growth and coastal developments in vulnerable communities. To attempt to mitigate such risks, spatial planning, early warning and hard defensive structures (Esteban, et al., 2013) have been introduced to improve the resilience of vulnerable coastal communities. Even though a variety of different tsunami countermeasures can be attempted, typically due to budgetary limitations early warning systems are the most common type attempted against far-field tsunamis[1]. IOTWS (Indian Ocean Tsunami Warning System) is a one such example of an early warning system.

The Japanese coastal engineering community widely uses the concept of Level 1 and Level 2 tsunamis (Sato, 2015). Typically, hard measures are not designed to protect properties against Level 2 tsunamis, with the prevention of human losses in such cases relying on soft measures. Therefore, residents are always encouraged to undertake training to understand how to evacuate in the case of extreme events. However, the author interviewed several key informants regarding the IOTWS and identified that community participation in tsunami drills is very low in countries bordering the Indian Ocean. Therefore a quick and smooth evacuation cannot be expected in an emergency. Even for the case of Japan Shibayama et al., (2013) highlighted the necessity to put in place hard measures to provide sufficient time to evacuate, based on the experience of 2011Tohoku Earthquake Tsunami. A methodology to find the optimum level of hard defensive measures based on the increase in evacuation time was proposed by Utami et al., (2014), centered around a case study in Kamakura City, Japan. According to such research it is clear that it is important to find an optimum combination of tsunami mitigation measures.

[1] Private discussion with the Vice - Chair IOTWS (Indian Ocean Tsunami Early Warning System) (Dr. Sam Hettiarchchi), Mount Lavinia Sri Lanka in September, 2015

One of a major disadvantage of early warning systems is their inability to protect the properties of coastal communities. Other than that, Ryan, (2015) described the technological limitations of IOTWS to provide accurate and reliable tsunami forecast after an earthquake in the Indian Ocean. Several false tsunami warning were reported in in the countries bordering the Indian Ocean after major earthquakes in March 2005 March, September 2007, September 2009 and April 2012. Burglaries were reported in many places after the community evacuated from their houses. Accidents were also reported due to the sudden mass evacuation from the coastal regions. Thus, and given also other issues related to reliability and poor maintenance of early warning systems and lack of participation in tsunami drills, the present work will argue that ultimately hard defensive structures can often be far more effective than early warning systems.

Burbidge, et al., (2009) carried out a probabilistic tsunami hazard assessment for Indian Ocean countries, finding that probable maximum tsunami amplitudes at the 100m bathymetry line are significantly different from place to place. Areas where very important economic activities are concentrates, yet where the tsunami amplitudes are unlikely to be very high should be protected by hard defensive measures. However, such measures are still to be developed in many developing coasts due to financial constraints.

Burbidge et al., (2008) published the return periods of different magnitude earthquakes in the Indian Ocean. However, one of a major challenge that prevented him to recommend investing on hard defensive structures was the high return periods of these events. Therefore, the present theses focus on developing a methodology to assess the viability of hard defensive structures from both the disaster risk prevention and the economic development point of view. In other words, it is important that the construction of hard structures helps to reduce the risk of tsunamis, at the same time as promoting the economic development of coastal areas. To be able to simultaneously evaluate both economic and resilience functions of coastal structures, the present research adopts the co-benefit approach.

The co-benefit approach was initially introduced to address climate change mitigation while achieving economic development goals. A widely cited papers in this approach is that of Smith and Haigler (2008), who studied how the mitigation of greenhouse gasses could also be preventing other health problems. They defined health protection as a co-benefit of the mitigation of greenhouse gasses. Nowadays, guidelines also freely available to quantitatively evaluate the co-benefits of climate change projects (Japan Kankyōshō, 2009).

The basic philosophy of the co-benefit approach also resembles the muti-functionality in resilience thinking, first introduced by Holling, (1973). A more multifunctional system is able to absorb more disturbances and thus sustain itself more easily. Fratini et al., (2012) introduced a tool to reduce urban flood risk and promote multi-functionality to address the needs of different stakeholders. However, the application of the concept of multi-functionality to disaster management field is quite new. Khew et al., (2015) argued that the co-benefits of many of the hard coastal infrastructure and housing contribute to increase community resilience in general. One example was that the local fishermen used the ground floor of piloti type buildings as a shelter to sell their agricultural products.

To date little research has applied the co-benefit approach to understand the reduction in tsunami risk in developing countries that can come about as a result of the construction of other types of coastal infrastructure. Essentially, little research has been done on defining the exact tsunami mitigation benefits and measuring the economic feasibility of various types of coastal infrastructure. It is important also to remember that there is currently a debate of whether hard types of tsunami countermeasures destroy the aesthetic appeal of the coast, and evaluating the tsunami mitigation capacity of coastal structures is thus appealing as a way to solve the dilemma of protection vs. natural beauty.

If a coastal structure is designed for a purpose other than to mitigate tsunami, but the structure can also help to mitigate the effects of such hazards, this secondary function can be defined as the tsunami mitigation co-benefit of that coastal structure. This tsunami mitigation co-benefit will be denoted as a monetary value in this study.

1.2 General and Specific Objectives

The objective of this study is to assess the tsunami mitigation co-benefit potential of various types of coastal structures. A coast where vulnerability is high, but the hazard is low (for example a urban or semi-urban area where the potential tsunami heights are low) was thus selected as a case study to analyze the potential benefits of such structures.

The tsunami co-benefit of a given structure can be defined as the reduction in damage in the event of a tsunami due to the presence of the coastal structures. For example, a coastal revetment prevents beach erosion from extreme wave conditions, though it is also able to reduce damage if a tsunami takes place. Therefore, the main component of this research was the calculation of the reduction in damage due to the presence of certain structures under different tsunami scenarios.

However, coastal structures are typically not designed to resist extreme tsunami waves, and thus structural upgrades to them were proposed, and this cost was taken into account when considering the overall economic benefits of the system.

The level of acceptance of the coastal communities and their perception of the upgrades was measured using structured questionnaire surveys, focus group discussion and key informant interviews.

2 MATERIALS AND METHODS

A simplified methodology to determine the tsunami protection co-benefit of various types of coastal structures was proposed, as well as the effectiveness of these upgrading tsunami co-beneficial structures, as shown in Figure 1.

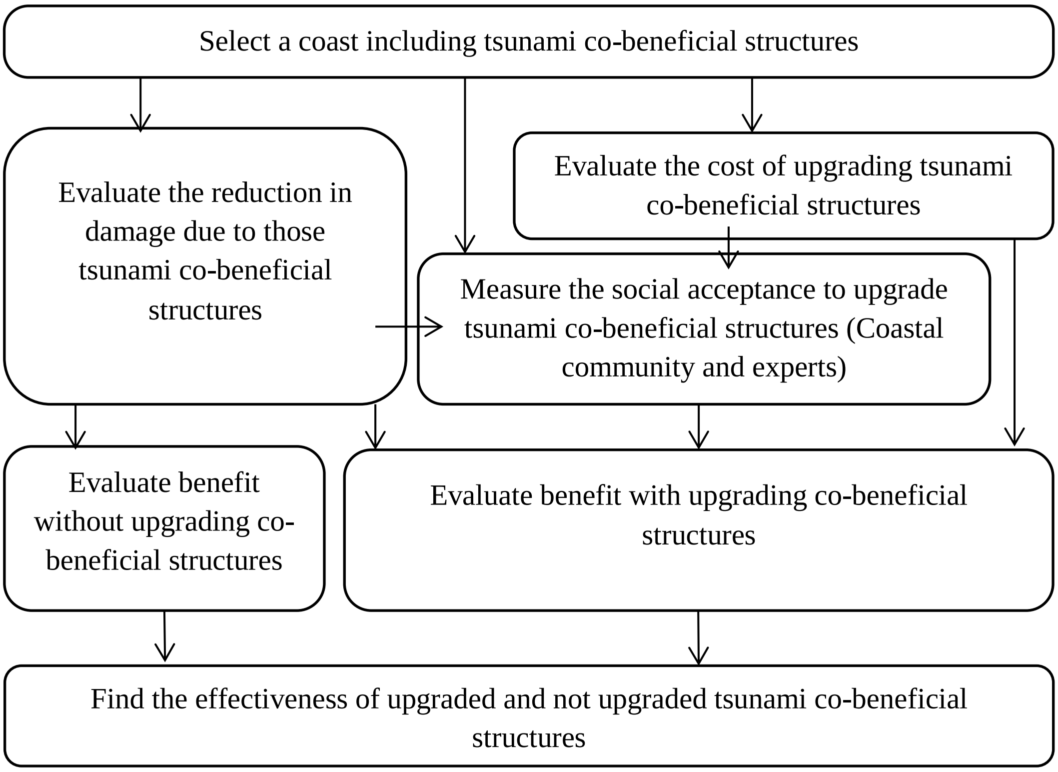


Figure 1: Research framework

2.1 Introduction to Case Study

The Indian Ocean Tsunami (IOT) in December 2004 caused devastating damage to the Eastern and Southern coasts of Sri Lanka and resulted in more than 35,000 deaths, even though the tsunami waves took 2-3 hours to arrive from the source (Titov, Rabinovich, Mofjeld, Thomson, & González, 2005). As a consequence, countries bordering the Indian

Ocean established an Early Warning System (EWS) with the financial and technical support of USA, Japanese Meteorological Agency (JMA), and UNECO's (United Nations Educational Scientific and Cultural Organization) Intergovernmental Oceanographic Commission (IOC) to reduce human losses in future tsunami events. The Indian Ocean Tsunami Warning System (IOTWS) become fully operational in 2013 April, aiming to warn against the threat of earthquakes greater than or equal 7.0 Mw in the Indian Ocean.

Sri Lanka relies currently only on Early Warning Systems (EWS) for tsunami protection, and essentially the Government has made a policy decision not to invest on hard defensive tsunami structures. The main reason for this resides on a lack of budget for the creation of such countermeasures, though EWS alone cannot protect properties against tsunami hazards[2].

Tsunami warnings following earthquake events were issued in 2005, 2007, 2009 and 2012, though none of these caused any significant waves in the vicinity of Sri Lanka. Warning towers are considered as the main medium for issuing of tsunami warnings, as opposed to the use of radio, television, telephones or megaphones. Towers constructed by the DMC issued tsunami warnings during a false alarm in 2012, though coastal residents complained that some of the warning towers did not work and as a result many of them did not hear the siren. The DMC in turn complained that the participation of coastal residents in the annual tsunami drill is low, and thus fears that human losses might be high in any future tsunami event.

The Eastern coast of Sri Lanka is exposed to the direct attack of tsunami waves from the main tsunami generation zone in the region (Figure 2). However, the Southern coast is

[2] Private discussion with the Deputy Director (Early Warning) (Mr. Pradeep Kodippili), Disaster Management Center (DMC), Sri Lanka in September, 2015

only exposed to diffracted waves (Burbidge, et al., 2009), and the height of such waves would be lower than those along the eastern coast.

The population density of the Eastern coast is low compared to the Southern and Western coasts. Hence, in the case of the Eastern coast, vulnerability is low but the hazard is high. Therefore, EWS can be an effective way to mitigate tsunami disasters in this case. However, in the case of Southern coast vulnerability is high, but the hazard is low, and thus this area could be effectively protected by small hard defensive structures.

Dimbulddoa and Wenamulla villages around Hikkaduwa city (Figure 3) in the South Western coast of Sri Lanka were selected as the case study area (Figure 4). A coastal revetment and a railway embankment are located along this stretch of the coast, as shown in Figure 4. These two coastal structures were not designed to protect against a tsunami, though their presence can help to mitigate the effect of a tsunami. Their existence represents an ideal case to check the technical and economic feasibility of structures with co-beneficial potential for tsunami disaster mitigation.

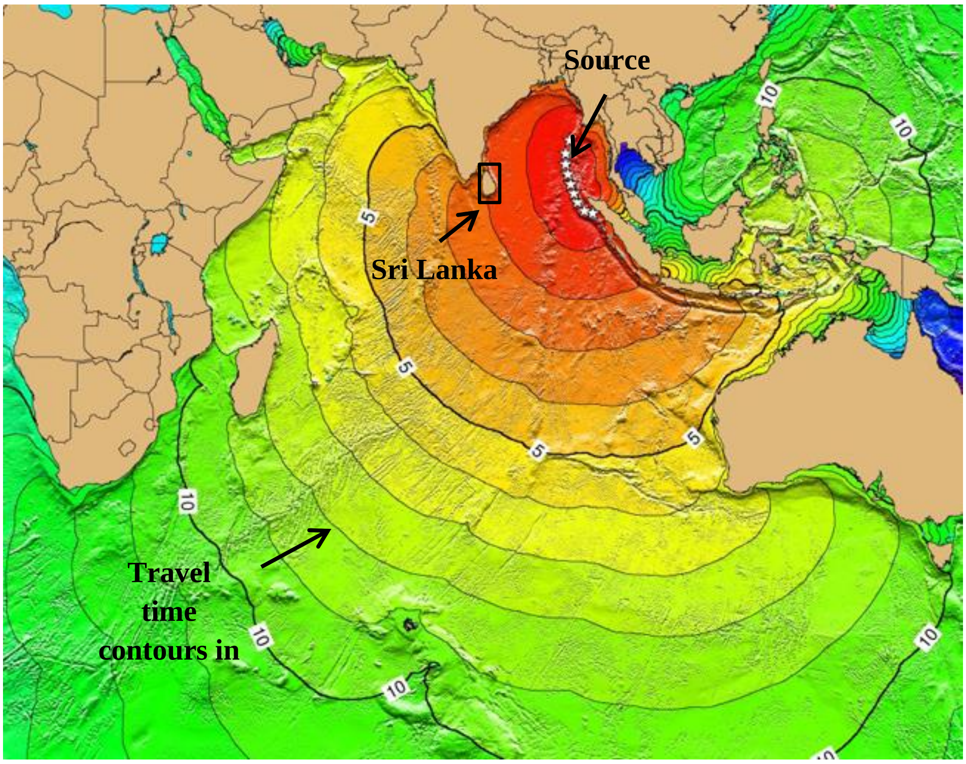


Figure 2: 2004 Indian Ocean Tsunami Travel Time Map
(Source:https://www.ngdc.noaa.gov/hazard/data/icons/2004_1226.jpg)

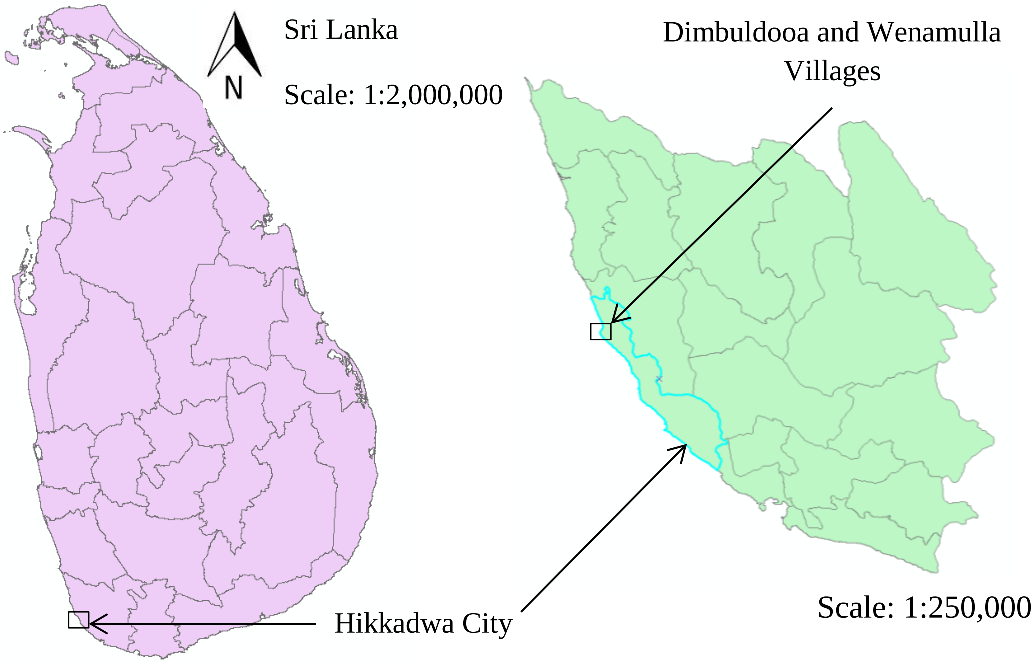


Figure 3: Location of Hikkaduwa city

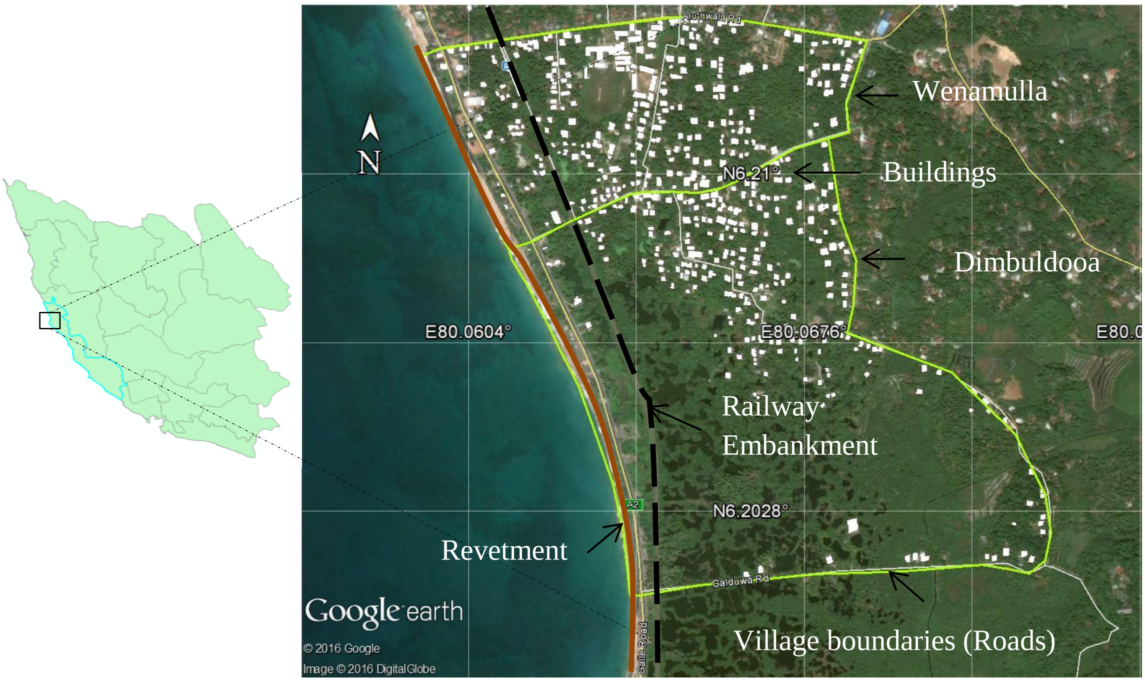


Figure 4: Location of Dimbuldooa and Wenamulla villages

Google image is between E 80.0568 - E 80.0748 and N 6.1992 - N6.2136

Hikkaduwa city is a famous tourist destination in Sri Lanka, well known for its coral reefs and sandy beaches. A number of villages surround the city, and the villages considered in the present case study (see Figure 2) are to the north of the city. Their total population is 2,324, with 613 families living in 494 houses and 51 public buildings located in the villages (Hikkaduwa City Office, 2015). According to the classification of Sri Lanka the area is considered to be semi-urban.

The area has experienced severe beach erosion due to the degradation of the coral reefs and expansion of the fishery harbor[3] in Hikkadauwa. As a consequence a revetment had already been constructed prior to the 2004 Indian Ocean Tsunami to stop coastal erosion. Following damage from this event, the Department of Coast Conservation reconstructed and reinforced the revetment, raising the crown height to +4.0m (from the Mean Sea Level, MSL) from the +3.5m before December 2004, as shown by the drawings collected by the author from the Department of Coast Conservation during the fieldwork conducted in September 2015. The total length of the revetment in the case study area is

[3] Private discussion with the Engineer (Mr. Chanaka Vinodh), Coast Conservation Department, Galle, Sri Lanka in September, 2015

1380m. The entire crest of the 900m southern portion of the revetment was washed away during the backward flow during the 2004 event (LHI-SL, NIRAS-Denmark, Sellhorn-Germany, 2005)

The top of the railway track was at a height of +4.5m from MSL prior to the 2004 IOT, as shown by the drawings collected from the Central Engineering Consultancy Bureau, Sri Lanka. The railway track in Dimbuldooa and Wenamulla was washed away in the 2004 IOT (Wijetunge, 2006). Then, in 2013 a 1380m railway embankment was constructed to improve the railway and reduce travel times, situated at a level of +7.0m from MSL.

2.2 Assessment of Benefit of Tsunami Co-Beneficial Structures

2.2.1 Definition of benefit

This study was mainly focused on evaluating the tsunami protection co-benefits of coastal structures, as explained in the research framework earlier. The potential benefit of co-beneficial structures was defined in Equation 1, and was calculated for different tsunami scenarios.

$$\boldsymbol{B = D_1 - D_2} \qquad (1)$$

Where B is the Benefit of co-beneficial structures; and D1 and is D2 are the damages due to tsunami inundation without and without tsunami co-beneficial structures in the case study area, respectively.

As the tsunami height increases there is a chance that the wave will exceed the level of crown height of the structure, and thus a possibility that the unpaved soil structure fails due to the tsunami overflow (Tsubaki, Ichii, Bricker, & Kawahara, 2016). Therefore, the author proposed two types of upgrades to tsunami co-beneficial structures: Increase the crown height and strengthen the structure for it not to fail under a tsunami event. For the case when structures are being upgraded the net benefit was defined by Equation 2.

$$B = D_1 - D_2 - C_s - C_h \tag{2}$$

where *Cs* is cost of strengthening and C_h is cost of increasing height.

León, (2006) outlined a complete methodology to predict the damage due to a disaster. However, when the resources and information are lacking, it is extremely difficult to apply such kind of very sophisticated method. Therefore, the author used a simplified methodology to calculate the damage due to tsunami inundation, as described later in this chapter.

The tsunami hazard was considered at the village scale. Ratnasooriya, et al., (2007) considered eight sectors to calculate the damage to coastal areas due to 2004 IOT. The sectors he considered were housing, tourism, fisheries, transportation, agriculture and livestock, water supply and sanitation, power and heath. 51% of the total damage was due to damage to the housing sector. The second largest damage was to the tourism sector (27% of the total damage). Thus, the present study focused mainly on damage to the housing sector. Though this greatly simplifies the problem, it allows for a clear answer to be obtained, which could then be further expanded in future work to include other sectors.

The expected losses for the housing sector for the selected scenarios were calculated using Equation 3.

$$D(Damage\ in\ hosing\ secto) = \sum_{i=1}^{4}\sum_{j=1}^{6} C_i A_i f(h_j) N_{ij} \tag{3}$$

where h_j is inundation depth, $f(h_j)$ is fragility function, C_i is unit construction cost of a house, A_i is median area of a house and N_{ij} is number of houses flooded. i represents the different type of houses in the case study area. Luxury houses, semi luxury houses, normal houses and informal houses are represented respectively by *i=1, i=2, i=3* and *i=4.* j represents the ranges of tsunami inundation depths. Tsunami inundation depths from 0m –

0.5m, 0.5m – 1.0m, 1.0m – 2.0m, 2.0m – 3.0m, 3.0m – 4.0m and greater than 4mwere represented respectively by *j=1, j=2, j=3, j=4, j=5 and j=6*. The mean value of each range was used to represent a given range, expect for the case other than in case when the inundation depths were greater than 4.0m. In the case when the inundation depths were greater than 4.0m, the minimum value (4.0m) represented that range. The criteria for dividing the range of inundation from 0-1m to 0-0.5m and 0.5m -1.0m are that the minimum inundation depth which can cause human casualties is generally considered as 0.5m (thus, the inundation maps presented can capture the areas where humans are at risk of losing their lives due to a tsunami). The criteria to consider inundation depths greater than 4.0m in one category was the nature of the fragility function. Nanayakkara & Dias, (2013) showed that the median inundation depth rage for complete collapse of masonry structures is 2.3-2.5m, and more than 98% of the houses in the case study area are masonry houses (Hikkaduwa City Office, 2015). Therefore, inundation depths greater than or equal to 4.0m were all placed on the same range (4.0m >) in this study due to very high probability to complete damage of houses.

2.2.2 Methodology flow chart

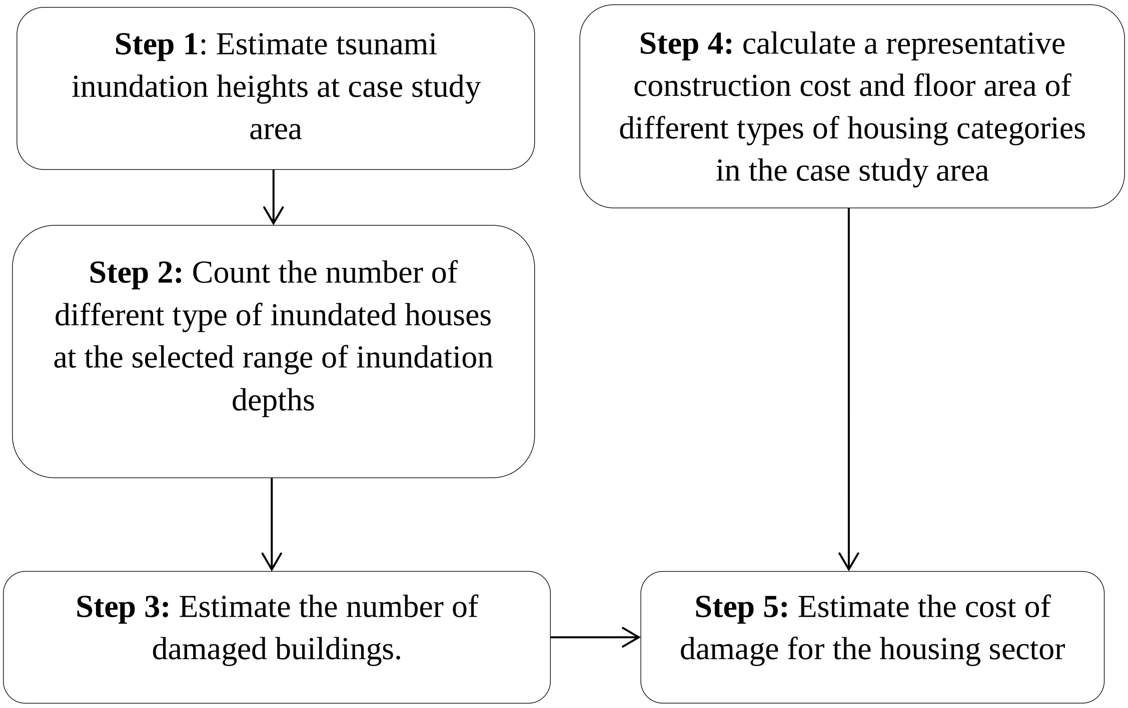


Figure 5: Methodology flow chart

2.2.3 Estimation of tsunami inundation heights in the case study area

The objective of this section is to explain the process of overlaying the tsunami inundation extent on the satellite map showing the building contours. The map showing the current building contours was generated by drawing polygons around buildings, identified by visual inspection of satellite images from Google Earth Pro.

The Community Model Interface for Tsunami (ComMIT), developed by NOAA/PMEL (National Oceanic and Atmospheric Administration /Pacific Marine Environmental Laboratory, Titov, et al., 2011) was used to simulate the tsunami inundation in the case study area for the different tsunami scenarios. ComMIT provides propagation and inundation mapping capability to countries that border the Indian Ocean region. The Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS II) uses ComMIT as its primary tool to generate tsunami inundation maps in the Indian Ocean region. This was the main reason to select ComMIT model among available tsunami models. The model is freely available for non – commercial activities, but registration is required in Pacific Marine Environmental Laboratory (PMEL). As with all other similar models, ComMIT requires information on sea bottom and coastal topography, initial and boundary conditions, and model run specific information. At present the MOST (Method of Splitting Tsunami) model is implemented to work with the ComMIT interface.

The entire process of tsunami generation, propagation and simulation is summarized in Figure 6.

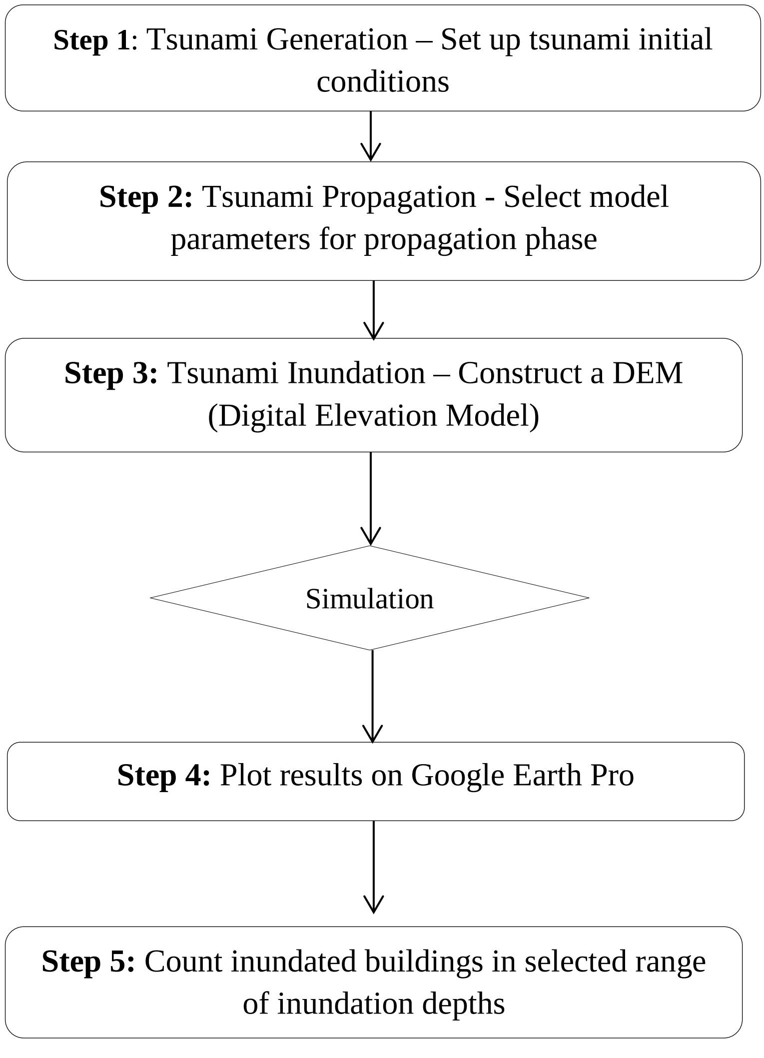


Figure 6: Process of obtaining number of inundated houses

2.2.3.1. Tsunami generation: set up tsunami initial conditions

Figure 7 shows the steps involved in the selection of the fault parameters for the generation of tsunamis from ComMIT. One of the biggest challenges to adequately model tsunamis involves the selection of fault parameters for hypothetical earthquakes. In order to do so, the present work followed the studies of Wells & Coppersmith, (1994) and Leonard, (2010).

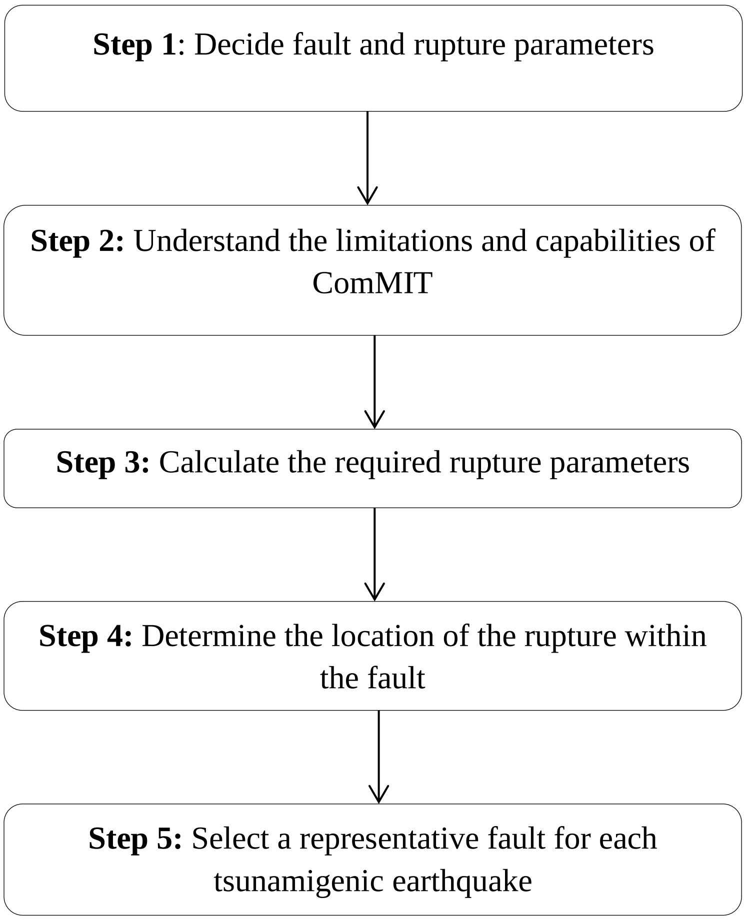


Figure 7: Steps involved in establishing the tsunami source

Step 1: Decide fault and rupture parameters

In the present work the author used the term fault to represent the Andaman zone Sunda Arc (Subduction Zone) and rupture to represent the extent of the lifted sea bottom in the event of an earthquake. Burbidge, et al., (2009) showed that the tsunami hazard in Sri Lanka is naturally dominated by the Andaman zone in Sunda Arc. Furthermore this author explained that the highest recorded maximum tsunamigenic earthquake was 9.2*Mw*, and that the possible maximum tsunamigenic earthquake was 9.5*Mw*. The Indian Ocean Tsunami Early Warning System IOTWS only activates for tsunamis greater than 7.0*Mw*. The magnitude of the Indian Ocean Tsunami in 2004 was *Mw* 9.1, and such an earthquake is believed to have a return period of 1000 years (Burbidge, et al., 2009). Earthquakes which have return periods greater than 1000 years were not considered in this study as such events are very rare. The comparatively low effectiveness of hard defensive measures against large tsunamis was demonstrated during the 2011 Tohoku Earthquake Tsunami (Shibayama et al., 2013). As a result the Japanese Government does not construct hard defensive structures against tsunamis with large return periods (Level 2 tsunamis). Thus, earthquakes with magnitudes greater than 9.1Mw were also not considered in this study, given also that Sri Lanka is more financially constrained than Japan, and protection against level 2 tsunamis should rely on evacuation measures.

Step 2: Understand the limitations and capabilities of ComMIT

The initial height of the tsunami at its origin was calculated using an in built function in the ComMIT software that is based on studies of Okada (1985). In order to do this the software does not require the direct input of dip angle, strike angle, depth of source and earth's rigidity to set up the initial surface elevation. Instead, it relies on the entry of the earthquake magnitude, size and the location of the rupture within the fault as initial conditions. The Sunda arc is a fault located between Eurasian Plate and Indo-Australian Plate at the bottom of Indian Ocean, and its northern part is referred to as the Andaman zone. Tsunamigenic earthquakes are often generated by this fault. The lifted area due to dip-slipped earthquakes is called the rupture. The fault can only modelled from 100km x 50km cells, and thus, the fault was divided into ~72 such cells (Figure 8) in ComMIT. Figure 8 illustrates how the rupture zone by a given earthquake (in darker colour) lies within the boundaries of the fault.

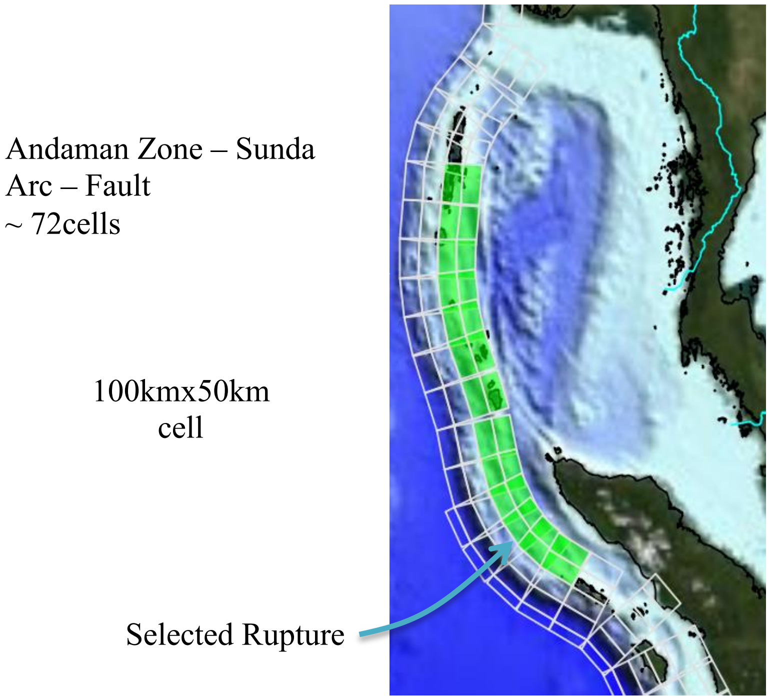


Figure 8: Fault consisted of 100km x 50km cells (ComMIT interface)

Step 3: Calculate the required rupture parameters

ComMIT uses the study by Somerville, et al., (1999) to calculate the slip of the rupture, though it provides flexibility as to whether to insert the *average slip* or *earthquake magnitude*, as shown in Equations 4 and 5. Mw is the earthquake magnitude in Richter's magnitude. Mo is the earthquake magnitude in SI units. $L,\ W\ ,\ \mu$ and u_o are rupture width, length, earths rigidity and average slip respectively.

$$\boldsymbol{M_w = \frac{2}{3} log(M_0) - 6.07} \quad (4)$$

$$\boldsymbol{M_0 = \mu u_0 L W} \quad (5)$$

The earthquake magnitude (*Mw*) was considered as an independent parameter in this study. Therefore, only a uniform average slip was considered for each unit. Length (*L*) and Width (*W*) were calculated using the semi-empirical formulas (Equation 6 and Equation 7) introduced by Leonard (2010).

$$\boldsymbol{log_{10} M_o = 2.5\, log_{10} L + 7.96} \quad (6)$$

$$\boldsymbol{log_{10} W = 0.667\, log_{10} L + 1.24} \quad (7)$$

Figure 9 shows the process to estimate the area of the rupture for a given earthquake. The rupture area was inserted to ComMIT model as 100kmx50km cells to generate the initial water surface elevation due to one of its limitation (PMEL, 2006). The Author used the process showed in Figure 9 to minimize the errors due to this software limitation.

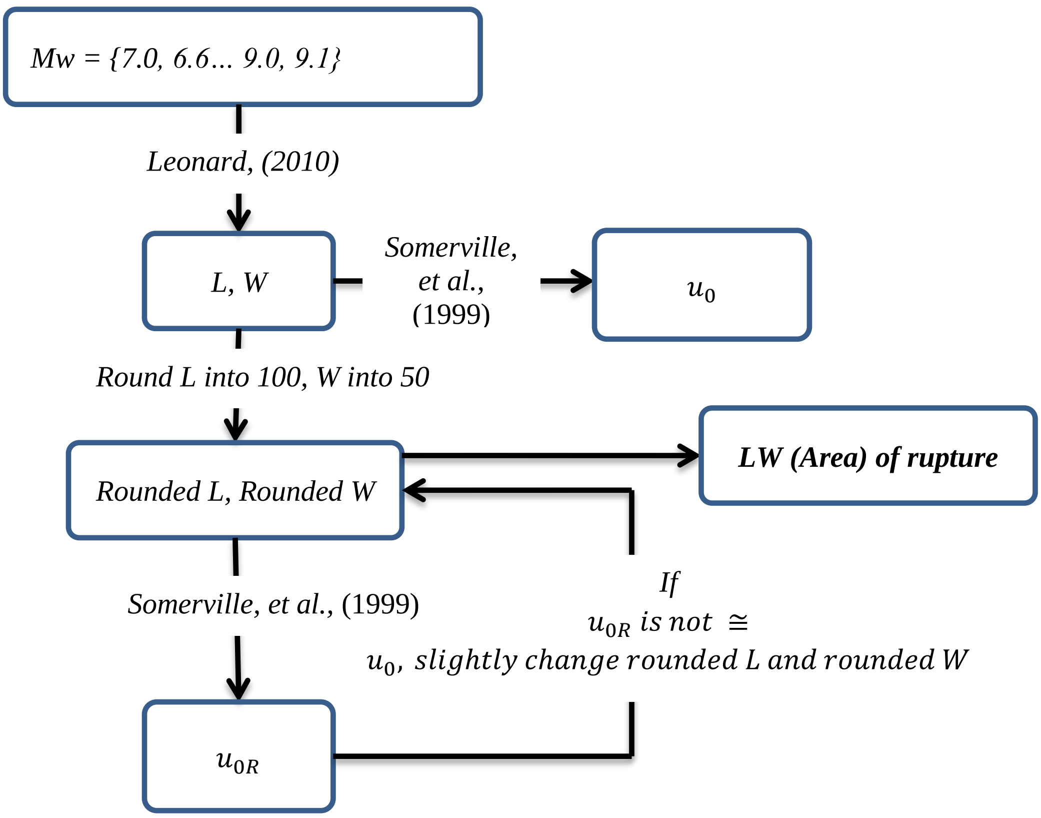


Figure 9: Process to estimate the area of the rupture

The *L* and *W* value for 7.0 *Mw* were 48km and 23km, and for a 7.8 *Mw* this corresponded to 144km and 48km. Due to software limitations the rupture can only be fed into ComMIT model by a minimum of one 100kmx50km unit, and thus earthquakes whose magnitudes are lower than *Mw* 7.8 cannot be considered in the analysis.

The results above result show the *L* and *W* of the rupture for each earthquake. The value of the calculated slip of rupture (*Uo*) from the rounded *L* and *W* was different from that of the calculated *L* and *W* .Therefore, the rounded *L* and *W* that were fed into ComMIT were modified, as shown in Table 1, using the process described in Figure 9.

Table 1: Estimated rupture area for the selected earthquakes

Mw	***L(km)***	***Rounded L***	***W(km)***	***Rounded W***	**Length of rupture n_L**	**Width of rupture n_W**
7.8	144	100	48	50	1	1
7.9	165	200	53	50	2	1
8.0	190	200	58	50	2	1
8.1	218	200	63	50	2	1
8.2	250	300	69	50	3	1
8.3	287	300	76	100	3	2
8.4	330	300	83	100	3	2
8.5	378	400	91	100	4	2
8.6	435	400	100	100	4	2
8.7	499	500	110	100	5	2
8.8	573	600	120	100	6	2
8.9	658	700	132	150	7	3
9.0	755	800	145	150	8	3
9.1	867	900	159	150	9	3

Where n_L and n_W are respectively the length of rupture and with of rupture in terms of the number of 100kmx50km cells, as shown in Figure 9. The rupture area in the ComMIT model was comprised of a combination 100kmx50km cells. The set of light green cells which represented the selected rupture for a given earthquake example are shown in Figure 8.

The size of the rupture was calculated as shown in Table 1. The author assumed a uniform slip throughout the entire rupture area. However in real earthquakes the slip is not uniform throughout the rupture area (PMEL, 2016, Tanioka et al., 2006, Barrientos et al., 2011). Burbidge, Mueller, & Power, (2015) describe in detail the uncertainties in rupture parameters and bathymetry in predicting maximum tsunami heights. Despite this, and in order to simplify the methodology the present study used some realistic assumptions instead of probabilistically modelling the tsunami hazard.

Step 4: Determine the location of the rupture within the fault

The next step was to find the location of the rupture within the fault area, as shown in Figure 10. The rupture can occur at any place within the fault. ComMIT model has fixed faults which are represented by 100kmx50km cells, as explained in the section above. The fault (Andaman zone in the Sunda Arc) was divided into 72 units (Figure 10) in ComMIT. The left hand side grid in Figure 10 shows the spatial layout of the fault. The highlighted section represents the rupture that will generate the tsunami, using the information provided in Table 1 for each earthquake contemplated. The numbers of rupture orientation which can lie on the fault were calculated from equation 8. One of a possible orientation of rupture for selected earthquake was shown in light green cells in Figure 10.

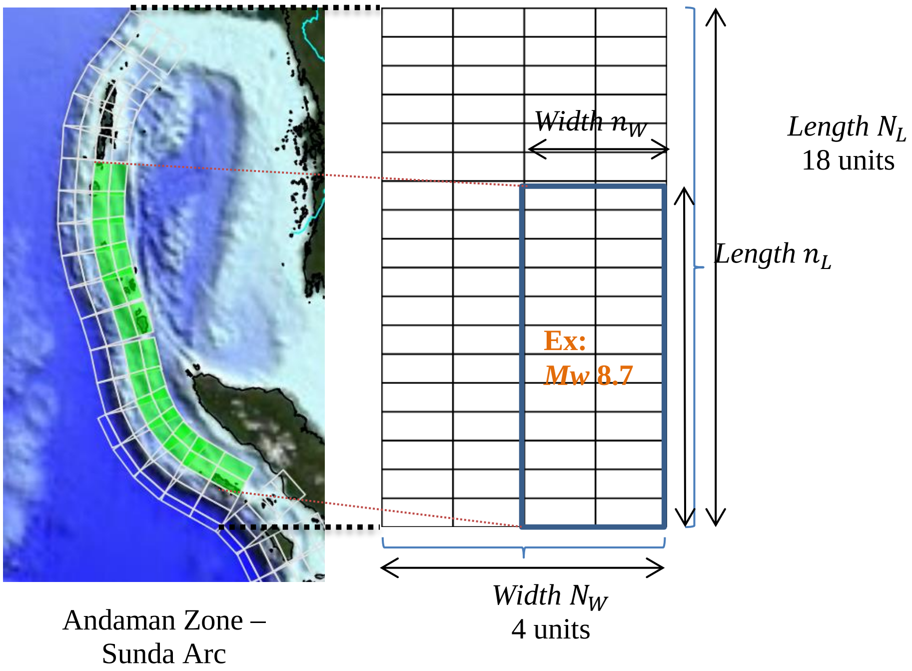


Figure 10: Schematic diagram of Andaman Zone in Sunda Arc, represent by 100kmx50km cells

The number of possible rupture orientations was calculated from equation 8.

$$Number\ of\ combinations = (N_L + 1 - n_L)(N_W + 1 - n_W) \qquad \textbf{(8)}$$

Step 5: Select a representative fault for each tsunamigenic earthquake

Author simulated each tsunami for possible rupture orientations for each earthquake magnitudes from ComMIT. Then the maximum tsunami height at coast (at Mean Sea Level) was calculated. Table 2 shows the number of possible ruptures orientations and the resulting maximum tsunami height at the coastline of the case study area.

Table 2: Earthquake magnitude vs Maximum tsunami height

Mw	Number possible combinations	Maximum Wave height in coast (m)
7.8	72	0.26
8.2	64	0.88
8.3	48	0.82
8.4	48	1.12
8.5	45	1.40
8.6	45	1.97
8.7	42	3.04
8.8	39	3.42
8.9	24	4.52
9.0	22	4.72
9.1	20	5.06

After the fault parameters were determined, the resulting tsunami propagation was numerically estimated by running ComMIT model for each possible rupture orientations. The simulation results for earthquakes with a magnitude lower than Mw 8.4 did not create an inundation wave height greater than 1.0 m. The height of the existing revetment in the case study area is +4.00m. Thus, it was assumed that the existing structures were sufficient to provide protection when the tsunami inundation wave height was lower than 1.0m at the coastline. Therefore, only earthquake with magnitudes between 8.4 and 9.1 were considered when determining the tsunami source.

Figure 11 shows a whisker box diagram of the range of maximum tsunami height at coast (0m contour) possible for each earthquake magnitude. The location of ruptures which were equivalent to the median shown in the figure was considered as representative for each earthquake magnitude. This consideration is discussed in more detail in the section of tsunami damage calculation.

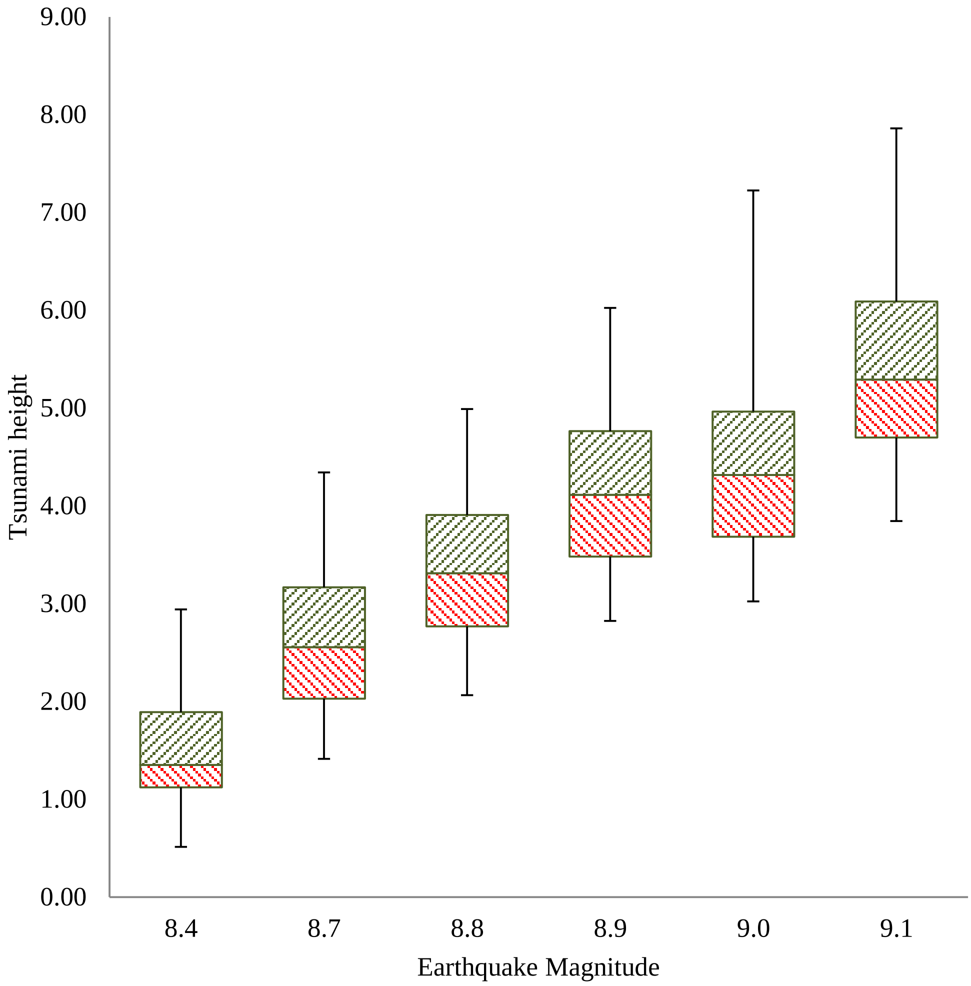


Figure 11: Range of tsunami height for each earthquake magnitude

2.2.3.2. Select of model parameters for propagation phase

ComMIT numerically solves nonlinear shallow water equation to give the tsunami inundation heights in the area of interest with the aid of three nested domains. The domain information was tabulated in Table 3 .ComMIT use the domain called Indian Ocean domain which consists both source and the area of interest in the propagation phase (Figure 11). The resolution is 120.0 arcseconds. The extent of the propagation domain is demarcated in Figure 11. Domain A, B and C are the nested domain system of inundation phase calculation.

Figure 12, 13 and 14 shows the map of extent of domains A, B and C

Table 3: Domain information

Parameter	Domain A	Domain B	Domain C
Latitude extent degrees	3.3618 to 10.0618	4.9929 to 6.6846	6.1797 to 6.2230
Latitude spacing ΔX arcsec	120.0	30.0	0.16
Longitude extent degrees	77.0959 to 84.5959	79.8060 to 81.3310	80.0477 to 80.0844
Longitude spacing ΔY arcsec	120.0	30.0	0.16
Dimensions XY	226 x 202	184 x 204	810 x 954
Maximum time step (CFL condition) s	17.49	4.24	0.33
Data Source	ETOPO 1	ETOPO 1	Modified (ETOPO 1 and CGIAR SRTM)

Domain C is the most important for the accurate resolution of the simulation. However, only DEM of CGIAR SRTM (Digital Elevation model of Consultative Group for International Agricultural Research Shuttle Radar Topography Mission) is freely available for the case study area. The square domain resolution was 3 arcs second (~92.2 m)

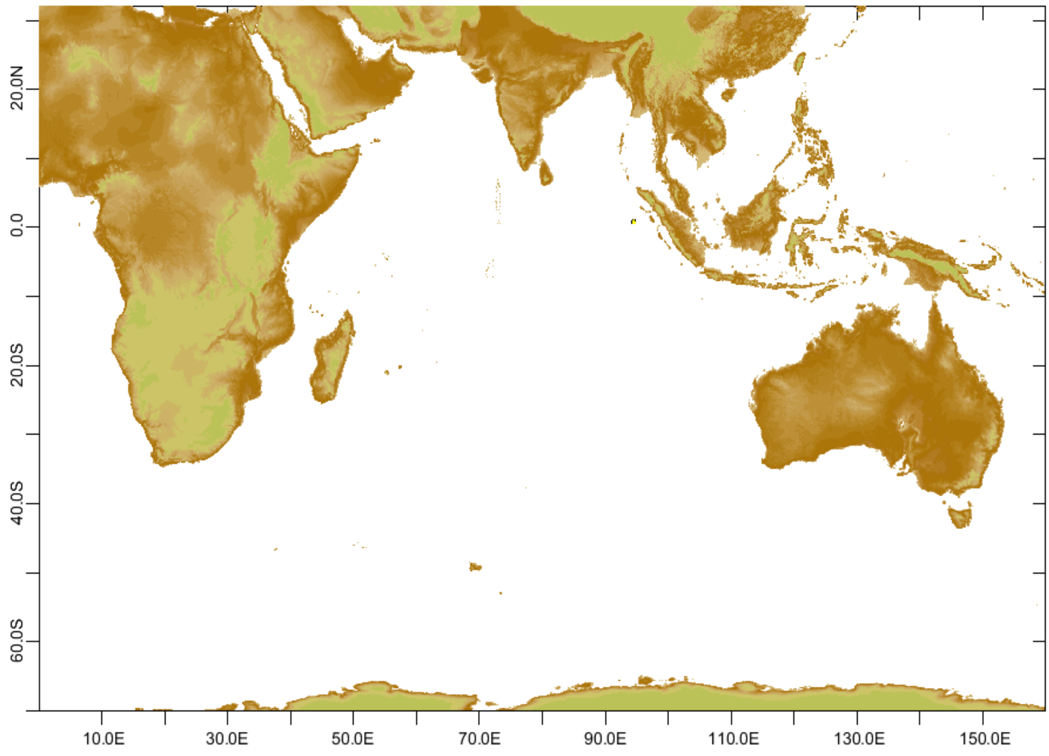


Figure 12: Extent of domain of Indian Ocean

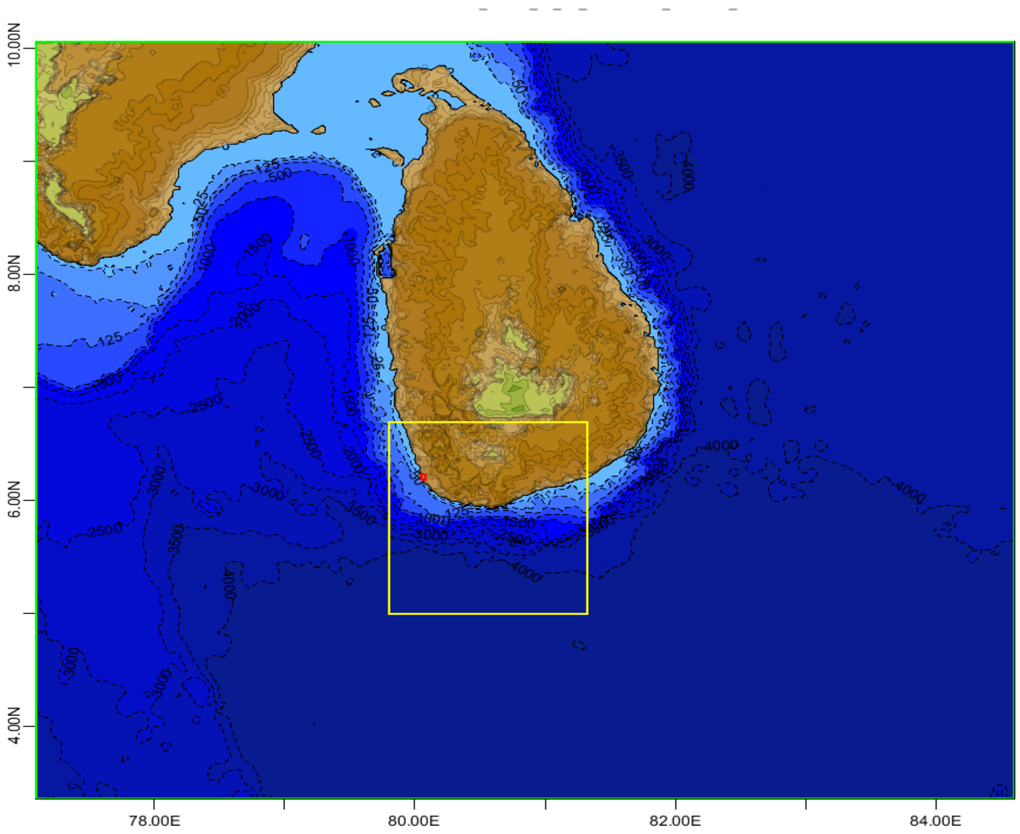


Figure 13: Extent of domain A

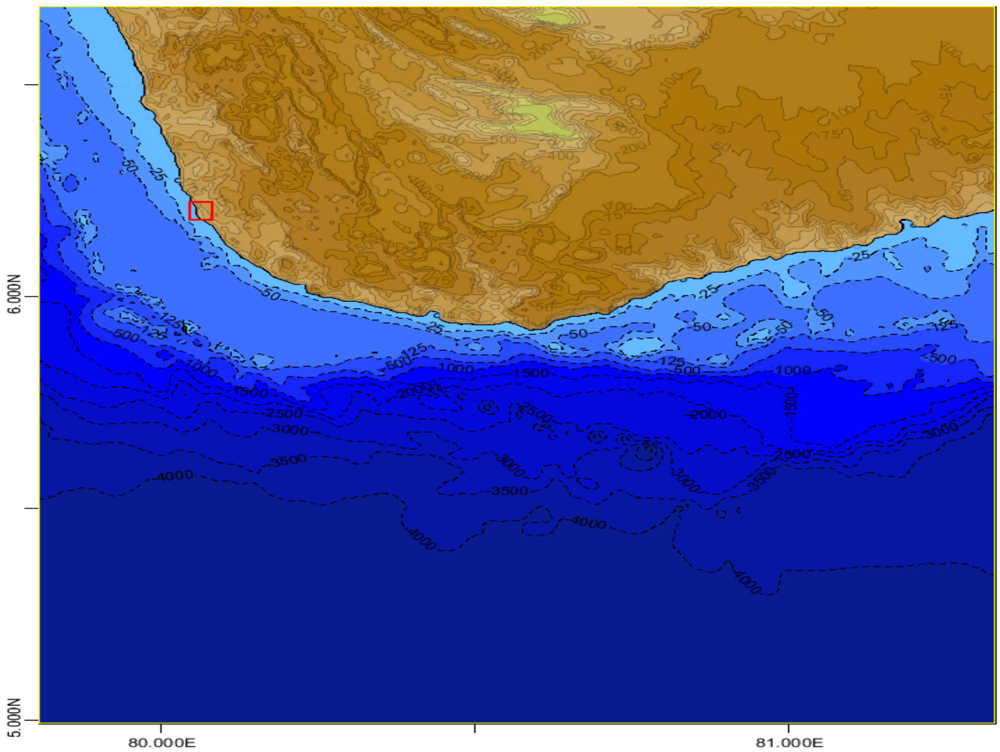


Figure 14: Extent of domain B

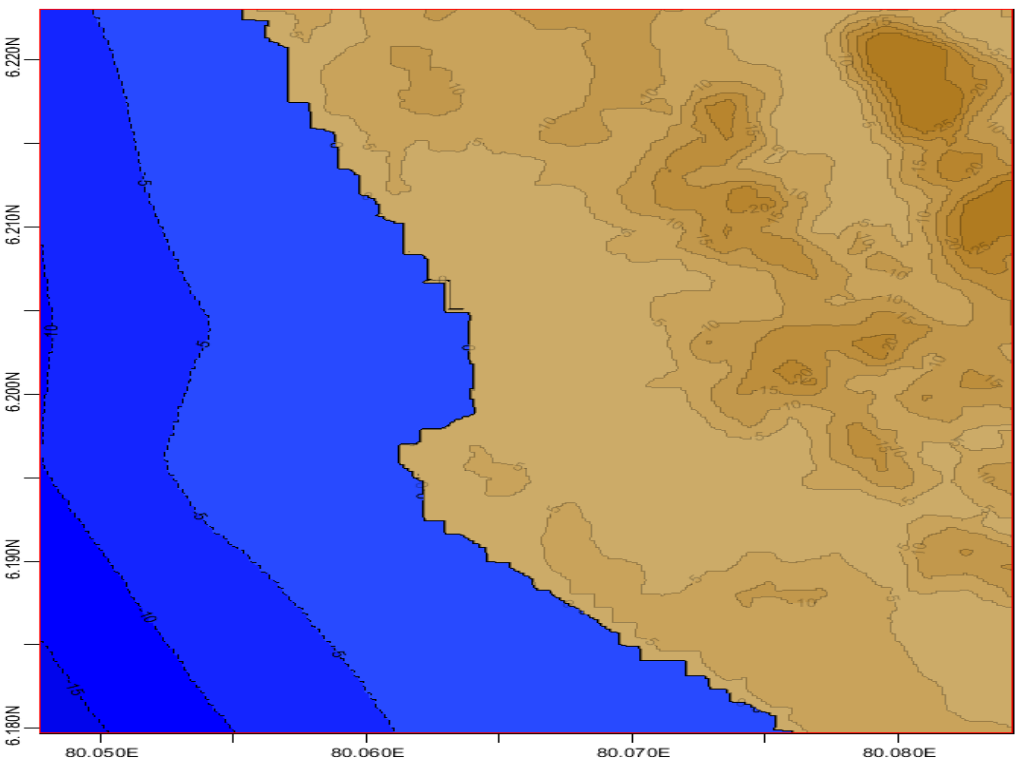


Figure 15: Extent of domain A

2.2.3.3. Tsunami Inundation – Construct a DEM (Digital Elevation Model)

For the correct resolution of the ComMIT model it was necessary to insert a minimum width of the revetment (~5 m) to the DEM. Appendix A describes the procedure which used to interpolate data from the coarse domain to create more detailed data. Figure 16 shows a summary of steps.

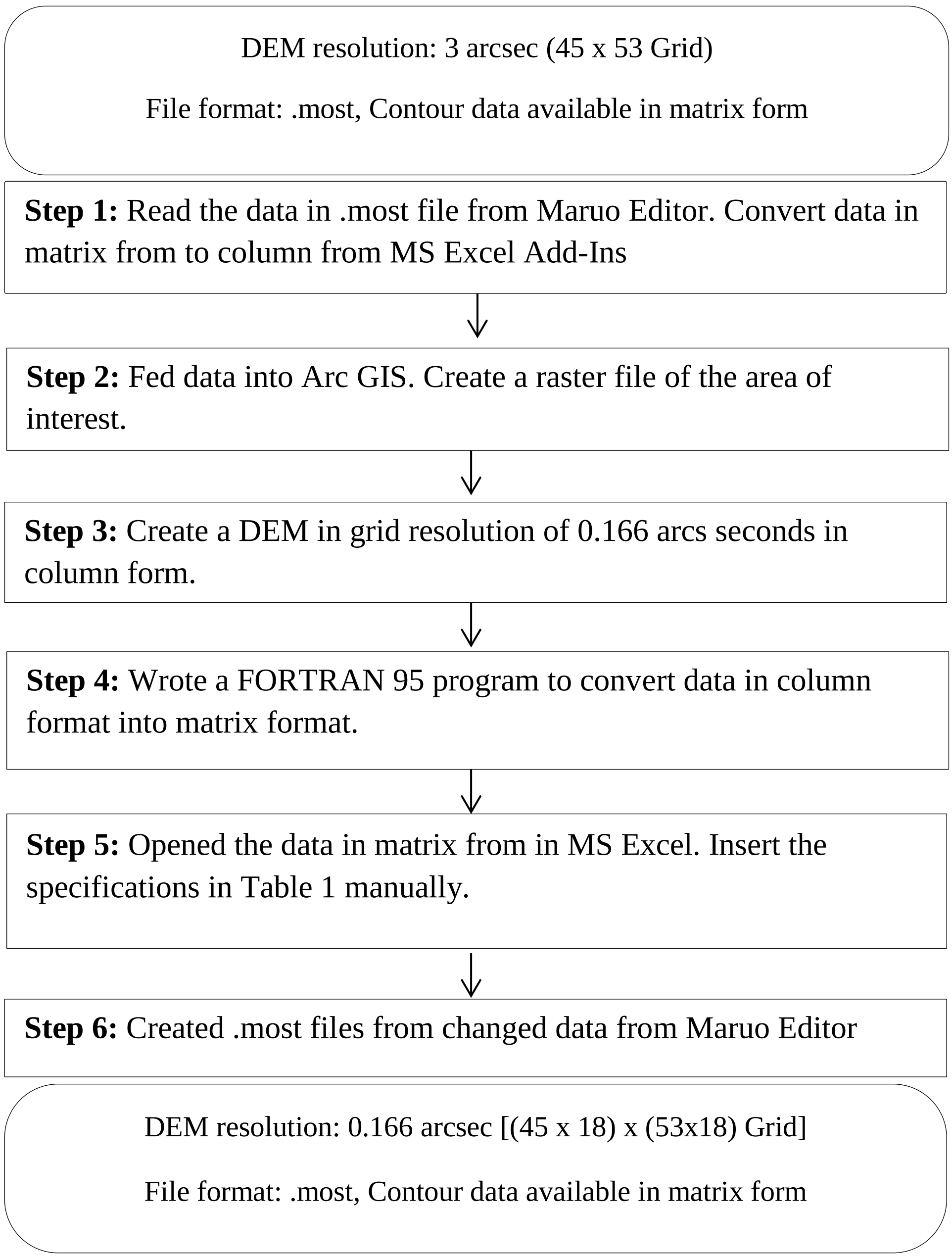


Figure 16: Steps for generating domain C

One of the most important parameters in the inundation phase is Manning's roughness coefficient. Manning's roughness coefficient was selected as 0.04 in accordance to the recommendation of Bricker, et al., (2015) for a low density non-commercial urban area.

Friction coefficients (Manning's roughness coefficients), topography, earthquake magnitude, rupture size and rupture location are the important parameters in simulations. The other important parameter is the domain C in ComMIT (Digital Elevation Model to obtain tsunami inundation depth and extent). Figure 17 shows a Google Earth image of the domain for inundation phase simulation (domain C in ComMIT). The details of this domain are explained in detail in next section. In total, 8 simulation scenarios were considered.

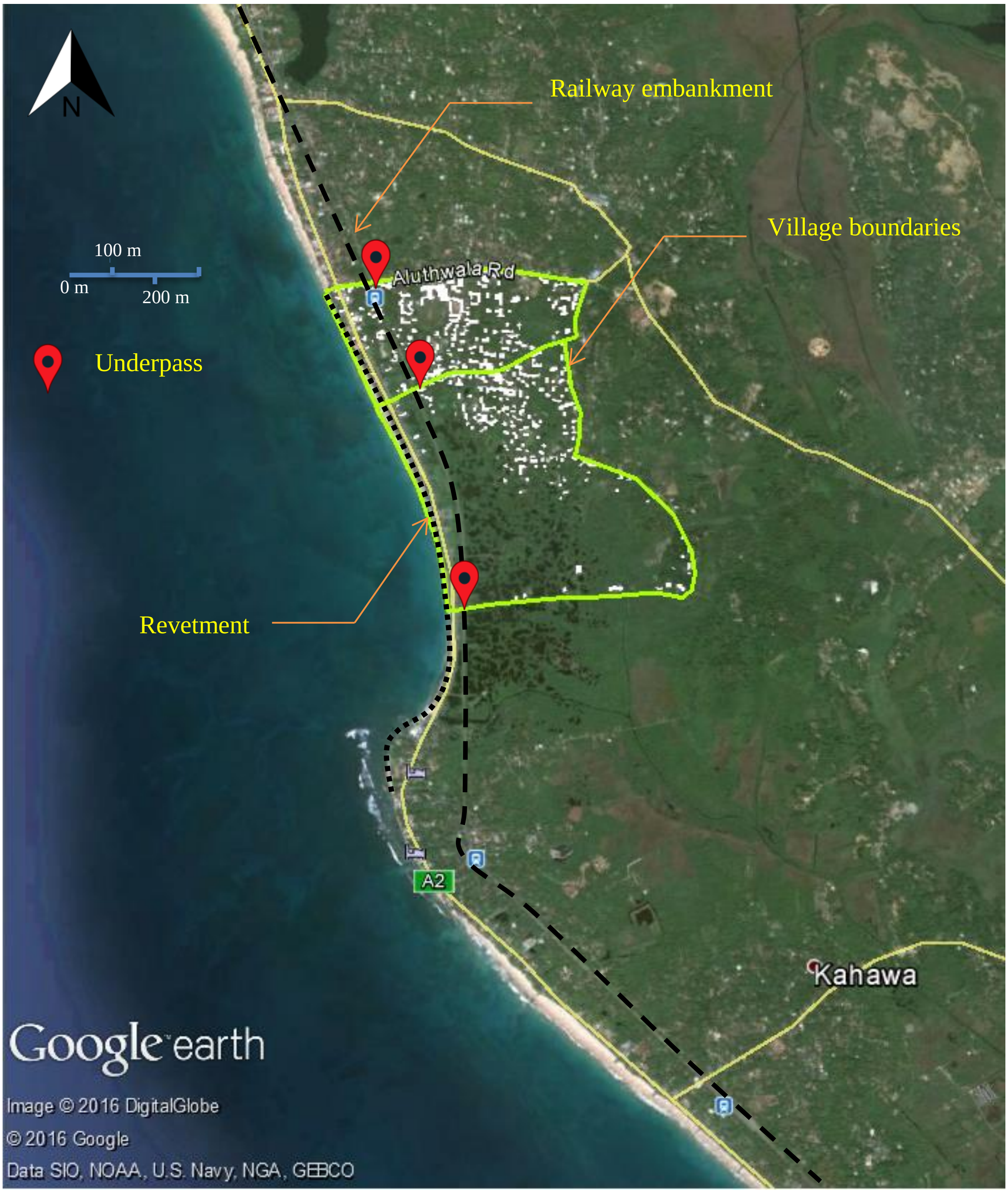


Figure 17: Google Earth Pro image of the simulation domain for the inundation simulation

Scenario 1 – Topography without co-beneficial structures -DEM 1 (Digital Elevation Model 1)

Scenario 1 represents the situation without any structures in the case study area. The finest domain (Domain C) was fed into the ComMIT model (Appendix A), used without any modification in topography in DEM (Digital Elevation Model). Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw, 8.9Mw, 8.8Mw and 8.4Mw earthquakes from ComMIT.

Scenario 2 – Topography with revetment - DEM 2

Scenario 2 represents the situation with revetment in the case study area. The length of revetment is 2,208m. It lies from point (6.212264, 80.059451) to point (6.194206, 80.061900), as shown in Figure 16, with a height of +4.0m from mean Sea Level (MSL) and width of 5.0m. The rest of topography was kept as same as in scenario 1. Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw, 8.9Mw, 8.8Mw and 8.4Mw earthquakes from ComMIT.

Scenario 3 – Topography with railway embankment with grade crossings - DEM 3

Scenario 3 represents the situation with a railway embankment with grade crossings. The length of railway embankment is 2,000m. It lies from (6.222797, 80.056386) to (6.179667, 80.077769), as shown in Figure 17. Height is 7.0m from the MSL. Width is 5.0m. Rest of topography kept as same in scenario 1. Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw, 8.9Mw, 8.8Mw and 8.4Mw earthquakes from ComMIT.

Scenario 4 – Topography with railway embankment with underpasses - DEM 4

Scenario 4 represents the situation with railway embankment with underpasses. The topography kept as same in scenario 3 only with following modifications. 5.0m openings were considered in railway embankment as underpasses in the places where railway embankment crossed the roads in three points (6.208978, 80.061082), (6.208978, 80.062601), (6.201103, 80.064434) as shown in Figure 17. Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw, 8.9Mw, 8.8Mw and 8.4Mw earthquakes from ComMIT.

Scenario 5 – Topography with both revetment and railway embankment with grade crossings DEM 5

Scenario 5 represents the situation which with both revetment and railway embankment with grade crossings exists in case study area. Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw, 8.9Mw, 8.8Mw and 8.4Mw earthquakes from ComMIT.

Scenario 6 - 10 -– Topography with revetment (Revetment height at 4.0m, 4.2m, 4.4m, 4.6m, 4.8m and 5.0m). – DEM 6 – 10

Scenario 6 -10 represents the situation of different heights in revetments. DEM 2 was created with +4.0m revetment height. Another five DEMs (DEM 6, DEM 7, DEM 8, DEM 9 and DEM 10) were created by increasing the revetment height by 0.2m intervals until 5.0m. Tsunami inundation depths and extents were numerically calculated for 9.0Mw earthquake from ComMIT using each DEM. Tsunami inundation depths and extents were numerically calculated for 9.1Mw, 9.0Mw and 8.9Mwearthquakes from ComMIT. Tsunami inundation depths and extents were not numerically calculated for 8.4Mw and 8.8Mw, because representative tsunamis did not overflow the revetment of 4.0m height.

2.2.3.4. Plotting of results on Google Earth Pro and determination of the number of inundated buildings in the selected range of inundation depths

The ComMIT simulation was run in a NOAA server and the results were saved as Network Common Data Form (NetCDF) in a hard drive. The results were then plotted on the Google Earth Pro and the number of inundated buildings was counted manually.

2.2.4 Estimation of the number of damaged buildings

The map of tsunami inundation extent for different hypothetical tsunamis was overlaid on the Google Earth with the identified building profiles to calculate the number of inundated buildings for each of the selected range of inundation depths. Then, the tsunami fragility function (Suppasri, et al., 2013) was used to estimate the damage for each inundated houses for a given inundation depth. An extensive literature review was conducted to select the most suitable fragility function. Then, the graphs found in existing literature were replotted, as most researchers did not share the equations of the fragility function in their publications.

After the 2004 Indian Ocean Tsunami some tsunami researchers developed fragility functions, as shown in Table 4. Nanayakkara & Dias (2013) stated that the fragility function was expressed in cumulative log normal distribution by Peiris, (2006) and fragility function was expressed in cumulative normal distribution by Murao and Nakazato, (2010). In Table 4 μ and $\overline{H}$ represent the means and σ standard deviation of the inundation depths in each data set. CDF (Cumulative Distribution Function) represents the probability of occurrence of damage.

Table 4: Tsunami fragility function in Sri Lanka

Study	Data Set	Building topology	Damage criteria	Fragility function
Murao & Nakazato, (2010) Suppasri, et al., (2012)	Sri Lanka – Southern Coast 2004 IOT	Masonry & woodwork	Complete damage (*Complete structural damage*)	$\emptyset\left\{\frac{H-\mu}{\sigma}\right\}$
			Heavy damage (*Structural damage and unusable*)	
			Moderate damage (*No visible structural damage and reusable*)	
Nanayakkara & Dias, (2015)	Sri Lanka 2004 IOT	Single story masonry	Complete (*Complete damage*)	$\emptyset\left\{\frac{1}{\sigma}\ln\left(\frac{H}{\overline{\overline{H}}}\right)\right\}$
			Partial (usable) *Cracks on wall, outside the 100m buffer zone*	
			Partial (unusable) *Cracks on wall, with in the 100m buffer zone*	

$$\emptyset\left\{\frac{H-\mu}{\sigma}\right\} = CDF = \frac{1}{2}\left(1 + erf\left(\frac{H-\mu}{\sigma}\right)\right) \tag{9}$$

$$\emptyset\left\{\frac{1}{\sigma}\ln\left(\frac{H}{\overline{\overline{H}}}\right)\right\} = CDF = \frac{1}{2}\left(1 + erf\left(\frac{\ln H - \ln \overline{H}}{\sigma}\right)\right) \tag{10}$$

The points in the graphs provided in the literature were extracted and converted into JEPG images using online digitizer software (Digitize scanned graphs and get original (x,y) data, 2016) and then the graph was replotted using MS Excel. A curve fitting technique was used to regenerate the equation of the given function.

2.2.5 Collect housing data

The author also conducted semi structured interviews with three architects and one real state housing agent in Sri Lanka to estimate the average construction cost of a unit area of a house in the case study area. They categorize houses into four categories, namely luxury houses, semi-luxury houses, normal houses and informal houses. The characteristic of the categorization was tabulated in Table 5. Pictures of representative samples of each type of houses are included in APPENDIX C.

Table 5: Characteristics of houses categorizations

Features of houses	***Luxury***	***Semi – Luxury***	***Normal***	***Temporary***
Type of wall material	Masonry	Masonry	Masonry	Masonry without plastering/timber planks/ metal sheets
Steel Gate	With masonry fence	With a hedge	Only a hedge, No gates	Only a hedge, No gates
Shower room	Attached to house	Separate	Separate or not	No
Roofing-structure	Hip and valley roof	Hip/Gable	Gable	Gable/flat/ shed
Flooring	Tile	Tile/cement	Cement	Cement/ clay
Ceiling	Cement fiber/wood	Cement fiber/wood or a partial coverage	Wax papers	No

The average construction cost of a unit area of each house category was found out from the interview results. The average floor area of each house category is required to estimate the average construction cost of each house categories. But such kind of data was not available from the city office, and thus the author visited the houses in the study area in February, 2016 to collect data and categorize houses in case study area as into luxury, semi-luxury, normal and informal.

All buildings were marked as polygons in Google Earth Pro, and then the area of each polygon was calculated. All the polygons were then categorized by using two criteria and walking along the roads in the case study area. The first criteria regarded the number of stories in each construction (whether they were single story buildings, piloti type buildings and buildings which had more than one story). The second criteria related to a categorization of the buildings luxury houses, semi luxury houses, normal houses and informal houses. The field work data was analyzed using MS Excel.

2.2.6 Assumptions

The following assumptions were made to calculate the total damage cost, as described in detail in early sections:

1) Both Wenamulla and Dimbildooa villages were considered as a one community.
2) All the houses in the community were masonry houses.
3) Cost of a house reconstruction was equal to total cost of the house.
4) The partially damaged houses were neglected.
5) Damage to the housing sector was equal to total damage.

2.3 Upgrade Tsunami Co-Beneficial Structures

2.3.1 Data

The importance of upgrading coastal defences was identified using an extensive literature review. Existing railway embankments and revetment currently do not have the capability to resist a large tsunami; see for example Yamamoto, et al. (2006), who investigated the failure mechanisms of coastal structures in Sri Lanka due to 2004 Indian Ocean Tsunami. The destruction of revetments and seawalls was caused by both incident wave pressure and return flow. Wijetunga (2006) observed that overturning, sliding and scouring were the main failure modes due to the tsunami loading. Sliding was caused by the incident wave pressure. Scouring at the toe of the landward side of structures was caused by incident waves, and afterwards the return flow overturned structures towards the sea or sometimes washed them away entirely. Even though the studies in Sri Lanka did not describe the failure mechanisms in detail, further analysis was provided by Kato, et al. (2012) and Jayaratne et al., (2014) following the 2011 Tohoku Earthquake tsunami (MLIT, 2012). It should be noted how for the case of Sri Lanka interlocking blocks were seldom used to construct revetments, and therefore the rock boulders used were easily washed away during the 2004 Indian Ocean Tsunami.

The entire crest of a 900 m long portion of the southern stretch of the revetment in the case study area was washed backward during the 2004 event. However, the portion to the north was only slightly damaged (LHI-SL, NIRAS-Denmark, Sellhorn-Germany, 2005). The railway embankment in the case study area was completely washed away (Wijetunge, 2006) as shown in Figure 18.

Figure 18: Heavily damaged railway embankment in due to the 2004 Indian Ocean Tsunami

The author walked along the railway embankment and revetment in September, 2015 and inspected whether the current structures in the area are able to resist a tsunami. Furthermore, the author visited the government and private agencies who the constructed the railway embankment and revetment and discussed with engineers the challenges to upgrade these coastal structures. Also, the the potential co-benefitial effect in resisting a tsunami were also discussed, as summarised in Table 6. These meetings were also used to collect a variety of data regarding construction rates and design drawings.

Table 6: Collected data from the resource persons consulted in the various government agencies visited

Structure	Coastal railway embankment	
Agency Visited	**Interviewed expert**	**Collected data**
Central engineering consultancy bureau, Colombo, Sri Lanka	Engineer (Mrs) Chathuri Madushanka	Enginering drawings and rates of construction of railway embankment
Structure	**Revetment**	
Agency Visited	**Interviewed expert**	**Collected data**
Coast conservation department, Galle, Sri Lanka	Engineer Chanaka Vinodh	Engineering drawings and rates of construction of railway embankment

2.3.2 Analysis

The drawings collected from the various government agencies were carefully studied in order to understand what modifications could help improve the structures so that they offer protection against a possible future tsunami. The drawings of the revetment before and after the 2004 Indian Ocean Tsunami showed that the only major difference between them was the increased crown height. Therefore, the author proposed a series of modifications to improve the effectiveness of the structures against a potential future tsunami in accordance to the guidance provided by MLIT, (2014)

1) The earth around the landward toe of the structures would be improved to prevent toe erosion.
2) The soil embankments would be properly covered to avoid water induced soil erosion.
3) The landward slope of the structure would be covered with interlocking blocking to prevent the dislocation of the armour.

4) A concrete sea wall would be used (instead of rubble boulders) in the sea ward side of the revetment.

The lengths, areas and volumes of the proposed modifications were then calculated.According to this, the cost to upgrade the structure could be calculated by using the construction rates collected from the government agencies, as shown in the results section of the present thesis.

2.4 Survey on Social Acceptance to Upgrade Tsunami Co-Beneficial Structures

Social acceptance to upgrade revetment and coastal railway embankment was measured from a willingness to pay questionnaire. The significance of the results were verified using the triangulation method (Bryman, 2004), which involved focus group discussions and expert interviews.

2.4.1 Expert interviews

The objective of the expert interviews was to get an in-depth understanding of the challenges to upgrade the exiting railway embankment and the revetment. The experts interviewed and their affiliations were tabulated in Table 7, also showing the topics that were discussed and the date of interview

.

Table 7: Summary of Interviews with Experts

Area	Date	Resource Person	Topics covered in interview
Galle	September 6	Eng. T. L. C. Vinodh, Regional Engineer (Galle) Coast Conservation & Coastal Resource Management Department	• What are the practical limitations to upgrade revetments?
Colombo	September 8	Prof. Priyan Dias, Mr. A. H. R Ratnasooriya, Leading tsunami researchers in Sri Lanka, Professor in the University of Moratuwa	• What are the latest and ongoing studies of structural vulnerability of buildings subjected to tsunami loading?
Colombo	September 9	Mr. Pradeep Kodippili, Deputy Director, Early Warnings, Disaster Management Center (DMC) , Ministry of Disaster Management, Sri Lanka	• What is current status of Early Warning System in Sri Lanka? • What are the newly launched projects of DMC?
Colombo	September 13	Eng. (Mrs.) Chathuri Madushanka, Design Engineer, Southern Railway Development Project, Central Engineering Consulting Bureau , Sri Lanka	• What are practical limitations to upgrade railway embankments?
Colombo	September 15	Prof. Samantha Hettiarachchi, Vice – President, Indian Ocean Tsunami Early Warning System (IOTWS)	• What are the current limitations of IOTWS? • What are the newly launched projects of IOTWS?

2.4.2 Questionnaire

Two structured questionnaires (see APPENDIX B) were administered by the author to local residents to evaluate the willingness to pay to upgrade the coastal railway embankment and revetment, as examples of structures that have tsunami protection co-benefits. The questionnaire consisted of four parts

- Question 1 -3: Respondent's general information
- Question 4 – 9: Respondents awareness of benefits of the selected structure
- Question 10 – 12: Willingness to pay to upgrade the selected structure
- Question 13 – 20: Respondents awareness of tsunami risk

Author selected only one respondent from one housing unit. The questionnaires covered five Grama Niladari divisions (villages) in the Hikkaduwa area (Figure 19).The villages where the author conducted the questionnaires are highlighted in in yellow.

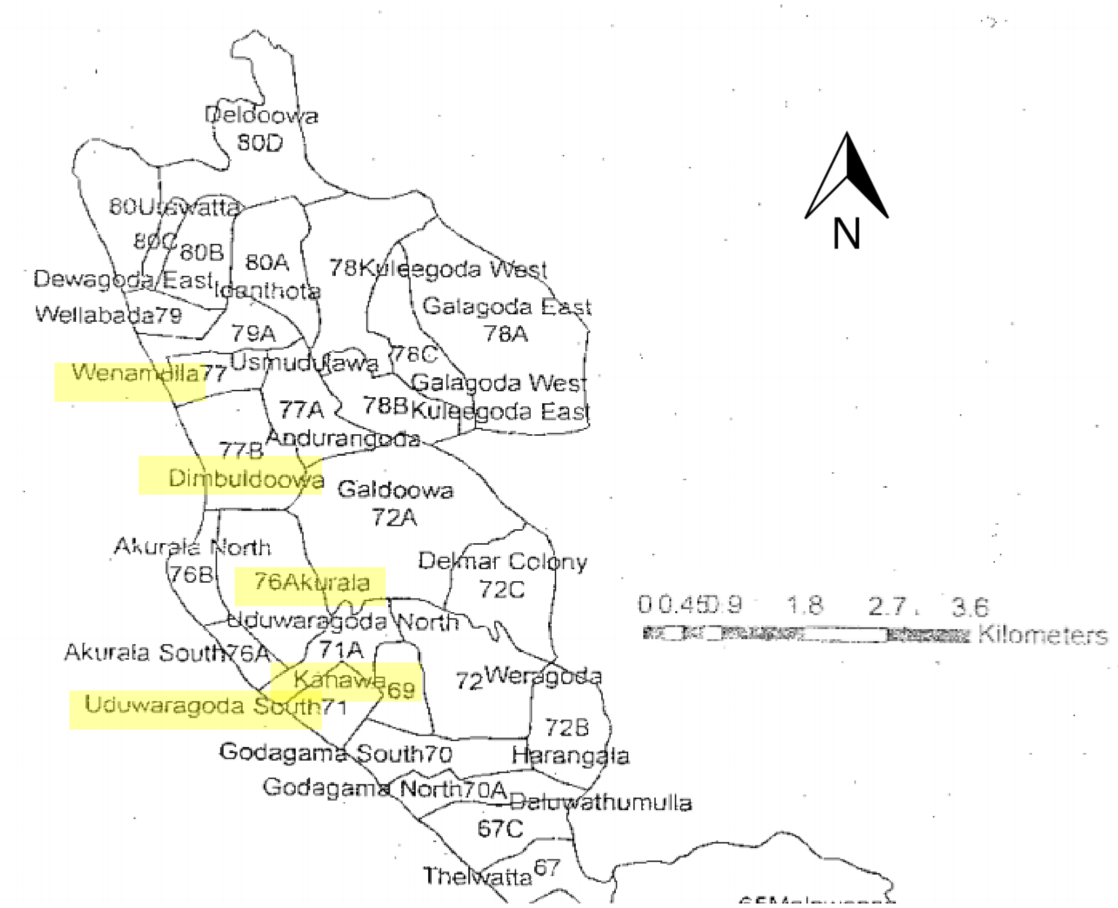


Figure 19: Villages where the questionnaire survey was carried out (Source: Scanned copy of a document in Hikkaduwa City office collected during an interview in September 2014)

The questionnaires regarding the willingness to pay to upgrade the railway embankment were conducted in Kahawa, Uduwaragoda South and Akurala villages, while the questionnaire regarding the willingness to pay for the upgrade to the revetment was conducted in Wenamulla and Dimbuldooa villages. The reason to conduct above two questionnaires separately was to avoid the confusion of respondents. The number of required samples (Number of houses) to achieve 90% precision was determined from the guidelines given by Israel, (2013). The sample sizes of the questionnaires which conducted in 2016, September were tabulated in Table 8. The number of affected buildings during 2004 Indian Ocean Tsunami was collected from the Department of Census and Statistics, (2005).

Table 8: Sample sizes of conducted questionnaires in September, 2015

Structure	Village	Conducted date of questionnaires September, 2015	Number of affected buildings form 2004 Tsunami	Number of samples require for 90% precision	*Number of collected questionnaires
Revetment	Wenamulla Dimbuldoowa	12, 13, 15	187	97	104
Railway Embankment	Akurala Kahawa Uduwaragoda South	18, 19, 20	177	95	96

* Questionnaires were conducted within the boundary of the inundation of 2004 Indian Ocean Tsunami

The questionnaire that focused on revetment and railway embankments covered nearly 55% and 54% of the target population, respectively. Pictures of the author conducting the questionnaires can be found in APPENDIX C.

2.4.3 Focus group discussion

Two focus group discussions were organized in February, 2016 to triangulate the results of the questionnaires and expert interviews. Furthermore, possible potential adverse effects of upgrading infrastructure were also discussed in detail during these discussions. To select the members of the focus group discussion a religious leader in the case study area was contacted, who recommended a group of residents who had a fair level of education. The focus group discussion was conducted in a hall at Wenamulla temple. The details of the focus group discussions were tabulated in Table 3.

Table 9: Specifications of conducted focus group discussions in February, 2016

Date	Participants	Number of participants	Duration of the discussion	Discussion points
13^{th}, February Saturday – Evening	Only women	6	1hour and 30 min	• Discussion of the significance of the results from the questionnaire • Drawbacks of upgrading structures that have potential tsunami prevention co-benefits
14^{th} , February Sunday – Evening	Only men	4	More than 2 hours	

2.4.4 Data analysis

The main objective of the willingness to pay questionnaire was to find the community's willingness to pay to upgrade the selected structures. In addition, to calculate the value of willingness to pay to upgrade, a logits regression model was used (Edward, Michael, & John, 1973) to obtain the socio-economic factors which influenced the community's willingness to pay by using the methods given by Stock & Watson, (1988) and Torres-Reyna (2012). STATA SE 13 software was used for the analysis.

The data gathered from expert interviews and focus group discussions was interpreted as qualitative data, and the main findings are summarized in the next section.

3 RESULTS

3.1 Assessment of Benefit of Tsunami Co-Beneficial Structures

3.1.1 Wave heights at inundation area

The tsunami inundation results, overlaid on Google Earth Pro maps, are shown below. Figures 20-24 show the tsunami inundation depth without any co-beneficial structures. Figures 25-29 show the tsunami inundation depth with the revetment. Tsunami inundation depths with an upgraded railway embankment with graded railway crossing and with underpasses are shown in Figures 30-34 and 35-39, respectively. Figures 40-42 show the tsunami inundation depth for the cases with both revetment and railway embankment with grade crossings. Figures 43-47, 48-52 and 53-57 show the tsunami inundation depths for increasing the height of revetment from 1.0m in 0.2m intervals at 9.0Mw, 8.9Mw and 9.1Mw respectively.

3.1.1.1 Without Co-beneficial Structures

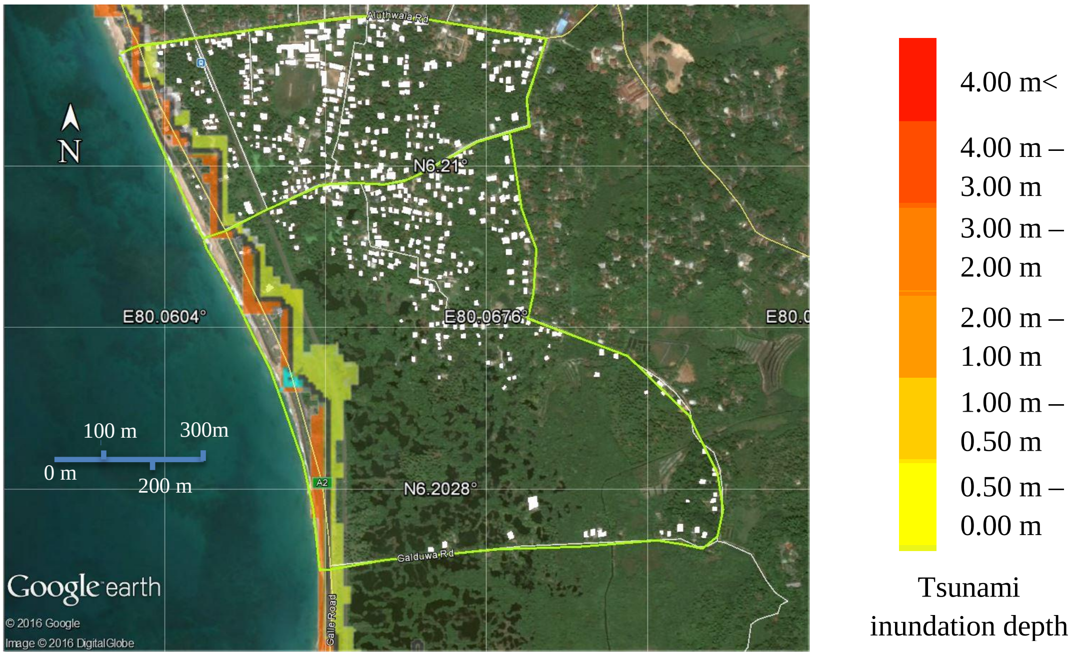


Figure 20: Tsunami inundation depth – Scenario 1 (Mw = 8.4)

Table 10: Scenario 1 (Mw = 8.4)

Case	Scenario 1 Mw = 8.4			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	2	9	1
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	0	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	0	0

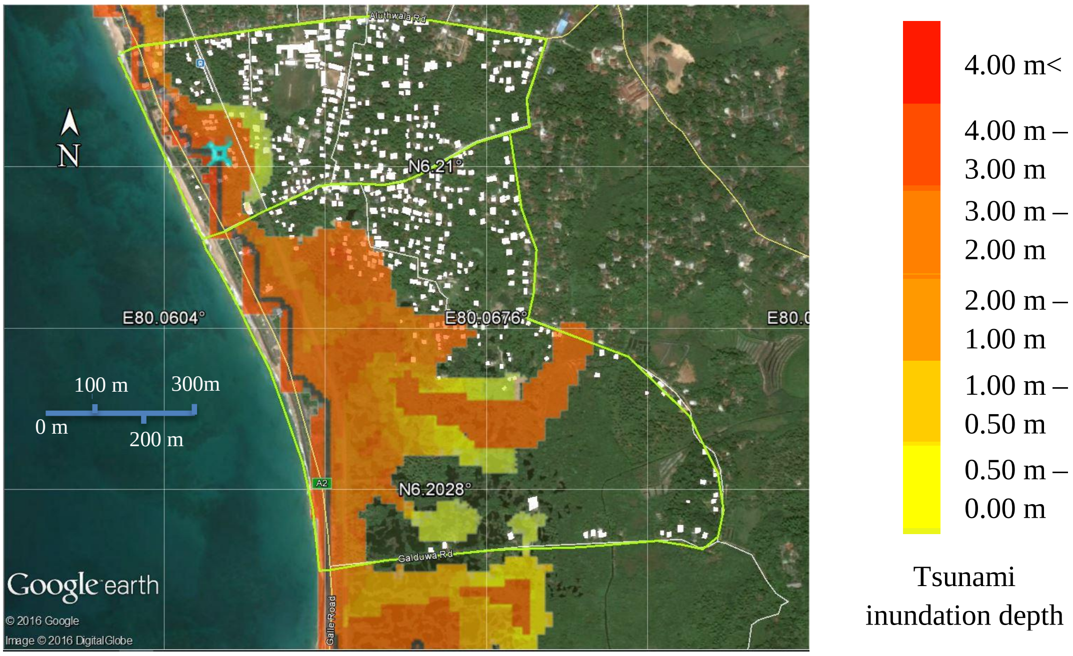


Figure 21: Tsunami inundation depth – Scenario 1 (Mw = 8.8)

Table 11: Number of inundated houses – Scenario 1 (Mw = 8.8)

Case	Scenario 1 Mw = 8.8			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	3	16	1
0.5 - 1.0	0	1	6	1
1.0 - 2.0	0	1	6	1
2.0 -3.0	1	4	22	2
3.0 - 4.0	0	1	7	1
4.0<	0	1	6	1

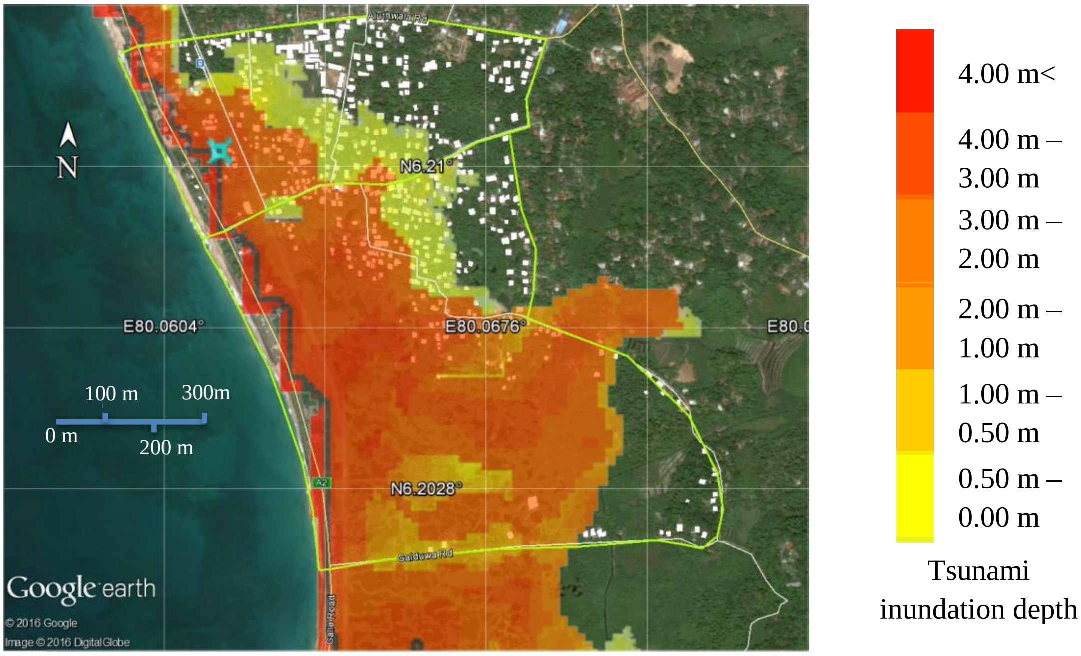


Figure 22: Tsunami inundation depth – Scenario 1 (Mw = 8.9)

Table 12: Number of inundated houses – Scenario 1 (Mw = 8.9)

Case	Scenario 1 Mw = 8.9			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	6	25	137	13
0.5 - 1.0	1	3	14	1
1.0 - 2.0	1	3	14	1
2.0 -3.0	2	9	48	4
3.0 - 4.0	1	3	16	1
4.0<	1	3	16	1

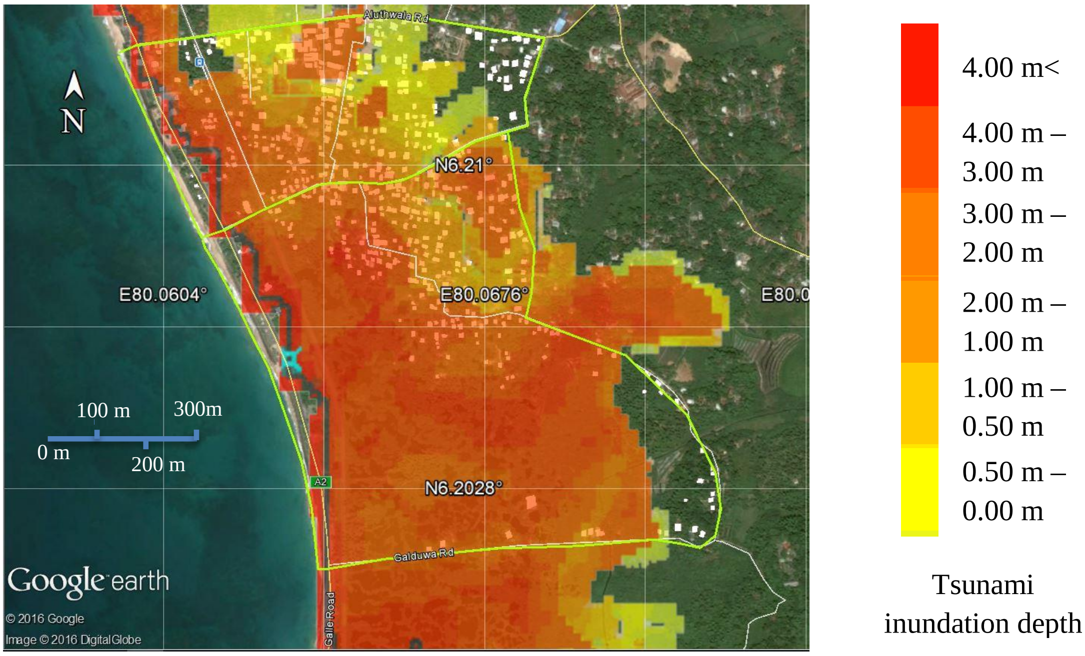


Figure 23: Tsunami inundation depth – Scenario 1 (Mw = 9.0)

Table 13: Number of inundated houses – Scenario 1 (Mw = 9.0)

Case	Scenario 1 Mw = 9.0			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	2	10	51	5
0.5 - 1.0	1	5	24	2
1.0 - 2.0	1	5	24	2
2.0 -3.0	4	14	78	7
3.0 - 4.0	1	5	26	2
4.0<	3	11	60	6

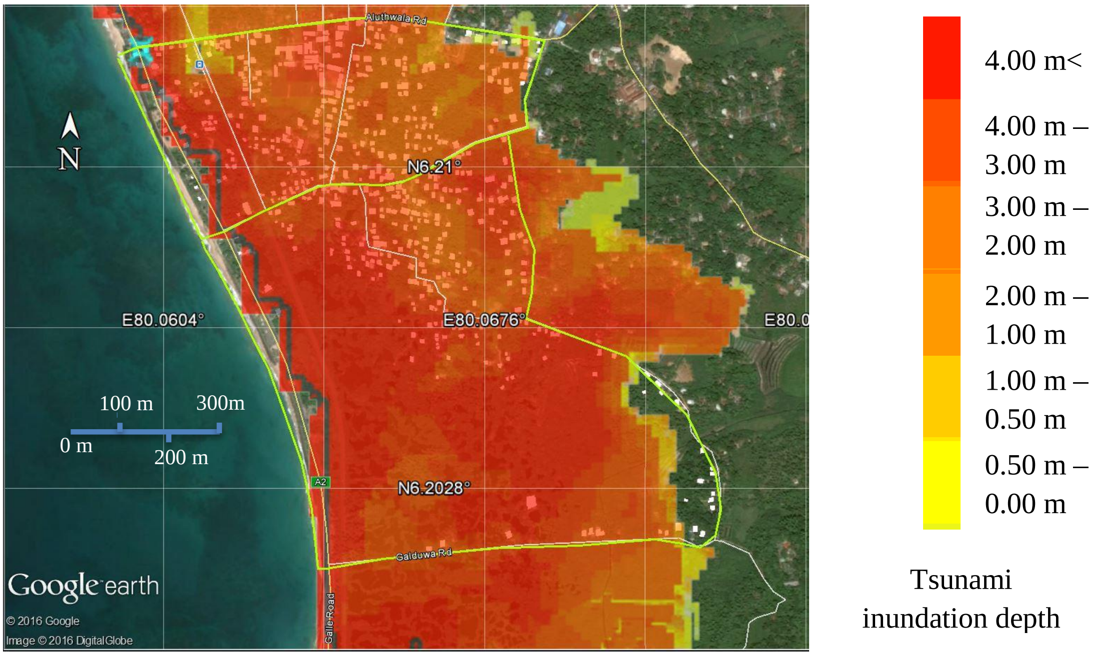


Figure 24: Tsunami inundation depth – Scenario 1 (Mw = 9.1)

Table 14: Number of inundated houses – Scenario 1 (Mw = 9.1)

Case	Scenario 1 Mw = 9.1			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	2	11	1
0.5 - 1.0	1	5	28	3
1.0 - 2.0	1	5	28	3
2.0 -3.0	3	12	62	6
3.0 - 4.0	1	4	21	2
4.0<	6	24	128	12

3.1.1.2 With revetment

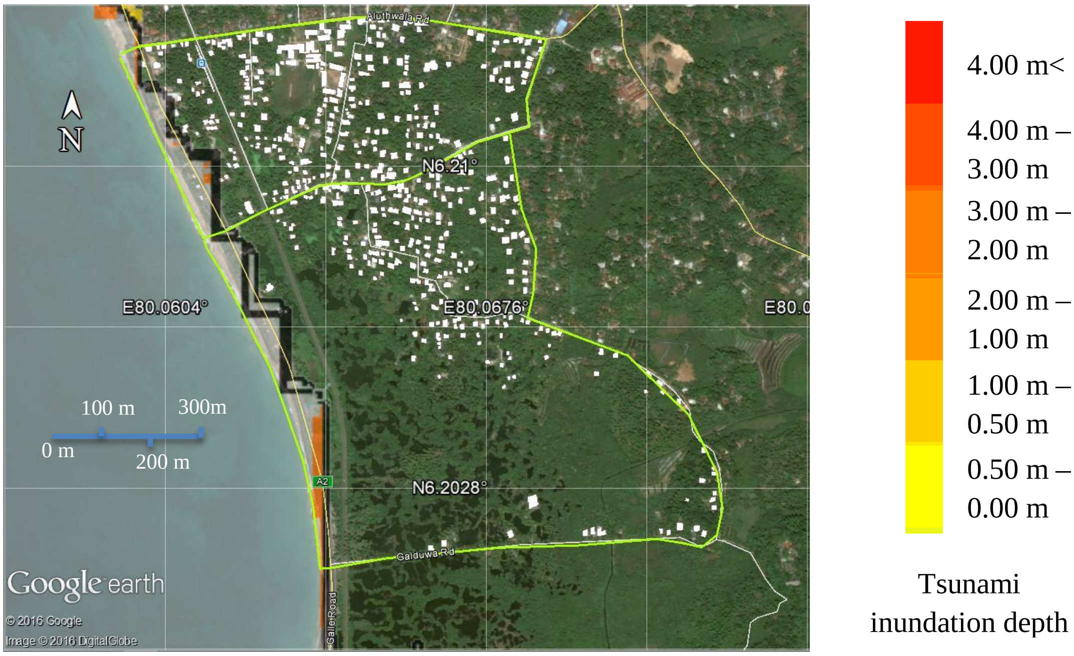


Figure 25: Tsunami inundation depth – Scenario 1 (Mw = 8.4)

Table 15: Number of inundated houses – Scenario 1 (Mw = 8.4)

Case	Scenario 1 Mw = 8.4			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	0	0
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	0	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	0	0

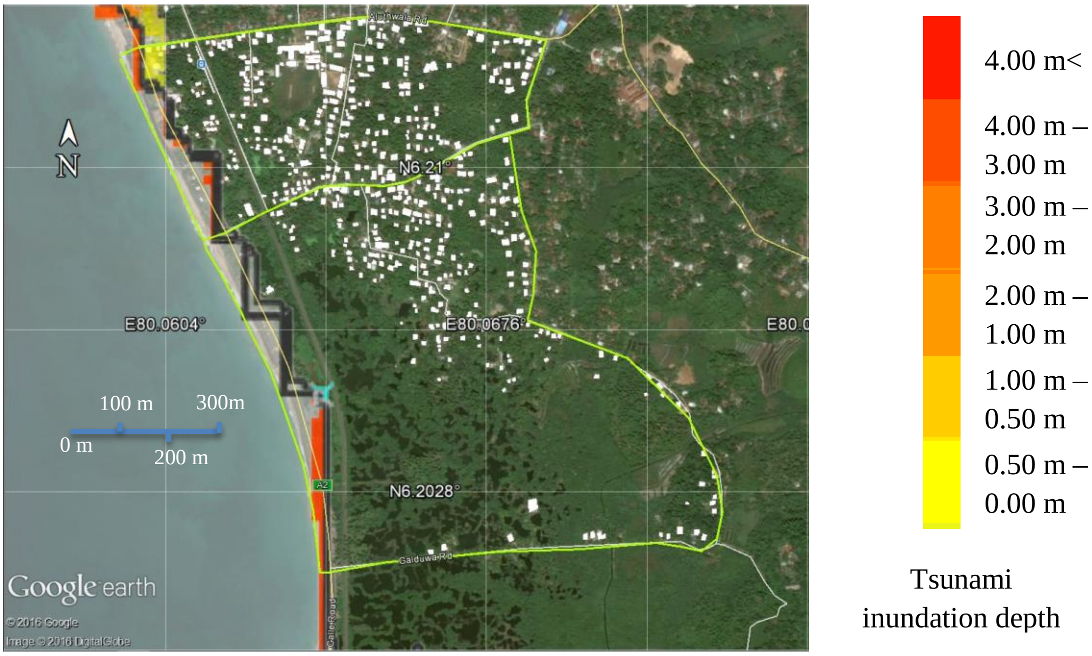


Figure 26: Tsunami inundation depth – Scenario 2 (Mw = 8.8)

Table 16: Number of inundated houses – Scenario 2 (Mw = 8.8)

Case	Scenario 2 Mw = 8.8			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	5	0
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	0	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	0	0

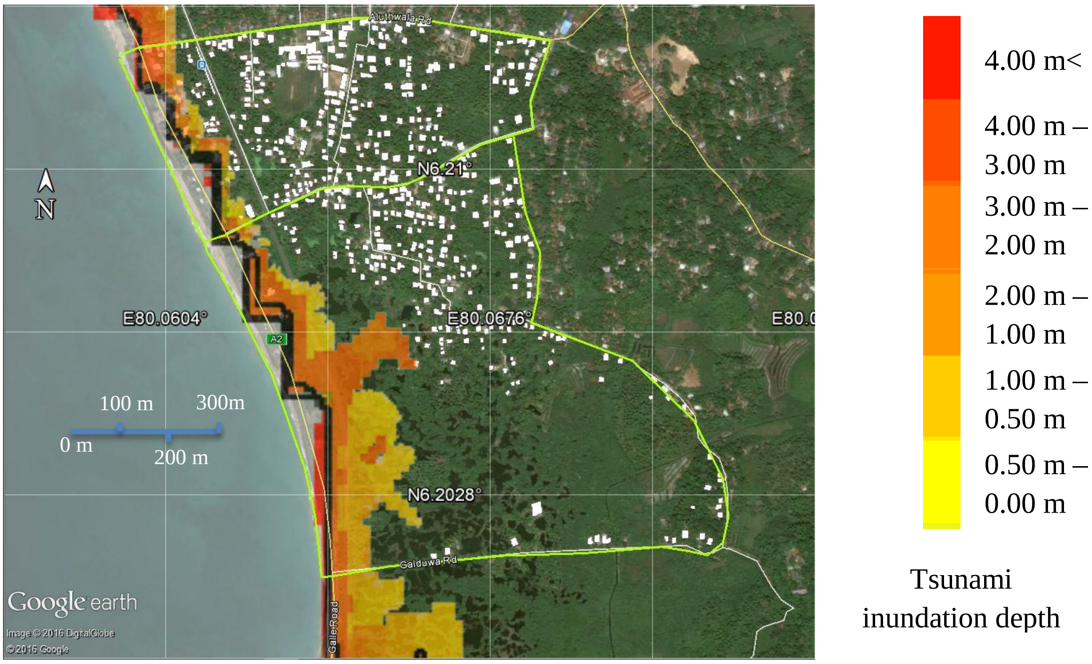


Figure 27: Tsunami inundation depth – Scenario 2 (Mw = 8.9)

Table 17: Number of inundated houses – Scenario 2 (Mw = 8.9)

Case	Scenario 2 Mw = 8.9			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	3	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	0	0
2.0 -3.0	0	1	6	1
3.0 - 4.0	0	0	2	0
4.0<	0	1	4	0

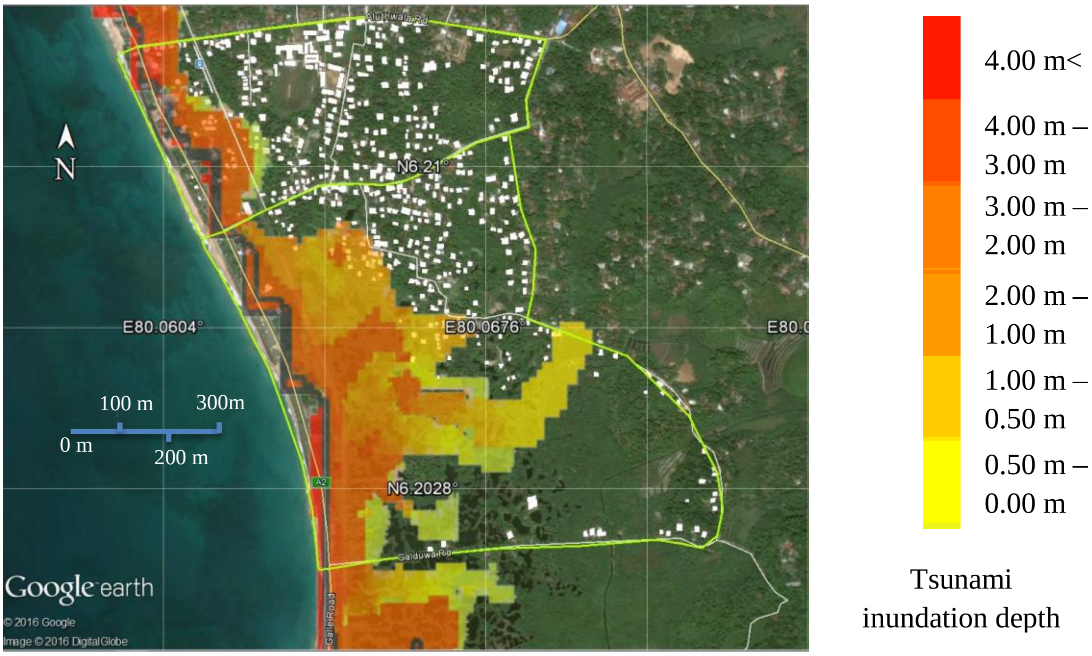


Figure 28: Tsunami inundation depth – Scenario 2 (Mw = 9.0)

Table 18: Number of inundated houses – Scenario 2 (Mw = 9.0)

Case	Scenario 2 Mw = 9.0			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	2	11	1
0.5 - 1.0	0	2	10	1
1.0 - 2.0	0	2	10	1
2.0 -3.0	1	2	12	1
3.0 - 4.0	0	1	4	0
4.0<	0	1	7	1

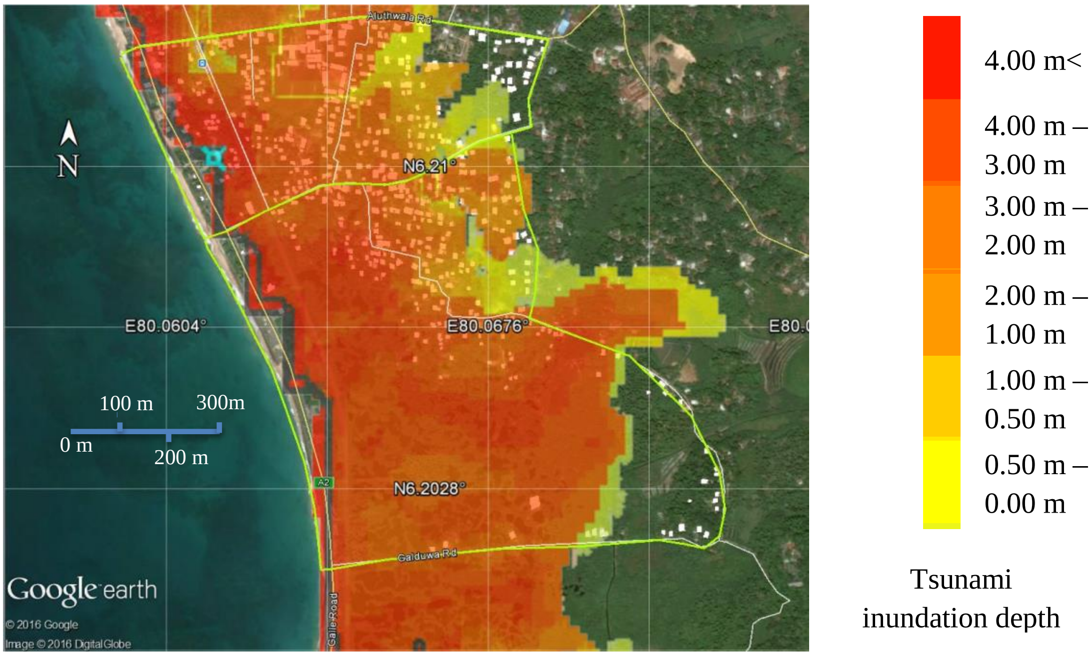


Figure 29: Tsunami inundation depth – Scenario 2 (Mw = 9.1)

Table 19: Number of inundated houses – Scenario 2 (Mw = 9.1)

Case	Scenario 2 Mw = 9.1			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	5	28	3
0.5 - 1.0	1	4	23	2
1.0 - 2.0	1	4	23	2
2.0 -3.0	5	20	106	10
3.0 - 4.0	2	7	35	3
4.0<	1	5	29	3

3.1.1.3 With railway embankment with grade crossings

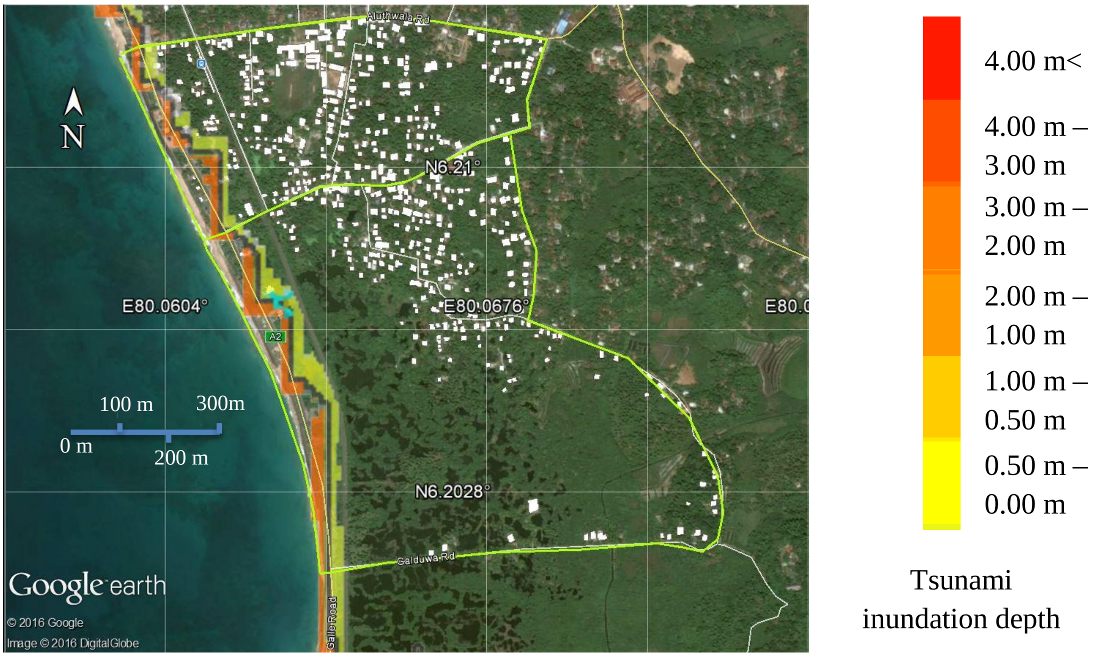


Figure 30: Tsunami inundation depth – Scenario 3 (Mw = 8.4)

Table 20: Number of inundated houses – Scenario 3 (Mw = 8.4)

Case	Scenario 3 Mw = 8.4			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	2	9	1
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	0	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	0	0

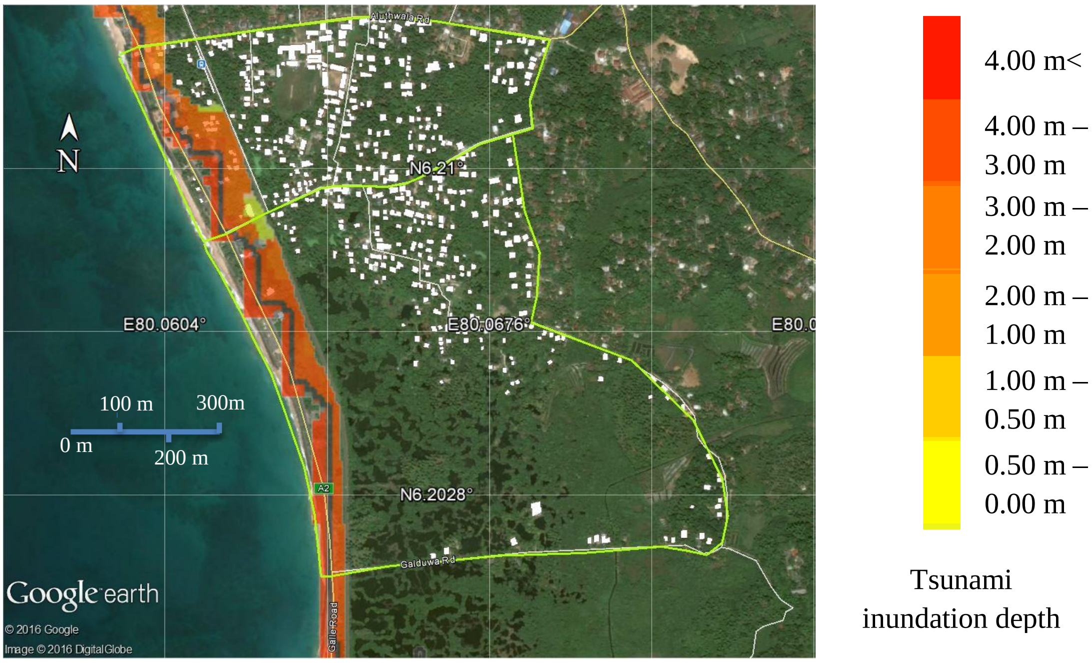


Figure 31: Tsunami inundation depth – Scenario 3 (Mw = 8.8)

Table 21: Number of inundated houses – Scenario 3 (Mw = 8.8)

Case	Scenario 3 Mw = 8.8			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	2	0
0.5 - 1.0	0	1	4	0
1.0 - 2.0	0	1	4	0
2.0 -3.0	0	1	7	1
3.0 - 4.0	0	0	2	0
4.0<	0	0	0	0

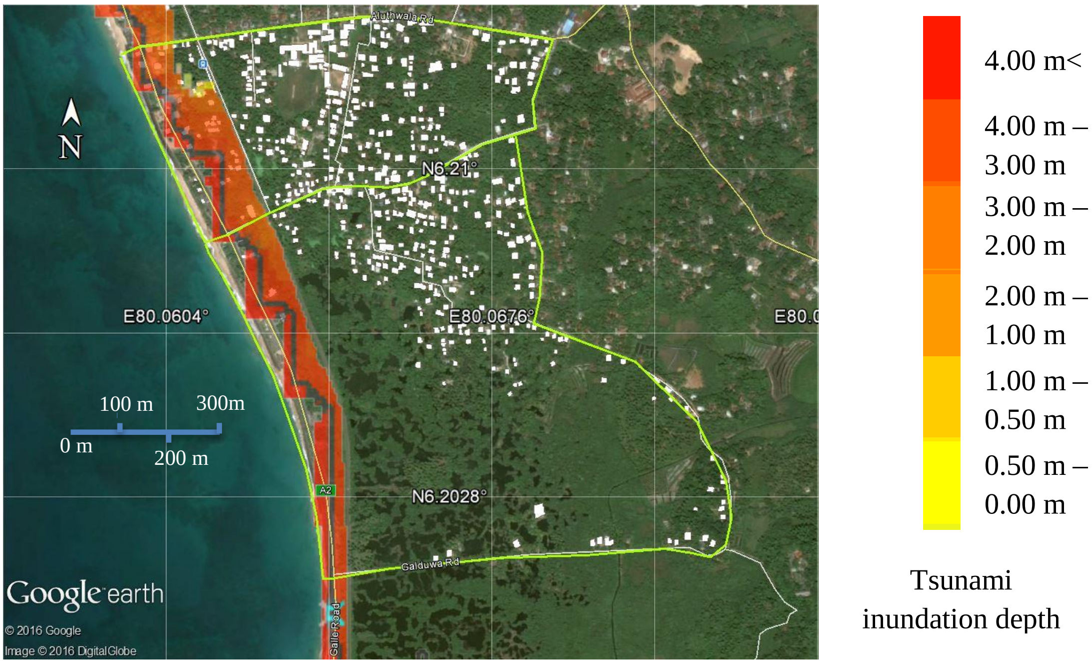


Figure 32: Tsunami inundation depth – Scenario 3 (Mw = 8.9)

Table 22: Number of inundated houses – Scenario 3 (Mw = 8.9)

Case	Scenario 3 Mw = 8.9			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	4	0
0.5 - 1.0	0	1	4	0
1.0 - 2.0	0	1	4	0
2.0 -3.0	0	1	7	1
3.0 - 4.0	0	0	2	0
4.0<	0	1	6	1

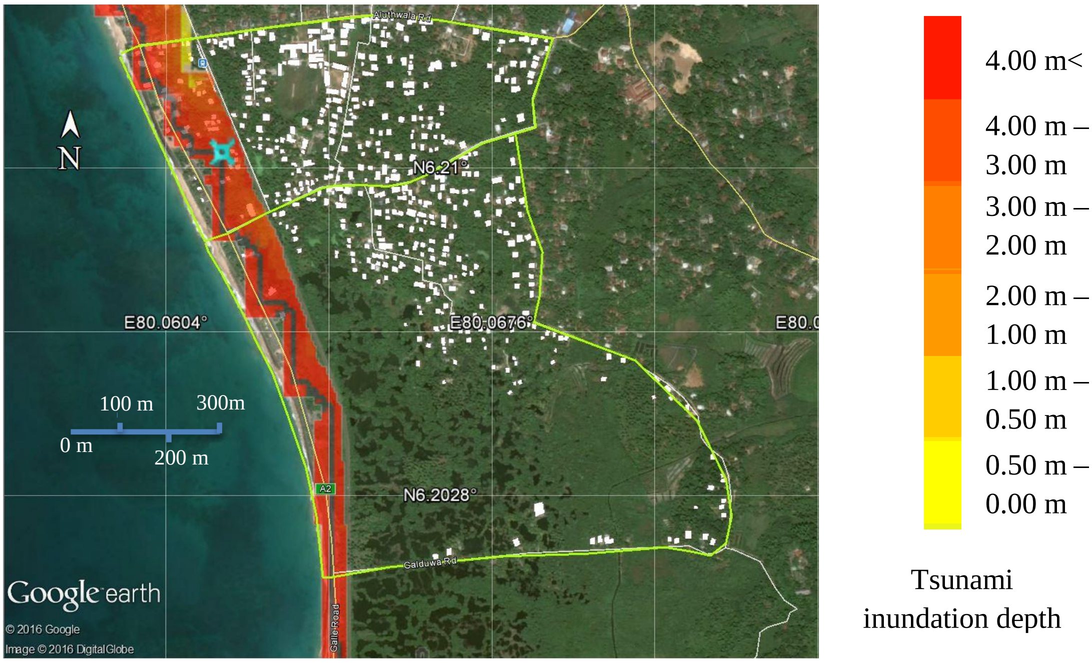


Figure 33: Tsunami inundation depth – Scenario 3 (Mw = 9.0)

Table 23: Number of inundated houses – Scenario 3 (Mw = 9.0)

Case	Scenario 3 Mw = 9.0			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	4	0
0.5 - 1.0	0	1	4	0
1.0 - 2.0	0	1	4	0
2.0 -3.0	0	1	7	1
3.0 - 4.0	0	0	2	0
4.0<	0	1	6	1

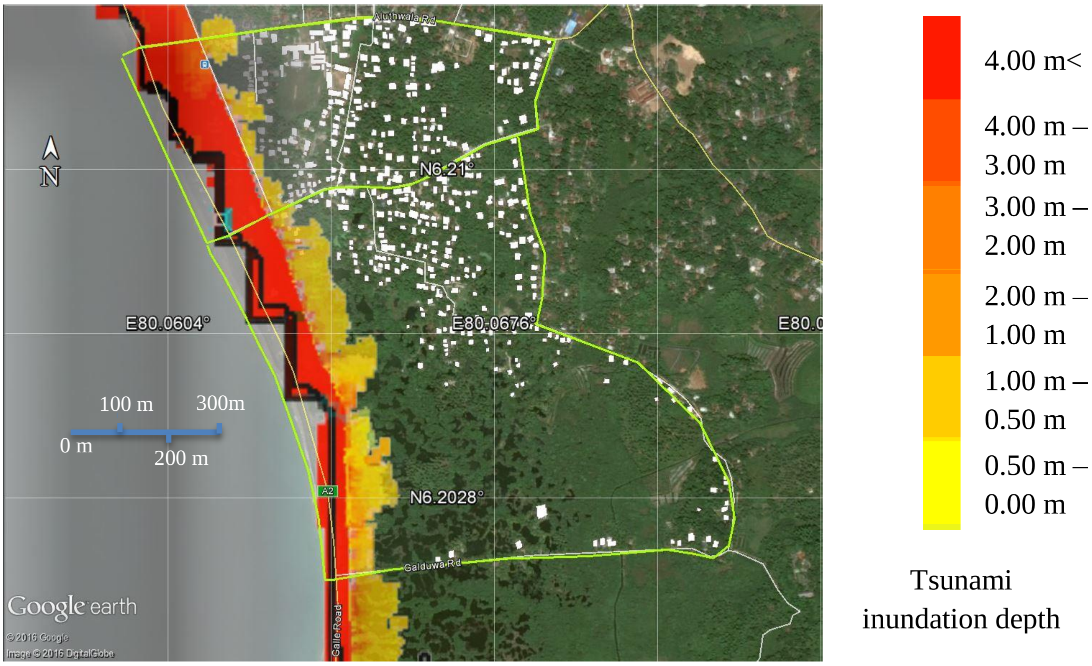


Figure 34: Tsunami inundation depth – Scenario 3 (Mw = 9.1)

Table 24: Number of inundated houses – Scenario 3 (Mw = 9.1)

Case	Scenario 3 Mw = 9.1			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	0	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	0	0
2.0 -3.0	0	1	3	0
3.0 - 4.0	0	0	1	0
4.0<	2	6	34	3

3.1.1.4 With railway embankment with underpasses

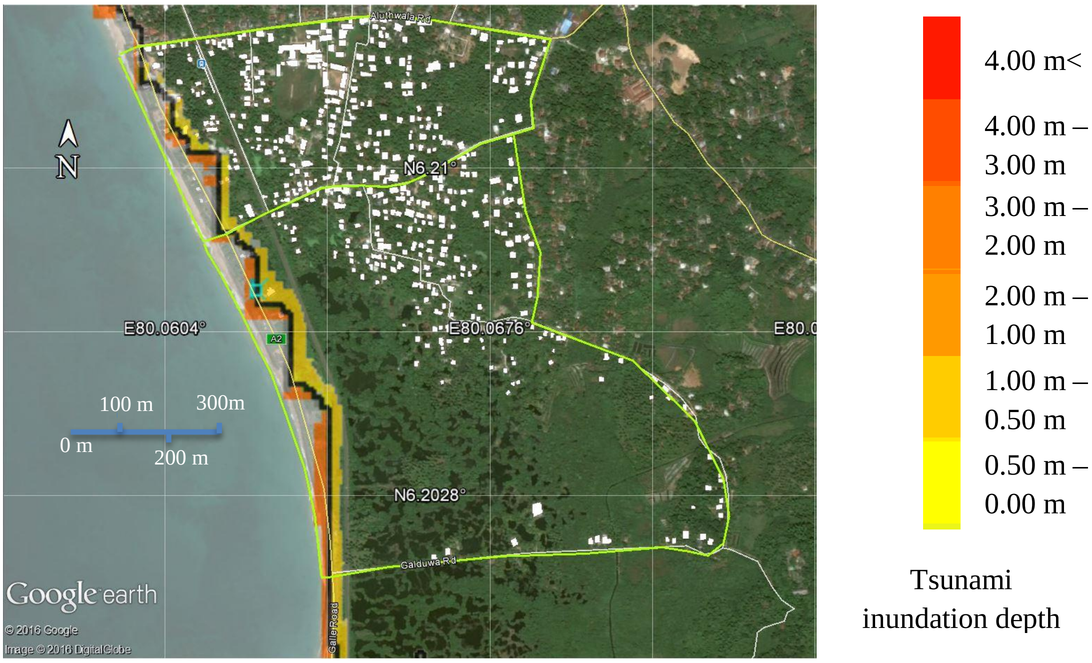


Figure 35: Tsunami inundation depth – Scenario 4 (Mw = 8.4)

Table 25: Number of inundated houses – Scenario 4 (Mw = 8.4)

Case	Scenario 4 Mw = 8.4			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	2	9	1
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	0	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	0	0

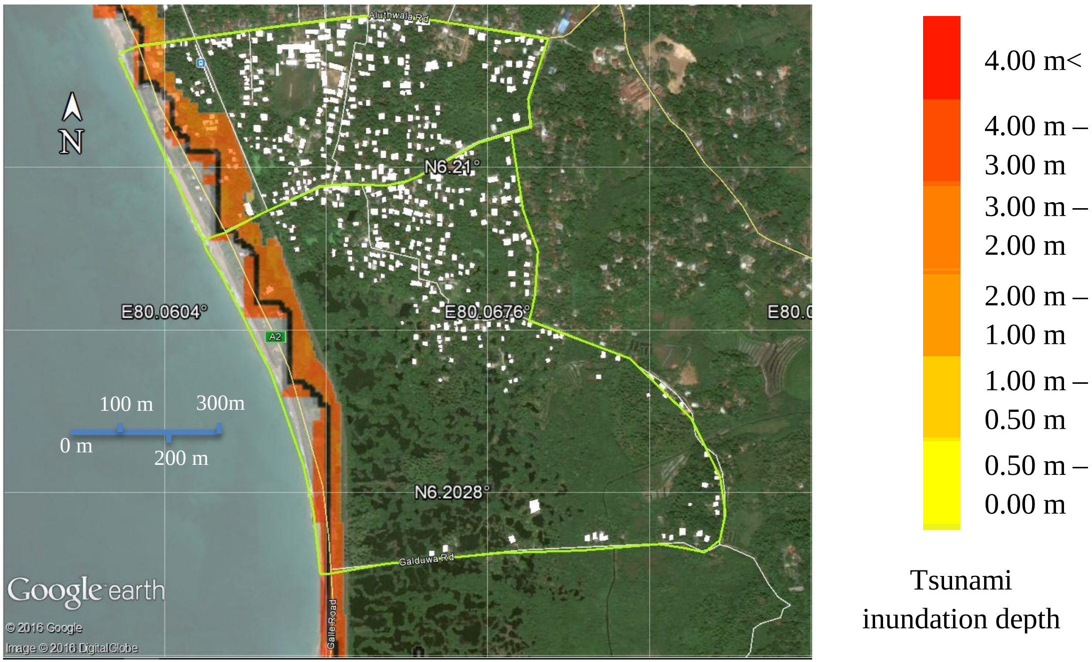


Figure 36: Tsunami inundation depth – Scenario 4 (Mw = 8.8)

Table 26: Number of inundated houses – Scenario 4 (Mw = 8.8)

Case	Scenario 4 Mw = 8.8			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	2	0
0.5 - 1.0	0	1	4	0
1.0 - 2.0	0	1	4	0
2.0 -3.0	0	1	7	1
3.0 - 4.0	0	0	2	0
3.0 - 4.0	0	0	0	0
4.0<	0	0	2	0

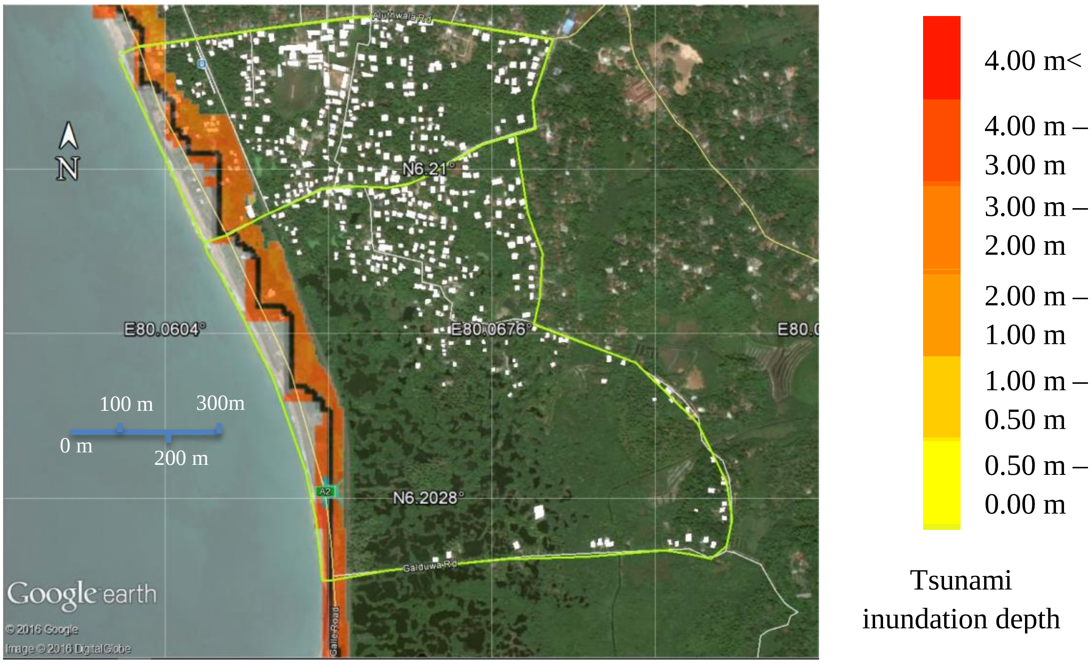


Figure 37: Tsunami inundation depth – Scenario 4 (Mw = 8.9)

Table 27: Number of inundated houses – Scenario 4 (Mw = 8.9)

Case	Scenario 4 Mw = 8.9			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	6	1
0.5 - 1.0	0	1	4	0
1.0 - 2.0	0	1	4	0
2.0 -3.0	0	1	7	1
3.0 - 4.0	0	0	2	0
4.0<	0	1	6	1

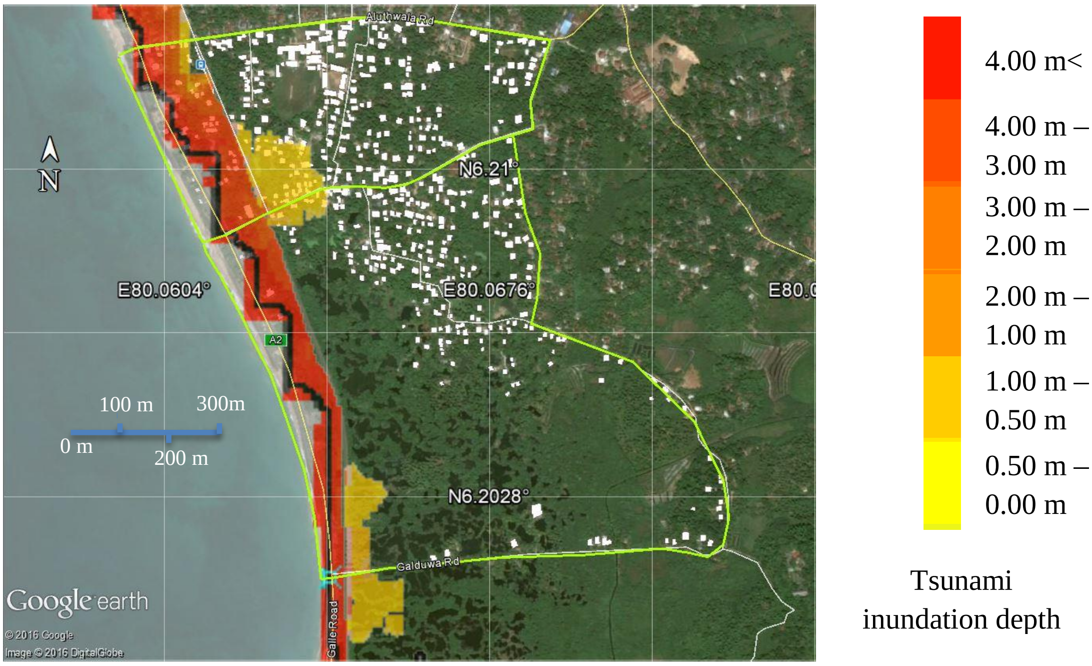


Figure 38: Tsunami inundation depth – Scenario 4 (Mw = 9.0)

Table 28: Number of inundated houses – Scenario 4 (Mw = 9.0)

Case	Scenario 4 Mw = 9.0			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	5	0
0.5 - 1.0	0	2	11	1
1.0 - 2.0	0	2	11	1
2.0 -3.0	1	3	15	1
3.0 - 4.0	0	1	5	0
4.0<	1	3	17	2

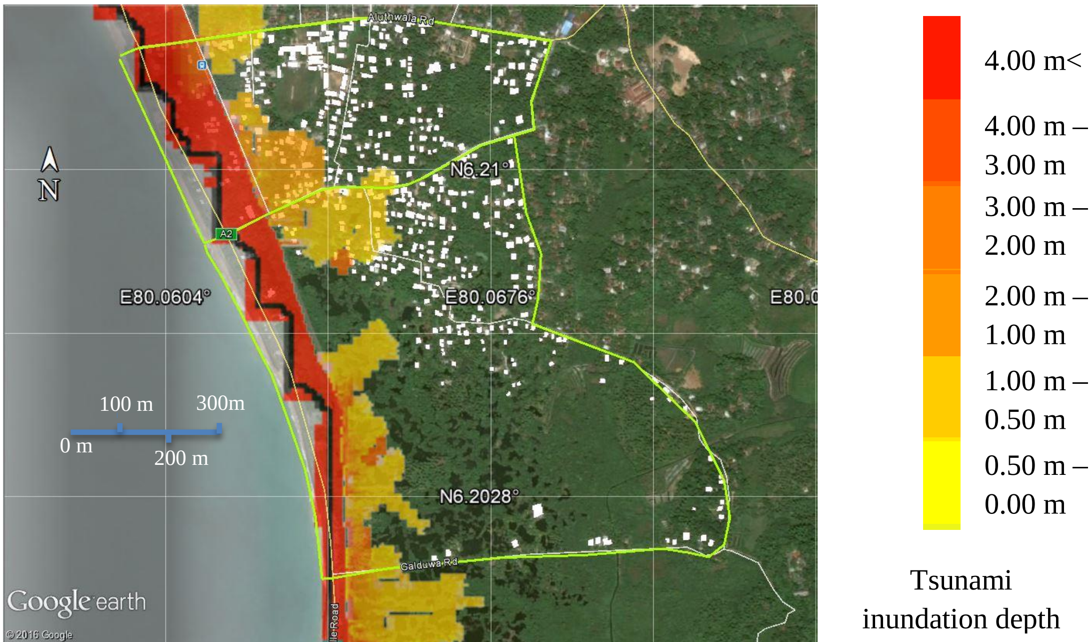


Figure 39: Tsunami inundation depth – Scenario 4 (Mw = 9.1)

Table 29: Number of inundated houses – Scenario 4 (Mw = 9.1)

Case	Scenario 4 Mw = 9.1			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	4	20	2
0.5 - 1.0	0	2	11	1
1.0 - 2.0	0	2	11	1
2.0 -3.0	0	1	5	0
3.0 - 4.0	0	0	2	0
4.0<	2	6	32	3

3.1.1.5 With both revetment and railway embankment with grade crossings

Author did not consider the case of earthquake magnitude of 8.4Mw and 8.8Mw. Because tsunamis generated by earthquake magnitude 8.4Mw and 8.8Mw did not overflow the revetment.

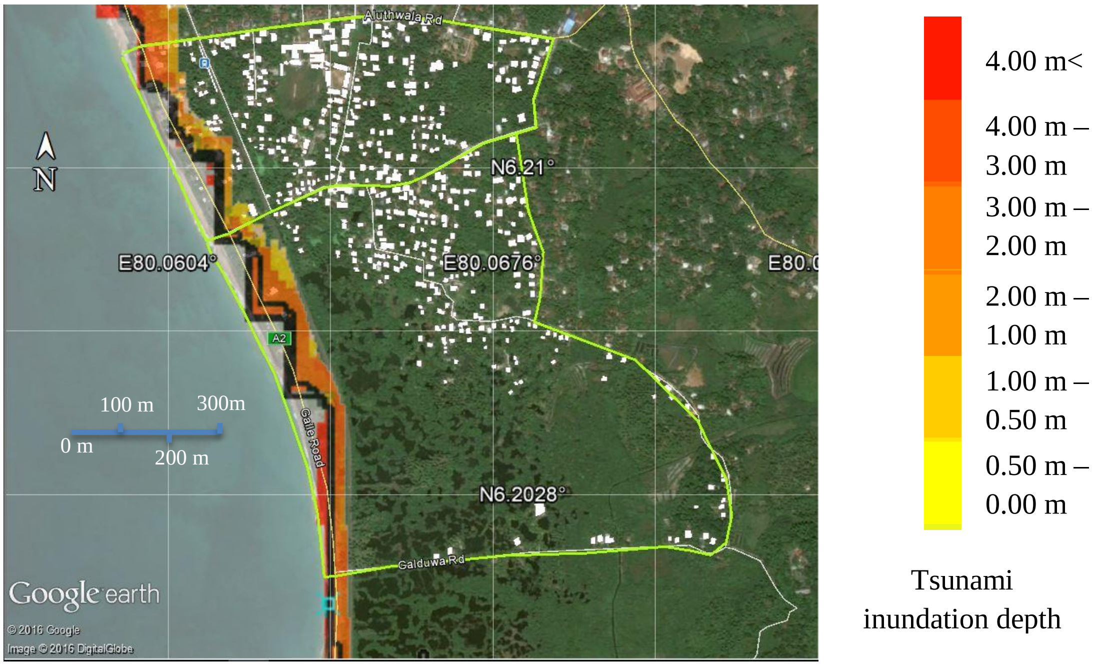


Figure 40: Tsunami inundation depth – Scenario 5 (Mw = 8.9)

Table 30: Number of inundated houses – Scenario 5 (Mw = 8.9)

Case	Scenario 5 Mw = 8.9			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	3	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	0	0
2.0 -3.0	0	1	6	1
3.0 - 4.0	0	0	2	0
4.0<	0	1	4	0

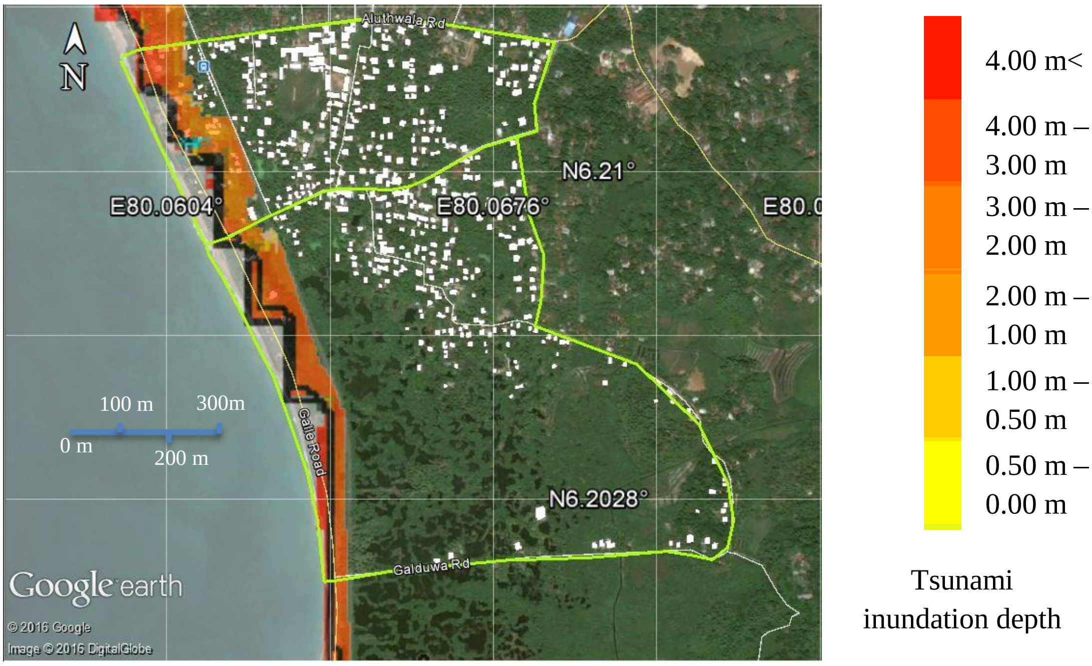


Figure 41: Tsunami inundation depth – Scenario 5 (Mw = 9.0)

Table 31: Number of inundated houses – Scenario 5 (Mw = 9.0)

Case	Scenario 5 Mw = 9.0			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	2	0
0.5 - 1.0	0	0	1	0
1.0 - 2.0	0	1	5	0
2.0 -3.0	1	0	8	1
3.0 - 4.0	0	2	7	1
4.0<	1	2	4	0

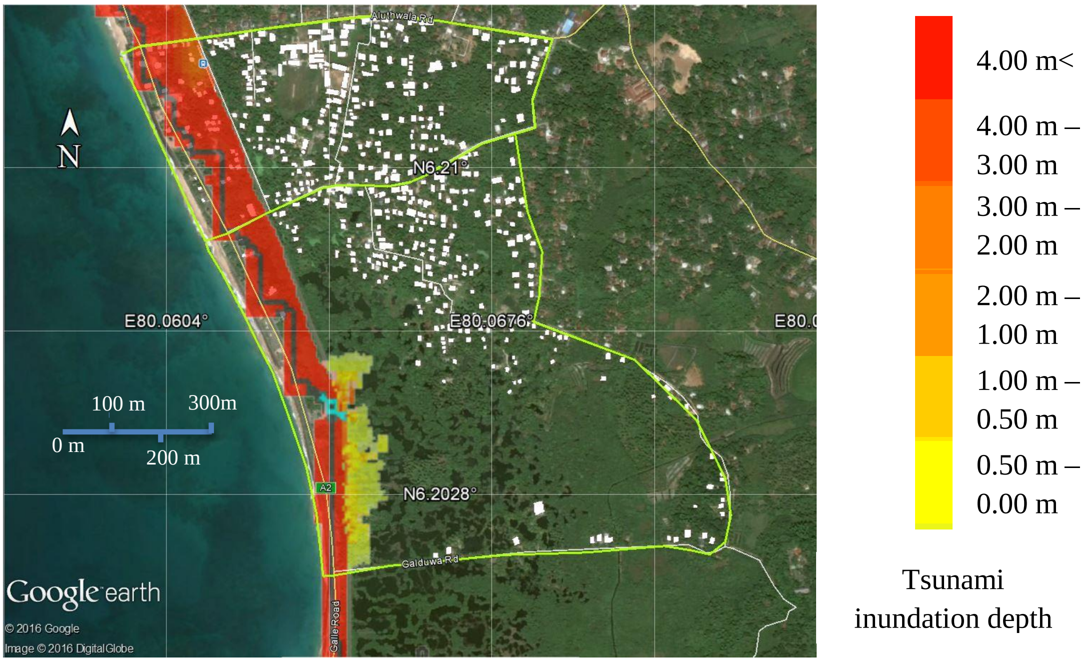


Figure 42: Tsunami inundation depth – Scenario 5 (Mw = 9.1)

Table 32: Number of inundated houses – Scenario 5 (Mw = 9.1)

Case	Scenario 5 Mw = 9.1			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	0	0
0.5 - 1.0	0	0	1	0
1.0 - 2.0	0	2	9	1
2.0 -3.0	1	1	6	1
3.0 - 4.0	0	2	11	1
4.0<	1	2	10	1

3.1.1.6 Increase revetment height from 4.0m to 5.0m by 0.2 intervals at Mw=9.0

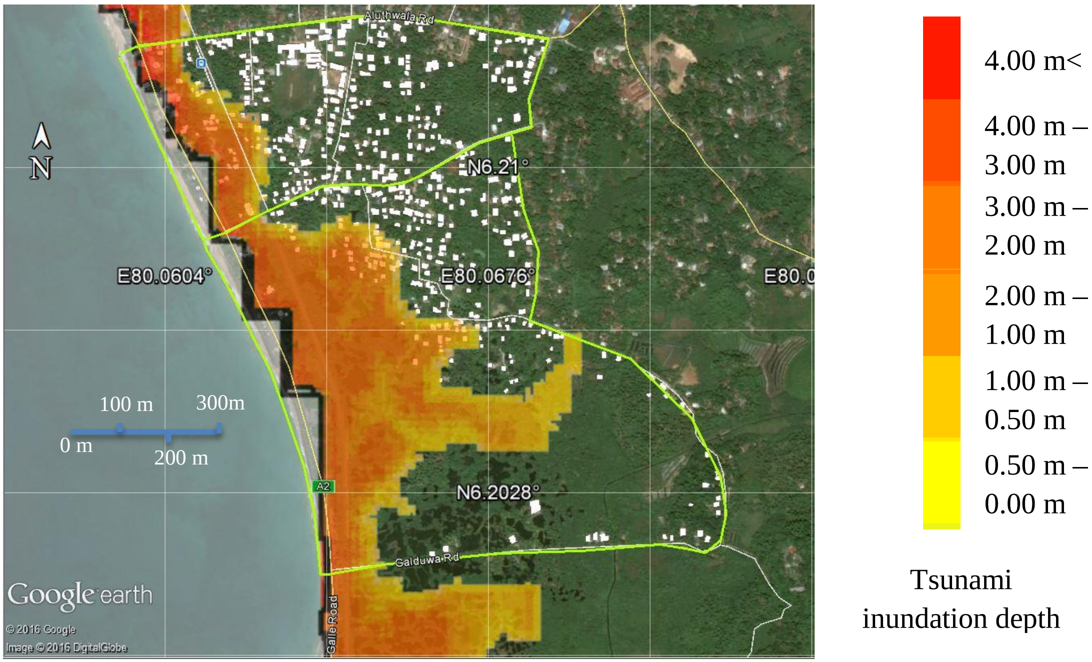


Figure 43: Tsunami inundation depth – Scenario 6 (Mw = 9.0)

Table 33: Number of inundated houses – Scenario 6 ((Mw = 9.0)

Case	Scenario 6 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	1	8	1
0.5 - 1.0	0	1	9	1
1.0 - 2.0	1	3	17	0
2.0 -3.0	0	1	5	0
3.0 - 4.0	0	0	3	0
4.0<	0	1	7	1

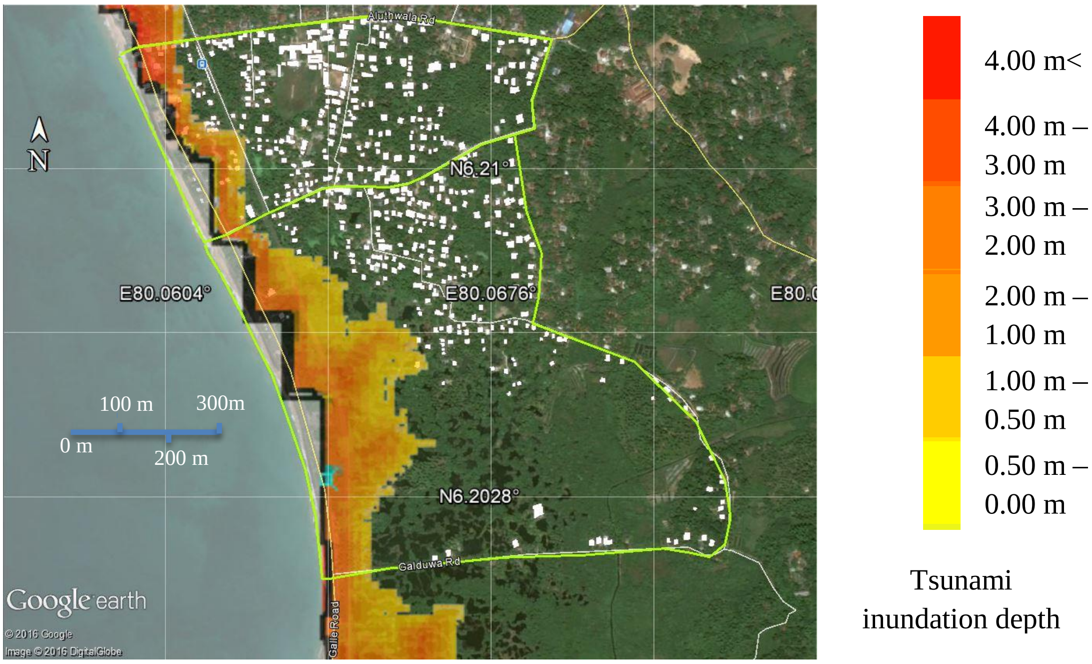


Figure 44 – Tsunami inundation depth – Scenario7 (Mw = 9.0)

Table 34: Number of inundated houses – Scenario 7 (Mw = 9.0)

Case	Scenario 7(Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	1	0	6	2
0.5 - 1.0	1	0	7	1
1.0 - 2.0	0	1	5	0
2.0 -3.0	0	2	9	1
3.0 - 4.0	0	1	5	1
4.0<	0	2	5	0

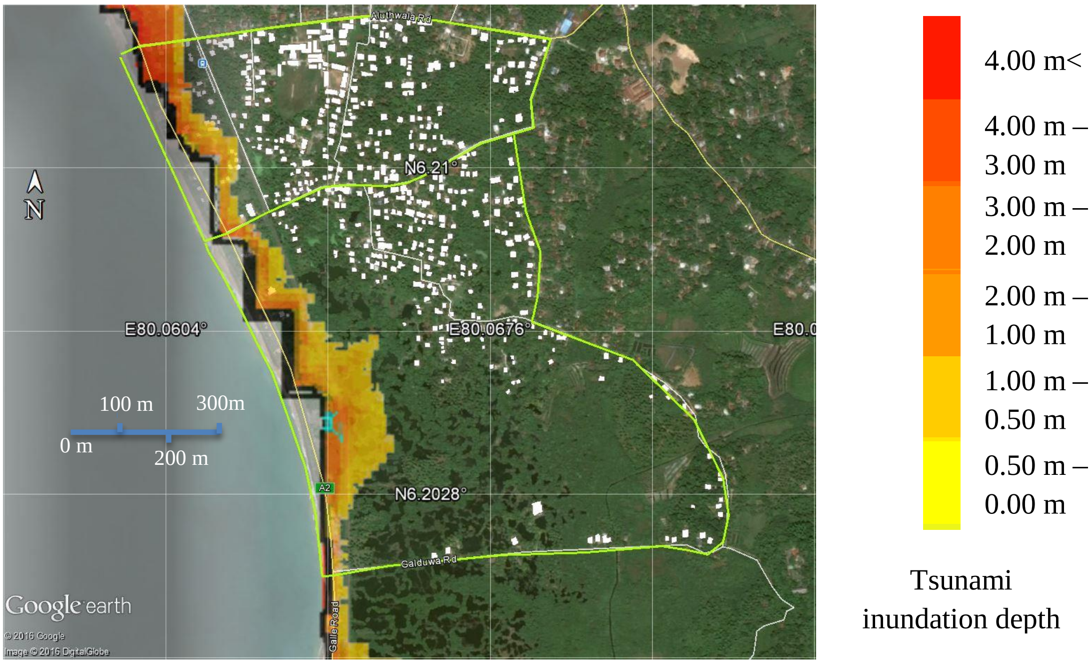


Figure 45: Tsunami inundation depth – Scenario 8 (Mw = 9.0)

Table 35: Number of inundated houses – Scenario 8 (Mw = 9.0)

Case	Scenario 8 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	2	1
0.5 - 1.0	0	2	4	0
1.0 - 2.0	0	1	3	0
2.0 -3.0	0	2	7	0
3.0 - 4.0	0	1	2	1
4.0<	0	2	5	0

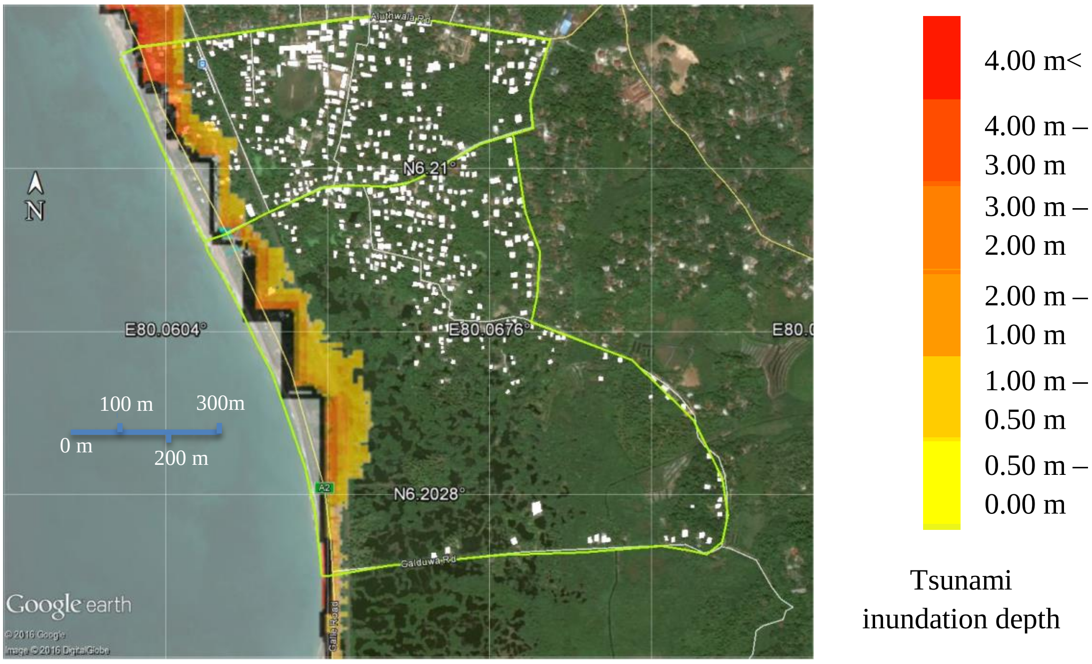


Figure 46: Tsunami inundation depth – Scenario 9 (Mw = 9.0)

Table 36: Number of inundated houses – Scenario 9 (Mw = 9.0)

Case	Scenario 9 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	2	0
0.5 - 1.0	0	2	3	0
1.0 - 2.0	0	1	3	0
2.0 -3.0	0	0	3	0
3.0 - 4.0	0	1	5	1
4.0<	0	1	5	0

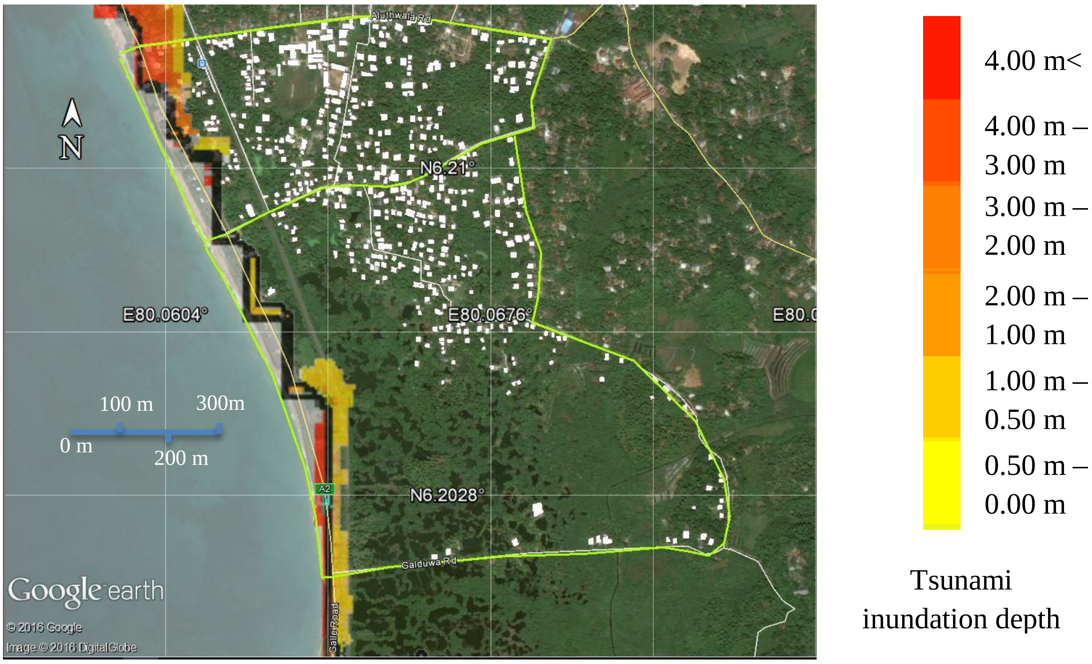


Figure 47: Tsunami inundation depth – Scenario 10 (Mw = 9.0)

Table 37: Number of inundated houses – Scenario 10 (Mw = 9.0)

Case	Scenario 10 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	1	0
0.5 - 1.0	0	1	3	0
1.0 - 2.0	0	1	3	0
2.0 -3.0	0	0	1	0
3.0 - 4.0	0	1	7	1
4.0<	0	1	3	0

3.1.1.7 Increase revetment height from 4.0m to 5.0m by 0.2 intervals at Mw=8.9

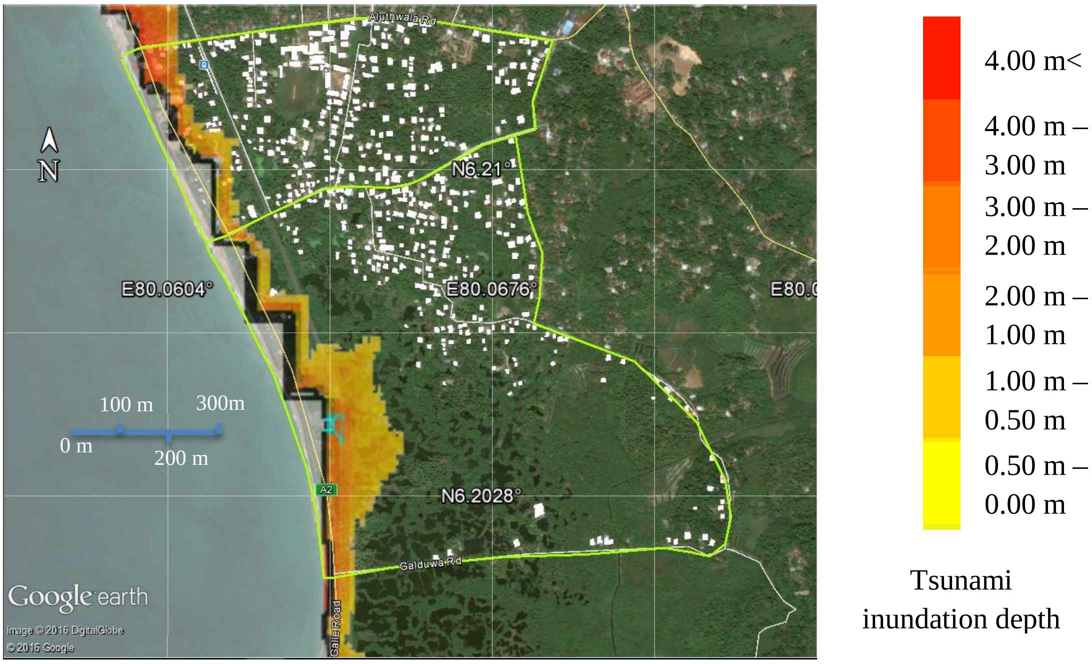


Figure 48: Tsunami inundation depth – Scenario 6 (Mw = 8.9)

Table 38: Number of inundated houses – Scenario 6 (Mw = 8.9)

Case	Scenario 6 (Mw = 8.9)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	3	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	1	5	0
3.0 - 4.0	0	1	4	0
4.0<	0	0	2	0

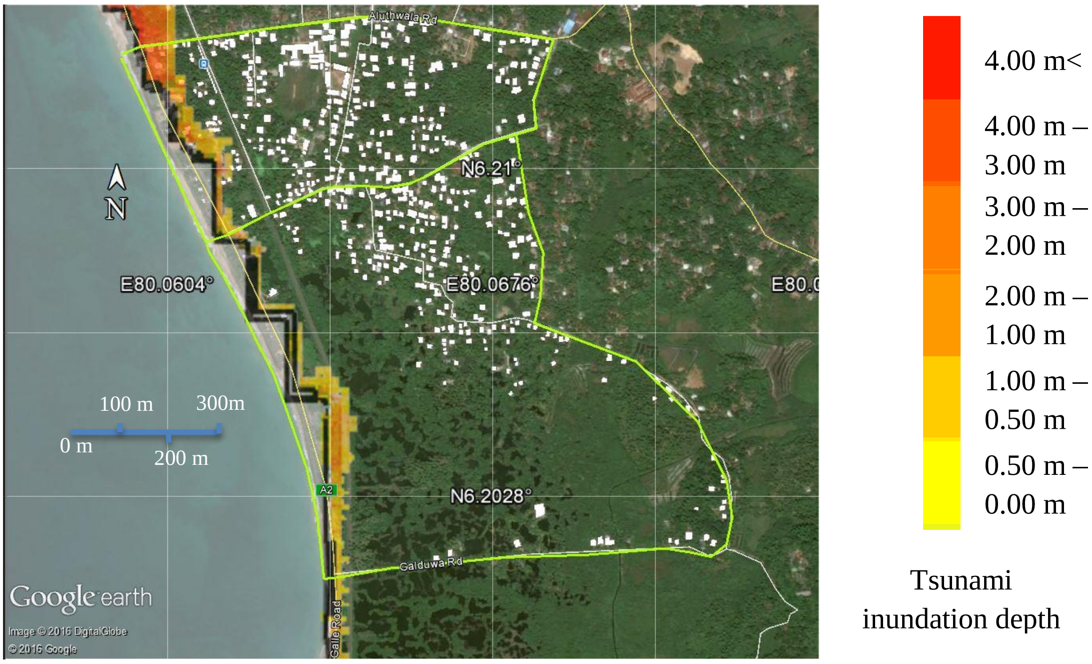


Figure 49: Tsunami inundation depth – Scenario 7 (Mw = 8.9)

Table 39: Number of inundated houses – Scenario 7 (Mw = 8.9)

Case	Scenario 7 (Mw = 8.9)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	1	4	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	0	0
2.0 -3.0	0	1	3	0
3.0 - 4.0	0	1	4	0
4.0<	0	0	2	0

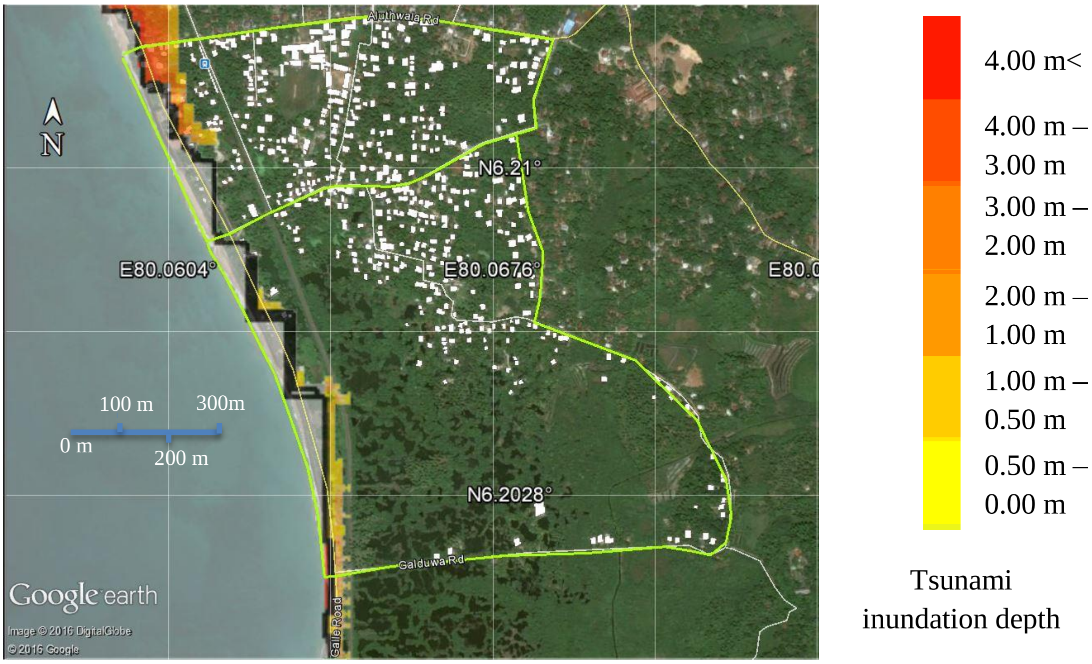


Figure 50: Tsunami inundation depth – Scenario 8 (Mw = 8.9)

Table 40: Number of inundated houses – Scenario 8 (Mw = 8.9)

Case	Scenario 8 (Mw = 8.9)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	1	0
0.5 - 1.0	0	0	2	0
1.0 - 2.0	0	0	2	0
2.0 -3.0	0	0	2	0
3.0 - 4.0	0	1	4	0
4.0<	0	0	1	0

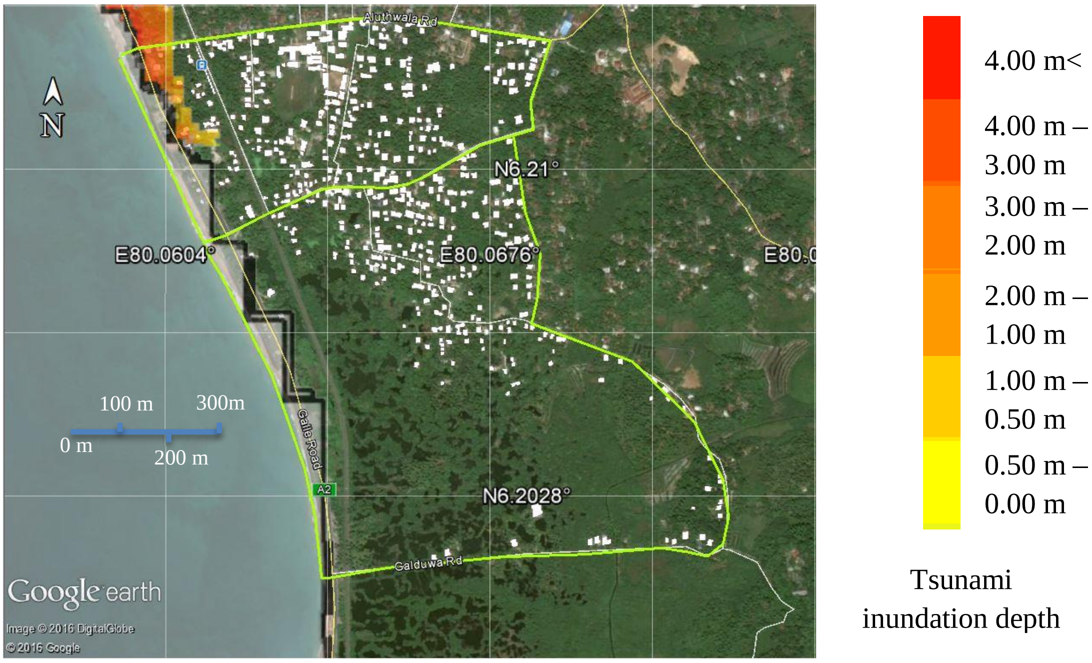


Figure 51: Tsunami inundation depth – Scenario 9 (Mw = 8.9)

Table 41: Number of inundated houses – Scenario 9 (Mw = 8.9)

Case	Scenario 9 (Mw = 8.9)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	2	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	0	0
2.0 -3.0	0	0	2	0
3.0 - 4.0	0	1	3	0
4.0<	0	0	1	0

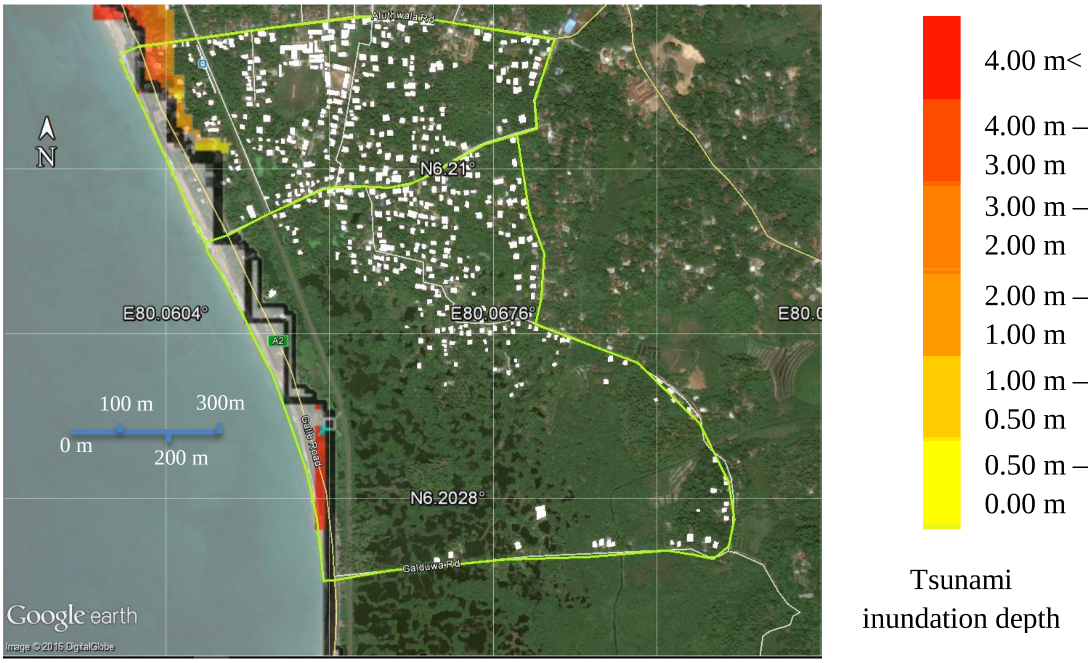


Figure 52: Tsunami inundation depth – Scenario 10 (Mw = 8.9)

Table 42: Number of inundated houses – Scenario 10 (Mw = 8.9)

Case	Scenario 10 (Mw = 8.9)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	0	0	2	0
0.5 - 1.0	0	0	0	0
1.0 - 2.0	0	0	1	0
2.0 -3.0	0	1	3	0
3.0 - 4.0	0	0	2	0
4.0<	0	0	0	0

3.1.1.8 Increase revetment height from 4.0m to 5.0m by 0.2 intervals at Mw=9.1

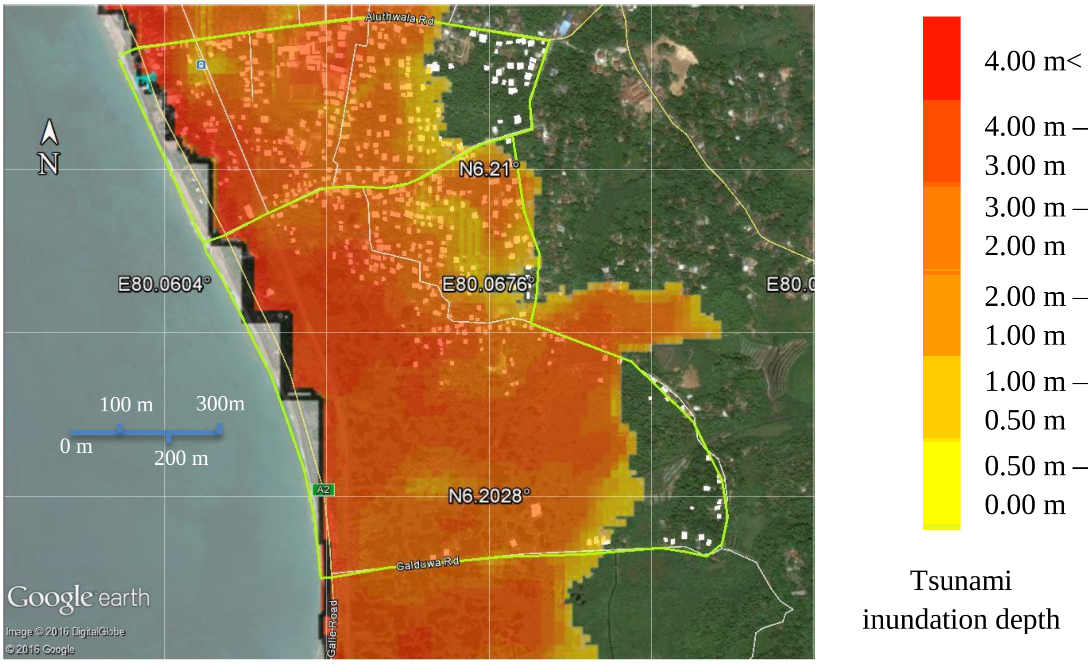


Figure 53: Tsunami inundation depth – Scenario 6 (Mw = 9.0)

Table 43: Number of inundated houses – Scenario 6 (Mw = 9.0)(

Case	Scenario 6 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	2	10	53	5
0.5 - 1.0	1	5	29	3
1.0 - 2.0	2	5	58	5
2.0 -3.0	2	7	38	4
3.0 - 4.0	1	4	22	2
4.0<	2	8	43	4

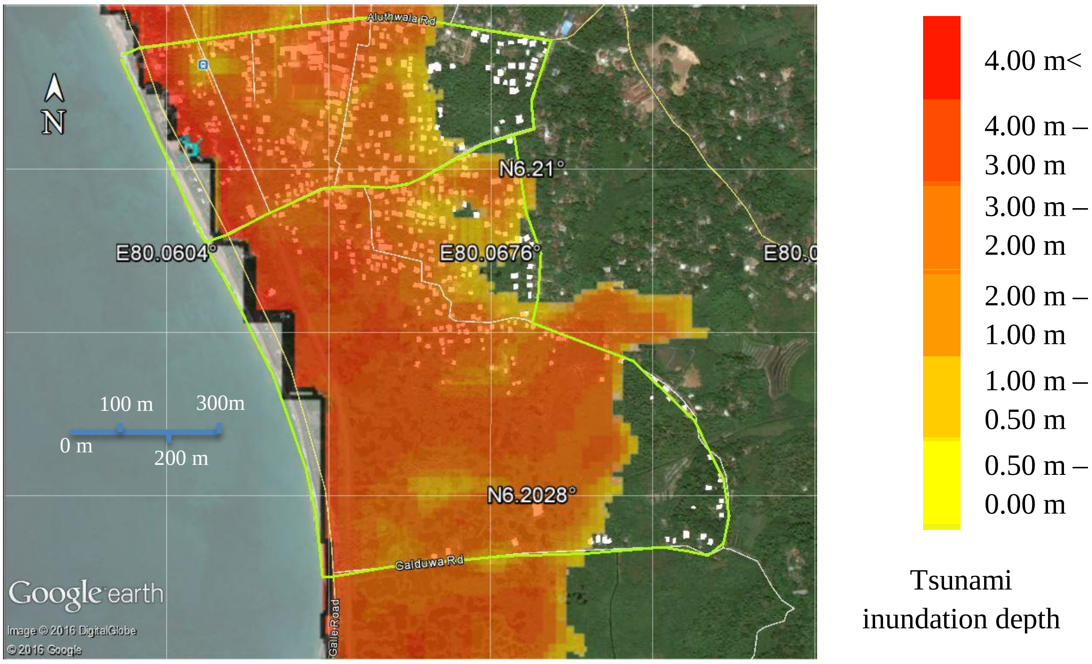


Figure 54: Tsunami inundation depth – Scenario 7 (Mw = 9.0)

Table 44: Number of inundated houses – Scenario 7 (Mw = 9.0)

Case	Scenario 7 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	2	7	35	3
0.5 - 1.0	2	7	37	3
1.0 - 2.0	2	7	39	4
2.0 -3.0	3	13	70	7
3.0 - 4.0	1	5	27	3
4.0<	1	5	29	3

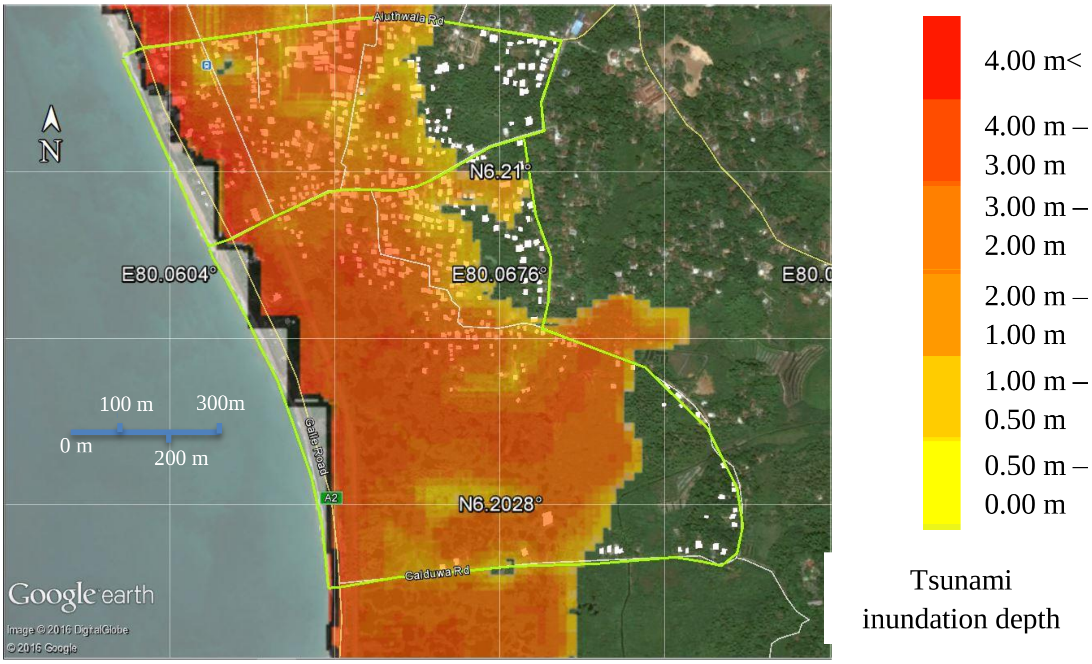


Figure 55: Tsunami inundation depth – Scenario 8 (Mw = 9.0)

Table 45: Number of inundated houses – Scenario 8 (Mw = 9.0)

Case	Scenario 8 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	2	10	51	5
0.5 - 1.0	2	10	53	5
1.0 - 2.0	1	2	13	1
2.0 -3.0	3	11	60	6
3.0 - 4.0	2	6	33	3
4.0<	1	4	23	2

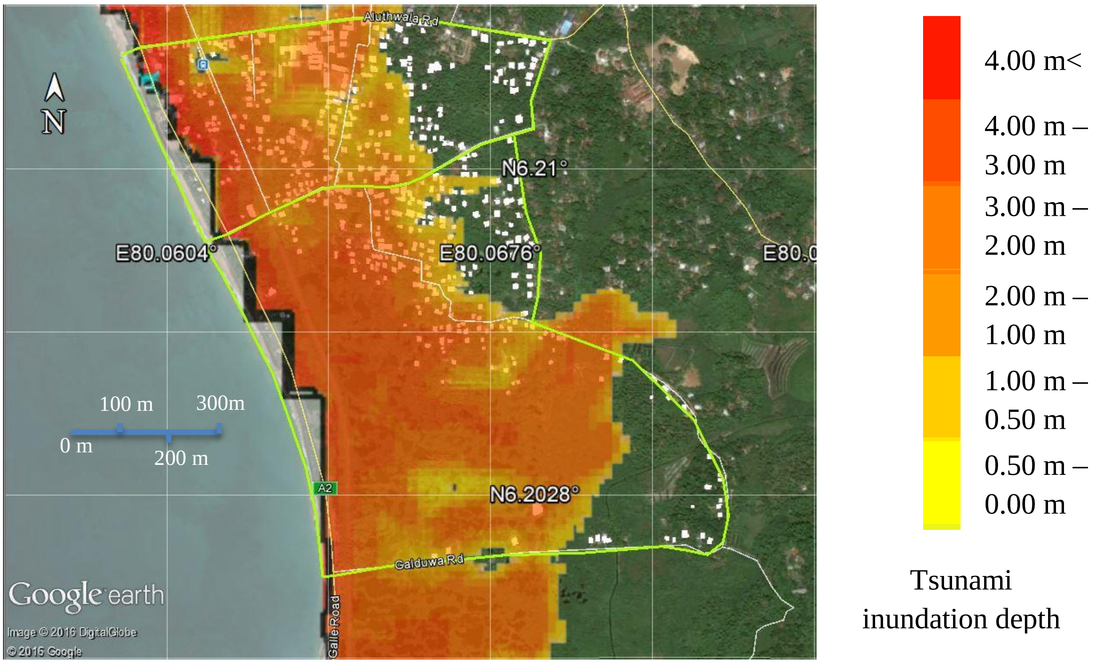


Figure 56: Tsunami inundation depth – Scenario 9 (Mw = 9.0)

Table 46: Number of inundated houses – Scenario 9 (Mw = 9.0)

Case	Scenario 9 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	3	11	61	6
0.5 - 1.0	2	7	36	3
1.0 - 2.0	1	4	23	2
2.0 -3.0	3	14	75	7
3.0 - 4.0	1	2	13	1
4.0<	1	3	17	2

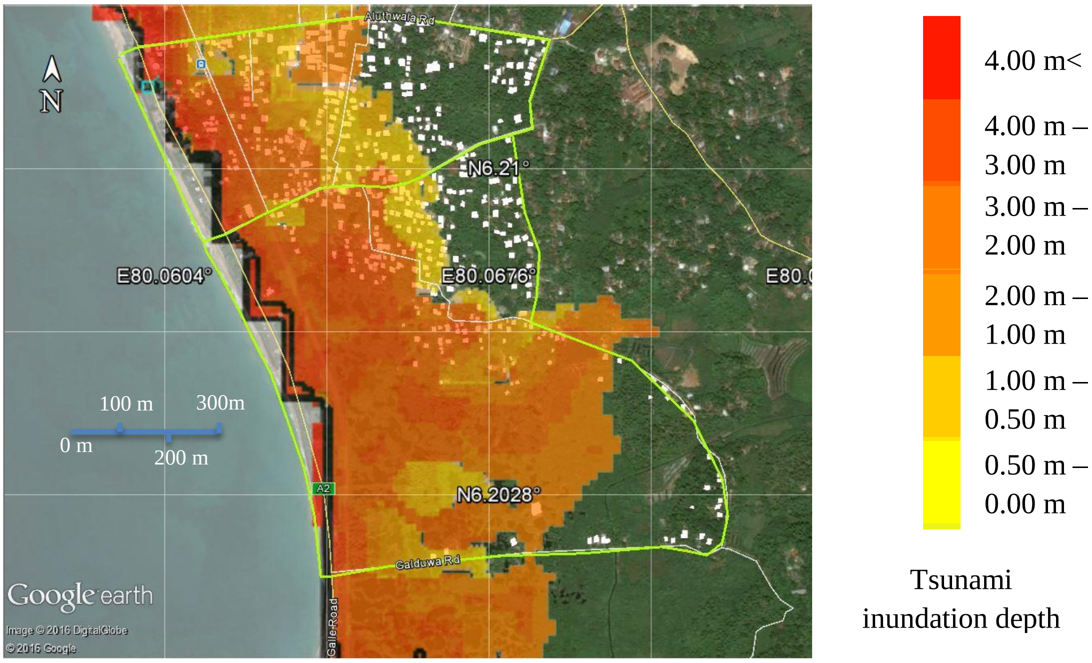


Figure 57: Tsunami inundation depth – Scenario 10 (Mw = 9.0)

Table 47: Number of inundated houses – Scenario 10 (Mw = 9.0)

Case	Scenario 10 (Mw = 9.0)			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Range of inundation (m)	Number of houses			
0.0 - 0.5	3	11	61	6
0.5 - 1.0	1	4	19	2
1.0 - 2.0	1	4	22	2
2.0 -3.0	3	13	72	7
3.0 - 4.0	1	4	21	2
4.0<	0	2	9	1

3.1.2 Number of damaged houses

Figure 58 shows the replotted fragility function of Ø {(H-μ)/σ}, based on the various fragility curves found in literature.

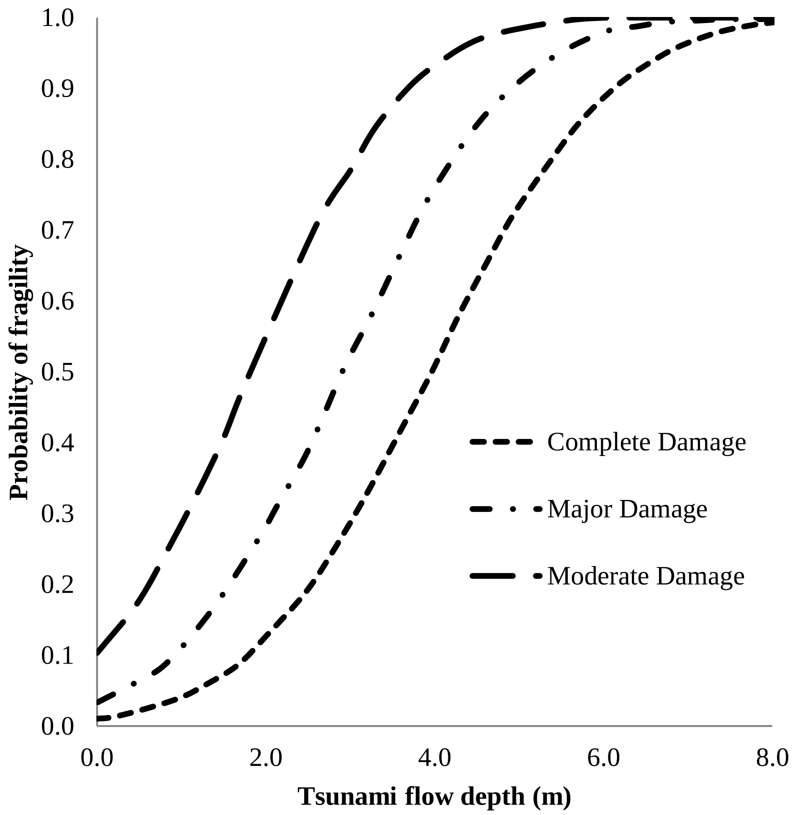


Figure 58: Fragility function of Ø {(H-μ)/σ}

These functions are limited to different damage states (complete damage, major damage and moderate damage). Major damage and moderate damage are defined by authors in each study due to lack of worldwide acceptable standard to define exact damage states. The fragility function was used in this study to calculate damage. Damage cost due partial damage varies from case to case depending on the type of partial damage. Therefore damage cost due to partial damage cannot be easily calculated as damage due to complete damage. Hence, cost of damage was calculated only from fragility functions of complete damage in this study. Most of the researchers did not display the equation of fragility function and only published the fragility function graphically. Therefore mathematical expression of fragility function was derived from the methodology described in methodology section. μ,σ values that were assumed in each iteration were plotted in Figures 59 and 60, which show the estimated fragility curves in different iterations. Figure 61 shows the result of Murao & Nakazato, (2010) and Figure 59 shows the result of Peiris, (2006). The best fit curve was selected as the fragility function in each case and tabulated in Table 48.

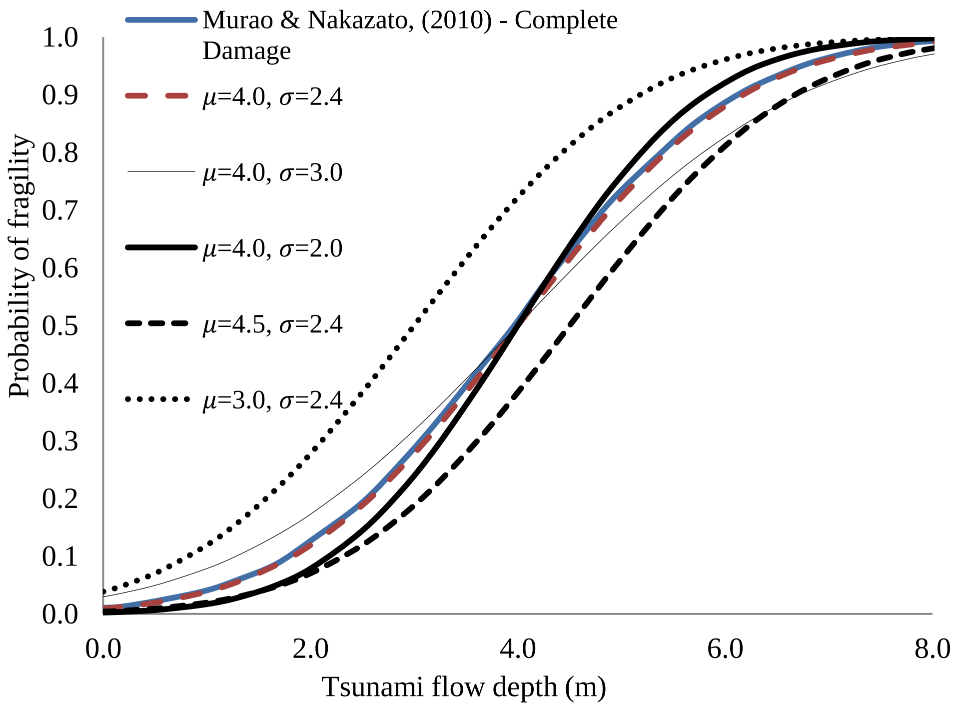


Figure 59: Fragility function of ∅ {(H-μ)/σ} – Different trials in iteration process

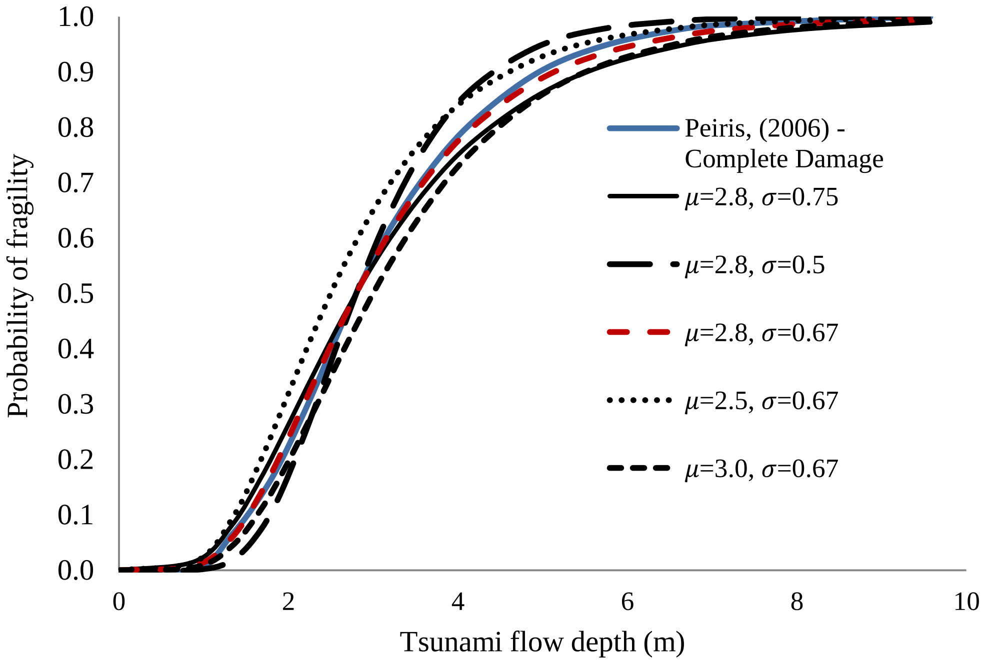


Figure 60: Fragility function of ∅ {1/σ ln (H/‾H)} – Different trials in iteration process

When μ = 4.0 m, σ = 2.4 m, the best fit curve was obtained for the fragility curve of given by Murao & Nakazato (2010). When μ = 1.03 m, σ = 0.67 m, the best fit curve obtained was the fragility curve of Peiris (2006).

Table 48: Tsunami fragility function for Sri Lanka

Study	Fragility function (Probability of fragility)
Murao & Nakazato, (2010)	$p = \frac{1}{2}\left(1 + erf\left(\frac{H - 4.0}{2.4}\right)\right)$
Peiris, (2006)	$p = \frac{1}{2}\left(1 + erf\left(\frac{ln\, H - 1.03}{0.67}\right)\right)$

Figure 61 illustrates that there is a big difference between the fragility functions obtained. Therefore both functions were used to estimate the number of completely damaged buildings for a given inundation depth.

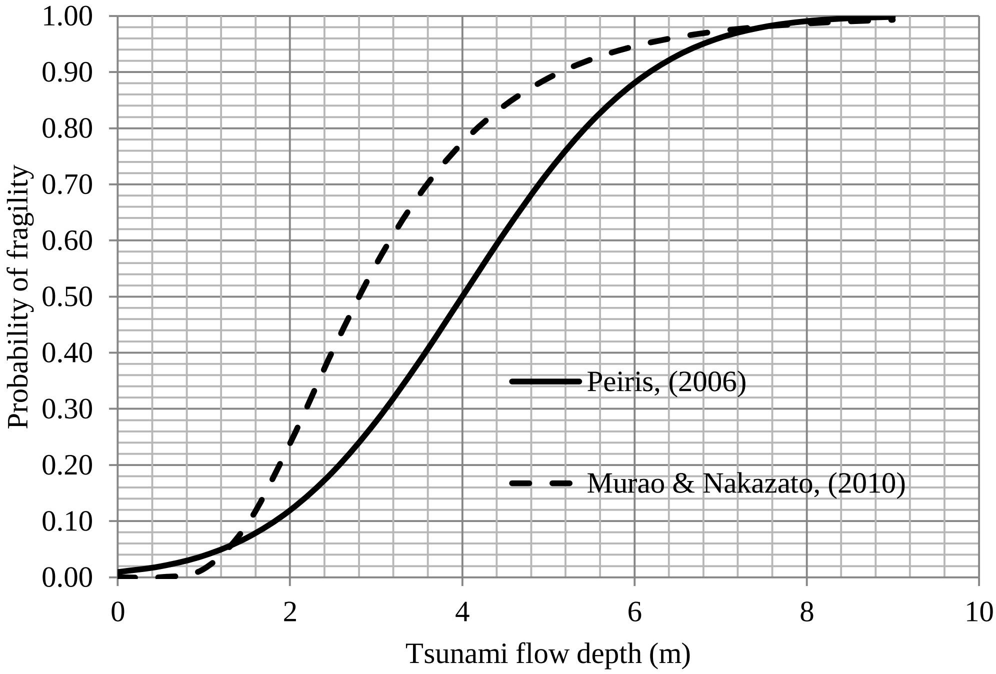


Figure 61: Comparison of selected tsunami fragility function in Sri Lanka

The number of damage houses was calculated from both fragility curves. It should be noted once more that only completely damaged houses were considered in this study. Even though it was possible to estimate the number of partially damaged houses, it was very difficult to estimate their recovery cost and they were thus excluded. Thus, the results of the present study represent a conservative assessment of the damage that could result from any given tsunami.

The estimated numbers of complete damaged houses were tabulated in Tables 49- 56 for each scenario and earthquake magnitudes.

Table 49: Number of completely damaged houses – Scenario 1

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	1	2	11	1
8.9	1	5	26	2
9.0	3	11	58	5
9.1	4	16	87	8
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	2	10	1
8.9	1	5	25	2
9.0	3	12	67	6
9.1	5	22	116	11

Table 50: Number of completely damaged houses – Scenario 2

Used equation	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	0	0	0
8.9	0	1	5	0
9.0	0	2	8	1
9.1	2	9	50	5
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	0	0	0
8.9	0	1	5	0
9.0	0	2	9	1
9.1	2	9	48	4

Table 51: Number of completely damaged houses – Scenario 3

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	1	3	0
8.9	0	1	6	1
9.0	1	2	11	1
9.1	1	3	18	2
Used equation	**Peiris, (2006)**			
Equation used	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	0	2	0
8.9	0	1	7	1
9.0	1	3	15	1
9.1	1	5	27	2

Table 52: Number of completely damaged houses – Scenario 4

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	1	3	0
8.9	0	1	6	1
9.0	1	3	14	1
9.1	1	4	19	2
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	1	3	0
8.9	0	1	6	1
9.0	1	3	17	2
9.1	1	5	27	3

Table 53: Number of completely damaged houses – Scenario 5

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	0	0	0
8.9	0	1	5	0
9.0	1	2	7	1
9.1	1	2	11	1
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Tsunami Magnitude Mw	Number of houses			
8.4	0	0	0	0
8.8	0	0	0	0
8.9	0	1	5	0
9.0	1	3	8	1
9.1	1	3	16	2

Table 54: Number of completely damaged houses – Mw = 9.0 (With different revetment heights)

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	0	2	8	1
4.2	0	2	7	1
4.4	0	2	7	1
4.6	0	2	5	0
4.8	0	1	5	0
5.0	0	1	5	0
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	0	2	9	1
4.2	0	2	9	1
4.4	0	2	8	1
4.6	0	2	6	1
4.8	0	2	8	1
5.0	0	1	7	1

Table 55: Number of completely damaged houses – Mw= 8.9 (With different revetment heights)

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	0	1	5	0
4.2	0	1	4	0
4.4	0	1	3	0
4.6	0	0	3	0
4.8	0	0	2	0
5.0	0	0	1	0
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	0	1	5	0
4.2	0	1	4	0
4.4	0	1	4	0
4.6	0	1	4	0
4.8	0	1	3	0
5.0	0	0	1	0

Table 56: Number of completely damaged houses – Mw = 9.1 (With different revetment heights)

Equation used	**Murao & Nakazato, (2010)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	2	9	50	5
4.2	2	7	43	4
4.4	2	8	42	4
4.6	2	7	39	4
4.8	2	6	31	3
5.0	2	6	31	3
Equation used	**Peiris, (2006)**			
Hosing category	Luxury	Semi-luxury	Normal	Informal
Height of revetment (m)	Number of houses			
4.0	2	9	48	4
4.2	2	9	54	5
4.4	2	8	45	5
4.6	2	7	42	4
4.8	2	4	24	2
5.0	2	4	24	2

3.1.3 Hosing data

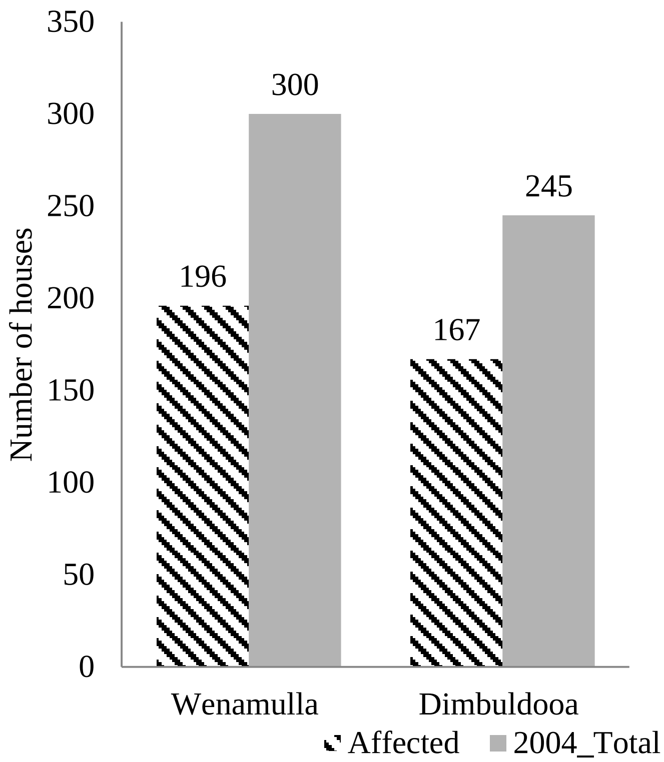


Figure 62: Total number of houses in 2004 and affected houses from 2004 IOT

Figure 62 shows the total number of houses in 2004 and affected houses from 2004 IOT. 65% of houses in Wenamulla and 68% of houses in Dimbuldooa were affected by the 2004 Indian Ocean Tsunami. However, in order to attempt to understand the risk posed by any future tsunami, it is also worth considering the change in housing patterns that have taken place in the area in recent years (Figure 63).

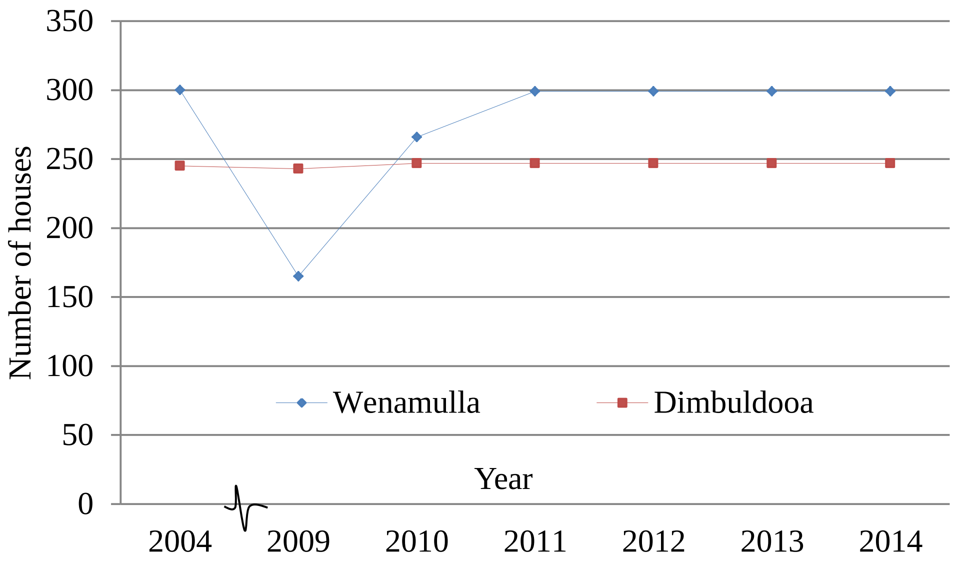


Figure 63: Changes in the total number of houses in Wenamulla and Dimbuldooa

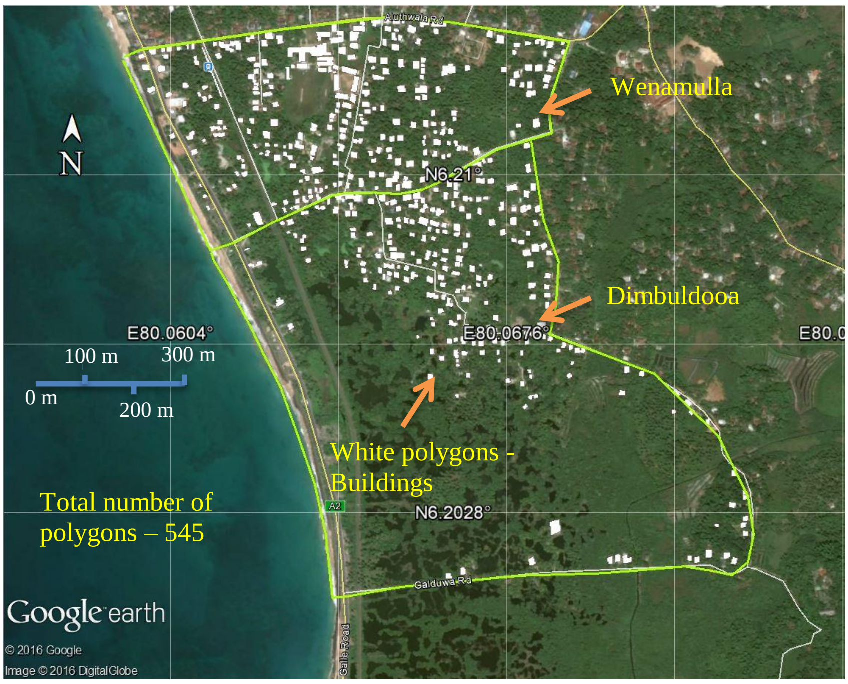


Figure 64: Buildings in the case study area (Source: Google Earth Pro, Date of image: 2016 – 01 – 16, Accessed date: 2016 – 03 – 01)

Figure 64 shows a Google Earth Pro image of the case study area in 2014, where a large number of houses can be observed near to the sea in Wenamulla village. Reading this

Figure together with Figure 63 indicates how many houses were heavily damaged in Wenamulla village, and that the recovery process took longer than in the case of Dimbuldooa village. However, it is also worth noting that the number of houses remained unchanged during last four years, essentially returning to the values seen in 2004, as shown in Figure 63. Population change after the 2004 Indian Ocean Tsunami and the change in the number of families living in the area are shown in Figures 65, 66 respectively. The number of families living in the area is a very important parameter in context of housing in Sri Lanka, as there is a cultural belief that each family should live in separate house for a happy family life to evolve.

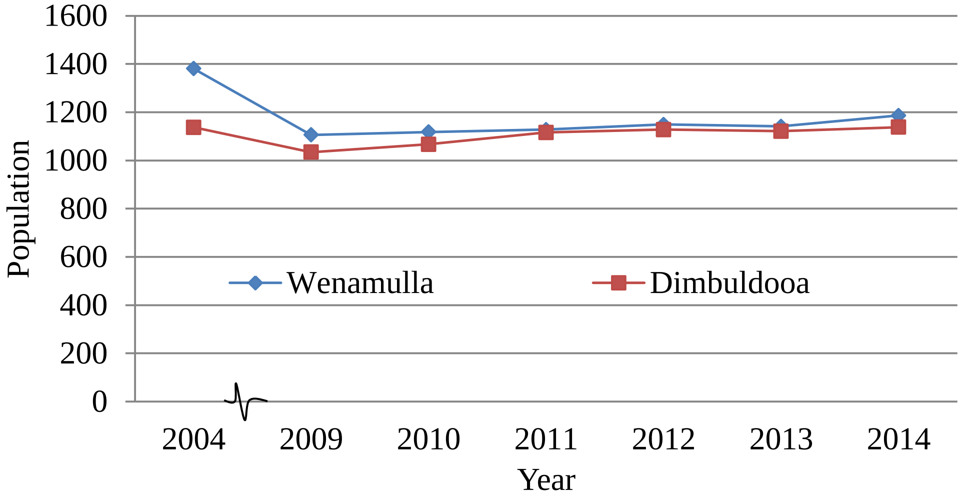


Figure 65: Population change in Dimbuldooa and Wenamulla

Population in 2014 still did not reach the level of the population in 2004 in Wenamulla village. The population growth is small, but nevertheless positive in value. Some of the families who lived in Wenamulla moved to Dimbuldooa village after the 2004 Indian Ocean Tsunami. Therefore, in the present research both villages were considered as one unit to compare the different between number of families and number of houses. The number of families was greater than the number of houses; therefore the author concluded there was a demand for new houses, according to Sri Lankan customs. Thus, it is difficult to state that the number of houses will not change during near future. However, in order to be conservative, the number of houses present in the area in 2014 was considered to remain constant in the future, in order to obtain conservative results.

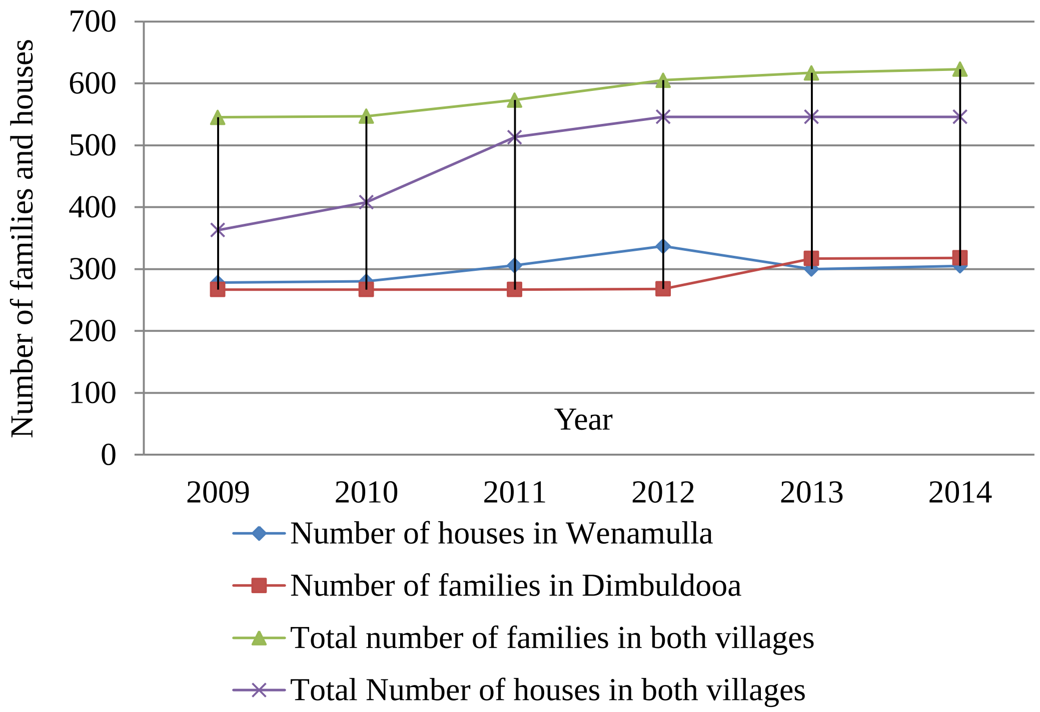


Figure 66**:** Comparison of the change in number of families and houses in both villages

Table 57 shows the distribution of materials (DCS, 2016) used for the construction of the walls of the houses in the case study area. Most of the houses in Wenamulla and Dimbuldooa were made out of bricks, cements blocks and soil blocks. These types of walls are considered to be masonry walls.. As the number of houses did not change significantly in the Wenamulla and Dimbuldooa area (Figure63), the types of wall materials in 2014 was almost equal to the types of wall materials in 2012.

Table 57: Distribution of wall materials used in the construction of houses in Dimbuldooa and Wenamulla

Type of wall	**Number of houses**			
	Wenamulla		Dimbuldooa	
	Number	Percentage %	Number	Percentage %
Brick	117		172	
Cement block	128	98	62	97
Soil bricks	3		3	
Mud	2			
Metal/Wood plank	1	2	4	3
Sheet/Other	2		0	
Total	253	100	242	100

98% of houses in Wenamulla and 97% of houses in Dimbuldooa villages were masonry houses. According to this, all houses in the selected area were assumed to be masonry houses, for the purposes of simplification.

The construction cost per unit area of houses is shown in Figure 67. These costs were suggested by key informant interviews interviewed, as detailed earlier in this chapter. The mean value of each category was taken and used as the representative value of the unit cost of house construction in Southern Sri Lanka. Those results were tabulated in Table 58.

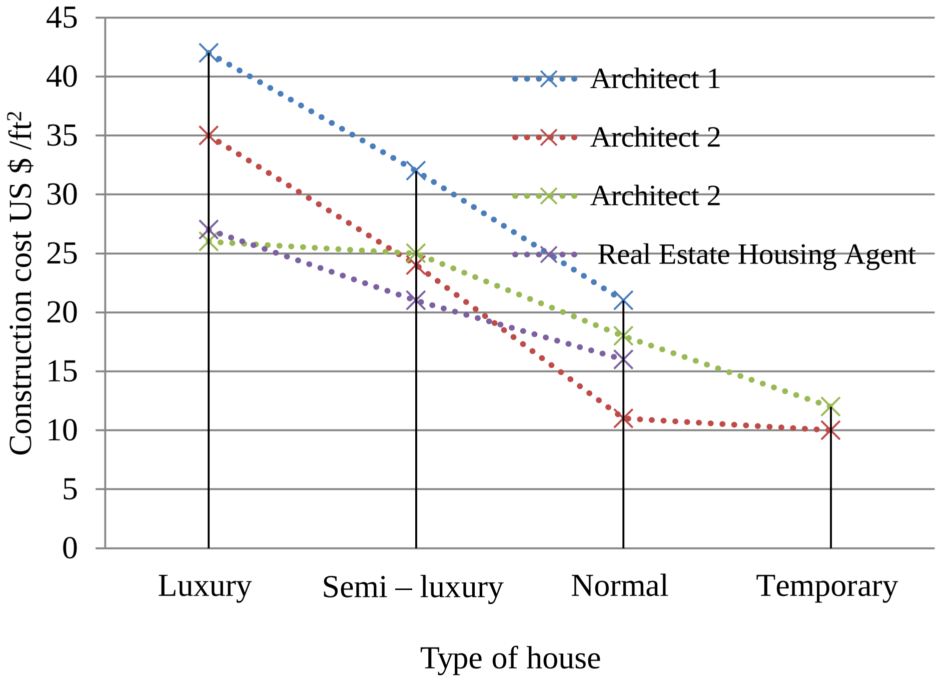


Figure 67**:** Construction cost per unit area of a house according to experts interviewed

Table 58: Construction cost of a unit area of a house

House category	**Construction cost US $ / ft^2**	**Construction cost US $ / m^2**
Luxury	35	377
Semi-luxury	27	290
Normal	16	172
Temporary	11	118

The characteristics of the buildings in Dimbuldooa and Wenamulla are presented in Table 59.

Table 59: Characteristics of buildings/ houses in Dimbuldooa and Wenamulla

Category	**Number of houses/ buildings**			
	Wenamulla		Dimbuldooa	
	Number houses/ buildings	Percentage %	Number houses/ buildings	Percentage %
House	282	84	263	93
Other buildings		16		7
Single story	282	91	263	90
More than one story		9		9
Piloti type		0		1
Luxury	236	4	244	3
Semi luxury		12		16
Normal		80		71
Informal		4		10

The characteristics of both villages were not significantly different from each other. Therefore, both villages were considered together in the damage calculations. In the calculations,

The representative floor area of each hosing category was selected as the median value of each type of building category, as shown in Figure 68. The selected representative floor area of each housing category was tabulated in Table 60.

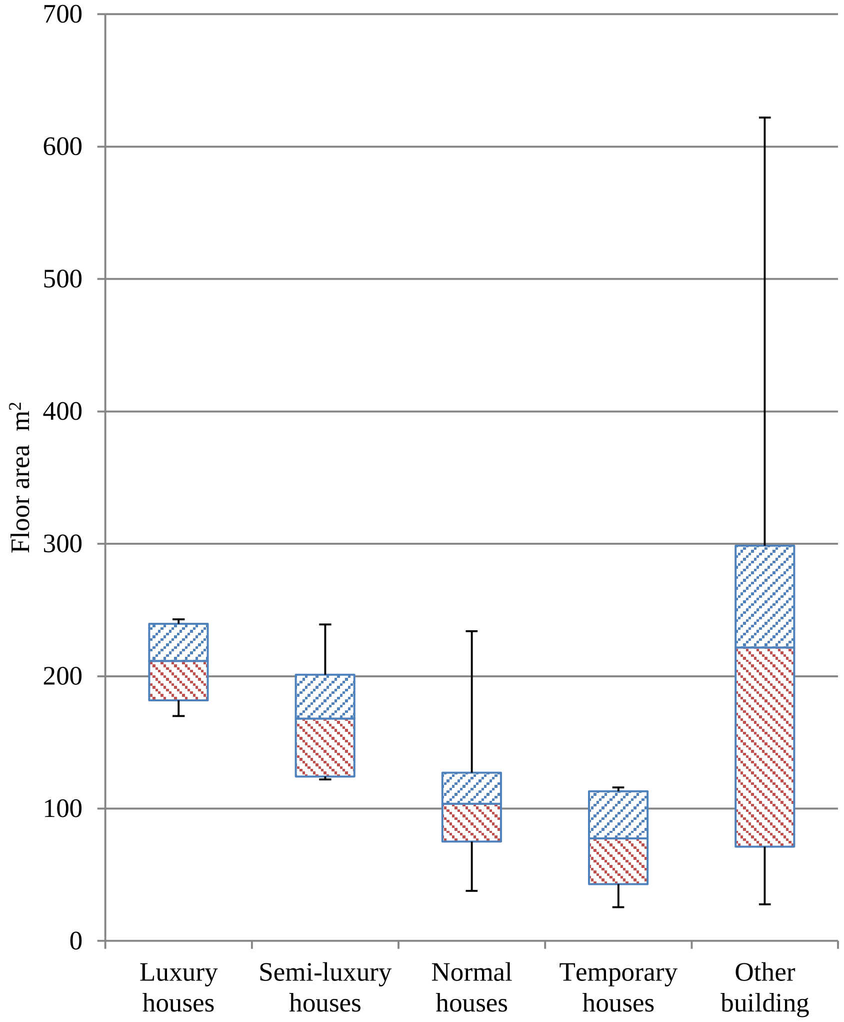


Figure 68**:** Whisker – Plot Diagram of floor area of different type of building categories in Dimbuldooa and Wenamulla villages

Table 60: Representing floor area of each category of houses

House category	**Median floor area m^2**
Luxury	211
Semi-luxury	168
Normal	103
Temporary	77

3.1.4 Damage Cost

The damage cost was calculated from Equation1 for the following cases for each of the fragility curves.

i. Without structures for 8.4, 8.8, 8.9, 9.0 and 9.0 earthquake magnitudes
ii. With revetment for 8.4, 8.8, 8.9, 9.0 and 9.0 earthquake magnitudes
iii. With railway embankment with grade crossings for 8.8, 8.9, 9.0 and 9.0 earthquake magnitudes
iv. With railway embankment with underpasses for 8.8, 8.9, 9.0 and 9.0 earthquake magnitudes
v. With both revetment and the railway embankment with grade crossings for 8.8, 8.9, 9.0 and 9.0 earthquake magnitudes
vi. By increasing the height of the revetment in 0.2m intervals up to 5m from 4.0m for 8.9, 9.0 and 9.1 earthquakes

Each earthquake can produces a number of possible tsunami ruptures (*n*), as shown in Table 1. Therefore, the damage by earthquake is given by the equation 11, where p_i represents the probability of each rupture and D_i the damage produced by that rupture. $D_{Mw=j}$ represents the damage of earthquake magnitude.

$$\boldsymbol{D_{Mw=j} = \sum_1^n p_i D_i} \qquad \textbf{(11)}$$

Each rupture pattern produces different maximum tsunami inundation heights at the case study area. It means that the p_i *is* a constant value which is equal to inverse of number of possible tsunami ruptures as shown in Table 61.

Table 61: Probability of a tsunami for an earthquake

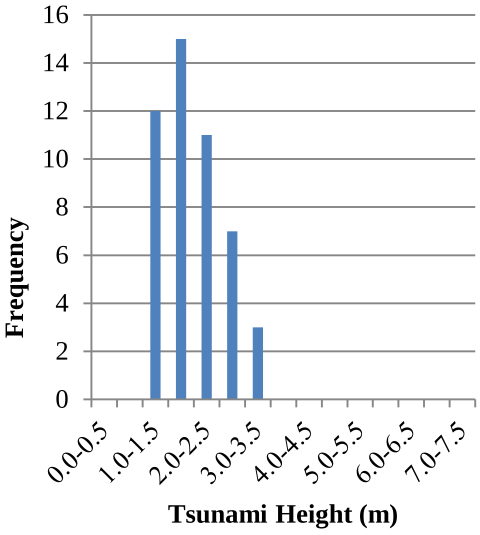
Earthquake (*Mw*)	Number of possible ruptures from Table 2	p_i for each earthquake value
8.4	48	1/48
8.8	39	1/39
8.9	24	1/24
9.0	22	1/22
9.1	20	1/20

Therefore the Equation 11 become

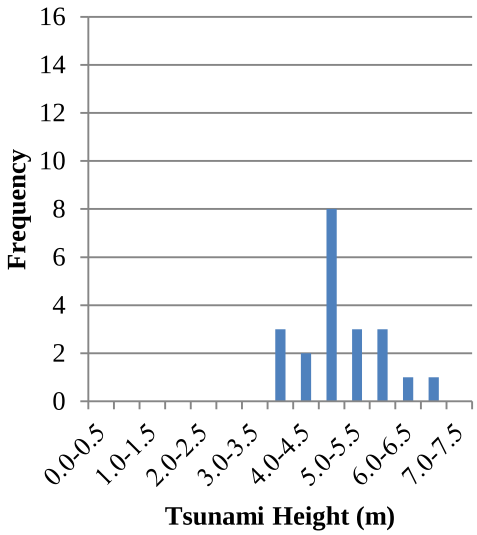
$$\boldsymbol{D_{Mw} = \frac{1}{n}\sum_{1}^{n} D_i} \quad \textbf{(12)}$$

Author numerically estimated the maximum tsunami height at the coast per each rupture for one earthquake event (Section 2.2.3.1). The rupture equivalent to the median value of maximum tsunami heights was considered as the representing rupture of the selected earthquake magnitude.

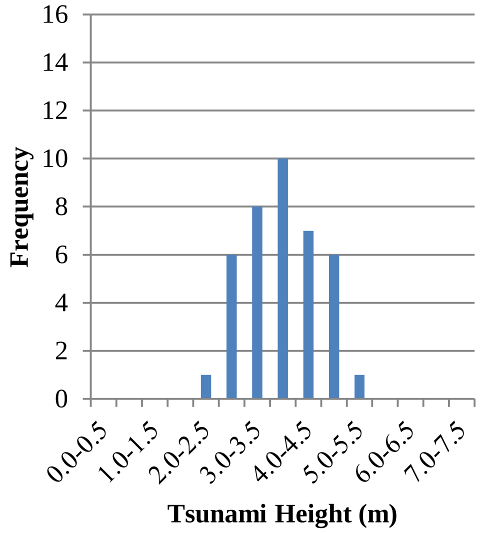
Frequency of maximum tsunami height at the coast for each tsunami was plotted in Figure 69. These distributions are nearly bell shape distributions. Therefore median values of maximum tsunami inundation height of considering earthquake are close to that of their mean values.



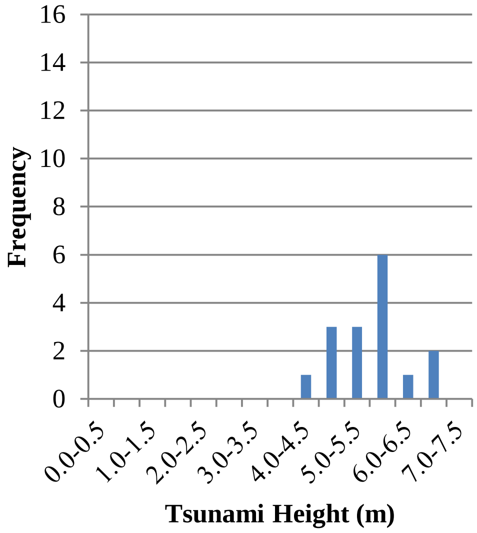
Mw = 8.4



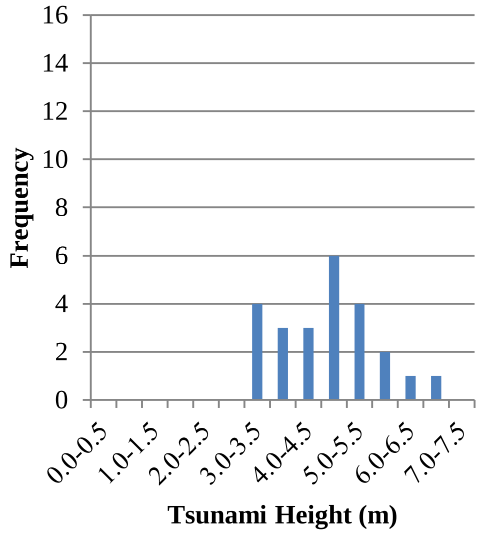
Mw = 8.8



Mw = 8.9



Mw = 9.0



Mw = 9.1

Figure 69: Frequency distribution of maximum tsunami inundation heights for each possible earthquake ruptures for one earthquake magnitude

Another concern in this study is that the case study area is small compared to the incoming wave regimes and damage along the coast is proportional to the inundation extent. However the inundation extent is not proportional to the damage. Figure 70 shows the relationship between the damage and tsunami height at the coast. The damage is proportional to tsunami height. The rupture equivalent to the median value of maximum tsunami height represents tsunami rupture of the selected earthquake is a valid assumption in this case.

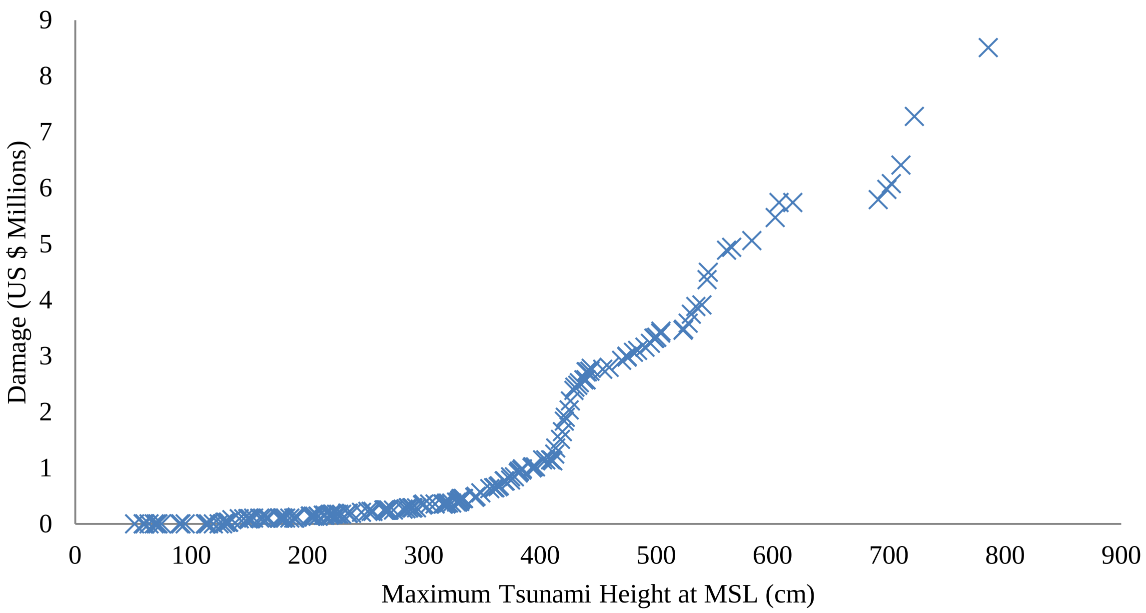


Figure 70: Tsunami damage vs. tsunami height (Without co-beneficial structurers)

The damage for scenarios 1 - 5 was tabulated in Table 62. The damage for scenarios 6 – 8 was tabulated in Table 63. The damage for both fragility curves and mean between them is also shown in these tables.

Table 62: Damage cost for scenarios 1- 5

Scenario	Mw	Damage from fragility function of Murao & Nakazato, (2010) US $ Millions	Damage from fragility function of Peiris, (2006) US $ Millions	Damage US $ Millions
1	8.4	0.000	0.000	0.000
	8.8	0.380	0.283	0.332
	8.9	0.801	0.783	0.792
	9.0	1.845	0.247	1.954
	9.1	2.708	3.620	3.164
2	8.4	0.000	0.000	0.000
	8.8	0.000	0.000	0.000
	8.9	0.137	0.137	0.137
	9.0	0.265	0.249	0.257
	9.1	1.526	1.482	1.505
3	8.4	0.000	0.000	0.000
	8.8	0.101	0.035	0.069
	8.9	0.163	0.181	0.173
	9.0	0.380	0.500	0.440
	9.1	0.561	0.818	0.690
4	8.4	0.000	0.000	0.000
	8.8	0.035	0.101	0.069
	8.9	0.181	0.163	0.173
	9.0	0.500	0.482	0.332
	9.1	0.818	0.628	0.651
5	8.4	0.000	0.000	0.000
	8.8	0.000	0.000	0.000
	8.9	0.137	0.137	0.137
	9.0	0.230	0.296	0.263
	9.1	0.380	0.526	0.454

Table 63: Damage cost for scenarios 6- 8

Mw	Height of revetment	Damage from fragility function of Murao & Nakazato, (2010) US $ Millions	Damage from fragility function of Peiris, (2006) US $ Millions	Damage US $ Millions
8.9	4.0	0.137	0.137	0.120
	4.2	0.120	0.120	0.120
	4.4	0.102	0.120	0.111
	4.6	0.053	0.120	0.086
	4.8	0.035	0.102	0.069
	5.0	0.018	0.018	0.018
9.0	4.0	0.248	0.266	0.257
	4.2	0.230	0.266	0.248
	4.4	0.230	0.248	0.239
	4.6	0.186	0.212	0.199
	4.8	0.137	0.248	0.193
	5.0	0.137	0.181	0.159
9.1	4.0	1.527	1.483	1.505
	4.2	1.297	1.598	1.447
	4.4	1.328	1.390	1.359
	4.6	1.226	1.279	1.252
	4.8	1.027	0.797	0.912
	5.0	1.027	0.797	0.912

Benefit (Equation 1) of tsunami co-beneficial structures and revetment of different heights was tabulated in Table 64 and 65. Whether the tsunami overflowed the structure or not was also stated in both tables.

Table 64: Benefit of tsunami co-beneficial structures

Tsunami co-beneficial structure	Earthquake magnitude	Benefit (US $ Millions)	Tsunami overflowed Yes/No
Railway embankment with grade crossings	8.4	0.000	No
	8.8	0.263	No
	8.9	0.620	Yes
	9.0	1.514	Yes
	9.1	2.474	Yes
Railway embankment with underpasses	8.4	0.000	No
	8.8	0.263	No
	8.9	0.620	No
	9.0	1.622	No
	9.1	2.514	Yes
Revetment(Revetment height = 4.0)	8.4	0.000	No
	8.8	0.332	No
	8.9	0.655	No
	9.0	1.697	No
	9.1	1.660	Yes
Railway embankment with grade crossings and revetment (Revetment height = 4.0)	8.4	0.000	(Both structures) No
	8.8	0.332	(Both structures) No
	8.9	0.655	(Revetment) Yes (Railway embankment)No
	9.0	1.691	(Revetment) Yes (Railway embankment)No
	9.1	2.711	(Both structures) Yes

Table 65: Benefit of revetment at different heights

Height of revetment	Earthquake magnitude	Benefit (US $ Millions)	Tsunami overflowed Yes/No
4.0	8.9	0.120	Yes
	9.0	0.257	Yes
	9.1	1.505	Yes
4.2	8.9	0.120	Yes
	9.0	0.248	Yes
	9.1	1.447	Yes
4.4	8.9	0.111	Yes
	9.0	0.239	Yes
	9.1	1.359	Yes
4.6	8.9	0.086	Yes
	9.0	0.199	Yes
	9.1	1.252	Yes
4.8	8.9	0.069	No
	9.0	0.193	Yes
	9.1	0.912	Yes
5.0	8.9	0.018	No
	9.0	0.159	Yes
	9.1	0.912	Yes

Tsubaki et al., (2016) published fragility functions (Equation 13) for railway embankments in Japan. The flow depth over the structure was obtained from the inundation simulation results. Then the probability of failure under tsunami flow was tabulated in Table 66 and 67 for tsunami co-beneficial structures and revetment of different heights, respectively. The case when both a revetment and railway embankment exist in the area was not calculated from equation 13. The reason was that the failure of railway embankment and the failure of revetment cannot be assumed as two independent events. Failure of revetment can affect the failure of railway embankment. Because of this uncertainty, combined effect was not considered in this section.

$$\boldsymbol{p = \frac{1}{2}\left(1 + erf\left(\frac{ln(\Delta h/0.22)}{0.525}\right)\right)} \quad \textbf{(13)}$$

Table 66: Probability of failure of tsunami co-beneficial structures under tsunami overflow

Tsunami co-beneficial structure	Earthquake magnitude	Tsunami flow depth over structure (*Δh) (m)*	Probability of failure (*p)%*
Revetment(Revetment height = 4.0)	8.9	0.6	100
	9.0	2.0	100
	9.1	3.0	100
Railway embankment with underpasses	9.1	0.2	40
Railway embankment with grade crossings	9.1	0.2	40

Table 67: Probability of failure of revetment (different heights) under tsunami overflow

Height of revetment	Earthquake magnitude	Tsunami flow depth over structure (*Δh*) (*m*)	Probability of failure (*p*)
4.0	8.9	0.6	100
	9.0	2.0	100
	9.1	3.0	100
4.2	8.9	0.4	95
	9.0	1.0	100
	9.1	3.0	100
4.4	8.9	0.2	40
	9.0	0.6	100
	9.1	2.0	100
4.6	8.9	0.1	2
	9.0	0.2	40
	9.1	0.4	95
4.8	9.0	0.2	40
	9.1	1.0	100
5.0	9.0	0.1	2
	9.1	1.0	100

3.2. Upgrade Tsunami Co-Beneficial Structures

3.2.1 Coastal railway embankment

In the selected case study there was a 1400 m stretch of existing railway embankment (Figure71). The height of railway embankment is ~ 8 m from MSL (Mean Sea Level) and ~4.8m from existing ground, according to the drawings obtained by the author from the Central Engineering Consultancy Bureau, Colombo, Sri Lanka.

Figure 71: Picture of existing railway embankment in the case study area

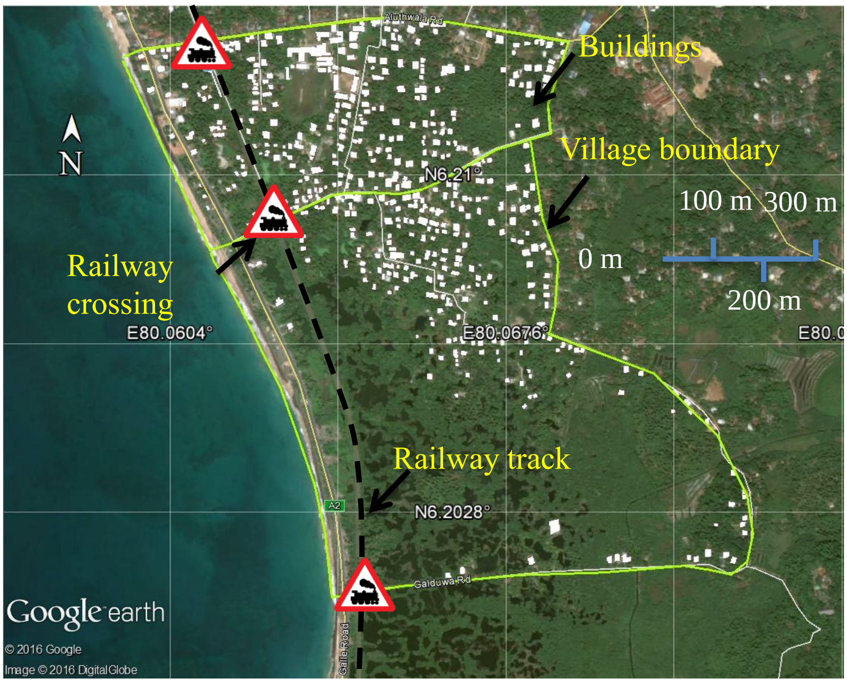


Figure 72: Google Earth image of existing railway embankment in case study area, showing also the railway crossing

When the railway embankment crossed a road, underpasses (see Figure 73, left) were provided in many places to ensure the safety of pedestrians and other traffic. However, it should be noted how these were not present at all locations (see Figure 73, right).

Figure 73: Railway embankment with and without an underpass

Figure 74 shows a sketch of the proposed modifications. The cross sectional areas of the various types of materials that would be used were calculated according to this sketch, with the final results being displayed in Table 68.

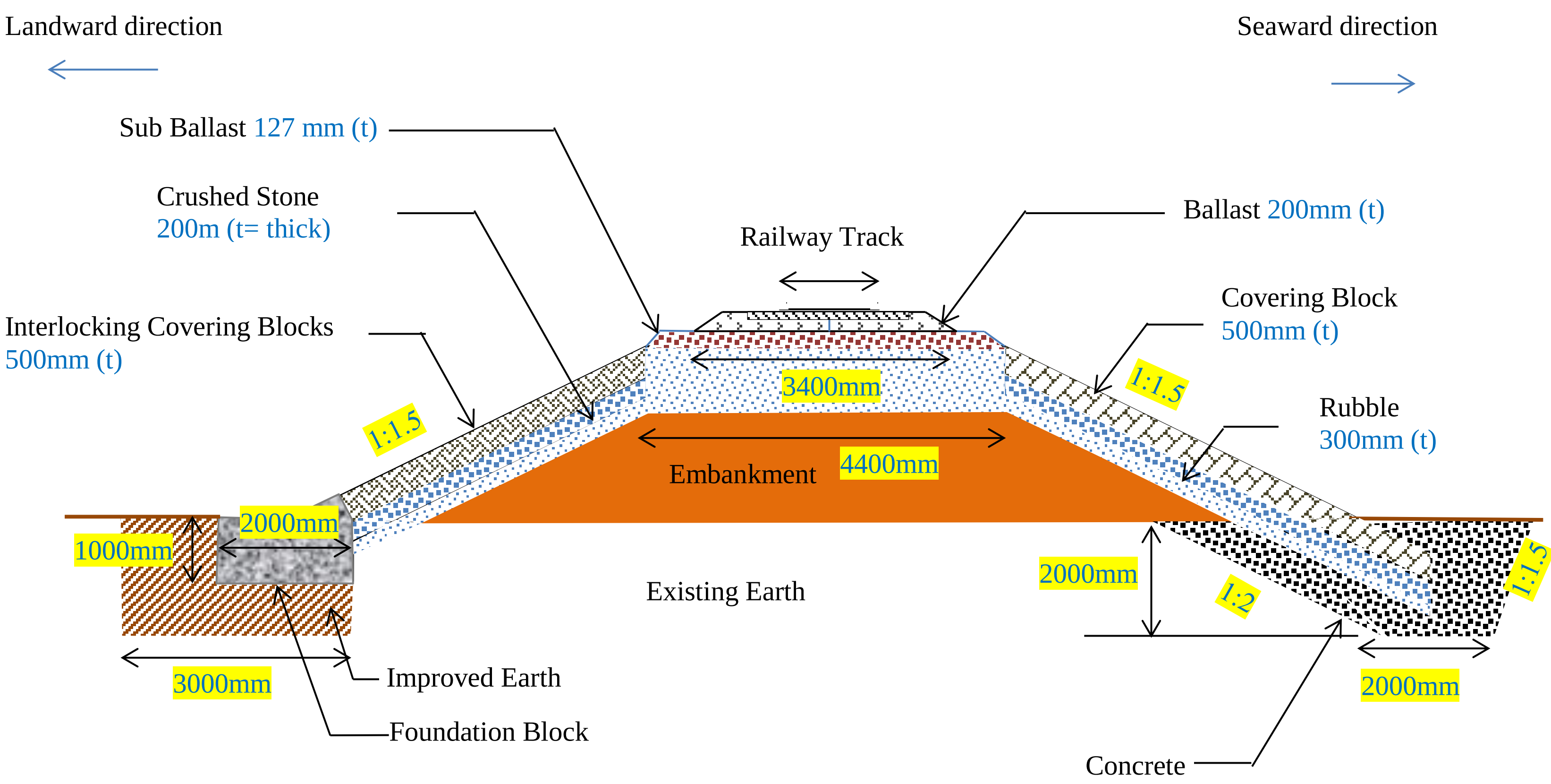


Figure 74: Schematic diagram of proposed modifications to railway embankment

Table 68: Bill of Quantities for the cost to upgrade the existing coastal railway embankment

Item .No	Description	Unit	Quantity	Unit rate	Amount (SLR)(Sri Lankan Rupee)
1	Foundation Block	m^2	2.20	4,500.00	9,900.00
2	Pre - loading	m^2	8.00	17.00	136.00
3	Reinforced protection	m^2	8.00	32.00	256.00
4	75mm thick 1:3:6(38mm) cement concrete screed in foundation.	m^2	9.00	8,500.00	76,500.00
5	Crush stone layer	m^2	2.68	3,600.00	9,648.00
6	Rubble layer	m^2	6.20	1,700.00	10,540.00
7	Interlocking Blocks (1.5/m)	item	6.90	3,000.00	20,700.00
8	Covering Blocks (1/m)	item	4.60	1,300.00	5,980.00
Total cost					133,660.00
9	Underpass	item	3.00	238,312.50	714,937.50

Underpasses was proposed to ensure the safety of residents from the moving trains, as the railway track does not have a fence at either side to prevent the access to pedestrian onto the tracks. Construction of an underpass more expensive than the construction cost of a grade crossing, though there are a few underpasses already in the area. All three roads are classifies as Grade C roads (medium service class roads) by the Road Development Authority, Sri Lanka. According to this, the author assumed the size of the opening of the underpass to be 5m. The total cost of the upgrade, together with the underpasses, was calculated as 1.245 Million US $ and the cost of the upgrade without underpass was calculated to be 1.240 Million US $, using September, 2015 rates according to Equation 14. The cost of upgrade, unit cost of underpass, number of underpasses, cost of upgrading unit length of road, length of road segment and foreign exchange rates are denoted from C, u_1, n_u, u_2, L and $, i$ respectively.

$$C = i(u_1\, n_u + Lu_2\,)10^{-6} \quad \textbf{(14)}$$

Table 69: Upgrading cost of railway embankment

Type of railway embankment	Upgrading cost (US $ Millions)
With grade crossings	1.240
With underpasses	1.245

3.2.2 Revetment

There was a 1380m stretch of existing revetment (Figure 74) in the selected case study area. The height of revetment is ~ 4.8m from MSL (Mean Sea Level). Figure 74 shows a cross sectional profile of the existing revetment, together with a picture of the current state of the revetment.

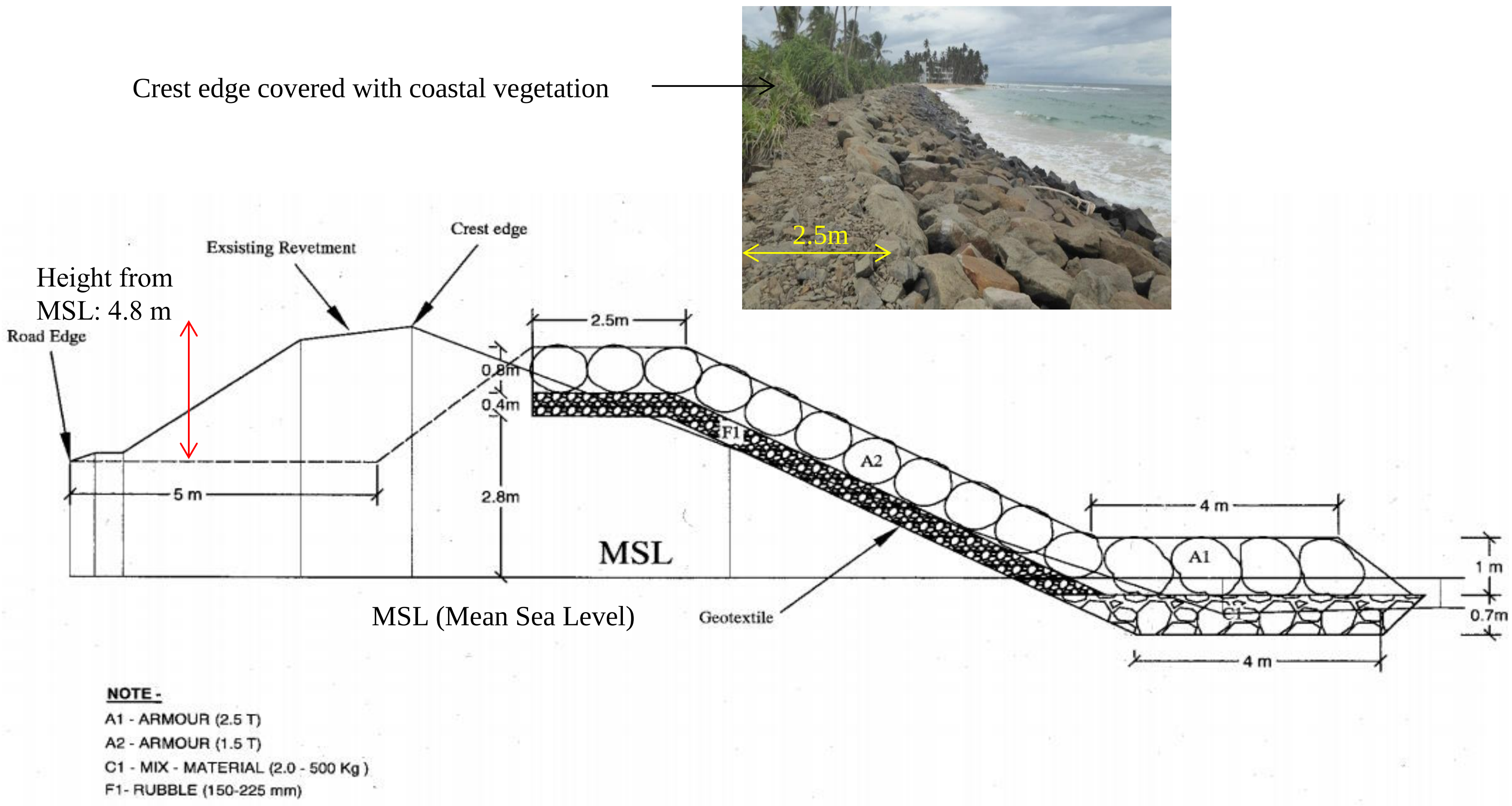


Figure 75: Engineering drawing and a picture of existing revetment in the case study area

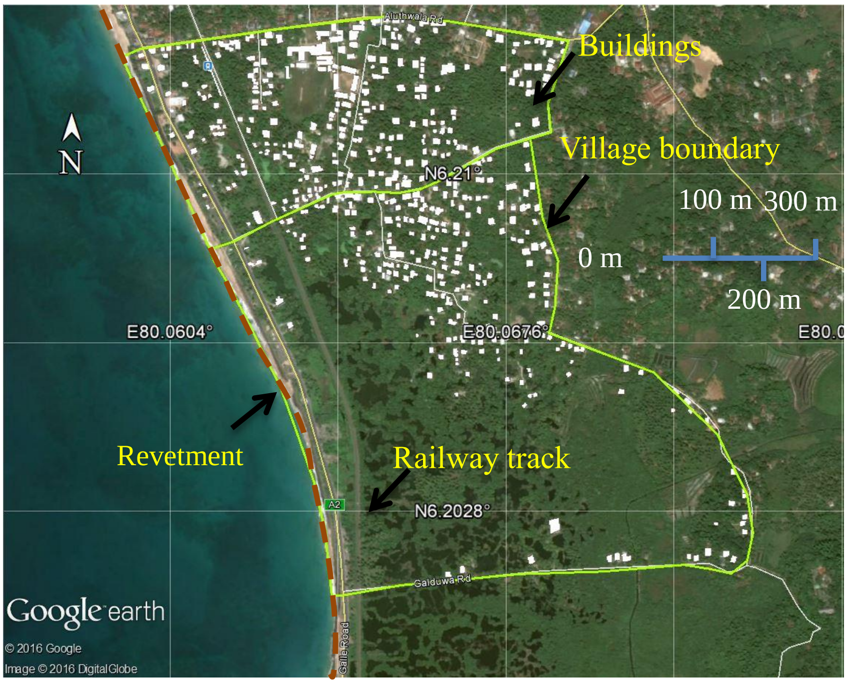


Figure 76: Google Earth image of existing revetment in case study area

Figure 75 shows a sketch of the proposed modifications. The bill of quantities for the materials required for the upgrade could thus be calculated using this figure, with the final results displayed in Table 62 for an increase in height of 4.0m.

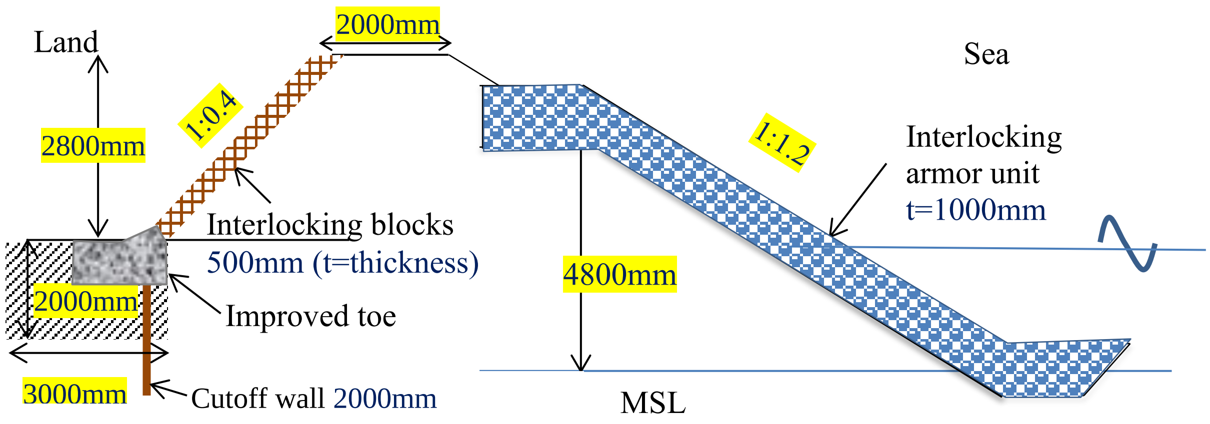


Figure 77: Schematic diagram of proposed modifications to the revetment (cross section)

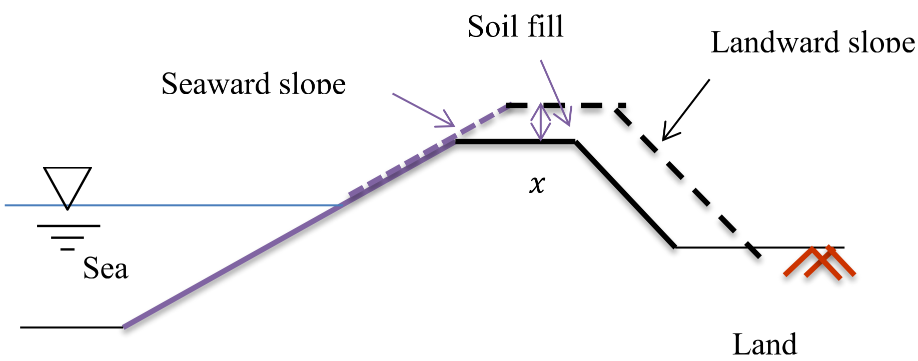
Table 70: Summery of calculated cost of upgrade of revetment

Item .No	Description	Unit	Quantity	Unit rate	Amount (SLR)
1	Foundation Block	m^2	2.20	4,500.00	9,900.00
2	Pre - loading	m^2	8.00	17.00	136.00
3	Reinforced protection	m^2	8.00	32.00	256.00
4	Interlocking Blocks (Big)	Item	15.00	9,000.00	135,000.00
5	Cutoff-Wall	M	2.00	750.00	1,500.00
6	Interlocking Blocks (1.5 /m)	Item	4.30	3,000.00	12,900.00
Total					12,900.00

Thus, the cost of the upgrade was calculated as 1.499 Million US $ using September, 2015.

The cost to increase the revetment height in 0.2m intervals was tabulated in Table 71, with Figure 77 showing the increase in materials needed for a given increase in height *x*. 4.

Figure 78: Schematic diagram of cross section of revetment



The cost of increased the height of the structure could be simply calculated from the Equation 15. The Upgrading cost was denoted by $C'_{revetment}$, and the cost of upgrading landward slope, seaward slope and soil filling were denoted from r_1, r_2 and r_3, respectively.

$$C'_{revetment} = C_{revetment} + \frac{\sqrt{29}}{5} x\ r_1 + \frac{\sqrt{61}}{5} x\ r_2 + (2.92 + 0.8x) x\ r_3 \quad \textbf{(15)}$$

Table 71: Cost of upgrading (Including the increased height of revetment)

Height of revetment	Upgrading cost (US $ Millions)
4.0	1.499
4.2	1.510
4.4	1.521
4.6	1.533
4.8	1.544
5.0	1.556

3.2.3 Discussion of results

The cost of upgrading the railway embankment with underpass and with grade crossings appears to be similar in the present case study, though their existance clearly has an effect on actual tsunami flooding. Even though underpasses were considered in the present economic study, their actual influence on the extent of the inundation in the event of a tsunami was not simulated in this study due to software limitations. Essentially, for the present study they were considering as an opening in the railway embankment, though this clearly simplifies the hydraulic characteristics of the tsunami flow around them.

Rates of constructions are currently rapidly increasing in Sri Lanka due to the high inflation rate in the country. Figure 79 was drawn from data published by Central Bank of Sri Lanka (CBSL, 2016) (clearly showing that inflation is extremely high. Inflation rate (*d*) and interest rate (*e*) for sri lanka are 4% (Sousa & Fedec, 2016) and 8.2% (CBSL, 2016) respectively

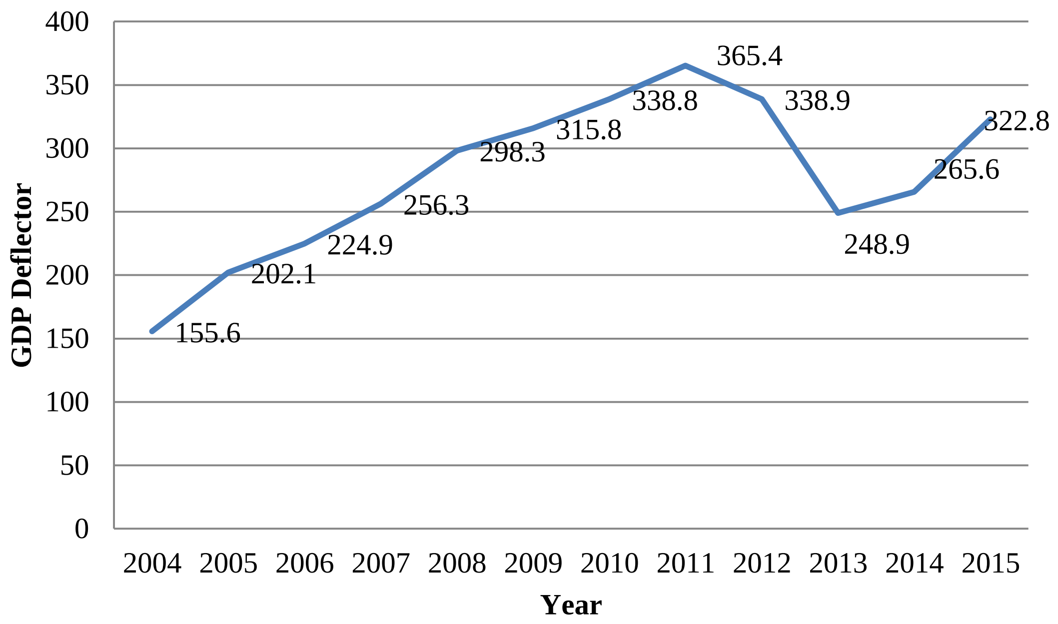


Figure 79: GDP Deflector in Sri Lanka (Year 2002 =100)

Discounting rate(i) was calculated from Equation 16 the value was equal to 4%.

$$\boldsymbol{i = \frac{(1+e)}{(1+d)} - 1} \qquad \textbf{(16)}$$

Design life *(n*) of revetment and railway embankment are respectively 25yrs and 40 years. Annual discounting cost (*A*) was calculated from Equation 17. Here the PV (Present Value) equals to the upgrading cost.

$$\boldsymbol{PV = \sum_{i=1}^{n} \frac{A}{(1+i)^n}; A = \frac{PV}{\sum_{i=1}^{n} \frac{1}{(1+i)^n}}} \qquad \textbf{(17)}$$

Annual discounting cost of revetment (for different heights) was tabulated in Table 72 and railway embankment was tabulated in Table 73.

Table 72: Annual discounting cost of revetment upgrading

Height of revetment	Upgrading cost (US $ Millions)	Annual discounting cost (US $)
4.0	1.499	95,954
4.2	1.510	96,658
4.4	1.521	97,362
4.6	1.533	98,130
4.8	1.544	98,834
5.0	1.556	99,603

Table 73: Annual discounting cost of railway embankment upgrading

Type of railway embankment	Upgrading cost (US $ Millions)	Annual discounting cost (US $)
With grade crossings	1.240	62,649
With underpasses	1.245	62,902

The design lives of the structures considered in the present study are substantially different. Essentially, the design life of a railway embankment is greater than that of revetment, and thus the life cycle cost of upgrading is different. The upgrading cost of revetment (Height = 4.0m) is 53% greater than upgrading cost of railway embankment with grade crossings.

Finally, it is important to note that only the size and the location of the structures were considered to propose improvements of how they could better protect against a tsunami. Only two types of structures were considered in the present study, namely the railway embankment and revetment, though other coastal infrastructure such as buildings, seawalls as well as natural features such as sandy beaches or mangrove forests can also be upgraded to help to reduce the effects that tsunamis can have on coastal communities.

Expected damage reduction was calculated from Equation 18

$$E(Mw) = \sum_{r=1}^{n}(nCr\,(\frac{1}{T})^{r}(1-\frac{1}{T})^{n-r})(rB)(1+i)^{r} \quad \textbf{(18)}$$

where *E(Mw)* is expected benefit of selected earthquake, *n* is design life of structure *T* is return period of tsunamigenic earthquakes, *B* is benefit (reduction in damage) as defined in Equation 1and *i* is the annual discounting rate. Expected damage for railway embankment and revetment was showed in Figure 80. The expected damage of railway embankment is higher than that of revetment in low earthquake magnitudes and vice versa.

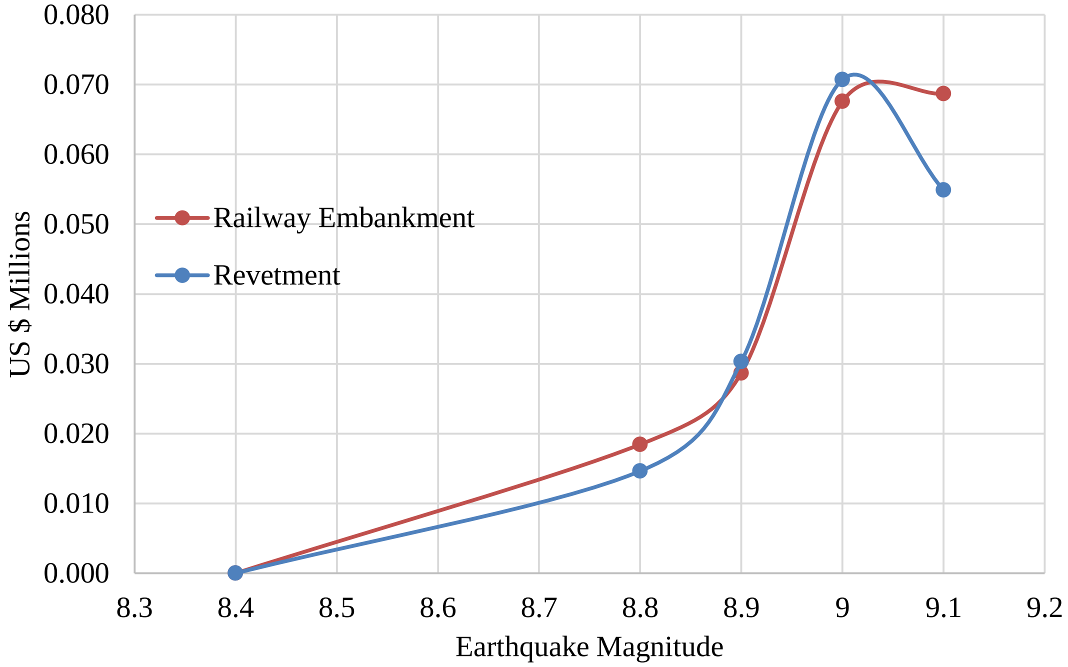


Figure 80: Expected reduction in damage of railway embankment and revetment

3.3. Survey on Social Acceptance to Upgrade Tsunami Co-Beneficial Structures

3.3.1 Awareness of tsunami risk

98% of respondents were residents of the case study area. 86% of respondents witnessed the 2004 Indian Ocean Tsunami. Approximately half of the respondents were composed of housewives and retired people. 39% housewives, 12% retired and rest respondents were employed in different sectors.

The Government of Sri Lanka had decided not to invest to construct hard defensive structures[4]. The Government had already established a unit referred to as the DMC (Disaster Management Center) to properly invest on EWS (Early Warning Systems). 47% of residents completely agreed with this policy. Essentially, this group of respondents believed that saving

[4] Private discussion with the Engineer (Mr. Chanaka Vinodh), Coast Conservation Department, Galle, Sri Lanka in September, 2015 (Confirmed by Vice - Chair IOTWS (Indian Ocean Tsunami Early Warning System) (Dr. Sam Hettiarchchi), Mount Lavinia Sri Lanka in September, 2015.)

life should be given more priority than protecting physical property. However, the majority of respondents (53%) did not agree with this policy. 96% of respondents were well aware of the existence of a tsunami hazard in the area. 91% of respondents were aware about National Tsunami Early Warning System (NTEWS), though 47% of them did not believe that they were safe under NTEWS.

For instance, the DMC issued a tsunami warning in April, 2012 due Mw = 8.6 earthquake in Sunda Arc. , But fortunately tsunami waves did not strike Sri Lanka coast. However, the tsunami warning tower (Figure 81) did not work at the time; people only got the information from NEWS alerts. Most of the questionnaire respondents (48%) received the tsunami alert from neighbors, police and village representatives and 31% of residents got the alert from public media. Most of the residents worried about them would receive a tsunami alert during night time. One warning tower can cover approximately 7km^2 of area. These towers were constructed in a location both near shore fishermen and coastal residents can hear the siren. DMC did a study to identify the suitability of selected locations of warning towers. The Deputy Director, Early Warning (EW), DMC confirmed that 51% (39) of the early warning towers were located in optimum places where large number of people can here, during the interview. However focused group discussion results confirmed that the uncertainties in dissemination of tsunami warnings and poor maintenance of the warning towers were the main reasons for lower trust on EWS.

Figure 81: Tsunami Early Warning Tower in Sri Lanka

82% of respondents joined at least once a tsunami drills, and the responses regarding participation in drills are shown in Table 64.

Table 74: Respondents participation in tsunami drills

How often the respondents participated in tsunami drills	**Participation as a percentage (%)**
Not answered	1.5
Never	36.0
Only once	14.5
Four to two times	38.0
Eight to five times	4.5
Every year	5.5

36% of respondents had never participated in a tsunami drill during the last decade, even though the DMC has organized one drill per year from 2006 onwards. The respondents who had never participated in tsunami drills did not provide any reason for their absence.

The community perception of functional efficiency of coastal railway embankment and revetment are shown on Figures 82 and 83. More than 50% of respondents were satisfied with the functional efficiency of the revetment and coastal railway embankment. Essentially, respondents considered that the revetment was effective if it could protect the beach from coastal erosion. The embankment was seen to serve its purpose if it could provide a certain level of safety and convenience to the railway.

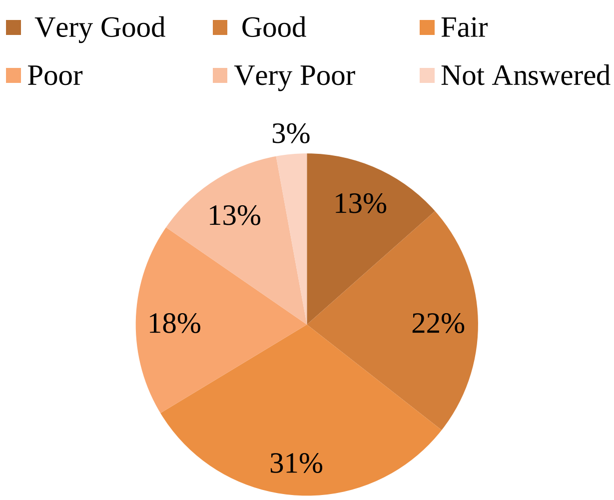


Figure 82: Functional efficiency of the revetment (n=104)

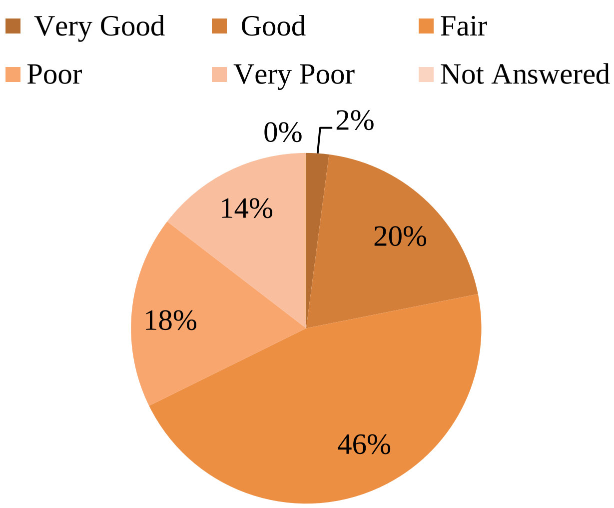


Figure 83: Functional efficiency of the railway embankment (n=96)

Respondents did not feel that the presence of these structures would make them safer in the case of a tsunami event (see Figures 84 and 85). The reason was that they did not believe those structures had the ability to hold back a significant tsunami wave. Only 18% and 13% of respondents felt more secure due to the present of the revetment or railway embankment, respectively. These results highlighted the importance of upgrading the structures to resist against a significant tsunami event, given that the population has direct experience of the 2004 Indian Ocean tsunami and they recognize that the present structures are not of sufficient height to act as effective countermeasures.

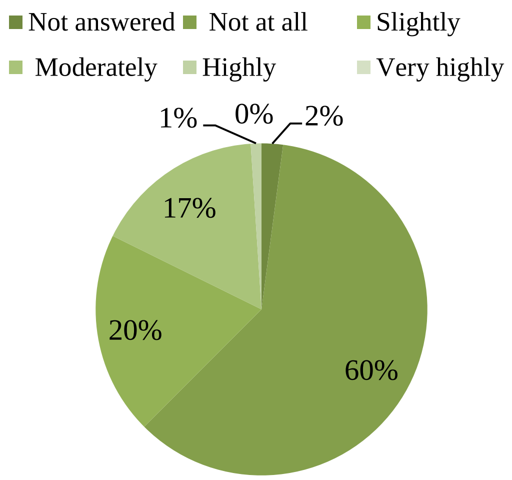


Figure 84: Feeling of security from revetment against a tsunami (n=104)

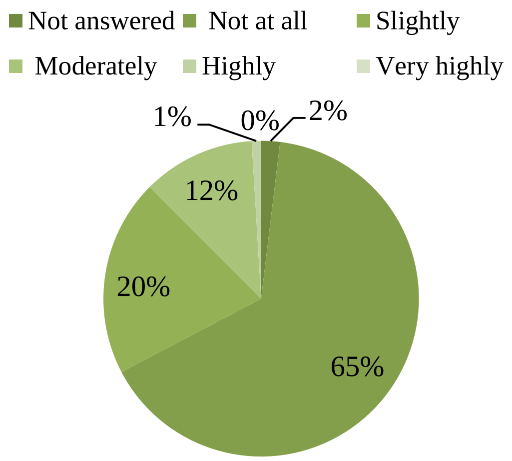


Figure 85: Feeling of security from railway embankment against a tsunami (n=96)

The paying capacity (how much respondents estimated that they could pay in a month during a one year period to community project like this) of 200 respondents was summarized in Figure 86.

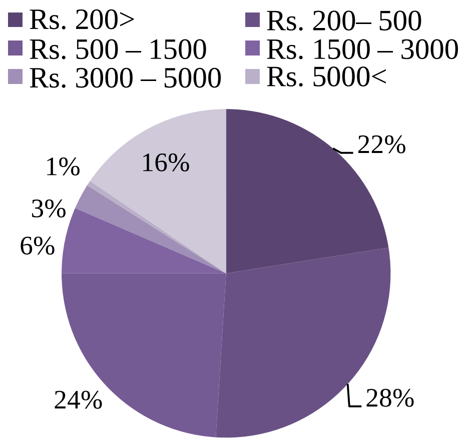


Figure 86: Community paying capacity (in Sri Lankan rupees)

3.3.2 Community willingness to pay (WTP)

Figure 85 and 86 summarize the results of the community willingness to pay to upgrade both the railway embankment and the revetment. The willingness to pay to upgrade the railway embankment is higher than that of the revetment. The result was verified during the focus group discussion. Drawings of a potential upgraded structure and the cost of the upgrade were shown to respondents and asked what percentage they could pay in one year.

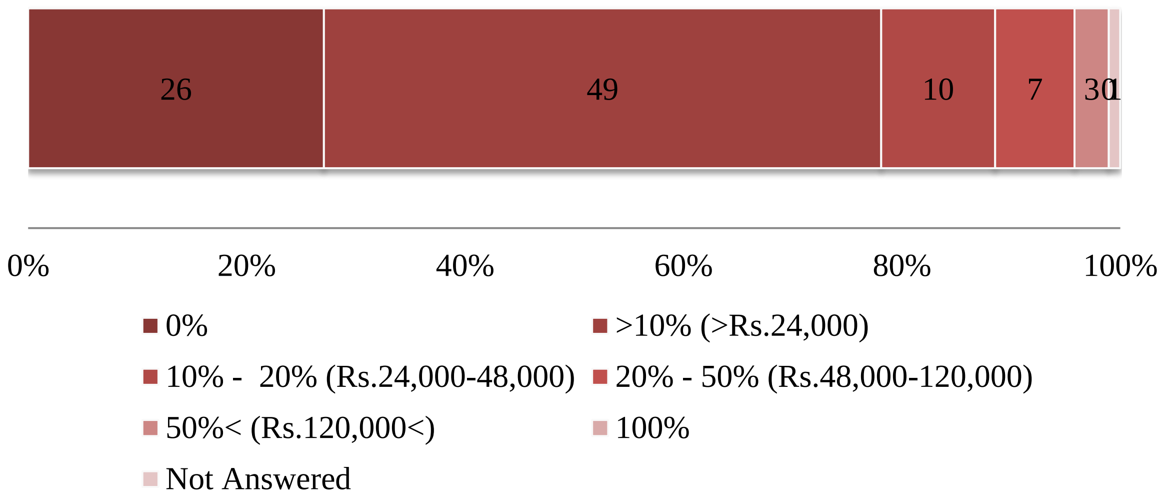


Figure 87: Percentage of contribution to upgrade the railway embankment

$$\boldsymbol{WTP = \frac{24{,}000}{2} x\, 0.49 + \frac{24{,}000+48{,}000}{2} x\, 0.10 + \frac{48{,}000+120{,}000}{2} x 0.07 + \frac{120{,}000+240{,}000}{2} x 0.03 + 240{,}000 x 0.00 = Rs.\ 20{,}760} \quad \textbf{(19)}$$

The community's willingness to pay to upgrade the railway embankment was Rs. 20,700 per household, as shown in Figure 87. The community's willingness to pay to upgrade the revetment was Rs. 9, 490 per household.

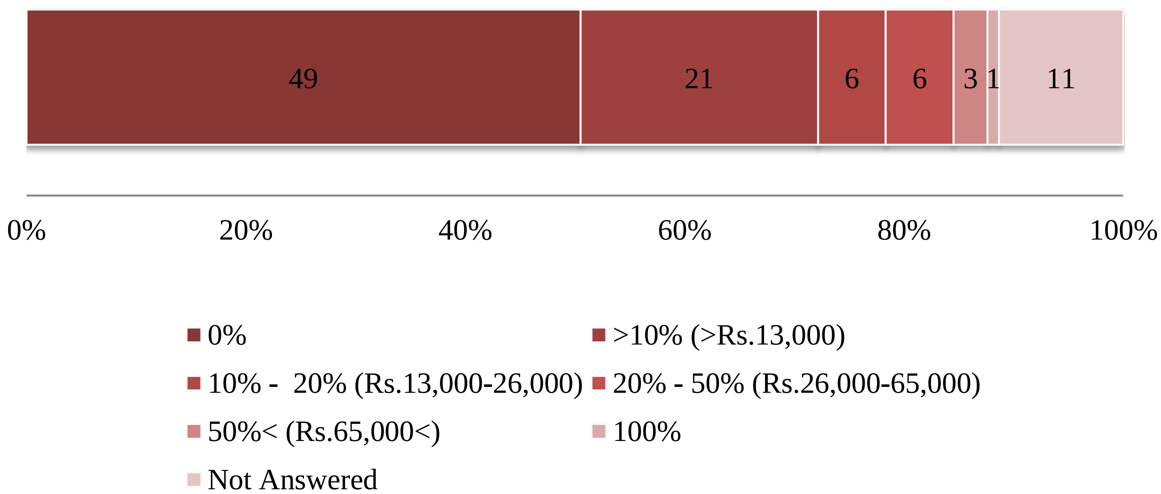


Figure 88: Percentage of contribution to upgrade the revetment

$$WTP = \frac{13,000}{2} x\ 0.21 + \frac{13,000 + 26,000}{2} x\ 0.06 + \frac{26,000 + 65,000}{2} x0.06$$

$$+ \frac{65,000+130,000}{2} x0.03 + 130,000x0.01 = Rs.\ 9,490 \qquad \textbf{(20)}$$

53% (n=104) of respondents were willing to pay to upgrade the revetments and 72% (n=96) of respondents were willing to pay to upgrade the railway embankment. The reason behind this difference appears to reside in the economic effects that the construction of the embankment had on local construction materials. As already explained in previous chapters most of the houses in the case study area had masonry walls. Rocks are one of an important material for the base of masonry walls. The cost of rocks increased due to the construction of the revetment in 2005, and currently local residents are afraid of future increments of cost of rock. During the construction of the revetment, the cost of rubble also increased significantly, to the point that it was no longer affordable by many people, who fear this could happen again if the revetment is upgraded. Also, during its construction coastal vegetation would be removed, and some of the residents are worried about the possible reduction in the number of tourists and the potential for beach erosion. Nevertheless, it is significant to note that structures have already been constructed, and it is unlikely that an upgrade to it would significantly change things. Small traditional boats (APPENDIX C) cannot anchor inside fishery harbours due to its small size. Local fishermen anchor boats in beach before construction of the revetment. However, no such objections were found for the case of upgrading the railway embankment. This is another reason to lower WTP to upgrade the revetment.

3.3.3 Representation of WTP from logistic regression model

It is important to understand which factors influence people in order to give policy recommendations to improve the community's willingness to pay. The author assumed that WTP was dependent on nine independent parameters to use logistic regression, namely whether individuals were resident of the area, agreed with government policy, the perception of structural functionality, witnessing the 2004 tsunami, occupation, trust on EWS, participation in tsunami drill, awareness of safe places and paying capacity.

People were asked whether they lived (1) or not (0) in the area, whether they agreed with the government policy on disaster management (1) or not (0), whether they had witness to 2004 Indian Ocean Tsunami (1) or not (0), whether they trusted EWS would save their lives (1) or not (0), whether they had participated in a tsunami drill at least once (1) or not (0), whether they were aware on safe places and safe routes (1) or nor (0) and whether they could pay more than the mean paying capacity (1), all of which were considered as the main independent variables in logistic regression. Housewives and retired respondents were not considered as having an occupation. Therefore unemployed respondents, retired respondents and housewives were considered as 0 and other respondents were considered as 1 in the logistic regression.

The regression equation is given below ($\beta_{1,}$ - β_9 are the model coefficients and ξ is the model constant)

$$\begin{aligned}\textbf{WTP} = {} & \beta_1\,\textbf{(Residency of the area)} + \beta_2\,\textbf{(Agree with Govt. policy)} \\ & + \beta_3\,\textbf{(Perception of structural functionality)} \\ & + \beta_4\,\textbf{(Witness to 2004 Indian Ocean Tsunami)} \\ & + \beta_5\,\textbf{(Occupation)} \\ & + \beta_6\,\textbf{(Trust on EWS)} + \beta_7\,\textbf{(Participation to tsunami drills)} \\ & + \beta_8\,\textbf{(Awareness of safe places)} + \beta_9\,\textbf{(Paying capacity)} + \xi \qquad \textbf{(21)}\end{aligned}$$

Table75 shows the primary status of WTP model after doing the probability regression calculations for 200 observations.

Table 75: Primary status of WTP model

Model parameter	**Value**
Number of observations	200
Likelihood Ratio(LR) of chi squared test	42.19
The probability of getting LR test statistics more than the observed null hypothesis	0.0000
McFadden's pseudo R-squared	0.1538

The probability of getting LR (Likelihood Ratio) test statistics more than the observed null hypothesis was lower than 0.05 (Torres-Reyna, 2012). Therefore the coefficients in the model did not equal to zero. Table 66 shows notation used to describe the various independent variables that were analyzed.

Table 76: Notations of independent variables

Independent variable	**Notation**
Residency in the area	RE
Agree with government policy	Gov.
Perception of structural functionality	St_F
Witness to 2004 tsunami	Wit_2004IOT
Occupation (Occupied = 1 or not = 0)	Occ.
Trust on EWS	TrEWS
Participation to tsunami drill (at least 1 = 1, else 0)	Drill
Awareness of safe places and safe routes	Aw_S_Place
Paying Capacity	$_Capa.

The stability of each regression coefficient **(β)** of independent variable was checked by comparing regression coefficients of each variable by adding one by one each variable to the regression model, as shown in Table 77. If a variable has a strong contribution to the regression model, its sign does not change while adding it, otherwise the proposed variable cannot be considered as a variable in the model.

Table 77: Regression coefficients obtained by adding parameters one by one to the model

Parameter	**Regression coefficients β**								
RE	1.69	1.67	1.70	1.93	1.88	1.84	1.83	2.09	2.37
Gov.		-0.04	-0.04	-0.05	-0.06	-0.05	-0.05	-0.05	-0.24
St_F			0.09	0.09	0.06	0.06	0.05	-0.01	-0.04
Wit_2004IOT				-0.44	-0.46	-0.47	-0.49	-0.56	-0.40
Occ.					-0.19	-0.20	-0.19	-0.15	-0.18
TrEWS						-0.12	-0.13	-0.12	0.03
Drill							0.06	0.09	0.40
Aw_S_Place								-0.78	-0.81
$_Capa.									2.08

The coefficient of perception (β_3) of the current level of functionality of each type of structures and the coefficient of trust (β_6) on the early warning system showed instability, as indicated in Table 77. Therefore, these two parameters were excluded from the model, and the analysis was rerun using only the other parameters. Logistic regression analysis results are presented in Table 78.

Table 78: Regression analysis results

Variable	Regression coefficients (β)	Stand. Err	z	P>|z|
RE	2.369	1.263	1.880	0.061
Gov.	-0.235	0.324	-0.730	0.468
Wit_2004IOT	-0.401	0.558	-0.720	0.472
Occ.	-0.180	0.323	-0.560	0.576
Drill	0.405	0.351	1.150	0.249
Aw_S_Place	-0.802	0.442	-1.820	0.069
$_Capa.	2.079	0.402	5.170	0.000
Model constant	-1.682	1.313	-1.280	0.200

Residency in the area, awareness of safe places and evacuation routes and paying capacity had a significant contribution to WTP. A 90% confidence was obtained regarding the coefficients of residency in the area and awareness of safe places and safe routes in the model. 99% confidence was obtained for the coefficient of community paying capacity. The final results of the WTP model are summarized in Table 79.

Table 79: Primary status of WTP model

Model parameter	Value
Number of observations	200
Likelihood Ratio(LR) of chi squared test	42.10
The probability of getting LR test statistics more than the observed null hypothesis	0.0000
McFadden's pseudo R-squared	0.1537

The regression coefficients show the contribution of each factor to the model. A positive sign (+) represents a positive correlation and a negative sigh (-) a negative correlation with regards to WTP. The slope of the probability curve of a given variable (while other variables are kept constant), is referred to as the marginal effect in binary regression models This marginal effects was considered to compare how likely it is that each variable contributed to WTP, as shown in Table 80.

Table 80: Marginal effects of independent variables

Variable	**Sign of regression coefficients (β)**	**Marginal effect (%)**
RE	+	47
Gov.	-	5
Wit_2004IOT	+	8
Occ.	-	4
Drill	+	8
Aw_S_Place	-	16
$_Capa.	+	41

Respondents who lived in the case study area, who had a high paying capacity (Paying capacity is higher than its mean value), who had witnessed the Indian Ocean Tsunami in 2004 and those who had participated in a tsunami drill at least a once were more willing to pay to upgrade the revetment and railway embankment. Most of the people who participated in tsunami drills got exposed to deficiencies in the evacuation process, and therefore this positively correlated to the WTP. Respondents who were not satisfied with the government policy avoiding to construct hard defensive countermeasures against tsunamis, who were occupied and who were aware of safe places and safe evacuation routes were not willing to pay to upgrade the revetment and the railway embankment. However, the lowest contribution to the WTP model was from the variable of occupation.

The correctly classified value of the regression model was 69.50%. As this value was greater than 50%, the model was accepted.

3.3.4 Discussion of results

According to the results of an interview with officials at the Disaster Management Center (DMC) in Sri Lanka most of the people who participated in the tsunami drills were women. Most of the questionnaire respondents that declared that they did not have an occupation were housewives. This helps to explain why the correlation between those respondents who had a job and the WTP was negative.

Retired respondents were neither willing to pay (Probability > chi2 = 0.0461, P>|z| = 0.050) nor aware of EWS (Probability > chi2 = 0.0417, P>|z| = 0.029) or safe places to evacuate. (Probability > chi2 = 0.0521, P>|z| = 0.043). Thus, the results of the questionnaire survey point out to the fact that the main victims of the disaster are likely to be the elderly (Ngo, 2011).

The respondents who participated in tsunami drills every year generally trusted the EWS (Probability > chi2 = 0.0049, P>|z| = 0.032). Conversely, those who did not participate in tsunami drills every year did not trust EWS. If residents actively participate in tsunami drills, there is a possibility to increase the trust on EWS.

The importance of upgrading tsunami co-beneficial structures was initially described in the questionnaire sheet. But when the author started asking questions regarding the willingness to pay to upgrade the selected structures, many respondents changed their facial expressions, generally indicating they were reticent to pay themselves. It was a clear example to the displacement of the value of upgrading from cost of upgrading from human mind.

The answers to Questions 7, 8 and 11 (see Appendix B, regarding expected performance of tsunami co-beneficial structures in future tsunami events and past tsunamis, and the preferred method to calculate WTP) were rejected due to unreliability of answers, as most of respondents seemed confused by the technical nature of the questions.

All respondents were informed that the questionnaire was conducted for educational purposes only and that the questions were not to confirm the community's actual willingness to contribute to a project. Therefore the biggest limitation in the WTP questionnaires was that it does not reveal the real WTP, as respondents might have answered differently if asked about a real project were they were expected to contribute. However this limitation was accepted in many other WTP research (Breidert et al., 2006).

The revetment that had been constructed in the area aimed to counteract the severe coastal erosion that had taken place in that coastline. The reason[5] behind this erosion is the interruption of coastal longshore drift due to the construction of a new breakwater in Hikkaduwa fishery harbor expansion project. The case study area is also famous for its coral reefs, which were covered in sand deposits due to 2004 Indian Ocean Tsunami.

The selected villages were located in the south western cost of Sri Lanka. The tsunami travel time map of the Indian Ocean (corroborated by the events on the27, August, 1883 and 26, December, 2004) clearly showed that the arrival time to the area is nearly two hours after an earthquake in the Andaman zone region (NCEI, 2016). Figure 89 shows a Google Earth image the case study area showing the road network, which could be sufficient to evacuate

[5] Focus group discussion with local residents in Dimbuldooa and Wenamulla, at Wenamulla temple, Sri Lanka in February 2016 (See photographs in APPENDIX C)

within two hours. However, it should be noted that in an emergency traffic jams could reduce the evacuation time (though examining this is outside of the scope of the present work, and should be clarified by future studies). 82% of respondents were aware of evacuation centres and routes, and their WTP was negatively correlated with this awareness Nevertheless, both community awareness and the condition of evacuation routes clearly contribute to a successful EWS.

Figure 89: Locations of tsunami evacuation centers in the case study area (Source: Map data ©2016 Google Imagery ©2016, CNES / Astrium, Cnes/Spot Image, Digital Globe, Landsat)

Table 74 describes the implications of regression model, given by Equation 22. Having witnessed the 2004 Indian Ocean Tsunami is an unchangeable variable as it was a personal experience in the past. Awareness of safe places and safe routes need to be further studied as explained earlier. Some of possible ways to increase the WTP was tabulated in Table 81.

Theoretically speaking the WTP might be increased if people were encouraged to live in coastal zone, though this would increase their exposure to tsunami hazard. Otherwise, it appears that residents are more willing to pay, and the WTP could be increased by encouraging residents to participate in tsunami drills and improving their income.

$$\textbf{WTP} = 2.369\,(\text{Residency of the area}) - 0.235\,(\text{Agree with Govt. policy}) - 0.401\,(\text{Witnessed the 2004 Indian Ocean Tsunami}) - 0.180\,(\text{Occupation}) + 0.405\,(\text{Participation in tsunami drills}) - 0.802\,(\text{Awareness of evacuation centers}) + 2.079\,(\text{Paying capacity}) - 1.682 \quad \textbf{(22)}$$

Table 81: Possible ways to increase the WTP

Variable	Correlation with WTP	Suggestions to increase WTP
Residency in the area	Positive	Difficult. Practically difficult to increase number of houses
Agree with government policy	Negative	Educate the community about capabilities about hard defensive measures
Witnessed the 2004 tsunami	Positive	Cannot change
Occupation	Negative	Encourage those with jobs to participate in tsunami drills
Participation to tsunami drill	Positive	Encourage people to participate in tsunami drills
Awareness of evacuation centres and safe routes	Negative	Further studies are required
Paying Capacity	Positive	Improve the income of the residents

4 DISCUSSION

The reduction in potential damage due to the presence of tsunami co-beneficial structures goes through a maximum value. The inundation extent due to low magnitude earthquakes is rather limited, and thus the reduction in damage for such events is rather small (as very limited damage would take place anyway). For large earthquakes the structures would be completely overwhelmed and there would be no reduction in damage. Therefore the expected pattern of the reduction in damage with regards to the earthquake magnitude is shown in Figure 90. Thus, this methodology of calculation of reduction in damage can be used to determine the optimum levels of tsunami co-beneficial structures for different magnitude earthquakes.

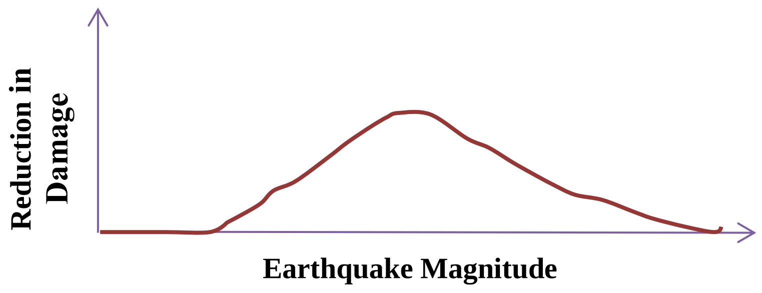


Figure 90: Expected results of reduction in damage vs. earthquake magnitude (Schematic diagram)

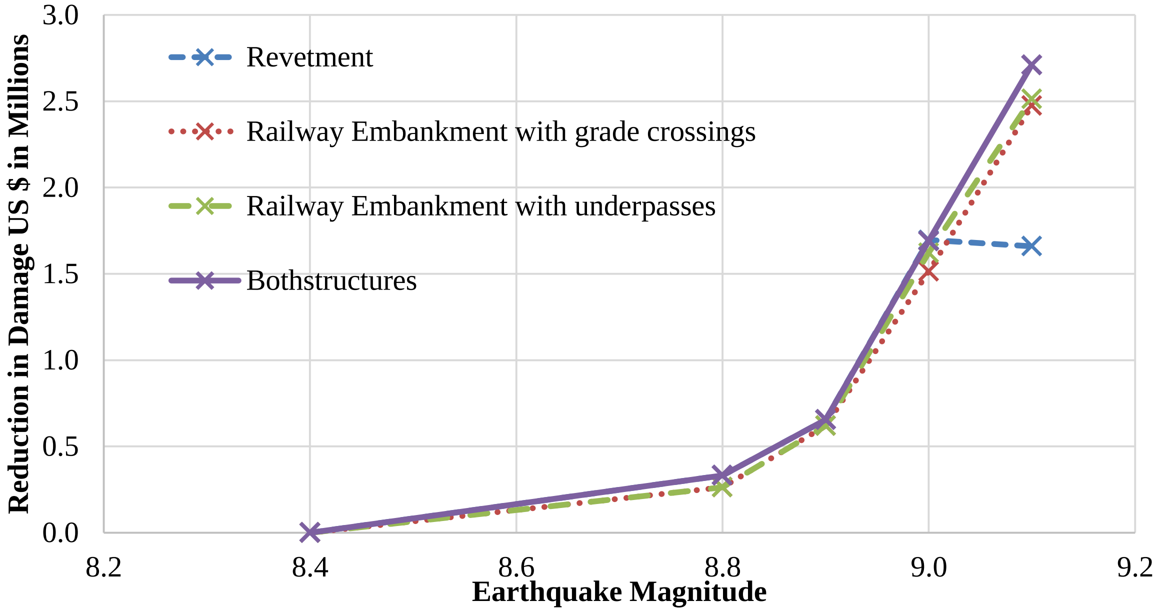


Figure 91: Reduction in damage vs. earthquake magnitude

Revetments are very effective to reduce damage for the case of low magnitude earthquakes. But revetment is not that much effective in high magnitude earthquakes. Effectiveness in damage reduction of railway embankment is lower than that of revetment for the case of low magnitude earthquakes. The reason is that the revetment is located at the beach but the railway embankment is nearly 100m away from the coast line. Therefore the tsunami inundation extent in the case where only a railway embankment is present is higher than that when there is only a revetment. This explains some of the differences observed in Figure 90.

The reduction of damage due to railway embankment with grade crossings is slightly higher than that of railway embankment with underpasses. Basically, the inundation extent in the case of railway embankment with grade crossings is smaller than that of railway embankment with underpasses. The reason for this variation was the increased wave height (~1.0m) at the seaward side of the railway embankment with grade crossings. The railways embankment with underpasses allows the tsunami to flow through the underpass opening, which can lead to small inundation heights even for small magnitude tsunamis

The overall damage density in the case study area was defined according to equation 23.

$$\textit{Damage Density} = \frac{\textit{Damage}}{\textit{Inundated Area}} \quad (23)$$

The maximum value of the damage density occurs when the whole case study area is completely damaged. Some of expected patterns of damage density for different protection scenarios are shown in Figure 92. The damage density due to railway embankment with or without grade crossings heavily depends on the house distribution and type of houses. Thus, selecting the use of a railway embankment with grade crossings as a protection strategy can only be recommended if pattern 2 can be obtained.

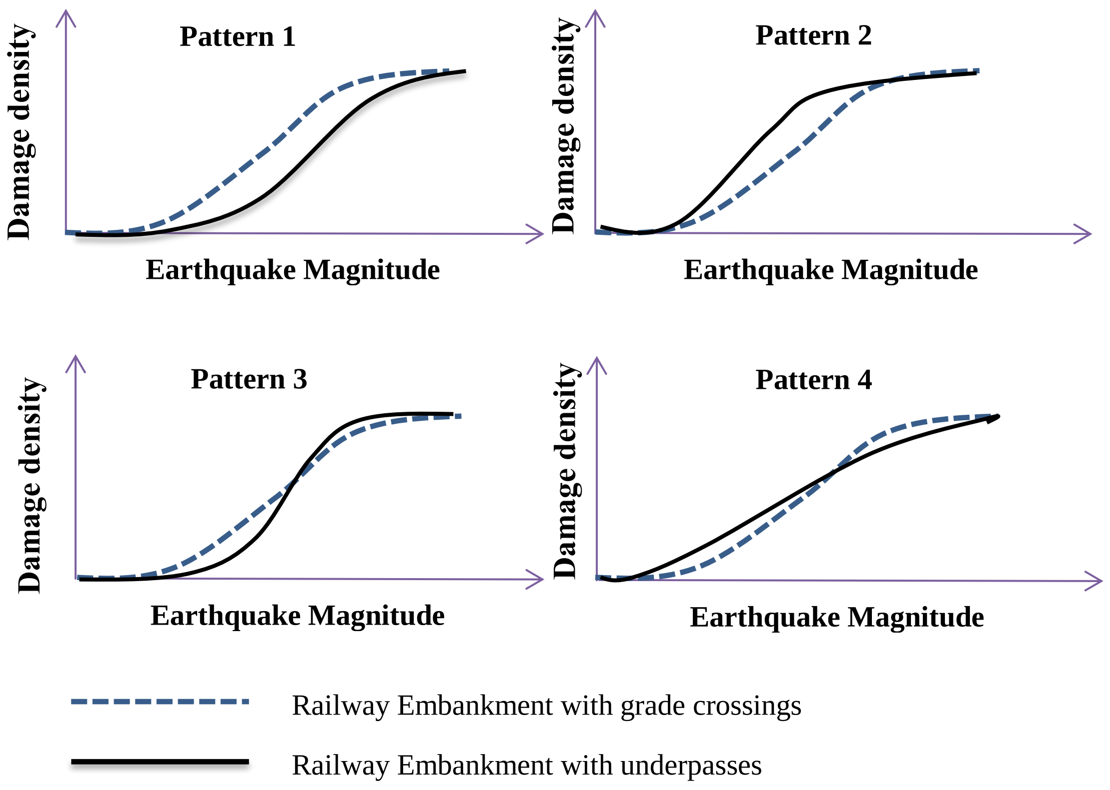


Figure 92: Expected results of damage density vs. earthquake magnitude (Schematic diagram)

The computed patterns of the damage density are shown the Figure 92.

Railway embankment with underpasses significantly contributes to reduce the damage due to tsunamis generated by 9.0Mw and 9,1Mw. It should be noted that whether grade crossings or underpasses are used makes no difference for the case of low magnitudes earthquakes.

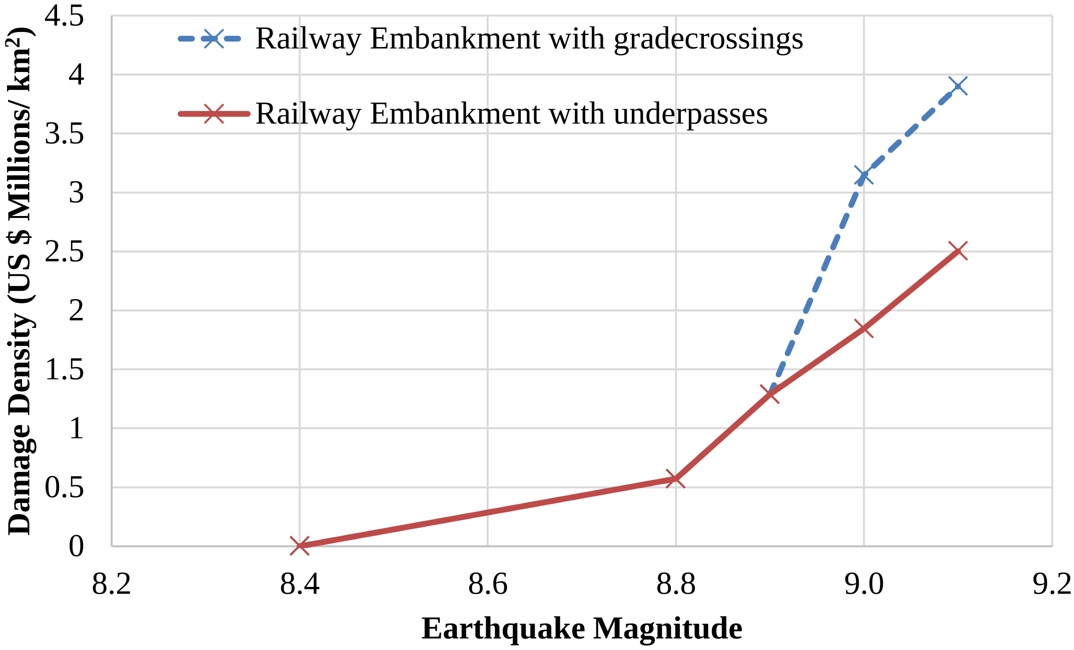


Figure 93: Damage density vs. earthquake magnitude

The earthquake return periods (T) for 8.4, 8.8, 8.9, 9.0 and 9.1 earthquake magnitudes are 350, 750, 900, 1000 and 1500 years, respectively (Burbidge & Cummins, 2008). Therefore the probability of occurrence ($p = 1/T$) of a large earthquake is very low. One of worldwide accepted definition for quantitative evaluation of risk (R) was adapted in this study (Equation 24, where D is the damage due to the tsunami)

$$\boldsymbol{Risk} = \boldsymbol{Probability\ of\ earthquake} \times \boldsymbol{damage\ due\ to\ tsuanmi} \qquad (24)$$

$$\boldsymbol{R} = \left(\frac{1}{T}\right) \times \boldsymbol{D}$$

Equation 24 was modified to become Equation 25 to illustrate the reduction of risk ($R^{\prime}$) due to tsunami co-beneficial structures. $D^{\prime}$ is the reduction in damage due to co-beneficial structures.

$$\boldsymbol{R^{\prime} = \left(\frac{1}{T}\right) \mathrm{x}\, D^{\prime}} \qquad \textbf{(25)}$$

This approach can be used to recognize the most suitable design earthquake. Figure 94 shows the graph of reduction in risk verses earthquake magnitude. The most suitable design tsunami height was that generated by 9.0Mw earthquake.

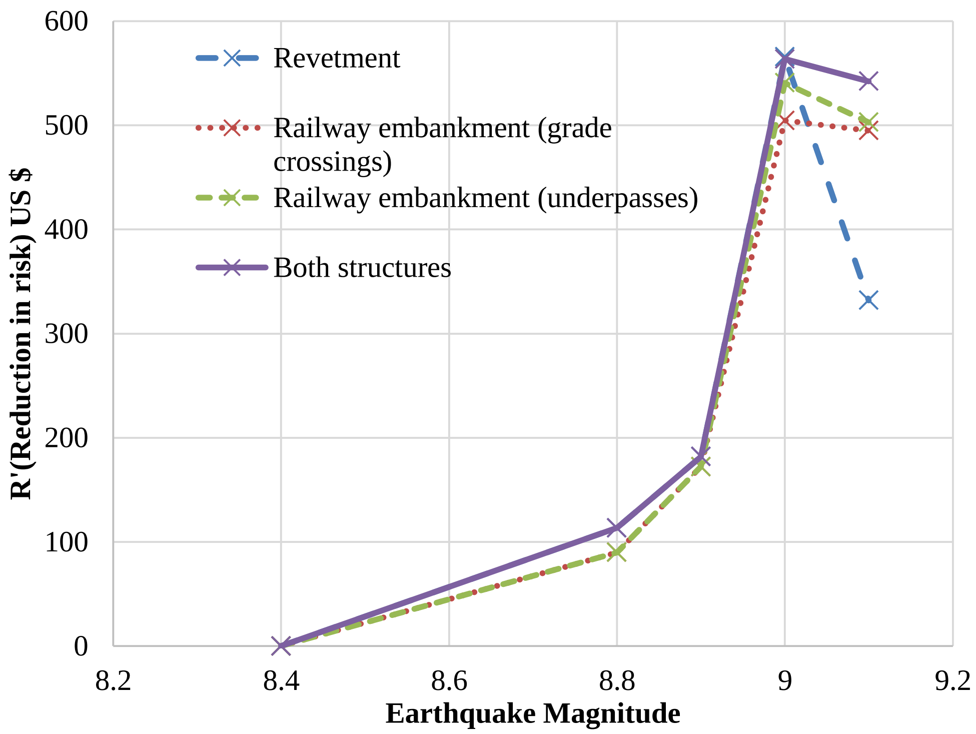


Figure 94: Reduction in risk vs. earthquake magnitudes

However, when taking into account the potential failure of the structures due to tsunami overflow, the risk reduction patterns change, as indicated by Figure 95. The author assumed that the structures would fail when the probability of failure is greater than 50%.

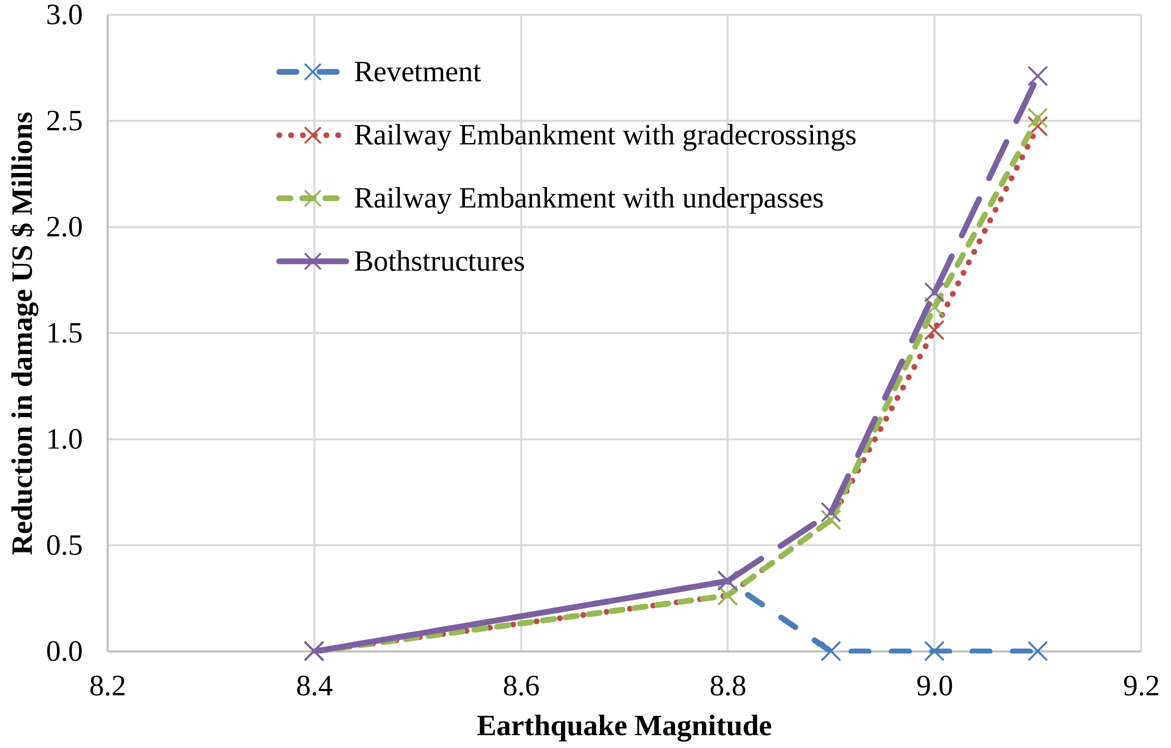


Figure 95: Reduction in damage vs. earthquake magnitudes (for the case when the tsunami co-beneficial structures collapse due to tsunami overflow) (Schematic diagram)

Table 82 shows the earthquake magnitude which gives that optimum value for selected co-beneficial structures taking into account two assumptions (as stated earlier in this thesis) a) The value in brackets is the maximum tsunami height at the coast; b) The tsunami co-benefit value is equal to the reduction of damage when the tsunami co-beneficial structures are not upgraded.

Table 82: Optimum tsunami co-benefit values

Assumption	Structure will not collapse due to tsunami overflow		Structure will collapse due to tsunami overflow	
Structure	Earthquake magnitude Mw (Maximum tsunami height at coast)	Tsunami co benefit (US $ in Millions)	Earthquake magnitude Mw (Maximum tsunami height at coast)	Tsunami co benefit (US $ in Millions)
Revetment	9.0(4.3m)	1.697	8.8(3.3m)	0.332
Railway embankment with grade crossing	9.0(4.3m)	1.514	9.0(4.3m)	1.514
Railway embankment with underpasses	9.0(4.3m)	1.622	9.0(4.3m)	1.622
Railway embankment with grade crossings and revetment (Both structures)	9.0(4.3m)	1.691	9.0(4.3m)	1.691

Tsunamis generated by earthquakes greater than or equal to 8.9*Mw* and 9.1 will overflow the revetment and railway embankment, respectively. However, these structures do not fail suddenly due to the tsunami overflow and can provide time for residents to evacuate.. One important characteristic in this case study area is that the amplitude of first wave is not the maximum tsunami amplitude, and thus the structures will likely only be overtopped by the second or third waves.

In the simulations carried out the first tsunami wave did not overflow the railway embankment in the 9.0*Mw* earthquake tsunami. The second tsunami wave reached the coast and overflowed the railway embankment with grade crossings after 40 minutes, and thus it can be concluded that the evacuation time was increased by at least 40 minutes.

It was clear that the tsunami co-beneficial function of coastal structures is negligible for large scale tsunamis, unless these structures are upgraded. Strengthening the tsunami co-beneficial structures without changing their heights to resist under a tsunami was defined as upgrading, as described in the section of upgrade tsunami co-beneficial structures. Net tsunami co benefit *(B)* due to upgrading is defined in Equation 24. Equation 24 is a simplified version of Equation 2. Figure 96 shows the effect of net benefit due to upgrading. (C_s is the strengthening cost of co-beneficial structures)

$$\boldsymbol{B = D' - C_s} \quad \textbf{(26)}$$

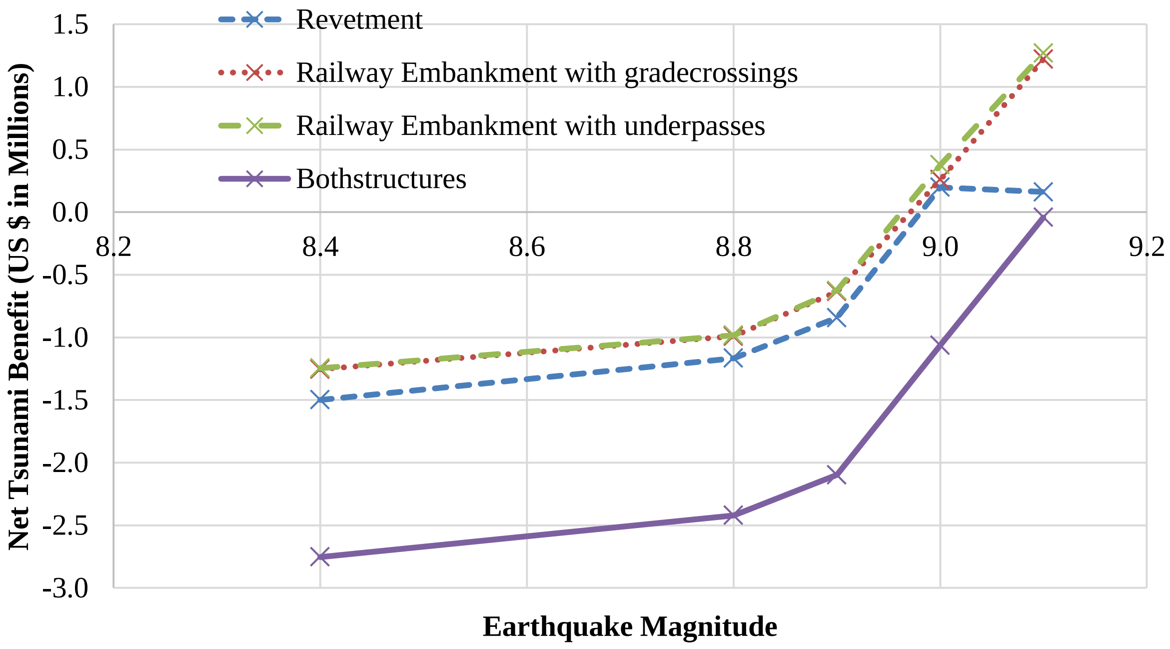


Figure 96: Net tsunami co-benefit vs. earthquake magnitudes

Upgrading does provide any benefits for the case of low magnitude tsunamis. Upgrading both structures also does not provide any benefit. The structural strengthening gives comparatively less benefits for the case of upgrading the revetment. Therefore, the height of the revetment was increased by 0.2m intervals from 1.0m to study the behavior of the co-benefit of the revetment also calculated to completeness of study.

Table 83 shows the cost of upgrade and WTP of these structures. WTP value is a very small value and its contribution is negligible in this case as shown in Table 83.

Table 83: Upgrading cost and WTP

Structure	Cost of upgrade (US $ in Millions)	WTP (US $ per year per house)	WTP (US $ in Millions)
Revetment	1.499	65	0.033
Railway embankment with grade crossing	1.240	143	0.078
Railway embankment with underpasses	1.245	143	0.078

Tsunami co-benefit value without upgrading, with upgrading and expected reduction in damage (Figure 80) was tabulated in Table 84.

Table 84: Tsunami co-benefit value with upgrading, without upgrading and reduction in damage

Scenario	Mw	Tsunami co-benefit (US $ Millions)		Expected reduction in damage US $ Millions
		Without upgrading	With upgrading	
Revetment	8.4	0.000	-1.499	0.000
	8.8	0.332	-1.167	0.015
	8.9	0.000	-0.844	0.030
	9.0	0.000	0.199	0.071
	9.1	0.000	0.161	0.055
Railway Embankment with grade crossings	8.4	0.000	-1.240	0.000
	8.8	0.263	-0.977	0.018
	8.9	0.620	-0.620	0.029
	9.0	1.514	0.274	0.063
	9.1	0.000	1.234	0.069
Railway embankment with underpasses	8.4	0.000	-1.245	0.000
	8.8	0.263	-0.982	0.018
	8.9	0.620	-0.626	0.029
	9.0	1.622	0.377	0.068
	9.1	0.000	1.268	0.070

The tsunami co-benefit of the revetment for different tsunami heights is shown in Figure 97 (note that the reduction in potential damage for a given earthquake is also shown risk was drawn in secondary axis as its units were different.

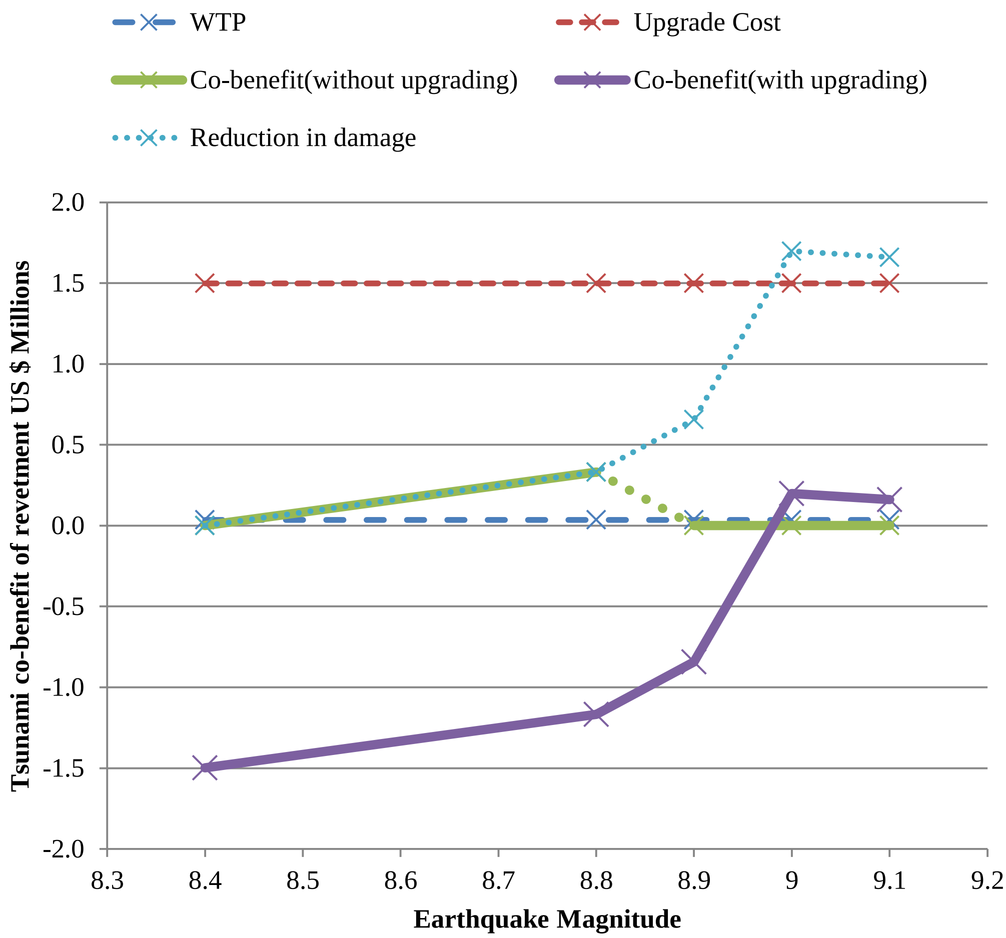


Figure 97: Tsunami co-benefit of revetment vs. earthquake magnitude

The value of the WTP was very small. Maximum reduction in risk was shown for the 9.0Mw earthquake. The Revetment should be upgraded so that it does not collapse in the event of a 9.0Mw earthquake. The maximum tsunami co benefit value reduces from 0.322 US $ M – 0.199 US $ M due to upgrading. The expected reduction in damage increases until 9.0 Mw. To get the maximum benefit, the revetment is recommended to upgrade.

Expected reduction in damage due to railway embankment with underpasses was slightly greater than that of railway embankment with grade crossings. However, the cost of the railway embankment with underpasses was only slightly greater than the case with grade crossings. Maximum tsunami co-benefit of railway embankment with underpasses is slightly greater than that of railway embankment with grade crossings. It is difficult to conclude that the tsunami co-benefit railway embankment with underpasses is greater than that of railway embankment with grade crossings as this result is only based on a one case. However for this case study, the railway embankments with underpasses are recommended.

The tsunami co-benefit of railway embankment with underpasses at different tsunami heights was shown in Figure 98. Reduction in risk was drawn in secondary axis as its units were different. Tsunami co-benefit value is a negative for low earthquake magnitudes, because of higher upgrading cost.

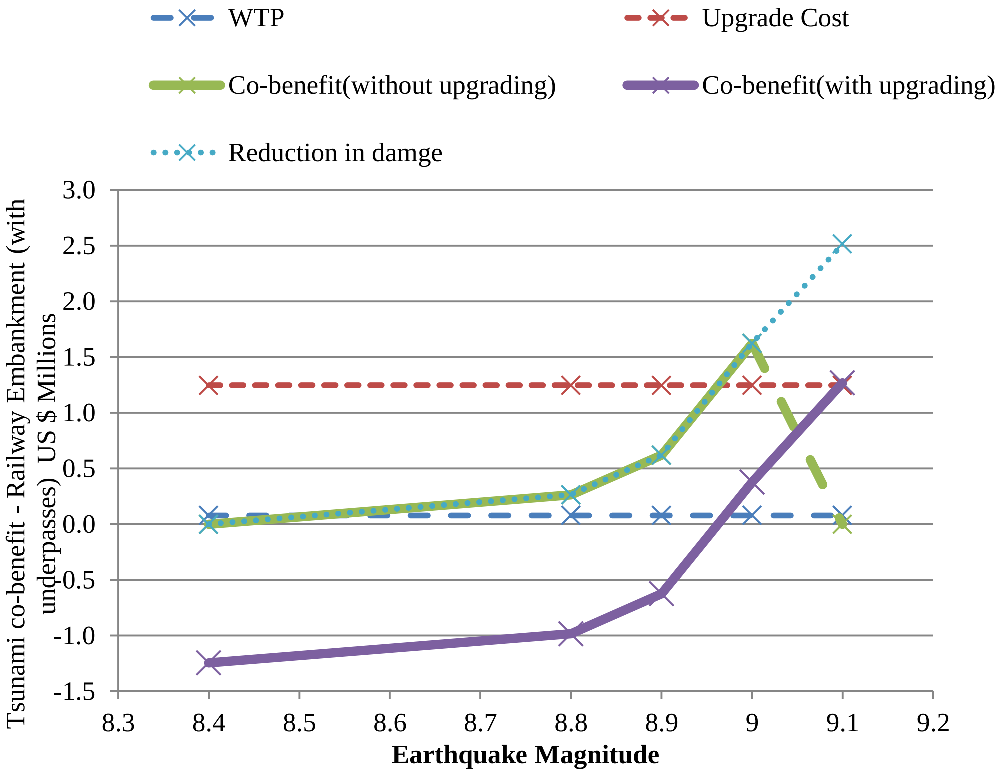


Figure 98: Tsunami co-benefit of railway embankment with underpasses vs. earthquake magnitude

The simplified methodology used in this study can be used to find out the optimum height of structures with potential tsunami mitigation co-benefits.

The community's willingness to pay is not sufficient to cover the entire cost of upgrading the project (73% of residents are willing to contribute to upgrade railway embankment and 53% of residents are willing to contribute to upgrade revetment). When upgrading the revetment, the coastal vegetation will be removed. Therefore the community contribution to upgrade the revetment is lower than that of railway embankment.

The effect of increasing the height of revetment on overall damage is shown in Figure 99. Increasing the height of the revetment is very effective to defend against large scale tsunamis. However, the author believes that given the small return period of large earthquakes increasing the height of revetment should not be recommended.

The reduction in damage cost of upgrading and tsunami co-benefit of increasing height are shown in Figure 100. Maximum tsunami co-benefit value was obtained for a 9.1Mw earthquake when revetment height was equal to 4.8m. However slight height increments in revetment were effective for large tsunamis, and not effective for medium tsunamis.

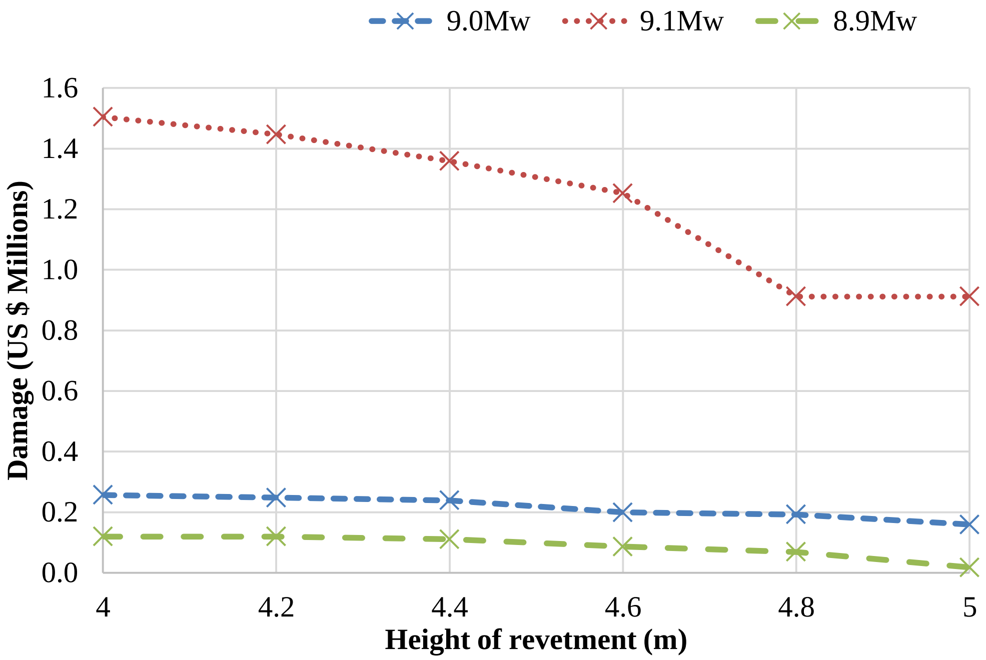


Figure 99: Damage vs. height of revetment

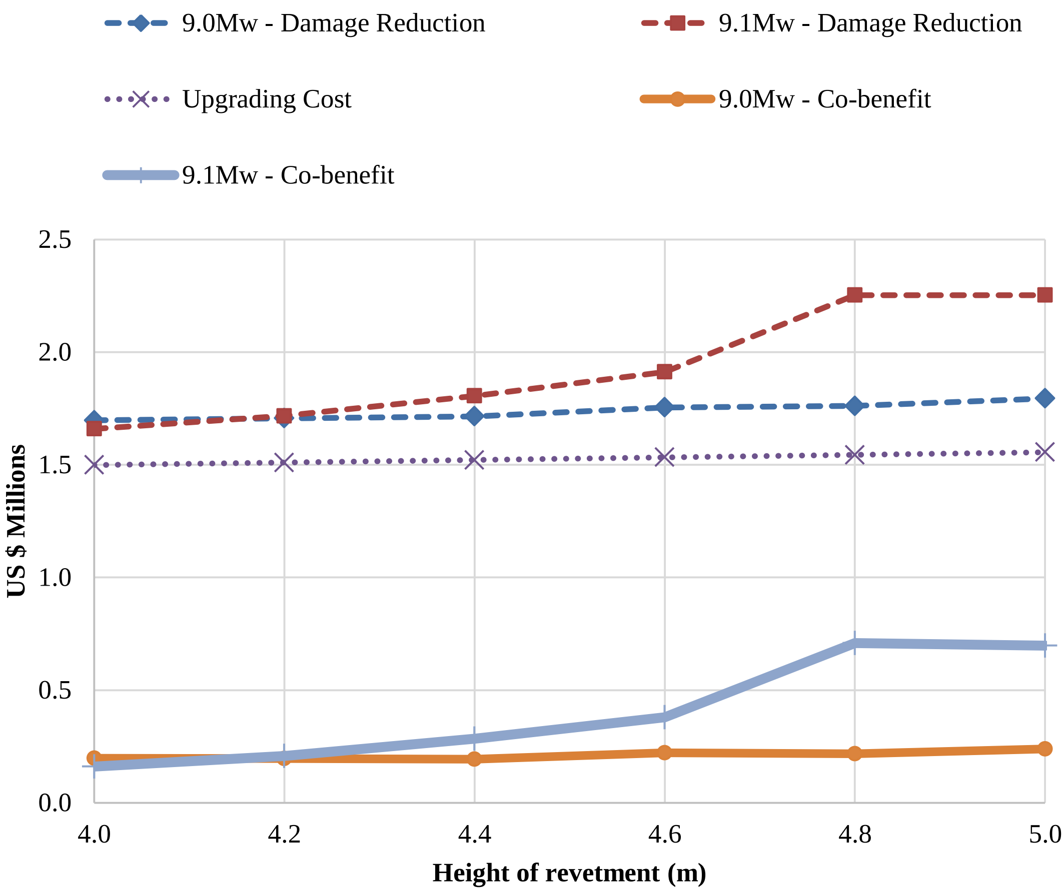


Figure 100: Tsunami co-benefit vs. height of revetment

The optimum height of structures with tsunami co-benefits can be found from this graph. Figure 101 illustrates this concept more clearly.

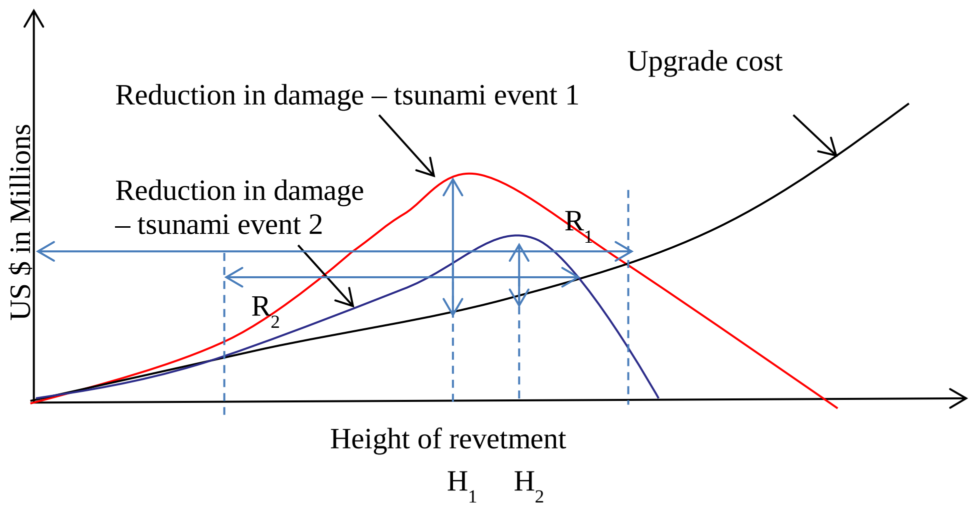


Figure 101: Expected reduction in damage and upgrading cost vs. height of the revetment (Schematic diagram)

The range of heights of the revetment which would be economically helpful (in that their cost would be lower than the reduction in damage they could bring about) is R_1 for tsunami event 1 and R_2 for the tsunami event 1. Thus, the present study was able to identify the range of height of coastal structures which can provide tsunami co-benefits function.

The difference between the reduction in damage due to tsunami event 1 and cost to upgrade become is largest when the height of the revetment is H_1. Based on the probability of occurrence of tsunami event, disaster managers can recommend to designers the range of heights which can provide the tsunami co-beneficial function as well as the optimum height which gives the height expected reduction in damage.

5 CONCLUSIONS AND RECOMMENDATIONS

Two villages (Dimbuldooa and Wenamulla) in the Southern coast of Sri Lanka were selected as the case study area with population of nearly 2200. A coastal railway embankment and a revetment were chosen as types of structures that could have co-beneficial features to mitigate the damage due to tsunamis. The revetment cannot provide tsunami mitigation co-benefit when the earthquake magnitude is greater than 8.9Mw. The maximum expected reduction of damage due to revetment occurs for the 9.0Mw earthquake. Therefore revetment is recommended to upgrade to achieve maximum benefits. The maximum expected reduction of damage due to railway embankment occurs between 9.0Mw and 9.1Mw. Railway embankment can provide tsunami mitigation co-benefit even without the need for it to be upgraded for these co-benefits these earthquake magnitudes. Therefore, the present research does not recommended to upgrade the railway embankment.

Community willingness to pay to upgrade both structures is small in magnitude. Community willingness to upgrade railway embankment is higher than that of revetment due to the expected negative consequences of upgraded revetment, such as an increase in the cost of construction materials throughout the session. Railway embankment with underpasses gives slightly larger benefits compared to that of railway embankment with grade crossings. Thus, if any upgrades to the railway embankment to be considered, the author recommends minor improvements to existing grade crossings into underpasses.

Tsunami mitigation co-benefit is a highly sensitive value. Therefore conducting quantitative analysis is required to improve the resilience of coastal communities. The methodology which proposed in this study can help disaster risk managers to understand the best solution from both a coastal disaster management and coastal development point of view.

The existing structures have clear tsunami mitigation functions, and thus present significant co-benefits top their original purpose. However, it would happen that upgrading them will not properly enhance their co-beneficial function to mitigate tsunamis. Nevertheless, it would eventually be important to measure the benefit due to improvement of main function of these structures due to upgrading, though this is outside the scope of the present thesis.

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APPENDIX A: Process of creation of a high resolution digital elevation model for ComMIT to simulate tsunami inundation

It was necessary to insert a minimum width of the revetment (~5 m) to the DEM for the correct resolution of the C domain of ComMIT model. Appendix A shows the procedure. Figure 103 used to interpolate data from the coarse domain to create more detailed data.

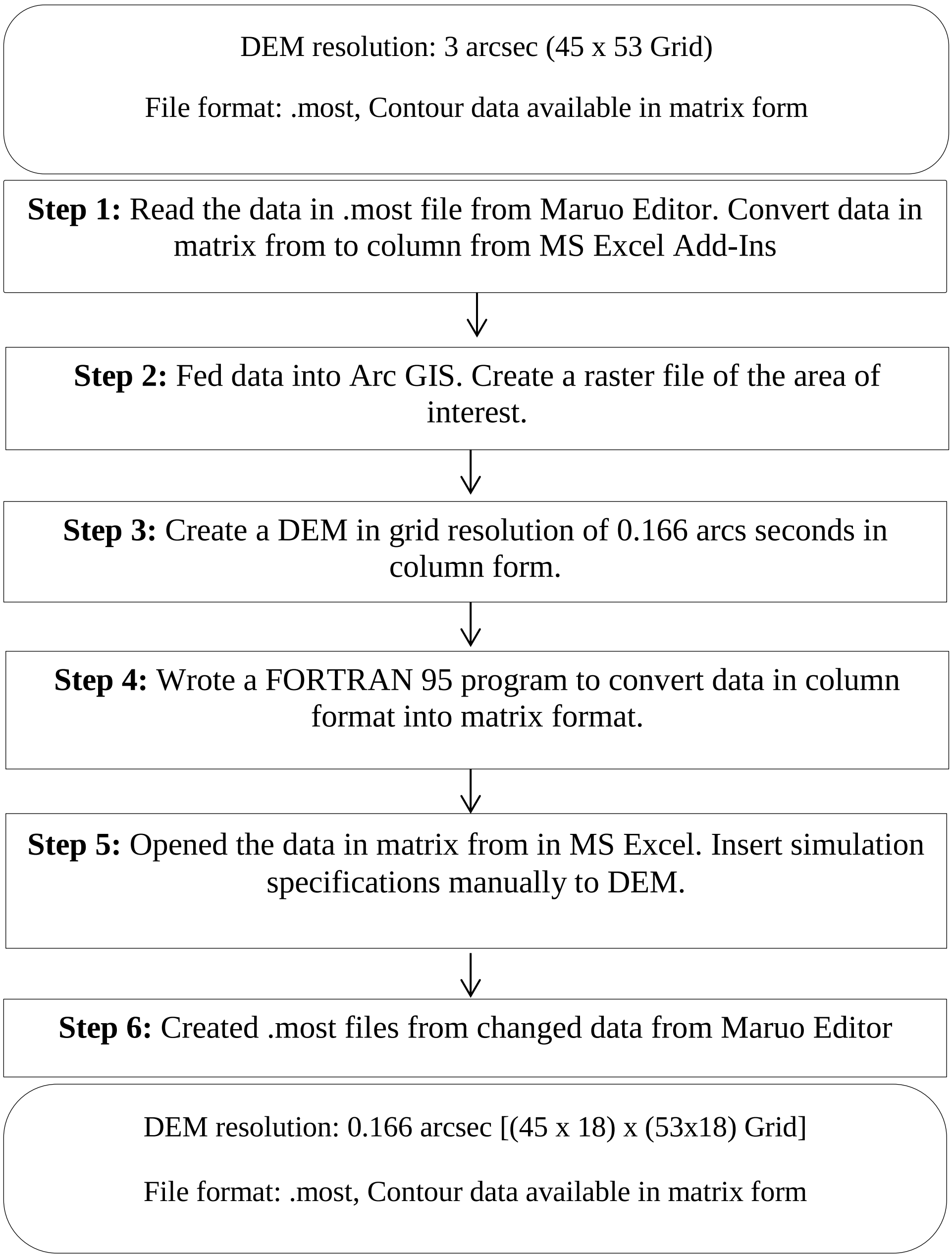


Figure 102: Steps of generating Domain C

Step 1

Step 1.1: Recognize the .most file format

ComMIT software provided ETOPO 1 and CGIAR SRTM data in up to 3.0 arc second resolution for the Hikkaduwa area. The datum was Mean Sea Level (MSL). The data was saved in .most file format in C drive. Files in .most file format can be opened using Maruo editor (Figure 104).

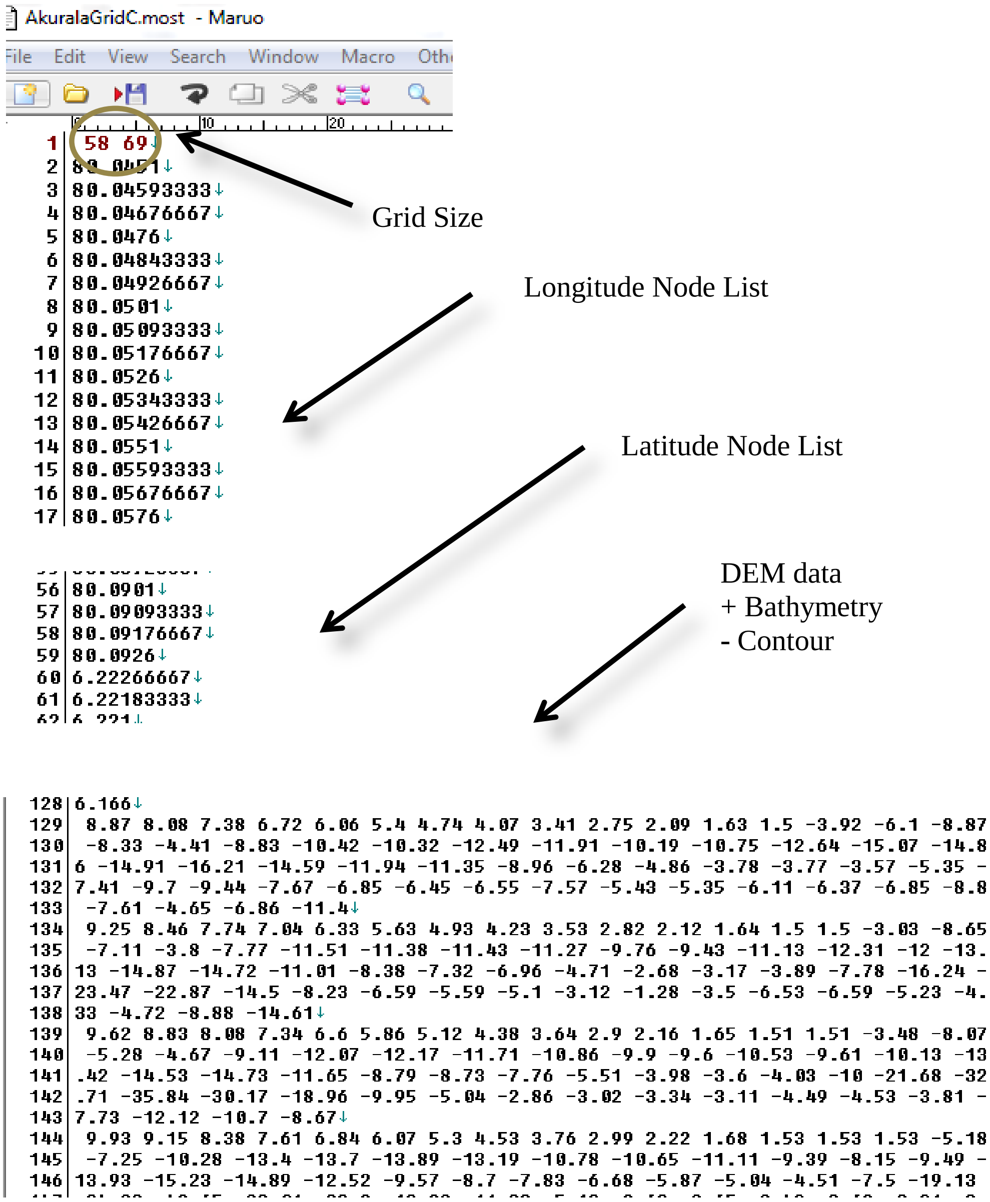


Figure 103: Data format of DEM (Digital Elevation Model) (Opened using Maruo Editor)

The number of longitude nodes and number of latitude nodes appears in the first raw. The longitude node list will appear first and then the latitude node list appears. The elevation model appears next in Metrix form.

Step 1.2: Open the file in MS Excel

The data file was imported to MS Excel file. The DEM in matrix form easily opened using MS Excel. With the aid of the "conditional formatting" command, the contour map can be visualized (Figure 3). Figure 4 shows the contour map, which was generated by the ComMIT software.

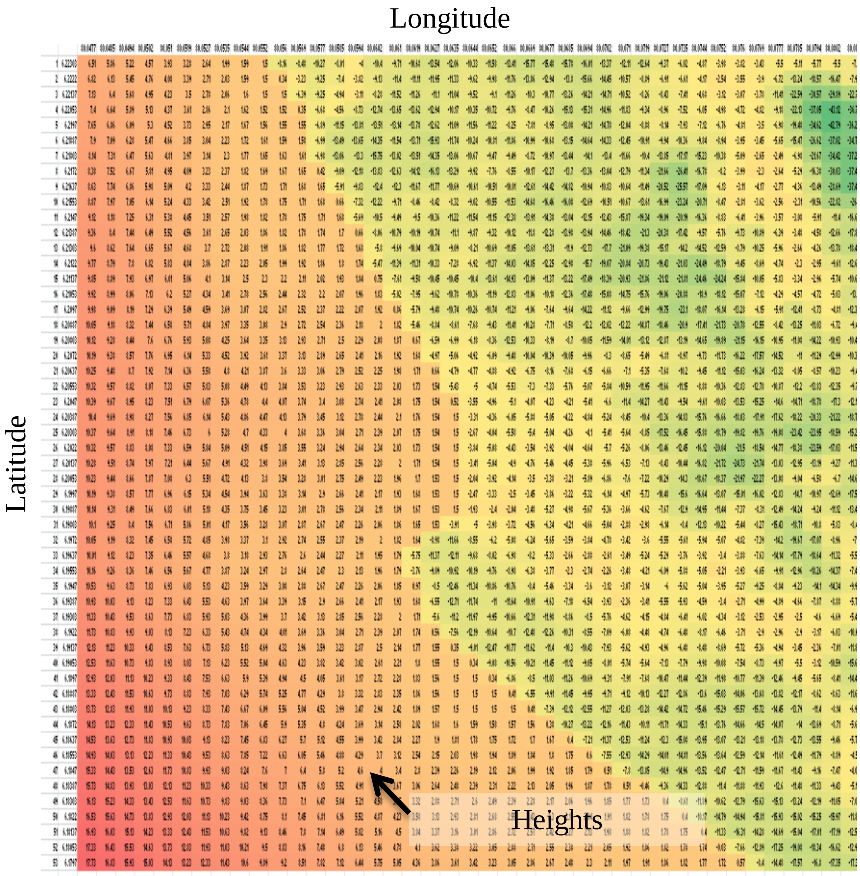


Figure 104: DEM (Digital Elevation Model)   (Opened using MS Excel)

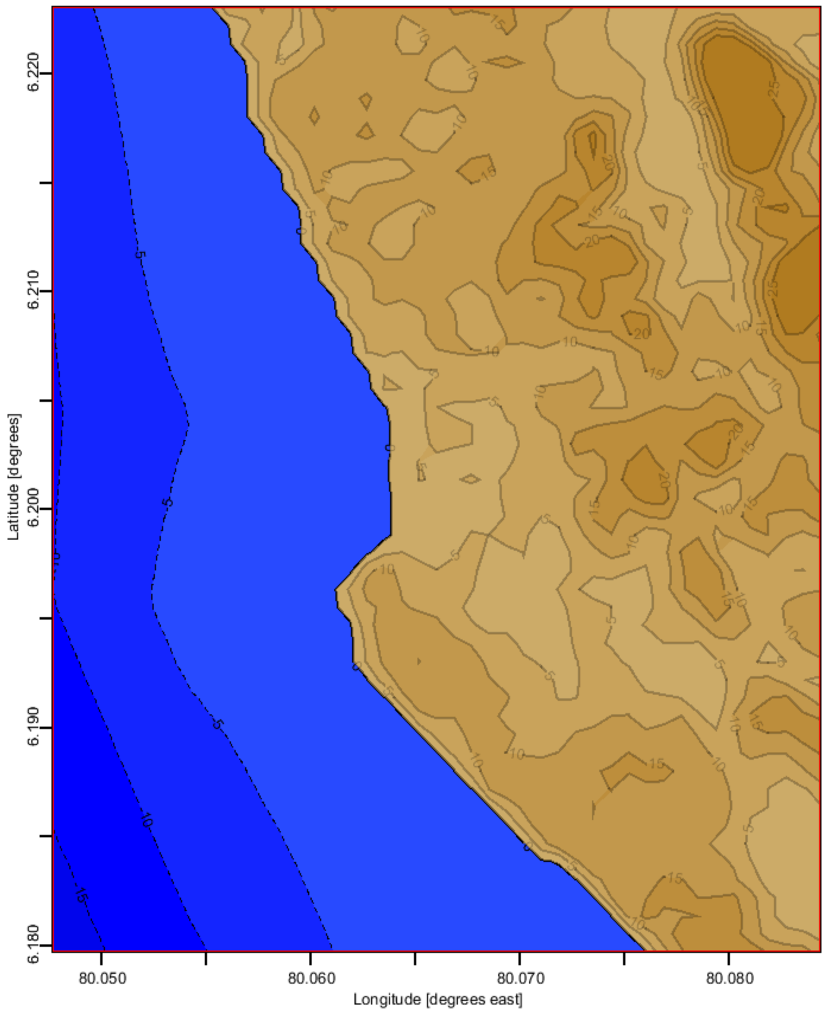
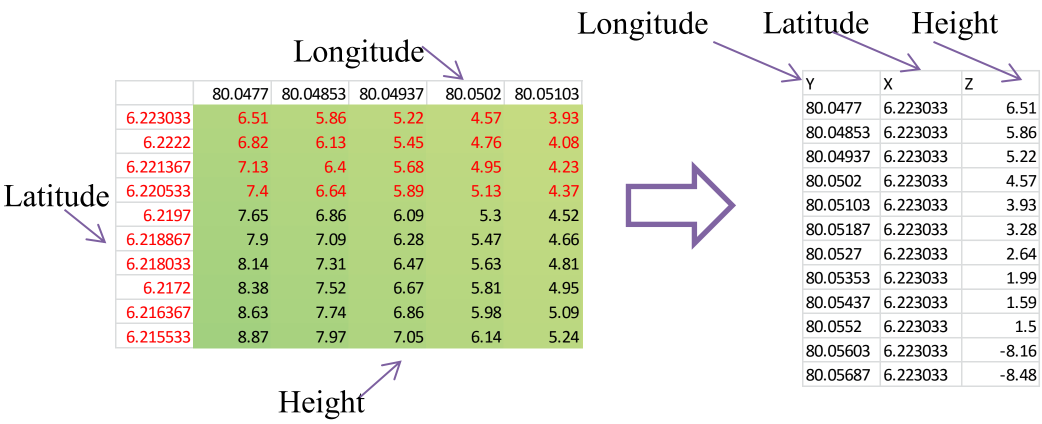


Figure 105: DEM (3.0 arcsecond resolution) (Opened using ComMIT) Contour interval: 5m)



	80.0477	80.04853	80.04937	80.0502	80.05103
6.223033	6.51	5.86	5.22	4.57	3.93
6.2222	6.82	6.13	5.45	4.76	4.08
6.221367	7.13	6.4	5.68	4.95	4.23
6.220533	7.4	6.64	5.89	5.13	4.37
6.2197	7.65	6.86	6.09	5.3	4.52
6.218867	7.9	7.09	6.28	5.47	4.66
6.218033	8.14	7.31	6.47	5.63	4.81
6.2172	8.38	7.52	6.67	5.81	4.95
6.216367	8.63	7.74	6.86	5.98	5.09
6.215533	8.87	7.97	7.05	6.14	5.24

Y	X	Z
80.0477	6.223033	6.51
80.04853	6.223033	5.86
80.04937	6.223033	5.22
80.0502	6.223033	4.57
80.05103	6.223033	3.93
80.05187	6.223033	3.28
80.0527	6.223033	2.64
80.05353	6.223033	1.99
80.05437	6.223033	1.59
80.0552	6.223033	1.5
80.05603	6.223033	-8.16
80.05687	6.223033	-8.48

Figure 106: DEM in column format (Right hand side) and matrix format (Left hand side)

Step 1.3: Convert the DEM in matrix format to column format

The right hand side of Figure 107 shows the data in column format and the left hand side of the figure shows the data in matrix format. The author used ArcGIS software to interpolate the data to obtain a finer data set to insert the revetment into the contour map. The data from is in Matrix form. However, ArcGIS favors column format. Therefore MS Excel Add-Ins was used to convert data from matrix format to column format to feed the DEM into ArcGIS.

Step 2: Create a raster file of the area of interest.

Following sequence was used to create a raster file. The DEM was converted into a shape file. Then, a raster file was created. Figure 108 shows the raster file which was created using elevation data of 2358 points. The raster was bounded by latitudes between 6.2230 and 6.1797 and longitude between 80.0477 and 80.0843.

<u>Command</u>

Display X, Y Data

Data → Export Data → Cerate .shp file

Step 2.3: A raster file was created where we can extract the height in any point

<u>Command</u>

3D Analysis tool → Create TIN → (Insert the created .shp file) → (Create a TIN surface)

3D Analysis tool → TIN to raster → (Insert the tin surface) → (Create a raster file)

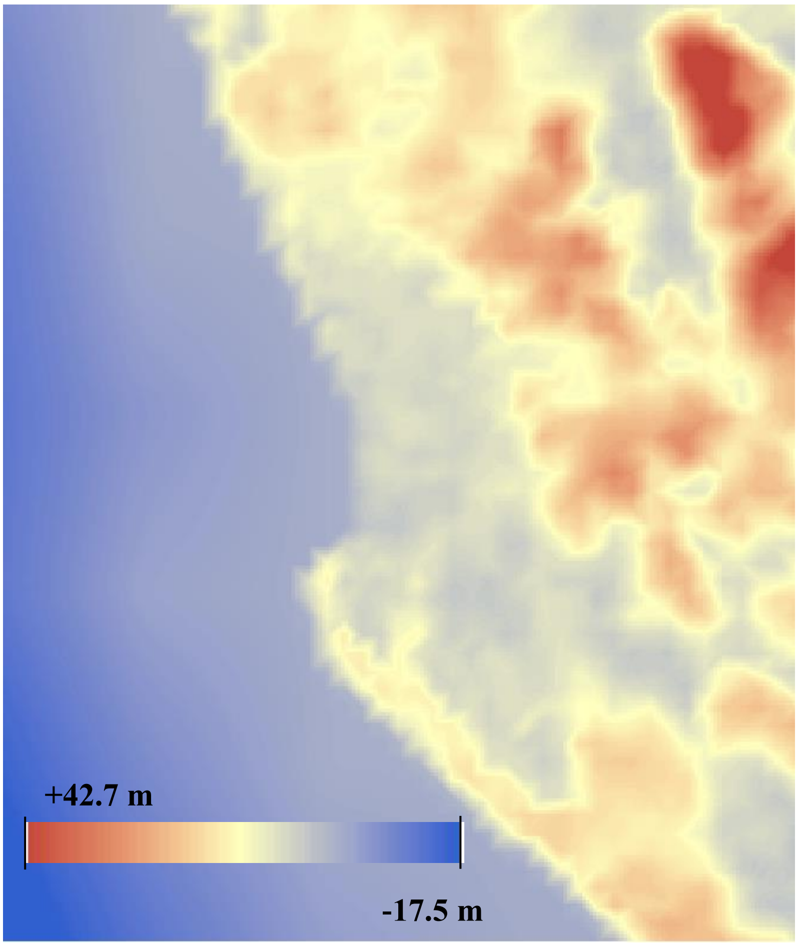


Figure 107: DEM (Digital Elevation Model) (Opened using Arc GIS- Raster (Created using 2385 Points))

Step 3: Create a DEM in domain resolution of 0.166 arcs seconds in column form

The raster created had 45 x 53 points. The resolution was 3.0 arcseconds (~90m domains). When the author extracted points in 0.166 arcseconds resolution (~5m domains), the number of points increase from 18x18. The new domain sixe was (45x18) x (53x18) points. A domain of 0.166 arcsecond was created by writing a small program using FORTRAN 95. Figure 109 shows the programme code. The new domain was obtained in column form with the aid of FORTRAN program. $X_{1,}$ X_2 ....X_{772740} were latitudes and Y1, Y_2 ....Y_{772740} were longitudes in the new domain. Table 84 shows the format of the created domain to extract the finer DEM from the raster.

Table 85: Format of the domain required to extract the DEM from the raster

Point	Latitude	Longitude
1	X_1	Y_1
2	X_2	Y_1
--	----	---
810	$X_{(45x18)}$	Y_1
---	----	----
758160	X_1	$Y_{(53x18)}$
758161	X_2	$Y_{(53x18)}$
---	----	----
772740	$X_{(45x18)}$	$Y_{(53x18)}$

Firstly created a shape file from these 772740 points and then extracted the points using extraction tool of ArcGIS

Command

Spatial Analysis Tool →Extraction →Extract multi values to points → (Input point features and raster) → (Open the attribute table of output feature class) → Export → (Export data in .txt format)

```
implicit none
integer i,j
integer,parameter :: imax=810, jmax=954
real a(imax), dx, dy, d, b(jmax)
        dx = (80.08436667 - 80.047700)/imax
       dy = (6.223 - 6.1797)/jmax

        a(1) = 80.047700
        b(1) = 6.223033
        do i=2,imax

       a(i) = a(1) + dx*i

        end do

        do j=2,jmax

       b(j) = b(1) - dy*j

        end do


open(8,file='X.txt')


do j=1,jmax
       do i=1, imax

       write(8,*) a(i), b(j)
        end do
end do

        close(8)

        end
```

Figure 108: FORTRAN 95 code to create the domain

Step 4: Wrote a FORTRAN 95 program to convert data in column format into matrix format

The obtained data set (DEM in 0.166 arcsecond resolution) from Step 3 was in column format (in a .txt file). The DEM was converted into Matrix form using another simple FORTRAN 95 code (Figure 110).

```
integer i,j
integer,parameter :: imax=810,jmax=954,ijmax=772740
real a(3,ijmax),c(1,ijmax),d(jmax+1,imax+1)


open(7,file='test.txt')


do j=1,ijmax
 read(7,*) a(1:3,j)
 c(1,j)=a(3,j)
end do

close(7)

open(8,file='testout.txt')


do i=1,jmax
  do j=1,imax
  d(i,j)=c(1,imax*i-imax+j)

 end do
end do


do i=1,jmax
write(8,*) (d(i,j),j=1,imax)
end do

close(8)

end
```

Figure 109: FORTRAN 95 code to convert the DEM in column format to matrix format

Step 5 and Step 6:

The required adjustments and modifications were conducted according to the specifications in co-beneficial structures. The DEM in 0.166 arcsecond was formed in .most format as showed in Step 1. The new contour map was created as Figure 111 from ComMIT.

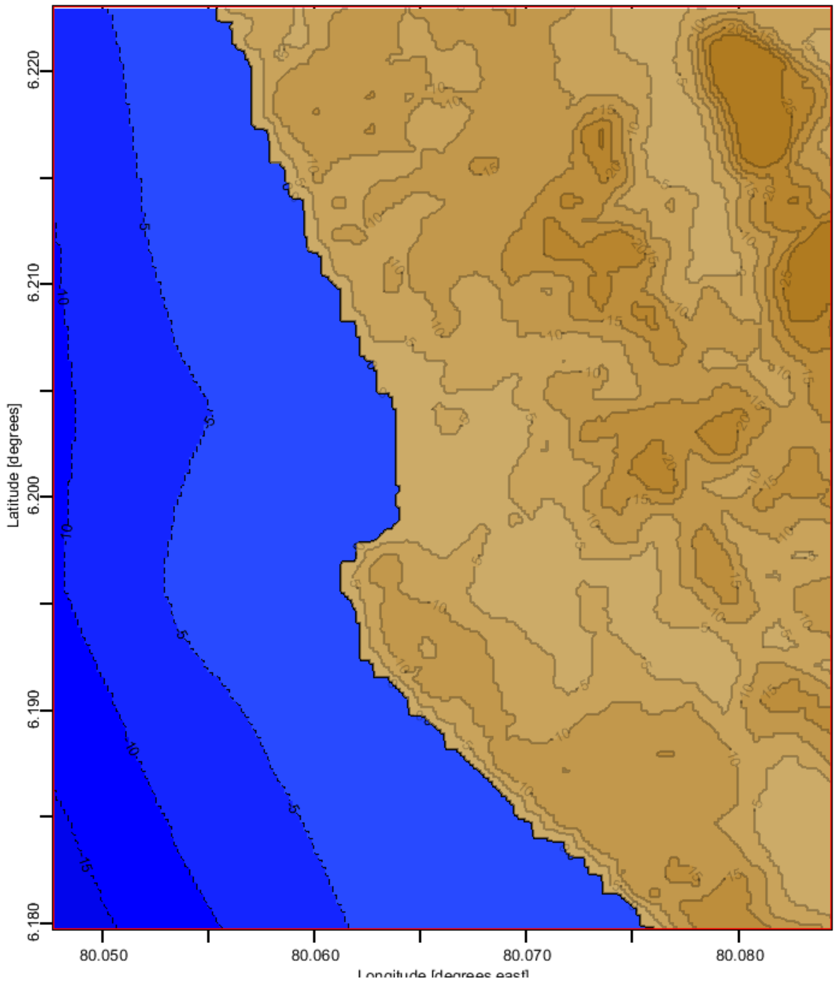


Figure 110: DEM (0.166 arcsecond resolution) (Opened using ComMIT) Contour interval: 5m)

APPENDIX B: Questionnaires

Questionnaire on Willingness to Pay for Tsunami Hard Defensive Measures

【The purpose of the questionnaire】

For tsunami disaster prevention, hard defensive measures are important, alongside appropriate special planning as well as Early Warning Systems (EWS). Residents also need to understand the importance of hard defensive measures for preparation against disasters. The researcher (Sameera Samarasekara) is a master candidate at Jun Sasaki Laboratory, Graduate School of Frontier Sciences, the University of Tokyo. This questionnaire is a part of a research project, focusing on residence willingness to pay for modifications of existing coastal structures which have tsunami mitigation potential, the South-Western Coast of Sri Lanka. This result of the questionnaire will be relevant not only for your area but also worldwide other areas that vulnerable to tsunamis. We will only use your answers for this purpose. We kindly ask for your cooperation.

This is a short questionnaire with 20 questions. Completing this questionnaire should take you only about 10 minutes.

All information provided will be kept strictly confidential

Date: ………………………………………………………………………………………….

Time: …………………………………………………………………………………………

Name of Interviewer: ……………………………………………………………………...

Location: GN Division: …………………………………………………………………...

The Notation of Google Earth Location in Map: ………………………………………...

Respondent's General Information

1. Are you a resident or do you work in this area?

   ☐ Yes ☐ No

2. Did you witness to the 2004 Indian Ocean Tsunami?

   ☐ Yes ☐ No

3. Occupation

   ☐ Fisherman
   ☐ Business
   ☐ Office Worker
   ☐ Self – employed - Lime Production
   ☐ Teacher
   ☐ Social service
   ☐ Undergraduate/ Graduate Student

- Self – employed - Coconut Husk Coir Production
- Retired
- House wife
- Other (…………………..)

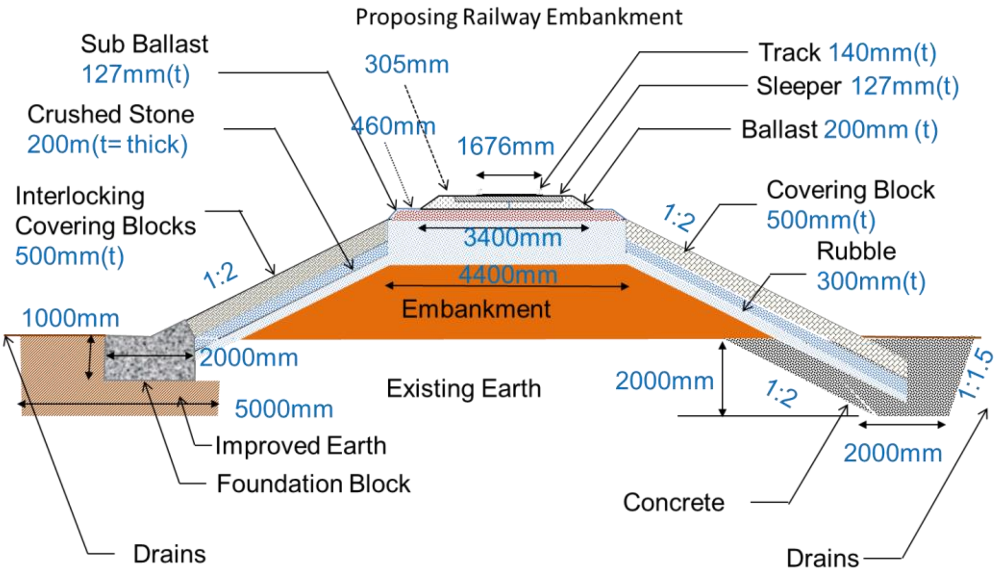
Willingness to Pay

This is the railway embankment which provides convenient and safe path to the trains.
When the train is moving on an embankment, people cannot enter to railway track easily, and use the bypasses to local roads. Therefore the train can move fast.

http://www.panoramio.com/photo/92521781?source=wapi&referrer=kh.google.com

4. In your opinion, what is the level of safety and convenience to rail transportation from this embankment?
   - ☐ Very Good
   - ☐ Good
   - ☐ Fair
   - ☐ Poor
   - ☐ Very Poor
5. Do you feel more secured from tsunami with this embankment structure?
   - ☐ Not at all
   - ☐ Slightly
   - ☐ Moderately
   - ☐ Highly
   - ☐ Very highly
6. Do these revetments have tsunami mitigation capability for huge tsunamis like 2004 Tsunami?
   - ☐ Not at all
   - ☐ Slightly
   - ☐ Moderately
   - ☐ Highly
   - ☐ Very highly
7. If the answer is "No at all", why?
   - ☐ Cannot stand against tsunamis; damage will be increased due to failure
   - ☐ Cannot stand against tsunamis; damage will not be increased due to failure
   - ☐ Other ……………………………………………………………………………………………
8. What protective functions does it perform for huge tsunamis like 2004 Tsunami?
   - ☐ Prevent the movement of wave and save properties
   - ☐ Hold the wave and provide sufficient time to evacuate
   - ☐ Other………………………………………………………………………
9. Government has decided only to provide warning and not to provide hard protection, do you agree to this?
   a. Yes
   b. No

If we propose this kind of upgrade to the railway embankment, it would protect you against tsunamis like 2004 Indian Ocean Tsunami. We can increase the height as well. The cost of modification would be roughly **Rs. 240,000/=** per one house.



10. What % should residents contribute from upgrade cost?

- ☐ 0%
- ☐ >10% (>Rs.24,000)
- ☐ 10% - 20% (Rs.24,000-48,000)
- ☐ 20% - 50% (Rs.48,000-120,000)
- ☐ 50%< (Rs.120,000<)
- ☐ 100%

11. What kind of payment option do you prefer?

If you are a resident

- ☐ I cannot pay
- ☐ Upgrade paid with respect to the protected land area of residents
- ☐ Upgrade paid with respect to the value of the properties of residents
- ☐ Upgrade paid with respect to the number of family members

If you are not a resident

- ☐ I cannot pay
- ☐ Upgrade paid via train ticket
- ☐ Not Upgrade, but a donation can be paid directly to city office
- ☐ Upgrade can be deducted from my salary

☐ Other………………………………………………………………………………………

12. In general, maximum how much can you contribute per month?

- ☐ >Rs. 200
- ☐ Rs. 200 – 500
- ☐ Rs. 500 – 1500
- ☐ Rs. 1500 – 3000
- ☐ Rs. 3000 – 5000
- ☐ Rs. 5000<

Current Tsunami Awareness

13. Are you aware about tsunami risk of your residency or workplace?

- ☐ Yes
- ☐ No

14. Do you know about the national Tsunami Early Warning System (EWS)?

- ☐ Yes
- ☐ No

15. If "Yes", Do you think you are safe under a tsunami due to the early warning systems (EWS)?

- ☐ Yes
- ☐ No

16. From where would you obtain alert about tsunami (Tsunami Bulletin)?

- ☐ Television/Radio
- ☐ Internet
- ☐ Sirens in Warning Towers
- ☐ From village representatives
- ☐ From government officers
- ☐ Other (…………………………………………………………………………………………)

17. Do you know the evacuation routes and safe places?

- ☐ Yes
- ☐ No

18. How often do you participate to a tsunami drill?

- ☐ Every Year
- ☐ More than 8
- ☐ 8 – 5
- ☐ 4 - 2
- ☐ Only One
- ☐ Never

19. If the answer is "No", what was the reason?

- ☐ I was not aware about tsunami drill
- ☐ I am not interested in the drill. It is too boring
- ☐ I went out from the area in the date of drill
- ☐ I had a very important work on the date of drill
- ☐ Other (……………………………………………………………………………)

20. On average what is the rental of shop/house in these area?

- ☐ 5,000>
- ☐ Rs. 5,000 – 10,000
- ☐ Rs. 10,000 – 20,000
- ☐ Rs. 20,000 – 50,000
- ☐ Rs. 50,000<

-THE END-

Questionnaire on Willingness to Pay for Tsunami Hard Defensive Measures

【The purpose of the questionnaire】

For tsunami disaster prevention, hard defensive measures are important, alongside appropriate special planning as well as Early Warning Systems (EWS). Residents also need to understand the importance of hard defensive measures for preparation against disasters. The researcher (Sameera Samarasekara) is a master candidate at Jun Sasaki Laboratory, Graduate School of Frontier Sciences, the University of Tokyo. This questionnaire is a part of a research project, focusing on residence willingness to pay for modifications of existing coastal structures which have tsunami mitigation potential, the South-Western Coast of Sri Lanka. This result of the questionnaire will be relevant not only for your area but also worldwide other areas that vulnerable to tsunamis. We will only use your answers for this purpose. We kindly ask for your cooperation.

This is a short questionnaire with 20 questions. Completing this questionnaire should take you only about 10 minutes.

All information provided will be kept strictly confidential

Date: ……………………………………………………………………………………………….

Time: ………………………………………………………………………………………………

Name of Interviewer: ………………………………………………………………………………..

Location: GN Division: ……………………………………………………………………………...

The Notation of Google Earth Location in Map: ………………………………………………...

Respondent's General Information

21. Are you a resident or do you work in this area?

☐ Yes ☐ No

22. Did you witness to the 2004 Indian Ocean Tsunami?

☐ Yes ☐ No

23. Occupation

- ☐ Fisherman
- ☐ Business
- ☐ Office Worker
- ☐ Self – employed - Lime Production
- ☐ Teacher
- ☐ Social service
- ☐ Undergraduate/ Graduate Student
- ☐ Self – employed - Coconut Husk Coir Production
- ☐ Retired
- ☐ House wife
- ☐ Other (…………………..)

Willingness to Pay

This is a beach revetment which prevents the net coast line erosion from strong wave conditions.

The rubble mounted armor units cannot stand against a tsunami; there is a high chance to they will be washed away.

http://www.panoramio.com/photo/15524633?source

24. In your opinion, what is the level of protecting the beach from net erosion?

- ☐ Very Good
- ☐ Good
- ☐ Fair
- ☐ Poor
- ☐ Very Poor

25. Do you feel more secured from tsunami with these revetments?

- ☐ Not at all
- ☐ Slightly
- ☐ Moderately
- ☐ Highly
- ☐ Very highly

26. Do these revetments have tsunami mitigation capability for huge tsunamis like 2004 Tsunami?

- ☐ Not at all
- ☐ Slightly
- ☐ Moderately
- ☐ Highly
- ☐ Very high

27. If the answer is "No at all", why?

- ☐ Cannot stand against tsunamis; damage will be increased due to failure
- ☐ Cannot stand against tsunamis; damage will not be increased due to failure
- ☐ Other

……………………………………………………………………………………………

28. What protective functions does it perform for huge tsunamis like 2004 Tsunami?

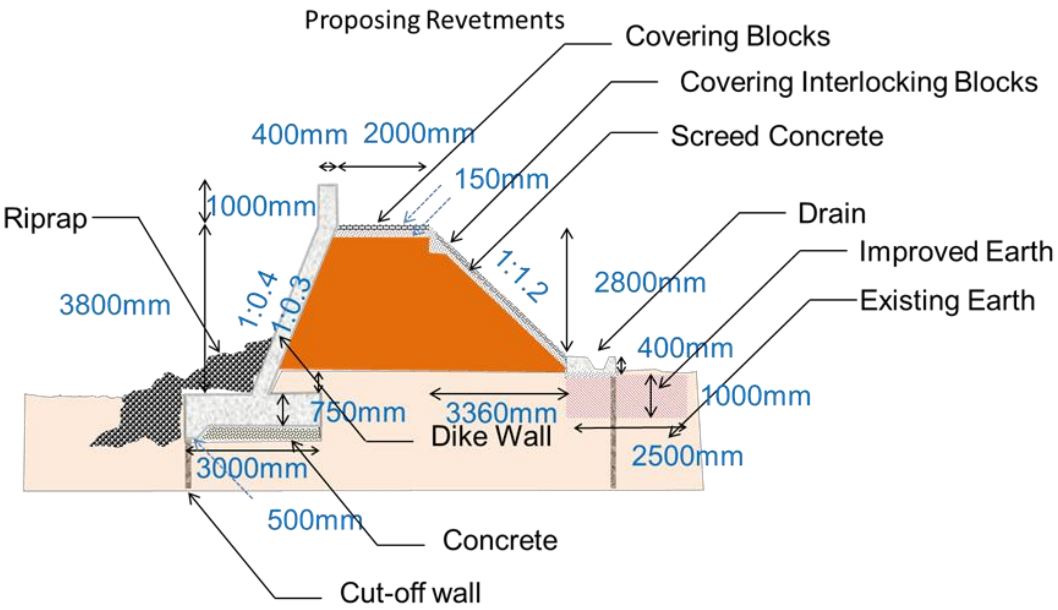
- ☐ Prevent the movement of wave and save properties
- ☐ Hold the wave and provide sufficient time to evacuate
- ☐ Other………………………………………………………………………

29. Government has decided only to provide warning and not to provide hard protection, do you agree to this?

a. Yes

b. No

If we propose this kind of upgrade to revetments, it would protect you against tsunamis like 2004 Indian Ocean Tsunami. We can increase the height as well. The cost of modification would be roughly **Rs. 130,000/=** per one house.



30. What % should residents contribute from upgrade cost?

- ☐ 0%
- ☐ >10% (>Rs.13,000)
- ☐ 10% - 20% (Rs.13,000-26,000)
- ☐ 20% - 50% (Rs.26,000-65,000)
- ☐ 50%< (Rs.65,000<)
- ☐ 100%

31. What kind of payment option do you prefer?

If you are a resident

- ☐ I cannot pay
- ☐ Upgrade paid with respect to the protected land area of residents
- ☐ Upgrade paid with respect to the value of the properties of residents
- ☐ Upgrade paid with respect to the number of family members

If you are not a resident

- ☐ I cannot pay
- ☐ Not Upgrade, but a donation can be paid directly to city office
- ☐ Upgrade can be deducted from my salary

- ☐ Other……………………………………………………………………………………

32. In general, maximum how much can you contribute per month?

- ☐ >Rs. 200
- ☐ Rs. 200 – 500
- ☐ Rs. 500 – 1500
- ☐ Rs. 1500 – 3000
- ☐ Rs. 3000 – 5000
- ☐ 5000<

Current Tsunami Awareness

33. Are you aware about tsunami risk of your residency or workplace?

☐ Yes ☐ No

34. Do you know about the national Tsunami Early Warning System (EWS)?

☐ Yes ☐ No

35. If "Yes", Do you think you are safe under a tsunami due to the early warning systems (EWS)?

☐ Yes ☐ No

36. From where would you obtain alert about tsunami (Tsunami Bulletin)?

☐ Television/Radio
☐ Internet
☐ Sirens in Warning Towers
☐ From village representatives
☐ From government officers
☐ Other (…………………………………………………………………………………………)

37. Do you know the evacuation routes and safe places?

☐ Yes ☐ No

38. How often do you participate to a tsunami drill?

☐ Every Year
☐ More than 8
☐ 8 – 5
☐ 4 - 2
☐ Only One
☐ Never

39. If the answer is "No", what was the reason?

☐ I was not aware about tsunami drill
☐ I am not interested in the drill. It is too boring
☐ I went out from the area in the date of drill
☐ I had a very important work on the date of drill
☐ Other (……………………………………………………………………………)

40. On average what is the rental of shop/house in these area?

☐ 5,000>
☐ Rs. 5,000 – 10,000
☐ Rs. 10,000 – 20,000
☐ Rs. 20,000 – 50,000
☐ Rs. 50,000<

-THE END-

APPENDIX C: Important photos of Dimbuldooa and Wenamulla villages

Conducting questionnaire in Wenamulla

Conducting questionnaire in Dimbuldooa

Local fishing boats are anchored in beach

Focus group discussion with women in Dimbuldooa (February, 2016)

Focus group discussion with men in Dimbuldooa (February, 2016)

Luxury house

Semi –luxury house

Normal house

Informal house

Piloti – type structure