

東京大学大学院新領域創成科学研究科  
社会文化環境学専攻

平成 18 年度

修士論文

**Analysis of damages in Hikkaduwa and South West Coast of  
Sri Lanka in 2004 December Sumatra tsunami**

2006 年 08 月提出

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**Abstract**

After December 2004 Sumatra earthquake tsunami, the importance of understanding the mechanism of tsunami propagation, deformation and analysis of damages to Sri Lanka was a high priority. Since it was the most tragic and catastrophic incident which Sri Lanka has ever experienced in the history of natural disasters.

This study will discuss results of field observations and investigations carried out in west, south west and south coast of Sri Lanka by University of Tokyo, Japan. Main focus of the research was to identify the localized damages along the west, south west and south coast of Sri Lanka and how to interpret damage mechanisms in terms of geomorphological characteristics, inundation and incident direction.

Field observations were further extended to examine the detailed damages in Hikkaduwa in the Southwest coast of Sri Lanka. Hikkaduwa was one of the most severely affected areas due to the location and low-line topography.

This study discusses the analysis of damages in the west, south west and south coast of Sri Lanka in general. In order to understand the tsunami arrival time and incident direction, a new tsunami propagation model has formed. The results of the numerical simulation and field observations are compared to find the causes of damages.

Analysis of the damages in overall observations showed that damages were highly localized. Effect of strong nearshore deformations and trapping of wave energy was evident.

Analysis of the damages in Hikkaduwa showed that, Hikkaduwa went under multiple wave attacks due to such strongly formed edge waves.

**Acknowledgement**

I wish to express my sincere gratitude to my research supervisor, Prof. Yukio Koibuchi for his kind support and contribution to make this study a success. Without his advices and directions this study wouldn't have been this much success.

Also I wish to thank Prof. Shinji Sato, co-supervisor of my research for his valuable contribution in organizing the field survey in Sri Lanka in 2005 March. Also his valuable support in numerical modelling of tsunami is highly appreciated.

I am grateful to Prof. Masahiko Isobe, for his advices on my research direction and academic guidance's from beginning to end of my research. His valuable comments on my research helped me to increase the knowledge on tsunami science.

Encouragement and kind support given by the Prof.Yoshimitsu. Tajima is highly appreciated. His advices on numerical simulations made a valuable contribution to this study.

Advices and direction given in numerical modelling by Prof. Guangwei Huang is kindly appreciated.

My sincere thank goes to Mr. Takahide Honda, for his valuable contribution in making the Sri Lankan field observations a success.

Also I should remind Prof. Samantha Hettiarachchi and Dr. Saman Samarawickrama from University of Moratuwa, Sri Lanka for their kind support in making the Sri Lankan field observations a success.

My sincere thank goes to members of the faculty, staff and students of the Department of Frontier Sciences for giving this opportunity to pursue my masters degree studies in most amiable atmosphere.

I also like to remind all the members in coastal engineering laboratory and coastal environmental engineering laboratory for their kindness and support in academic and non academic matters. This made my studies more successfully and comfortably within a tight time framework.

I also grateful to Asian Development Bank, for facilitating all the financial support during my study in Japan for two year period.

Finally I would like to thank my loving mother, father and sister whose unwavering support provided constant inspiration and confidence.

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# **Chapter 1**

## **Introduction**

## 1.1 What is a tsunami

The Earth is a dynamic planet. It is active and productive, offering humanity enormous opportunities. However, living on it also presents us with many dangers. Of all tsunami can be considered as one of the most devastating in the history of natural disasters on earth.

Of all the water waves occur in the world one of the most fearsome is tsunami. The term tsunami, originating from the Japanese words “*tsu*” (harbor) and “*nami*” (wave), is used to describe waves of seismic origin in near field Japan. Tectonic earthquakes, i.e. earthquakes that cause a deformation of the seabed, appear to be the principal seismic mechanism responsible for the generation of tsunamis. Coastal and submarine landslides and volcanic eruptions have also triggered tsunamis.

A tsunami is a chain of fast moving waves that are generated when water in the ocean is rapidly displaced by a sudden trauma in the form of an earthquake, volcanic eruption, landslide or impact of a meteorite.

## 1.2 History of Tsunamis

History of the tsunamis is running even thousands and even millions years back. There are many evident available all over the world recorded by various means since then. But most of those very old incidents were only of the form of stories or hand drawn pictures. At an era where the science of the tsunami was not developed to understand those events people thought it was a miserable force which punishes the people.

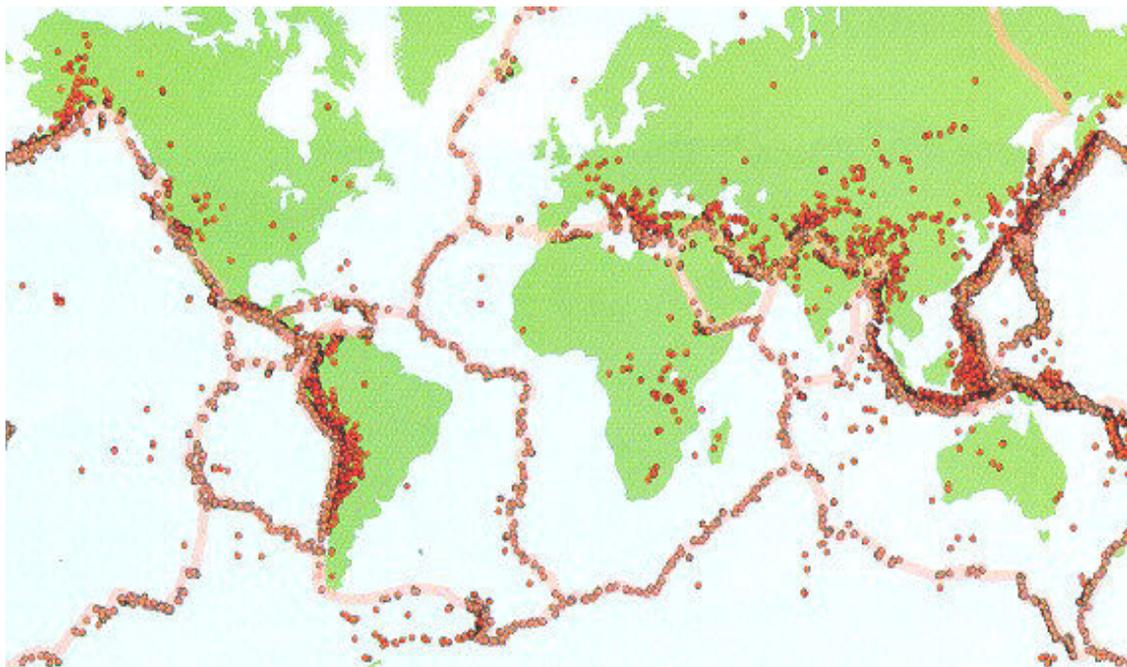


Fig 1.1: seismic activity around the world (by [www.discoverourearth.org](http://www.discoverourearth.org))

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However recent history of the tsunamis is starting around three centuries back where more than 500 tsunamis have been reported and recorded. Most of these tsunamis occurred in the Pacific Basin and around Indonesian islands, along the Sunda trench. This is because most of the major tsunamis were associated with earthquakes, and most seismic activity beneath the oceans are concentrated in narrow fault zones in the great oceanic trenches, which are highly active and dynamic. See fig 1.1 (seismic activity around the world). According to the figure it can be clearly identified that most of the active trenches are predominately concentrated around Japan, around Indonesian islands and Pacific Ocean.

Table 1.1 gives the great tsunamis occur around the world over last several decades. The loss of life due to tsunamis has been immense. Among them in the past, great Tokaido-Nankaido tsunami of Japan killed more than 30,000 people in Japan in 1707. In 1868, great Peru tsunami caused 25,000 deaths in America. In 1896, Great Meiji Sanriku tsunami claimed more than 27,000 lives in Japan. In very recent past the great Aleutian tsunami, 1946 killed 173 persons in Hawaii, where tsunami heights were recorded more than 16 meters. Then in 1960, great Chilean tsunami killed 330 people in Chile, 61 in Hawaii and 199 in distant Japan. Also in 1964, Alaskan tsunami killed 107 people in Alaska and 15 in America.

### **1.3 Tsunami Generation**

In general, undersea earthquakes of magnitude greater than 6.5 on the Richter scale with focal depths less than 50 km generate tsunamis. They are very long period waves (5min to several hours) of low height (as one meter or less) when traveling across oceans. But in general Tsunamis over a meter or two in height are not common. A submarine earthquake greater than magnitude (Richter scale) M8 must happen to make a mega tsunami. According to Steven (2004), on a global average, about one M8+ earthquake occurs per year. Of these, maybe 1-in-10 strikes under the ocean with a fault orientation favorable for tsunami excitation. Thus, tsunamis that induce widespread damage number about one or two per many decades. Although one's concepts might be cast by rare mega tsunami or famous as "killer tsunamis", many more benign ones get lost in the shuffle. Today, ocean bottom pressure sensors can detect a tsunami of a few centimeters height even in the open sea. Because numerous "baby" tsunamis occur several times per year. Moderate ( $\approx$ M6.5) earthquakes can bear waves of the baby tsunami. They pass by generally unnoticed, except by scientists. Perhaps while swimming in the surf, riding on a boat person has already been in a tsunami.

Year	Affected area	Earthquake Loc/ magnitude	Casualties	Description of Incident
1703 Dec 03	Genroku, Japan	-	100,000	Damages recorded in Awa
1707	-	Tokaido-Nankaido	30,000	-
1755 Nov 1	Lisbon	-	275,000	6 m high wave
1868	America	Peru	2,5000	-
1782	-	South china sea	40,000	-
1883 Aug 27	Java and Sumatra	-	36,000	40 m wave
1896 June	Meiji, Japan	Sanriku	27,000	30m
1908 Dec 28	Southern Italy	-	200,000	13m
1946 Apr 01	Alaska and America	Aleutian Island off coast of Alaska	159	-
1958 July 9	Alaska	Lituya bay, Alaska. 8.3	-	Inundation was 576 m
1960 May 22	Chile, Hawaii and Philippines	Off coast Chile	1,500	11 m
1964 March 27	Alaska, South California	Alaska	107	67 m
1976 Aug 16	Philippines	-	5,000	-
1998 July 17	North coast of Papuwa New Guinea	Off coast north of Papuwa New Guinea	2,200	12 m
1992	Flores Island, Babi Island	Nicaragua	2,500	-

Table 1.1: Tsunamis occurred around world (referenced by Tibballs, 2004 and Johnson, 1994)

#### 1.4 Theory of tsunami

There are several theories to understand the tsunami mechanism. Amongst them Classical theory of tsunami envisions a rigid seafloor overlain by an incompressible, homogeneous, and non-viscous ocean subjected to a constant gravitational field. Classical tsunami theory has been investigated widely, and most of its predictions change only slightly under relaxation of these assumptions. This article draws upon linear theory that also presumes that the ratio of wave amplitude to wavelength is much less than one. Linearity is violated only during the final stage of wave breaking and perhaps, under extreme nucleation conditions.

In classical theory, the phase  $c(\omega)$ , and group  $u(\omega)$  velocity of surface gravity waves on a flat ocean of uniform depth  $h$  are ;

$$c(\omega) = \sqrt{\frac{gh \tanh[k(\omega)h]}{k(\omega)h}} \quad \text{Equation 1.1}$$

$$u(\omega) = c(\omega) \left[ \frac{1}{2} + \frac{k(\omega)h}{\sinh[2k(\omega)h]} \right] \quad \text{Equation 1.2}$$

Here,  $g$  is the acceleration of gravity ( $9.8 \text{ m/s}^2$ ) and  $k(\omega)$  is the **wave number** associated with a sea wave of frequency  $\omega$ . Wave number connects to wavelength  $l(\omega)$  as  $l(\omega) = 2\pi/k(\omega)$ . Wave number also satisfies the relation

$$\omega^2 = gk(\omega)\tanh[k(\omega)h] \quad \text{Equation 1.3}$$

For surface gravity waves spanning 1 to 50,000 s periods, Fig. 1.2 plots  $c(\omega)$ ,  $u(\omega)$ , and  $l(\omega)$ . These quantities vary widely, both as a function of ocean depth and wave period. Waves whose velocity or wavelength varies with frequency are called **dispersive**. During propagation, dispersion “pulls apart” originally pulse-like waves into their component frequencies. It is emphasized that dispersion’s strong influence on attenuating tsunamis. Common waves at the beach have periods near 10s and wavelengths around 100m (see Fig. 1.2).

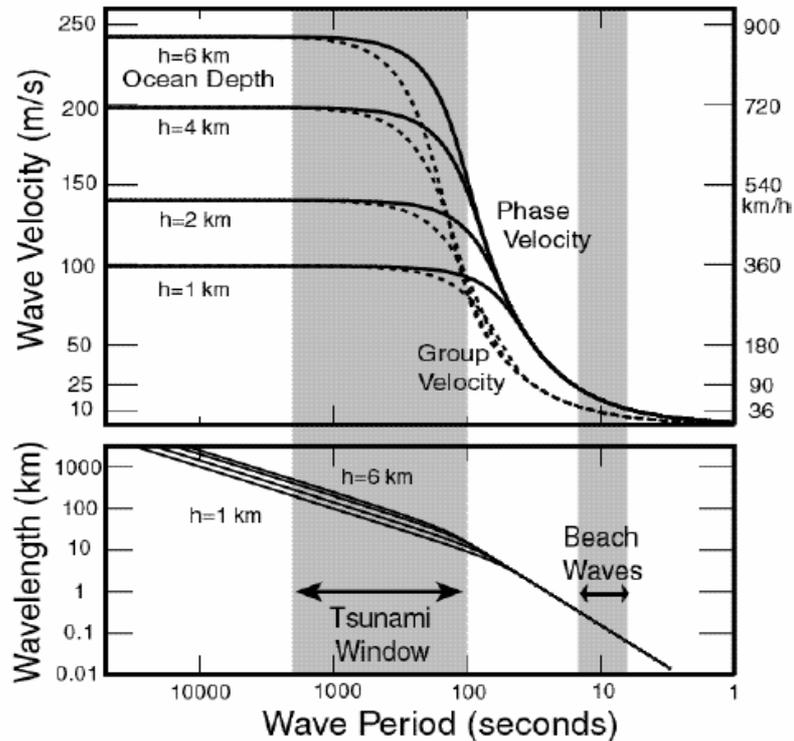


Figure 1.2 : (Top panel) Phase velocity  $c(\omega)$  (solid lines) and group velocity  $u(\omega)$  (dashed lines) of tsunami waves on a flat earth covered by oceans of 1, 2, 4 and 6 km depth. (Bottom panel) Wavelength associated with each wave period. The ‘tsunami window’ is marked.

Tsunamis on the other hand, because they are generated by seafloor shifts, must have  $kh \rightarrow 0$ , wavelengths greater than twenty times the ocean depth at the point of their origination. This fact fixes a shorter wavelength bound on tsunamis near 10km. The dimension of the sea floor disturbance itself fixes the upper wavelength bound. The greatest earthquakes might deform a region 500km across. The left gray band of Fig. 1.3 colors the “tsunami window” ( $l = 10\text{km}$  to  $500\text{km}$ ) that spans 100s to 2000s periods. Waves in the tsunami window travel rapidly, reaching speeds of 160m/s to 250m/s

(600km/hr -900km/hr) in the open ocean, about the speed of a commercial jet airliner. Consequently tsunamis are not discernible in the deep ocean and pass unnoticed by ships and invisible by air.

As tsunami reaches the shallow waters (entering to continental shelf), the leading waves begin to travel more slowly in the shallower water. Then it starts to travel at 10m/s (40km/hr), about the speed of a moped. Once tsunami fully entered into the shallow water it undergoes wave refraction, reflection, shoaling, diffraction and bay or harbor resonance. As a result of those effects waves begin to catch up, piling up water and creating a high, destructive, wave. Thus, a wave that was only 45cm high in deep water may become 35m tall as it reaches land. The great period of wavelength of tsunami waves preclude their dissipating energy as breaking surf. Instead, they are apt to appear as a rapidly rising water levels and only occasionally as bores.

The long period, great wavelength, and high velocity of tsunamis help account for their destructive power. Discussions of waves of length  $l$  in oceans of depth  $h$  sometimes include two simplifications: a long wave approximation ( $l \gg h, l/k \gg h$ ) and a short wave approximation ( $l \ll h, l/k \ll h$ ). Under a long wave approximation,  $kh \rightarrow 0$  and equations (1) to (3) predict non-dispersive wave propagation with  $c(w) = u(w) = \sqrt{gh}$ . Long wave theory holds for the flat part of the curves in Fig 1.3. Under a short wave approximation,  $kh \rightarrow \infty$  and the equations predict dispersive propagation with  $c(w) = 2u(w) = (\sqrt{g\lambda(\varpi)}/2\pi)$ . Short wave theory holds to the right in Fig. 1.2, where all the curves lie atop each other. Waves in the tsunami window have intermediate character, behaving like shallow water waves at their longest periods and like deep-water waves at their shortest periods. Neither the long nor short wave simplification serves adequately in tsunami studies. A rigorous treatment requires an approach that works for waves of all lengths.

Many properties of tsunamis can be understood by examining their *eigenfunctions*. An eigenfunction describes the distribution of motion in a tsunami mode of a particular frequency. Vertical ( $u_z$ ) and horizontal ( $u_x$ ) components of tsunami eigenfunctions normalized to unit vertical displacement at the sea surface are;

$$u_z(\omega, z) = \frac{k(\omega)g}{\omega^2} \frac{\sinh[k(\omega)(h-z)]}{\cosh[k(\omega)h]} e^{i[k(\omega)x - \omega t]} \quad \text{Equation 1.4}$$

$$u_x(\omega, z) = \frac{-ik(\omega)g}{\omega^2} \frac{\cosh[k(\omega)(h-z)]}{\cosh[k(\omega)h]} e^{i[k(\omega)x - \omega t]} \quad \text{Equation 1.5}$$

Fig. 1.3 plots tsunami eigenfunctions versus depth in a 4km deep ocean at long (1500s), intermediate (150s) and short (50s) periods. The little ellipses can be thought of as tracing the path of a water particle as a wave of frequency  $w$  passes. At 1500s period (see left of fig 1.3), the tsunami has a wavelength of  $l = 297km$  and it acts like a long wave. The vertical displacement peaks at the ocean

surface and drops to zero at the seafloor. The horizontal displacement is constant through the ocean column and exceeds the vertical component by more than a factor of ten. Every meter of visible vertical motion in a tsunami of this frequency involves  $\gg 10\text{m}$  of “invisible” horizontal motion. Because the eigenfunctions of long waves reach to the seafloor, the velocities of long waves are sensitive to ocean depth (see top left-hand side of Fig. 1.3). As the wave period slips to 150s (middle, Fig. 1.3), wave length decreases to 26km, comparable to the ocean depth. Long wave characteristics begin to break down, and horizontal and vertical motions more closely agree in amplitude. At 50s period (right, Fig. 1.3) the waves completely transition to deep-water behavior. Water particles move in circles that decay exponentially from the surface. The eigenfunctions of short waves do not reach to the seafloor, so the velocities of short waves are independent of ocean depth (see right hand side of Fig. 1.3 top). The failure of short waves ( $l \ll h$ ) to “feel” the seafloor also means that they cannot be excited by deformations of it. This is the physical basis for the short wavelength bound on the tsunami window that is mentioned above.

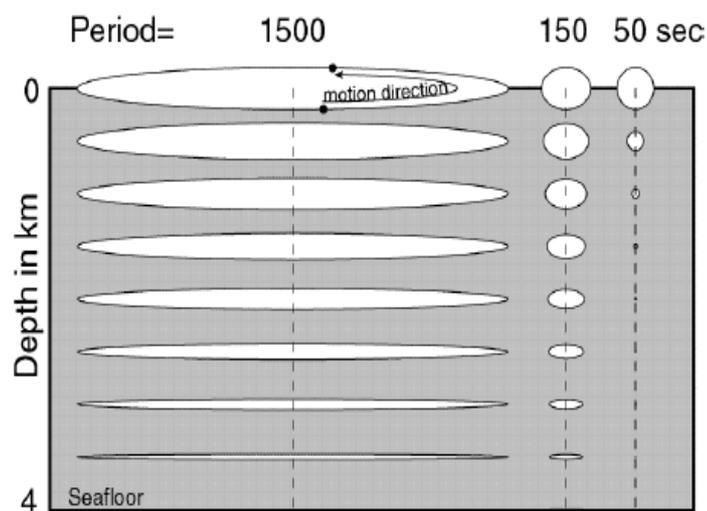


Figure 1.3: Tsunami eigenfunctions in a 4 km deep ocean at periods 1500, 150 and 50s. A vertical displacement at the ocean surface has been normalized to 1 m in each case.

### 1.5 Detection of tsunami

Most of the tsunamis occur either due to submarine earthquake or landslide. Since earthquakes or landslides can not be predicted, there is no way to predict the occurring of the tsunami. On the other hand as mentioned above most of those earthquakes are not resulting major tsunamis.

However if a tsunami can be detected with significant distance damages can be minimized by effective warning and evacuation. By analyzing the seismic waves generated by the earthquakes, epicenter of earthquake can be found fairly accurately, hence can predict the possible tsunami using

pervious studies and real-time simulation. Also tsunami can be detected by satellite altimeter data. Most reliable method of tsunami detection is the tsunami buoy deployed in deep ocean. Compared to the frequency of tsunamis occurrence, cost of deployment and maintenance make such devices less attractive. Hence it is not practicable for having buoy type detectors in all locations.

However McGehee (1997) suggests how the nearshore pressure transducers can be effectively used to detect tsunamis. In contrast Tatehata(1997) discusses how real time numerical modelling based on seismological data monitored can be used to predict the tsunamis. He further discuss the dissemination of tsunami warning can be effectively done through a satellite network within few minutes. This method considered as one of the most reliable and efficient method of tsunami detection.

Shuto (1997) proposed a natural tsunami warning system by considering the properties of the approaching waves. When tsunami is entering into shallow water it converts into fast moving tidal bore which sounds like a locomotive. Such a roaring sound can be heard even the tsunami is few kilometers away from the coast. Such a method can be effectively used as a reliable warning system.

# Chapter 2

## Sumatra 2004 Earthquake Tsunami

---

## 2.1 Introduction

On 26<sup>th</sup> December 2004, a bright sunny morning, sea was calm, the people living in coastline witnessed the devastating impact of a boxing tsunami. This was resulted as a outcome of earthquake occurred 00:58:50 GMT (06:58) hrs Sri Lanka Standard time, off the west coast of Northern Sumatra (Nicorbar islands) at 3.316°N, 95.854°E (at a depth of 6.2 miles below mean sea level) which had a magnitude of 9.1 on the Richter scale(USGS , 2004 )

The 2004 Sumatra earthquake tsunami was more powerful than all of the worlds quakes over the previous five years put together. It was the third largest earthquake ever recorded in the history of four decades. The strength of the tsunami explained in terms of deaths of over 3.0 million and damaging houses and property fort more than 10.0 million people. The energy released in the tsunami generation was calculated as five megatons of TNT, which was more than the total explosives used in the world war two. It was recorded that some witness explained that tsunami was approaching like a roar of a jet and smashed everything by seconds. In some places wave reached more than 20 m height in the ground and in some places inundations were found more than 2 km inside land.

## 2.2 Damages to Sri Lanka

Damaged to Sri Lanka was immense since it was the most tragic natural disaster ever occurs in the history of Sri Lanka. It was totally unexpected and unaware that tsunami reached Sri Lanka even after a long journey of more than 1 and half hours crossing more than 1200 km in the Indian Ocean. That taught a good lesson on horror of tsunamis to more than two third of the costal inhabitants in Sri Lanka. It also claimed more than 37,000 lives and displaces more than one million people.

Figure 2.1 shows the areas which were affected in the 2004 Dec tsunami. Most of the cities around the east, south and south west coast were completely destroyed. The high number of casualties indicate that it was a completely unaware and high energetic.

Hence among the several other victims of the tsunami attack Sri Lanka was also a worst affected.

1. the close proximity to the source of earthquake and
2. Victim of the leading wave , which carries more energy
3. Sri Lanka's complex near shore geomorphology. Resulted most of the incoming waves went under shoaling and refraction and focusing toward the open coastal zone, propagating hundreds of meters inland smashing all on the way. Damages were further enhanced by the bay action and converging towards headlands
4. 65 % of the Nations population is concentrated in the 1 km stretch of land in the coastal zone.
5. All most all the coastal inhabitants were unaware of the phenomenon of the tsunami.

Therefore Sri Lanka was selected as a typical example for further research and investigations. Also

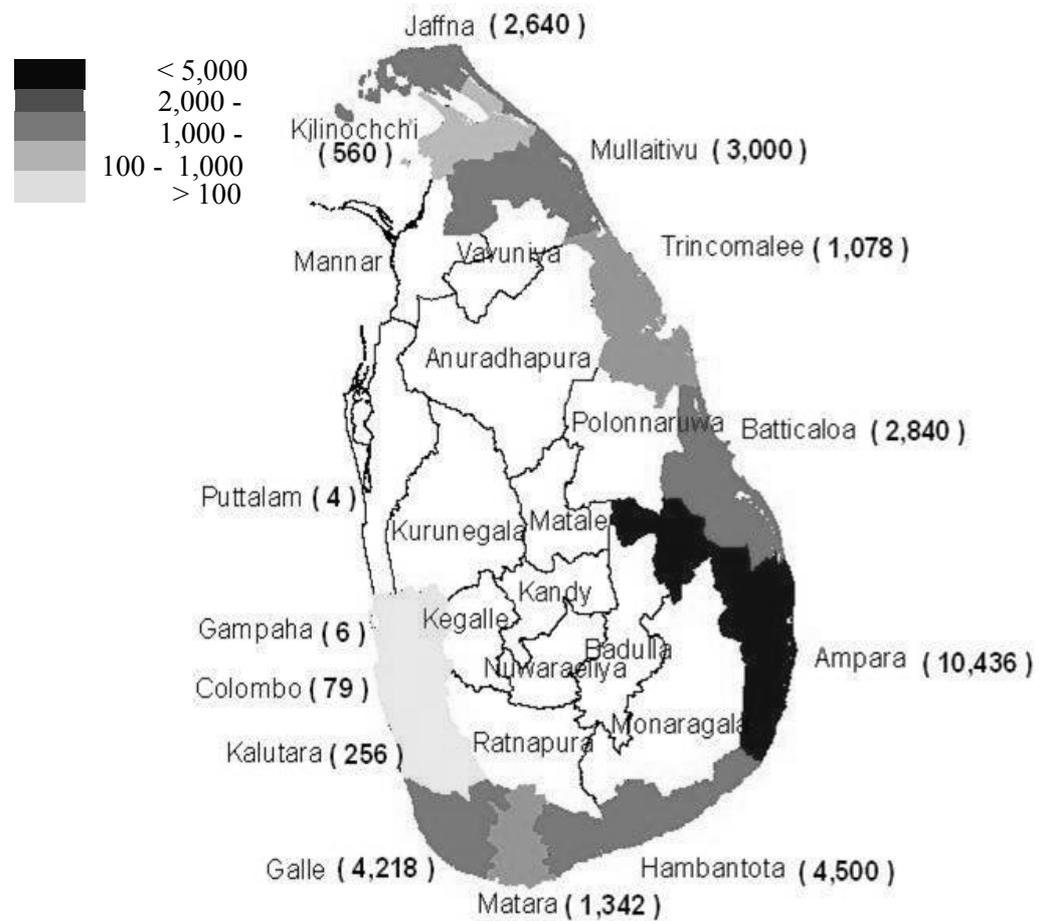


Fig 2.1: number of casualties in Dec 2004 tsunami, Sri Lanka. (referenced by Recoverlanka, 2005)

Sri Lanka was useful as a real life case study for many coastal engineers to study the link between the tsunami and how it damages the coastline. Also Sri Lanka was found to be one of the countries which damaged only due to the effect of tsunami. When analyzing the south west coast of Sri Lanka, near-shore transformations made the tracing back the root of most damages more complicated than it was expected. Also the coastal topography and other coastal features were also as important as the near shore morphology.

### 2.3 Research direction and motivation

Soon after the tsunami attack attention on many scientists focused on Sri Lanka for investigating the damages and collecting the information. Many research teams from all around the world started conducting surveys in Sri Lanka with various aspects of tsunami. In line with University of Tokyo formed two survey teams, one lead by Prof. Tsuji, Y. from Earthquake Research institute on surveying the damages in Indonesia and second one was lead by Prof. Shinji Sato from coastal lab of Department of Civil Engineering on surveying the Sri Lanka.

The research team consists of five members including.

1. Prof Shinji Sato (Senior Professor, Department of civil engineering)
2. Prof Yukio Koibuchi (Assit. Professor, Department of frontier sciences)
3. Mr. Takahide Honda ( Research associate, Department of civil engineering)
4. Mr. Suminda Ranasinghe (Master degree student , Department of civil engineering)
5. Mr. Thisara Welhena (myself)

Objective of research was to investigate the west, south west and south coast of Sri Lanka within 5 day research trip for studying the localized damages took place from north of Negombo to Yala. Details of the field survey will be discussed in coming chapters.

# **Chapter 3**

## **Field observation in Sri Lanka**

### **3.1 Introduction**

During the field survey of tsunami damages in Sri Lanka, it was decided to select the south coast and west coast as the survey domain. With respect to the total damaged coastal zone, south coast and west coast covered more than half of that. On the other hand, damages to west coast and south coast were exceptional and explanation for such damages was unknown by many researchers. It was understood that without having proper set of information on damages, it could not be explained reasonably.

### **3.2 Objective**

There were several important objectives behind the research visit of Sri Lanka. Priority was to visit as much as observation points from North of Negombo to most distant Yala. Due to the availability of the time and the resources the numbers of observations were limited. Results obtained by previous tsunami survey teams and views of local experts were also useful in predetermination of observation points. Among them two principle objectives could be studied as briefly discussed in the following.

1. Study the overall damage to the affected coastal zone from North of Negombo, Marawila (07° 22' 35.3"N, 79 ° 49' 23.1"E) up to Yala (06° 20' 38.3"N, 81 ° 29' 50.8"E) in general and to identify any relationship between alternative damage pattern and the nearshore topography and nearshore morphology. Presence of alternative capes and valleys in the south west coast of Sri Lanka had an effect on such rhythmic damages.

In south and southwest coast (North of Negombo to Yala) of Sri Lanka, combined nearshore transformations made the tracing back the root of damages more complicated than many engineers expected it. Results of this kind of study can be effectively used as a basis for finding solutions to more complex nearshore transformation phenomena of tsunami arrival.

2. Reveal if there was any positive contribution from existing coastal structures (such as breakwaters, revetments, groins and sea walls) and land structures in the coastal zone (such as hotels, houses and boundary walls) towards diminishing the damages to sheltered areas by those structures. Among the coastal structures, breakwaters were of prime importance during this study. On the other hand hotels and large buildings were also considered in most of the urbanized coastal cities.

Rationale of the field observation was further extended by relative comparison of inundation measurements and the level of damages based upon the fact that high congestion of coastal inhabitants in most of the coastal cities. In Sri Lanka more than 70 % of the populations live in an area less than 2.0 km from the coast. It was understood that intensity of the damages could not be

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simply explained by the inundations only. It was a hybrid effect of the tsunami arrival direction, momentum of waves, way of interacting with coastal structures, breakwaters, buildings and any other topological features. Therefore some damaged cities received more severe damages even it experienced the same pattern of waves in neighboring cities which received very few damages or not. It was understood that studying the effect of such local effects towards either aggravating or diminishing the damages were significant in understanding the effectiveness in tsunami protection schemes in the future. Among them breakwaters, revetments, dunes, large buildings and low-line areas followed by rivers or water bodies were of prime importance. On the other hand hotels and large buildings were the key considerations among the inland structures.

### **3.3 Surveyed Area**

Having the above objectives in mind, comprehensive survey carried out from in the south coast and west coast of Sri Lanka covering a distance more than 300 km including severely affected cities along the west coast and the south coast. Survey was started from North of Colombo and went down up-to most distant southern coast regions like Yala. Figure 3.1 shows the main cities and observation points covered during the field observations and table 3.1 gives the field observation schedule in Sri Lanka.

The main survey was divided into four main phases based on the damages identified. The first phase was to identify the damages in North of Colombo and up to Kalutara. Based on the preliminary data and information it was decided that even north of Colombo was significantly inundated.

The next phase was to identify the damages in south west coast and south coast. During this stage it was given more attention to areas which was not surveyed by previous survey teams. Hence more attention was paid to Hikkaduwa, Unawatuna, etc. the third phase covered the tail end of our research domain, Hambantota and Yala.

Final phase of the research was to identify a location as a case study and carryout detail inundation measurements. It was decided that Hikkaduwa was abnormally affected compared to the other major damaged cities in the South west coast.

On 26<sup>th</sup> Feb. 2005, early morning survey started from Negombo and went towards North of Negombo, Vennapuwa, Marawila and Lancigama. In following day we went up to Hikkaduwa, observing main damaged areas Panadura, Kalutara, Payagala, and Akurala. On the third day, from Hikkaduwa it went up to Hambantota. In the following day survey was started from Hambantota and went up to Yala. During the fly back Kirinda was observed. Having completed the overall investigations, detail survey was started on Hikkaduwa on the fifth day. In the final day , a floating

video survey was carried out from Galle to Payagala in order to identify the damage pattern along the main highway.

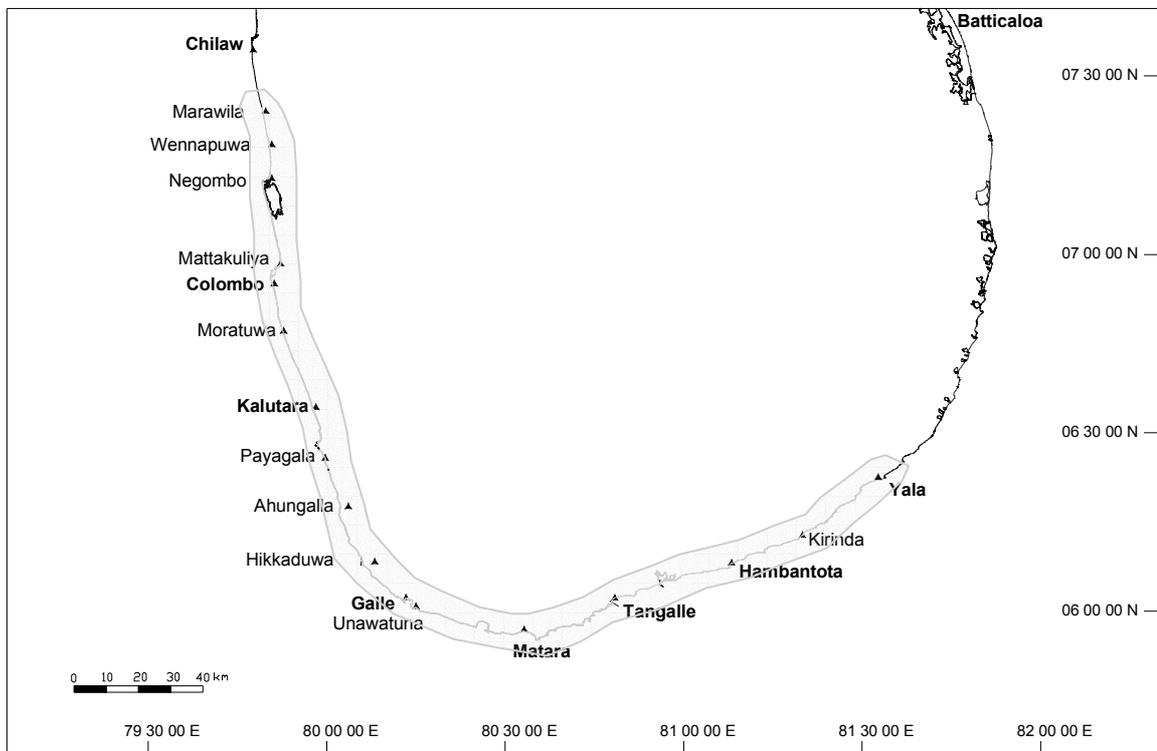


Fig 3.1: Area covered during the field observations

Date	Place	Task
2005 Feb. 24	Arrival in Sri Lanka	-
2005 Feb. 25	Marawila to Colombo	Overall investigations, measurements, interviews
2005 Feb. 26	Colombo to Hikkaduwa	Overall investigations, measurements, interviews
2005 Feb. 27	Hikkaduwa to Hambantota	Overall investigations, measurements, interviews
2005 Feb. 28	Hambantota and Yala	Measurements, Video capturing, interviews
2005 Mar 01	Hikkaduwa	Detail survey at Hikkaduwa.
2005 Mar 02	Hikkaduwa to Colombo	Detail survey at Hikkaduwa and video capturing, areal survey from Colombo to Batticaloa.
2005 Mar 03	Left from Sri Lanka	-

Table 3.1: schedule of field observations in Sri Lanka

### 3.4 Method of surveying

Survey was carried out focusing localized damages identified by the observations. Inundation heights and distances were collected on those selected locations. Except for that data was collected as information by field interviews, videos and images.

### 3.4.1. Inundation measurements

Measurement of inundation heights was the basic and most important in tsunami damage data collection. Having those objectives set in mind, predetermined sites of research importance were studied and information was collected by means of measurement of inundation heights and run-up in selected locations. Inundation height (run-up) was the maximum vertical elevation of a point located on initially dry land inundated by the waves and inundation was the maximum horizontal penetration of the tsunami in the dry land measured perpendicular to the coast. See fig 3.2. Identification of the inundation levels were done based on the water marks left on buildings, trees, telephone poles and any other structures left undamaged. Most of the cases it was found that debris was deposited or imprints of mud in the walls. In some cases it was found that disturbance of roof tiles or partially broken roof structures were also indicating the tsunami inundation height. Further these facts could be verified by hearing to eyewitness of tsunami arrival. However it was not easy to observe the inundation marks in remote locations where there were no buildings or no eyewitnesses such as Yala. Then we had to rely on the pattern of damages observed in vegetation and trees in the coast.



Fig 3.2: Inundation heights identified by watermarks left in the walls, damaged buildings

Especially the abnormally broken branches in trees and mud levels left in the trees were useful. In certain cases it was found long and high sand dunes covered by vegetation, running along the coast as a dyke was partially washed away. These marks could give some reasonable clue on inundation in those areas. For an example the sand dunes in the Hambantota and Yala was observed like that. See fig 3.6.

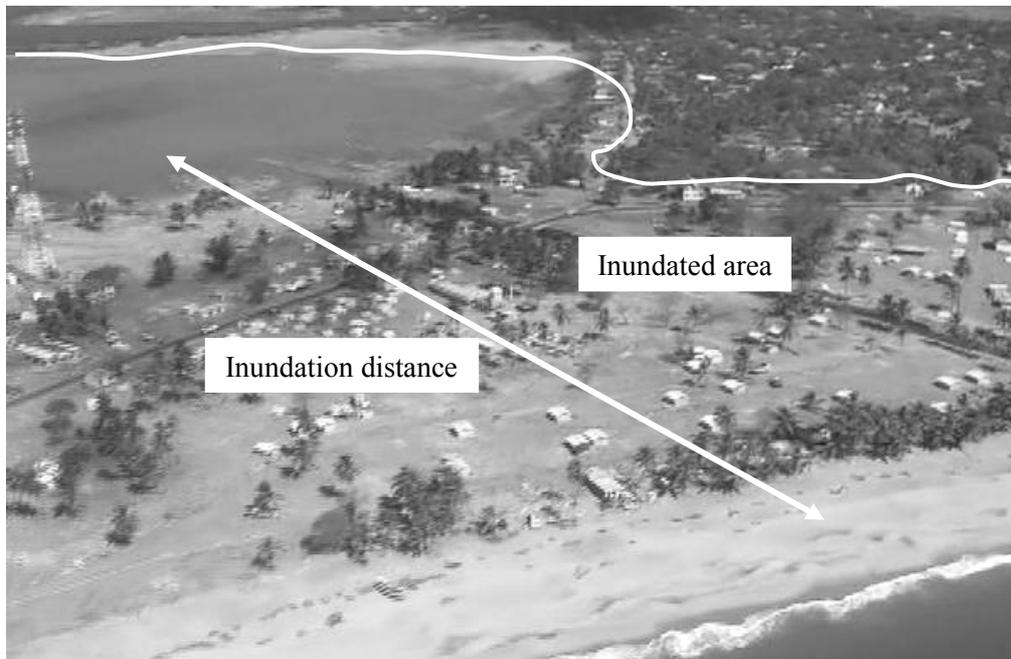


Fig 3.3: Inundation heights identified by damaged buildings, trees and scouring of the ground.

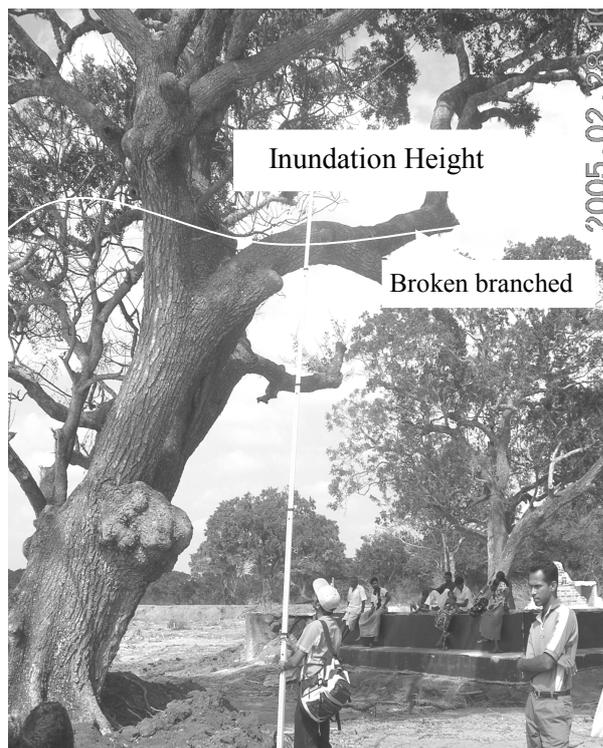


Fig 3.4: Inundation heights identified by damaged trees.

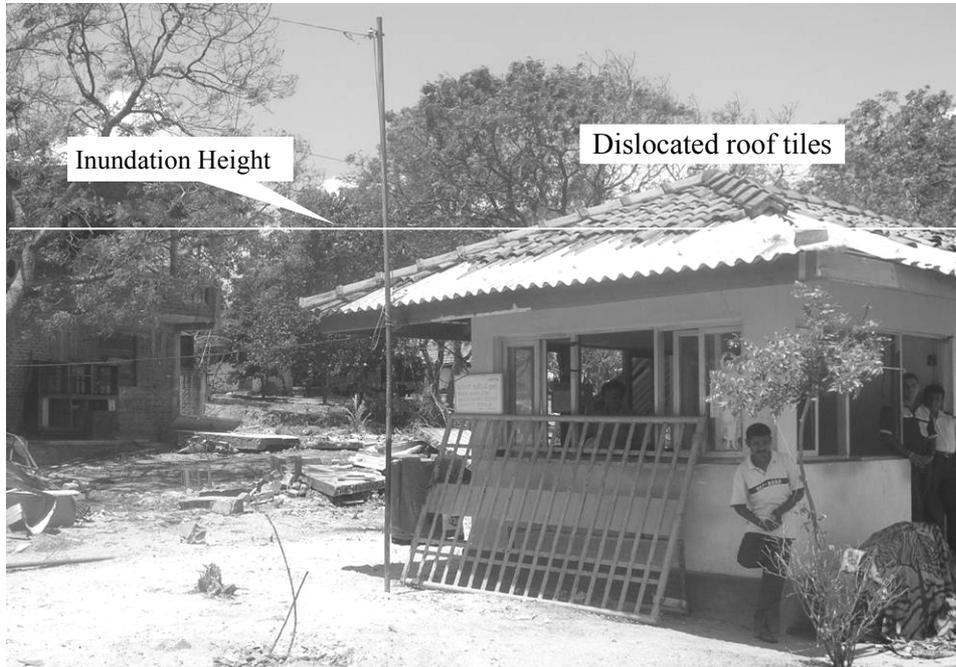


Fig 3.5: Inundation heights identified by dislocated roof tiles (Kirinda)

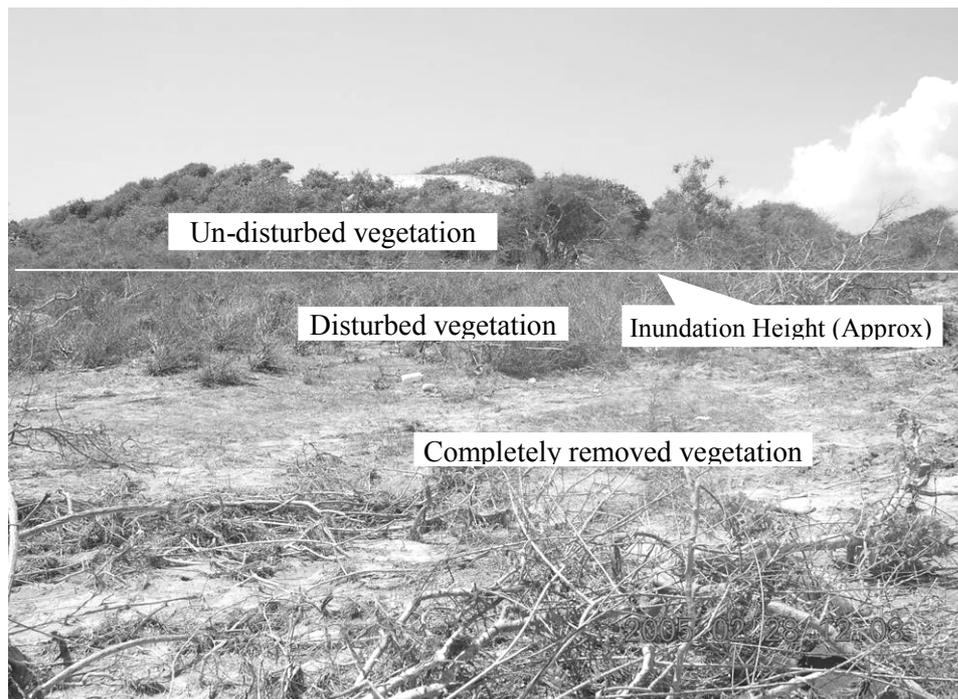


Fig 3.6: Inundation heights identified by damaged and eroded vegetation cover in sand dunes. (Yala)

Once a data point has been identified, location was recorded by the GPS technology, where the accuracy was within 5m in normal conditions. The inundation distance and height were measured by using precise electronic distance and level measurement equipment. Inundation heights were recorded with respect to the MSL. Fig 3.8 shows the results of the inundation measurements collected from West and South coast.

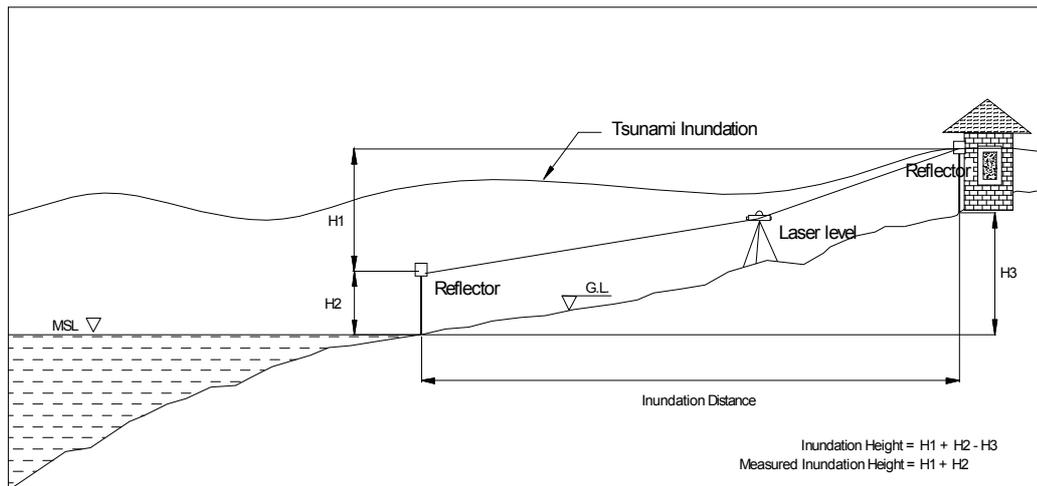


Fig 3.7: measurement of inundation heights

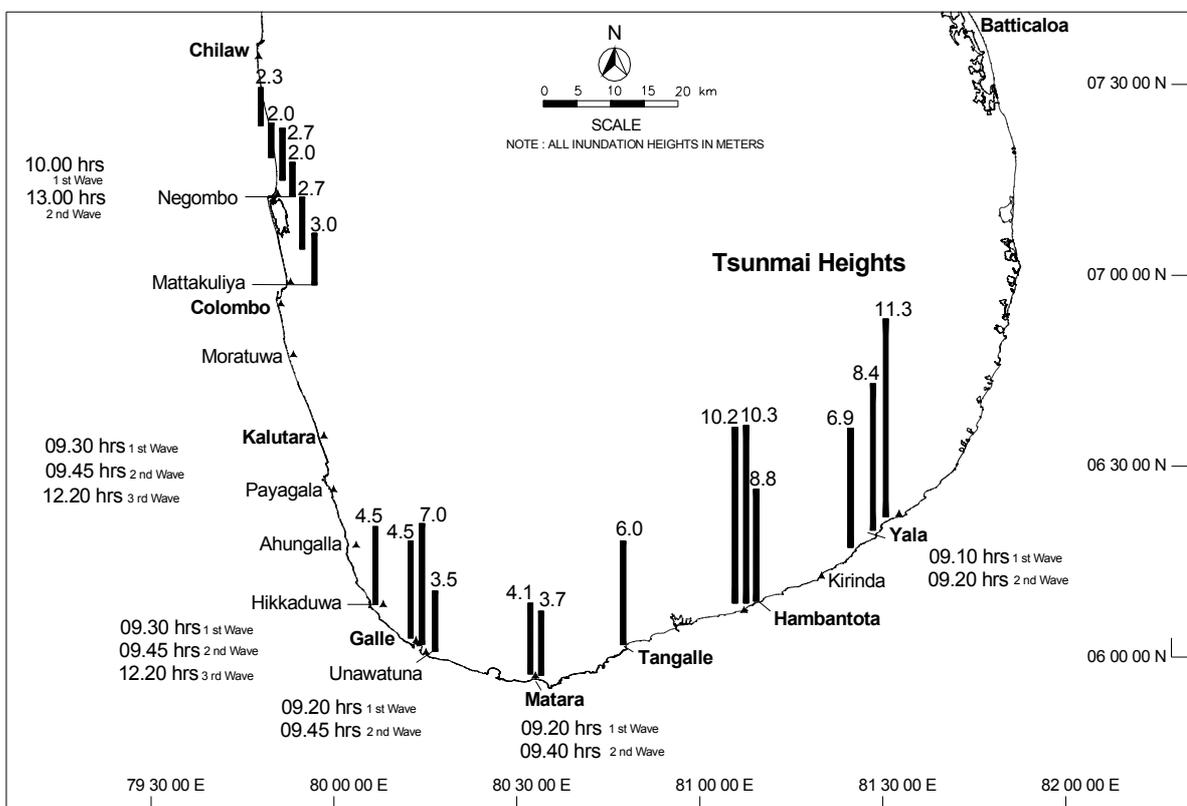


Fig 3.8: Summary of the Inundation heights (meters).

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**3.4.2. Field Interviews**

One of the main sources of information collected during the tsunami survey was the field interviews with the intention of collecting information of the real time picture of the tsunami attack at that particular observed location. Most of the interviews were conducted with tsunami eyewitness in order to record their experience in tsunami attack, both from the standpoint of documenting the physical properties of waves making up the tsunami through parameters such as arrival time, arrival direction, height and how people responded in such a situation. It was clearly identified all the eyewitnesses were completely unaware of the tsunami. More than 95 % of the interviewed people were selected as they were living very close to the beach. In very few cases we couldn't find any individuals who have experienced the real situation. In that case people who have already aware of the situation very well were interviewed instead. Interviews were conducted very carefully since most of the people were laymen and they tend to magnify the facts to get attention of the interviewer. Hence questions were selected very carefully and not to induce the participants to produce any biased information such as inundation height and number of deaths.

Following will discuss the detail information gathered from the field interviews as west coast, south west coast and south coast.

**(a) West coast**

Even west coast was less affected compared to the south west and south coast of Sri Lanka, it was important in studying to understand the arrival times of tsunami, which gave an idea on tsunami propagation as a trap wave along the west coast. Fig. 3.9 includes locations where those respective interviews were carried out. Marawila was the furthest location observed in the north of Colombo and Kalutara was considered as the last location towards south in the west coast.

According to the interviews made in Marawila ( $7^{\circ} 22.5'N$ ,  $79^{\circ} 49.42'E$ ), the effect of the tsunami was a minimum. However people in the Marawila also observed the abnormal variation of the sea tide during 12.30 noon. Further it was revealed that there were no flooding occurred in that area. But an area towards south of Marawila along the coast it was found that flooding occurred in the near coastal zone.

When came down Marawila, around Katuneriya ( $7^{\circ} 21.20'N$ ,  $79^{\circ} 49.56'E$ ), the coastal inhabitants experienced tsunami much stronger. One of the women who interviewed said that first tsunami was arrived North direction along the beach and then it started attacking from all the directions. Finally it flooded whole the area for some time. Damages were not so severe and it was found no damages to houses except for temporary structures. However we listened that severe erosion took place in tsunami draw down which damaged sewerage and water supply.

An interview held with one of the hotel workers at Vennapuwa ( $7^{\circ} 17.00'N$ ,  $79^{\circ} 50.45'E$ ) explaining

the incident said, that sea level was increased like a wall and pushed into land around 12.30 p.m. He further said that there was no fast moving wave attack. Flooded water was drawn down after 15 minutes. But during the field observations it was found that flood heights were considerable.

When came to Negombo, the experiences by the victims were vivid. According to the interviews held at the Negombo Browns beach hotel and Beach around the Negombo Off shore breakwaters ( $7^{\circ} 14.15'N$  ,  $79^{\circ} 50.45'E$ ), it was found that rough sea was observed even around 10.00 a.m. but tsunami was attacked around 1.00 p.m. It was observed as a fast moving tidal wave which made considerable damage. From the interviews it was revealed that tsunami had a considerable kinetic energy around Negombo area. Another important fact which was revealed that, recession of the sea level was also experienced before the main attack.

Based on the interviews held in Negombo Lagoon fishery Port ( $7^{\circ} 9.33'N$ ,  $79^{\circ} 49.66'E$ ), it was found that tsunami was attacked in that area around 10.30 A.M. The waves were more energetic and there was high inundation. Boat owner explained that waves could easily damaged large number of boats and some of the boats were fully broken and some were drowned.

When it came further down from Negombo, in area called Talahena ( $7^{\circ} 8.00'N$ ,  $79^{\circ} 49.44'E$ ) it was learned that the damages were not severe as previous. One who was living closer to the beach explained that sea was rough from the morning. Further he explained that sea was receded for around 25 minutes and then suddenly appeared a wall of water. There were some inundation but it didn't make any damages according to him. We observed that there was a high sand dune which lies at the sea side edge of the Negombo lagoon protecting inland.

When it comes to Colombo it was learnt that the tsunami damages were highly localized. Some of the areas were considerably damaged and some areas were not. Such variation found to be related with nearshore topography. Interview made in Mattakuliya in Colombo ( $6^{\circ} 58.67'N$ ,  $79^{\circ} 52.17'E$ ), near the beach revealed that inundations were high as 1.8 m and multiple wave attacks were experienced. A person living closer to beach explaining the incident mentioned that direction of the tsunami wave attack was not so clear since there were many waves. But it attacked Colombo between 10.00 a.m. and 12.30 p.m. several times.

Next most severely damaged location in the west coast was the area around Panadura Fishing port ( $6^{\circ} 42.95'N$  ,  $79^{\circ} 54.08'E$ ) and damaged small village near by. Based on the interviews held with some of the inhabitants it was found that there was a high wave like a wall suddenly appeared and pushed towards land. Attacks were experienced around 10.30 a.m. in the morning and sea was rough even several hours after that. Information of tsunami arrival direction could not be found in this area.

Another most important location observed was the Kani Lanka hotel in Kalutara ( $6^{\circ} 33.95'N$ ,  $79^{\circ} 57.75'E$ ). This was severely flooded and damaged. Interviews revealed that the effect of the river was significant in entering the tsunami waves further inland. It was found that first wave attacks were experienced around 9.30 a.m. and there were several waves even after that. Manager of the hotel, who had the experience explained that he could make a narrow escape of life by climbing up to a roof top. Few who were on a boat in the river were also made a narrow escape since tsunami was strongly attacked the river.

Based on the interview data it was found that many in the west coast had never experienced tsunami and it was a thrilling experience. Some of the inhabitants in the North of Colombo said that they knew it before it was really attacked. But it was clear that no one didn't expect the effect if tsunami would go even further in Colombo and Negombo. It shows that the poor understanding of natural disasters among civilians and their ignorance in such kind of a situation.

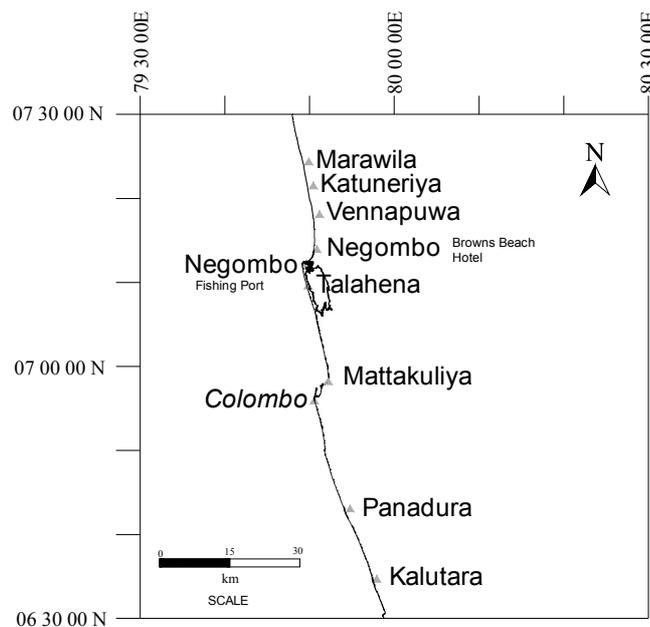


Fig 3.9: Selected locations in the West coast where the field observations and interviews were carried out

### (b) South west coast

South west coast can be considered as one of worst affected areas in Sri Lanka. Even it was found in the opposite side of the main tsunami arrival. Strong effect of trapped waves and diffracted waves were experienced by some of the worst affected areas like Beruwala, Payagala, Akurala, Hikkaduwa, Galle and Unawatuna. Starting point of the interviews was the Beruwala and it went up to Unawatuna. See fig 3.10 for locations of the field observations and interviews carried out.

First interview was carried out in Beruwala fishery port ( $6^{\circ} 28.5'N$ ,  $79^{\circ} 58.86'E$ ) with the Manager of

the Fishery Port. It was found that there were heavy attacks. Even behind the breakwaters there was high inundation. But important information revealed was that there were no severe damages behind the breakwaters. He explained that breakwaters experienced severe erosion and damages, hence most of the waves were broken and energy was dissipated before it reaches inland. Arrival time of the tsunami was recorded as 9.45 a.m. in Beruwala.

According to the interviews held at Payagala point ( $6^{\circ} 31.24'N$  ,  $79^{\circ} 58.45'E$ ) , which is closer to the Payagala railway station , it was found that area was completely flooded for long time and flooding took place even 1 km inside the coast. A woman who was living near to the station explaining her real life experience said that waves approached like a monster. According to her there were several waves and second wave was much significant than others. First wave approached the Payagala was high but it was not strong. She said that she made an escape after the first wave attack, with her children and husband even completely drowned in the water. Just after escaping from first wave second main was attacked and it was much stronger and moving fast. She further explained that this was the wave which killed many people, damaged the nearby railway station and washed the roof of her house.

Another important set of information was revealed in interviews held in Peraliya ( $6^{\circ} 9.90'N$ ,  $80^{\circ} 5.51'E$ ), location where the world biggest railway accident happened ever in the history. Person who was living at the vicinity of beach explaining his real life experience said that, tsunami attacked severely than any other areas in South west coast. According to him there was an initial wave of height around 2.0 m at around 9.30.a.m. This flooded almost all the Akurala area since most of the area was low-line. The train which was passing that area at that time was stopped because of this flood. People who were living either side of the railway line and people who were around that area got into train to avoid that flood. Within few minutes train was jam packed and people were seen even hanging outside the train for escaping their life. Many thought they were safe since they were above water level. But it was only for several minutes. Another large wave appeared as high wall and it flushed the train like a toy, scattered train carriages and toppled the driving engine. All the carriages were completely drown. Tsunami height was about 7 m to 10 m according to him. Due to the low-line topography and wetlands, tsunami was flooded even more than 1.0 km from the beach. Because floods didn't draw down easily and remain there for more than several hours. It made difficult for reaching rescue teams and even unnoticed by many. At the end more than 1200 died in this accident. He further explained that his house was wiped off. Large rock armours, even weigh more than 1 ton was transported easily and hit his house. Even he was fortunate to escape, his two daughters sacrificed their lives.

Next fatally affected area was the Hikkaduwa ( $6^{\circ} 8.41'N$  ,  $80^{\circ} 6.25'E$ ) . There were several interviews conducted in Hikkaduwa area for identifying the tsunami arrival direction and arrival time. Interview held with one of the shop owner who was doing business close to the Hikkaduwa beach

explained that there was an initial wave of 1.5 m and after that sea was started to receding. They observed most of the corals, rocks which were not exposed earlier. Mean time they observed a formation of a tidal bore as a cloud at the far end of sea. Some of the people who noticed that climbed to high places. And some were so curios and went closer to the beach to have a better view. Suddenly that wall turned into a massive wave and flushed coast within several seconds. Interview held with manager of the fishery port further revealed that waves were as high as even windows of the second floor was completely broken. According to him tsunami was arrived from north west direction and after that it started coming from all the other directions.

Interview held with one of the hotel owners in Hikkaduwa revealed another good set of information. According to him also there was a significant recedence of sea level before the main attack. During the first attack, furniture in his hotel was flushed away. However during the second attack everything went under water. It was as high as 5 m to 7 m and flooding took place around half an hour. Also he said that waves were attacked like a wall from the north west direction. He could escape his life by running away into high area along road. He further added that even though road behind the large series of hotels were flooded but there was no strong currents.

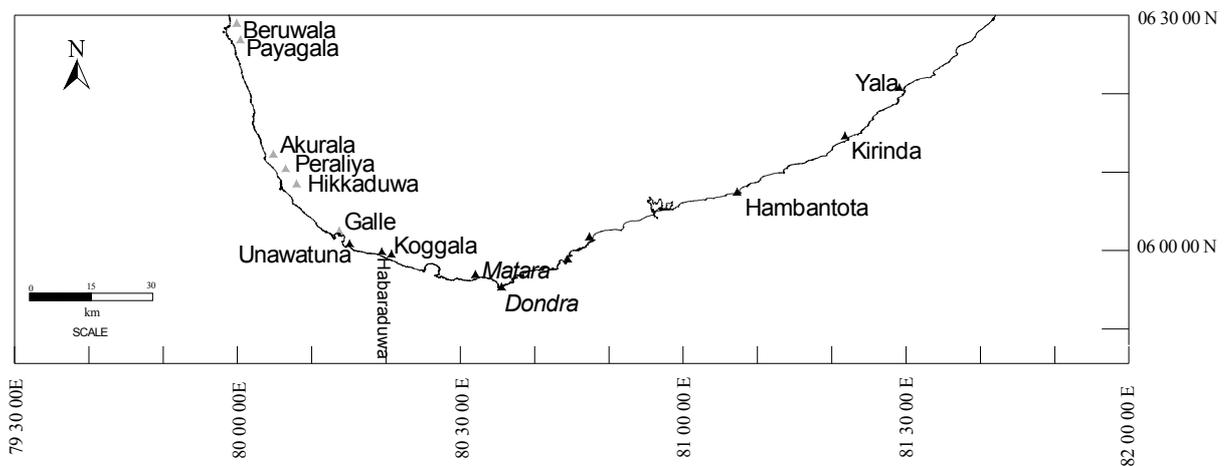


Fig 3.10: Selected locations in the south west coast and south coast where the field observations and interviews were carried out.

Last interview of the south west coast was at Unawatuna ( $6^{\circ} 1.50'N$ ,  $80^{\circ} 15.11'E$ ). It was again fatally affected by killing many people. This experienced the local effects of the morphology and topography. A boy who explaining his experiences said that, there was an initial wave followed by recedence. Such recedence took place over 20 minutes before the major attack. Major attack was took place around 10.00 a.m. and wave went more than 500 m inside the land. He could escape by climbing to a coconut tree and hanging it until the flood drained off. While others caught by the waves and flushed away. He further added that except for who could run up most of them who

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caught were died since waves attacked fiercely and unexpectedly.

**(c) South coast**

In south coast several interviews were held in selected locations. It was started from Habaraduwa ( $6^{\circ} 0.00'N$ ,  $80^{\circ} 17.01'E$ ) and final location was Yala ( $6^{\circ} 22.00'N$ ,  $81^{\circ} 31.00'E$ ). See fig 3.10.

According to the security guard who was interviewed in Habaraduwa, working in a hotel ( $6^{\circ} 0.30'N$ ,  $80^{\circ} 17.45'E$ ), it was revealed that tsunami was not such strong as south west coast. According to him there were high wave heights around 4 m to 5 m. when the tsunami was attacked he was close to the beach. There was an initial wave and second wave. During the second wave he ran behind the hotel and hanged on a window panel to avoid himself flushing with waves.

Another interview was made near the river mouth training breakwater at Koggala ( $5^{\circ} 59.00'N$ ,  $80^{\circ} 20.01'E$ ). Interview held with three people who were living closer to the river mouth revealed that area behind the breakwaters were less affected. They experienced only 1 m flooding in their house. But the area just away from the breakwater was severely affected. Also it was found that during the tsunami large flow took through the river.

Next main interview held at Hambantota with a hotel staff member ( $6^{\circ} 7.14'N$ ,  $81^{\circ} 7.21'E$ ). A hotel worker who was living closer to the beach explaining his experience said that it was an unbelievable and most of the people who got caught were died except for very few. Tsunami arrived Hambantota in the morning around 9.15 a.m. Also it was one of the cities which experienced the direct tsunami waves. Most of the houses in Hambantota town were completely flushed away. Because of this reason it was really hard to find a person who experienced the waves at the beach of Hambantota.

A short interview made in Kirinda fishery port ( $6^{\circ} 13.66'N$ ,  $81^{\circ} 18.86'E$ ) revealed that damages to Kirinda were mainly due to the disturbance of the sand dunes. According to the worker in the Kirinda fishing port it was revealed that tsunami incident direction was oblique to the shore line. It was from a direction south east and moved along the Kirinda coast. he explained that heavy sand dredger was moved into land by tsunami waves.

Final location was the Yala, which is a national wildlife reservation having unique geographical features. Also this was the last destination of the field observation in Sri Lanka. An officer explaining the situation revealed that there was limited number of victims of the tsunami in Yala since it is reserved forest. According to him there were 30 casualties of part visitor. Initial wave was experienced around 9.10 a.m. and it flooded more than several kilometers due to the low-line topography of Yala. Then there were several waves and around 9.20 a.m. second largest wave was noticed. Important piece of information revealed in Yala was that even with severe wave attacks,

there was not a single animal found to be dead inside the jungle. He further explained that normally animals are hanging round near the beach since there are many water bodies around but all of them felt the tsunami well before it advanced inland and could escape

Following table (Table 3.2) shows the summary of all main interviews carried out during the overall survey.

Area	# Interviews	Type of information	tsunami was known before
West	10	Tsunami arrival time. Inundation height.	no
South West	6	Tsunami arrival direction, time and initial wave height. Number of wave attacks. inundation levels	no
South	5	Tsunami arrival direction. Time how long the tsunami waves were proceeding the beach. Recedence of the beach before the tsunami	no

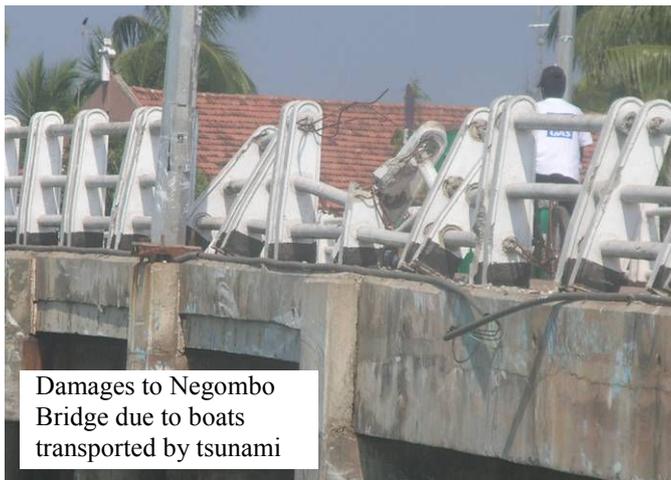
Table 3.2: summary of the main interviews in field observations

Important fact behind all the interviews was that most of them produced the time of initial tsunami arrival. This was one of the most important facts in tsunami survey, which could not be assessed from the physical measurements. However many of the witness mentioned that they have observed the recedence of the sea at least 20 minutes before the main wave attack. Since this was a new experience and most of the people gathered to beach to observe it. That showed people were not aware of the phenomena of tsunami and its risk.

### 3.4.3. Identification of damages and causes by visual observations.

Visual observation recorded can be analyzed to reveal the information of real life situation at the time of the tsunami attack. Further by comparing the visual information with interview data, it can be derived important conclusions of the tsunami wave attack.

Based on the field observations it was clearly seen that damages to the west coast was due to the effect of strong propagated edge wave along the coast. During the field investigations it was not reported any loss of life in north of Colombo areas even though some of the areas were heavily flooded However localized effects more significant in some areas like Negombo and Mattakuliya (in Colombo).



Damages to Negombo Bridge due to boats transported by tsunami



Tsunami inundation level in Browns Beach Hotel, Negombo



Inundation in Mattakuliya.



Damages in Mattakuliya.

Fig 3.11: Damages in Negombo and Mattakuliya

Most affected city in the west coast was identified as community housing scheme near the Panadura fishery port. It was observed that most of the houses located near to the coast were fully wiped off.



Panadura completely damaged house.



Panadura severely damaged house

Fig 3.12: Damages in Panadura, community housing scheme near the fishery port.

When moving towards south direction next severely affected location was the Payagala point. It was found that some of the buildings of railway station were completely washed away during the tsunami. Following figures shows the damages to the buildings in the railway station and nearby house.



Fig 3.13: Damages in Payagala point.

Kosgoda was the next location which found to be severely damaged. It was seen that railway track was completely destroyed. Such strong damage was caused by the heavy flow took through the Kosgoda river, which is wider in that particular area.



Fig 3.14: Damages in Kosgoda railway track.

Next most important location observed was the Peraliya, where a large number of people died while train was caught by tsunami. Based on the observations it was found that area where the accident took place was just above the mean sea level and surrounding area was also low-lying. Following figures show the damages took place on that site.

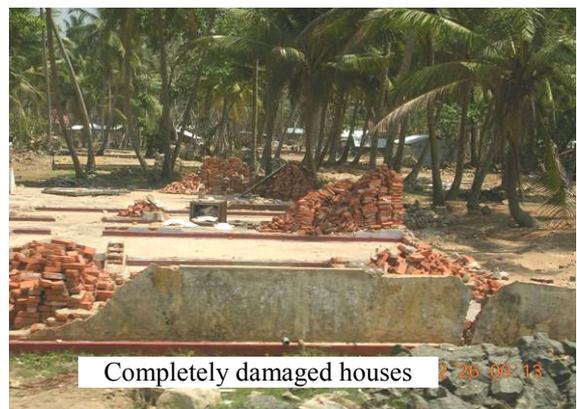


Fig 3.15: Damages in Peraliya, Hikkaduwa South.

Immediately after Akurala, Hikkaduwa was found to be the next severely affected community. Damages were vivid and spread over a large area. By visual observations it was again found Hikkaduwa also experienced large waves due to localized effects of the near shore morphology. Such waves could easily wipe off many houses which were old and not strong. Following shows some of the structural damages found in Hikkaduwa.



Fig 3.16: Damages in Hikkaduwa

Next to the Hikkaduwa, most number of casualties was reported from Galle. Since Galle is located right behind a large bay which is surrounded by high ground areas. Hence more damages were caused by local amplification of tsunami. Following shows some of the damaged houses, building caught in tsunami.



Fig 3.17: Damages in Galle

Next observed location was the Unawatuna, which a village south of Galle, surrounded by a mountain. Following figure shows the extent of the damages taken place in the Unawatuna area. It was mainly affected due to the amplification of tsunami by bay effect.



Fig 3.18: Damages in Unawatuna

Hambantota is one of the most severely affected in the south coast since it was the most populated city located close to the sea. Following shows the damages to Hambantota.



Fig 3.19: Damages in Hambantota

Kirinda was another good evidence for tsunami damages in the south coast. Observations made in Kirinda showed the magnitude of the trapped wave, which was moving parallel to the Kirinda Fishery Port. Also it was observed that heavy movement of sand across the shore.



Fig 3.20: Damages in Kirinda

Final location of the field survey was the Yala, which is inside a national reserved forest. Damages were identified as exceptional in some of the locations .

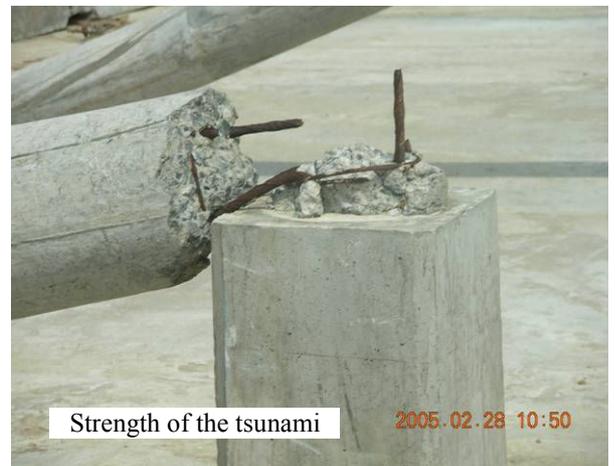
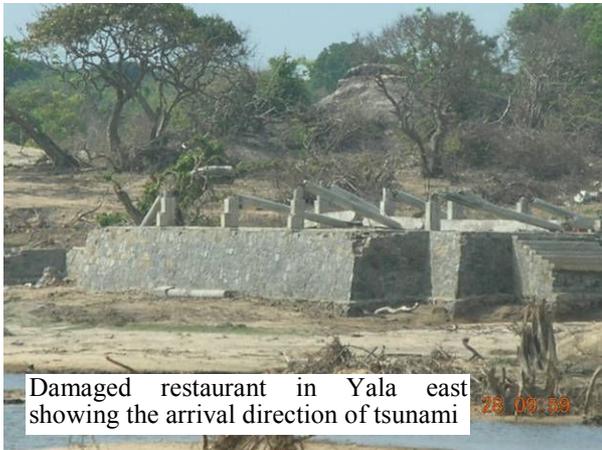


Fig 3.21: Damages in Yala

**3.4.4. Floating video survey**

For relative comparison purposes, damages to houses were recorded by a floating survey via capturing the videos on either side of the road with synchronized GPS data logging. Analyses of those data were used to drive the pattern of damages in the South west coast of Sri Lanka. Meantime an areal survey was carried out by covering an area of Colombo to Batticaloa covering the coastal zone to view the damages more clearly and in detail. Objective of this survey was to identify the inundations along southwest coast, south coast and some part of east coast.

Fig 3.22 – fig 3.24 shows the results obtained from visual survey in South West coast, covering Galle to Payagala.

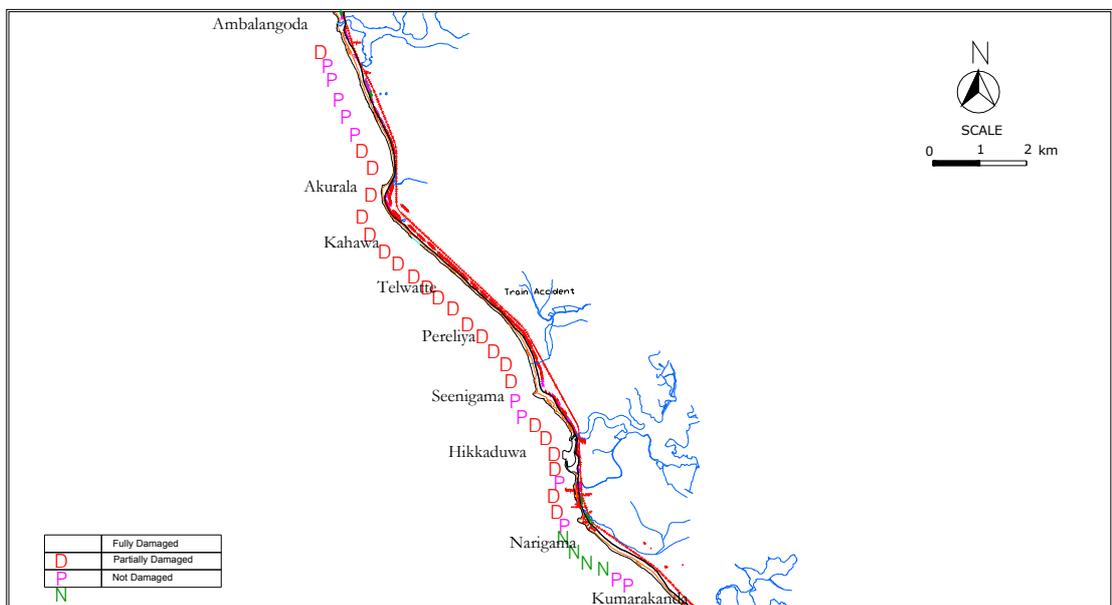


Fig 3.22: Pattern of damages to houses ( South Hikkaduwa to Ambalangoda)

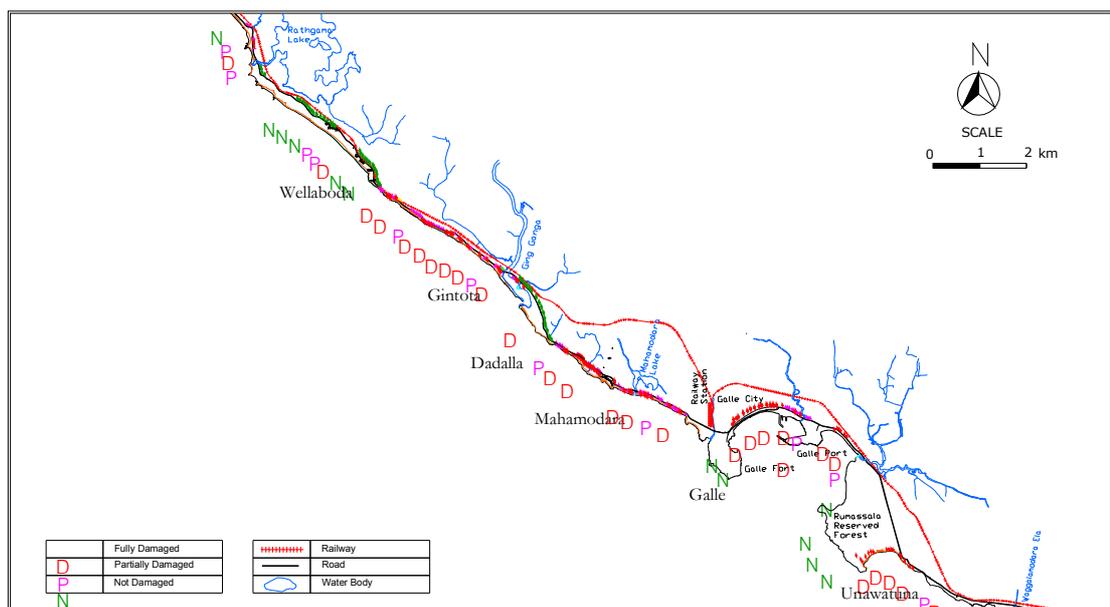


Fig 3.23: Pattern of damages to houses (Unawatuna to South of Hikkaduwa)

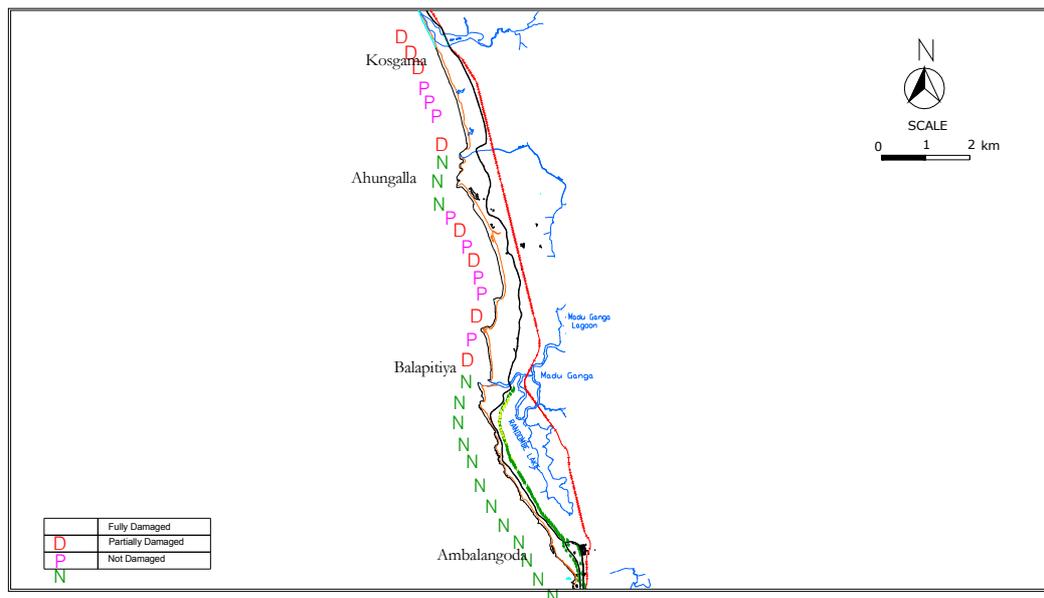


Fig 3.24: Pattern of damages to houses (From Ambalangoda to Kosgoda)

Damages in the above plot has been categorized based on the assumptions that fully damaged houses are the structures which was fully destroyed or can not be used for living without rebuilding. Partially damaged houses are the one which can be used after repair . Non damaged houses are falling into the category that houses which were not affected or experienced only mild flooding. However sometimes it was found that some houses were old and not strong as modern reinforce concrete structures.

Based on the above results it can be found some areas were highly damaged and some areas were not damaged. When comparing the damage data with geography of south west coast it can be found that there is rhythm between damages and geography. Such a rhythm can be the cause of moving edge wave along the south west coast.

### 3.5. Classification of the damages:

Interpretation of damages can be done via numerical models and use of existing information collected based on the judgments of previous studies. In this chapter the observations will be analyzed in the point of view of distribution nearshore bathymetry and Numerical-modeling results will be discussed in a separate a chapter.

Understanding of the type of the damages and level of damages is important in proceeding with damage interpretation. Sri Lanka was a country which showed much complicated mechanism of damages in last 2004 Dec tsunami. Damages were varied from overtopping of sea level to much destructive inundation spreading over several hundred meters inside the country. When analyzing the field observation data it can be found four main levels of damages in South and south west coast of Sri Lanka.

1. inundation without damages
2. inundation with damage to property

3. Severe inundation with damage to property and life.
4. Complete destruction

For understanding the damages it is convenient to classify the damages into different levels. As common to any other natural disaster, Level of the tsunami damages can be measured in terms of two factors;

1. Strength of Disaster (Tsunami arrival Height, arrival direction, speed)
2. Vulnerability of the region considered. (Whether particular area is under threat)

Strength of the tsunami can be categorized by various methods. The most extensive research work on estimating the tsunami strength was done by Tsuji et al. (1995) after the 1994 east Java earthquake and tsunami. Also Abe(1995) have tried to establish a relationship between tsunami heights and earthquake magnitudes and Murakamai et al.(1993) tried to find the critical inundation height which can increase the number of damaged houses. But it is questionable how far those are applicable for the Sri Lankan context as it was far from the tsunami source. On the other hand there is no recorded history of tsunami damage to Sri Lanka for such comparison purposes. Anyhow by referring to the global history of tsunamis, Tiballs(2005), it can be concluded that Sumatra 2004 was an extreme event. Hence it can be considered that, highest tsunami potential is equivalent to the Dec 2004 tsunami. Also based on the Wijeratne(2005). March 2005 tsunami can be considered as the lowest tsunami damage potential due to M8+ earthquake. In fact it was only a tidal variation. There may be many cases available in between Dec 2004 case and March 2005, but it cannot be really find which one is less powerful and which one is more powerful. Hence we can consider all of these cases as moderate or strong. Therefore it can be defined three classes of strength of tsunami as

1. Extreme
2. Moderate/High
3. Minor/low

However in the Sri Lankan frame work it can not be found any records on moderate or low tsunami attack. Some of the far field tsunamis around Sunda trench caused some rough sea in Sri Lankan nearshore, but was not recorded as tsunamis.

Based on the risk and damage theories it can be identified, three basic categories in tsunami vulnerability in south west coast of Sri Lanka. It can be defined as follows;

*Type -1:* Areas where there is no potential vulnerability is no or minimum due to its geography. Reflective bathymetry, high ground elevation and no headlands or bays. Inundation height is minimum or no. With respect to last tsunami, amongst the areas exposed, very few areas were falling into that category. The stretch starting from east of Matara and going up to Dondra can be considered like that.

*Type -2:* In this category, we can find areas where there was inundation, but very minimum damages. Most of these areas were not directly exposed to the tsunami. Might have experienced the secondary

effect of the propagated tsunami. This can be due to sheltering of neighboring areas, where tsunami energy was concentrated on those areas coupled with less conductive bathymetry for tsunami energy. Inundation height is even less than 1.0m. Examples are South of Hikkaduwa, Negombo.

*Type –3* Where there is a moderate risk of tsunami. Shallow near shore bathymetry combined with low-line coastal topography. Most of these areas experienced the tsunami inundation, with damages of moderate scale. Most of the houses, roads, and bridges were found damaged. Meantime some of the inland features were effective in dissipation of wave energy. If area is covered by long stretches of wide beaches, sand dunes, vegetations or even series of buildings, revetments or coastal protection works. However the inundation distances were found to be several hundred meters and inundation height was several meters. Examples are Hikkaduwa, Kalutara, Bentota and Beruwala

*Type –4:* All the nearshore, offshore and topography are supportive for tsunami amplification and create severe inundation. These areas are also influenced by the local effects like headlands, large inland water bodies connected with sea (lagoons) and fewer obstructions to incoming waves. Especially the areas where there was no proper coastal protection works, minimum amount of sandy beaches and vegetation were considered under this category. Inundation distance found to be even more than 1.0 km and inundation height was more than 6.0-7.0 meters in some cases. Typical examples are Galle and Hikkaduwa North and Unawatuna.

By summarizing the tsunami strength and local vulnerability, following risk potential matrix can be derived. Refer fig 3.25

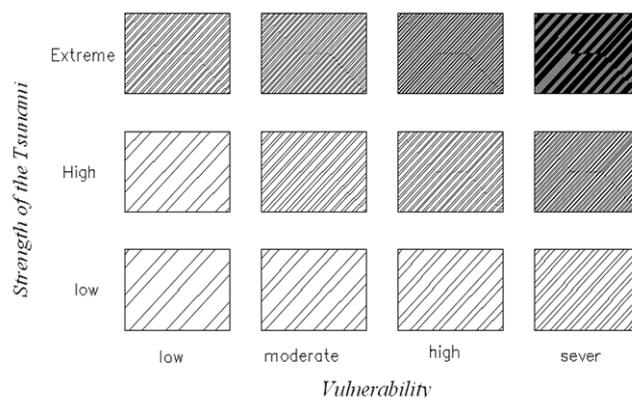


Fig 3.25: Tsunami damage risk potential matrix

According to the above classification, most of the affected areas in the south coast, south west coast and even in west coast received several series of high, long period waves. Since there was no historical record of tsunami damage to Sri Lanka proper to 2004 Dec, it can not be relatively compared. But it was clearly understood that Dec 2004 event was exceptional. However in terms of potential there is a wide variation of damages in the south coast and west coast.

### 3.6 Damage analysis in selected locations

Based on the overall field observations it was found that there are several important areas to be understood in terms of the damage mechanisms. Such damage analysis can be done with respect to the extent of the damages undergone, topographical features and geo-morphological features. Most of the key locations/towns were observed by various types of observations to reveal the most recent cause of damages.

#### 3.6.1 Galle

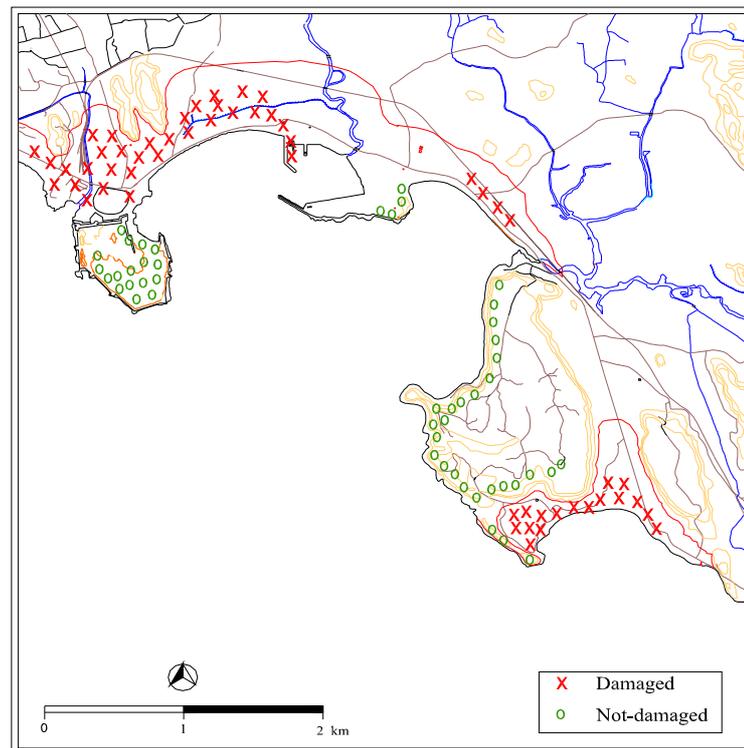


Fig 3.26: Damages to Galle.

Galle can be considered as a special location in terms of its vulnerability for a tsunami attack. From the last tsunami it was learnt that local morphological effects and topography had an abnormal effect on absorbing and amplifying the incoming tsunami. By refereeing to the damage areas main two areas of Galle can be found as were extremely compared to the others. One area is behind the Galle Harbour and other area is behind the famous Unawatuna bay. During the field observations it was learnt that both the areas received high and long duration waves. Headland around the Galle fort was effective in trapping much of the tsunami energy passing across the Galle. Heavy erosion and high damages behind the Galle fort showed that, severe wave attack came through the canal adjacent to the fort. However the effect of the main breakwater of the Galle port was moderate in protecting some area behind the port. Again the area between the port and the Unawatuna went under severe damages as due to the similar mechanism explained above.

In south of Galle, Unawatuna area, damages were intensified due to the low-line topography around the Unawatuna bay. Even higher elevations found inside the land, the narrow area surrounded by the mountains were found just above the mean sea level. Inundation measurements showed that even more than 200 m inside from the coast, there were inundations of 1.5 m scale. Hence the effect of the local topography is significant in analyzing the roots of the damages.

### 3.6.2 Hambantota

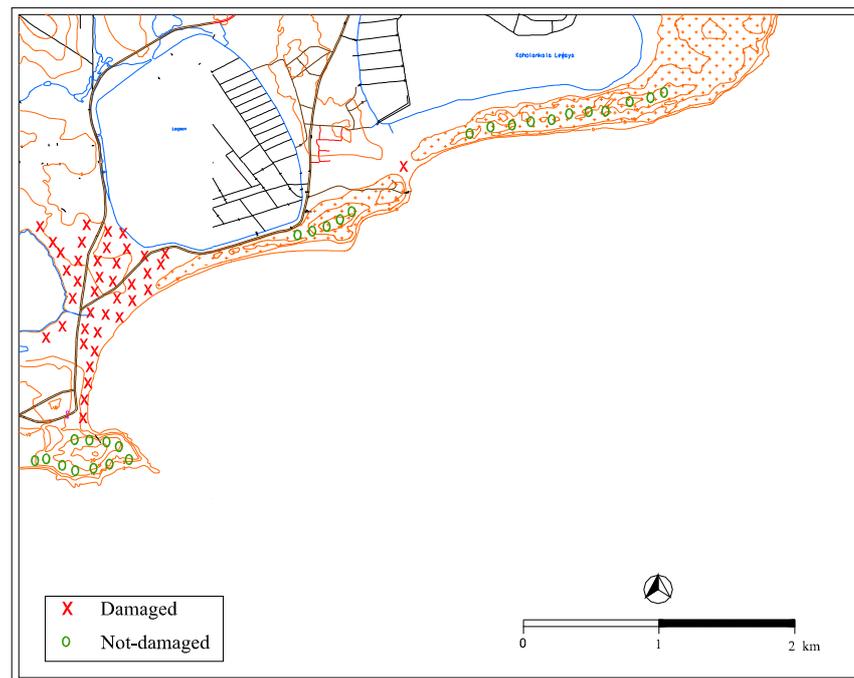


Fig 3.27: Damages to Hambantota.

Hambantota is another city which was severely affected in the south coast of Sri Lanka. The damage of the Hambantota itself claimed more than 7000 lives and many left homeless. Also based on the statistics, Hambantota was the most heavily affected city in the South coast. Heavy inundations found to be concentrated in the narrow land strip between Hambantota bay and salt pans. This again gives a good example of combined effect of bay amplification and acceleration on low-line topography. Near the coast it was found very high inundations and wiping off all the houses. Meantime heavy erosion was found even inside the land. The typical example was the complete destruction of telecommunication tower in the Hambantota town.

Another explanation for receiving high waves in Hambantota bay can be explained with respect to the nearshore bathymetry around the Hambantota headland. Based on the nearshore bathymetry data, it is clearly shown that projecting bathymetry facilitates for refraction of incoming waves towards the bay. Effect of the bathymetry will be further discussed under the numerical modeling of the tsunami propagation.

However, passing west to east of Hambantota it was found that there was a strong formation of beach sand dune, which was even more than 8.0 m at some places. During the tsunami those sand dunes were effective as natural dykes. However in some of the areas it was found that sand dunes were severely eroded and waves overtopped. See fig 3.28. Heavy siltation in lagoons and salt pans were due to such eroded materials transported from dunes.

Another important fact which is noticed in Hambantota was the coastal vegetation. Even though there was not much effect in completely protecting, those were effective in increasing the resistance for wave propagation. Sand dunes covered with vegetation found to be less eroded and were very effective in protecting the hinterland. See fig 3.29.

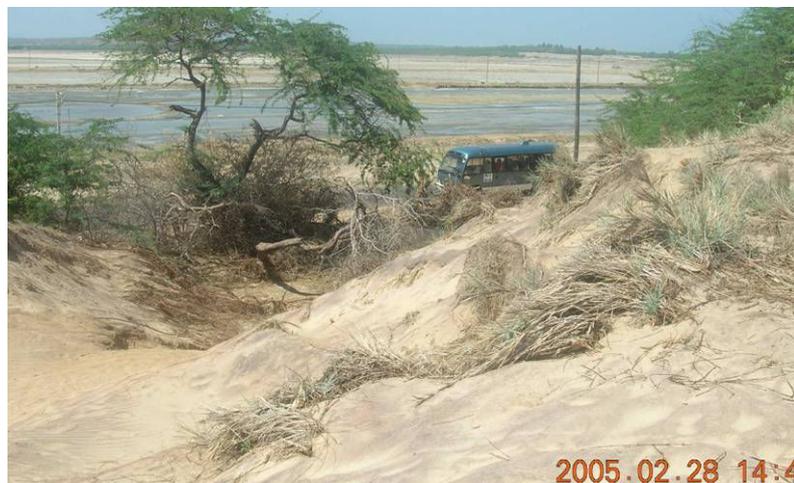


Fig 3.28: sand dunes severely eroded in east of Hambantota.



Fig 3.29: sand dunes protected by vegetation in west of Hambantota.

## 3.6.3 Yala

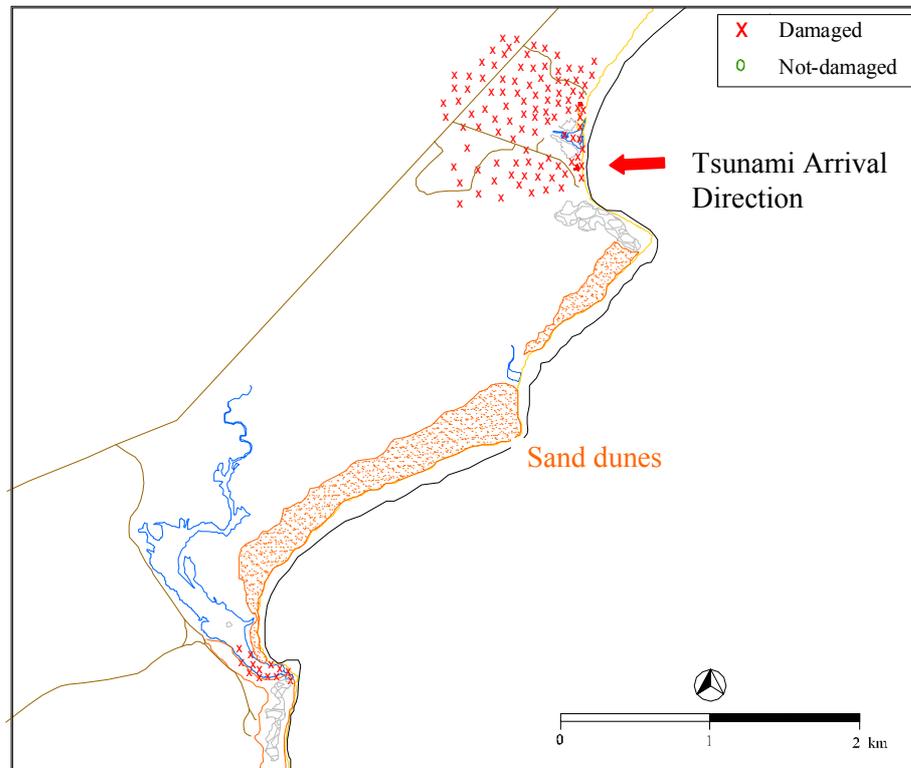


Fig 3.30: Damages to Yala.

Except for the severely affected cities and towns the other main focus during the field observation was Yala. Yala is an area which is declared as a national sanctuary. Hence it is not populated at all. However several casualties were reported as tourists and visitors, including 18 Japanese. Observations of Yala were important since it was the furthest accessible point in the south east coast during the field observation. With respect to the location Yala received tsunami well before other cities in the south coast.

Unlike populated areas, in Yala there was very few evidence of damages. Those damages revealed that wave attack was tremendous and inundations were very high. According to the observation it was found that inundation heights in the beach were even higher than 12.0 m. However Yala was protected by the natural sand dunes as similar to sand dunes in Hambantota.

Most important evidence found in the Yala was the tsunami arrival direction. It was very clear that tsunami was arrived perpendicular to the beach by observing the deformed reinforced concrete pillars of the building. See fig 3.21.

### 3.7. Effect of the Sri Lankan continental shelf.

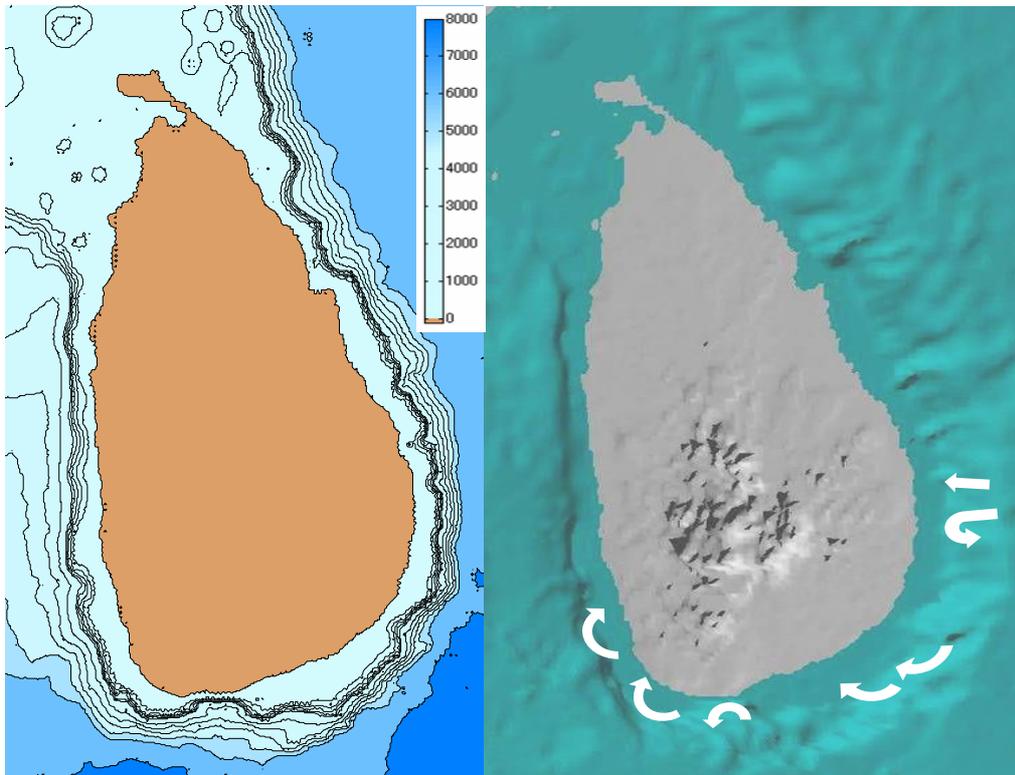


Fig 3.31: Continental shelf around Sri Lanka.

Based on the field observations carried out it was realised that most of the severe damages in the west and south west coast of Sri Lanka has a relationship with nearshore bathymetry of Sri Lanka. According to fig 3.31 it can be found some specialty of Sri Lankan continental shelf. East part of the shelf shows that there is a steep slope in the shelf at the boundary and then it continues as a mild slope towards the country. See fig 3.32. Hence most of the tsunami energy received might have reflected back to sea from the steep front of shelf. However the eastern coast received undisturbed waves directly traveling along the Indian Ocean and resulted significant damages. Based on the field observations by Byung et al. (2005) it showed inundation heights in the east coast were even high as 8-10 meters. But when it comes to south east coast, bathymetry is not steeper as east coast. See fig 3.33.

Difference between east coast and south coast was that, tsunami waves approach the south coast as an oblique wave. In such a situation refraction could easily concentrate waves into coast and could result high wave heights. Especially the areas like Yala and Hambantota were severely affected due to this severe refraction of incoming waves.

However the bathymetry of the continental shelf of south west coast was much milder than others. See fig 3.34. Such a bathymetry is ideal for amplifying waves in several numbers before it approach shore. It was clearly evident that high peaks of inundation measurements observed in Hikkaduwa and

Galle was as a result of that. Most important explanation for the high amount of tsunami energy approaching the south west coast can be considered as the edge or trapped waves which were propagating along the coast. The energy which was already trapped in the shelf starting from south east could easily move forward along the shelf by further trapping. Tsunami attacked on some areas was multidirectional since waves could refract back in opposite to propagating direction. The worst scenario of the south west and west coast is that such trapped energy was not transfer back to ocean and was further trapped with incoming waves from south.

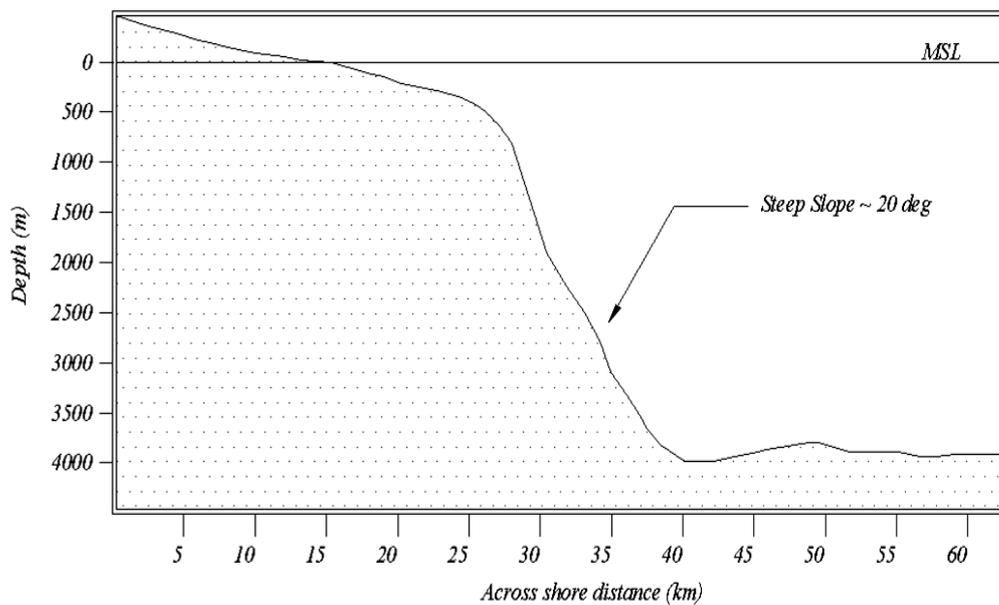


Fig 3.32: cross sectional view of continental shelf of east coast.

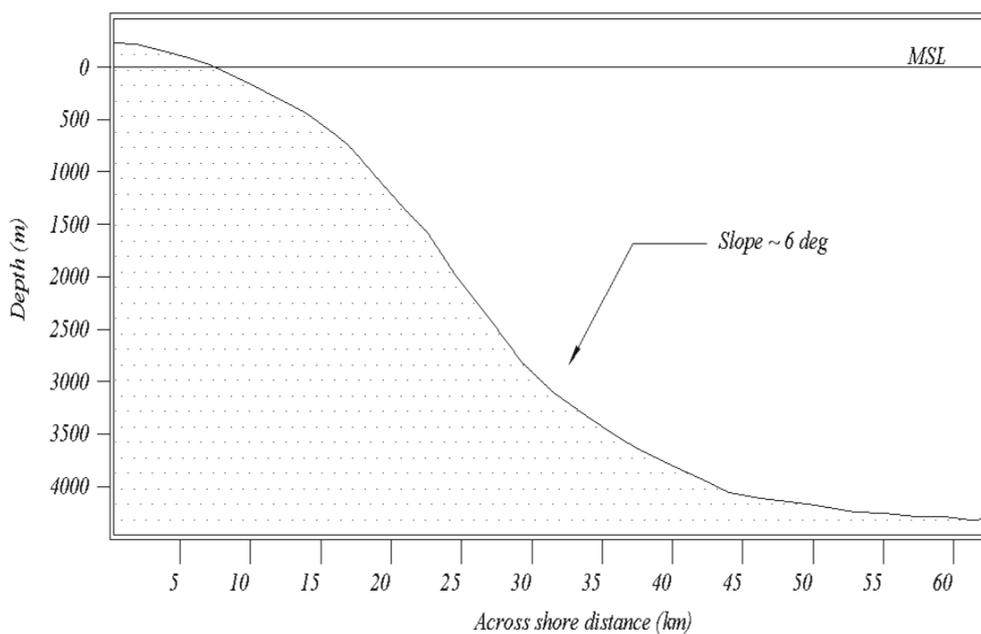


Fig 3.33: cross sectional view of continental shelf of south coast.

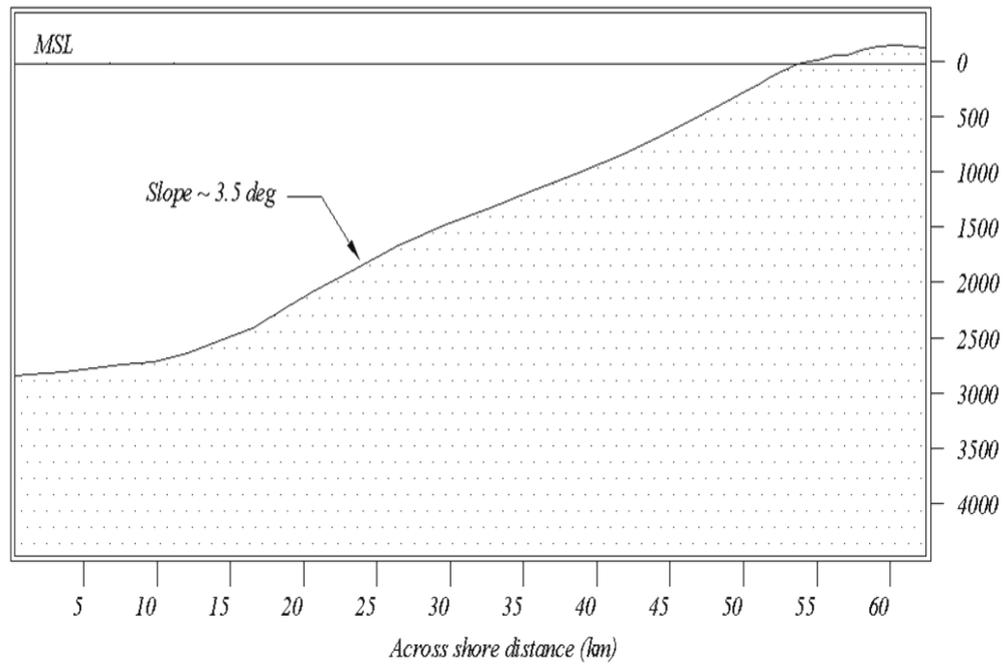


Fig 3.34: cross sectional view of continental shelf of west coast.

# **Chapter 4**

## **Hikkaduwa Field Observations**

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## **4.1 Introduction**

At the end of the overall field observation, it was decided to select a location where the damages were severe, abnormal and need for revealing cause of such damages in a theoretical basis. It was obvious that most of the south coast and east coast were directly exposed to the morning waves of the tsunami and experienced heavy damages without any prior notice. Batticaloa, Kalmunai, Akkaraipattu, Yala and Hambantota were fatally affected since no one didn't know anything until deadly waves arrived at their doorsteps. There was no prior notice by warning system or no sign of sea getting rough or bad weather. However once the tsunami stroked heavy populated cities like Batticaloa, Kalmunai and Hambantota, the message was passed to other parts of south coast and west coast in Sri Lanka. There was a clear time lag of tsunami arrival times in East coast and West coast (according to field investigations and numerical modelling) for effective evacuation in most of the southwest coast al cities. Even some people received the message via radio, telephone and television unfortunately most of the people didn't know about tsunami for their life and never thought such a wave could be even more deadly in the west coast. Highly energetic edge wave created due to the shallow curved continental shelf on Sri Lanka was the key phenomenon to explain massive waves in the southwest and west coast. This moving wave can be identified as a trapped wave, which was moving right across the southwest coast and reaching even in Colombo. Most of the cities in the south west coast situation became further severe by superimposing edge wave with direct refracted waves from deep ocean.

Except for a clear local bathymetric or topological effect such as headland, bay (In Galle, Unawatuna) it is complicated to find the exact cause of damage in most of the cities in the south west coast such as Hikkaduwa, Akurala, Payagala and Kalutara. There was a strong necessity for understanding such complicated nearshore tsunami with respect to magnitude and direction in those areas. Many international post tsunami survey teams visited Galle and Akurala in South west coast for field investigations for finding the roots of damages. But only few teams visited Hikkaduwa, Payagala for their detail investigations after the 2004 Dec tsunami.

## **4.2 Significance of Hikkaduwa**

However Hikkaduwa was identified as a significant location for identifying and interpreting those complicated damage phenomena by observing the tsunami arrival direction and duration. Fig 4.1 shows the arrival direction of waves in Hikkaduwa by numerical simulation results. Morning wave for the Hikkaduwa was from a direction southwest. Then it received several other waves from the southwest direction and south direction. Meantime the propagated edge waves were again reflected back from North of Hikkaduwa and trapped with direct refracted wave from deep ocean. This created another incident wave from Northwest direction. This alternative wave direction change shows the strength of the edge waves around Hikkaduwa.

At a glance it seems complicated to understand such a multidirectional wave attacks and it is so.

Hence it was required for simulating the situation via numerical models to solve this dilemma.

Anyhow during the field observations it was convinced that this multidirectional wave attack was experienced by most of the coastal inhabitants in Hikkaduwa area. There was no clear way to see the exact direction of wave attack since most of the observers were on the beach and couldn't see much distant towards ocean. The most reliable way to determine the tsunami attack direction is by partially damaged structures, deformed concrete poles, broken walls or disturbed vegetation. (Tsuji et al. 1995). However due to the multiple wave attacks and strong backwash it was difficult to judge the major tsunami attack direction in Hikkaduwa.

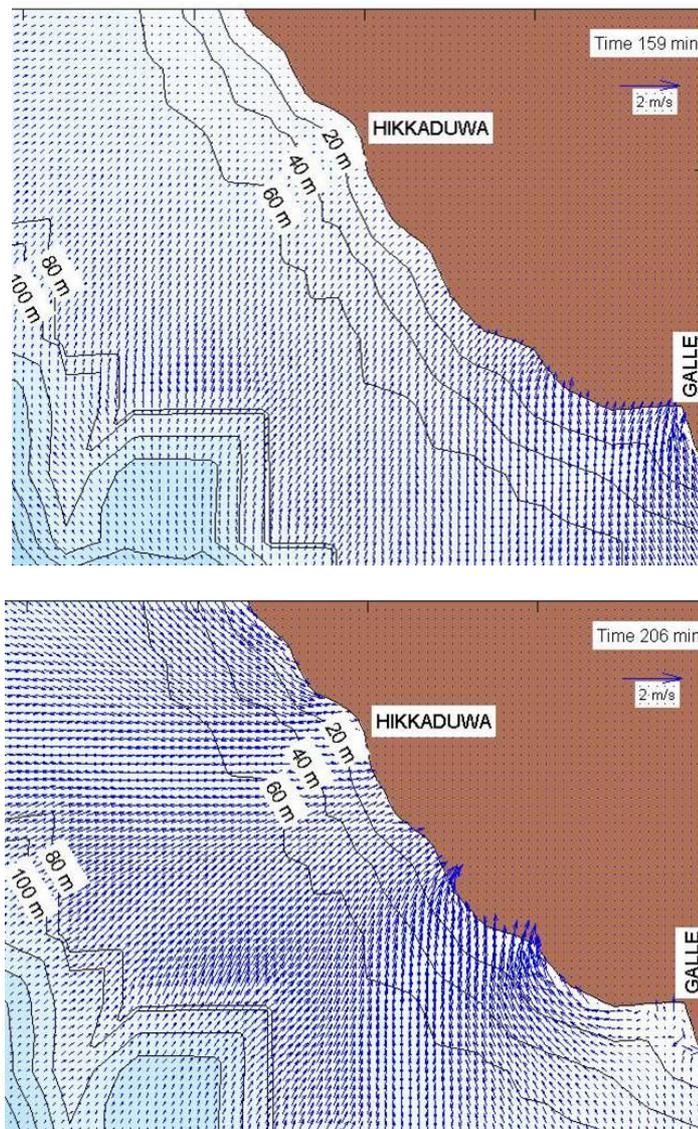


Fig 4.1 Tsunami arrived Hikkaduwa in south (bottom) and north (top)

In addition to the point of view of tsunami, the following physical and social facts in Hikkaduwa were also important in selecting Hikkaduwa as a detailed case study;

1. Positioning the fishery harbour at the center of the Hikkaduwa city sheltering almost one kilometer along the highly populated area in the Hikkaduwa city.
2. Shallower nearshore bathymetry and the near shore rock platform consisting gaps and curving shape near the fishery harbour.
3. Topology of the Hikkaduwa town area confined with low-line areas within the first several kilometers from the shoreline.
4. Hikkaduwa river mouth.

In the point of view of social factors Hikkaduwa was again important due to

1. Concentration of population and resources within a small stretch of land over a distance of less than 2 kilometers.
2. High density of fishing communities around the Hikkaduwa town area.
3. Extreme damages and large number of casualties occurred during the tsunami. (source UN, tsunami rehabilitation, 2005 SL). See fig 4.2.

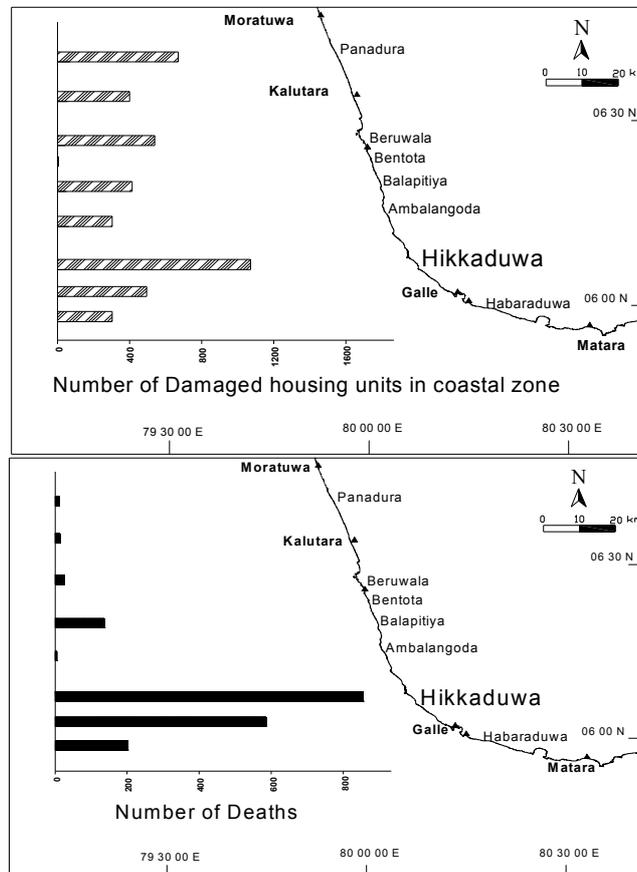


Fig 4.2: Number of damages in the south west coast compared with Hikkaduwa.

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### **4.3 Field observations in Hikkaduwa**

#### **4.3.1. Data**

The extent of the observations and type of observations were clearly planned in order to interpret the damages in Hikkaduwa with respect to the arrived tsunami and the physical features of land and ocean. Having the goals set in mind, a stretch of nearly 1650 m across the Hikkaduwa city experienced severe damages was subjected to detailed measurements via;

- Inundation measurement survey (Inundation height and distance)
- video capturing and images (ground and air)
- Field interviews.

In addition to those topological data and bathymetric data were collected by already available information.

\* Digital data of Sri Lankan coastal belt

\* Admiralty chart –South west coast of Sri Lanka.

In addition to the main stream of measurements, several measurements were taken in breakwaters to locate their height and size.

#### **4.3.2. Methodology**

Inundation measurement survey was conducted by two phases, first was along the railway track. Second was along the road. Measurements were taken as offsets to the road and rail and positions were recorded by GPS technology. The purpose of two surveys was to identify any effect on tsunami inundation due to congested pile of buildings between road and railway. There is an important point that some of the measurements showed a drastic variation of inundation heights due to some local effects. Especially a congested city like Hikkaduwa, the arrived tsunami could be easily deformed once it enters the land. Such variations couldn't identify unless the whole area of survey was finished. Also, exact causes of those variations were not clearly justified without analysis of the tsunami height and direction. All measurements were made with respect to MSL and corrected for tidal variation.

Meantime video captured data and still photographs were also used to collect any other damage information in the area. Especially the areal videos captured were useful in understanding inundation and damages in areas where it was not accessible by foot.

First it should be important to consider the geographical features of Hikkaduwa area. See fig 4.3. Hikkaduwa has a unique topography and morphology which has much variation within several hundreds meters. Most important is the low-line topography in the North of Hikkaduwa and High ground topography in the South of Hikkaduwa. Also it can be seen that effect of the breakwaters are important since it shelters large area of Hikkaduwa. Hikkaduwa bathymetry consists of shallow water reef which spreads large area in the near shore region. Another important fact is the large headland in the south of Hikkaduwa, which extrudes very much into sea. River of the Hikkaduwa is another

important feature in the sense of tsunami flooding and inundating in low-line areas.



Fig 4.3: Geography of Hikkaduwa area

4.4. Observation Results

Fig 4.4 shows the summary of the observation data made in Hikkaduwa. It can be clearly seen that there is a difference between inundations observed in north of Hikkaduwa and south of Hikkaduwa. Meantime figure 4.5 and figure 4.6 shows the distribution of bathymetry and topology in sea around Hikkaduwa and Hikkaduwa city area. It can be clearly seen that edge of the continental shelf in front of Hikkaduwa was not steep hence received most of the energy transferred from south part of Sri Lanka. Those received waves were further amplified by the shallower nearshore bathymetry in Hikkaduwa. This can be seen as one of the cause of receiving very high waves in west coast of Sri Lanka.

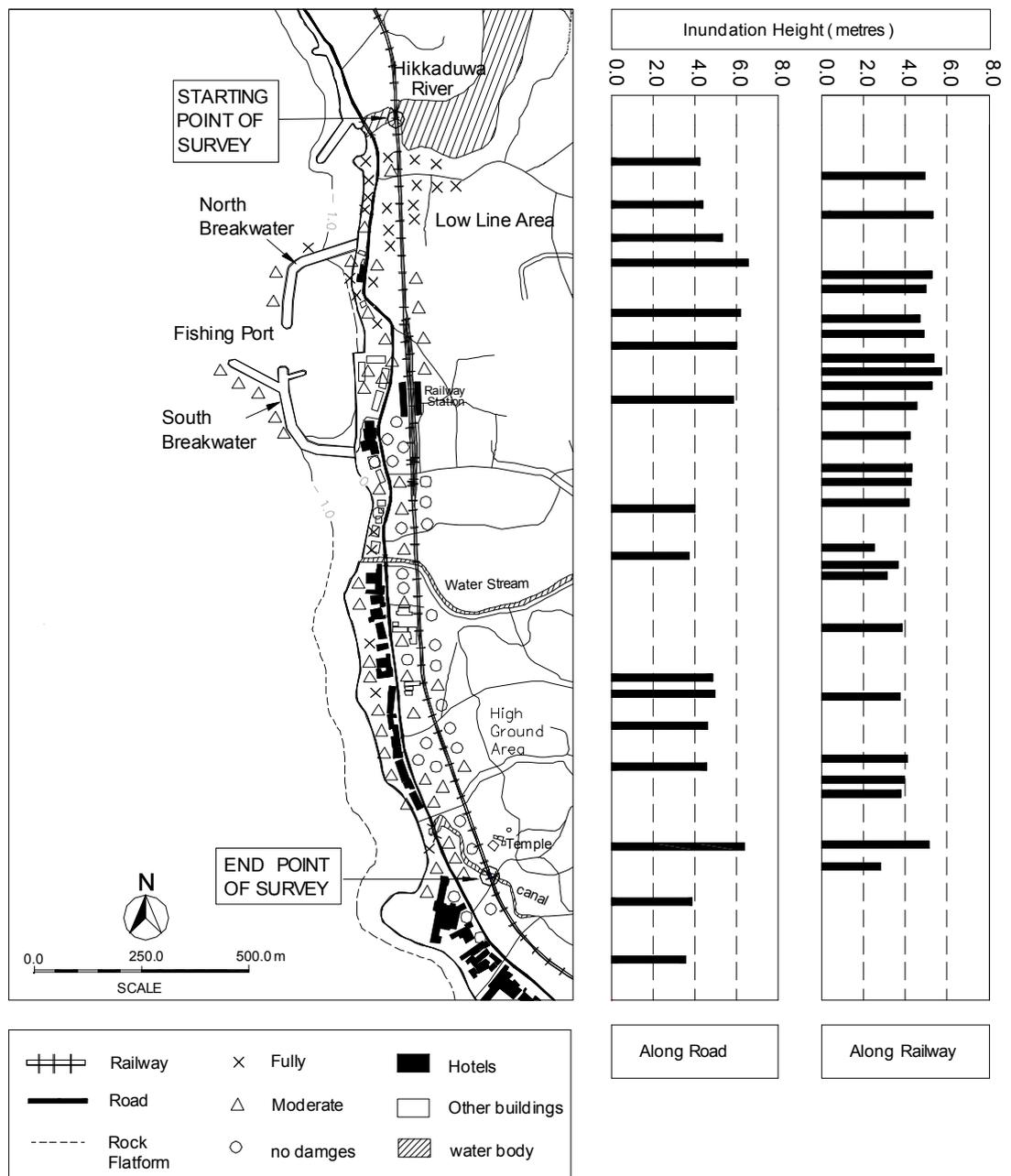


Fig 4.4: Inundation measurements in Hikkaduwa

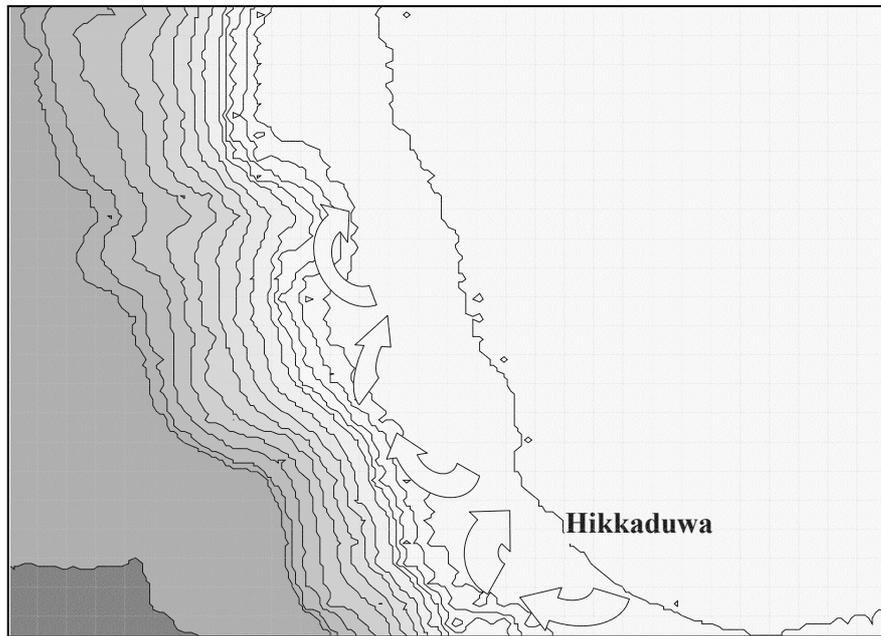


Fig 4.5: Nearshore Morphology of South west coast and west coast.

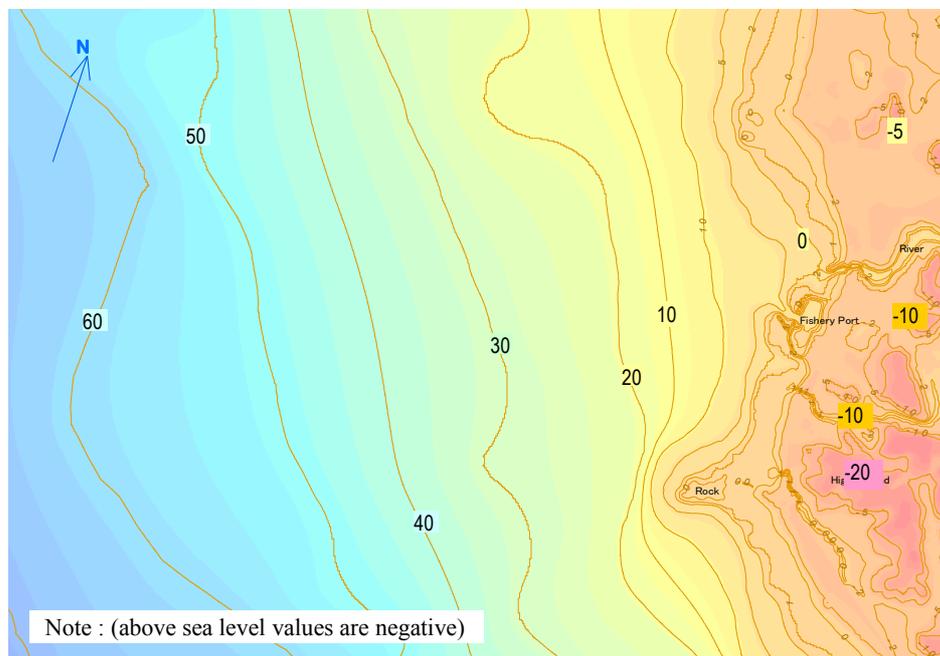


Fig 4.6: Nearshore Morphology of Hikkaduwa.

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#### **4.5. Damage analysis for Hikkaduwa**

As already mentioned in the previous section, risk of tsunami attack can be identified in terms of the regional vulnerability and strength of tsunami attack. To express the vulnerability of a particular area it is required to understand the geo-physical and geo-morphological characters, which directly influence the tsunami propagation and run-up. Such as slope of the nearshore coast, influenced by bays and headlands. Also the geometry of crest and valley type formation in nearshore bathymetry is also important factor in forming edge waves. Effects of those physical features are discussed by many scientists.

Based on the previous classification, Hikkaduwa can be identified as a high-risk area for tsunami attack in terms of vulnerability. Referring to the inundation heights measured, Hikkaduwa has experienced sufficient damages compared to other cities in south west coast. As already explained in previous chapter Hikkaduwa has experienced the strong effect of edge waves due to the location of Hikkaduwa city. Again shallow and low lying bathymetry showing a typical feature of amplification of waves by several times and making less reflectance back towards sea. Worst situation arises if such waves find fewer obstructions in the coast and be nearshore topography.

If it is considered the coastal stretch starting from Narigama to Seenigma (fig. 4.3) most of the areas are consists of low-line topography. Only exception found is the some part of south of Hikkaduwa where there is a high ground area. Generally speaking Hikkaduwa town was severely affected by tsunami compared to the other surrounded areas. Hence according to the above classification of tsunami risk, Hikkaduwa can be considered as damage type 3 or more based on the chapter 3.0 damage classifications. South of Hikkaduwa can be considered as type 3 and north of Hikkaduwa can be considered as above type 3.

In order to understand the energy of tsunami waves received Hikkaduwa, not only the inundation heights it is necessary to observe arrival direction, momentum of leading waves. However the possibilities of getting accurate and detailed information on arrival direction and speed of waves are limited in case of a post tsunami survey. Hence we had to rely on the information collected via field interviews and visual observations made on damages in buildings and houses. In this chapter first it is discussed the inundation heights and next it is discussed the tsunami arrival direction and velocities.

##### **4.5.1 Inundation heights**

Fig 4.10 shows the trend of damages taken by the results of surveys along rail and road. In general terms Hikkaduwa was inundated 4.0m to 5.0 m (from MSL) within first 50 m from the coast. That was a quite high inundation compared to other cities in south west coast. Meantime it can be found

some variation of inundation heights across the shore and along the shore. Along shore variation shows that there is an increase of inundations in north of Hikkaduwa compared to South part of Hikkaduwa. This can be the general resistance against run-up in high-elevated areas. However it is really interesting to discuss the effect on inundation by some of important physical features in Hikkaduwa and how they could react in case of a large tidal wave. It is believed that effect such complicated damage distribution in Hikkaduwa was due to combine effect of those features. Following discuss the effect of key features identified during the field investigations in Hikkaduwa.

#### 4.5.2 Effect of Breakwaters:

First and the most important feature we find is the fishery port in North part of city. It has two main breakwaters of average height around 4.0 m from MSL. From further investigations and observations of that area it was revealed that those backwaters were originally built on two rock cliffs which was in fact a part of the shallow water reef in Hikkaduwa town. From 4.7 it can be seen that bathymetry around the south breakwater is a kind of a small headland hence waves can easily concentrate towards the fishery port. In fact this was evident from the numerical modelling of tsunami run-up in Hikkaduwa. However the breakwaters have an effect of dissipation up to certain extent. But in case of a high tidal bore such effectiveness of a shallow breakwater is not so significant since most of the waves could easily overtop. And some of the waves could easily concentrate through the mouth of the breakwater and pushed towards beach. Even by field interviews it was found that large waves were arrived from mouth of the fishing port and moving fast towards land.



Fig 4.7: overview of the Hikkaduwa Fishery Port.

Most important evidence revealed was severe damages right behind the north breakwater and area between river mouth and north breakwater. Most of the houses attacked by the tsunami found to be severely damaged or completely washed away. Fig 4.8 shows the area behind the breakwaters suffered severe damages. Meantime by referring to the inundation heights measured, it is clear that increase of inundation heights than that of average around this area. See fig 4.10. So in Hikkaduwa it is found that north breakwater was not effective in obstructing tsunami.



Figure 4.8: Damages Observed Behind breakwaters at location L - 1

#### 4.5.3 Effect of the topography of Hikkaduwa town

It was found during the field investigations and existing topographic data that there is a variation of ground height between north and south of Hikkaduwa. Fig 4.9. In north part of Hikkaduwa consist more flat and low-line areas. Also there is a large valley found in ether side of the river.

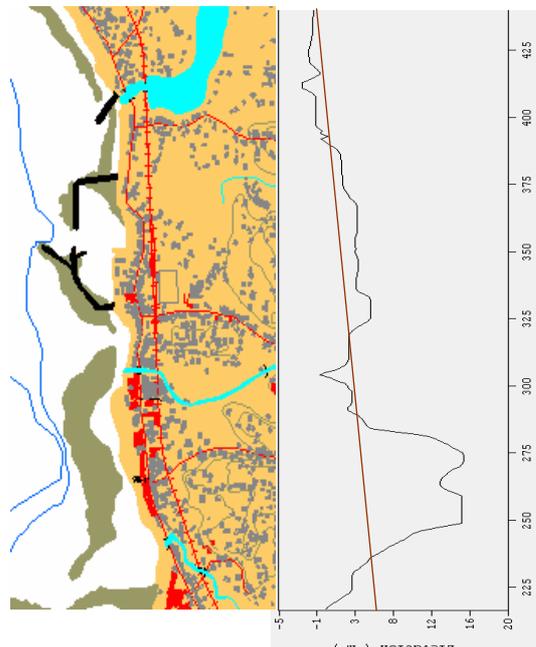


Fig 4.9: Distribution of ground elevation in Hikkaduwa

But most important point is that there is a big difference between the change of topography in across shore direction between North and South. Following figure shows the cross section of elevation data around Hikkaduwa fishery port and around the South headland. It clearly shows that there is a flat area behind the railway embankment and that area is even lower than that of railway embankment. Once high tidal waves found a flat low-line area they could easily travel much inside the land and could make larger inundations.

However south of Hikkaduwa is having a different topography compared that of North .It shows that much higher elevated areas found inside the land. Even the tsunami was concentrated around south headland and attacked with high velocity there was a less damage. These high ground areas prevented further damage inside the Hikkaduwa area.

By analysis of Inundation heights it could find that higher inundations were reported near the water bodies or water streams. In south of Hikkaduwa, high inundated areas were found either side of those water canals. See fig 4.10.

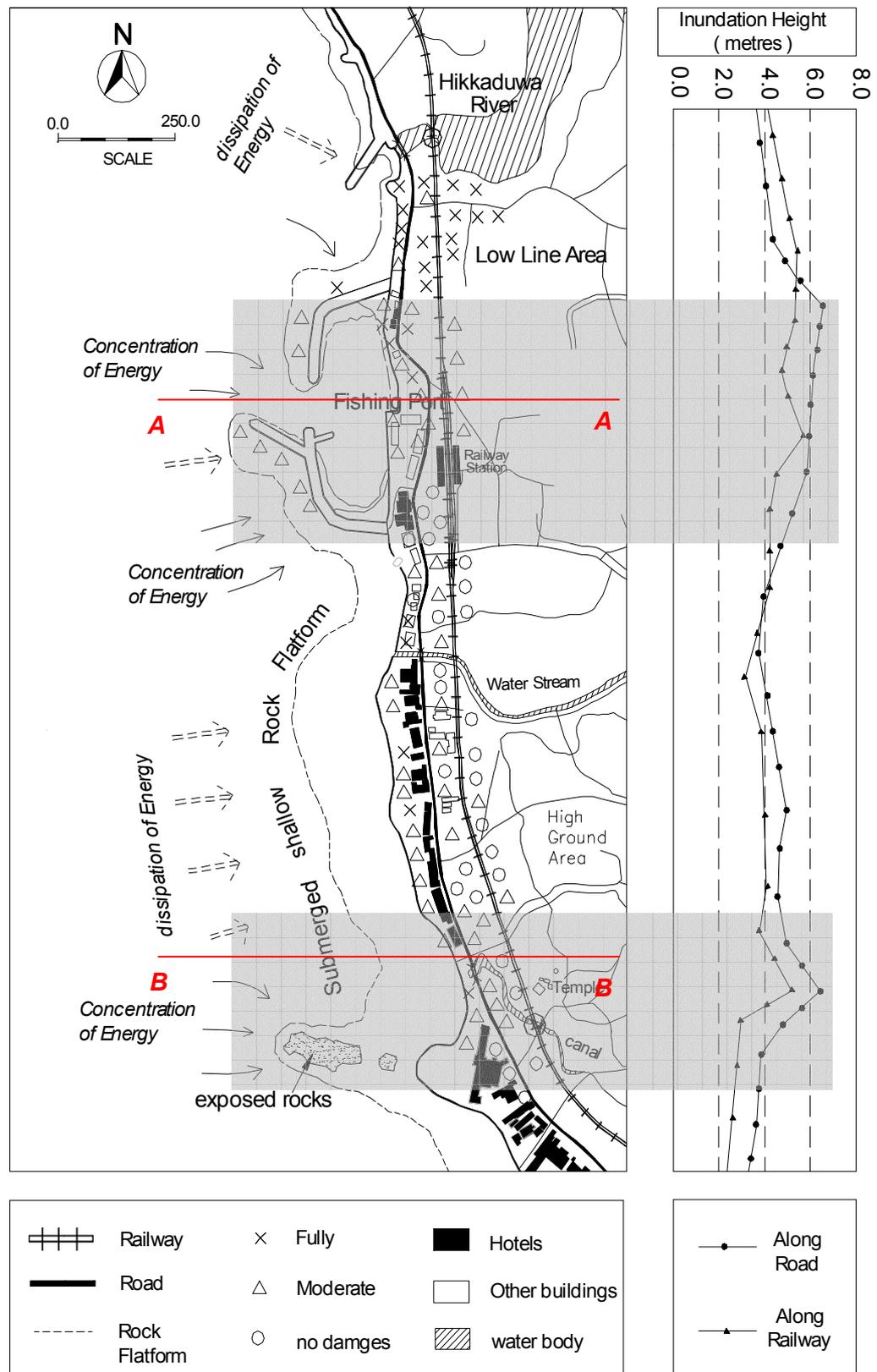
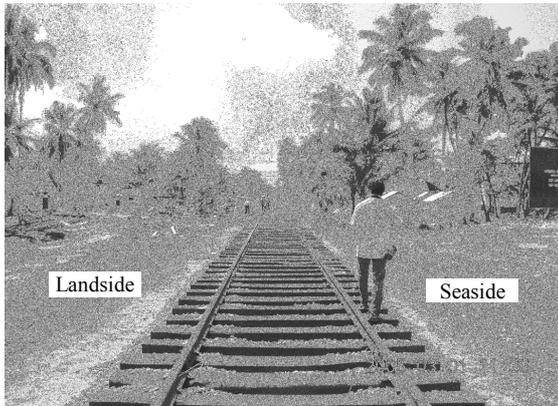
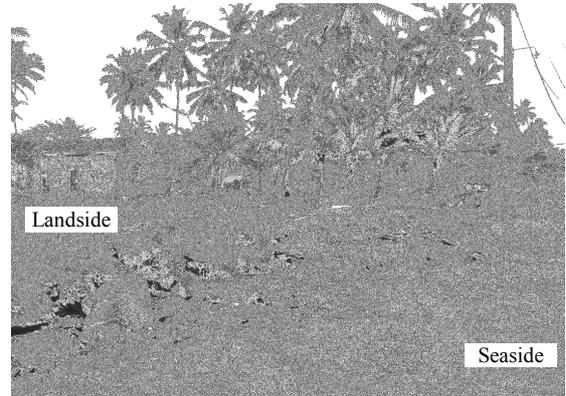


Fig 4.10 Comparison of Inundation heights

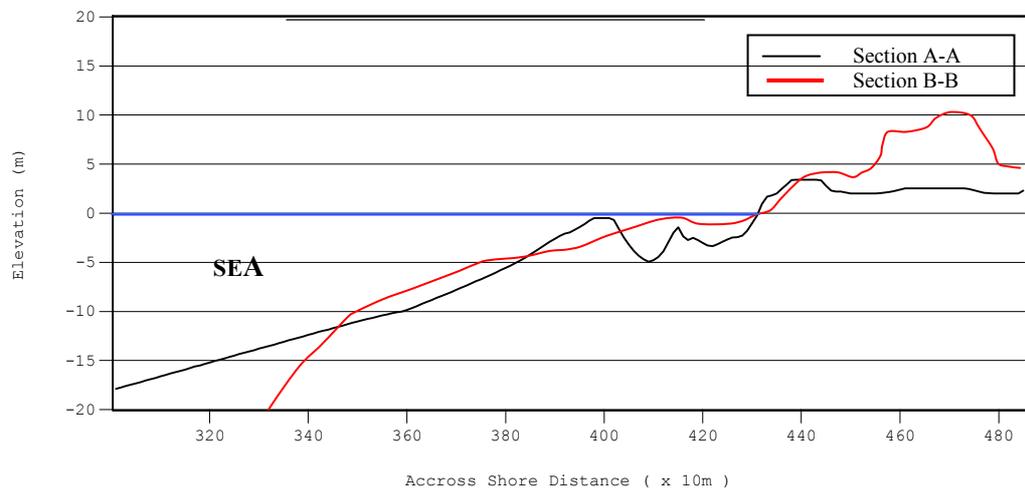


Cross section across the railway line



Large flat area behind breakwaters

North part of Hikkaduwa



Low line area surrounded by Hikkaduwa river



Headland in South of Hikkaduwa

South part of Hikkaduwa

Fig 4.11: Cross section in Hikkaduwa topography – South of Hikkaduwa and North of Hikkaduwa.

# **Chapter 5**

## **Numerical Modelling of Tsunami Propagation**

## 5.1 Introduction

In this chapter, it will be discussed some aspects of numerical simulation in Dec 2004 Sumatra tsunami propagation in the viewpoint of Sri Lankan inundations. In order to explain the mechanism of damages, it is required to understand the tsunami arrival time and distribution of inundations around the country.

This chapter will discuss the simulation of tsunami propagation over the Indian Ocean and how Sri Lanka is affected. Results will discuss the inundation height distribution and arrival time of tsunami in Sri Lanka.

## 5.2 Formulation of a Numerical model

### 5.2.1 Research review

Numerical simulation of tsunami has been running back decades since the importance of understanding the increasing threat of tsunamis were felt around the world. Following will discuss the review of some tsunami numerical simulations, which introduced key turning points in numerical modeling.

Compared to the wave length and the wave height, tsunami can be considered as a long wave in the deep ocean since it has a wave length of several hundreds of kilometers, the depth to length ratio is in the order of  $10^{-2}$  and the wave steepness is in the order of  $10^{-3}$

Hence according to Kajiura (1963), Aida (1978), Imamura (1995) showed that in the theory of long waves, the vertical acceleration of the water particles are negligible compared to the gravitational acceleration except for propagation over a continental shelf or propagation in a river. Consequently the vertical movement of water particles has no effect on the pressure distribution. Hence depth integrated equations are widely used as governing equations for tsunami propagation simulations. The following shallow water wave equation by Imamura (1995) was introduced for tsunami propagation calculations;

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad \text{Eq (1)}$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{d} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{d} \right) + gd \frac{\partial \eta}{\partial x} + \frac{\tau_x}{\rho} = A \left( \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) \quad \text{Eq (2)}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial y} \left( \frac{Q^2}{d} \right) + \frac{\partial}{\partial x} \left( \frac{PQ}{d} \right) + gd \frac{\partial \eta}{\partial y} + \frac{\tau_y}{\rho} = A \left( \frac{\partial^2 Q}{\partial x^2} + \frac{\partial^2 Q}{\partial y^2} \right) \quad \text{Eq (3)}$$

Where  $x$  and  $y$  are horizontal coordinates and  $z$  is the vertical coordinate.  $\eta$  is vertical displacement

of water surface above the still water level (see fig 5.1) ,  $g$  is the acceleration of gravity,  $d$  is the total water depth given by  $d=h+\eta$ , where  $h$  is the water depth. Where  $\tau_x$  and  $\tau_y$  are bottom frictions in the  $x$  and  $y$  directions.  $A$  is the horizontal eddy viscosity which is assumed to be constant in space and time.

$M$  and  $N$  are considered as depth averaged water discharge across the unit width of model domain given as;

$$M = \int_{-h}^{\eta} u dz = \bar{u}d \quad N = \int_{-h}^{\eta} v dz = \bar{v}d$$

Where  $\bar{u}$  and  $\bar{v}$  are depth average water velocities in  $x$  and  $y$  directions respectively.

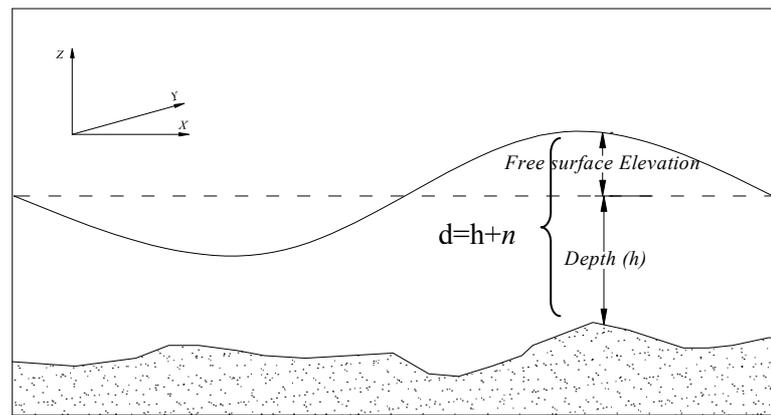


Fig 5.1: space domain of the governing equations

However based on very small wave height to length ratio and wave steepness, tsunami can be considered as a linear long wave in the deep ocean.

Based on the Aida (1978) and Shuto (1991) it is shown that linear long wave theory gives the best representation of the tsunami waves in the deep ocean and even up to a considerable depth in the nearshore. Therefore non-linear terms of the above equation 2 and 3 can be dropped in tsunami propagation calculations in deep ocean.

As the tsunami approaches shallow water it starts to feel the effect of sea bottom than that of deep ocean. Wave steepness becomes high. Hence it starts to deform by disappearing trough and increasing crest. Ultimately the shape of the wave becomes more similar to a solitary wave profile. Such waveforms are generally categorised as N waves. Hence nonlinear effects are important at this stage. According to tsunami wave theory reviewed by Satake (1995), which explains that linearity of waves, are valid even up to 50m depths. Fig 5.2 shows the applicability range of linear long wave

theory according to Bryant(2001).

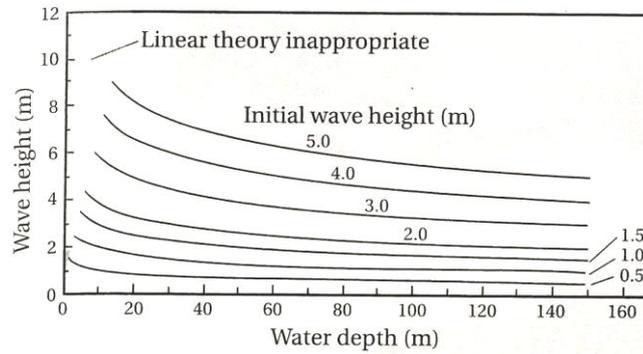


Fig 5.2: applicability range of linear long wave theory

Other specialty is since depth of the oceans can never be greater than 5.0 km the majority of the tsunami is considered as shallow water waves. However all the individual waves resulting in a tsunami generation do not travel by the same speed. Long period waves over run the short period waves, so that a tsunami wave train after traveling across an ocean tends to reach shore with regular long period waves followed by short period waves. This phenomenon is known as dispersion.

Hence in this research, the main calculations are divided into two parts. Where the linear long wave equation is considered in deep ocean propagation. Calculations in the shallow water are based on the original equation proposed by Imamura (1995).

### 5.2.2 Tsunami Propagation in deep ocean

Following equation has been considered as governing equations in deep ocean propagation

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad \text{Eq (4)}$$

$$\frac{\partial P}{\partial t} + gd \frac{\partial \eta}{\partial x} + \frac{\tau_x}{\rho} = A \left( \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) \quad \text{Eq (5)}$$

$$\frac{\partial Q}{\partial t} + gd \frac{\partial \eta}{\partial y} + \frac{\tau_y}{\rho} = A \left( \frac{\partial^2 Q}{\partial x^2} + \frac{\partial^2 Q}{\partial y^2} \right) \quad \text{Eq (6)}$$

### 5.2.3. Bottom friction

Commonly used bottom friction formula given by Manning is considered, after Imamura (1995);

$$\frac{\tau_x}{\rho} = \frac{gn^2}{d^{7/3}} M \sqrt{M^2 + N^2} \quad \frac{\tau_y}{\rho} = \frac{gn^2}{d^{7/3}} N \sqrt{M^2 + N^2}$$

where  $n$  is the Manning's roughness coefficient, which is given by:

$$n = \sqrt{\frac{fD^{1/3}}{2g}}$$

For propagation of tsunami in the deep ocean  $n$  can be considered as 0.03. However the effect of bed friction is not much significant in deep ocean propagation.

#### 5.2.4 Coriolis force

Since the consideration domain is of several thousand of kilometers, it is important to consider the effect of the Earth rotation. Coriolis force is given by Maa (1990);

$$fq_y = 2\Omega \sin(\phi) \cdot Q$$

$$fq_x = 2\Omega \sin(\phi) \cdot P$$

Where  $\Omega$  and  $\phi$  are angular speed of earth rotation and altitude of the location being considered respectively. The effect of the rotation of earth is not so significant for tsunami propagation over a short distance close to the equator.

#### 5.2.5 Horizontal eddy viscosity

The term  $A$  represents the Horizontal Eddy viscosity coefficient. Yan (1987) showed that horizontal eddy viscosity is around  $0.001m^2s^{-1}$  for simulation of current field. Anyhow use of high eddy viscosity coefficient tends to result in stable calculation but other hand it tries to damp the wave heights unnecessarily.

### 5.3 Numerical Scheme

From the early stage of developing the numerical simulation, the finite difference based upon the Taylor expansion series has one of the most fundamental and standard numerical methods. In finite difference approach continuous domain is descriptive so that dependent variables exist only in discrete points.

However numerical schemes in marching problems can be divided as *explicit* and *implicit*. For *explicit scheme* only one unknown appears in the difference equation but in *implicit scheme* there are two or more unknowns appear, requiring simultaneous solution of several equations involving the unknowns.

There are several schemes available for simulation of long waves. Staggered Leapfrog, Crank-Nicholson and two-step Lax-Wendorff. Among them staggered leapfrog is the widely used since it is explicit, stable, efficient and produce enough accuracy in tsunami simulation. Crank-Nicholson is the basic implicit scheme and requires more CPU time compared to leapfrog scheme, Lax-Wendorff

method is more popular in modelling shock waves and discontinuous flows, such as tsunami generation due to impact of meteorites.

In this study, staggered leapfrog scheme introduced by Imamura (1995) and Aida (1978) is used in securitizing the linear long wave equation. Following shows the one dimensional discretisation of the linear long wave equation neglecting friction, Coriolis and eddy viscosity terms, which is given for one dimensional case by;

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} = 0 \tag{Eq (7)}$$

$$\frac{\partial P}{\partial t} + gd \frac{\partial \eta}{\partial x} = 0 \tag{Eq (8)}$$

Discretization of Equation (7) and (8) are given by:

$$\frac{\left[ \eta_{j+1/2}^{n+1/2} - \eta_{j+1/2}^{n-1/2} \right]}{dt} + \frac{\left[ M_{j+1}^n - M_j^n \right]}{dx} + O(dx^2) = 0 \tag{Eq (9)}$$

$$\frac{\left[ M_{j+1}^n - M_j^n \right]}{dt} + g \left( \frac{d_{j+1/2} + d_{j-1/2}}{2} \right) \frac{\left[ \eta_{j+1/2}^{n+1/2} - \eta_{j-1/2}^{n-1/2} \right]}{dx} + O(dx^2) = 0 \tag{Eq (10)}$$

Where  $dx$  and  $dt$  are the model grid size and simulation time step respectively. Where the  $O(dx^2)$  is the truncation error of the second order approximation, which is in fact the difference between the partial derivative and its finite differential representation. The point schematics for the numerical scheme and arrangement of the points in staggered leapfrog scheme are shown in the following figures;

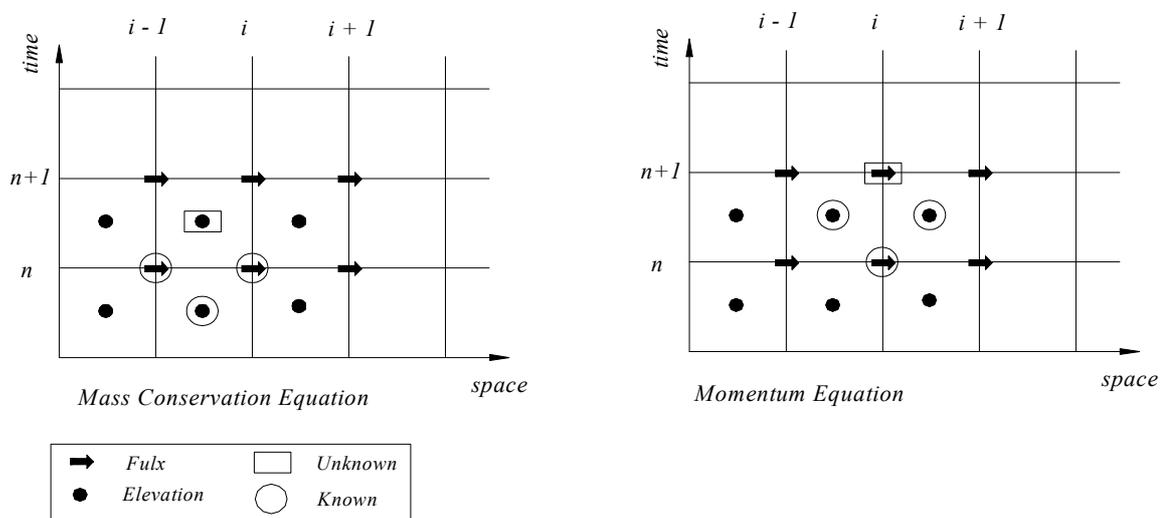


Fig 5.3 : Arrangement of points in staggered leapfrog scheme

## 5.4 Simulation Grid

Selection of grid type, size and cell size is far most important in finite difference models since there is a high tolerance of results in depends upon the model domain, type of grid and cell size. Most commonly used grid is the rectangular grid. However Tsuji (2005) discussed that influence of the curvature of earth is important if the calculation domain has a length more than 1000 km. In that case he suggests to use polar coordinate system to represent the governing equations.

Grid size was carefully chosen to make the effects of numerical and physical dispersion equal. Shuto (1991) has suggested that there are at least 20 grid cells to be used in representing one full wave length. Again Shuto (1991) suggest that considering finer mesh and coarser mesh, coarser mesh will give better approximation in representing the linear long wave.

*Imamura et al.* (1990) showed that the choice of the grid size can be evaluated using the Imamura number,  $I_m$ , defined as;

$$I_m = \frac{dx \sqrt{1 - \left( c_0 \frac{dt}{dx} \right)}}{2 \cdot h}$$

Where,  $c_0 = \sqrt{gh}$

For simulating the linear long wave equation value of  $I_m$  should be less than 1.

In this simulation a rectangular grid of (1021 x 1024) is selected. For deep (depths are greater than 2000m) ocean propagation calculations a cell size of  $dx$  of 2 min (3704 m) is used. For simulation around Sri Lanka, two step-nested grid was applied. For shelf area (depths are greater than 200 m) a cell size of 1 min (1856m) and for shallower area (less than 200 m) cell size of 30 s (925 m) are used. Following figure 5.0(a) and Fig 5.0(b) show the arrangement of model grid used in this study.

On the other hand CFL condition should also be satisfied for stability in the numerical calculations.

This is given by:

$$\frac{dx}{dt} = \sqrt{2 \cdot g \cdot h_{\max}}$$

Approaching to the shoreline  $h$  become smaller, hence in order to maintain the stability condition smaller  $dx$  is selected in near shore area keeping the  $dt$  constant. For these calculations, the  $dt$  was selected as 1.0 s, hence, which satisfies the CFL condition for all the  $dx$  and  $h$ .

### 5.4.1 Grid Nesting:

Various grid-nesting techniques have been used for Leap Frog scheme by different modelers. Aida (1978), Liu et al.(1994), and Imamura et al.(2006) have discussed the nested grid technique. In this study, the method proposed by Aida is used. According to the figure 5.5.(a), the boundary of two

regions with two different grid sizes across X direction can be represented by free surface elevation and flux computed by the following equations;

$$H_{i,j}^{t+dt} = H_{i,j}^t - \frac{dt}{dx} \left[ P_{i+1,j}^{t+(dt/2)} - (P_{k,l}^{t+(dt/2)} + P_{k,l+1}^{t+(dt/2)})/2 + Q_{i,j+1}^{t+(dt/2)} - Q_{i,j}^{t+(dt/2)} \right] \quad Eq (11)$$

$$P_{k,l}^{t+(3dt/2)} = P_{k,l}^{t+(dt/2)} - g \frac{dt}{dx_2} \left[ d_{x,k,l} + (HB + \eta_{k-1,l})/2 \right] [HB - \eta_{k-1,l}] \quad Eq (12)$$

where,

$HB = (H_{i,j}^{t+dt} / 2) + (H_{i,j-1}^{t+dt} / 6) + \eta_{k-1,l}^{t+dt} / 3$  is given by linear interpolation of the free surface elevation.  $H, \eta$  are free surface elevations in coarse domain and fine domain, respectively. Similarly  $P$  and  $p$  are depth average flow in coarse domain and fine domain, respectively. Other notations are the same as previous.

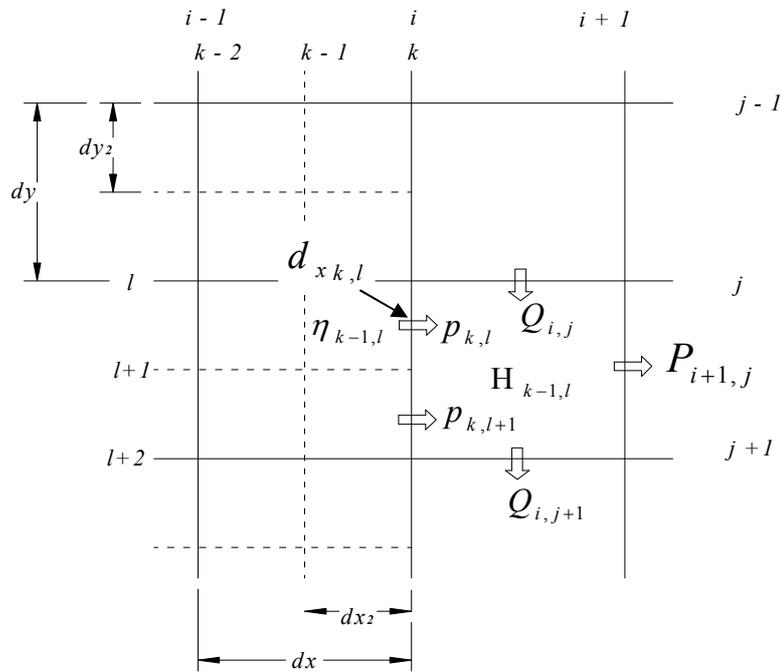
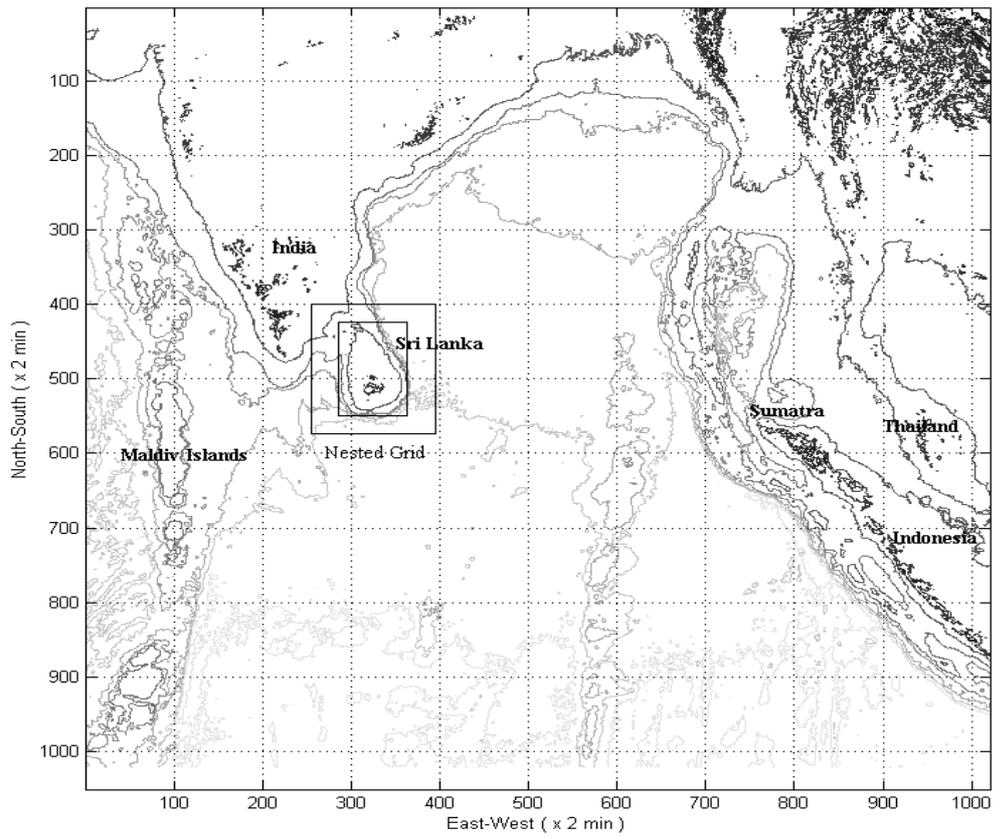
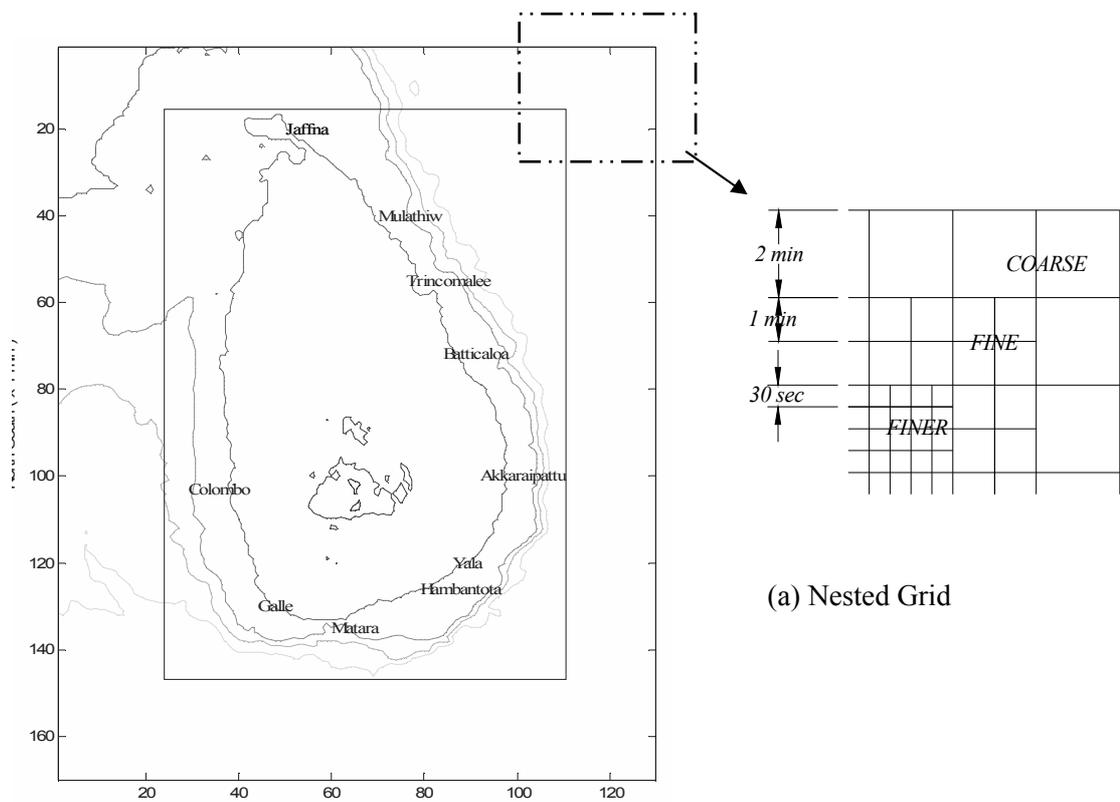


Fig 5.4: Notations of various quantities related to the boundary between two different grids in X direction.



(b) Arrangement of Main Grid



(a) Nested Grid

Fig 5.5 : Arrangement of Nested Grid inside the main Grid

**5.5. Model Input data**

Most importantly for any of the hydrodynamic modelers are the input data. In case of tsunami simulation it is essential to have a reasonably accurate bathymetry and correct tsunami initiation conditions. Even though the results of the numerical simulations are not up to the real life figures having appropriate boundary conditions and bathymetry would give a better result.

**5.5.1. Bathymetry, topological data**

The widely used ETOPO 2 global data by NOAA (2005) are used to generate the model bathymetry. For nested modelling, they ETOPO 2 data have been interpolated accordingly. For obtaining more reasonable calculation domain the interpolation has been done up to 30s. However it was clearly seen that interpolation beyond the 30s tends to distort the actual geometry around Sri Lanka.

Topological data was not required for propagation modelling since the land water boundary was considered as fixed and full reflective.

**5.5.2. Tsunami Generation in Sunda Trench (Sumatra)**

The most immediate method of finding the tsunami generation is the calculating the initial sea surface deformation at the time of earthquake triggered. Such Initial sea surface deformation in formation of tsunami has been studied by many scientists. Basically all the methods can be categorized as either inversion of wave heights based on observations at land, air or recorded by tide gauges. But this method has many limitations since it cannot be used for tsunamis generated considerably far from the observed locations. Number of observations or tidal recording stations and their location with respect to the initial tsunami generation location is also important. Second method is the most commonly used, which is based on the calculation of the sea bed deformation by the properties of the earths crust and energy released by the respective earthquake. This method also has limitations since the properties of the earth crust are not known exactly. Even though the estimation of the magnitude of the earthquake by inversion of seismic waves can be determined by fairly accurately, in case of multiple shocks followed by the main shock can not be clearly distinguished from the main shock. Another thing is it is assumed that water is incompressible and deformation of the sea bottom is almost equal to the sea surface deformation. However this assumption is not purely valid in case of a large water body undergoes large impact.

In order to represent the accurate tsunami initiation conditions it is required to represent the initial sea surface deformation by spatially (area and depth) and temporally. In terms of deriving initial condition wave inversion methods are advantageous over the seismological approach since what is already seen or observed (by air or tracked by satellite altimeter data) are more reliable than unseen deformation of the seabed. However the availability of the number of record stations or gauges and their resolution should be enough to derive reasonable result. Most of the gauges are originally meant

to record tidal variations of swell waves hence required correct filtering in deriving the sea surface variation only due to tsunami. Hence most of the researchers still rely on sea bottom deformation calculation based on elastic theory approach. The study by Okada (1985) is one of the commonly used models.

After 2004 Dec Sumatra tsunami, many scientists came up with different suggestions on how the tsunami was initiated near the Sumatra islands.

However the derivations of tsunami initiation condition by such complicated numerical methods are cumbersome and time consuming. Hence, in this research two initial conditions are used. One is proposed by Koshimura (2005) in his calculations in 2004 Dec, Sumatra tsunami. Other condition is based on the results of calculations using Sea surface deformation calculation model by Okada (1990). In these calculations, the data and results obtained by Namegaya(2005), Hirata(2005), Yamanaka (2005) and USGS (2004) have been referred.

Fig 10 gives the initial conditions calculated by Koshimura and based on the Okadas Model. Results obtained on each way have some difference in width and size of the initial sea surface deformation. It can not exactly say which result is better since both methods involved in assumptions on elastic properties on earth crust, which is not fully revealed yet. For both of the conditions hypocenter, strike, width and length of the fault was almost similar. Both the methods found that 2004 Dec Sumatra occurred in two main steps as the fault divides around Nicobar Islands.

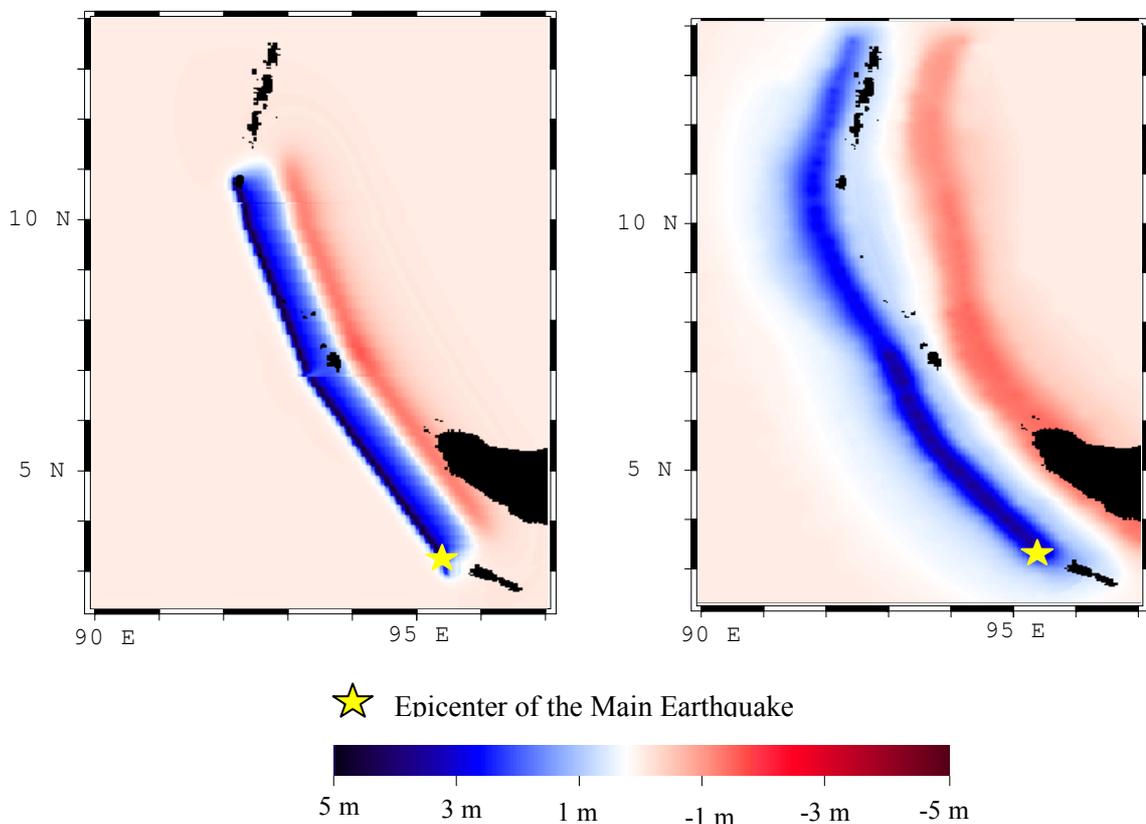


Fig 5.6.: Tsunami Initiation condition based on Koshimura (left) based on the Okadas model (right)

## 5.6. Results and comparison

As mentioned above objective of these calculations is to estimate the tsunami inundation heights, arrival times and potential risk for Sri Lanka in case of another tsunami incident.

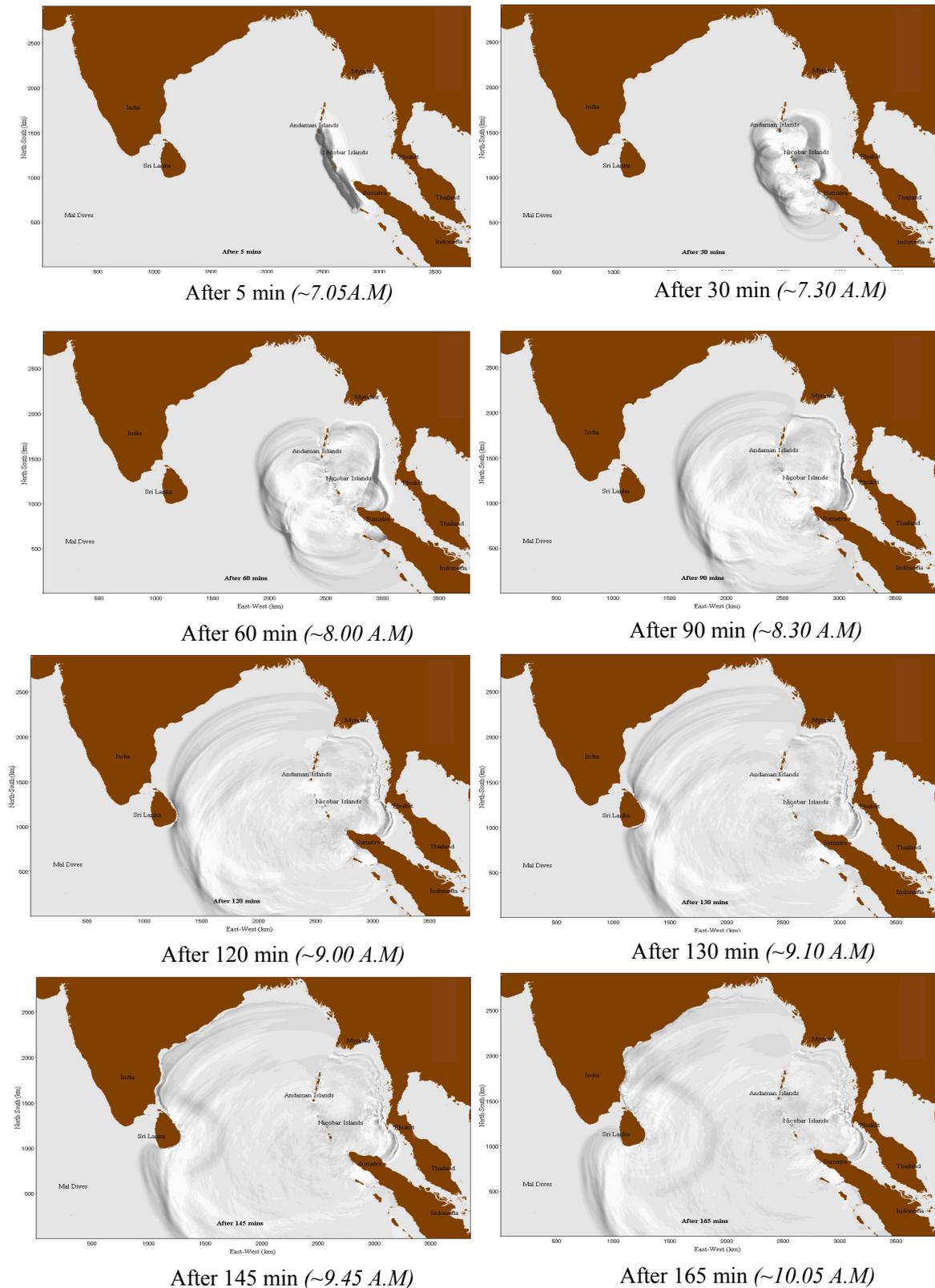


Fig 5.7: Arrival time of Tsunami (from the time of tsunami initiated at Sumatra)

5.6.1. Inundation heights observed

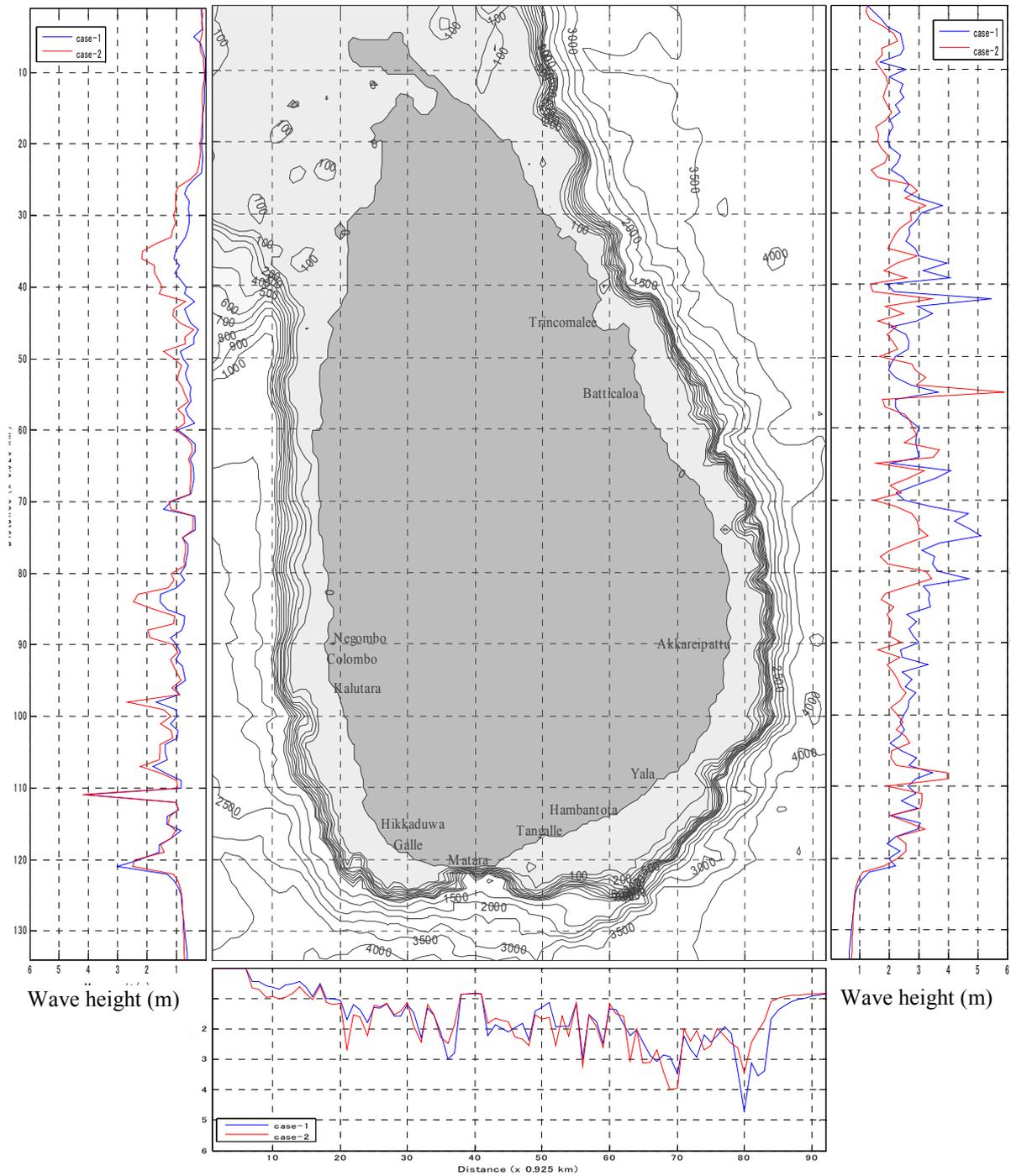


Fig 5.8.: Maximum inundation heights calculated based on two tsunami initiating conditions, by Koshimura and Okadas model.

Based on the fig 5.8, inundation heights calculated seems reasonable. Based on the two tsunami initiation conditions the condition derived by Koshimura gives higher values in some locations in south coast. Except for that both the conditions gives agreeable result.

The inundation heights are distributed as high in east coast and decaying towards west coast. Based on the results it can be said that most of the tsunami energy received in the east coast. However there

are some peaks of the observation can be seen in the south coast and west coast. Specially the Hambantota and around Galle and Hikkaduwa tsunami has been amplified tremendously. This can be explained as the formation of strong edge wave along the south west coast of Sri Lanka. Sudden draught in the tsunami height can be seen off coast of Dondra, which was found to be very steep and narrow.

### 5.6.2 Comparison of Inundation heights with Field Observations

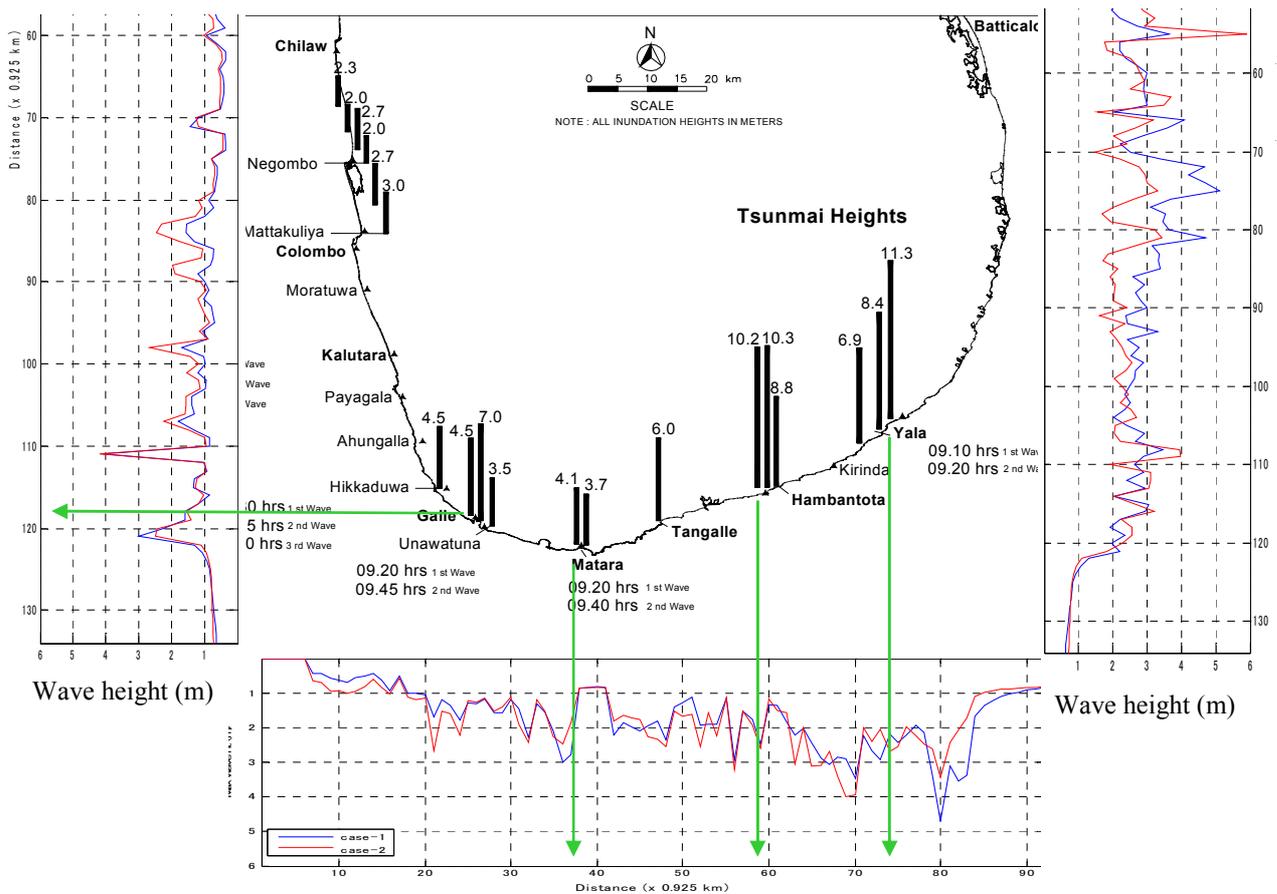


Fig 5.9: Comparison of Inundation heights calculated with inundation heights observed

When it compares calculated inundation heights with field measurements, it can be found that there is a good agreement of results in terms of the pattern of the tsunami height distribution. Which shows that high inundation heights around Hambantota and Yala. Heights were gradually decreasing towards the west of Sri Lanka. Also it can be seen that sudden increase of inundation heights around Galle and Hikkaduwa, which was same as similar to the field observations.

However when it compares the magnitude of inundation heights, it can be found that there is a significant difference between the magnitudes of the heights even though the pattern of the values was agreed with the measurements. Explanation for this can be the vertical acceleration of tsunami in

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the nearshore bathymetry, in fact which is not exactly represented by shallow water wave equations. Another reason is this numerical calculation does not treat tsunami run up on land. So that it under predicts inundation values calculated.

### **5.6.3 Tsunami deformation around Sri Lanka**

According to the chapter 3.0 it was found that near shore morphology of Sri Lanka had a great effect on deforming the tsunami waves around Sri Lanka. Those complicated deformation of tsunami can be express up to certain degree by calculating the tsunami velocities around Sri Lanka. Following figures show the variation of velocities around east coast, south coast and west coast at different time intervals.

#### **(a) East coast**

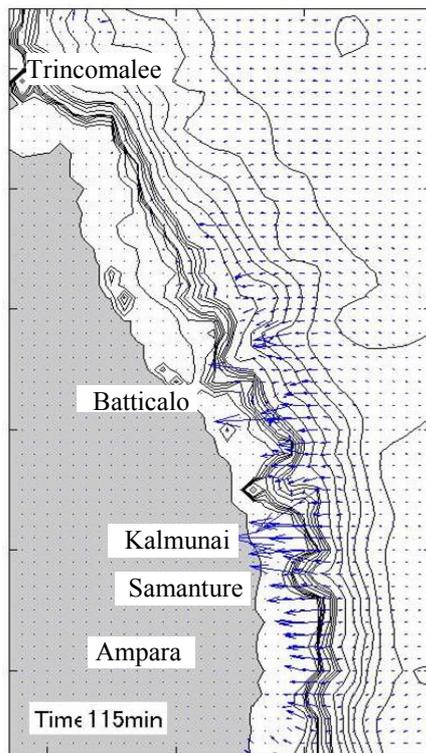
Based on the fig 5.10-(a) it can be seen that tsunami is directly approaching the east coast. However it can also be seen from fig 5.10-(b) and fig 5.10-(c) that most of the waves were reflected back towards sea. Meantime convergence of energy can be seen at valleys in the continental shelf. Such waves made high velocity vectors towards the land. Fig 5.10- (d) shows that even after 30 minutes of initial attack of tsunami, strong reflection take place at east coast of Sri Lanka.

#### **(b) South coast**

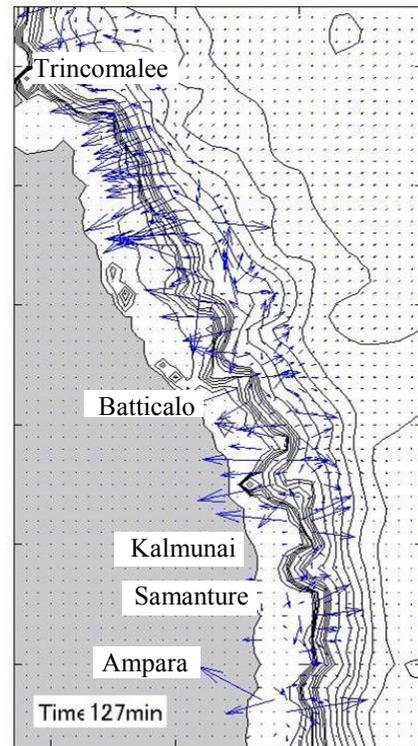
Tsunami arrival vectors are plotted in fig 5.11 .Based on those figures it can be seen that tsunami is refracting towards inland and focusing towards land (fig 5.11-(a)). Also it can be seen that such focusing of energy is highly local. that can be explained as one of the reasons for localized damages appeared in South coast. Such focused energy is reflected back into sea and move forward along the southern shelf (fig 5.11-(b)). Another important thing is 20 minutes after the initial arrival of the tsunami, there are no high velocity vectors visible around the south coast. (fig 5.11-(c)). So it explains that trapped waves were not static.

#### **(c) West coast**

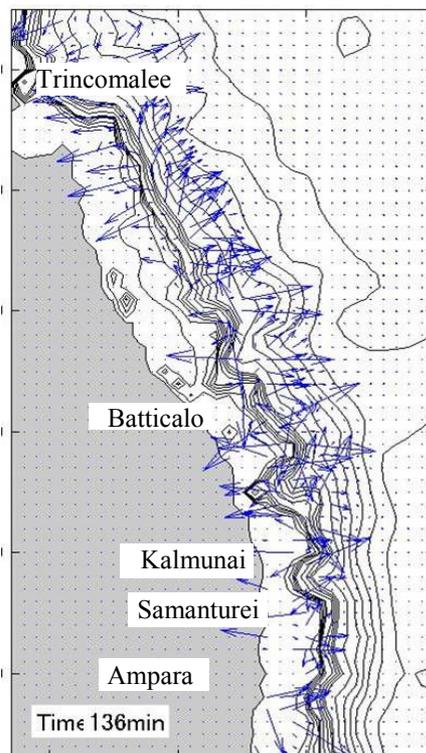
West coast found to be different than east and south coast in terms of tsunami deformation. Fig 5.12- (a) and fig 5.12-(b) shows that west cost experiences the trapped wave from the south coast. This is the strong formation of edge wave which create heavy damages in the west coast. Fig 5.12-(c) and fig 5.12-(d) shows that reflected waves reverse the direction and attack back in the west coast. This can be another specialty in west and south west coast where most of the people experienced multiple wave attacks during the tsunami. Since there is no effect from the direct propagating wave only edge wave and refracted wave are dominant in this area.



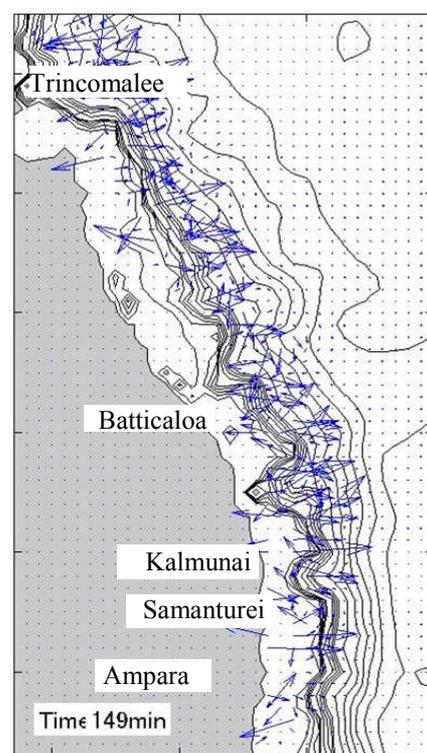
(a)



(b)

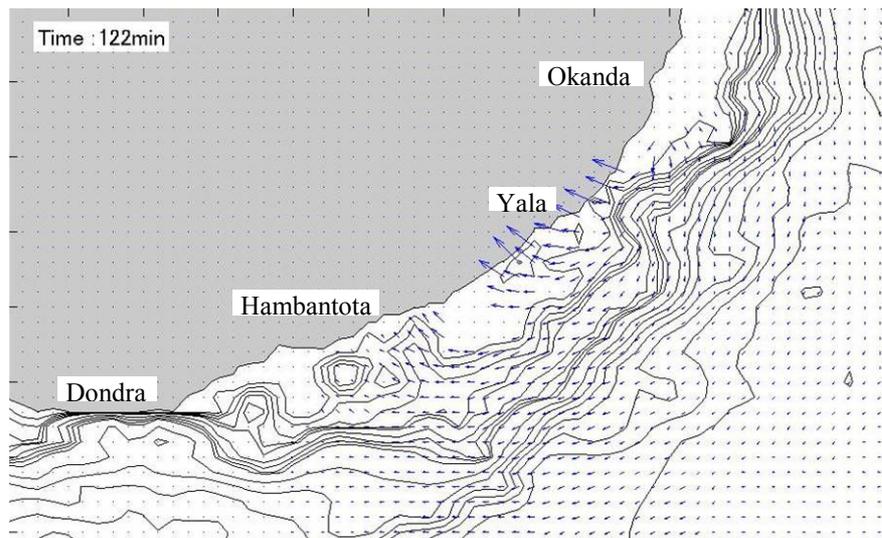


(c)

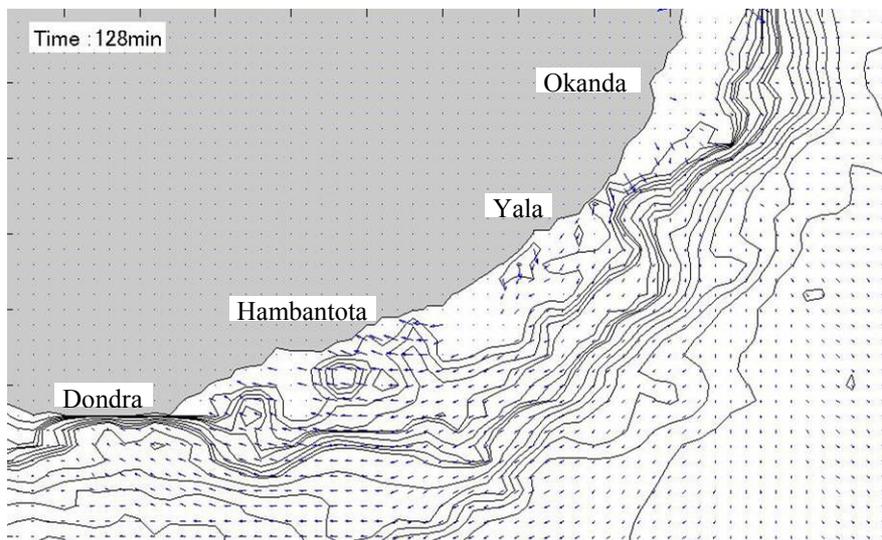


(d)

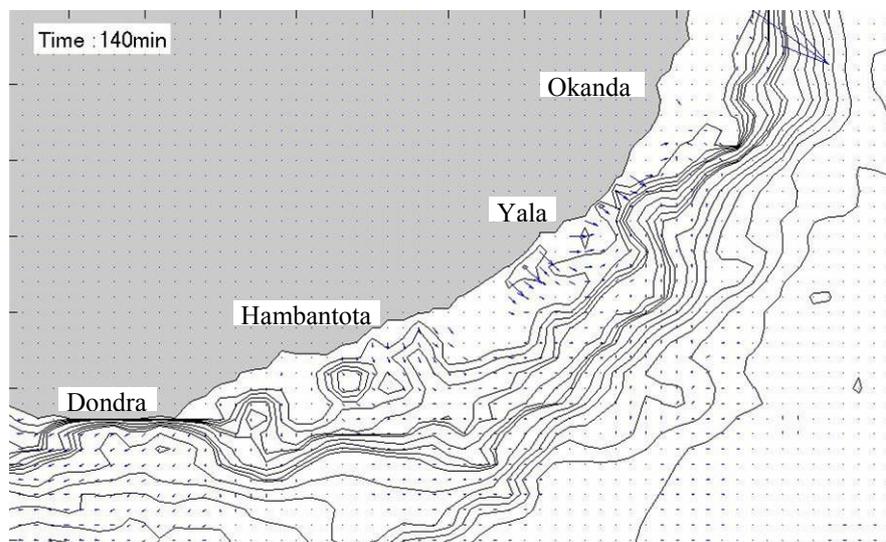
Fig 5.10: Tsunami Deformation in East Coast



(a)



(b)



(c)

Fig 5.11: Tsunami Arrival South Coast

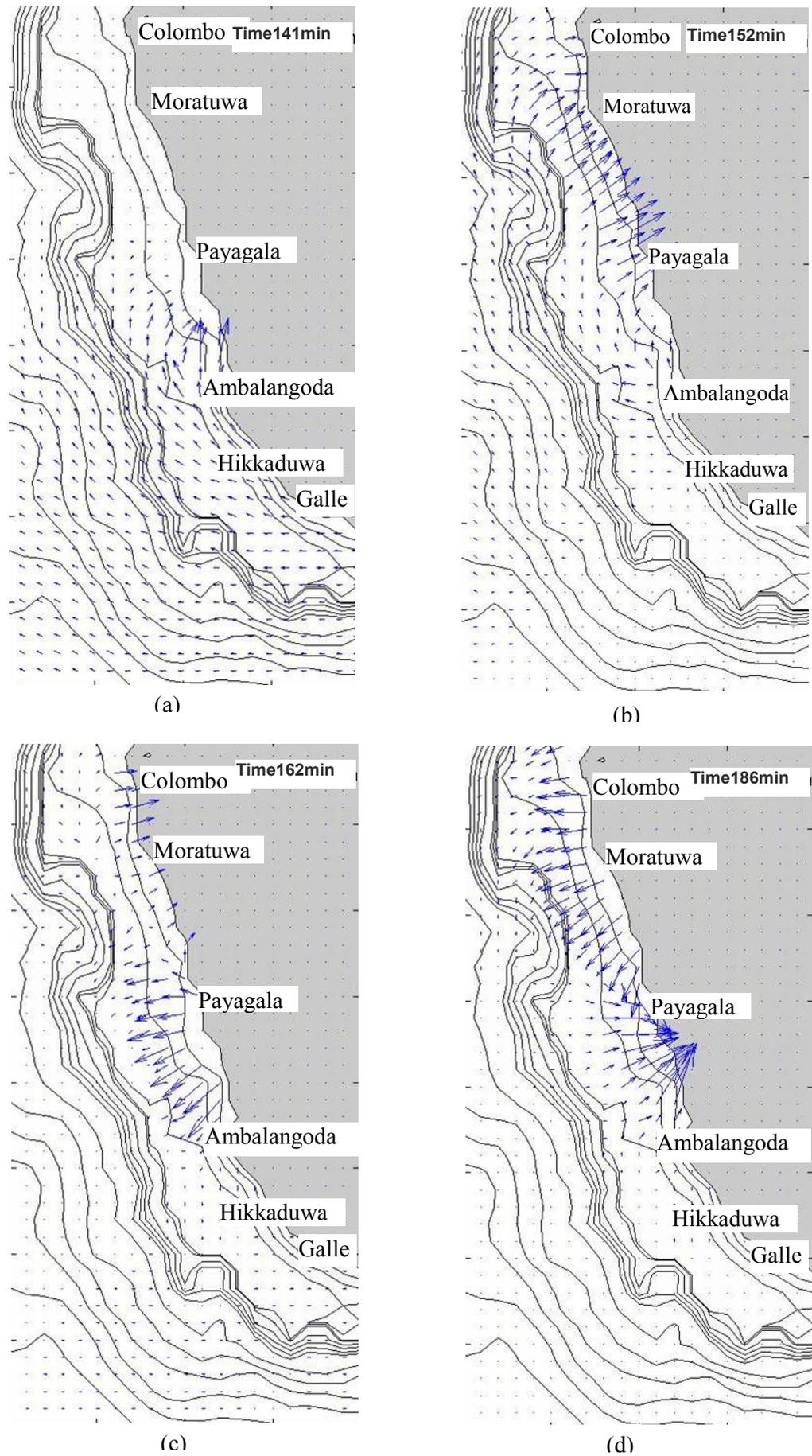


Fig 5.12 : Tsunami Arrival South West Coast

### 5.7 Reflection from Maldives Islands

Most of the Sri Lankans in the west coast experienced another big wave very much after the main tsunami attack. Even during the field observations the reason was not clearly explained. The one argument was the strong reflection from India made such a wave and another argument was the reflection from Maldives Island.

However based on the bathymetric data it can be seen that the narrow strip between the India and Sri Lanka is on the same continental shelf and depth is shallow and uniform. Hence most of the waves which passed the west coast and went to South India were dissipated. There was some turbulence experienced by some of the coastal inhabitants in the north of Negombo due this effect. However such kind of effect can not be considered as another separate wave. By numerical calculations of tsunami propagation across the Indian Ocean it can be seen that after 211 minutes of the occurring of the main shock there is a heavy reflection from Mal Dives. That reflected wave reached Sri Lankan west coast around 300 minutes of main shock. In other words it reached Sri Lanka around 12.00 noon which was exactly agreed with the many observers in the west coast. See following figure.

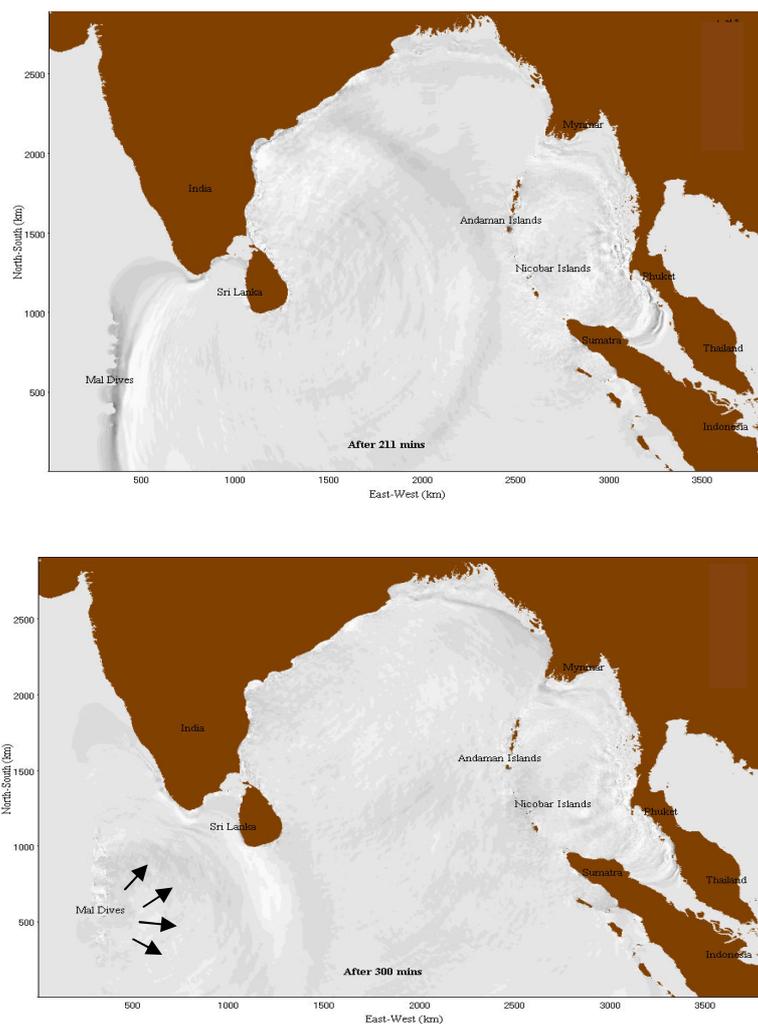


Fig 5.13: Effect of tsunami reflection from Maldives Islands.

### 5.8 Potential risk of tsunamis

It is obvious that last 2004 event was an extreme case not only for Sri Lanka but also in the global scale. It is really hard to predict whether such kind of a thing will repeat again in the same location. But after the last incident it was learnt that if such a scale tsunami is occurred, Sri Lanka will be in danger. By the previous results of numerical modelling of tsunami propagation in the Indian Ocean showed that high inundation values in Sri Lankan east coast, south coast and even further up to wet coast. Following figure shows the maximum water surface elevation distribution in Indian Ocean during the propagation of 2004 Dec tsunami. According to this result it can be said that energy of the wave rays has concentrated along two paths. Energy released from South of the propagated towards Maldives and some African countries. Energy released from the north of the fault has propagated directly towards Sri Lanka. From the following figure it is very much clear that Sri Lanka was heavily affected due to the tsunami generated from north of the fault.

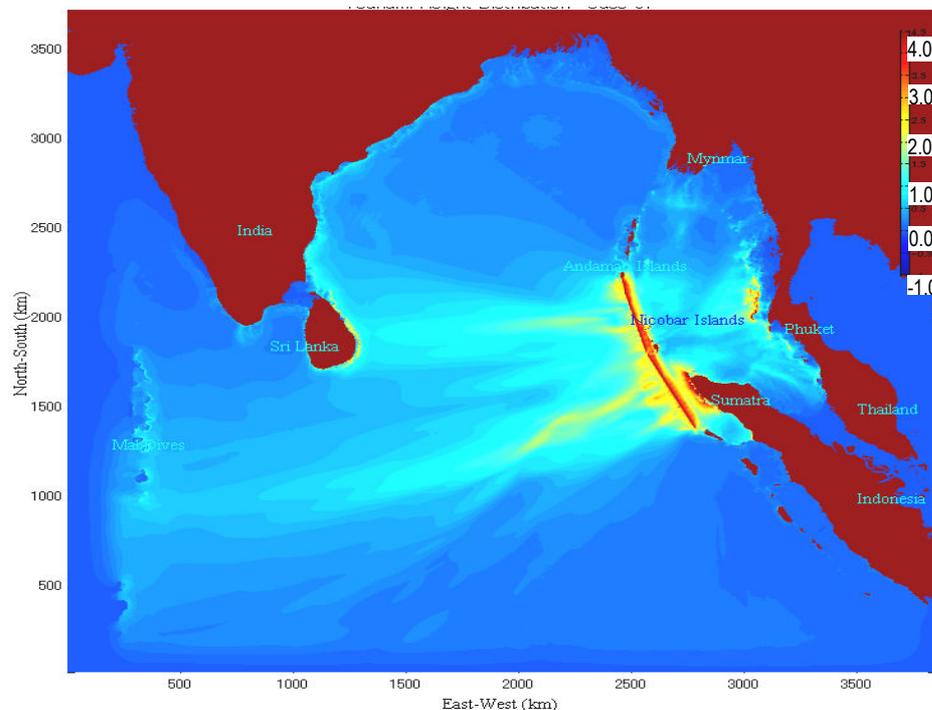


Fig 5.14: Maximum wave height distribution across the Indian Ocean during December 2004, Sumatra tsunami.

However from the following two case studies it is revealed that if a tsunami generated from south of the Sumatra, then the potential risk of tsunami damage to Sri Lanka is minimum. Following shows the maximum tsunami wave height distribution in the Indian Ocean due to 1833 off Sumatra earthquake and 2005 March Sumatra earthquake. 1833 event created a significant tsunami. However from the calculations it is evident that the effect to the Sri Lanka is a minimum. 2005 Sumatra earthquake tsunami was not so significant as 2004 even though the magnitude of the earthquake was of same order.

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**5.9 Other cases in west coast of Sumatra**

It is required to find out the effect on Sri Lanka for any other possibilities of tsunami attack from Sumatra direction. By referring the history of tsunamis around the Sumatra islands, it was found that Sunda trench was very active even in recent history. Most of the major tsunamis recorded in the southern part of the fault and very few in the northern (Except 2004 Dec). In this study two other cases were considered for finding the effect of a tsunami generated from Southern part of the Sunda trench.

1. 2005 March –Sumatra west coast Tsunami. (Magnitude 8.5)
2. 1833 Tsunami near Karakatoa Islands (magnitude 8.1)

Even the earthquake magnitudes were almost equivalent to the 2004 Dec Sumatra earthquake; the resultant tsunami was not so severe due to the depth of the location and direction of energy distribution. However the effect of the 2005 March even was clearly felt the Sri Lankan waters and it was recorded by NARA (Wijeratne, 2005). By referring to the history of natural disasters there was not such a record found in 1833.

Comparison of the inundation height distribution along the south coast and east coast showed that there are not significance wave heights (fig 5.17). However the wave heights in the south west coast are significant in comparison to the wave heights in the south and east coast. This reflects the ability of west continental shelf to catch the waves and form a trap wave.

However again it should be emphasized that Dec 2004 Sumatra was an exceptional incident and recurrence of such a scale disaster within recent years is highly unlikely.

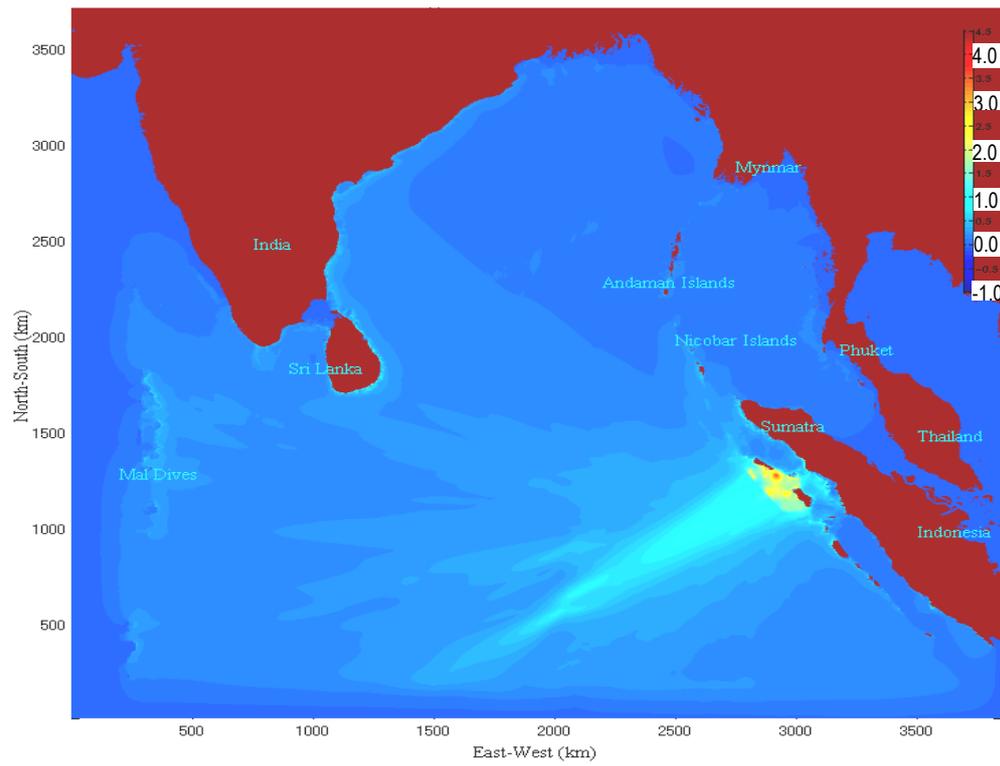


Fig 5.15: Maximum wave height distribution across the Indian Ocean during March, 2005, Off Sumatra tsunami.

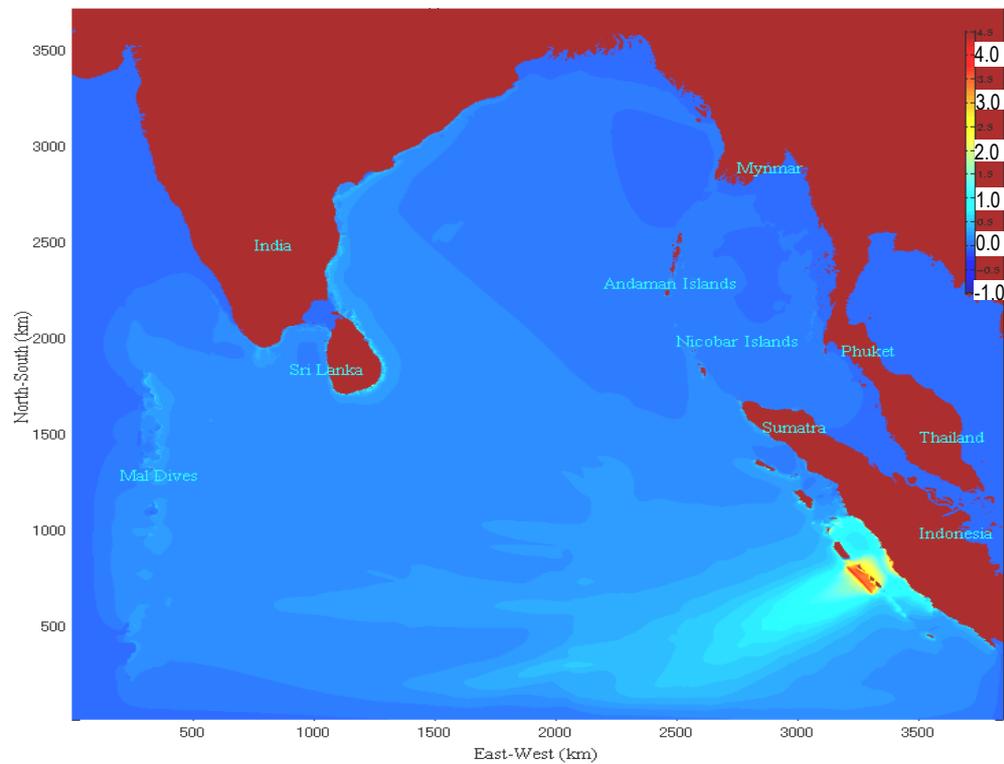


Fig 5.16: Maximum wave height distribution across the Indian Ocean during 1833, Karakatoa tsunami

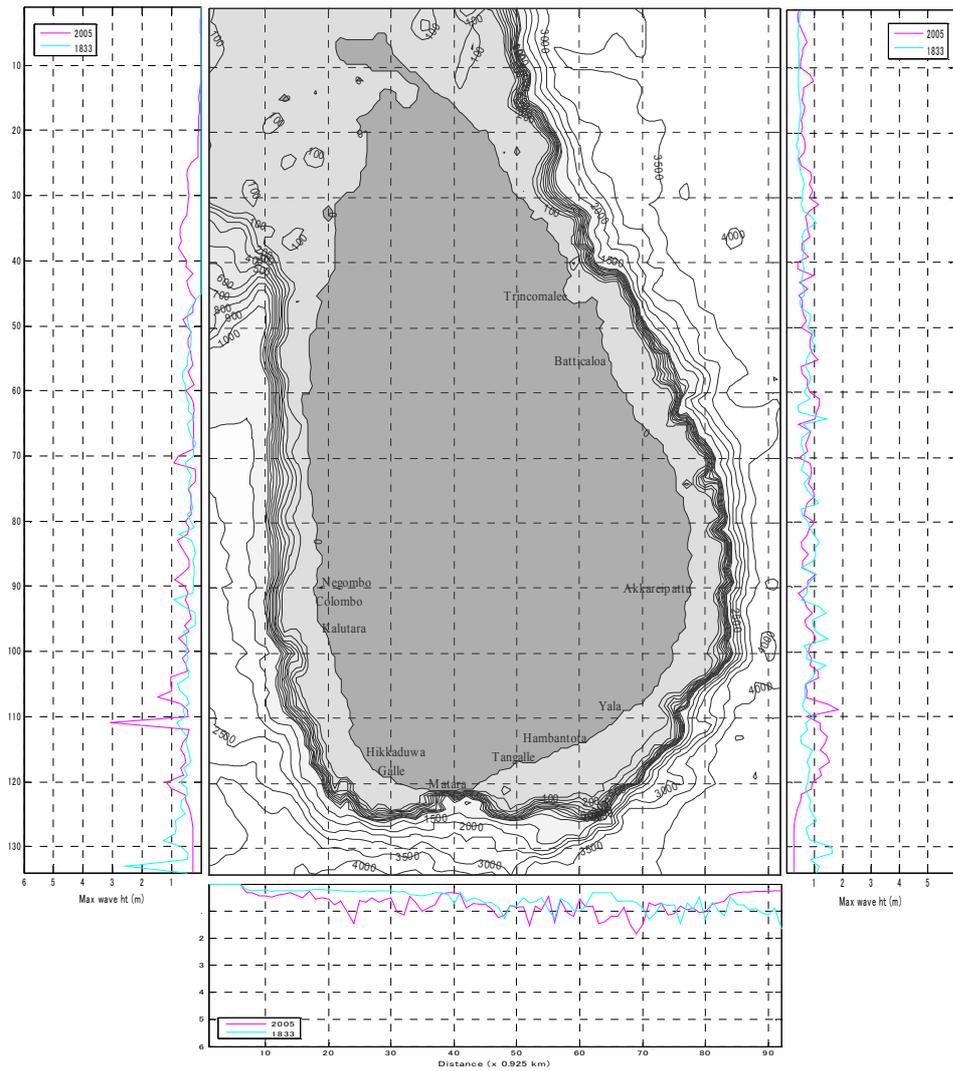


Fig 5.17: Results of the tsunami inundation due to March 2005 Sumatra tsunami (pearl color) and 1833 Karakatoa earthquake tsunami (light blue)

# **Chapter 6**

## **Summary, Conclusions and Recommendations**

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**6.1 Overall**

Based on the field observations and numerical calculations it is clear that Sri Lanka has a potential risk of tsunami in the Indian Ocean. Analysis of the damages showed that most of the coastal cities and communities were damaged due to undisturbed waves flushing inside the land. Inundations were severed by the existing topography and nearshore bathymetry. Summarising the field investigations it can be said that damages in the Sri Lankan coast were highly localized.

If we consider the east coast, most of the energy was reflected back into the ocean. However the fraction which transmitted into land made heavy damages even 2 km inside the land. But in south east south coast, the tsunami was propagated parallel or slightly oblique to the continental shelf which is in fact having the ideal shape for shoaling. Hence waves refracted towards were further amplified by the shelf to make more than 10 m inundation heights. Further it can be seen that waves were not trapped so long in the south and south east coast since most of the trapped energy was reflected back and forward towards to west side. Such reflected waves again trapped with the incident waves from deep ocean and converged towards south and west of Sri Lanka.

Refracted waves in the southwest coast acted differently from that of Hambantota and Yala. Since most of the energy attempt to more and more concentrate and made a strong edge wave. This in fact, made some further points of south west coast completely inundate and destroyed. Specially referring to the incident wave directions in Hikkaduwa, it can be seen that multiple waves reached Hikkaduwa. Such incident can not be easily understood without proper numerical analysis of edge waves coupled with accurate nearshore morphological data.

Also by referring to the other tsunamis in the Indian Ocean, it can be concluded that there is a less risk of tsunamis which take place south of the Simule Islands in Indonesia. However compared to the Dec 2004 event most of the past event were not so exceptional.

**6.2 Hikkaduwa**

Hikkaduwa can be considered as area which has experienced the effect of strong edge waves formed in the south west continental shelf. Based on the field observations it is clear that Hikkaduwa has experienced several waves, approached in several directions. Analysis of detailed inundation heights in the Hikkaduwa showed that there was a significant effect of the topography of the Hikkaduwa. Then further it can be seen there was an effect in Hikkaduwa breakwater in attenuating waves. However headland effect of south of Hikkaduwa create significant local damage and which was further accelerated by canal mouth open to sea.

Effect of the river mouth can not be seen as the cause of severe damages in the north of Hikkaduwa anyhow the north of Hikkaduwa was found to be low-lying. Most of the waves attacked the Hikkaduwa flooded in the low-line areas and water was trapped in those areas for considerable

before it actually draws off.

Another important observation made in the Hikkaduwa was the effect of the series of hotels which is lying in the south of the Hikkaduwa. Those hotels were severely attacked by the tsunami hence most of the energy was dissipated before the water flooded inside. The effect of the hotels can be found by detail inundation modelling which can accommodate such kind of buildings.

It summary it can be said that Hikkaduwa was attacked by several waves coming different directions. This was the effect of strong trap wave generated in South west coast. Hence it is difficult to judge which structure is more effective in dissipation of waves. Having a water body connected to sea facilitates a higher flow towards inland. So effect of the Hikkaduwa river should be considerable.

### **6.3 Recommendations**

It is strongly recommended further research studies are required to understand the complex damage pattern in the Sri Lankan south west coast. Special focus should be given to edge wave formation and calculation of energy trapped in the southwest coast. Existing depth averaged hydrodynamic models and techniques are not sufficient to understand such a complex mechanism.

The available morphological data in Sri Lanka are not sufficient to study the detailed inundation models and calculation of tsunami amplification in the nearshore. It is recommended to have a more reliable and finer bathymetry data in nearshore in areas like Hikkaduwa, Galle and Hambantota.

Inundation calculations are very important in preparing hazard maps for disaster preparedness. Especially the areas where heavily populated should be studied by inundation models, which can calculate the high risk areas and high vulnerable areas. At present only very few studies have done in this area due to the lack of knowledge of proper tsunami inundation models.

In addition to the research work, as an immediate disaster preparation and prevention action, Sri Lanka should set up a reliable public warning system which is connected with a central tsunami monitoring network. If Sri Lanka had such a system, more than 30,000 lives could have saved in December 2004. Advantageous point for Sri Lanka is tsunami takes at least one and half hours to propagate from Sumatra to Sri Lanka even at worse conditions. Hence public warning system can be considered as the top priority in disaster prevention.

Going beyond the public warning systems, natural tsunami protection systems can be used in most of the suburbanized areas in south and east coast. Natural sand dunes, mangroves or combination of them can be used for effective prevention. (Example Yala, Hambantota). This method can be used in urbanized areas by reclamation of the sea and artificially setting up dunes. However as for many other development works in the coastal zone it should be considered the multiple interests of integrated users.

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