The Indian Ocean Tsunami of 26 December 2004: Mission Findings in Sri Lanka and Thailand

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February 2006

ISBN 0 901297 41 0

EEFIT gratefully acknowledges the support of its corporate members:
Arup Group
British Geological Survey
BNFL
CREA Consultants
Giffords
Halcrow
Risk Management Solutions

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Preface

Preamble

On the 26th December 2004 the western world awoke to the news that a great earthquake had occurred on the northern edge of Sumatra. This earthquake caused a series of tsunami waves that spread across the Indian Ocean crashing with enormous power on the shores of several countries, affecting locations both near and far from the epicentre. Initial life loss estimates were of the order of 1,500, but as the days passed it became apparent that this was a tragedy of immense proportions. By New Year's Eve the death toll estimates exceeded 100,000 and were continuing to rise dramatically. People across the world watched in disbelief as television channels transmitted video after video of giant waves crashing onto shores. Such basin-wide tsunami events are rare and the world had not experienced one since the great earthquake off Chile in 1960 when several nations around the Pacific Ocean shores including Japan, were affected. Such events are even less frequent in the Indian Ocean where the last basin-wide tsunami occurred in 1883 after the catastrophic volcanic eruption of Krakatau in the Sunda Strait.

The EEFIT Mission

EEFIT responded to this crisis by issuing a call for volunteers for a field mission to some of the affected regions to its wider membership on January 5, 2005. By the 11th January 2005 sufficient interest was raised amongst engineers and academics for the EEFIT committee to officially announce the launch of the mission. The field team was assembled by January 17th and the mission departed from Europe on January 21st with the last member of the team returning to Europe on February 2nd.

Team formation and itinerary

The members composing the Indian Ocean Tsunami Field Investigation Team (IOFIT) are presented in Table 1.1, Figures 1.1 and 1.2. After deliberation amongst team members it was decided that IOFIT would visit Sri Lanka and Thailand. Consideration was given to visiting the region of Banda Aceh in Indonesia but this eventually proved impossible due to the difficulties in finding local support. Considering the fact that two countries were to be visited, the mission was organized in two parts, some members visiting only one of the countries whilst others visiting both, as shown in the Table 1.1 below.

The mission in Sri Lanka took place between the 22nd and 26th January 2005, whilst that in Thailand took place between the 27th January and 1st February 2005. In Sri Lanka it was decided to visit the region between Colombo and the country's southernmost city of Dhondra (i.e. the Western and Southern districts). It was not possible to visit the Eastern and Northern districts that were also severely affected due to lack of time and the large distances involved. In Thailand the team surveyed most of the worst affected regions, mainly concentrating on the western coast of Phuket island, the island of Koh Phi Phi and the region of Khao Lak in mainland Thailand (Phang Nga province). It was not possible to visit the affected coastline of the Krabi province due to the large distances involved.

Table 1.1: The EEFIT Team.

Team Member	Affiliation	Countries Visited	Areas of Expertise
Antonios Pomonis (Team Leader)	Risk Management Solutions	Sri Lanka and Thailand	Earthquake Engineering, Risk Assessment, Structural Vulnerability, Natural Hazards and the Built-Environment
Dr Tiziana Rossetto	University College London	Sri Lanka and Thailand	Earthquake Engineering, Risk Assessment, Structural Vulnerability
Dr Sean Wilkinson	University of Newcastle	Sri Lanka and Thailand	Earthquake Engineering, Design of High-rise structures
Domenico del Re	Buro Happold	Sri Lanka and Thailand	Structural Engineering, Risk Assessment
Dr. Navin Peiris	Arup, UK	Sri Lanka	Geotechnical Engineering, Earthquake Engineering, Risk Assessment, Sri Lanka national
Dr Stewart Gallogher	Halcrow	Sri Lanka	Geotechnical Engineering
Raymond Koo	Arup, Hong Kong	Thailand	Geotechnical Engineering
Raul Manlapig	Arup, Philippines	Thailand	Structural Engineering

Figure 1.1: The EEFIT Team in Sri Lanka.

Figure 1.2: The EEFIT Team in Thailand.

Mission objectives and methodology

The general aims of EEFIT may be seen in the following web site: www.eefit.org.uk. The specific aims of the Indian Ocean Tsunami Field investigation were as follows:

- To investigate the building practice and design codes in Sri Lanka and Thailand
- To survey the damage to different types of buildings. In Sri Lanka the performance of vernacular housing, as well as several other buildings and industries were investigated. In Thailand the investigation focused on the performance of hotel structures.
- To investigate the performance of lifelines in the two countries.
- To collect perishable data on the height and other physical attributes of the tsunami waves and relate these to the findings of other missions.
- To understand the vulnerability of coastal settlements and building types to tsunami waves through detailed damage surveys and on-site tsunami attribute assessments.
- To investigate the human casualty patterns in relation to tsunami heights.
- To investigate the effects of coastal bathymetry on tsunami.
- To relate the tsunami to the seismotectonic aspects of this great earthquake.

To publish on the web a preliminary report on the key findings of the mission (this was posted on the EEFIT and EERI web sites on February 20, 2005)

Report Structure

In this report a general introduction to the December 26, 2004 Sumatra earthquake and tsunami is given in Chapter 1. The mechanism of the event, the plate tectonics, seismology and historical seismicity of the epicentral region are discussed. A brief overview of the effects of the ground shaking and tsunami in Indonesia (where almost three quarters of the life loss occurred) and other countries around the Indian Ocean Basin is also given.

Chapters 2 and 3 present in detail the observations made by the EEFIT Team during the field mission in Sri Lanka and Thailand, respectively. Within these Chapters the observed performance of lifelines and different types of buildings is discussed. Detailed building damage and tsunami water height surveys made on-site by the Team are presented, and local building codes and construction practice are discussed. A new tsunami Intensity scale is proposed and used to compare the degree of building damage observed in the two countries. The economic and social impact of the tsunami on these countries is also discussed.

Finally, in the last section, conclusions drawn from the field mission observations are summarised and recommendations are made for the reduction of future losses due to large tsunami events.

Acknowledgements

The IOFIT Team would like to express their thanks to Dr Dina D'Ayala of Bath University for her insightful comments and review of this EEFIT Report.

1 Overview of the 26 December 2004 earthquake and tsunami and its effects

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1.1 Introduction

On the 26th December 2004 at 00:58:53 GMT (7:58:53 am local time) an enourmous earthquake occurred off the west coast of northern Sumatra, Indonesia, which cd across the Indian Ocean causing damage and life loss in 11 countries. The earthquake, initially reported by the United States Geological Survey (USGS) to have had a moment magnitude (M_W) 9.0, has now been attributed a moment magnitude (M_W) 9.3 (i.e. 2.5 times greater energy release, Stein and Okal, 2005). The Boxing Day 2004 earthquake was the second biggest earthquake to have ever been recorded, surpassed only by the M_W 9.6, 1960 Chile earthquake. The associated ground shaking caused damage to buildings in Banda Aceh, Indonesia, and was felt in many of the countries that were subsequently devastated by the tsunami waves.

In the following sections the initial misinterpretation of the earthquake magnitude and its influence on the tsunami prediction is discussed. The tectonics of the Sumatran region and the historical seismicity and tsunamis of the area are presented. The Boxing Day 2004 earthquake event and tsunami formation are described and an overview of the damage caused by the ground shaking and tsunami to Indonesia and other countries arround the Indian Ocean Basin is given. References for further reading are given for readers who wish to learn more about the effects of the tsunami in these countries. Finally the overall effects of the tsunami in terms of human casualties, economic losses, disaster management and tsunami warning in the affected regions is described.

1.2 The Earthquake Event

1.2.1 The Earthquake Magnitude

The December 26, 2004 earthquake is one of the largest earthquakes ever recorded on Earth. This event has inspired research into better techniques for the estimation of the seismic moment and magnitude of large earthquakes, in order to improve the rapid magnitude estimation for future tsunamigenic earthquakes. The conventional method used by USGS to estimate earthquake magnitudes is based on the Harvard Centroid Moment Tensor solution. This uses seismic surface waves with periods up to 300 seconds (www.seismology.harvard.edu/projects/CMT) and is adequate for the magnitude estimation of all but the largest events. However this method does not consider the contribution to energy release of longer period waves, as are emitted by very large events. Stein and Okal (2005) used an analysis technique developed 30 years ago (but not used to date due to the very rare occurrence of such large earthquakes), to include ultra-long period waves of up to 3200 seconds in the earthquake seismic moment calculation. By analysing 7 seismograms of the event measured around the world, they found that a large amount of energy was released in the very long period range. They believe that this is due to the very slow slip-rate of the northern part of the rupture zone of the earthquake. They also suggest that this slow slip area contributed to exciting the tsunami (see section 1.4).

The seismologists' preferred measure of earthquake size (Jackson, 2001) is the *seismic moment* (M_0) defined as:

$$M_0 = \mu A \bar{u}$$

where μ is the rigidity of the faulted rock (typically about 3 x 10^{10} Nm^{-2} in the earth's crust), A is the fault rupture area (in m^2) and ū is the average slip on the fault (in metres). The seismic moment has a physical meaning that can be easily understood, and can be calculated from parameters directly derived from seismograms recorded far from the earthquake. As its values are unwieldy e.g. the 2004 earthquake would have a seismic moment of ~ 10^{24} N·m or ~ 10^{30} dyn·cm based on Stein and Okal (2005), the *moment magnitude* was introduced by Kanamori (1977):

$$M_W = 2/3 \log_{10} M_o - 10.73$$

(where the seismic moment (M_o) is measured in dyn·cm) to provide a measure of magnitude consistent with other older magnitude scales. Moment magnitude provides a more reliable estimation of the size of large earthquakes than the previously used *Richter magnitude* (originally proposed in 1935, and denoted by M_L) and its subsequently developed equivalents of *surface wave and body wave magnitude* (M_S and m_b, respectively). Body waves are waves that travel through the earth's interior with a period of 1 second and surface waves travel along the earth's surface with a period of 20 seconds. Both of these magnitude scales saturate once earthquakes exceed a certain size (6.5 for the body waves and 8.4 for the surface waves). This happens because very large earthquakes release much of their energy at longer periods.

The process of earthquake magnitude determination has a great bearing on the subject of tsunami warnings because it is known that significant tsunami are only generated by large earthquakes (usually of moment magnitude above 7.5). Body and surface waves travel far faster than tsunami waves giving seismologists a short window of time in which to assess the magnitude of the earthquake and decide whether a tsunami warning should be issued. On December 26, 2004, earth scientists only realized that this was an extremely large earthquake when the aftershock pattern emerged. The Pacific Tsunami Warning Center in Hawaii, announced that this was a magnitude 8 earthquake 15 minutes after its occurrence and just 10-15 minutes before waves crashed onto the Aceh province's western shores. Harvard University's calculation of moment magnitude 8.9 was issued 4.5 hours after the occurrence of the event (USGS is due to get this Harvard technology in 2005), by which time the tsunami waves had travelled past the Maldives and were on their way to the Seychelles and Somalia.

According to Petersen et al. (2004) the average return period of an earthquake of this magnitude in the whole of the Sumatra subduction zone is believed to be 250-300 years which would mean that the return period in the northern segment that ruptured in December 2004 would be even longer. Using the earthquake catalogue of Petersen et al. (2004), Thio et al. (2005) propose that the December 26, 2004 tsunami was an approximately 500 to 1,000 year event. Further research is needed to better determine the seismic hazard in the Sumatra subduction zone and the tsunami hazard in the various coastal regions of the Indian Ocean.

1.2.2 The Earthquake Rupture Zone and Tectonics

The geological causes of this event can be traced back over 120 million years to when the southern super-continent of Gondwanaland split up. The subcontinent of India separated from Antarctica and began its steady motion northward. About 50 million years ago it collided with Asia, raising the Himalayas and forming the Tibetan plateau. The plate collision continues today as the Indian plate moves northward. The south-eastern continuation of the Himalayan plate boundary extends along the west coast of Myanmar to link across the Andaman Sea with the subduction zone that underlies the island of Sumatra.

The plate boundary extends along the Sunda Trench on the west coast of Sumatra, where the 26th December 2004 earthquake fault rupture was initiated. Along this trench an oceanic part of the Indian plate subducts beneath the Burma plate. The Burma plate is a small sliver (or microplate) between the Indian plate and the Sunda plate that contains much of Southeast Asia. At this location the Indian Ocean floor (Indian Ocean plate) is moving in a general north-east direction at an average rate of 6 cm/year relative to the huge Eurasian plate and at a rate of 2cm/year with respect to the Burma microplate (known from global positioning satellite data, USGS). This subduction zone is one of the most seismically active regions in the world. Four earthquakes with M_w>8 have occurred in the region within the last two centuries, including the recent M_w8.7 event on the 28th March 2005. The tectonic setting of this region is shown in Figure 1.3.

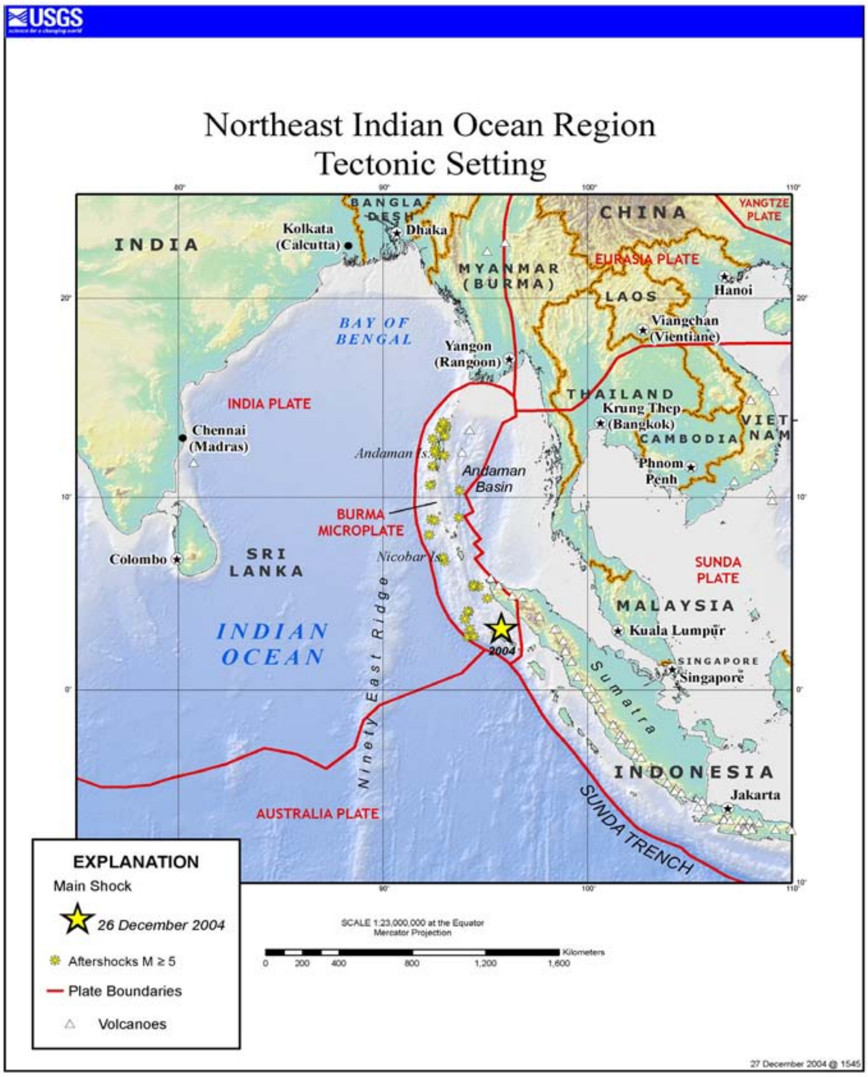


Figure 1.3: General tectonic setting in the north-eastern part of the Indian Ocean (Source: USGS)

The epicentral coordinates are estimated at 3.308^0 N and 95.874^0 E (Source: http://earthquake.usgs.gov/eqinthenews/2004/usslav/) or 3.09^0 N and 94.26^0 E (Source: EERI Newsletter, March 2005), approximately 250km offshore of the western Sumatra coast. The fault rupture initiated at a depth of approximately 30 km and propagated to the surface between the interface of the subducting Indian plate and overriding Burma microplate. The distribution of aftershocks recorded in the hours and days following the main event revealed a very large rupture zone. The fault rupture, illustrated in Figure 1.4, is 150-200 km wide and extends from the continental rift to the south of the epicentre to the Andaman Island chain 1250 km north of the epicentre.

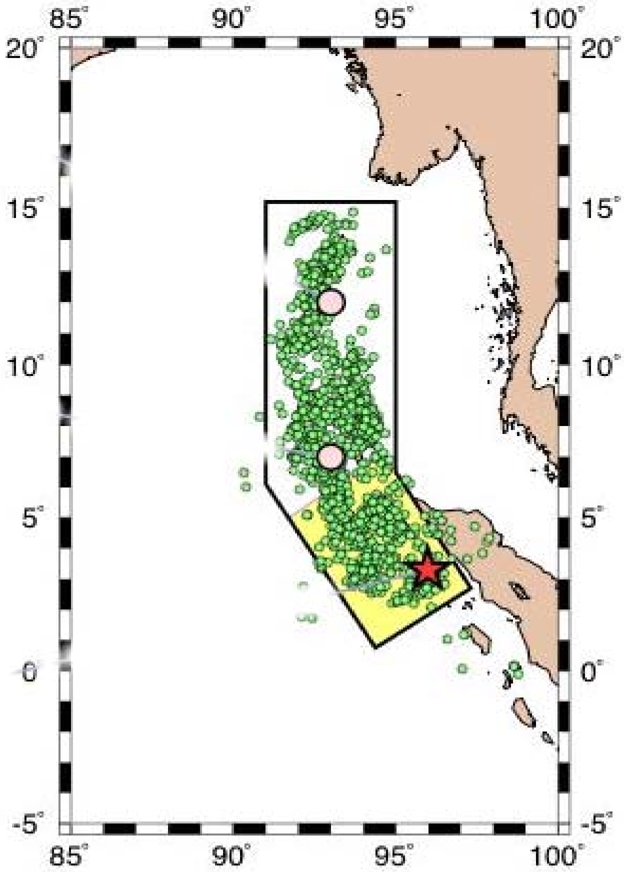


Figure 1.4: The epicentral location of the M_w9.3 Indian Ocean Earthquake of 26th December 2004 (with aftershocks up to February 20, 2005). Shaded area is the zone of fast slip defined from the body wave analysis. (Source: http://www.earth.northwestern.edu/people/seth/research/sumatra.html).

A fault rupture of this magnitude that effectively involved almost the entire Burma microplate resulted in a significant change in the local topography. As the Indian plate attempts to pass beneath the Burma microplate, interlocking at their interface causes deformation stresses to accumulate. Over time this has the effect of "dragging down" the overriding plate (the Burma microplate) at the interface and "lifting it up" further inland. When the earthquake occurs the accumulated energy is released and the overriding plate can be considered to "spring back". There is a consequent downward movement of the ground inland and an uplift of the ground at the plate interface (see Figure 1.5). These vertical movements are accompanied by a general horizontal movement of the deformed sections of the overriding plate towards the trench line. It is the vertical movement that displaces the overlying water column to produce the tsunami. NASA estimated this vertical movement to have been 5 metres at the plate interface east of the Sunda trench (http://earthobservatory.nasa.gov/NaturalHazards). Coral terraces present along the west coast of Sumatra are evidence of the repeated uplift and subsidence of the overriding plate. Studies are being carried out to determine the historical frequency of occurrence of large earthquakes and tsunamis in this region through observation of the growth patterns and U-Th[1] dating of coral microattols in the region (Sieh et al. 2004). Evidence of the scale of the deformation associated with the Boxing Day earthquake can be seen from preliminary GPS readings made by the Geophysical Institute, who recorded a distancing of the Eastern coast of Sumatra from Singapore on the day of the earthquake, (Source: http://www.pmel.noaa.gov/tsunami/sumatra20041226.html). Figure 1.6 shows that Sumatra, which lies closer to the Sunda trench, underwent a sudden south-westerly movement of approximately 11cm with respect to Singapore, consistent with the concept of a return of the deformed section of the Burma microplate to its undeformed position (i.e. the horizontal translation

[1] U-Th is a radioactive isotope that is retained in limestone and corals and its decay is used to derive the age of the corals.

mentioned above). It is expected that areas of the Burma microplate closer to the trench-line would have undergone much larger movements.

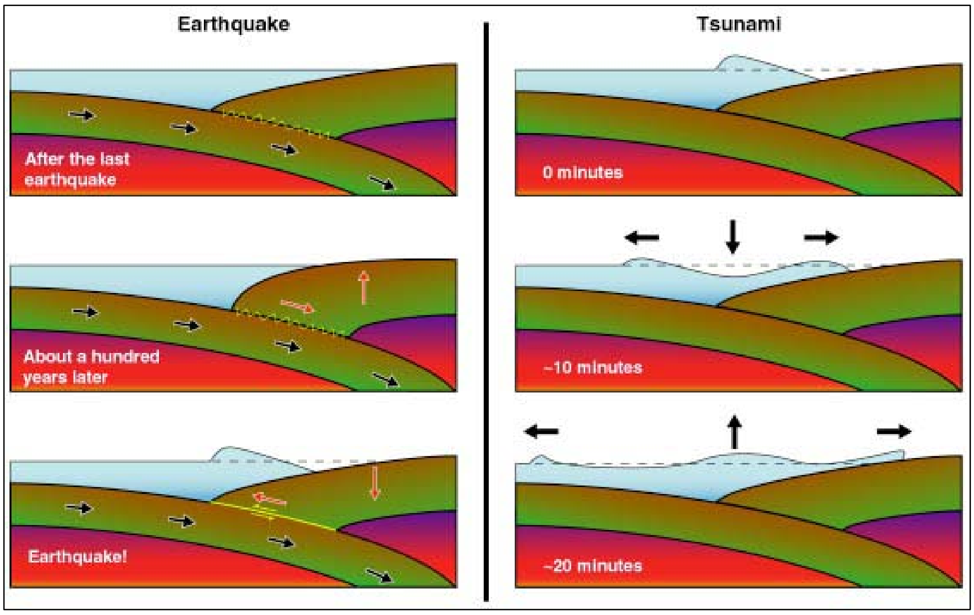


Figure 1.5: Diagrammatical explanation of the formation of a tsunami and associated subduction zone plate movements (Source: http://www.soest.hawaii.edu/tsunami).

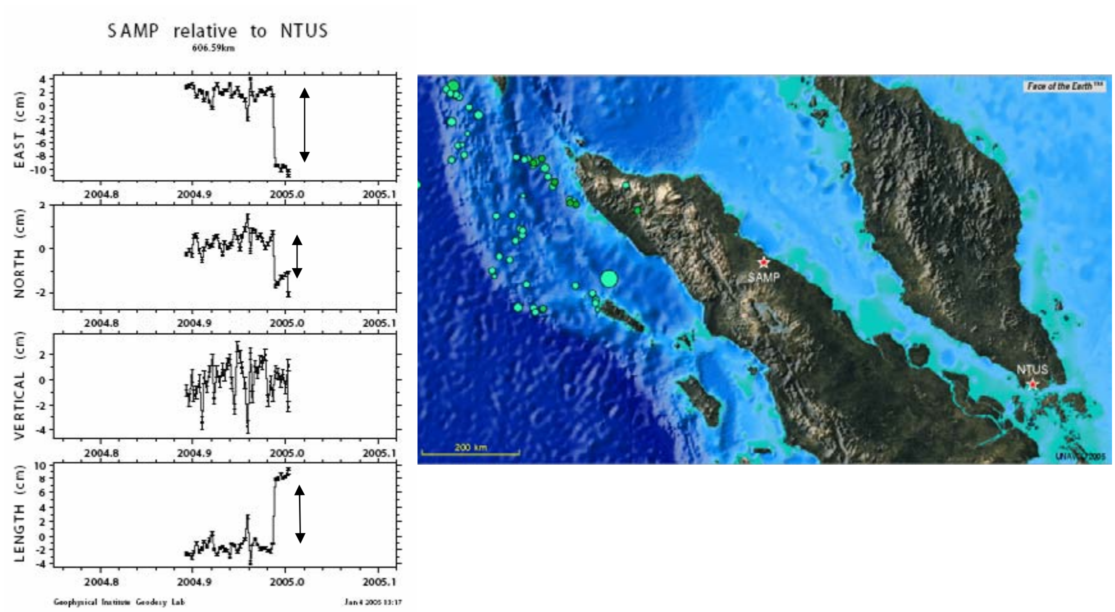


Figure 1.6: Preliminary geodetic strain readings show a relative movement of the Island of Sumatra eastwards from Singapore. This correlates with the theory of overriding tectonic plate “spring back” at the time of the earthquake (Source: Geophysical Institute Geodesy Lab, http://www.pmel.noaa.gov/tsunami/sumatra20041226.html).

Soon after the earthquake some controversy arose regarding the size of the rupture zone (Sieh, 2005). Although the aftershock distribution clearly suggested the rupture zone described above, analyses of seismic body-waves indicated that the rupture zone was only 400 km, thus raising fears that large unfailed sections to the North might be poised to deliver another tsunami. However, Stein and Okal (2005) concluded that the fault slip had to exceed 10 metres from the observations that tsunami run-up on the western shores of the Aceh province measured 25-30 metres, and that tsunami wave run-ups typically do not exceed twice the fault slip. From re-analysis of the earthquake seismograms Stein and Okal (2005) also suggest that the fault slipped in two phases; the southernmost third of the rupture zone slipped rapidly (the surface waves from this "fast slip" giving rise to the first estimates of M_w9.0 for the event) and then the rupture propagated north at a slower rate. They also suggest that the whole rupture zone indicated by the aftershock distribution contributed to the tsunami formation. It is well known that tsunami amplitudes are greatest when perpendicular to the fault rupture (assuming the entire aftershock zone slipped), and from simulations and back-analysis of wave height data from satellites, the Pacific Marine Environmental Laboratory concluded that the entire 1200 km rupture zone must have contributed to the tsunami formation in order to obtain the observed large tsunami run-ups in India and Sri Lanka. The important implication of this is that the strain accumulated from the subduction of the Indian plate beneath this section of the Burma microplate has been released, and there is no immediate danger of a similar tsunami being generated on this part of the plate boundary.

Ni et al. (2005) determined the duration of the earthquake high frequency energy radiation to be about 500 seconds (8 minutes and 20 seconds) with an average rupture speed of 2.5 km/s translated into a rupture length of about 1200 km, comparable to the length of the aftershock distribution. This is the longest earthquake rupture ever recorded and is bigger than that associated with the 1960 Chilean earthquake (duration 340s). However, the tectonic setting in the Sunda Trench subduction zone is very different to that in the Pacific Ocean at Chile. Namely, the Indian Ocean plate is relatively old and dense at 60 million years old (the Pacific plate at the south Chile subduction zone is geologically young and less dense at 15 million years old) and the plate convergence is oblique to the trench, (especially in the region of the Andaman Islands), whereas in Chile it is nearly normal to the trench. It must also be noted that the northern end of the earthquake rupture coincides with a change in the tectonic environment since north of the Andaman Islands the plate boundary turns eastwards (towards the coast of Burma) and earthquake fault motions are more oblique. This is presumably the reason why the rupture zone ended at this point. Also noteworthy is the fact that the earthquake epicentre lies on the boundary of the Indian Ocean and Australian plates. This plate boundary was only recently discovered by Van Orman et al. (1995), before which it was thought that the two plates were one (i.e. the Indo-Australian plate).

Sieh (2005), an authority in the tectonics of the Sunda trench with a long record of field research in the region, argued that the most likely part of the Sunda trench to rupture next would be that immediately to the south of the rupture zone of the December 26, 2004 earthquake. McCloskey (2005) calculated stress perturbation tensors using the slip distribution of the Boxing Day event and predicted a stress increase of up to 5 bars in the region 50 km south of the rupture zone, confirming this prediction. An earthquake of M_W 8.7 occurred just 11 days (March 28, 2005) after the publication of these papers, with an epicentre located exactly to the south of the 2004 rupture zone. However, McClosky (2005) and Sieh (2005) also show concern that the huge Sumatra fault that runs across the island of Sumatra might also be activated, with McCloskey (2005) having calculated a strong positive loading of up to 9 bars along a 300 km stretch of the Sumatra fault near the city of Banda Aceh.

The December 26, 2004 earthquake's rupture zone exceeds 200,000 km^2 and is one of the largest known. A consensus has been reached amongst leading seismologists that slip of entire rupture zone contributed to the tsunami formation. The risk of further tsunamis being generated from this zone is therefore currently low, however, strong earthquakes are probable inland in the near future.

1.2.3 Regions Affected by Ground Shaking

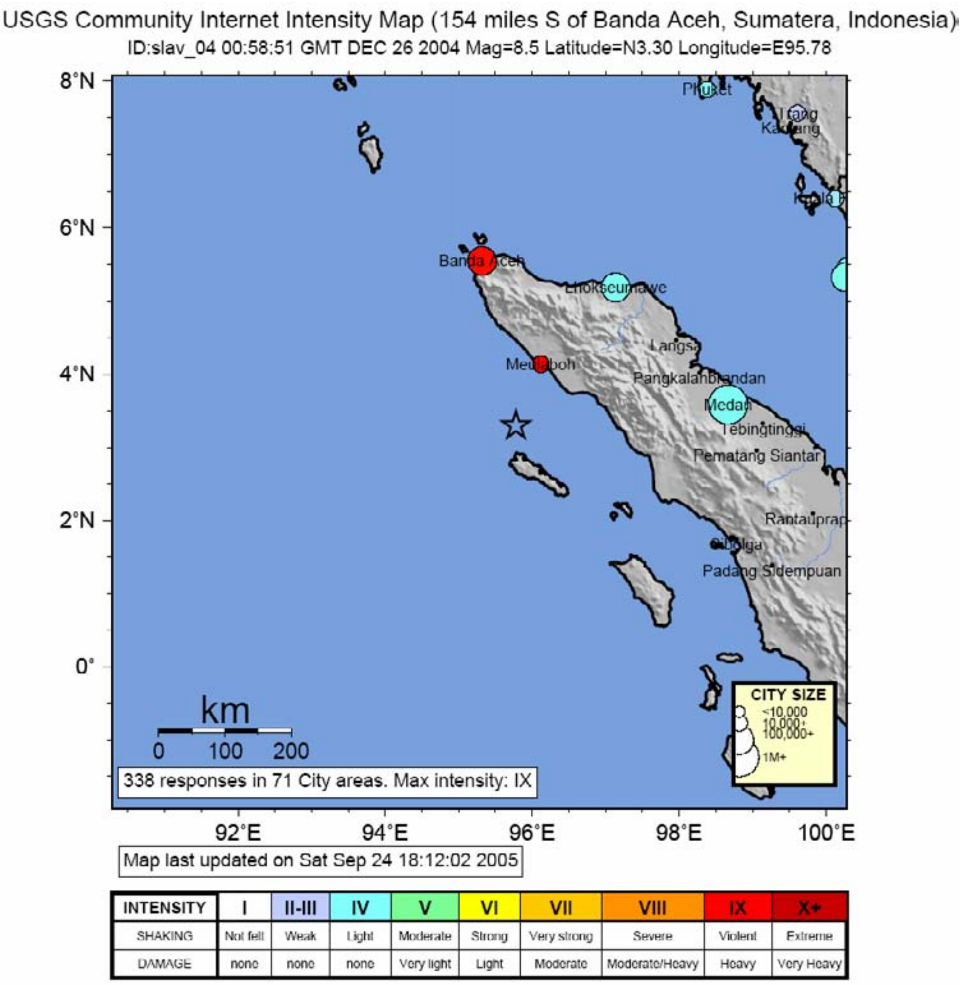
Ground shaking was felt in 9 countries around the Indian Ocean basin. Heavy damage, building collapses and panic were reported from Indonesia's Aceh province, especially from the main city of Banda Aceh (see Figure 1.8). Figure 1.7 shows ground shaking damage to a mid-rise reinforced concrete building in Banda Aceh. An assessment of the western islands off the coast of Sumatra found considerable damage to housing and livelihoods. UNICEF found that at least 80 percent of education facilities on Simeulue Island were destroyed (Mar-10, Jakarta Post). A recent UNICEF assessment following the March 28, 2005 earthquake revealed that virtually all remaining education facilities were destroyed on Simeulue Island (population 78,000). The islands west of Sumatra were nearer the rupture zone of the earthquake and thus suffered most of the ground-shaking related damage in this earthquake (see Figure 1.8b for attenuation of felt intensity with fault distance). The earthquake also caused considerable panic in the city of Medan (population 2.5 million) located on the north eastern coast in the neighbouring province of Sumatera Uttara.

On the Andaman & Nicobar Islands many buildings suffered direct damage from ground shaking. At Port Blair cracks appeared in the roads and the buildings were violently shaken. Severe shaking, strong enough to knock people to the ground, was experienced at Car Nicobar and some buildings within the Indian Air Force base were seriously damaged.

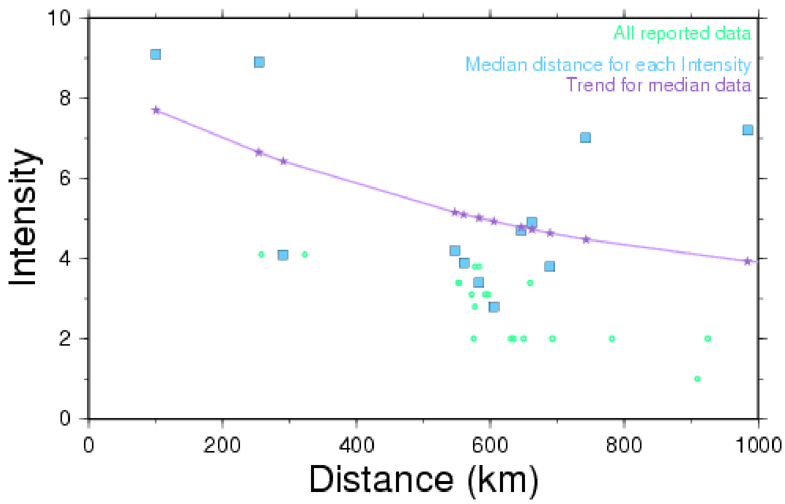
The earthquake was also widely felt along the east coast of India. In Tamil Nadu, people felt distinct tremors in most parts of Chennai. At Bhubaneswar in Orissa many people left their homes, and ground shaking was experienced in Mayurbhanj, Jajpur, Koraput and Sunabeda. Tremors were also reported from the coastal belt of Andhra Pradesh from Srikakulam to Chittoor as well as in the cities of Nellore, Vishakhapatnam and Vizianagaram. People in Vishakhapatnam ran out of their homes in panic, especially at the East Point Colony, MVP Colony and Seethamanmadhara areas. Tremors were felt in Kochi in Kerala and Bangalore in Karnataka. A few buildings developed cracks at Bhubaneswar, Chennai and Vishakhapatnam; however there are no reports of major damage from any parts of mainland India due to this earthquake. The earthquake was also felt in Kolkata (West Bengal), in Dhanbad and the surrounding towns in Jharkhand.

Figure 1.7: Ground shaking damage to 6-storey RC frame structure in Banda Aceh
(Source:http://www.usc.edu/dept/tsunamis/2005/tsunamis/041226_indianOcean/sumatra/sumatra.html)

In Sri Lanka, locations in the centre of the island such as Kandy felt the tremors of a significant duration. The tremor was also felt in Bangkok, Chiang Mai and other cities in Thailand. In Malaysia, several high-rise buildings were evacuated including in Penang and Port Klang. The shock was also felt at Alor Star and Pangkor. Residents of Singapore also felt the earthquake. In Bangladesh, the quake was felt at Dhaka and Chittagong and in most parts of the country. (Main Source: Amateur Seismic Center – India; http://asc-india.org/events/041226_bob.htm).



(a)



(b)

Figure 1.8: Indian Ocean 26th December 2004 Earthquake intensity distribution: (a) Maps of felt ground shaking reports in Sumatra. (b) Graph of attenuation of earthquake felt intensity with distance from the fault. The map and graph are produced from 317 reports by the U.S. Geological Survey (Source: www.usgs.gov).

1.3 The Tsunami

The sudden and violent vertical displacement of the sea floor caused a disturbance to the overlying water column, which generated at least three waves that propagated rapidly across the whole of the Indian Ocean. These types of waves are called “Tsunami” after the Japanese for “harbour waves” a term used to describe the fact that local fishermen were surprised upon return to land to find that waves they had not felt whilst at sea had caused damage on the coast. In this section a brief explanation of the terminology used to describe the tsunami and its effects is firstly given. The mechanics of formation and propagation of the tsunami wave are then briefly discussed.

1.3.1 Tsunami terminology

The terminology used to explain the tsunami in this report is explained in Table 1.2 and Figure 1.9.

Table 1.2: Tsunami terminology used in this report. (Source: Natural Environment Research Council, Coventry University and University College London)

Term	Description
Amplitude	The vertical distance between the wave trough and crest
Crest	The highest point of the wave
Draw-down	A noticeable sudden retreat of the sea water. This is caused by the arrival at the shore of the tsunami trough.
Inundation	The maximum distance travelled inland (from the shore line at mean sea water level) by the tsunami
Period	The time between successive crests (or troughs). Although a tsunami wave train may consist of different period waves that are superimposed, one or two will generally dominate, giving the perception of a series of discrete waves.
Run-up	The height above mean sea level of the tsunami at maximum inundation level
Trough	The lowest point of the wave
Velocity	The speed at which a tsunami travels. It refers to the wave train not the movement of water within the wave.
Wave (or Tsunami) height	Height of the tsunami water profile above the ground or above mean sea level, as specified.
Wave length	The distance between one wave crest and the next.

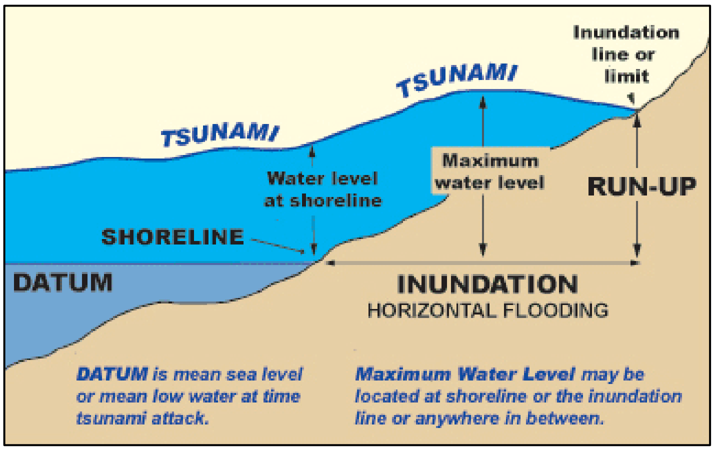


Figure 1.9: Illustration of the terminology used to describe the tsunami in this report (Source: International Tsunami Information Center).

1.3.2 The 26th December 2004 tsunami formation and propagation

The sudden uplift of the Burma microplate at its interface with the Indian Ocean Plate during the earthquake caused a disturbance to the overlying water column. The induced imbalance in the water surface caused an oscillatory motion to be set up that produced a series of waves. The waves propagated out from the source east across the Andaman sea and west across the Indian Ocean in a direction approximately perpendicular to the plate boundary. The waves travelled across the Indian Ocean at a velocity estimated to be 640km/hr (NASA: http://www-misr.jpl.nasa.gov/). However, the wave velocity will have decreased as the tsunami travelled across the Bay of Bengal and past the Maldives Islands, where the water depth is less, (2900m and 5800m compared to 6800m). The tsunami impacted with enormous force on the shores of Indonesia, Thailand, Sri Lanka and India amongst others. A time line for the event was assembled by Annunziato and Best (2005) from newspaper reports and eyewitness statements, and is summarised in Table 1.3. In this timeline the minimum reported time for the tsunami arrival in Sri Lanka is less than that reported for Thailand. However, there are uncertainties associated with this arrival time and simulations (Annunziato and Best 2005) estimate the tsunami arrival in Sri Lanka to have occurred about 15 minutes after it hit Thailand.

Typically, in open ocean waters, tsunami waves have long wavelengths of the order of hundreds of kilometres. The predominant wave period is determined mainly by the size of the source, with its value being set at the source and changing very little as the wave spreads out from the source. Larger sources produce longer-period waves, the wave period being approximately equal to the length of time that a wave would take to cross the smallest dimension of the source in the depth of water above the source (Source: The Tsunami Initiative, http://www.nerc-bas.ac.uk/tsunami-risks/index.html). Large earthquakes can produce tsunami with periods of up to an hour compared to the 20-25s maximum periods of storm generated surface waves. The large periods, wavelengths and velocities of the tsunami waves in deep water combined with the fact that the energy of the wave is spread through a very large volume of water both vertically and in the direction of motion, mean that the crest to trough amplitude is very low, (typically of the order of few tens of centimetres). The small amplitudes of the waves with respect to the water depth and the very long wavelengths allow the waves to conserve energy as they propagate over large distances in deep oceanic waters as very little energy is lost to turbulence in the water or through boundary friction at the sea-bed. From images and measurements of the December 26, 2004 tsunami waves taken by the TOPEX/POSEIDON NASA radar satellite, Annunziato and Best (2005) have estimated that the wave amplitude over the Indian Ocean to have been of the order of 120 cm and the wave length of 760 km.

As the waves enter the shallower waters of coastal areas, their amplitude increases dramatically and their velocity reduces, resulting in violent wave impacts and extensive flood inundation inland. The variation in the heights of the impacting waves and levels of damage sustained by the countries affected by the Boxing Day tsunami are described in detail in Section 1.7.

Table 1.3: The tsunami propagation timeline (Annunziato and Best 2005).

Location	Distance (km)	GMT minimum time of impact	GMT maximum time of impact	Minimum delay from event	Maximum delay from event
Earthquake Epicentre	0	0:58:00		0:00:00	
Indonesia (Sumatra)	116	1:15:00	1:30:00	0:17:00	1:30:00
Thailand	610	2:45:00		1:45:00	
Sri Lanka (East Coast)	1690	2:30:00	3:00:00	1:32:00	3:00:00
Sri Lanka (Colombo)	1797	2:20:00	2:50:00	1:22:00	2:50:00
India	2053	2:45:00		1:47:00	
Maldives	2499	4:00:00	4:30:00	3:02:00	4:30:00
Somalia	5300	8:00:00		7:02:00	
Tanzania	6314	9:45:00	9:45:00	8:47:00	9:45:00

1.4 Historical Seismicity of the Sunda trench – Andaman Islands Region and Tsunami in the Indian Ocean

In this section a brief summary is presented of the seismicity and past tsunami in the Indian Ocean. The subduction zone of the Java trench extending east until the island of Timor is excluded. The earthquakes and tsunamis that are reffered to in the text are summarised in Table 1.4 and in Figure 1.10. All the tsunami events described are of a local nature with the exception of the 1883 tsunami caused by the Krakatau eruption.

1.4.1 Events associated with the subduction of the Australian Plate

Sumatra straddles a 1600-km-long portion of the boundary between the Sunda, Indian and Australian plates. GPS measurements indicate that near Sumatra the Sunda and Australian plates are converging NNW at about 7 cm/year. This motion is partitioned between the Sumatran subduction zone (the Sunda Trench) and the dextral Great Sumatran Fault. Historical seismicity of the subduction zone is dominated by three very large (M_W ~8.4 to 9.2) earthquakes in:

- 10th August 1797 (~M_W 8.4, Sieh et al. 2004)
- 24th November 1833 (~M_W 8.7-9.2, Sieh et al. 2004 and Zachariasen et al. 1999)
- 16th February 1861 (~M_W 8.4)

All three earthquakes caused tsunami on the western shores of Sumatra. The November 1833 earthquake was preceded by a smaller event on January 29, 1833 that apparently also caused a tsunami in the same region.

The 1797 and 1833 earthquakes occurred in part of the subduction zone south of the equator, west of Siberut and Mentawai islands. The north-western limit of both ruptures is less than 40 km northwest of Sipora Island. The south-eastern limit of the 1797 rupture is well constrained to beneath the southern part of South Pagai Island giving a total rupture length of 200km and an estimated slip of 3m (Sieh et al. 2004). The south-eastern limit of the 1833 rupture is poorly constrained, but extended well beyond South Pagai Island and is estimated to have slipped 7m during the earthquake (Sieh et al. 2004). Both earthquakes involved rupture of the same area of the subduction interface, but slip extended farther downdip and southeast in the 1833 earthquake. From studies of coral microatolls Sieh et al (2004) found evidence of uplift of the Sipora, North Pagai and South Pagai Islands, (which span a 160-km length of the outer-arc ridge), by the 1797 and 1833 events of 0-70cm and 100-230cm, respectively. The areas affected by the 1833 tsunami were: Bengkulen, Padang, Priana and Indrapura (the distance between Bengkulen in the south and Padang in centre of Sumatra's western shore is around 400 km). In June 2000 an earthquake of M_W 7.8 occurred south of the 1833 rupture's south-eastern limit and caused 103 deaths.

The February 16, 1861 earthquake occurred north of the equator with a rupture zone reaching up to Nias Island. Tsunami waves of at least 1m height are reported from several islands off the coast of Sumatra (Soloviev and Go 1974). This event was followed by an earthquake on March 9, 1861 in the same area.

On December 28, 1935 an earthquake of surface-wave magnitude 7.7 (M_W 8.1) occurred in the equatorial region near the Batu islands, and was followed by a smaller event in the same area on November 17, 1984 (M_W 7.2). Neither of these two earthquakes caused a tsunami.

Further north, an earthquake of surface-wave magnitude 7.5 (M_W 7.8) occurred in the region near Simeulue island on January 4, 1907 and caused a tsunami and damage to Nias island.

Table 1.4: List of earthquakes and tsunami in Sunda Trench – Andaman Islands region

Year	Month	Day	Hour	Min	Lat (°N)*	Long (°E)	M	Tsun.	Affected Areas
1797	8	10					8.4	T	Padang
1833	1	29						T	Bengkulu, Padang, Priana
1833	11	24			-3.5	102.2	8.7	T	Bengkulu, Padang, Indrapura
1847	10	31			7.3	93.7		T	Nicobar islands
1861	2	16			-1.0	97.8	8.4	T	Padang, Batu & Nias isl.
1861	3	9			0.3	99.4		T	Padang, Batu island, Simo
1881	12	31			12.0	92.0	8.0	T	Car Nicobar, Andamans
1907	1	4	12	19	2.0	96.3	7.8	T	Gunung Sitoli (Nias island)
1935	12	28	9	35	0.0	98.2	7.7		
1941	6	26	18	51	12.5	92.5	8.1	T	Andaman islands
1967	4	12	11	52	5.4	97.0	7.5	T	Andaman sea
1984	11	17	13	49	0.2	98.0	7.2		Nias island
2000	6	4			-5.2	102.0	7.8		Bengkulu, Manna, Enganno island
2002	11	2	8	26	3.0	96.1	7.5		North of Simeulue isl.

*The location of events prior to 1900 were not instrumentally located, therefore may be inaccurate.

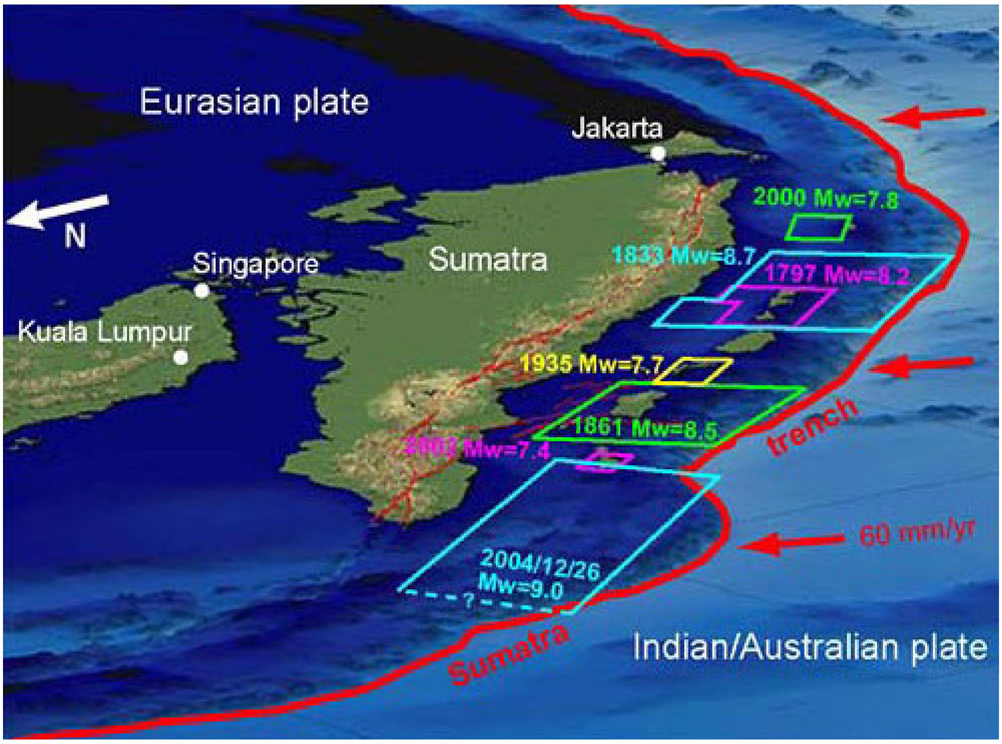


Figure 1.10: Map showing the Sumatra subduction zone (Sunda trench) and the estimated rupture zones of previous earthquakes. As mentioned in the text the rupture zone of the 2004 earthquake extends all the way to the north of the Andaman island chain. (Source: http://www.geo.uib.no/seismo/quakes_world/Sumatra-2004/Tectonics/SEQ-Tectonics.html referring to the work of Sieh in the California Institute of Technology, Sumatran Plate Boundary Project).

1.4.2 Events associated with the subduction of the Indian Plate

On December 31, 1881 an earthquake of magnitude 8.0 occurred in the vicinity of Car Nicobar Island that generated a destructive tsunami which affected the entire Andaman and Nicobar island group, and quite possibly the entire Bay of Bengal. Waves of 1.2m were reported in Port Blair and Nagappattinam, of 0.76 in Car Nicobar (Berninghausen 1966). Waves of 1 meter height were recorded by a tide gauge station at Chennai, on the East coast of India. On October 31, 1847 another tsunamigenic event is believed to have occurred in the Nicobar Islands, but very little is known about the effects of this event.

The June 26, 1941 earthquake (M_W 8.1) originated in the Andaman Islands and was followed by a tsunami that hit the islands and eastern India (Murty and Rafiq 1991). This tsunami is believed to have caused at least 5,000 deaths on the shores of eastern India (although this number is not certain as the tsunami occurred during an on-going war). Further destruction due to ground shaking and tsunami occurred in the Andaman and Nicobar islands (it was particularly destructive in the Middle and South Andaman Islands and caused considerable damage at Port Blair, Port Anson and surrounding areas).

The April 12, 1967 event was also within the rupture zone of the 2004 event but was an intermediate depth event (focal depth around 50 km) and the reported tsunami's run-up did not exceed 2 metres, although it is said to have caused the destruction of boats and the death of 13 people near the mouth of the Tinambung river, Indonesia (National Geophysical Data Center).

Prior to the 2004 event there was a precursor earthquake that occurred on November 2, 2002 (M_W 7.5) with epicentre at 3.00^0 N and 96.08^0 E, i.e. very close to the 2004 epicentre. The 2002 earthquake did not cause a tsunami. A tsunami warning was issued by the Meteorological Department of Thailand after the occurrence of this event. The result of this false alarm was the dismissal of the Department's director, who has this year been reinstated in his position.

1.4.3 Events elsewhere in the Indian Ocean

Events elsewhere in the Indian Ocean are described here as these are potential locations for future tsunami generation.

On June 16, 1819 a huge earthquake of magnitude 8.3 occurred in the Gulf of Kutch (western India) not far from the destructive Bhuj earthquake of 2001. This reverse fault earthquake is called the Allah Bund (Dam-of-God) earthquake, because it created a 6-m-high, 6-km-wide natural dam across the Puran or Nara river (which enters the Rann of Kutch from the north). A lake 30 km in diameter, Lake Sindri, was formed south of the Allah Bund and remains as a monsoon-filled depression to this day (although now partly filled with sediments and evaporates). Around 1,500 to 2,000 people are believed to have died in this event which is believed to have also generated a tsunami. Indeed, Sindree and adjoining country are reported to have been inundated by a tremendous rush from the ocean, and all submerged (Berninghausen 1966).

Another earthquake occurred in the Kutch Peninsula in 1845 which was felt in Karachi and is reputed to have generated a tsunami and to have caused changes in channel depth near and north of Lakput on the western edge of the Kutch Peninsula (Berninghausen 1966).

The November 27, 1945 Makran coast earthquake an M_W 8 event was centred about 100 km SE of the town of Gwadar (Baluchistan, SW Pakistan) near the border with Iran along an active subduction zone off the Makran coast of Pakistan, which marks the boundary between the subducting Arabian plate and over-riding Iranian microplate. It caused a tsunami that hit the coasts of Iran, Pakistan, Oman and western India. The estimated life loss in this event is 4,000 people mostly due to the tsunami. The tsunami reached a height of 13 m in Ormara and Pasni (Pakistan) and caused great damage to the entire Makran coastal region (Murty and Rafiq 1991). The fishing village of Khudi, some 30 miles west of Karachi, was completely obliterated. All the inhabitants and their huts were washed away. There was similar loss of life and crafts along the coasts of Makran (Iran) and Oman. The towns of Pasni and Ormara were badly affected. Both were reportedly "underwater" after the tsunami. Pasni's, postal and telegraph offices, government buildings and rest houses were destroyed. The tsunami was also recorded at Muscat and Gwadar. At Karachi, the tsunami arrived from the direction of Clifton and Ghizri. It ran along the oil installations at Keamari and flooded a couple of compounds. The waves were 2 m high in Karachi. The first wave was recorded at 5:30am, then at 7:00am, 7:15am and finally at 8:15am. The last wave at 8:15 was the biggest. There was no damage either to the port or to boats in Karachi Harbour. The tsunami had a height of 11 m in Kutch, Gujarat. It was also recorded in Bombay Harbour and other locations along the Maharashtra coast where several people were swept away (Source: http://asc-india.org/gq/mekran.htm).

The western coast of India (in Maharashtra) has also been hit by a tsunami in 1524, reported at the time to have caused considerable alarm to the Portuguese fleet assembled offshore of the Dabhol coast.

It is possible that a tsunami was generated during the April, 2, 1762 earthquake that occurred offshore of the Arakan coast of Myanmar, which may have affected Bangladesh and eastern India.

A basin-wide tsunami occurred on the morning of August 27, 1883 due to the huge volcanic eruption that destroyed the island of Krakatau in the Sunda strait. There were three tsunami waves associated with the last paroxysms of the eruption that led to the eventual destruction of the volcanic island of Krakatau. The third and final eruption occurred at 10:02 am (local time) and generated a tsunami with wave heights exceeding 30 meters in parts of the Sumatra and Java coasts nearer the volcano, where most of the 36,500 people killed in this disaster were located. The tsunami propagated across the Indian Ocean hitting India, Sri Lanka and coasts as far away as South Africa. However, the wave heights were not as high as those resulting from the December 26, 2004 event (Winchester, 2003). In Galle, the sea receded before the first wave arrived and a total of fourteen waves were observed. Although there are vivid accounts about what happened to the sea, there is no mention of damage to buildings or casualties. In Hambantota where the highest wave reached 4 metres, serious damage was caused to small craft but a contemporary report states clearly that there were no casualties. The tsunami went around the western side of Sri Lanka, and in Negombo (north of Colombo) the inundation extended to almost 1 kilometre inland of the coast.

The Indian Ocean has experienced many tsunami in the past (at least 12 are reasonably well documented since 1524). However, in the last 250-500 years it seems that only two events had basin-wide effects, in 1883 and 2004.

1.4.4 Tsunami Affected Regions

The waves arrived at the coast of Aceh province within half an hour of the main shock. Heavy damage and fatalities are reported from Banda Aceh (population approximately 330,000) and other towns in this province. Satellite photos show the true extent of the damage to the city, with large sections in the north of the town having been completely washed away. The Indonesian army and police cordoned off these sections to survivors as they cleared away thousands of bodies. Many fishing villages and towns such as Calang and Meulaboh, along the west coast also show near complete devastation. People are believed to have watched the water recede and then run to pick up fish left stranded on the seafloor, whilst others rushed to take photographs. The waves inundated the coast to a significant degree but in some places their force was arrested by high cliffs along the shore.

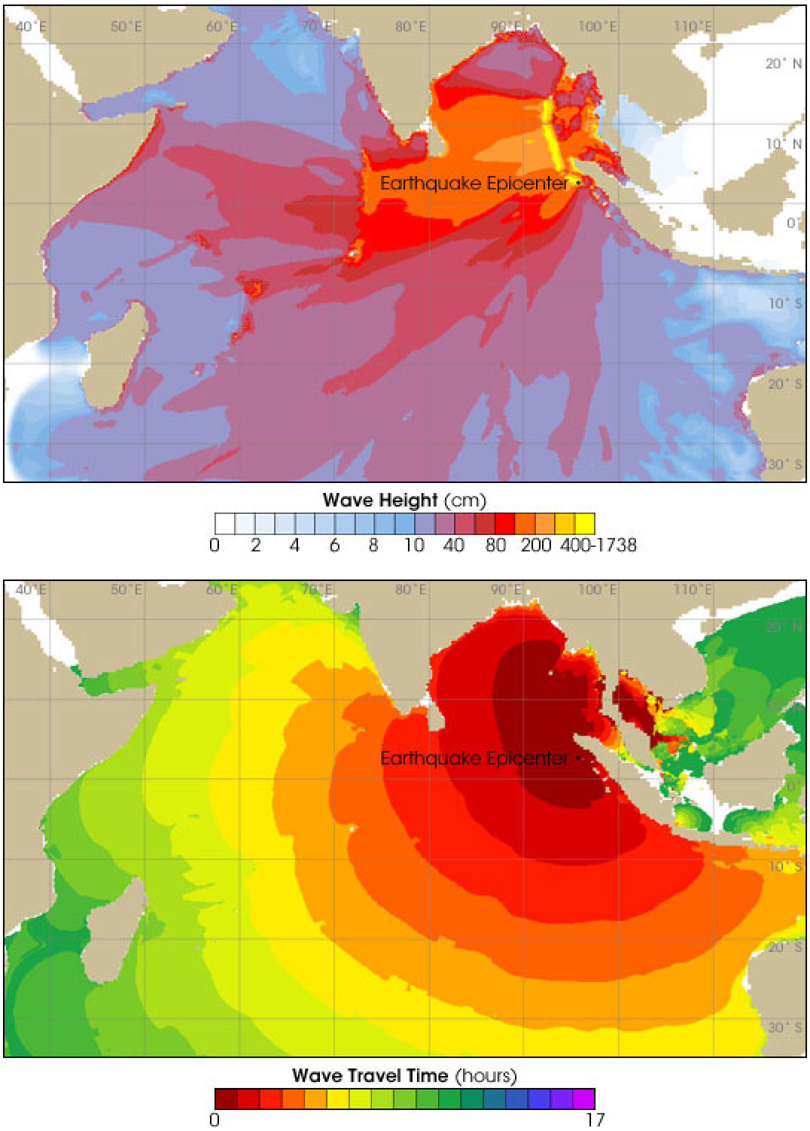


Figure 1.11: Graphical representation of the predicted 26th December 2004 Indian Ocean Tsunami wave heights and travel times (Source: http://earthobservatory.nasa.gov/NaturalHazards).

In Sri Lanka, a wave reported by the press as being 40 feet (12m) high struck the eastern and southern coast. Residents of Colombo sought refuge on higher ground in fear as coastal areas of the city were hit by the tsunami. Other affected areas include Batticaloa, Galle, Jaffna, Matara and Trincomalee to mention a few. A passenger train on its way from Colombo to Matara was washed away killing over a 1,000 people including locals who clambered aboard hoping it would save their lives. Buses and cars were washed out to sea and numerous seaside communities like Hambantota were devastated. Here, as in Indonesia, some people were puzzled by the recession of the water and rushed forward to view this rare phenomenon only to then be caught by the ensuing waves. People in Trincomalee were thought to have gathered "bag loads of colourful fish" before the tsunami crashed ashore.

Press agencies reported a wave nearly 16 feet (5m) high hit the resort island of Phuket in Thailand. Many parts of the Thai coast were badly affected and many popular tourist resorts like Khao Lak and Koh Phi Phi were completely devastated. Thousands of tourists vacationing in the area were amongst the fatalities. In the Khao Lak area, a Thai Navy patrol boat was found to have been washed 1.2km inland and elsewhere a shark was discovered in a hotel swimming pool and two dolphins were stranded in an inland pond.

In the Nicobar Islands, the tsunami caused widespread damage wiping out entire villages like Campbell Bay on Great Nicobar Island and Malacca on Car Nicobar Island. Waves nearly 3-storeys high, devastated the Indian Air Force base near Malacca. Satellite photographs detailed the extent of tidal inundation in these islands with some parts of Car Nicobar and Trinkat Islands permanently submerged. The worst affected island in the Andaman & Nicobar chain is Katchall Island with 303 people confirmed dead and 4,354 missing out of a total population of 5,312. The islands of Camorta, Car Nicobar and Trinkat also reported heavy human losses. In the Andaman Islands, considerable tsunami related damage was produced at Port Blair, leaving ships perched atop dockside walls and on adjacent roads.

Large tsunami also struck the eastern Indian seaboard. In the city of Chennai, the water covered the entire breadth of Marina Beach with cars and boats carried away. Local television stations showed panic stricken people fleeing in ankle-deep water along the roads of the Marina, with city landmarks such as the Ashtalakshmi Temple and the Santhome Church also flooded. The worst affected region in Tamil Nadu was the port city of Nagapattinam, where entire neighbourhoods were washed away and hundreds of pilgrims living around the Shrine of Our Lady of Health at Vellankani were drowned. Destruction was reported in Cuddalore, Pondicherry and Kanyakumari where hundreds of tourists were trapped at the Vivekananda Memorial for several hours before being rescued. Further north in Andhra Pradesh, tsunami damage was reported from Nellore, Machlipatinam and Vishakhapatnam amongst others. Many people that had gathered at a beach near Machlipatinam for religious ceremonies were swept away. Damage and fatalities were reported in parts of coastal Kerala (on the western side of the Indian sub-continent), the worst hit village being Kollam. North of Kerala, in Karnataka tsunami was reported in Mangalore and Suratkal and all along the coast of Goa including the city of Vasco. Minor damage was reported along the coast of Maharashtra, most notably in the region of Ratnagiri and Sindhudurg, where coastal flooding and strong currents swept away boats and inundated coastal roads and houses. Noticeable but smaller surges were also experienced in Mumbai. Tsunami waves were observed in Orissa and West Bengal but did not cause any damage. Again, eyewitnesses' state that the sea receded before the tsunami hit, leaving the sea bed exposed for a few moments during which children and adults alike rushed to gather stranded fish.

The tsunami also struck the Maldives killing 83 people (with 25 still missing) and submerging buildings in the capital, Male (population 300,000). The Maldives island group contains 200 low-lying islands that are highly vulnerable to sea-level rise. Fourteen of these were completely destroyed by the tsunami, leading to the abandonment of 3 of them. It was reported that 5% of the Maldives population lost their homes and that 25% of tourist resorts were affected by the waves. Tsunami activity was also reported in Malaysia and in Burma. In Malaysia the worst affected area was the island of Penang. In Burma many buildings and bridges were damaged in the town of Kawthaung (near the border with Thailand). The Australian Cocos Islands were hit by a half meter tsunami; however, no wave activity was reported on the Australian mainland. Surges inundated coastal areas of Oman and a few people were injured in 5-metre waves that hit the Maharaja region. Tsunami activity was also observed in East Africa with boats capsized in the Punt land region of Somalia resulting in many fishermen being washed away. Further south in the Seychelles, many fatalities were reported in the island of Mahe, which was submerged by the waters. In Malindi, Kenya, one person was killed and many others were reported missing. The Rodrigues Island and beaches on north Mauritius were flooded. The French administered Reunion Island suffered damage to boats in harbours from the tsunami. In the island of Zanzibar near Tanzania, hotel guests were evacuated to higher ground. A half meter wave was recorded at Port Elizabeth in South Africa and other locations such as Durban Harbour also recorded unusually strong currents. More than 1,200 people were left homeless by the waves on the east coast of Madagascar. Tide gauges in countries around the Pacific Rim recorded minor wave activity. Such activity was recorded as far as Alaska, Hawaii and San Diego in the United States, Callao and Inquique in Chile, in New Zealand, Fiji, Vanuatu and American Samoa. In Mexico, 8-foot waves slammed into the town of Manzanillo probably due to the curvature of the earth causing the tsunami waves to focus (Main Source: Amateur Seismic Center – India; http://asc-india.org/events/041226_bob.htm).

In the following section a summary of the effects of the tsunami in Indonesia is reported. It was not possible for the EEFIT team to visit Indonesia, but this section is included here because it is the country that suffered the worst effects and largest life loss due to the event.

1.4.5 Effects of the tsunami in Indonesia

The tsunami mainly affected the Aceh province in Indonesia, which is inhabited by 4,218,000 people (3,931,000 in the census of 2000) living in approximately 800,000 housing units. Apart from the city of Banda Aceh the tsunami destroyed virtually every village, town, road and bridge along a 170-kilometer (105-mile) stretch of coast that was not more than 10 meters above sea level along the western coast of the Aceh province, including the town of Meulaboh with population around 150,000 people. South of Meulaboh the effects of the tsunami were less severe with the island of Simeulue suffering limited casualties. It is thought that the latter is due to the indigenous people having an awareness of the fact that stroung ground shaking could be a precursor to a tsunami. The western coast of the Aceh province had a population of about one million distributed over six regencies, about half living in the heavily damaged northernmost three regencies (Aceh Besar, Aceh Jaya and Aceh Barat) and half in the southernmost three (Nagan Raya, Aceh Barat Daya and Aceh Selatan). The number of dead and missing is now estimated at 165,732 people, i.e. about 16.6% of this coastal population.

On January 17, 2005, the Indonesian Ministry of Social Affairs published the following fatality figures by location: Krueng Mane 117, Bireun 594, East Aceh 894, North Aceh 2,386, Banda Aceh 20,141, Lhokseumawe 189, Pidie 2,686, Sabang 12, Nagan Raya 1,338, Aceh Jaya 19,661, Calang 5,000, Meulaboh 28,251, Aceh Besar 17,564, Simeulue 8, Pulau Aceh 4,000, South Aceh 6, West Aceh 11,982, Southwest Aceh 6, Central Aceh 131, and Gayo Luwes 4. The number of deaths in North Sumatra was as follows: 227 in Nias, 8 in Pantai Cermin, 1 in Central Tapanuli, 8 in Deli Serdang, 4 in Sergai, 2 in Madina and 11 at the Adam Malik hospital in Medan. Total fatalities: 115,490. The death toll continued to rise reaching 128,645 when the tally was stopped on April 30, 2005.

The effects on the western coast were so severe that the area was very difficult to approach except by helicopter or from inland roads. This meant that this region, although the worst affected, remains under-investigated. The coastal road from Banda Aceh to Meulaboh was severely damaged and was only re-opened in late March 2005, after temporary bridge structures replaced the hundreds of destroyed bridges. The map of Figure 1.12 shows the tsunami affected areas in most of the Aceh province (from Meulaboh in the west to Lhokseumawe in the east).

Along the Eastern coast the effects of the tsunami were first surveyed in early January by Borrero (2005) who reported the following observations:

- Town of Idi (sea receded by 500 m before the arrival of two consecutive waves, the second being the largest with wave height 2.5 m and inundation distance of 500 m);
- Town of Panteraja (sea receded by 500 m about 30 minutes after the earthquake, followed by three consecutive waves, the third being the largest with wave height 4.2-4.7 m and inundation distance of 1000 m);
- Port of Kreung Raya the site of a marine oil transfer facility (wave height of 5m and inundation distance of 1000m).

In the city of Banda Aceh, according to eye witnesses, the first wave arrived around 25 minutes after the earthquake and in the city itself did not exceed 1 meter in height. The first wave was followed by a large withdrawal of the waters and the sea, followed by two more waves that were more devastating. The ground shaking was also severe and caused serious damage to many buildings including some mid-rise reinforced concrete structures that partially or totally collapsed (as seen on TV footage taken a few minutes before the tsunami waves hit the city). The city lies on the Aceh river delta that in this location splits into two branches, the main one running through the city centre and a narrower branch running 15-km to the east. Thus the city is located on soft ground liable to liquefaction and ground shaking amplification effects. Actually the city centre is separated from the sea to the north by nearly 2-km of low lying wetland and lagoons. However there was a sand spit area (called Uleele) that was populated by local fishermen and people related to the various aquacultures that were operating in the area.

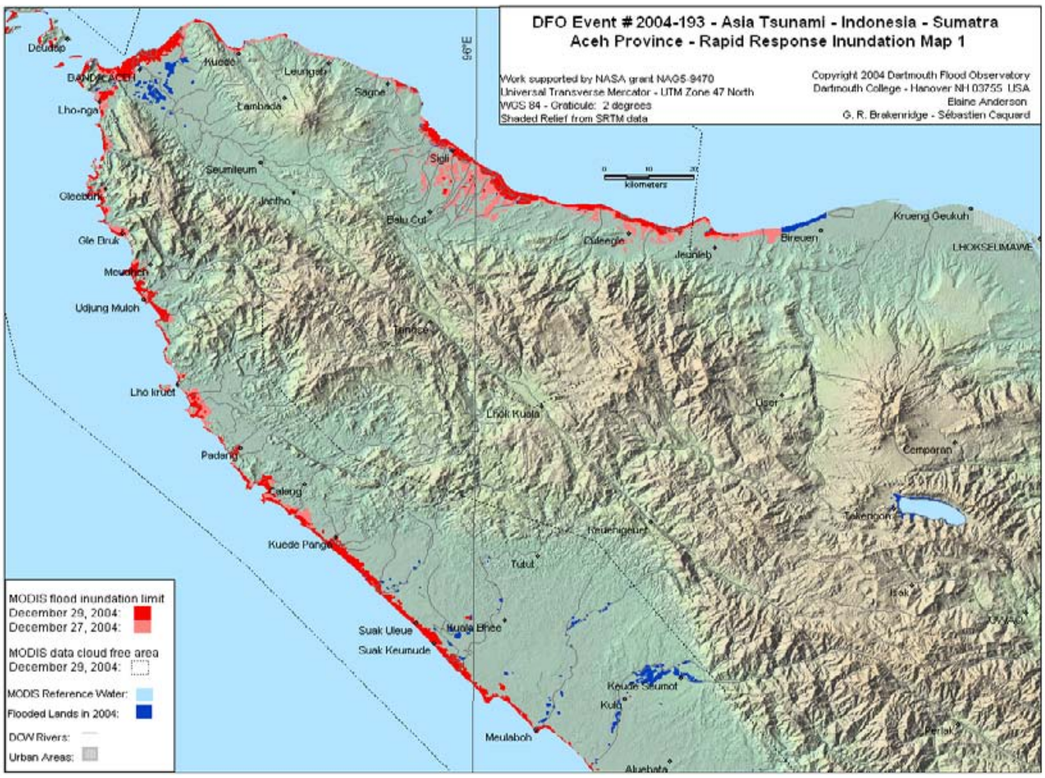


Figure 1.12: Extent of tsunami inundation along the western and eastern shores of the Aceh province (Source: Dartmouth Flood Observatory, http://www.dartmouth.edu/~floods/2004193.html).

Borrero (2005) was able to take many wave height readings throughout the Banda Aceh area, which ranged from 9m in Uleele, 3-7m in the first two kilometres of land from the coast that contains the northern part of the city centre, and 2-4m in the third kilometre of land from the coast that contained the southern part of the city. The inundation extended 3 to 4 kilometres due to the low-lying ground in Banda Aceh. The water level in the city reached the second floor of buildings, the waters dragging with them large amounts of debris that was deposited along the streets and the ground floor stores or dwellings. The main river channel served as a conduit ("path of least resistance") with water spilling over into the surrounding streets.

The most severe run-up (22-32m) was measured by Borrero (2005) and Tsuji et al. (2005) in the west of the city of Lho Nga. On the beach of Lho Nga stripped bark on trees indicated a sustained flow depth of over 13 metres at the shoreline. The mining facility of Lho Nga was severely damaged. A 90m long coal barge was deposited 160m inland. At the jetty of the mining facility a 100m freighter capsized. Further south along the western coast of Aceh province the town of Leupung was apparently obliterated with 95% of its 10,000 inhabitants considered dead. In the town of Gleebruk (Aceh Besar regency) there was also serious devastation. In the town of Calang (population around 10,000) reports suggest that 70% of the people have been killed. In the town of Teunom (Aceh Barat regency) it was reported that 8,000 people have died out of a population of 18,000.

The city of Meulaboh (Figure 1.13) was apparently hit by a series of seven tsunami waves. Life loss in this city was greater than in Banda Aceh, reaching 28,251 by January 17, 2005.

Figure 1.13: The devastating effects of the tsunami on the city of Meulaboh.

Simeulue Island was also hit by 5 meter waves but apparently no life loss occurred among the 75,000 inhabitants. Eight people died in the island, five due to the collapse of buildings on the western shores of the island. Reports suggest significant uplift on this island, and that the local indigenous people had a much higher awareness of tsunami risks. The mayor of Simeulue is quoted by the Australian newspaper “Herald” as saying that “people ran to higher ground immediately after the earthquake. Thousands of our people died in the 1907 tsunami”. On Nias island the tsunami waves killed 122 (official report) to 1,000 people (unofficial estimates).

1.5 Human Casualties and Displaced Population

The tsunami waves caused loss of life in 12 countries, the largest life-loss being incurred in Indonesia, Sri Lanka, Thailand and India, as is shown in Table 1.5. Almost 228,000 people are confirmed dead or missing, with almost three quarters in Indonesia’s Aceh province (see Note 1 under Table 1.5 for details of Indonesia’s dead and missing). The number of injured people is estimated by the WHO at around 500,000. The internally displaced population (IDP) as reported by four of the worst affected countries exceeds 1.8 million people. Thankfully, in spite of initial fears there have been no major outbreaks of disease in any of the affected countries so far.

A study on the life-loss in Indonesia, India and Sri Lanka by Oxfam International (Mar-26, BBC, AFP), stated that the tsunami disaster has left a gender imbalance in the affected areas because in certain locations the disaster claimed four times as many women as men. Women were worst-hit because they were waiting on beaches for fishermen to return or were at home looking after their children. In Thailand a large number of foreign tourists and residents were killed or are missing. Nationals of at least 36 countries are included among the 1,953 confirmed foreign deaths (a large number of foreigner’s bodies remain unidentified). Most were from North Europe as follows: Germany (60 dead, 639 missing); Sweden (52 dead, 893 missing); USA (35 dead, 18 missing); Switzerland (23 dead, 240 missing) and from many other countries such as Finland, Russia, and Israel etc. Sweden has never before suffered such a high loss of life as a consequence of a natural disaster.

More detailed analysis of the human casualty aspects is presented in Chapters 2 and 3 for Sri Lanka and Thailand, respectively.

Table 1.5: Loss of life and missing persons by country

Country	Confirmed Fatalities	People Missing	Total (Confirmed + Missing)	%Total	Internally Displaced Population
Indonesia[1]	128,645	37,087	165,708	72.7%	532,898
Sri Lanka[2]	31,187	5,644	36,831	16.2%	553,287
India	10,779	5,614	16,393	7.2%	650,000
Thailand[3]	5,396	2,822	8,217	3.7%	58,550
Somalia	298		298	0.1%	
Maldives	83	25	108	0.0%	300
Malaysia	68		68	0.0%	
Myanmar	90		90	0.0%	
Tanzania	10		10	0.0%	
Seychelles	2		2	0.0%	
Bangladesh	2		2	0.0%	
Kenya	1		1	0.0%	
SUM	176,706	51,192	227,873	100.0%	1,810,035

Note 1: Indonesia decreased the number of people missing by more than 56,000, saying most of them had been found alive in emergency camps. The National Disaster Relief Coordinating Board (Bakornas), which has been keeping the most detailed tally of victims among several government agencies doing a count, reduced the number of missing from 93,458 to 37,063. The agency said the number of dead had climbed by 174, to 126,915 (The Guardian, April 8, 2005). Bakornas stopped issuing daily reports on the number of dead, missing and displaced on April 30, 2005. To 30 April 2005, the total reported dead as a result of the 26 December 2004 tsunami stands at 128,515 in Aceh and 130 in North Sumatra. The number of missing has been revised downwards from 93,662 to 37,063 in Aceh, while the number of missing in North Sumatra remains at 24.

Note2: The Ministry of Public Security of Sri Lanka estimates 38,938 fatalities and around 4,900 missing; the figures above are from the National Disaster Management Center of Sri Lanka. Initially 800,000 people were displaced but this number has gradually fallen as people found alternative means of accommodation.

Note 3: The Asian Human Rights Commission (AHRC) reported that illegal migrant workers (mostly from Myanmar) have also suffered greatly in this event. The AHRC estimated that 2,300 died and 4,000 are missing, but the authorities report only 25 cases of migrant workers. The AHRC estimates are not included in the Table. The number of missing people in Thailand is much higher compared to that reported to the other worst affected countries.

Of the estimated population of 4.1 million in Aceh Province before the disaster; 575,000 people were in the provincial capital, Banda Aceh and surrounding Aceh Besar Regency. Multi-agency assessments find some 125,000 IDPs along the west coast (Jan-28, Reuters). The National Coordination Board for Natural Disaster Management (Bakornas) reported on February 28 that some 400,376 people remain displaced across 20 districts/cities. In the North Sumatra province, 19,260 people are displaced, with 14,731 people located in Medan City. Reuters reports that more than 514,000 people have been displaced (Mar-24, Reuters). In Sri Lanka the total number of IDPs increased to 553,287 after figures from additional districts were compiled and added. Of these, 141,985 are in “welfare centers” and 411,302 are with relatives or friends (Feb.16, UNJLC).

1.5.1 Why such a large loss of life?

It is certain that many lives could have been saved if a tsunami warning system coupled with public education and awareness programs had been in operation in the Indian Ocean. Such a warning system would have drastically reduced the death toll in countries such as Thailand, Sri Lanka, India, the Maldives and Malaysia were the tsunami waves arrived 1.5 to 3.5 hours after the earthquake’s occurrence. Indeed some evacuation might have been possible in the Aceh province too, since at least 25 minutes lapsed between the earthquake and the arrival of the first tsunami wave. Had there been knowledge of the impending danger, mosque loudspeakers could have been employed to deliver the warning to the population (although this could be problematic if there were power cuts due to the strong ground shaking). It is clear that very few people in the affected regions knew what was about to happen and just carried on with their normal activities.

Furthermore, in locations where the negative phase of the wave arrived first, the sudden recession of the sea waters triggered the curiosity of a large number of people who ventured to inspect the sea floor or flocked towards the sea to experience this unique sight personally, rather than seeking refuge on higher ground. When the wave suddenly arrived it was impossible for many of these people to save themselves, as the wave’s velocity was around 20 to 50 km/hour (depending on location). The immense power of the wave swept people away, in many cases taking them back into the sea as revealed by the large number of missing persons (one missing person for every 3.5 people killed).

In the areas in Sri Lanka and Thailand visited by the EEFIT team, it also became apparent that where the waves did not exceed 3 meters the survival rate increased. This was attributed to the fact that many were able to find refuge on the second floors of buildings. However when the waves exceeded 8 meters (as was the case in some locations in Thailand) even well built 3 storey reinforced concrete buildings that survived the tsunami with relatively moderate levels of damage, did not provide sufficient safety to their occupants. These buildings rapidly flooded up to the 3rd floor ceiling level, as windows and other openings failed immediately under the enormous hydrodynamic pressure of the waves (that were flowing here at velocities of 5-15m/s).

Preuss (2005) suggests that there is evidence in Sri Lanka that low-population-density areas experienced lower fatality rates, due to the availability of abundant opportunities for spontaneous pedestrian and non-motorized evacuation. This needs more detailed investigation because in the case of densely built-up areas such as for example Galle or Matara, most buildings are more than two storeys high, and it was observed that those immediately behind the first row experienced limited damage, thus providing ample safety to their occupants. This is very different from locations with a low-density of buildings, where there was predominance of single-storey structures which provided little protection to houses further inland and which in the worst affected regions were flooded up to or above the roof level. On the other hand it is certainly true that in densely populated towns there were many impediments to street evacuation, such as blocked traffic, narrow lanes and alleys. Vegetation seems also to have played a role in attenuating the power of the tsunami. This was especially observed in some locations in Sri Lanka where houses located within dense coconut plantations suffered less damage. However, Preuss (2005) noticed that a certain species of palm tree with serrated bark and very sharp fronds could have killed or lacerated people carried by the waters.

Environmental degradation is another factor that must be taken into account. Coral reef mining, grading of sand dunes and mangrove forest cutting all contributed to the degree of exposure of coasts. Half of the world’s coral reefs are actually found in the Indian Ocean but stocks are rapidly dwindling. The clash of interests between marine conservationism and the fishing industry is another important factor, since fisheries are an important part of the economy of all the affected countries and fish is a prime source of food and protein intake for their populations. Large fishing trawlers sweep the sea bottom near the coasts, often illegally, damaging the sea grass meadows and the coral reefs. Mangroves are cut down to make way for development or to sell to charcoal factories (Fahn, 2003). Population, human settlement and tourism development pressures on coastal areas are great and there was no planning for mitigating the effects of storm surges or tsunami. All of the affected countries are developing countries with very limited public fund resources to promote coastal environment protection and coastal hazard mitigation. However in Asia coastal urban areas alone are home to half a billion people. CIESIN (2005) have estimated that at the time of the tsunami, about 10.6 million people lived within 1 km of the affected coastal areas, and that 19.2 million lived within 2 km.

The astounding tragedy in the Indian Ocean is not just a human disaster of unbearable magnitude. Nor is it a matter of fate. It is the consequence of years of underinvestment in the scientific and technical infrastructure needed to reduce the vulnerability of developing countries to natural and environmental calamity» (Arthur Lerner-Lam and Leonardo Seeber (Lamont Doherty Earth Observatory) and Robert Chen (CIESIN)).

1.6 Estimates of Economic Loss

Table 1.6 summarises the economic loss estimates in the various countries affected by the Indian Ocean Tsunami. It is observed that there is a large variation in these estimates. The IMF in cooperation with the World Bank have also produced a report estimating the losses in the 6 worst affected countries (excl. India) according to which the total loss in these countries was expected not to exceed 7 billion US$.

Munich Re, estimate that the total cost of the disaster will be around US$13.6 billion. On February 16, UN Assistant Secretary General Hafiz Pasha stated that rebuilding the affected areas would cost some US$10-12 billion dollars over the next three to five years (Feb-16, AFP). In the four worst-affected countries, namely Indonesia, Sri Lanka, India and Thailand, the economic impact is expected to be manageable. The GDP growth for India is expected to be unaffected. The 2005 projected GDP growth rate now stands at 5.4% for Indonesia; 4.2% for Sri Lanka; and 4.3% for Thailand. According to a joint assessment carried out by the Asian Development Bank (ADB), the Japan Bank for International Cooperation (JBIC) and the World Bank (WB), reconstruction costs for areas affected by the disaster is likely to significantly exceed the preliminary estimates of US$7 billion. Former US Presidents Bill Clinton and George Bush senior visited some tsunami-affected countries in February and said at the end of their tour that some US$11.5 billion was needed for reconstruction.

The vulnerability of small island nations has again been highlighted by this disaster. Although the effects of the tsunami were not extreme in the Maldives and Seychelles, in relative terms their economies are the worst affected, with economic loss estimates in the Maldives reaching as high as 100% of the GDP. In the Seychelles the tsunami came at a time of economic crisis and will thus put additional strain to the country’s finances.

It will be many years before the true cost of this disaster has been estimated with accuracy by all the affected countries. To the direct loss of lives, property and infrastructure, other losses will have to be added, such as loss of revenue from tourism and fishing industries (two of the worst affected economic sectors). For example Visa’s executive vice-president for Southeast Asia in a recent interview said: “we found that US$3 billion is likely to be lost from the tourism industry in the region—but that is turning out to be a conservative estimate” (May-25, CNN).

Losses to the insurance industry from damage to property are expected to be limited due to the low penetration of earthquake insurance in all the affected countries. For example insurance penetration as a percentage of GDP in Indonesia is 1.49 per cent, compared with 10.81 per cent in Japan. However some losses will arise from hotels in Thailand, Sri Lanka and Malaysia that may have earthquake and business interruption cover as well as from life insurance and travel insurance related claims including thousands of tourists from around the world. Additional claims will arise from a number of major industries that have been impacted in several countries. Risk Management Solutions estimate that the total insured damage to property across all the affected countries will range between $2.5 and $3 billion. Life and health insurance costs are estimated to be less than $1 billion and travel insurance claims are estimated to be near $100 million (Jan-31, RMS Press Release).

Figure 1.14 shows the relationship of life loss to economic loss for the 29 most significant earthquakes around the world in the last 20-year period (1985-2004). A wide scatter is observed since economic losses in developed-industrialized economies are large and usually associated with limited life loss, while the opposite is true for developing countries. The December 26, 2004 earthquake occupies the rightmost side of the chart.

Table 1.6: Estimates of economic loss, and other vital statistics in the 11 affected countries.

Country	Population	GDP (billion US$)	GDP per head (PPP, US$)	Loss Estimate (misc. sources, million US$)	IMF Loss Estimate (million US$)
Indonesia[1]	238,453,000	758.8	3,200	4,500	4,500
Sri Lanka	19,905,000	73.7	3,700	3,500	1,000
India	1,065,071,000	3033	2,900	2,000	
Thailand	64,866,000	477.5	7,400	235	800
Maldives	339,000	1.25	3,900	1,300	400
Somalia	8,305,000	4.4	500		
Malaysia	23,522,000	207.8	9,000		
Myanmar	42,720,000	74.5	1,800		
Tanzania	365,888,000	21.6	600		
Seychelles	81,000	0.63	7,800		33
SUM	1,829,150,000	4,653		11,535	6,733

Note 1: Indonesia suffered additional losses due to the M8.7 earthquake near Nias Island on March 28, 2005. The government reported on April 8 that circa US$ 325 million would be needed to rebuild areas damaged by this earthquake that caused approximately 2,000 deaths.

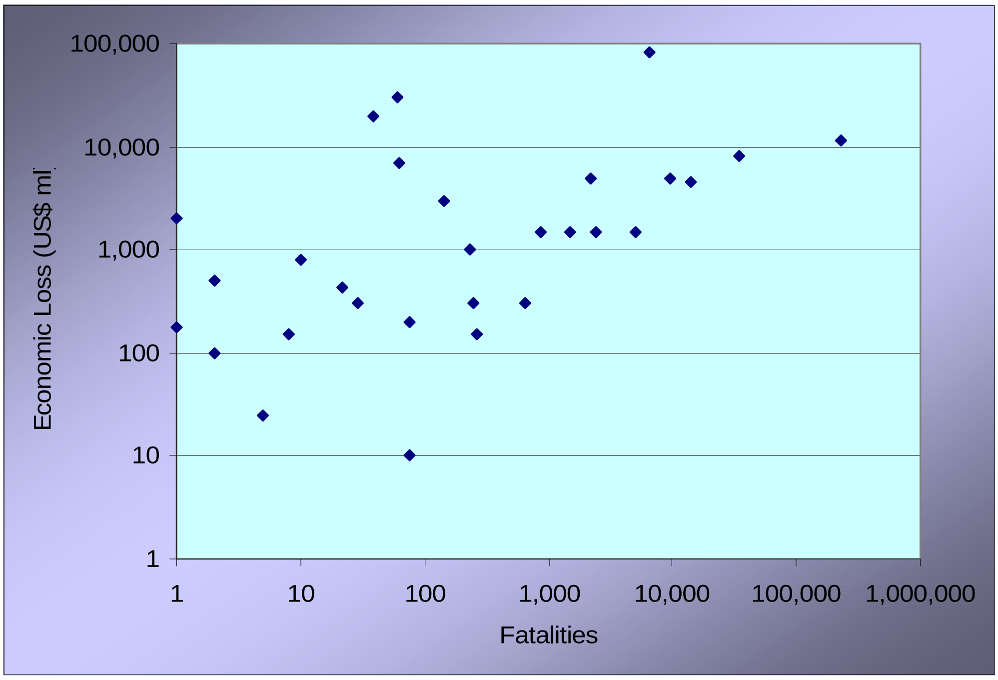


Figure 1.14: Economic loss versus life loss in 29 significant earthquakes in the period 1985-2004 around the world.

1.6.1 Agriculture and fishing industries

The The UN's Food and Agriculture Organization (FAO) reported at a workshop in Bangkok on March 31, that soil salinity in affected areas was less severe than previously thought. The FAO states that of the 47,000 hectares (ha) (116,100 acres) of agricultural land damaged by the tsunami in Indonesia, Sri Lanka, Thailand, Maldives, India and Thailand, some 38,000 ha (93,900 acres) can be cultivated this year, while the remaining 9,000 ha (22,240 acres), mainly in Aceh have been overtaken by the sea or can no longer be used (Apr-6, FAO).

The fishing industry is a very important economic sector in all of the affected countries. The FAO said that estimates from India, Indonesia, Maldives, Myanmar, Somalia, Sri Lanka, and Thailand put the combined costs of the fisheries sector alone at some US$520 million. FAO reports that it continues to provide direct assistance to farmers and fishermen. (May-19, FAO).

Below is a summary of the estimated damage to the fishing industry in the worst affected countries.

Indonesia

FAO states that 42,000 people in Aceh made a living from fishing and that fish provides over 50% of animal protein to the Indonesian population. 70% of the fishing fleet was destroyed by the tsunami, which requires at least 30 million US dollars to rebuild. More than 6,500 fishermen were killed and some 5,200 boats lost (FAO: Feb-18, AP).

The Asian Development Bank (ADB) on April 6, 2005 reported that damage to the agriculture and fisheries sector in Aceh and North Sumatra provinces had increased the number of poor by more than a million, raising the national head count ratio for the poor by half a percentage point to 18.7 percent. (Apr-6, AFP)

Sri Lanka

The ADB reported that the disaster led to significant job losses in Sri Lanka's fishing communities and small-scale traders, increasing the number of poor by 287,000 people and the national poverty level by 1.4 percentage points to 26.6 percent. In Sri Lanka 60% of the food protein comes from the fish diet. It is therefore very important that fishermen are helped to recover their losses so that they will be able to return to the sea (more details are given in Chapter 2).

Thailand

In total more than 2,400 fishing boats were damaged and 20,178 families directly involved with the fishing industry have been severely affected by the tsunami which ravaged six southern coastal provinces (Southern Coastal Natural resources Management Centre quoted in the Nation, Thailand's leading English language newspaper on December 30, 2004). The shrimp hatcheries industry was also severely affected, with reports that two thirds of the hatcheries in the three worst affected provinces (Phang Nga, Phuket and Ranong) have been damaged (Jan-8, The Nation). Thailand is the largest exporter of shrimp products to the United States. Fishermen in the southern seas of Thailand report that fish stock have seriously diminished, forcing many to look for other livelihoods (May-24, Bangkok Post).

Maldives

Eight percent of the fishing fleet was damaged.

1.7 The Pace of Recovery and the Distribution of International Aid

Jan Egeland, the UN Under-Secretary General for Humanitarian Affairs and Emergency Relief Coordinator, said on April 6, 2005 that the initial response to the tsunami disaster was successful, but the problem now was to maintain the momentum of aid. "There is in some communities a growing frustration. They have heard of the large sums of money pledged but they have not yet got their house rebuilt nor their livelihood and it will take more time," Egeland said. Egeland states that the total international promise of aid totals US$6 billion, although much of this might take years to materialize.

"I think it will be a difficult period that we are now entering. After a successful emergency relief phase and before we really get a development phase going, there will be several months of transition", (Apr-6, Reuters). The amount of money raised for the affected countries has in the meanwhile continued to grow reaching US$9 billion thus far (May-20, Reuters). Hence the money raised to date approaches some of the high economic loss estimates. It is clear that the critical issue now is to ensure that these donations are distributed in accordance with the real needs and used in the best possible way for the rapid recovery of the affected regions.

The Asian Development Bank (ADB) reported a US$4.22 billion shortfall in the US$7.76 billion estimate for required funds to help rebuild the four countries worst-affected by the Indian Ocean tsunami disaster: India, Indonesia, the Maldives, and Sri Lanka. To date, donor nations and agencies have committed US$3.54 billion. At an ADB-organized conference in Manila on March 18, the ADB presented its data in a "Tsunami Recovery Tracking Matrix". An ADB spokesman acknowledged that while the matrix was not definitive, it is hoped that it will be used as a fundamental planning tool, to obtain a broad view of what is needed, where it is needed, and how much it will cost.

The UN reported that humanitarian assistance to tsunami-affected countries totalled US$6.28 billion. The UN states that US$935 million of the US$977 million promised to meet a UN flash appeal for 6 months has been paid or committed for payments (this was later raised to US$ 1080 million), with private contributions totalling US$63 million. UN says it already has some US$550 million in the bank. (Mar-1, IHT, Feb-25, Reuters). The multinational development banks, namely the World Bank (WB), Asian Development Bank (ADB) and the Islamic Development Bank (IDB), are also providing US$412 million, US$675 million and US$500 million, respectively. The Organization of Islamic Conference (OIC), along with support from the Islamic Development Bank (IDB), has pledged some US$145 million for Indonesia's Aceh province, which is largely to be spent on children orphaned by the tsunami. (Feb-20, AFP). The International Federation of Red Cross and Red Crescent Societies (IFRC) on May 9 launched a US$1.2 billion 5-year plan to help 10 countries to rebuild (May-24, Reuters).

The pace of recovery is varied from country to country due to differences in response capabilities and availability of resources. As seen from the per capita income figures in Table 1.5, among the severely affected countries (Indonesia, Sri Lanka, India, Thailand and the Maldives), Thailand is the one country with most resources available and where the effects of the disaster were particularly severe only in small part of the country. The Thai government has thus rather honourably declined any foreign aid saying that resources should be directed to the other affected countries. In India, where 7% of the disaster's total life loss occurred, there is significant experience in disaster management due to the high frequency of earthquakes and monsoon floods. India is thus proceeding reasonably and was also efficient in its immediate relief operations. In Indonesia the scale of the problem is at a different level. The effects of the disaster were very severe and the task facing the Indonesian authorities is an immense one, exacerbated by the fact that in the Aceh province there is an on-going problem related to the local pro-independence movement (which was ongoing even at the time of the 1883 Krakatau eruption). Sri Lanka also has a severe problem since around 60% of its coastal population has been affected and 553,000 people are internally displaced (2.8% of Sri Lanka's population).

Below there are some more details on the recovery efforts in Indonesia, Sri Lanka and Thailand.

<u>Indonesia</u>

The road between Banda Aceh and Meulaboh was re-opened in late March, now containing 64 temporary bridges and 80-km of completely new road surface that is still to be asphalted. On March 8, 2005 Aceh Governor Azwar Abubakar said that the Government of Indonesia (GoI) will stop building shelters in Aceh and instead focus on making sure existing ones have proper sanitation and clean water. He says that the decision was reached after many survivors indicated that they would rather stay with relatives than in temporary housing. Survivors had also expressed concerns that the housing centres were too far from places where people would seek employment. The government had planned to house some 100,000 people in at least 24 temporary centres across the province. It was unclear how many had been built so far. However, in February, the Jakarta Post reported that some 3,281 families, or more than 11,500 people, were moved into more than 300 temporary barracks in Banda Aceh, Aceh Besar, Sigli, North Aceh, Aceh Jaya and West Aceh. GoI had planned on building some 803 semi-permanent barracks to accommodate the displaced for up to two years. Social Welfare Minister had said that after construction of the barracks, work would start on a second phase during which some 800,000 houses, each measuring some 387 square feet (36 square meters) would be constructed. Plans had some 30,000 of the houses to be built around Banda Aceh and 10,000 in Calang on the west coast.

The Indonesian President has appointed members to an agency which will oversee the reconstruction of the Aceh province, called the Rehabilitation and Reconstruction Agency (BRR-Badan Rehabilitasi dan Rekonstruksi) for Aceh and Nias. The National Development Planning Minister said that the agency should work according to a reconstruction blueprint adopted on April 15 as the master plan for reconstruction and that the new agency will be completely transparent to prevent corruption (May-9, Reuters, BBC). The BRR head said that around US$1.2 billion in foreign aid is ready to be spent on reconstruction projects in Aceh. This was pledged by the Consultative Group on Indonesia, made up of 30 international lenders. The GoI has yet to disburse its own aid for rebuilding (a fund of US$ 635 million) because it was awaiting approval from parliament (May-19, Reuters).

Sri Lanka

The Government of Sri Lanka (GoSL) said on March 23, that reconstruction has been delayed because donor aid is slow in arriving and aid agencies are reportedly still discussing a draft rebuilding plan released in January. The GoSL plan involves building some 62 townships, 75 miles (120 km) of electric railway, improving 55 miles (89 km) of highway and granting assistance to affected families to rebuild housing. The Chairman of the GoSL Taskforce for Rebuilding the Nation estimated that it will take 6-9 months to build houses, 1-3 years to build roads and a modern water supply system, and another 1-3 years to build new railway lines. The Finance Ministry said that it had received less than US$100 million in aid so far (Mar-23, Reuters).

Over 516,000 people remain displaced; over 100,000 still in camps or shelters, over 400,000 now living with relatives or friends (Mar-24, Reuters). Nearly 72,000 children and 2,700 teachers have been affected. More than 1,000 children were orphaned and at least 3,600 lost one parent (Mar-9, DPA). According to the GoSL the number of people living in tents and relief centres has dropped to around 50,000 and that temporary housing has been completed for 77,000 people (April-28). On May 16, GoSL announced that donations and debt relief (combined) reached some US$ 3 billion for a period of 3 to 5 years. This sum is nearly double that estimated by GoSL for reconstruction needs. The extra funds are intended to help Sri Lanka tackle poverty and rehabilitate war-ravaged parts of the country (May-20, Reuters). Recently it was reported that the prices of building materials have been rising sharply (Jun-1, Reuters).

Thailand

UNICEF reports that the number of people in temporary camps/shelters (6,000 as counted by field officers) continues to fall, and continuing emergency needs for affected population are largely met. According to the Ministry of the Interior a total of 791 permanent homes have been completed, with another 2,067 under construction. 200 permanent homes have already been built in the Phang Nga province, mostly by the military. According to the Royal Thai Army, troops based in Phuket will complete construction work on permanent housing by August. The Ministry of Interior also reports that 3,833 non-residential buildings were damaged by the tsunami but 2,430 can be repaired (May-27, UN).

The government is in process of creating a coastal management plan for the Andaman provinces, which includes a zoning plan with structures limited to 10 meters (33 feet) from shoreline (May-27, UN).

Lack of a comprehensive government plan for reconstruction and clean-up continues to hamper reconstruction in Phi Phi and Khao Lak (Phang Nga). Many small business owners say they have yet to see the 60 million baht (US$1.5 million) in emergency bank loans from the government's Bank of Thailand (May-27, The Nation).

The Marine and Coastal Resources Department says that the removal of garbage from various coral reef sites is 90 percent complete. Overall damage to coral reefs was reported at less than 15% (May-15, Bangkok Post).

1.8 Indian Ocean Tsunami Warning System

The International Coordination Meeting for the Development of a Tsunami Warning and Mitigation System for the Indian Ocean within a Global Framework was held at UNESCO Headquarters between 3 and 8 March 2005. The Meeting was attended by nearly 300 participants from 21 countries in the Indian Ocean region, 25 other International Oceanographic Commission Member States, 24 organizations, and 16 observers. The Meeting ensured that Indian Ocean Member States are fully informed, at the technical level, on tsunami warning and mitigation programs that are in place at the national, regional and global levels. The Meeting adopted a communiqué that provides guidance to all partners regarding the required actions that will lead towards the establishment of an Indian Ocean Tsunami Warning and Mitigation System. The Meeting also recommended the establishment of an Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System and drafted Terms of Reference for the Group. The full report of this meeting can be found at: http://ioc.unesco.org/indotsunami/paris_march05.htm.

Following this meeting the Asian Disaster Preparedness Center (with strong support from the Royal Thai Government) is establishing a regional multi-hazard end-to-end tsunami warning system for Southeast Asia. The countries participating in this system are Cambodia, Myanmar, Thailand, Vietnam, and Lao PDR (for multi-hazard). China, the Philippines, and Singapore are technical support partners. The technical design of the US$5 million system was completed in April 2005. Development of the regional monitoring and observation network has begun, with the installation of a tide gauge station at Koh Taphao Noi, near Phuket, in October 2005, under the IOC Global Sea Level Observing System. The station, now operated and maintained by the Royal Thai Navy, was established with the support of UNDP (Thailand). The Voluntary Trust Fund, created by the Royal Thai Government, will support the establishment of other network elements, while several funding agencies have been approached by ADPC to support community preparedness and disaster mitigation activities in the participating countries.

1.9 Acknowledgements

The authors of this Chapter would like to express their gratefulness to the following:

Dr. Robert Muir-Wood (Risk Management Solutions, Chief Research Officer) for reviewing the Chapter.

Dr. Pennung Warnitchai (Asian Institute of Technology, Thailand) for providing the latest information related to the Asian Disaster Preparedness Center's plans for a Tsunami Warning System.

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2 Sri Lanka

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2.1 Introduction to Mission to Sri Lanka

The Indian Ocean Tsunami that followed the northern Sumatra Earthquake on December 26, 2004 resulted in substantial damage and casualties in the populated coastal areas of Sri Lanka. The EEFIT team arriving on January 23, 2005 spent four days surveying the coastal areas of southwestern and southern Sri Lanka between Colombo and Dondra (see Figure 2.1). This chapter discusses the damage observations to buildings, lifelines, hospitals and healthcare facilities, schools, ports and industrial facilities followed by the impact on the society, the economy and the recovery process. The Eastern province was not visited due to time and resource constraints. However, the observations and information on damage in these provinces obtained from various sources are discussed in order to draw comparisons with the observations in the EEFIT surveyed areas.

Figure 2.1: EEFIT survey area in the southwest and southern Sri Lanka (shown in red).

2.2 Brief Damage Observations for the Region between Colombo and Dondra

The following sections provide a brief description of the overall damage observed by the EEFIT Team in Sri Lanka. Detailed descriptions of the structural types and damage scale used are given in Section 2.4. More detailed descriptions of the damage observed in some of the locations mentioned below are also given in Section 2.4.

2.2.1 Western Province

The Western Province contains the districts of Gampaha, Colombo and Kalutara (listed from north to south, see Figure 2.44). Some wave activity was reported along the coast from the Capital Colombo to Negombo in the Gampaha district near the Bandaranaike International Airport. However no structural damage was reported in this region with only one death reported.

2.2.1.1 Colombo District

Although casualty figures in Colombo district were very low (70 deaths, 64 injured and 12 missing), the number of persons displaced was 31,239. This may be attributed to inundation causing damage to homes though people were able to escape the incoming waves.

Colombo to Moratuwa

Inundation was observed along the coast between Colombo and Moratuwa with water reaching inland up to the Colombo to Matara railway line, which runs close to the shoreline in this region. There was structural damage to houses reported in isolated low-lying areas of Mount Lavinia and Wellawata.

Moratuwa

Continuous damage from the tsunami starts just south of Colombo, in the town of Moratuwa. This is the southernmost town in the Colombo district, close to the boundary with Kalutara district. Damage was concentrated on the coastal side of Road A2, where a number of low cost houses, perhaps of local fishermen and other relatively low income people, had settled on a narrow strip of land between the beach and the railway line. The main construction types are unreinforced masonry (URM) houses and timber dwellings. Almost all the coastal houses within 20-30m from the sea have been destroyed. The typical failure mechanism involves firstly the loss of load-bearing masonry stability due to inward out-of-plane collapse of the masonry wall panels from tsunami wave pressure, followed by the collapse of the roof. A few low-rise reinforced concrete frame houses are still standing with gaping holes in the place of the infill panels.

2.2.1.2 Kalutara district

This is the district worst affected by the tsunami in the Western province. The number of people killed and missing in this district was 256 and 155 respectively, with an additional 400 people injured and an estimated number of displaced persons at 27,713 (Source: Centre for National Operations, CNO, Sri Lanka). There are about 35 kilometres of Indian Ocean coast in this district. The main coastal towns are: Panadura, Wadduwa, Kalutara and Beruwala. Kalutara is 42-km south of Colombo and was once an important spice-trading centre controlled in turn by the Portuguese, Dutch and British during the 16^{th} to 20^{th} century period. Beruwala and Bentota (just to the south of Beruwala) are Sri Lanka's most important tourist resorts catering primarily for package tours. Beruwala, 58-km south of Colombo was the first Muslim settlement on the island, dating back to 1024AD and is the site of an important mosque. In Beruwala there is a small fishermens' and yachting port protected by massive rock fill breakwater structures.

Much of Road A2 between Moratuwa and Beruwala, runs several hundred metres inland and therefore much of the coastal damage could not be easily inspected. Linear town development takes place along the whole stretch of Road A2 in Kalutara district, with mostly detached housing and small commercial establishments, a characteristic that continues all the way to Dondra.

Paiyagala village

Driving south from Kalutara town it is clear that the level of tsunami inundation is becoming more and more severe with the first signs of devastation seen in Paiyagala village. This is the first coastal village on Road A2 south of Galle that was clearly devastated by the force of the tsunami. Its location is on the coast spreading out on either side of the road and the railway line roughly midway between the towns of Kalutara and Beruwala. Almost all of the masonry buildings adjacent to the roadway collapsed or were severely damaged, although some concrete frame 2-storey houses survived virtually intact. Extensive but repairable damage extended for about 200m inland of the coastal road. Evidence of flood inundation is visible up to 700m and according to local witnesses may have reached 1km. In general the damage to masonry was concentrated on panels facing the sea, whilst those perpendicular to it remained standing (see Figure 2.2).

Figure 2.2: Typical damage to brick masonry walls parallel to the coastline, observed in Paiyagala (Kalutara District)

2.2.2 Southern Province

The Southern Province contains the districts of Galle, Matara and Hambantota (listed from west to east, see Figure 2.45). Along with the Eastern and Northern provinces they form the worst affected parts of Sri Lanka where more than 95% of the life loss occurred. The number of people killed and missing in this province was 10,058 and 2,130 respectively, with an additional 7,326 people injured and an estimated number of displaced persons at 159,195 (Source: CNO).

2.2.2.1 Galle district

The first town entering Galle district from the north on Road 2 is Bentota, a tourist resort town. In this town there are two old railway bridges at the crossing of the river Bentota Ganga.

Bentota to Ambalangoda

Driving south from Kalutara town it is clear that the level of tsunami inundation is becoming more and more severe with the first signs of devastation seen in Paiyagala village as described earlier. Damage similar to that of Paiyagala is seen in parts of a 10-km stretch of road between Induruwa and the town of Balapitiya, including the tourist village of Kosgoda and the village of Ahungalla. The variation in damage severity along the coastal road is significant. Some locations such as just south of Ahungalla are devastated while others have less severe damage. Again damage to the masonry houses is most severe. Entering the main street of Balapitiya town (at this point the road runs approximately 500m inland) there is no damage except for some houses close to a river running between Balapitiya and Ambalangoda. On the stretch of road between Ambalangoda and the main tourist resort of Hikkaduwa there are many coastal hotels that have suffered some significant damage.

Ambalangoda to Hikkaduwa

Entering the main street of Ambalangoda town (approximately 500 m from the coast) there is no damage, but at the point where the road nears the beach, about 1-km south of the town centre, extensive damage is observed. In this locality a large group of local people wearing USAID T-shirts and hats were seen working on general clean-up of the area. Between Ambalangoda and Hikkaduwa there is a small fishermens' village called Kahawa that was seriously damaged. Building failure was mainly caused by a combination of deep scouring beneath the foundations and inundation (see Figure 2.3). Fishing boats had also been transported inland by the tsunami and just south of Kahawa there is a low-lying and small truss iron road bridge that has apparently been damaged but is now repaired and passable. In the stretch of road between Kahawa and the town of Hikkaduwa there is extensive devastation. Since this was the area with the greatest observed damage, the team ventured further inland to observe the extent of the affected area. It is within this stretch of land that a train bound for Matara was derailed by the tsunami waters, some 200 metres from shore, causing numerous casualties. Buildings beyond the railway line also suffered extensive damage however the damage in Hikkaduwa itself is fairly moderate. The town is among the most popular resorts in Sri Lanka and well known for the underwater attractions of the coral reef. It has grown to overtake the villages to its south and now stretches 3-4kms (toward Dodanduwa). Similar to Bentota, there is a coral reef sanctuary just 200m off the coast that may have significantly affected the way the tsunami acted on this stretch of coast. Damage in the southern part of town (between Thiranagama and Dodanduwa) certainly did not seem as serious as one might expect and this can probably be attributed to the natural breakwater protection offered by the coral reef. It should be noted that hotels along the coast suffered minor structural damage and were open to tourists at the time of the field mission.

Figure 2.3: Scour damage seen in Kahawa (Galle District)

Hikkaduwa to Galle

Damage is again very serious on the stretch of road between Boossa, Gintota and all the way to the entrance to the city of Galle.

Figure 2.4: Damage to masonry houses in Galle City

Galle City

The historical port town of Galle lies 115km south of Colombo and is home to 92,000 people. It is dominated by an 89-acre Dutch Fort, built in 1663, with its massive ramparts located on a promontory at the west entrance to the city. The fort sustained no visible structural damage, although flood damage to the museum within the fort walls has been reported. The main town is built along the coastline of the harbour bay between the Dutch Fort (to the west) and the main port (to the east). Heavy damage was observed in the first row of buildings facing the sea. These are located about 30m from the shore at an elevation of about 1m above mean sea level. The depth of water within the harbour ranges from 10m at the mouth of the harbour to 2m at the coastline. In Galle town centre, the main building types are low and mid-rise RC infilled frames of typically low quality construction with mixed commercial and residential use. A few buildings collapsed and many lost infill panels facing the seafront or sustained significant damage to the ground storey windows and shop fronts (see Figure 2.4). A fish market building consisting of a wooden truss roof supported on poorly constructed 400mm diameter circular masonry columns was also destroyed along the coast. Also collapsed were the lightly reinforced concrete bus stands at the main bus station, (scene of the widely reported and played video footage transmitted by various news organisations). Collapse of buildings and flood damage was observed to extend further inland towards residential areas located to the east of the main town.

The buildings and the quay walls at Galle Harbour, whose main purpose is to serve as a distribution point to the local cement plant, survived the incoming waves of the tsunami from both the east and west. A scour hole about 10m wide and extending 20m back from the eastern quay wall was visible however, no damage was observed to the quay wall itself. A cargo ship, with an approximate displacement of 500t, was washed up on to the quay wall in the northeast corner of the harbour and some other vessels were dragged about 300m from the quayside. However, the harbour was fully functional within days of the event and the cement plant did not suffer any structural damage. Although the inundation rose to approximately 3m above high water level and damaged the manufacturing plant this was replaced within one week of the event and the plant itself was back in operation, manufacturing cement, within 10days.

Galle to Unawatuna

Travelling south from Galle, the main road remains some distance back from the coastline before reaching the town of Unawatuna. The village is a popular location for tourists due to its flat sandy beaches and coral reef that stretches across the mouth of the bay. Generally, the damage observed consisted of partial collapse and generally moderate levels of structural damage to many of the homes. As expected heavier damage was experienced by the first row of buildings close to the shoreline.

Figure 2.5: Damage to hotel structures observed on the beachfront of Unawatuna (Galle District)

Figure 2.6: Evidence of Liquefaction damage to a small public utility building in Unawatuna (Galle District)

The building types in Unawatuna generally consist of commercial developments with a mixture of hotels and restaurants constructed from a combination of masonry and reinforced concrete. An example of foundation failure to a two storey concrete building on the shore is shown in Figure 2.5. This building was extremely close to the shoreline and was founded on very soft sand. It is believed that the damage was either due to scouring of the foundation or possibly liquefaction. Further evidence of liquefaction was witnessed approximately 200m from this location and is shown in Figure 2.6.

Unawatuna to Habaraduwa

The town of Dalawella is located 3km east of Unawatuna, on the road to Habaraduwa, and experienced the total collapse or severe structural damage to most houses within 300m of the shoreline. The construction is generally single storey dwellings consisting of either low-rise RC frame or poor quality masonry construction. Further along the coast is the town of Habaraduwa that although having a very flat coastline, has not been hard hit by the tsunami with only some sporadic flood damage observed in very poorly constructed masonry single storey dwellings. The local coastal bathymetry obviously has an important role in determining the level of damage experienced by either amplifying or attenuating the strength of the tsunami.

Habaraduwa to Weligama

The coastal region between Habaraduwa and Ahangama is sparsely populated. An airbase is located at Koggala between the two villages, but was observed to have sustained no visible damage. The buildings in Ahangama are again mainly single storey masonry dwellings. Severe damage is observed in about 70% of the houses within 200m of the sea. Very little damage is instead observed in the houses located in the wake of a breakwater along the east side of the city. Minor damage is also observed in the vernacular houses of Dehawalla where the houses are on land raised 4m above sea level. Little damage is observed all the way to the entrance to Weligama.

2.2.2.2 Matara district

Weligama

Weligama is the first main city within Matara district to be reached travelling south along Road A2. At this location rocky formations are visible offshore but a very flat coastline leads up to the first row of houses, set back about 30m from the shoreline. Most of these buildings are observed to have collapsed, with significant damage and partial collapse visible to vernacular houses up to about 300m inland. One, two storey, reinforced concrete frame in the first line of houses consisting of 400mm square columns and 300mm wide by 500mm deep beams under construction at the time of the tsunami survived with intact masonry infill panels and only minor damage to the timber shutters facing the sea.

Weligama to Matara

Travelling from Weligama to Matara extensive damage was observed along the coast between Mirissa and Kamburugamuwa. In the latter location there is almost total collapse of all vernacular houses up to about 400m from the shoreline. Moving along the coastal road from Kamburugamuwa to Matara heavy damage is also observed up to a distance of approximately 50m inland from the sea. The buildings types consist of low-rise RC frames and superior quality masonry, and typically show damage consisting of loss of all windows, doors and masonry panels facing the sea and in many cases extensions, porches and outhouses have been swept away. Matara is the largest town on the south coast of Sri Lanka, is inhabited by 42,000 people and is a popular tourist destination. The town does not have a large sea frontage and has generally not been affected by the tsunami. The team was able to run along a stretch of road along the sea where no structural damage is visible to large masonry houses and schools.

Matara to Gandara via Dondra

Dondra lies on top of a promontory and supports a lighthouse that defines the southernmost point of the Sri Lankan coast. It is known as the "City of the Gods" and is famous for the 7th Century AD shrine (which has survived the tsunami). The main road runs some distance from the coast due to the hilly nature of the topography. Any damage to smaller settlements on the coast is not apparent. However, where the road descends towards Gandara beyond Dondra Head the coast is again flat and settlements suffered severe structural damage. Fortunately, this area is only sparsely populated.

2.3 Run-up Data and the Characteristics of the Tsunami in Sri Lanka

2.3.1 Tsunami Water Level, Run-up and Inundation

Observations of the tsunami maximum water level, run-up height and inundation distance were made by the EEFIT team at several of the visited locations. Fallen trees and discoloured vegetation provided evidence of extent of inundation while mud traces on buildings, hanging debris and consistent levels of uplifted roof tiles were used as indicators of the tsunami water level. An example of the water level measurements carried out by EEFIT is shown in Figure 2.7 and Table 2.1 summarizes some measurements taken by EEFIT during their survey.

Figure 2.7: Example of the water height measurements carried out by EEFIT

Several research teams visiting Sri Lanka have also carried out measurements of inundation and run-up in collaboration with local university teams. Kyoto University Disaster Prevention Research Institute (KUDPRI) carried out a survey in the western and southern provinces stretching from Kalutara to Matara between January 4 and 6, 2005. The geographical distribution of the tsunami water levels measured by KUDPRI is shown in Figure 2.8. The highest water level of 10m in the above survey was recorded in Peraliya, at the location of the train disaster. Table 2.1 compares EEFIT and KUDPRI measurements, which shows a reasonably good correlation between the measured water levels of the two teams. It is interesting to observe that in Galle Port the water level measured increases with distance from the sea contrary to expectation. This may be due to a particular topographical feature or an erroneous recording.

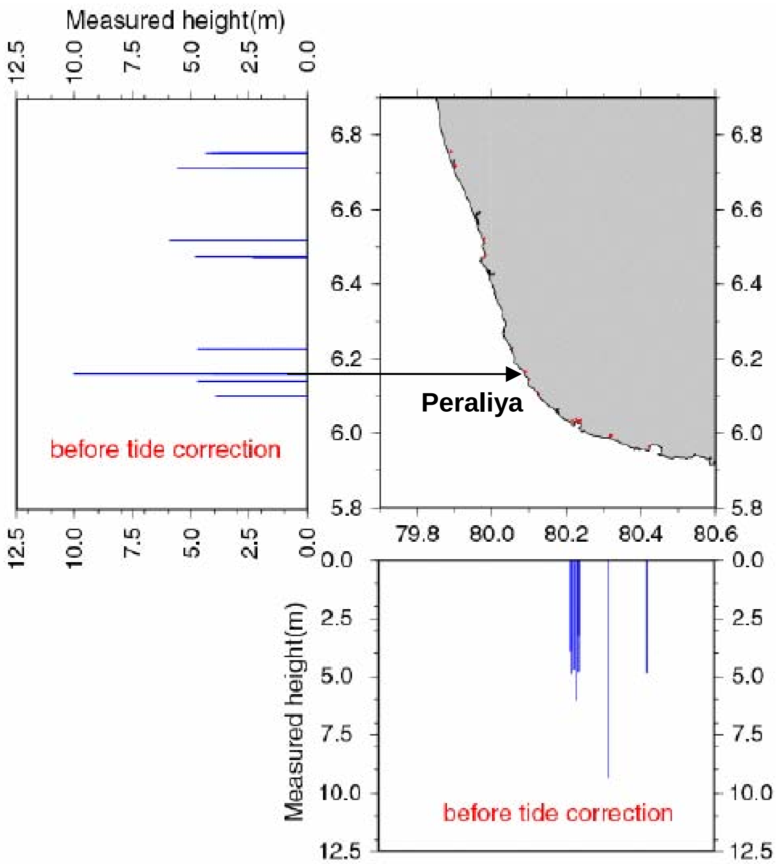


Figure 2.8: Water level measurements made by KUDPRI in Sri Lanka

Table 2.1: Comparison of run-up measurements (above msl) made in the Western and Southern Provinces by EEFIT and KUDPRI (shaded). (Note: These measurements are presented as being those before tide correction).

No	Location	Latitude (N)	Longitude (E)	Measured Height (m)	Distance from Shoreline (m)	Note
1	Paiyagala	6° 31' 10.4"	79° 58' 35.3"	3.64	60.0	Mud trace on side of building
	Paiyagala Station	6° 31' 18.4"	79° 58' 42.2"	5.95	36.0	Traces of the wall on the second floor
2	Peraliya	6° 10' 1.9"	80°05' 34.8"	6.0	800.0	Mud trace on wall of chimney
	Peraliya	6° 10' 1.9"	80°05' 34.8"	10.0	10.0	Mud trace on wall
3	Galle Port	6° 02' 01.4"	80° 14' 01.3"	5.05	50.0	Mud trace on wall of harbour office
	Galle Port	6° 01' 57.8"	80° 13' 58.0"	5.28	20.0	Trace inside the building
	Galle Port	6° 01' 57.8"	80° 13' 58.0"	6.03	190.0	Trace on the outside wall of the office

Yokohama National University (Japan) in collaboration with Ruhuna University in Galle carried out measurements of tsunami water levels from Galle to Hambantota extending to Yala National Park. Figure 2.9 shows their measurements corrected for the astronomical tide levels where the highest water level of about 11m on the southeastern part of the Island was measured in Hambantota harbour.

Peradeniya University (Sri Lanka) and Sungkyunkwan University (Korea) jointly carried out a tsunami inundation distance and run-up height survey from February 20th to 26th, 2005 where measurements were made at 25 locations throughout the island while recording eyewitness accounts of overland flow (Wijetunge, 2005). The measurements of inundation were then compared against the inundation distances obtained from ESRI satellite image vector data. A good comparison was obtained between the field measurements and the ESRI vector data hence an inundation map based on ESRI data was produced as shown in Figure 2.10 covering almost all of the tsunami affected coastline in Sri Lanka. Table 2.2 shows the inundation at selected locations around the coast from southwest to the northeast. The map shows that inundation was greatest in the east coast near Batticoloa where inundation distances were close to 4km. The greatest inundation in the south was observed in Hambantota. In the south-west, the largest inundation was deduced to be just under 1km in Galle and just north of Hikkaduwa possibly at Peraliya where a 10m high water level was recorded by KUDPRI. Generally the tsunami water levels measured by the Peradeniya/ Sungkyunkwan team at the shoreline were 4-6m in the Jaffna Peninsula, 5-7m in the east coast, 3-6m in the south coast and 4-5m in the west coast.

The overall pattern of tsunami water levels and inundation distances indicates that there is a considerable variation throughout the island even over short coastal stretches. Both tsunami water level and inundation distance depends on a number of factors; the travel path of the tsunami waves, the energy focusing effects (wave refraction and diffraction), the shape of the coastline, near-shore bathymetry, land topography and surface roughness, etc. For instance the eastern areas (Kalmunai, Batticaloa) experienced greater inundation since the tsunami came head on and the water levels were generally high and the terrain was low lying to a considerable distance inland (JPL-NASA, 2005).

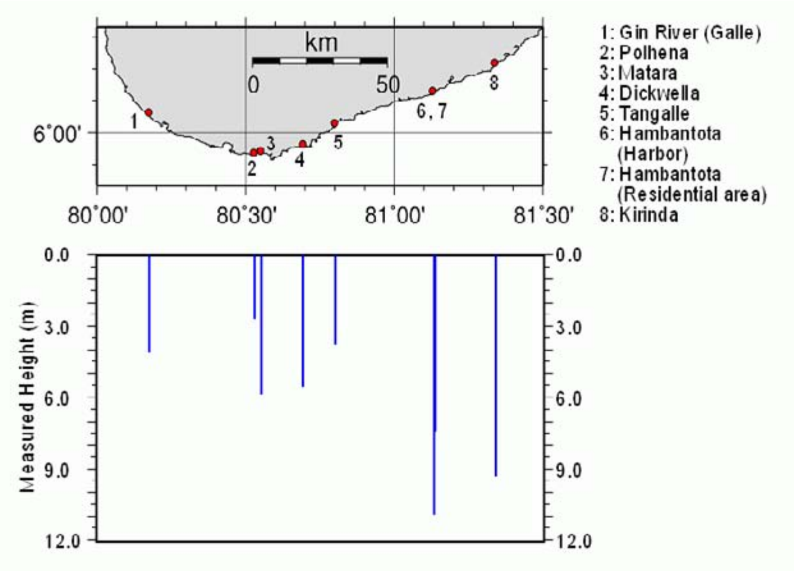


Figure 2.9 Water level measurements made by Yokohama National University and Ruhuna University

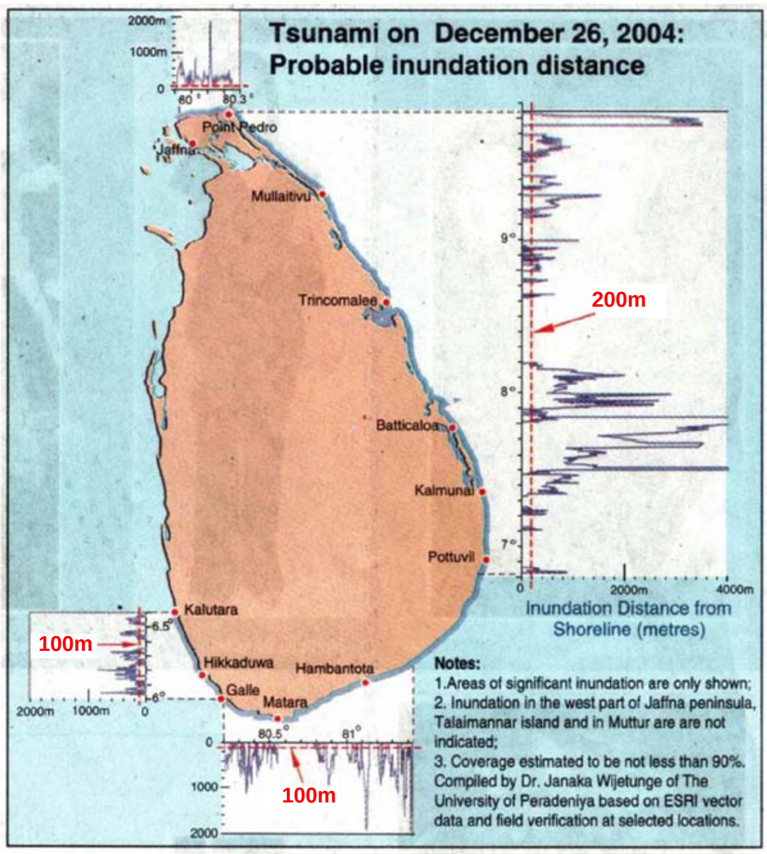


Figure 2.10: Inundation distance from ESRI vector data based on field measurements made by University of Peradeniya and Sungkyunkwan University

Table 2.2: Tsunami inundation around Sri Lanka

Location	Inundation (km)
Kalutara	0.4
Peraliya	0.9
Galle	0.8
Weligama	0.4
Matara	0.4
Tangalle	1.0
Hambantota	2.0
Pottuvil	0.9
Kalmunai	4.0
Batticaloa	4.0
Trincomalee	0.6
Mullaitivu	1.3
Point Pedro	3.4

2.3.2 Characteristics of the Tsunami

The characteristics of the tsunami that hit Sri Lanka differed considerably along the coastline given its direction of arrival from northern Sumatra. The tsunami that arrived in the eastern, northeastern and southeastern coastal stretches of Sri Lanka was in the form of a wave of considerable height and velocity resulting in significant extents of inundation inland. The tsunami waves that arrived in the southwest and western coastal areas were the result of refraction around the southern continental shelf of Sri Lanka coupled with localized diffraction. This resulted in considerable variability in the nature of tsunami where some areas experienced a massive tidal wave whereas other areas experienced a series of tidal waves with rising water level leading to inundation inland. The eyewitness accounts taken during the survey provided proof that there was considerable variability in the characteristics of the tsunami that arrived in the west and southwest coastal areas. This information together with the measurements of tsunami water level, run-up height, inundation distance, extent of damage and casualties are crucial in determining the tsunami hazard in these areas from a tsunami originating in northern Sumatra.

Figure 2.11: Photo of receding tsunami taken at Beruwala fishing harbour, Sri Lanka. Stagnant water from the earlier tsunami waves (Hamza, 2005)

The eyewitnesses in the surveyed areas claimed that there were at least three waves. This is consistent with the accounts reported by Spence and Pomonis (2005) based on 11 eyewitness reports between Galle and Weligama. The first two waves resulted in moderate inundation providing a warning of unusual sea behaviour, which prompted them to runaway to safety. The third wave (second in some accounts) was preceded by the sea receding to a considerable distance from the normal shoreline. Figure 2.11 shows an image of the recede captured on an eyewitness video at the Beruwala fishing harbour (Hamza, 2005) where the boats in the harbour were dragged away to the sea from the strong turbulent currents of the water receding away. Figure 2.11 also shows stagnant water behind the harbour probably from the earlier tsunami waves.

Figure 2.12: State after the tsunami waters have receded before the big wave (Hamza, 2005)

The fact that many people are wandering around in the exposed seabed as shown in Figure 2.12 is evidence that the recede has taken place for at least 15min at this location, which is consistent with the eyewitness accounts taken from the fishermen at the harbour. The extent of the recede was about 300m as seen by the satellite image captured in Kalutara shown in Figure 2.13, which is located 20km north of Beruwala.

Figures 2.14 shows the advancing tsunami waves following the recede as captured by the eyewitness video (Hamza, 2005). More waves followed with the momentous rise of the sea level following some wave arrivals. Figure 2.15 shows the tsunami waves arriving near the Beruwala harbour that inundated the Route A2. At this instant the fishing harbour in the distance was completely inundated. Figure 2.16 shows the state of the rockfill breakwater at the Beruwala fishing harbour when the recede took place and after the tsunami waves have arrived. The height of the water at this location could be estimated to be about 5m from the video images.

Figure 2.13: Satellite image of recede in Kalutara (Digital Globe, 2004)

Figure 2.14: Advancing tsunami waves following the recede (Hamza, 2005)

Figure 2.15: Arrival of more tsunami waves and inundation of Road A2 (Hamza, 2005)

Figure 2.16: State of the Beruwala fishing harbour breakwater during the recede and after the arrival of tsunami waves (Hamza, 2005)

Figure 2.17: Receding water at the Trincomalee harbour, Sri Lanka (Pillai, 2005). Drop in the water level at the Prima plant jetty

Figure 2.18: Arrival of a tsunami wave at the Trincomalee harbour (Pillai, 2005)

No video evidence is available in the public domain for the east coast. However, Figure 2.17 shows the emptying Trincomalee harbour in the northeast of Sri Lanka before the arrival of the big wave described by the eyewitnesses there (Pillai, 2005). The drop in water level seen at the Prima plant is about 2m exposing the piles of the jetty (Figure 2.17). The recede was followed by a series of advancing tidal waves similar to one that was photographed by an eyewitness as shown in Figure 2.18.

2.4 Surveys of Building Damage

EEFIT team has carried out detailed damage surveys at certain locations identified during the general survey as described in Section 2.2. These surveys involved identifying the building types, type of damage, extent of damage with location from the coast, evidence of tsunami water levels and inundation and gathering eyewitness accounts where possible. These detailed damage observations to buildings are described below with some analyses of the building damage observations. Additionally, a brief overview of damage in the Eastern province is presented to draw comparisons with the observations in the EEFIT surveyed areas.

2.4.1 Building Typologies in the EEFIT Surveyed Areas

The following is a description of the building typologies in the region between Colombo and Dondra. The division into the chosen building categories is indicative of different construction practice and observed building vulnerability. The observations described below are based on the inspection of many damaged buildings or buildings under construction.

2.4.1.1 Timber Light Frame Housing (Cat. A)

Timber light frame housing was found in some of the visited coastal areas. The structure consists of a timber frame where the wooden panels are attached to form the walls with a tiled or thatched roof. These houses are able to withstand the moderate wind conditions commonly existing in the coastal areas. However they are unlikely to survive lateral loads from gusty wind conditions hence they are most vulnerable to tsunamis.

2.4.1.2 Unreinforced Masonry Detached Housing (Cats. B and C)

Unreinforced masonry detached housing is very common throughout the coastal zones visited an example of which is shown in Figure 2.19. It consists of regular single storey dwellings that are free standing, varying in plan area but generally consist of a maximum of three rooms. The build quality of these houses varies where generally poor quality masonry structures (Category B) are made of semi-fired clay blocks (Figure 2.20). Good quality masonry construction (Category C) uses solid bricks (Figure 2.20) or cement blocks.

Figure 2.19: Example of the unreinforced masonry detached housing class of building

The average wall thickness is of the order of 250mm, but in some instances half-brick thick walls can be observed. The mortars generally exhibited poor strength due to low cement content and poor control during mixing. The thickness of the walls, quality of mortar and size and aspect of the bricks all influence the ability of the walls to resist wave impact and inundation loading. The wall footings are shallow and consist either of a thick reinforced concrete raft foundation or masonry strip foundations. The roof construction is normally assembled from pitched timber trusses, often up to 2m high, with clay tile covering and overhangs.

Figure 2.20: Semi-fired large clay blocks and solid bricks typically used for masonry construction

2.4.1.3 Low-rise Reinforced Concrete (RC) Detached Housing and Small Commercial Buildings (Cat. D)

These houses are non-engineered RC frames that are typically single or two storeys but can be seen to reach a maximum of 3 storeys in height. Both beams and columns typically have 250x250mm sections, which are reinforced with four smooth low-yield bars of about 12mm diameter and widely spaced 4mm ties with 90° hooks. Infill panels are masonry with materials similar to those described above for the unreinforced masonry building type and are not considered as structural members in their design. Figure 2.21 shows a typical low-rise RC detached house.

Figure 2.21: Example of the low-rise RC detached housing and small commercial buildings class of structure

2.4.1.4 Mid-rise Reinforced Concrete (RC) Non-residential Buildings (Cat. E)

These buildings have up to 6 floors and are designed according to the British Standards. The quality of construction is good and the buildings are subject to inspections from the Urban Development Authority during construction. Better detailing and larger load-bearing element dimensions than observed in the low-rise frames were seen. The occupancy of these buildings varies and they are mainly used as commercial and public buildings including large schools, hospitals, hotels and offices. Figure 2.22 shows an example of a mid-rise RC structure in Galle.

Figure 2.22: Example of mid-rise RC commercial building

2.4.2 Damage and Intensity Scales

The building damage observed in the southwestern and southern coastal areas of Sri Lanka was largely in unreinforced masonry structures (see Section 2.2). There is considerable difficulty in precisely defining the level of structural damage. Some structures that was able to resist the tsunami water force suffered structural damage due to scouring, which undermined the foundations leading to collapse into the newly formed scour holes. The structures that were severely damaged were either repairable or non-repairable. The following damage scale was therefore adopted in order to describe the direct structural damage to masonry structures and damage due to geotechnical failures. This scale is based on EMS98 but modified to account for damage typically induced by fast flowing waters. A similar damage scale is provided for reinforced concrete structures of Category D and E in Section 2.4.3.

- **No Damage (DM0) –** No visible structural damage to the structure observed during the survey
- **Light Damage (DM1)** – Damage limited to chipping of plaster on walls, minor cracking visible. Damage to windows, doors. Damage is minor and repairable. Immediate occupancy.
- **Moderate Damage (DM2) –** Out-of-plane failure or collapse of parts of or whole sections of masonry wall panels without compromising structural integrity. Masonry wall can be repaired or rebuilt to restore integrity. Most parts of the structure intact with some parts suffering heavy damage. Scouring at corners of the structures leaving foundations partly exposed but repairable by backfilling. Cracks caused by undermined foundations are clearly visible on walls but not critical. Unsuitable for immediate occupancy but suitable after repair
- **Heavy Damage (DM3)** – Out-of-plane failure or collapse of masonry wall panels beyond repair, structural integrity compromised. Most parts of the structure suffered collapse. Excessive foundation settlement and tilting beyond repair. Collapse of wall sections due to scouring and damage non-repairable. Structure requires demolition since unsuitable for occupancy
- **Collapse (DM4) –** Complete structural damage or collapse, foundations and floor slabs visible and exposed, collapse of large sections of foundations and structures due to heavy scouring

Figure 2.23: Photographs illustrating categories of damage DM1 to DM4 in unreinforced masonry structures in Sri Lanka

Figure 2.23 illustrates the typical damage associated with levels DM1 to DM4 for the unreinforced masonry structures in Sri Lanka. The above damage scale was also used for the timber light frame structures found in some of the visited coastal areas. Damage scale developed for Thailand in Section 3.4.3 was used to describe the damage to low-rise and mid-rise RC structures. Although many structures withstood the force of water from the tsunami with little or no damage, the damage to content could not be avoided due to inundation. The above damage scales developed are therefore limited to describing structural damage.

The EEFIT survey revealed that there is a considerable variation in the extent of damage to structures even over small areas. Many areas have a mixture of masonry and RC construction. In order to account for the variability in the building typology and extent of damage, a descriptive intensity scale was defined. This allows an objective assessment of the devastating force of the tsunami to be made and comparisons could be done between Sri Lanka and Thailand. The intensity scale was based on the EEFIT team on-site observations and the tsunami intensity scale of Papadopoulos and Imamura (2001). Section 3.4.3 provides further details of this intensity scale and Table 3.3 summarizes the intensity scale.

2.4.3 Detailed Damage Surveys – Paiyagala

The first sign of devastation while driving south of Kalutara along Road A2 is in Paiyagala where the road crosses over to the shore side and the railway line is now on the land side but running almost parallel to the road. Figures 2.24 shows the damage to masonry houses observed in this area. There were many collapsed houses (DM4) from the shoreline to Road A2 and even reaching the railway line at a distance of 100m or more. Near the railway line and more inland, there were many houses with masonry walls facing the sea collapsed. The collapse is such that these houses cannot be repaired (DM3) hence has to be demolished. Both poor quality (Cat. B) and good quality (Cat. C) masonry houses exist in this area, however most of the collapses and heavy damage was to Cat. B houses.

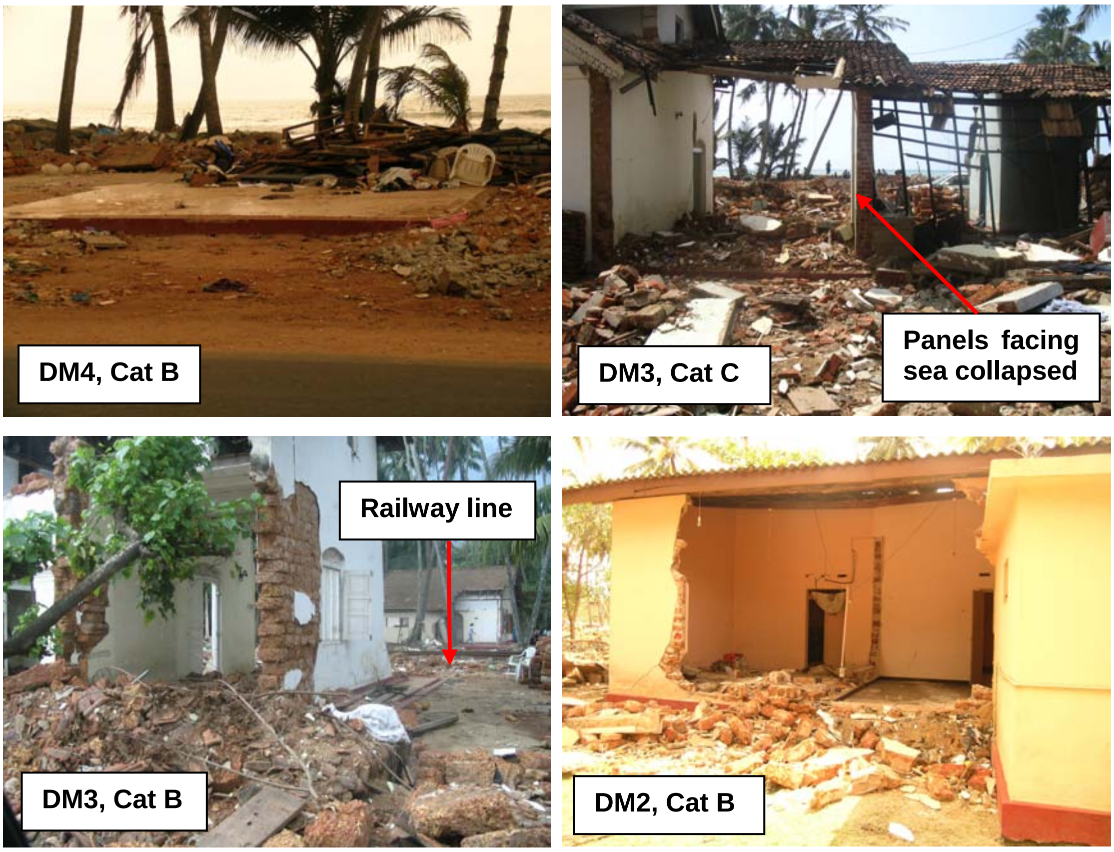


Figure 2.24: Damage to Cat. B and Cat. C masonry houses in Paiyagala, Sri Lanka

The extent of damage inland and evidence from changes to vegetation suggests that inundation at this location may have been as far as 700m from the coastline. Eyewitnesses stated that it was about 1km inland, which may have been the case as was seen from the satellite image shown in Figure 2.25 taken during the tsunami (Digital Globe, 2004). The water level measurement from the silt traces on the side of a masonry house that has survived was about 3.6m. Despite the magnitude and extent of damage, there were no evidence of erosion and scouring in this area. The railway line despite evidence of debris flow has remained intact. This may have been attributed to the surficial soils in the area, which appears to be dense sand or clayey sand. The sea is shallow in this area and there is a rock protection placed along the coast in most locations. The area is fairly dense with coconut trees and vegetation.

Figure 2.25: Inundation in Paiyagala (Digital Globe, 2004)

2.4.4 Detailed Damage Surveys – Kahawa, Peraliya, Thotagamuwa

The heaviest damage observed after Paiyagala was between Ambalangoda and Hikkaduwa covering towns of Kahawa, Peraliya and Thotagamuwa.

2.4.4.1 Kahawa

First sign of heavy scouring was observed in Kahawa by Road A2 as shown in Figure 2.26. The damaged pieces of foundation indicate that there was a house at this location prior to the tsunami. Scouring appears to be wide spread and was responsible for damage to some of the houses, which would otherwise have survived from heavy structural damage.

Figure 2.27 shows a masonry residential structure (Cat. C), which had lost part of the structure due to scouring and undermining of foundations (DM3). A close examination of the cross-section of scour holes revealed that the loose to medium dense sands in these areas exist to a depth of 3m or more, which appears to be underlain by dense clayey sandy soils. The loose to medium dense sand are susceptible to erosion and hence leading to scouring as observed in these areas.

Figure 2.26: Scouring and destruction of houses in Kahawa, Sri Lanka

Figure 2.27: Collapse of part of the Cat. C masonry structure to a scour hole in Kahawa

Apart from geotechnical failures, direct structural damage to masonry structures (predominant type in this area) was widespread ranging from collapses (DM4) or heavy damage (DM3) near the coastline and Road A2 to moderate (DM2) or light damage (DM1) further inland about 200m from the coast. Most of the structures observed during the survey were Cat. C masonry. Figure 2.28 show examples of typical damage observed. The damage as seen along the coastline is quite variable in that some structures appears to have survived, especially those made of good quality masonry (Cat. B) or those that exhibit confined masonry type construction (see Figure 2.28).

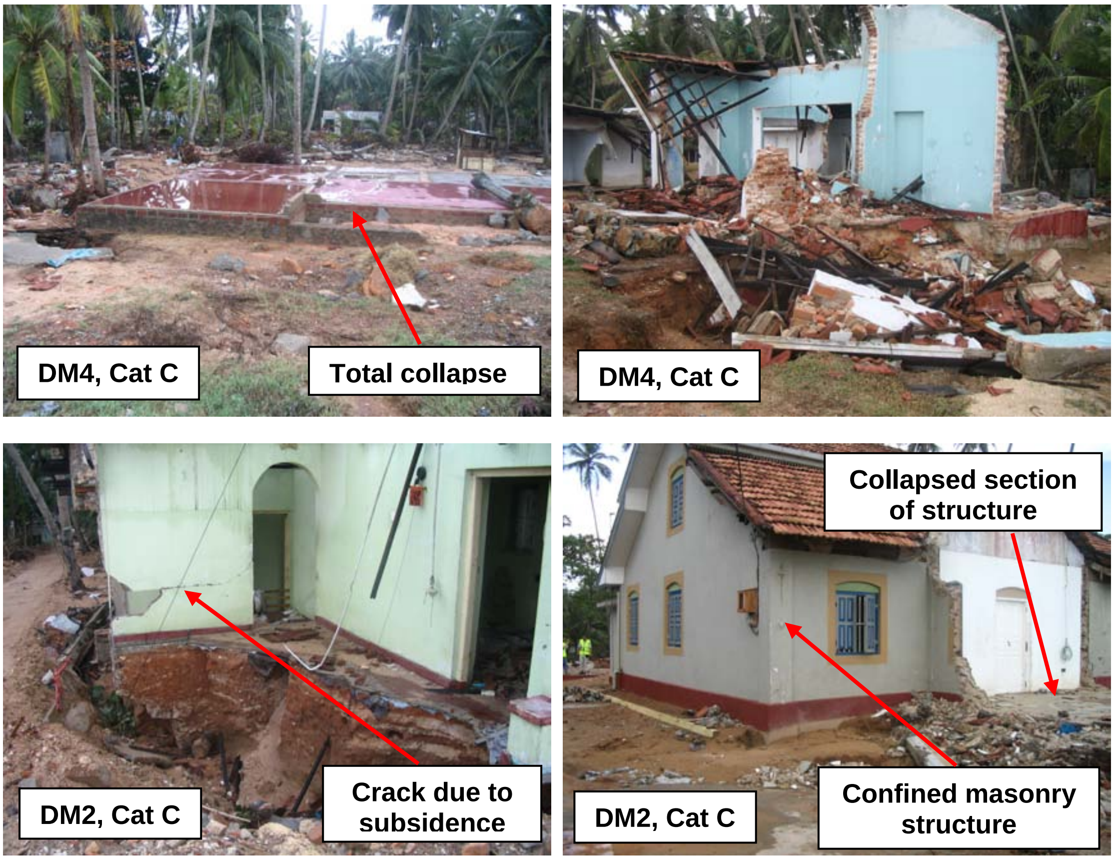


Figure 2.28: Direct structural damage to masonry houses in Kahawa

2.4.4.2 Peraliya

Peraliya was the site of the train that derailed during the tsunami killing about 1500 people, who were largely travelling on the train to Matara from Colombo. The site despite the dense coconut trees and vegetation was the site of the heaviest damage in the southwest of Sri Lanka. Figure 2.29 shows evidence of debris flow about 200m from the coastline. Evidence of high tsunami water levels is visible from the debris trapped on trees. KUDPRI measured a water level of 10m relative to the mean sea level at this location.

Heavy damage was seen as far as 300m from the coastline in many of the masonry houses, which were largely Cat. C (Figure 2.30). The structural damage was caused by collapse of masonry wall panels, which lead to the loss of structural capacity (DM3), hence many of the house will have to be demolished. The damage level becomes less severe away from the coastline. Figure 2.31 shows a moderately damaged masonry house (DM2, Cat. C) at about 400m from the coastline, which could be re-used following reconstruction of the damaged masonry panels. The displaced roof tiles are an indication of the water level at this location. Figure 2.31 also shows an undamaged 2-storey house (DC0, Cat. D), which was under construction prior to the tsunami. The house is of RC frame and slab construction with masonry infill panels made of solid brick for the first storey walls and cement blocks for the second storey walls. According to the eyewitness accounts the tsunami water has travelled as far as a lake about 800m from the coastline. Figure 2.32 shows the damaged parapet wall of a Buddhist temple located by the lake. The temple buildings are intact despite the water level at this location measured to be about 5m above ground level from the silt traces on the chimney wall (see Figure 2.7).

Figure 2.29: Site of debris flow at Peraliya and evidence of water level from debris on trees

Figure 2.30: Heavily damaged (DM3) masonry structures at about 300m from the coastline in Peraliya

Figure 2.31: Moderately damaged Cat. C masonry house at about 400m from the coastline. Undamaged RC frame and slab structure with masonry infill panels under construction prior to the tsunami

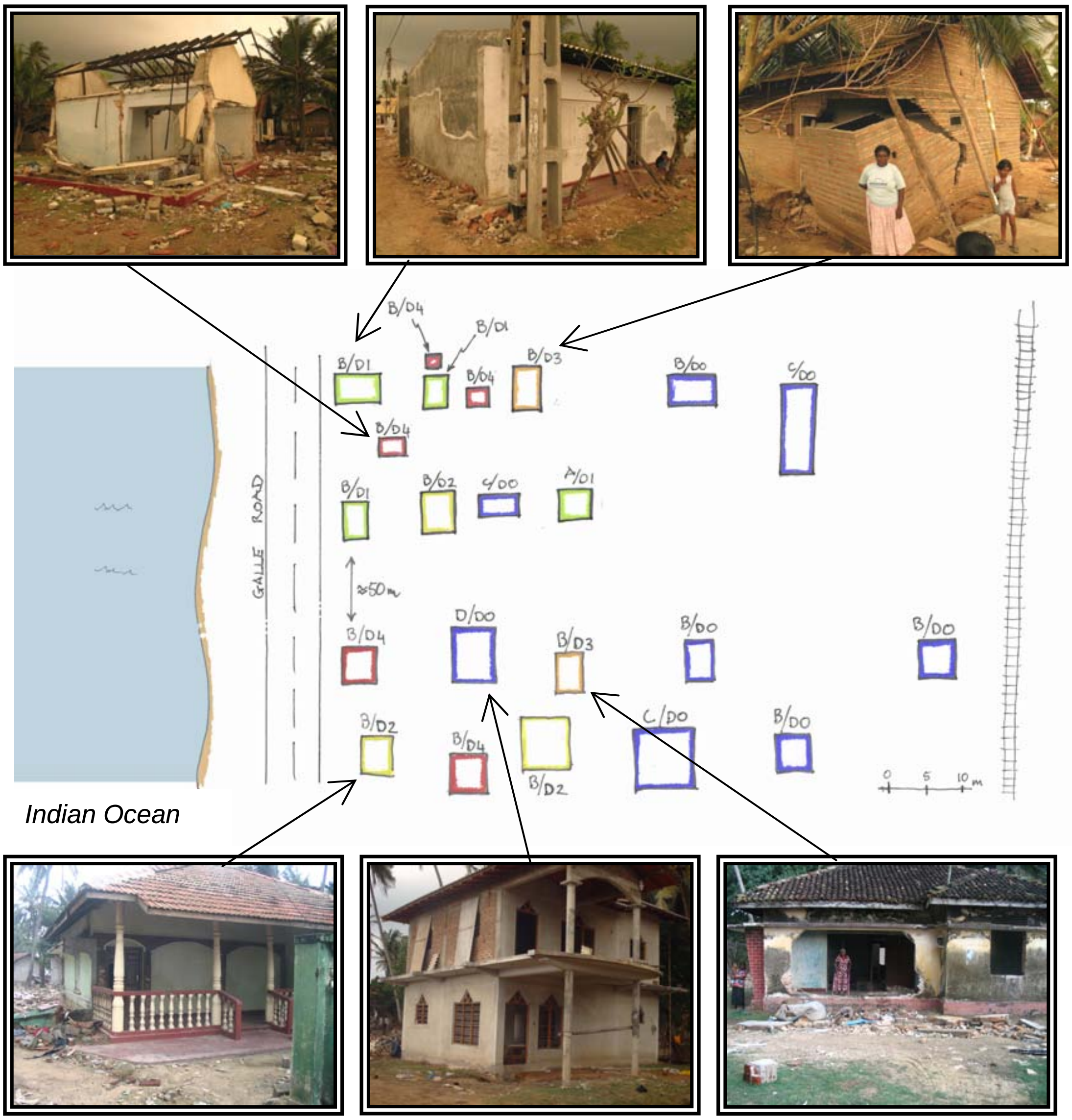
The distribution of houses is fairly sparse in Peraliya such that there are palm trees and shallow vegetation in the areas surrounding the detached houses. However, the flow velocities at Peraliya must have been high enough to cause extensive damage to a considerable distance from the coast. Figure 2.33 shows fallen palm trees at the location of the Buddhist temple about 800m from the coastline. Despite the height and extent of inundation, there was no evidence of erosion or scour in this area. The surficial soils in this area are dark brown clayey sandy soils. The shore appears to be shallow in this area and there is some rock protection along the coastline as shown in Figure 2.33.

Figure 2.32: Damaged parapet walls and columns at the Buddhist temple located about 800m from the coastline

Figure 2.33: Fallen coconut trees at about 800m from the coastline suggesting significant flow velocities at this distance. Coastal protection at the coastline of Peraliya

2.4.4.3 Thotagamuwa

Thotagamuwa located between Seenigama and Hikkaduwa town is typical of heavily damaged areas with a dense distribution of houses. Figure 2.34 shows a detailed damage distribution from the walkover survey carried out in this area. The area surveyed was on level land about 3m above the mean sea level. Silt traces on walls were observed at about 2m from the ground level in the first row of houses and dropping to 1.4m about 100m back from the coastline. The masonry structures in this area largely of Cat. B has either collapsed (DM4) or suffered heavy damage to the masonry wall panels facing the sea (DM3) within the first 30m from the shoreline. The extent of damage is quite variable in that among the collapsed or heavily damaged structures are those with moderate (DM2) or light damage (DM1). Generally the damage to masonry structures was light (DM1) beyond about 40m from the shoreline and no damage was observed beyond the railway line at about 150m from the coastline. Cat. C masonry structures have suffered less damage than Cat. B structures. In addition to masonry panel failure, there was evidence of wall collapse due to scour at the corner of a house as shown in Figure 2.34. Scouring at corners was evident in many houses although this has only led to minor cracking of masonry walls. The surficial soils appears to be loose to medium dense sand with little clay content, hence erosion and scouring is likely in this area.



	Legend			
	Damage State	B/D1		Construction type
D0	no damage		A	timber
D1	light damage		B	poor quality masonry
D2	moderate damage	Example: Poor quality masonry, light damage	C	good quality masonry
D3	heavy damage		D	low rise concrete frame
D4	collapse		E	mid rise concrete frame
Location: Thotagamuwa, north of Hikkaduwa				

Figure 2.34: Detailed walkover survey observations at Thotagamuwa

2.4.5 Detailed Damage Surveys – Galle City

Walkover surveys were carried out in several parts of Galle city and areas of damage and key observation locations are illustrated on a satellite image of Galle city in Figure 2.35 taken shortly after the tsunami (Sertit, 2005).

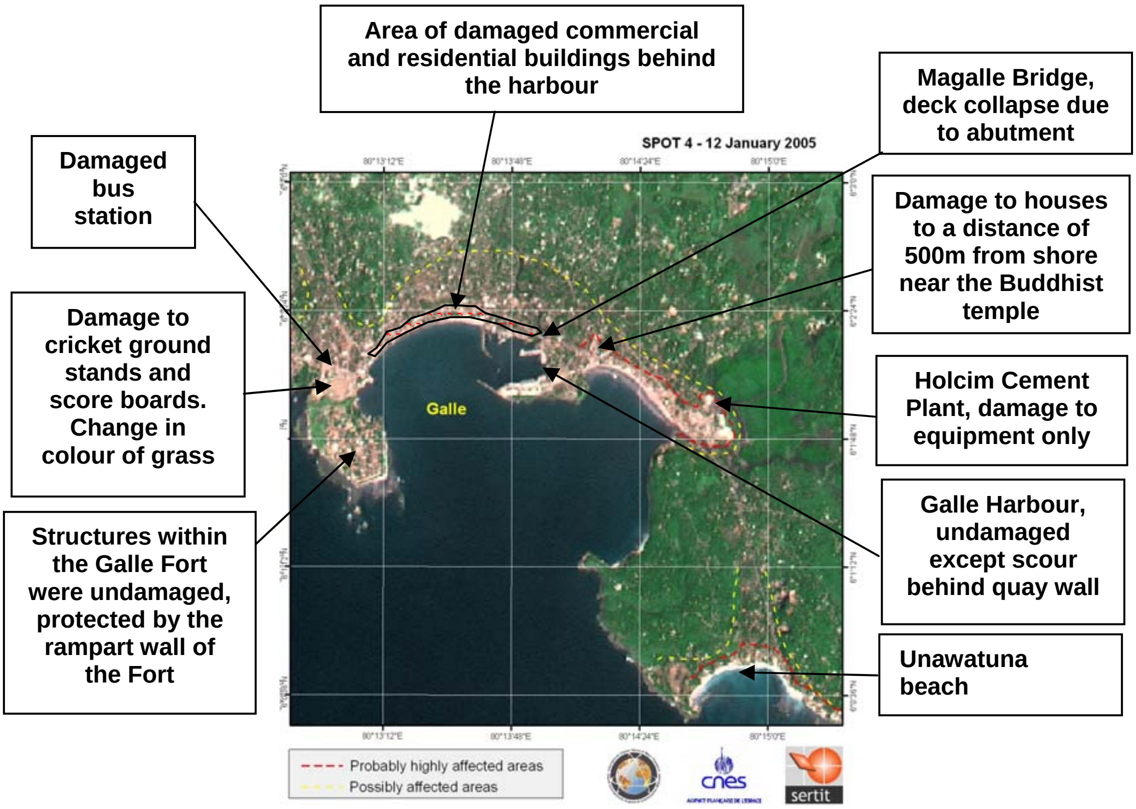


Figure 2.35: Damage survey in Galle city by EEFIT overlayed on satellite image following the tsunami (Sertit, 2005)

The bus station structures at the centre of the city were heavily damaged beyond use as shown in Figure 2.36 where there was evidence of tensile failure or reinforcement in the columns supporting the roof structures. Several ground floor shops adjacent to the bus stand appears to have suffered content damage due to inundation but there were no visible structural damage to the shopping complex, which is a 3-storey RC building with masonry infill (Cat. E). The steel structures of the stadium stands and the score board in the Galle international cricket ground were completely damaged and there was an obvious change in the colour of the grass, which can also be seen in the satellite image in Figure 2.35. The houses and commercial outlets within the Galle Fort escaped the direct impact of the tsunami, protected by the rampart wall of the Fort.

To the east of the city centre, the Road A2 runs around the natural harbour until it reaches the Magalle bridge near the road access to the Galle Harbour. The shops and other buildings facing the Road A2 behind the harbour suffered collapse or heavy damage as shown in Figure 2.37. These are a mixture of masonry structures and RC structures of 2 or 3-storey (Cat. D) with masonry infill walls. Several masonry structures collapsed such as the fish market building constructed of columns made of Cat. B masonry (see Figure 2.37). The damage in RC structures was to masonry infill panels facing the sea (DC2) and there were cases of roof damage and cracks in some RC structural members (DC3). There was no evidence of substantial structural damage in the streets behind Road A2 nearer to the city centre, which are largely commercial outlets of mixed masonry and RC construction.

Figure 2.36: Heavily damaged Galle bus station (photo by Dennis Knight, Halcrow). Tensile failure of reinforcing bars of columns supporting the roof structures of the bus station

Figure 2.37: Damaged commercial buildings behind Galle Harbour on Road A2

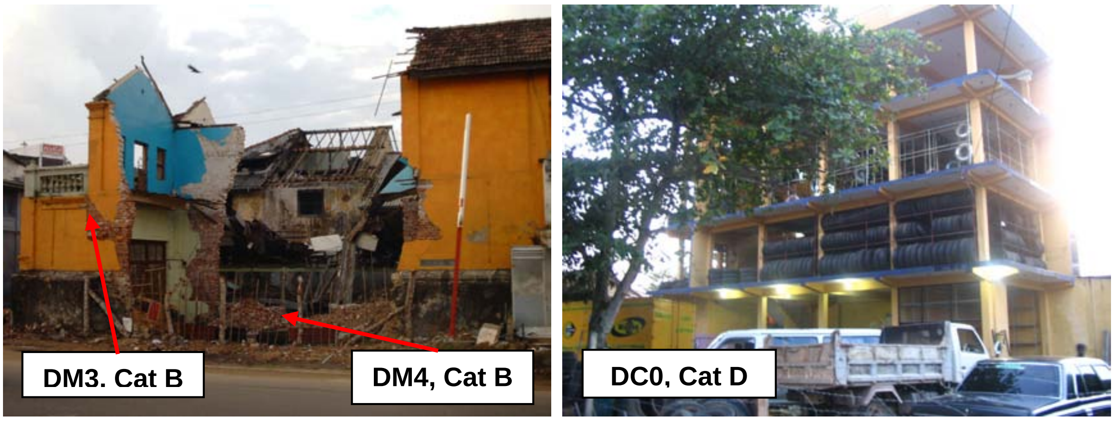


Figure 2.38: Damaged masonry structures in the street behind Road A2. Undamaged RC structure on the same street used for vehicle servicing

However substantial damage was observed in the street behind Road A2 nearer to Galle Harbour as shown in Figure 2.38. There were several damaged Cat. B and Cat. C masonry structures (DM2 and DM3) and infill wall collapses in RC frame and slab structures (DC2). One structure that survived undamaged was a 3-storey building with an open plan in the ground floor used as a service centre (see Figure 2.38).

The extent of heavy collapse and heavy damage appears to be as far as 100m from the harbour shores and beyond which any significant damage is not visible. To east of the town there were substantial damage further inland near the Magalle Bridge as identified in Figure 2.35. The damage in the area was largely to masonry houses of Cats. B and C and the magnitude of damage range from collapse (DM4) to light damage (DM1) over a distance of about 500m from the shore. In this area, a water level of 2m above ground level was measured in a masonry temple building, which is shown in Figure 2.7. There were no evidence of scouring in the damaged areas around Galle, except at the bank of the river east of Galle City where there was evidence of debris flow and erosion. The surficial soils in the residential areas appear to be dark brown clayey sandy soils.

2.4.6 Detailed Damage Surveys – Unawatuna

Unawatuna located to the east of Galle (see Figure 2.35) is a popular tourist area due to the coral reef and shallow sandy beaches. A walkover survey was carried out along the beach and normal to beach. The survey along the beach revealed that hotel developments typically a mixture of single storey to 3-storey RC frame and slab structures occupied the beachfront.

Figure 2.39: Undamaged hotel 20m from the shoreline. Collapse and heavy damage to a Cat B masonry house at the same distance

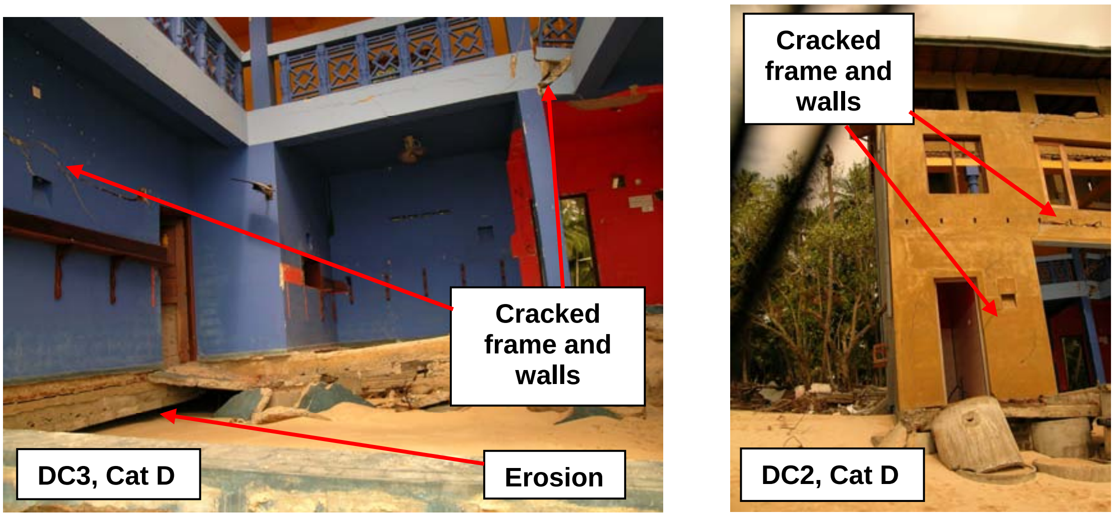
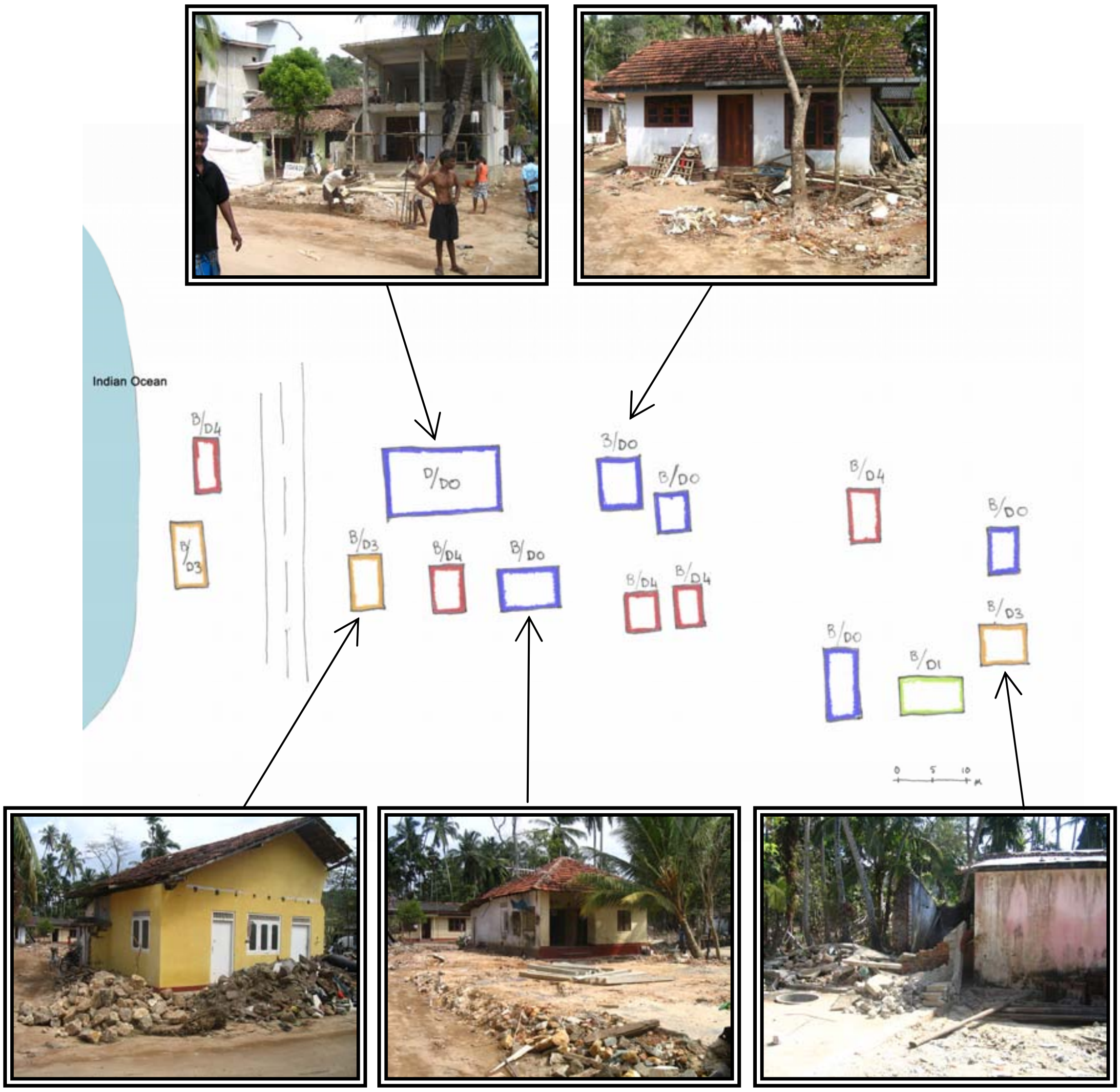


Figure 2.40: Erosion underneath the foundations resulted in settlement induced damage to an RC frame hotel structure. Damage and settlement of concrete foundations leading to tilting and cracked walls in the RC frame building



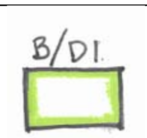
	Legend			
	Damage State			Construction type
D0	no damage		A	timber
D1	light damage		B	poor quality masonry
D2	moderate damage	Example: Poor quality masonry, light damage	C	good quality masonry
D3	heavy damage		D	low rise concrete frame
D4	collapse		E	mid rise concrete frame
Location: Unawatuna				

Figure 2.41: Detailed walkover survey observations at Unawatuna

The residential developments are mostly located behind these developments and the area is abundant with shallow and dense vegetation among coconut trees. Figure 2.39 shows an undamaged 3-storey RC frame and slab hotel structure about 20m away from the coastline and toward the eastern part of the bay. At the same distance from the shore and few blocks away is a Cat. B masonry house with part of the structure facing the sea collapsed and the remaining structure damaged beyond repair (DM3).

Although there was little evidence of direct structural damage to hotels in this area, there were hotel structures that suffered damage due to subsidence, settlement of foundations and scouring. Figure 2.40 shows some of the RC hotel structures that were damaged due to geotechnical failures. The RC frame in the hotel shown suffered major cracks and there were cracks in the wall panels due to erosion and scouring that undermined the foundations. Figure 2.40 also shows another RC structure that had tilted and has cracked wall panels. This was the result of the damage and settlement of the concrete foundations possibly due to scouring or liquefaction, which may have weakened the bearing capacity. Similar damage is also shown in Figure 2.5 (see Section 2.2) toward the western end of the Unawatuna Bay. The above-mentioned structures subjected to geotechnical failures are founded on beach sand close to the water hence were prone to erosion and scouring, and possibly liquefaction due to surges in the water level.

The walkover survey carried out normal to the bay revealed considerable variation in damage to masonry houses extending to about 120m from the shoreline. Many houses stood standing with little damage adjacent to collapsed buildings. Figure 2.41 presents a detailed damage distribution from the walkover survey on a road perpendicular and central to the sandy beach in Unawatuna Bay. The road was level and approximately 2m above the sea level. Silt traces from the tsunami inundation were observed at about 2m above the ground 50-60m from the shore. Most of the houses in the area are Cat. B masonry structures and damage level generally reduces with distance from the coastline. There was evidence of inundation beyond 120m from the discoloured vegetation in the area.

2.4.7 Detailed Damage Surveys – Weligama

Weligama bay is located between Galle City and Matara and the bay serves as a fisherman's landing site, where the beaches are shallow with widely visible rock outcrops. Walkover surveys were carried out along and normal to road A2 and the coastline in an area of medium urban density. The normal survey was carried out along a side road to A2 and this has shown that damage was only visible to a distance about 50m from the shoreline. Figure 2.42 shows a collapsed porch supports in a house (Cat. C masonry, confined) facing the Weligama bay but the house has suffered moderate damage and repairable. Next to the house along Road A2 is a filling station of RC construction (Cat. D), which is undamaged.

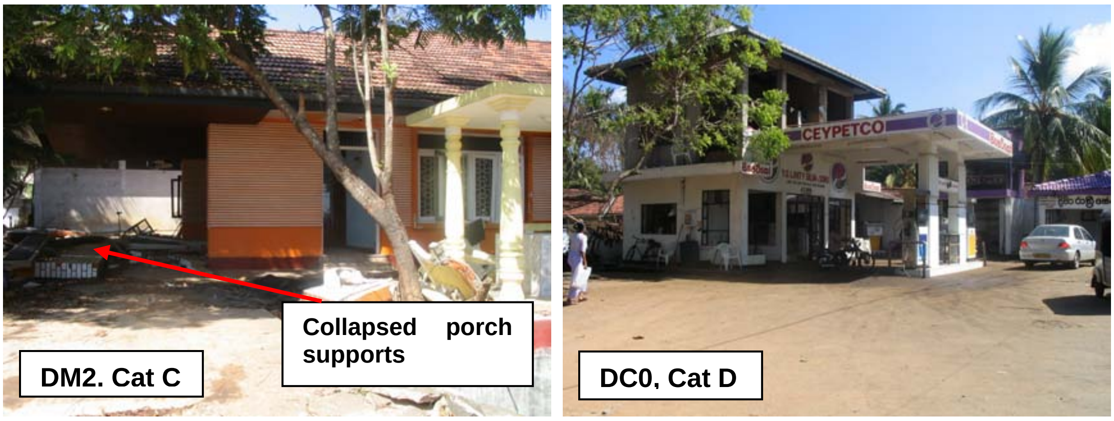
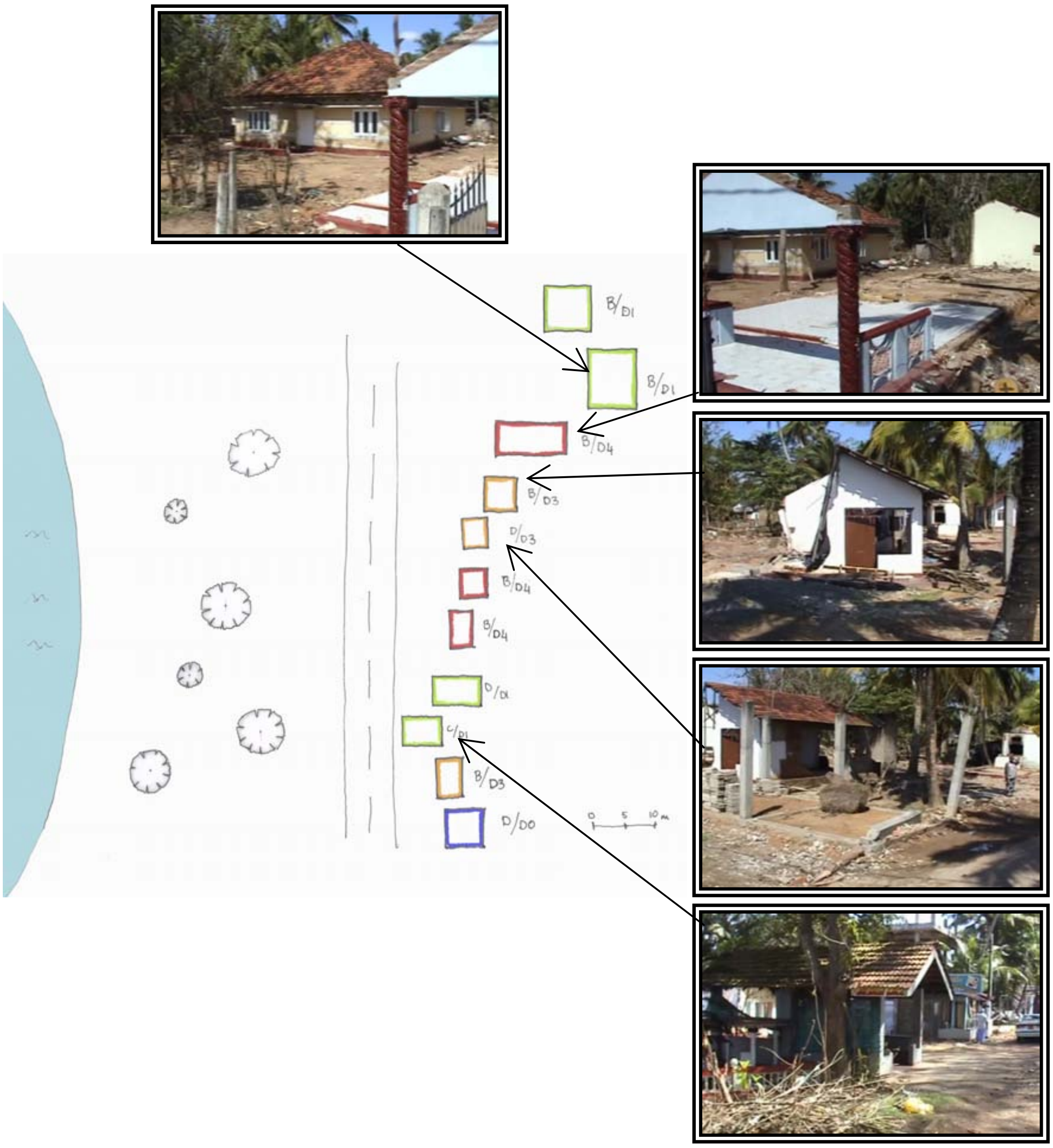


Figure 2.42: Moderate damage to a masonry house facing the bay. Undamaged filling station facing the bay

The survey along road A2 is shown in Figure 2.43. Between the coastal road and the shore is a strip of land with sparse vegetation consisting of mature coconut trees. There were silt traces on the walls of houses at a height of 2m above ground level at a distance of 80-90m from the shore. The ground is generally level and rising approximately 2.5m above the sea level at the shore. The size and construction types of the 11 buildings surveyed along the coastal road varied (Cat. B and C masonry and Cat. D RC structures) and as a consequence there was a considerable variation in the extent of damage. For the same tsunami hazard, some masonry buildings collapsed whilst others survived with very little damage. It was not possible to confirm whether the presence of cross walls might have improved the wave resistance capacity of the standing buildings.



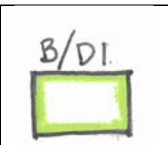
	Legend			
	Damage State			Construction type
D0	no damage		A	timber
D1	light damage		B	poor quality masonry
D2	moderate damage	Example: Poor quality masonry, light damage	C	good quality masonry
D3	heavy damage		D	low rise concrete frame
D4	collapse		E	mid rise concrete frame
Location: Welligama				

Figure 2.43: Detailed walkover survey observations at Weligama

2.4.8 Analysis of Damage Observations

2.4.8.1 Lateral Resistance of Masonry Houses

It is clearly evident from the general and detailed damage surveys conducted in the southwest and southern Sri Lanka that tsunami damage was largely in masonry houses. The detailed damage surveys discussed earlier revealed that direct structural damage was the result of the collapsed masonry walls due to loading from the tsunami waves. For a masonry house to be in a damage state of heavy (DM3) or collapse (DM4), the damage to masonry wall panels have to be such that the integrity of the load bearing system has to be compromised. Hence the out-of-plane load resistance capacity of a typical masonry wall is significant in order to evaluate its ability to withstand the forces generated from fluid loading due to a tsunami flow. If we ignore the contribution from arching action then the out-of-plane resistance or the design flexural resistance capacity, M_{Rd} of a masonry wall section may be determined from the relation;

$$M_{Rd} = f_{xk} Z/\gamma_m \qquad \text{(Tomazevic, 1999)}$$

where f_{xk} is the characteristic flexural strength, Z is the elastic section modulus of the wall section and γ_m is the partial factor to be applied on the characteristic strength. The above relation considers the extreme fibre stresses reaching the tensile yield strength of a masonry wall, which would typically occur in the mortar being weaker than the masonry block itself. FEMA 356 gives typical lower bound flexural tensile strengths and material factors for good fair and poor masonry where a strength value of zero is assigned for poor masonry. A value of zero is unrealistic for Cat. B masonry classified as poor in Section 2.4.1 since the wall sections can provide resistance against out-of-plane flexure. If we consider a tensile strength of 69kPa (10psi assigned for fair masonry) and γ_m of 1.3 after FEMA 356, then M_{rd} for a typical 300mm thick wall is 0.8kNm per m width of wall.

A vast majority of the masonry houses surveyed were non-engineered in that no design code provisions were considered in their design and construction. However, these houses located by the coast are subjected to regular wind loads in addition to the seasonal monsoon winds (including rain). There are no known regular cases of damage to masonry houses in the coast due to the wind in Sri Lanka. Hence these houses are able to withstand wind pressures without structural damage. Considering typical monsoon wind speeds, V in southwest and southern Sri Lanka from the wind data, a mean wind speed of 10m/s (23mph, Zubair, 2002) could be considered in deriving wind loads from the relation $F_w = 0.5\rho V^2 A C_D$ (where ρ, density of air at 1.23kg/m^3, A is the plan area of the wall and C_D is the drag coefficient). Assuming that this wind pressure acts uniformly over the entire plan area of a masonry wall panel (considering C_D of 1.0) then the wind induced pressure, p_w is 0.06kPa. The maximum bending moment M_{max} per m width of wall due to a uniform pressure could be calculated from $p_w h^2/16$ (assuming a simply supported wall section) where h is the height of the wall. Hence for a typical ground floor wall height of 3m, M_{max} is 0.03kNm per m, which is much less than M_{rd} calculated above as expected since there are no recorded cases of wind load induced masonry wall collapses.

According to FEMA 55, the forces acting on a building due to a tsunami are, wave impact forces, hydrostatic pressure, hydrodynamic pressure, buoyancy, debris impact and scouring. If we only consider the effect of hydrostatic and hydrodynamic pressures then the equivalent uniform pressure, p_t acting on a masonry wall due to tsunami water flow velocity, V is given by;

$$p_t = 0.5(\rho g h + \rho V^2 C_D)$$

The KUDPRI measurements in Figure 2.8 shows that typical tsunami water levels in the EEFIT surveyed area relative to the mean sea level were about 5m. From the detailed surveys discussed above, there was evidence of tsunami levels reaching almost the full height of walls of houses. The difficult parameter to estimate is the tsunami velocities since there are considerable variations depending on various factors. Choi et al (2005) estimated a tsunami flow velocity of 6m/s at Peraliya, the site of heavy damage where a water level of 10m was measured by KUDPRI. Lower flow velocities may be assumed for other areas. Assuming a tsunami flow velocity of 3m/s, the water pressure on a 3m high masonry wall is 19.5kPa. Hence M_{max} is 11.0kNm per m width of wall, which is much greater than 0.8kNm per m of resistance, which would therefore result in masonry wall failure in out-of-plane flexure.

2.4.8.2 Tsunami Intensity in the Surveyed Areas and Damage Statistics

Figures 2.44 to 2.46 show tsunami intensity map developed based on the damage survey findings in the EEFIT observed areas and the intensity scale given in Table 3.3 (It should be noted that the size of the shaded areas in no way represents the extent of damage from the coast). The intensity values were assigned by noting the damage observed typically within the first 300m from the coast. The intensity maps show that the tsunami intensity generally appears to have been strong (III) to destructive (IV) between Kalutara and Galle with very destructive (V) regions in Paiyagala, Kosgoda and Ambalangoda. The region between Ambalangoda and Hikkaduwa is assigned to be devastating (VI) and highest in the EEFIT survey given the worst structural damage and large numbers of casualties in this area. From Galle to Dondra, the tsunami intensity varied between light (II) and strong (III) with a destructive intensity (IV) in Weligama bay.

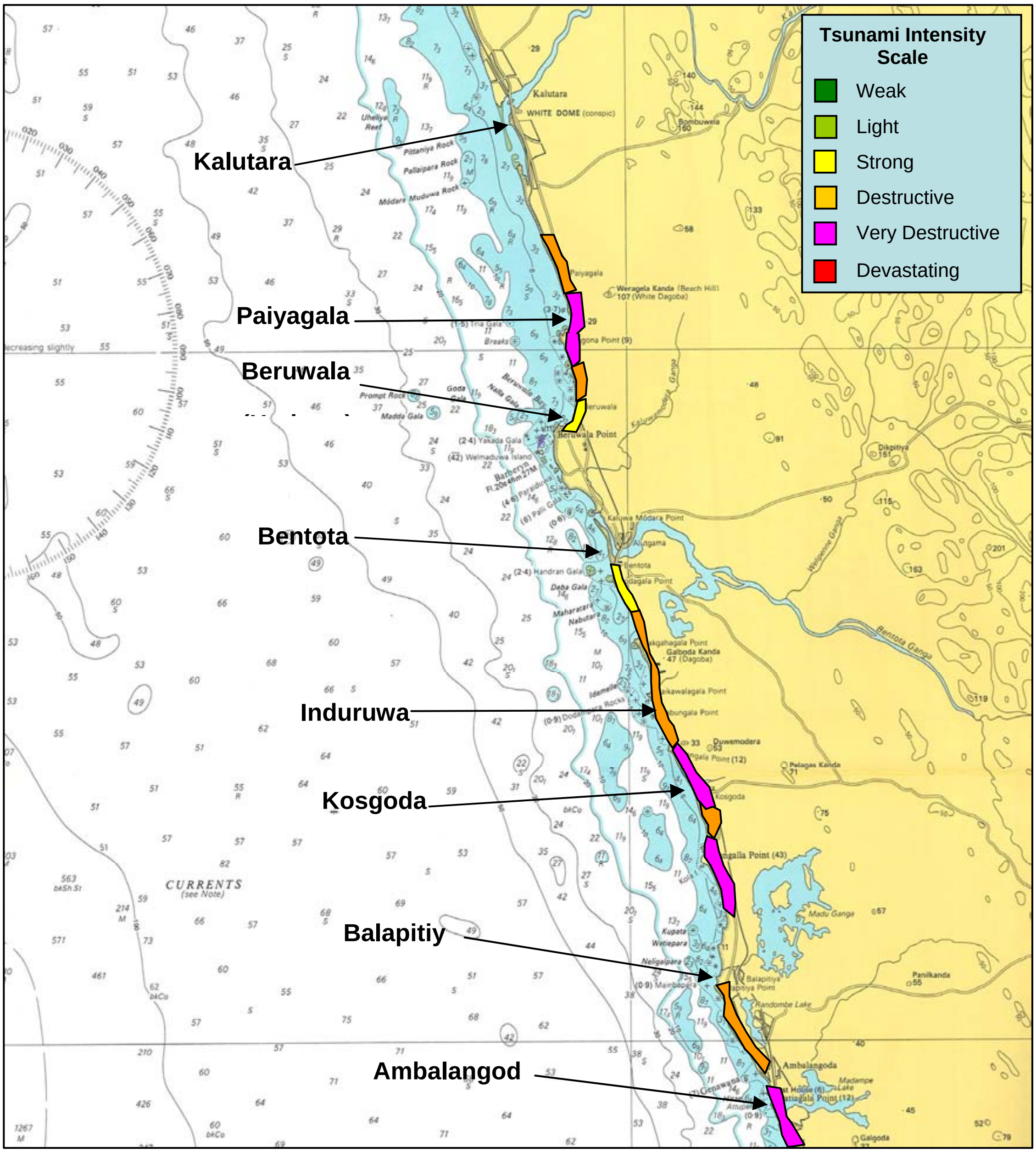


Figure 2.44: The surveyed damage and tsunami intensity between Kalutara and Ambalangoda

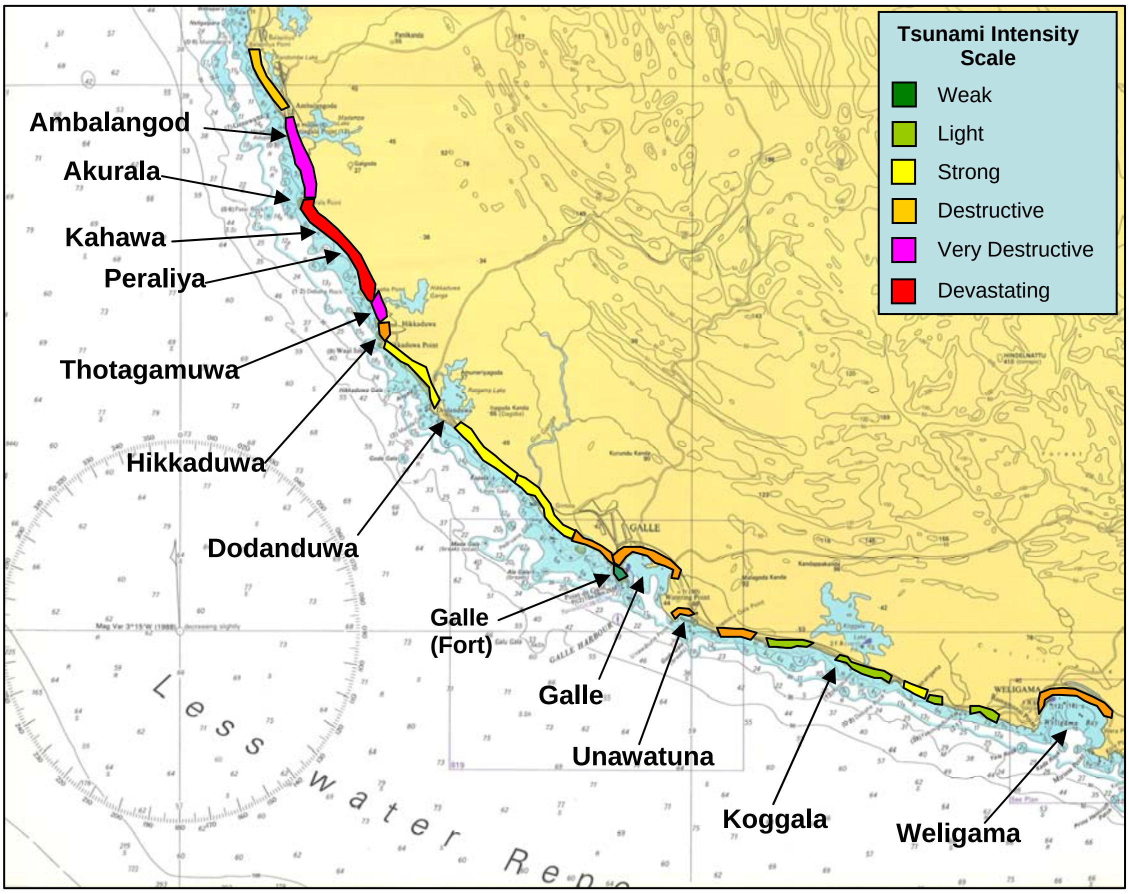


Figure 2.45: The surveyed damage and tsunami intensity between Ambalangoda and Weligama

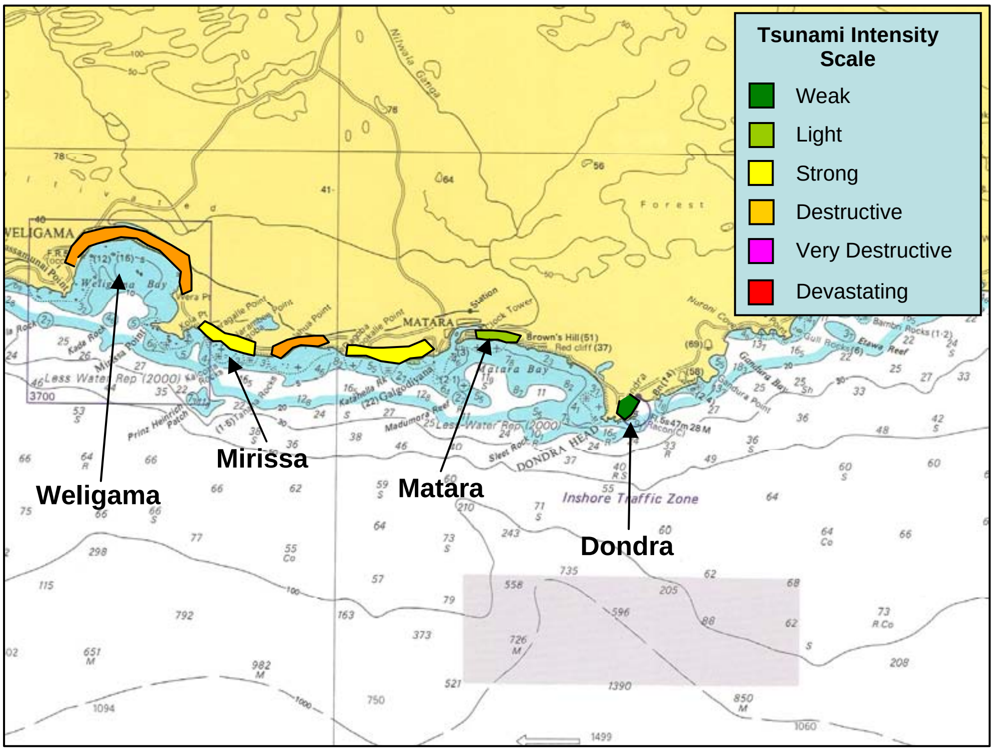


Figure 2.46: The surveyed damage and tsunami intensity between Weligama and Dondra

Figure 2.47 shows the number of damaged houses along the coastal Divisional Secratariat (DS) division from Colombo to Tissamaharama covering the EEFIT surveyed coastal areas (Source: Dept. of Census and Statistics, Sri Lanka). The number of damaged houses consists of those completely damaged (similar to DM4), partially damaged that cannot be used (similar to DM3) and partially damaged that can be used (DM2 or less).

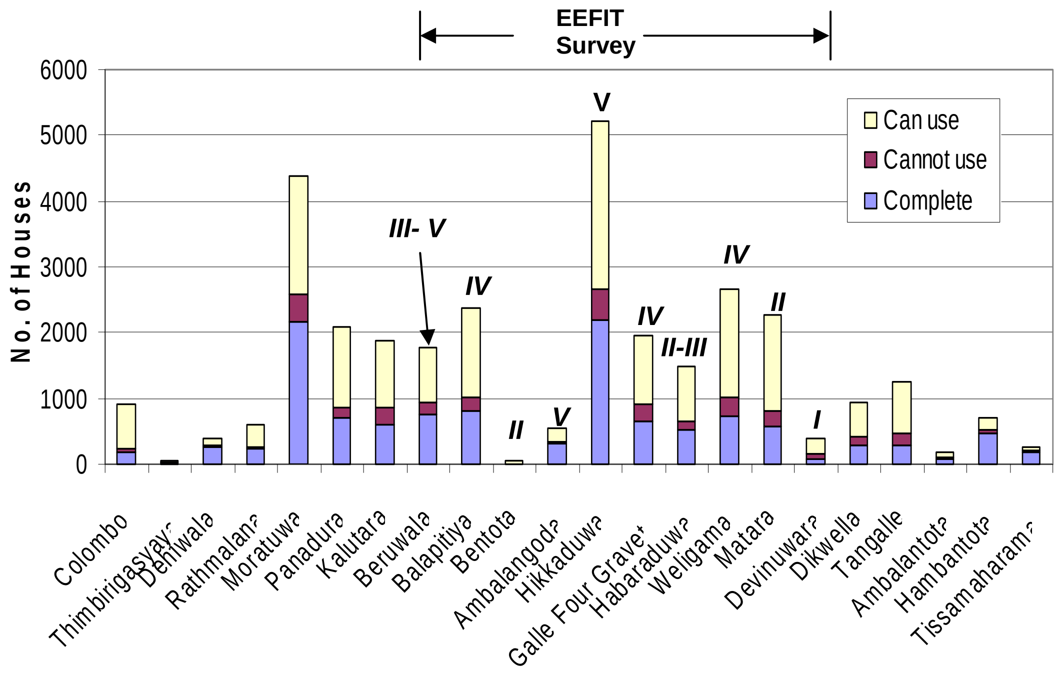


Figure 2.47 No. of damaged houses by DS division in Western and Southern Provinces (Department of Census and Statistics, Sri Lanka)

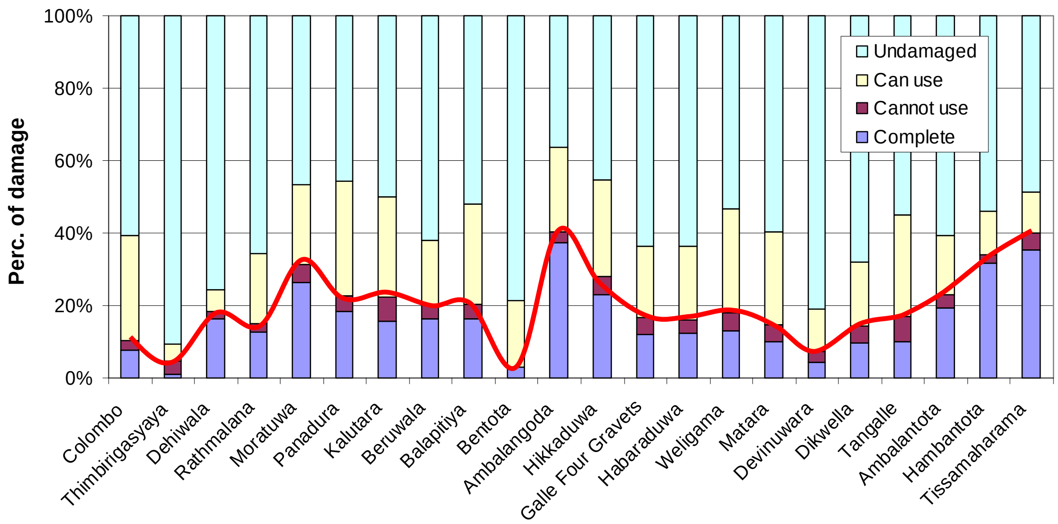


Figure 2.48 No. of damaged houses as percentage of total in the affected census blocks by DS division in Western and Southern Provinces (Department of Census and Statistics, Sri Lanka)

Comparing the variation of tsunami intensity and the distribution of damaged houses, Hikkaduwa DS division has the highest number of damaged houses, which correlates well with the highest intensity of VI assigned to the region covering Kahawa, Peraliya and Thotagamuwa. It should also be noted that this is also the area with the highest recorded water level of 10m by KUDPRI (Figure 2.8 and an inundation of 800m (Figure 2.10) Moratuwa DS division nearer to Colombo has also recorded a large number of damaged houses comparable to Hikkaduwa. This was largely attributed to the large number of timber frame houses (Cat. A), which were exposed to the tsunami in the highly populated coastal Grama Niladari (GN) divisions (lowest administrative level in Sri Lanka).

For other DS division in the EEFIT surveyed areas, it is difficult to deduce a relationship between the total number of damaged houses and intensity. For instance, Ambalangoda, which is assigned an intensity of V has only 500 damaged houses compared to Balapitiya with an intensity of IV, which has about 2300 damaged houses. The tsunami intensity scale in Table 3.3 represents relative damage for a given area as observed during the survey. Figure 2.48 shows the damaged houses as a percentage of the total number of houses in the affected census blocks within the affected GN divisions. The trend line following the total (percentage) of damage greater than DM3 is an indication of relative damage and appears to give a better correlation with the EEFIT tsunami intensity. Generally damage greater than DM3 in the EEFIT surveyed area was about 20%. The lowest recorded was in Bentota at 3% and highest in Ambalangoda at about 40%. Hikkaduwa despite the intensity of VI has a lower percentage of damage greater than DM3 compared to Ambalangoda. This is due to a larger number of houses in the affected census blocks of Hikkaduwa DS division that covers an area greater than the affected census blocks in the affected GN divisions of Ambalangoda DS divison.

Beyond Devinuwara (Dondra) the number of damaged houses in Figure 2.47 drops sharply reaching below 1000 in Hambantota and Tissamaharam in the southeast part of the Southern Province. These areas unlike the EEFIT surveyed region were directly impacted by the incoming tsunami (see Section 2.3.2) with higher water level measurements such as 11m in Hambantota with the highest inundation distance of 2km in the Southern Province (see Figures 2.9 and 2.10). The relative damage shown in Figure 2.48 indicates the rise in percentage of damaged houses (greater than or equal to DM3) from Dondra toward Hambantota and beyond, which better correlates with the water level and inundation measurements in this area.

2.4.8.3 Effect of Reefs, Rocks and Vegetation on Tsunami Intensity

The detailed surveys carried out by EEFIT encountered the presence of palm trees and shallow dense vegetation in areas where the damage intensity was as high as VI between Ambalangoda and Hikkaduwa (see Section 2.4.4) and as low as IV in Unawatuna (2.4.6). The presence of reefs and rock outcrops near the coastal areas were visible during the survey as shown in the bathymetry charts used for illustrating the tsunami intensity in Figures 2.44 to 2.46. However, the resolution of the survey carried out is such that it is difficult to deduce a direct correlation between, the tsunami water level, inundation distance and tsunami intensity with the presence of and densities of reefs, rocks and vegetation. Preuss (2005) states that anecdotal evidence exists that strongly indicates a direct correlation between coral reef mining, higher water levels, loss of life and building damage. Tsunami waves also appear to have entered inland with greater force in areas where sand dunes had been graded or where mangroves had been cut. A report by the United Nations Environment Program supports this view having found that most of the Yala and Bundala National Parks in the southeast of Sri Lanka were spared because of the vegetated coastal sand dunes dissipating the tsunami energy.

2.4.9 Damage to Buildings in the Eastern Province

The EEFIT mission did not survey the damage areas in the Eastern province due to limitation of time and access difficulties. Pillai (2005) has carried out a survey of damages at Trincomalee Harbour area and along the coastal routes stretching from Nilaveli (north of Trincomalee) to Kalmunai (south of Batticaloa). The surveyed areas were largely inhabited by fishermen and their houses were destroyed and suffered varying degrees of damage. Figure 2.49 shows typical damage observed to masonry houses, whose construction quality and methods were similar to those found in the Western and Southern Provinces. Direct structural damage has occurred resulting in total collapses (DM4) in many areas due to high water levels and large inundation distances particularly in the Ampara and Batticaloa districts coastal areas (see Figure 2.10). Damage to houses due to geotechnical failures such as scouring and undermining of foundations was also observed as shown in Figure 2.49 (Pillai, 2005). A modern masonry house appears to be well constructed has survived the undermining of the concrete foundation, however another house was not so fortunate in that large sections of its masonry wall has collapsed making the structure unsuitable for immediate occupancy and may well have to be demolished.

Figure 2.49: Typical damage to masonry houses in Eastern and Northeast Provinces (Pillai, 2005)

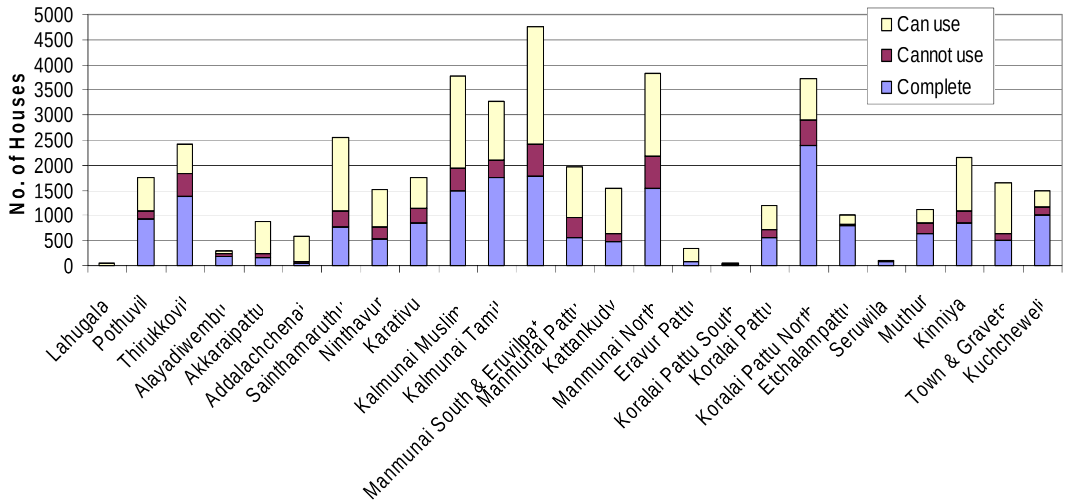


Figure 2.50: No. of damaged houses by DS division in Eastern province (Department of Census and Statistics, Sri Lanka)

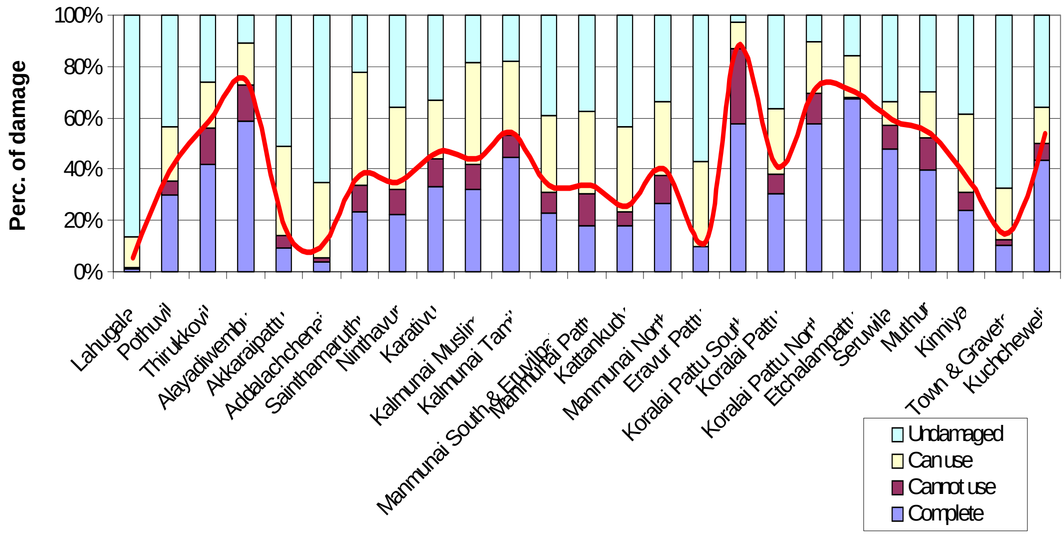


Figure 2.51: No. of damaged houses as percentage of total in the affected census blocks by DS division in Eastern province (Department of Census and Statistics, Sri Lanka)

Figure 2.50 shows the number of damaged houses along the coastal DS divisions from Lahugala in the southeast to Kuchcheweli in the northeast (Source: Dept. of Census and Statistics, Sri Lanka). The number of damaged houses consists of those completely damaged (similar to DM4), partially damaged that cannot be used (similar to DM3) and partially damaged that can be used (DM2 or less). The total number of damaged houses appears to reach a peak of 4700 in Mammunai South and is generally around 3500 between Kalmunai and Batticaloa, the region with the highest water level measurements and largest inundation distance (see Figure 2.10). Kinniya with about 2600 damaged houses was the largest number in the Trincomalee area.

Figure 2.51 shows the damaged houses as a percentage of the total number of houses in the affected census blocks within the affected GN divisions. The trend line following the total (percentage) of damage greater than DM3 is an indication of relative damage and the values on average about 40%, larger than the EEFIT surveyed areas (see Figure 2.48). Hence more areas in the Eastern province could be assigned a tsunami intensity greater than V.

2.5 Lifelines

2.5.1 Roads

Sri Lanka has a number of key routes connecting cities along the coastline, which were affected by the tsunami. Figure 2.52 shows the affected routes and locations of damage compiled by Road Development Authority (RDA). In the southern and western part of the island, Road A2 or locally known as “Galle Road” is the main route connecting the southern cities of Galle and Matara with Colombo. This route runs 160km from Colombo to Matara and continues further east to the town of Ambalantota and then turns north ending in Wellawaya on the southern edge of Badulla District in the Uva Province. For about one third of the distance between Colombo and Galle the road runs very near the sea and beaches and at other times is 300-800 metres inland with the coast hidden due to dense development and palm tree vegetation.

Road A2 was damaged in several locations, mostly due to erosion and scouring of the ground below and at locations of bridges and culverts. Figures 2.53 to 2.55 show examples of scour damage to the road where the extent of damage varied from light roadside scour to heavy damage across the road rendering it impassable. Roadside sections that are directly exposed to the seaside appear to have suffered severe damage. Some road sections although protected by a sea wall or an embankment with sufficient vegetation, suffered damage due to scouring, which undermined the founding subgrade (Figure 2.55). Locations of culverts were particularly vulnerable to scour damage. Figure 2.54 shows severe damage across the Road A2 in Seenigama (north of Hikkaduwa) where the culvert exposed to the sea was completely washed away making it impassable.

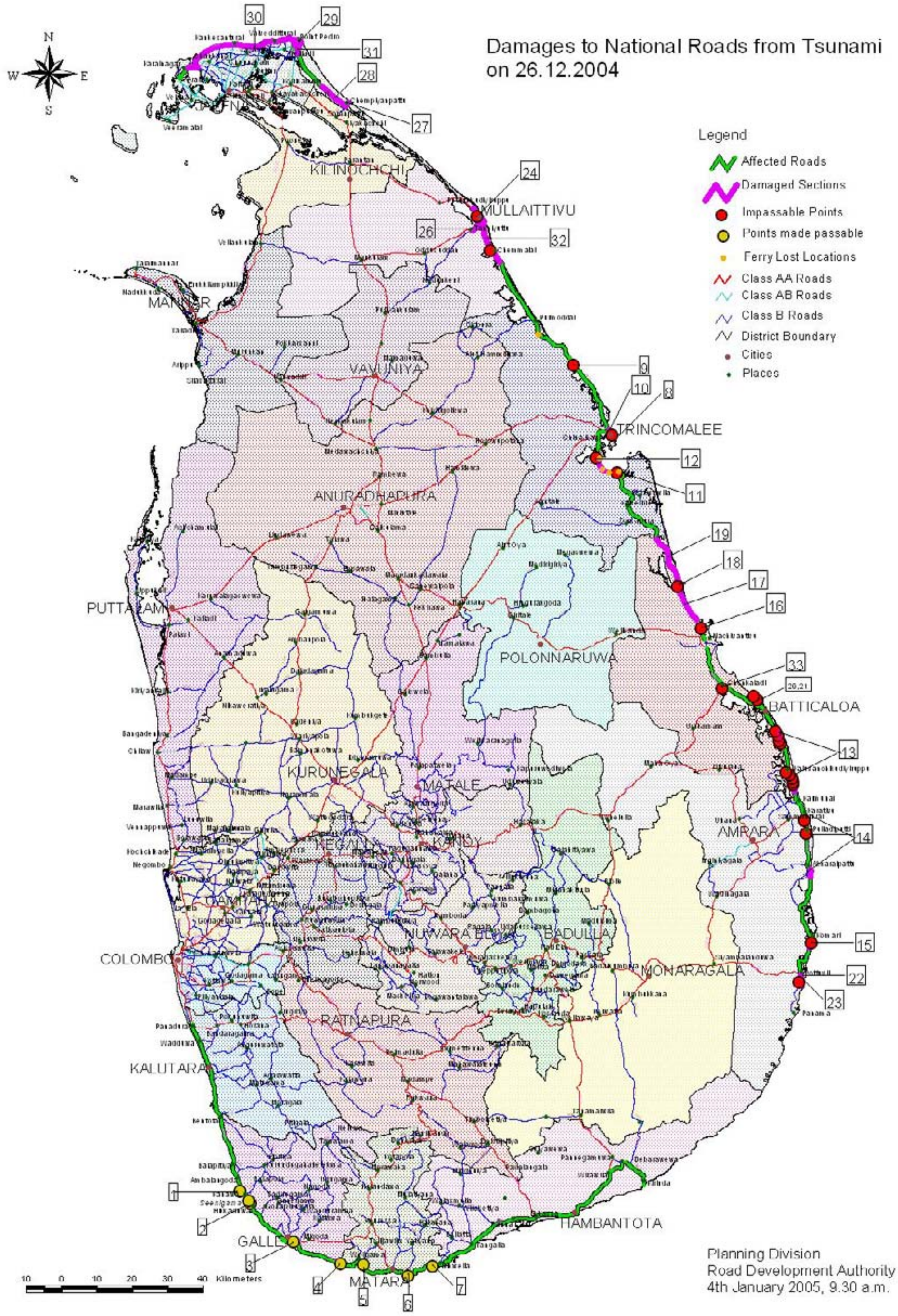


Figure 2.52: Damaged road sections showing locations made passable by January 4, 2005 (Road Development Authority, Sri Lanka)

Figure 2.53: Light scour damage at the roadside exposed to the sea (Photo by RDA). Collapse of part of the road in Hikkaduwa due to scour in the exposed side to the sea (photo provided by Dennis Knight, Halcrow-Sri Lanka)

Figure 2.54: Heavy damage to the road near Hikkaduwa due to scouring making the road impassable (Photo by RDA). Completely washed away culvert in Seenigama making Road A2 impassable (Photo by RDA)

Figure 2.55: Collapsed section of Road A2 in Kahawa due to scouring on the exposed land side (Photo by RDA) and the state after repair as observed by EEFIT

The typical road construction technique is clearly evident in Figures 2.53 and 2.55 where the bitumen road surface is founded on a compacted layer of gravely soils about 400mm thick overlying the sand. This type of profile is susceptible to the weakening effects of the underlying sand. The damaged locations of Road A2 were made passable within about 10days after the disaster as shown in Figure 2.52. Figure 2.55 shows a section of the road that has collapsed and the state observed at the time of the survey.

The damage to road sections in the Eastern province was severe where large sections of the coastal road network suffered heavy damage in addition to damage to bridge and culvert locations. Figure 2.52 shows that large sections of the Routes A4 and A15, which runs 300km from Arugambe to Mullaitivu passing Batticaloa and Trincomalee was impassable by the time Route A2 became passable. The heavy damage to large parts of the Eastern province has made it difficult to mobilize equipment to repair damaged road sections and crossing points. Figure 2.56 shows a typical damaged road section just south of Batticaloa (Pillai, 2005). Sand deposition in some areas meant that previous road alignments will have to be moved inland. The heavy damage suffered by large sections of the Eastern road network can be attributed to the greater severity of the tsunami in the East compared to Southwest. The tsunami damage was seen to exacerbate the already deteriorated state of the roads caused by lack of maintenance.

Figure 2.56: Typical heavily damaged road section near Batticaloa (Photo by Anton Pillai, Arup)

Nationally about 690km of Class A and B roads suffered damage from the tsunami. In addition, about 700kms of provincial roads (Classes C, D and E) and approximately 1100km of local government roads have been damaged. The damaged sections represent about 5% of the national road network and about 2% of the provincial and local government road networks (Asian Development Bank, 2005).

2.5.2 Railways

The railway connecting Colombo to the coastal districts of Kalutara, Galle and Matara is the country's most important rail corridor carrying about 80,000 passengers per day and freight from the Port of Galle. The 160km track from Colombo to Matara almost follows Route A2, sometimes to the seaward side (between Colombo and Paiyagala (in Kalutara district)) and sometimes to the landward side between Paiyagala, Galle and Matara with some exceptions. The dual track section between Colombo and Kalutara suffered minor damage, which was quickly repaired. From Kalutara onward, an approximately 20km length of track suffered severe damage, which included damage to embankments, bridges, buildings, track work, signalling and communication. Severely damaged sections were observed between Induruwa beach (just south of Bentota), Amabalangoda and Hikkaduwa.

Figure 2.57: Damaged section of railroad near Hikkaduwa due to collapse of the embankment possibly driven by erosion and scouring

Figure 2.58: Derailment in Peraliya, north of Hikkaduwa (by "Silumina" Newspaper, Sri Lanka)

Typical damaged section of the railway near Hikkaduwa is shown in Figure 2.57, where the embankment failure possibly caused by scouring and erosion led to the distortion of the recently repaired track. Figure 2.58 shows the derailment at Peraliya (north of Hikkaduwa). Water levels as high as 10m were recorded in this area by KUDPRI (Figure 2.8). The high water levels and possibly high velocities of flow would have been sufficient to uplift the rail carriages and drag them a considerable distance away from the railroad. At the time of the field mission, work was being done to prepare the ballast and place the precast reinforced concrete sleepers for the track. Clearly the railway authority has given great priority to making this lifeline operational as soon as possible.

The railway in the Eastern province areas suffered minor damage since the tracks are not located close to the shore. The minor damage was quickly repaired and rail service was quickly restored.

2.5.3 Bridges

The railway and Road A2 cross a number of rivers on the way south from Colombo. Some of these crossings are quite wide, such as the Kalu Ganga bridge in Kalutara and the Alutgama Bridge which crosses the Bentota Ganga river. Three bridge types were commonly identified in the surveyed region and they are classified as follows in order to describe the survey observations;

- Type 1 – Small span, typically consists of a simply supported concrete slab deck with reinforced concrete or masonry retaining wall type abutments with concrete facing
- Type 2 – Long span, typically steel truss type, built from steel or possibly wrought iron, riveted construction with reinforced concrete piers and abutments
- Type 3 – Long span, reinforced concrete slab decks connected to reinforced concrete piers via bearings, reinforced concrete abutments

Most road bridges were of Type 1 with some of Type 3. Most of the railway bridges observed were of Type 2 with some causeway bridges. Some of these bridges were built by the British in the early part of the 20^{th} Century. These bridges commonly have pipes from the water supply system embedded in the deck, thus damage to the bridge not only has a consequence on accessibility and traffic flow, but on water supply in the affected region.

A summary of the damage and performance of bridges observed along Road A2 between Kalutara and Dondra is given in Table 2.3 (see end of this section). Several key crossings for the Road A2 and the railway suffered severe damage, cutting off the southern route and disrupting the rail service in addition to the damage over land as described in the earlier (see sub-sections 2.5.7 and 2.5.8). The damage to most bridges was largely minor and repairable and typically consisted of damage to parapets or to the abutments, which could be quickly repaired and restored.

Three bridges suffered severe damage on the Route A2 in Akurala, Magalle and Goviyapana. Figure 2.59 shows the completely destroyed bridge at Akurala where the bridge deck appeared to have collapsed and disintegrated along with its abutments. The bridge appears to have been of Type 1 judging from the debris with a span of about 10m. The crossing has been restored by placing a temporary Bailey bridge.

Figure 2.59: Destroyed bridge (Type 1) at Akurala and the replaced Bailey bridge

Figure 2.60 shows the damaged Magalle Bridge (Type 1) south of Galle City on the route to Matara. The 8m long RC deck slab failed when its masonry retaining wall type abutment was severely damaged and washed away. The abutment disintegration appears to have been caused by scouring and erosion from the receding water where the retained side of the abutment was exposed to the river on the landward side as shown in Figure 2.61. The seaward side of the abutment is however protected by the abutment structures (or rock armour) running parallel to the road hence the advancing tsunami could not damage the abutments. A temporary Bailey bridge was placed to maintain the flow of traffic across this major route.

The 6.5m long Type 1 bridge at Goviyapana (between Ahangama and Weligama) lost its southbound lane (furthest from the sea) due to scouring of its abutments as shown in Figure 2.62. The damage to the masonry abutments appears to have taken place from the receding water since the abutment on the landward side is exposed as with the Magalle bridge. The southbound carriage was restored by a temporary Bailey bridge.

Figure 2.60: Collapsed Magalle Bridge (Type 1) south of Galle due to abutment erosion and scour damage. Temporary Bailey bridge in place to restore the vital crossing

Figure 2.61: Exposed retained side of the abutment in the landward side at damaged Magalle bridge. Protected abutment on the seaward side by abutment structures running parallel to the road

Figure 2.62: Collapsed southbound carriage of Goviyapana bridge (Type 1). Collapse due to erosion and scour damage to the abutment on the landward side. Temporary Bailey bridge in place to restore the carriage way

At Weligama two parallel 80m span bridges had performed well and were undamaged despite evidence (hanging debris) that they had been overtopped by rising water levels in the river due to the tsunami (Figure 2.63). The bridges consisted of a RC slab road bridge (Type 3) along Road A2 supported at 5m spans by reinforced concrete piers and a steel truss type railway bridge (Type 2).

Figure 2.63: Two parallel 80m span bridges (Types 2 and 3) at Weligama that performed well. Note the presence of a fishing net suspended from the base of the road bridge deck, indicating water probably overtopped the bridge during the tsunami

The 15m long bridge (Type 1) in Devinuwara (Dondra) has suffered damage to the approaches as shown in Figure 2.64. The approaches appear to have been exposed to the sea prior to the tsunami hence may have been damaged by the advancing tsunami. The approaches have been restored by backfilling to the level of the bridge and constructing a gabion protection wall. The bridge deck was not damaged despite the damage to approaches and exposure of the abutments since the abutments are reinforced concrete unlike the bridges in Magalle and Goviyapana where the abutments were masonry with a concrete facing. Gabion wall was constructed to reduce the exposure of the abutments to the sea.

Figure 2.64: Damage to Devundara (Dondra) bridge (Type 1) approaches. Approaches restored and gabion protection wall constructed on the side exposed to the sea

Although most of the railway bridges were Type 2 and suffered little or no structural damage, two causeway bridges were observed by EEFIT to have been destroyed. Figure 2.65 shows the causeway bridge at Kosgoda just north of Balapitiya where a 300m long causeway bridge section was complete destroyed. At the time of the survey, backfill was in place adjacent to the existing Road A2 to relay a new track. The 150m long causeway bridge just south of Ambalangoda was also destroyed and a new crossing was under construction at the time of the survey similar to that in Kosgoda.

Figure 2.65: Destroyed causeway bridge at Kosgoda (north of Balapitiya). Backfilling and leveling taking place to lay a new railway track

Unlike the Western and Southern provinces, the bridges in the Eastern province (which were largely road crossings) were either completely destroyed or suffered severe damage beyond repair. Figure 2.66 shows the destroyed causeway bridge at Komari cutting off the Road A4 from Colombo to Batticaloa via Ratnapura and Wellawaya. The steel deck truss bridge on the route to Arugambe (famous for wind surfing) has suffered severe distortions to the structure from the direct impact of the water and due to foundation settlements and shearing at the bridge connections to the piers as shown in Figure 2.67. Some causeways bridges have since being repaired to restore the damaged roads to allow relief supplies. Figure 2.68 shows a new causeway bridge in combination with a Bailey bridge constructed in Kinniya near Trincomalee.

Figure 2.66: Destroyed Komari causeway bridge on the Road A4 from Colombo to Batticaloa

Figure 2.67: Severe distortions to the Arugambe bridge due to tsunami impact and foundation settlement and shearing at the connections to the piers (Photos by RDA)

Figure 2.68: Restored causeway bridge in Kinniya near Trincomalee (Photo by Anton Pillai, Arup)

Table 2.3: Survey of bridges between Kalutara and Dondra

Location	Latitude (N)	Longitude (E)	Span (m)	Type	Damage State
Kalutara (railway)	6° 35' 10.4"	79°57'35.3"	300	2	2 bridges of 300m span, undamaged
Kalutara (road)	6° 35' 10.4"	79°57'35.3"	300	3	2 bridges of 300m span, undamaged
Kapugoda (north of Maggona)	6° 30' 37.2"	79 58 55.4	20	1	Undamaged
Nautukanda (south of Maggona)	6° 29' 57.6"	79 58 48.8	40	3	Undamaged structure, repaired approaches and some repair to pile caps
Kaluwamodara (Alutgama)	6° 26' 33.3"	79 59 32.1	25	1	Undamaged

Bentota (railway)	6° 25' 33.3"	79 59 51.5	250	2	Undamaged
Bentota (road)	6° 25' 33.3"	79 59 51.5	250	2	Undamaged
Yakgahagala (Induruwa)	6° 23' 45.0"	80 00 17.8	7	1	Undamaged
Kosgoda (railway)	6° 20' 28.1"	80 01 37.9	300	-	Causeway bridge completely destroyed
Kosgoda (road)	6° 20' 28.1"	80 01 37.9	300	3	Undamaged
Balapitiya	6° 16' 24.0"	80 02 21.5	20	3	Undamaged
Ambalangoda (railway)	6° 13' 45.2"	80 03 15.3	150	-	Causeway bridge completely destroyed
Ambalangoda (road)	6° 13' 45.2"	80 03 15.3	150	3	Undamaged structure, eroded embankments at both ends repaired
Akurala	6° 11' 56.3"	80 03 34.0	10	1	Bridge deck and abutments collapsed and destroyed completely
Hikkaduwa	6° 08' 47.0"	80 05 48.6	10	1	Undamaged structure. Some damage to the approaches repaired
Degalla (South of Hikkaduwa)	6° 06' 13.0"	80 07 24.3	25	3	Undamaged structure. Damage to approaches repaired
Gintota (north)	6° 03' 46.8"	80 10 19.2	25	3	Damage to handrails repaired
Gintota (south)	6° 03' 39.0"	80 10 27.5	10	1	Damage to handrails repaired
Mahamodara (Galle)	6° 02' 21.0"	80 11 50.3	20	3	Damage to handrails repaired
Galle Town	6° 02' 25.6"	80°12' 01.6"	12	1	Slight displacement of deck, but is fully functional.
Galle Town	6° 01' 58.7"	80°12' 51.6"	8	1	Undamaged
Galle (Magalle)	6° 02' 08.0"	80° 13' 53.0"	8	1	Collapsed due to abutments being scoured away
Dalawella (south of Galle)	6° 01' 41.5"	80° 14' 35.9"	10	1	Some parapet damage
Uragasgoda (railway,south of Galle)	5° 59' 39.4"	80° 17' 46.6"	7	2	Bridge abutments are under repair
Uragasgoda (road, south of Galle)	5° 59' 39.4"	80° 17' 46.6"	7	1	Undamaged
Koggala	5° 58' 59.2"	80° 20' 07.1"	15	3	Undamaged (note breakwaters are present just offshore)
Goviyapana (Ahangama)	5° 58' 10.8"	80° 22' 09.7"	6.5	1	Collapsed southbound lane due to scouring of the abutments
Denuwala	5° 57' 56.0"	80° 22' 49.6"	20	2	Western abutment has been washed away and was being repaired with

(railway)					granite rock
Denuwala (Road)	5° 57' 56.0"	80° 22' 49.6"	20	3	Minor parapet damage
Kumbalgama (Weligama)	5° 57' 54.8"	80° 23' 26.7"	7	1	Undamaged
Walliwala (Weligama)	5° 57' 40.8"	80° 25' 10.9"	10	1	Undamaged
Weligama (railway)	5° 57' 57.4"	80°27' 19.6"	80	3	Undamaged
Weligama (road)	5° 57' 57.4"	80°27' 19.6"	80	2	Undamaged
Mirissa (north)	5° 57' 52.0"	80°27' 21.3"	8	1	Undamaged
Mirissa (south)	5° 56' 43.5"	80°27' 34.9"	10	1	Undamaged
Kamburugamuwa	5° 56' 19.0"	80°29' 06.7"	3	1	Fallen parapets
Matara Town	5° 56' 45.9"	80°32' 55.8"	30	3	Undamaged
Dondra	5° 55' 52.9"	80°34' 57.8"	15	1	Failed approaches repaired and gabion protection wall in place on the seaward side

2.5.4 Water Supply, Sanitation and Electricity

2.5.4.1 Water Supply and Sanitation

The main water supply distribution system is located along major routes such as Road A2 in the Western and Southern provinces and across bridges where they need to cross a river. Hence any damage to sections of roads and bridges also caused damage to the water supply system, which supplies the drinking quality water to many homes along the coast. Much of the damage to pipes in the water distribution system is evident as shown in Figures 2.55 and 2.61. In addition to the main system, domestic wells are commonly used for purposes other than drinking since the drinking quality could not be achieved in many of the wells. During the tsunami, the wells in the inundated areas were flooded with silty saline sea water making them unsuitable for domestic use. In some cases wells were destroyed by erosion as the masonry caisson walls of the well were pulled out due to erosion and buoyancy.

Figure 2.69: Newly restored water supply across an old bridge crossing in Dondra adjacent to the bridge where the abutments were eroded

The drinking water supply system was restored within about 10days after the disaster in the Western and Southern provinces. Figure 2.69 shows a newly restored water supply across an old bridge crossing in Dondra adjacent to the bridge where the abutments were eroded (see Figure 2.64). Bottled water was supplied in the interim period. Some areas where the water supply system could not be repaired were supplied drinking quality water using tankers by the National Water Supply and Drainage Board (NWSDB). Figure 2.70 shows a tanker refilling from a roadside supply point in Hikkaduwa.

Figure 2.70: NWSDB tanker refilling drinking water from a roadside supply point in Hikkaduwa

Many individual household latrines were also damaged due to inundation, erosion and scour. The sewage pump house at Mount Lavinia, which is part of the Colombo sewerage system was damaged affecting many residences in the Colombo District that were not directly impacted by tsunami.

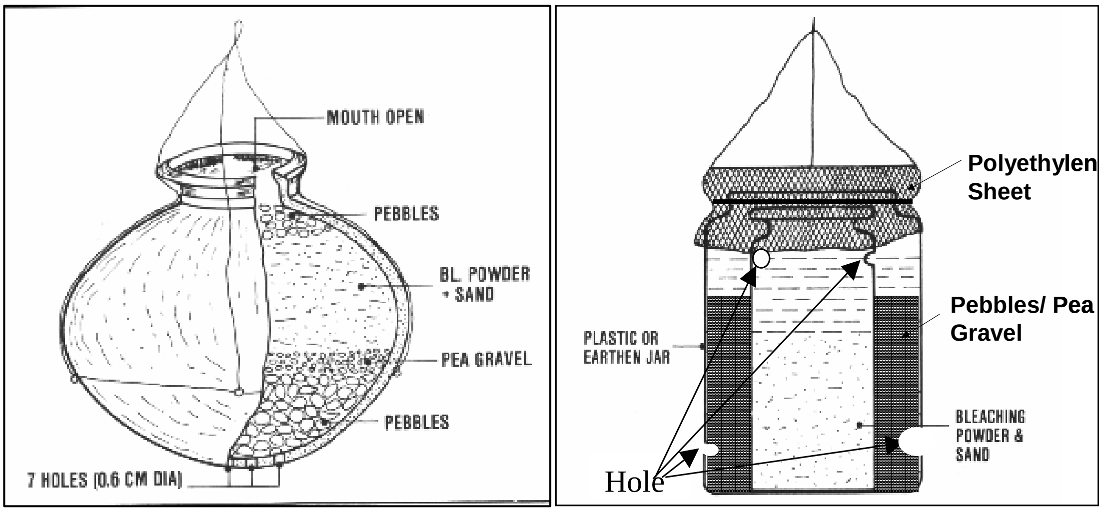


Figure 2.71: Purification of well water for drinking using pot chlorination (Surendran, 2005)

In the Eastern province, the low water table meant that constructing latrines in damaged areas proved difficult. A method was devised where the collection system was isolated from the water table using a drum collection system (covered in plastic liners) filled with charcoal and fire wood ash from cooking to keep out the smell (Surendran, 2005). Many damaged wells and water supply systems in the Eastern province could not be repaired since the road network was out of action to allow equipment and supplies to arrive at the locations. Furthermore the wells remained contaminated since the rain and flooding kept many areas inundated for a number of weeks following the tsunami. Drinking quality water was therefore supplied using tankers by the Sri Lankan military and NGOs operating in the areas. Although well cleaning has progressed the method of chlorination was in some cases inappropriate to ensure drinking quality water. Methods such as pot chlorination was used, which could be made of locally available material and bleaching powder (or chlorinated lime) as shown in Figure 2.71 (Surendran, 2005).

2.5.4.2 Electricity Supply

The damage to the electricity supply network was largely confined to the medium and low voltage distribution lines and transformers located in the coastal area. This is largely attributed to the supply network (power plants, major transmission lines and grid substations) originating from inland toward the coast unlike the water supply system, which runs along the coast. Figure 2.72 shows a damaged local supply pole and wires in Unawatuna Beach area south of Galle.

Figure 2.72: Damaged local electricity supply pole in Unawatuna Beach

Many supply poles were not damaged directly from the tsunami since their smaller cross sectional area offers little resistance to the flow of water. Damage shown above may have been due to debris flow and impact from other collapsing structures. Due to the localized damage, the power supply was quickly restored in the Western and Southern Provinces within two weeks. Lighting needs were met using paraffin lamps while electricity was being restored.

The Eastern province was largely out of electricity for several weeks after tsunami. Repairs to the damaged supply system could not be done since access was difficult due to damaged road sections and flooding that followed the tsunami. Locally operated electricity generators were used for electricity supply for camps but many houses that survived the tsunami were out of electricity supply for several weeks.

2.5.5 Telecommunication Systems

The telephone network runs parallel to the electricity supply network hence suffered localized damage as with the electricity network. Many poles carrying the cables collapsed due to debris impact disrupting the service to many homes. The network owned by Sri Lanka Telecom (SLT) managed partial restoration of services to affected areas in the Western and Southern provinces within two weeks. Service disruptions remain longer in the East and Northeast provinces due to access difficulties from damaged roads and floods. The damage to the mobile phone network was less severe than the landline network since many transmission towers were located away from the coastal areas. Although many people experienced disruption to the landline service, the mobile services remained the mode of long distance communication. Most of the damage to the mobile network was repaired within 72hours of the tsunami with complete restoration in 4 days.

2.6 Hospitals and Schools

2.6.1 Hospitals and Health Care Facilities

The damage to the health sector was substantial due to loss of health care facilities and health personnel creating a breakdown of the health system in the affected districts to support the needs following the tsunami. Health care is provided through a network of district general hospitals, rural hospitals, specialist care hospital to minor clinics and dispensaries. A total of 44 health institutions were totally damaged with 48 partially damaged (Ministry of Health (MOH)). Many of the health care facilities in the coastal regions were vulnerable to tsunami damage since they were located along the major coastal routes (such as Road A2 in the Southwest and A4 and A15 in the East) in order to provide easy access for the coastal populations. Figures 2.73 and 2.75 show the locations of damaged hospitals in the Galle, Trincomalee and Ampara districts respectively (MOH), which are located near the coastal routes that experienced tsunami inundation and damage.

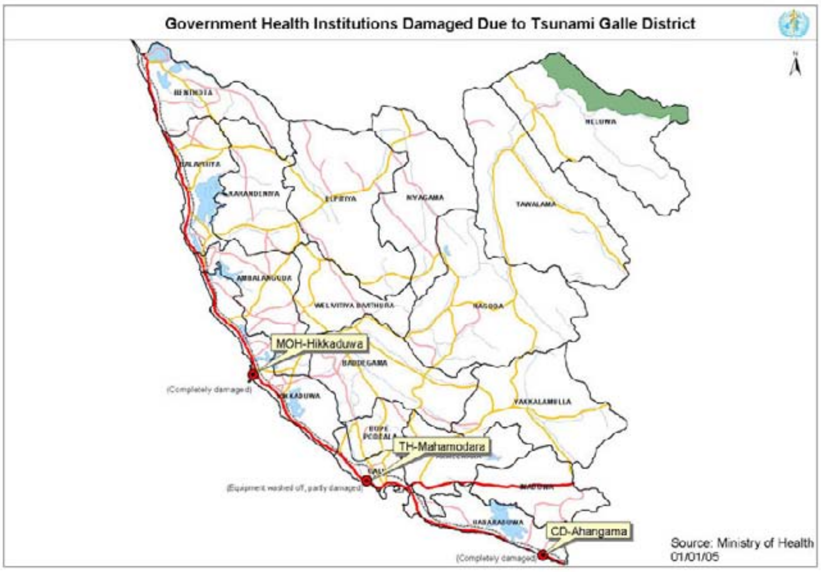


Figure 2.73: Damaged hospitals in Galle District (Southern Province)

Figure 2.74: Mahamodara hospital (Galle) suffered moderate damage but lost equipment in the ground floor due to inundation

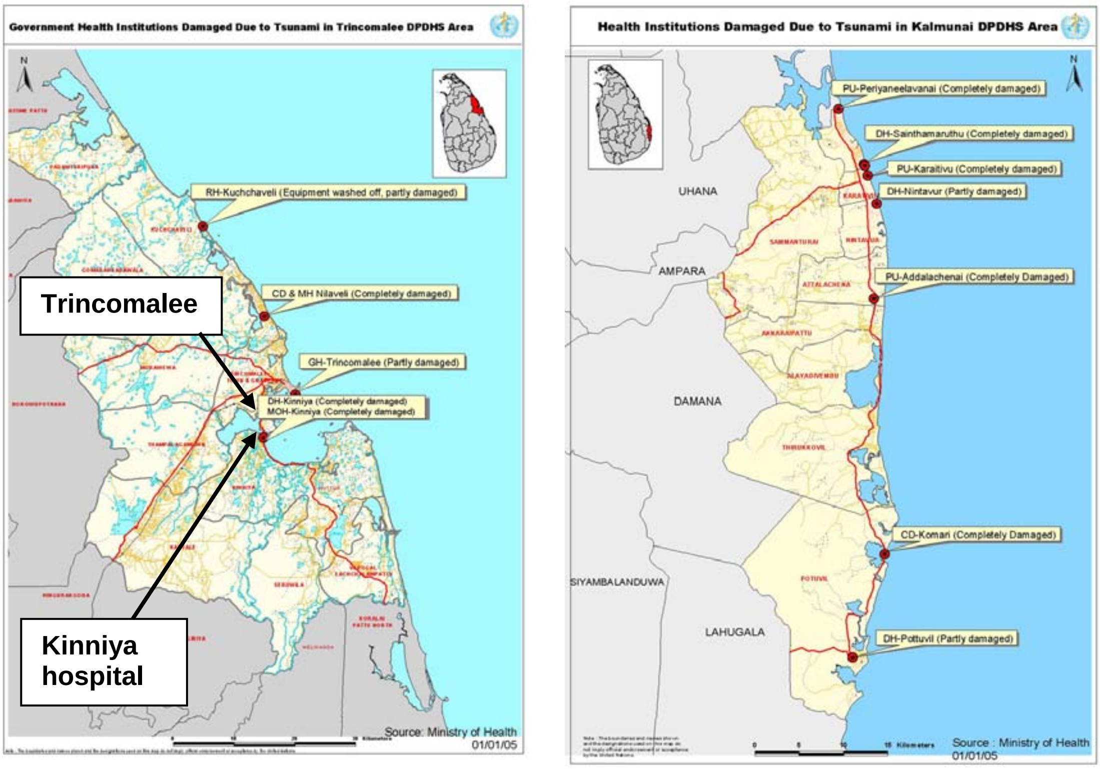


Figure 2.75: Damaged hospitals in Trincomalee district and Ampara district (Eastern province)

Figure 2.74 shows the Mahamodara hospital in Galle located within 100m of the coastline. The hospital structures were typically 3-storey reinforced concrete frame and slab type (Cat. D) with masonry infill panels. The structures suffered moderate damage (DC1) with the load bearing members intact. However the ground floor facilities were completely destroyed from the advancing tsunami and inundation killing and injuring patients and staff. It should be noted that patients, staff and those who managed to go up to the upper storeys survived the tsunami since the water level did not rise above the first floor as indicated from the disturbed tiles on the shading overhangs (see Figure 2.74). The hospitals services have since been moved to Karapitiya hospital in Galle that survived the tsunami since it is located on high ground at a distance of about 1km from the coast. More hospitals were damaged in the Eastern and Northeast Provinces as shown in Figure 2.75 and the damage was substantial since the exposure to the tsunami was high in these areas. Figure 2.76 shows the damaged Kinniya hospital in Trincomalee (Pillai, 2005). Many of the healthcare facilities were provided at makeshift hospitals set up near camps for internally displaced persons.

Figure 2.76: Damaged Kinniya district hospital in Trincomalee (Photo by Anton Pillai, Arup)

2.6.2 Schools and Educational Facilities

The tsunami caused damage to 168 schools, 4 universities and 18 vocation training and industrial training centres (Ministry of Education, 2005 and Ministry of Finance, 2005). The major proportion of the damage has been to primary and secondary schools, which account for over 90 percent of the damaged institutions. Buildings in 59 schools have been completely destroyed and further 91 schools, which have been destroyed or damaged are located close to coastline and therefore have to be relocated and reconstructed. The damage also included equipment, books, machinery, tools, furniture, teaching material and library resources, which have to be replaced. Much of the heavily damaged or destroyed schools were unreinforced masonry structures either Cat. B (poorly quality) or Cat. C (good quality). Figure 2.77 shows a school in Akurala that was completely destroyed (DM4) and a school in Gintota that has suffered heavy damage (DM3). The school in Gintota (Cat. B) has masonry columns confining the wall panels hence part of the structure did not collapse. Schools which suffered moderate to light damage had reinforced concrete frames with masonry infill. Figure 2.78 shows a school building of Cat. D in Matara, which has suffered little damage (DC1). Damage appears to have been to a masonry structure attached to a school building and to the boundary wall, which was under repair at the time of the survey. The largest numbers of damaged schools were reported in the Ampara district (38 schools) and Batticaloa district (33), which were followed by Trincomalee (27 schools) and Galle (22 schools). The four damaged universities are located in districts of Matara, Batticaloa, Ampara and Jaffna where the Jaffna University suffered the heaviest damage.

Figure 2.77: Destroyed school (Cat. C) in Akurala and heavily damaged school building (Cat. B) in Gintota (Southern Province)

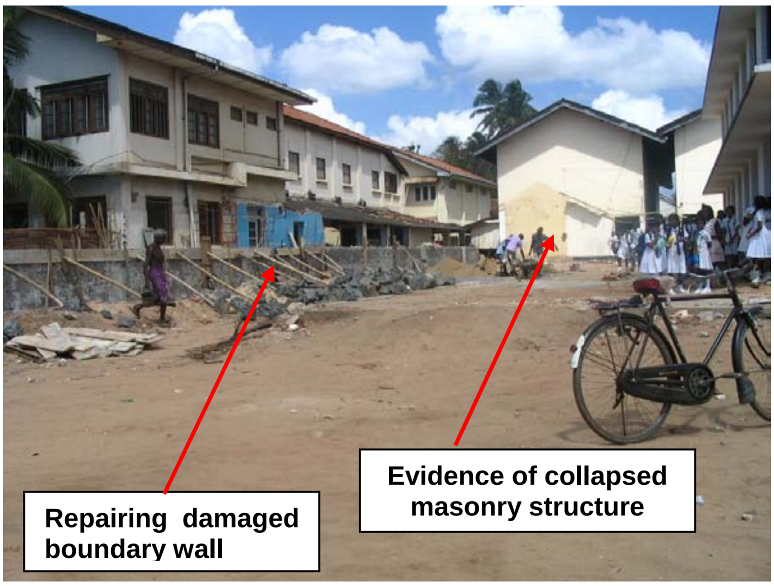


Figure 2.78: School in Matara (Cat. D) suffered minor damage with damage to a masonry structure attached to a school building and to the boundary wall under repair

2.7 Ports and Industrial Facilities

2.7.1 Galle Port

The Galle Port established in 1800 is located in the eastern end of the natural harbour as shown in Figure 2.35, which is a well known archaeological site due to its colonial history. According to the eyewitness account from the harbour manager, the tsunami waves arrived in the harbour from the west and east inundating the dock side and the harbour offices. The silt traces on the walls of the harbour management building were about 3m above the ground level (no photographs were allowed to be taken at the site). There was a scour hole about 10m wide and extending 20m from the eastern quay wall (see Figure 2.35). However the quay wall, which appears to be a concrete gravity wall structure was intact. Figure 2.79 shows a cargo ship (with an estimated displacement of 500T) typical of those visiting the harbour, sitting on a concrete quay wall at the northeast end of the harbour. The ship may have been lifted off the quay side from the rising water and this gives an indication of the height and the speed of the water arriving at the harbour in order to displace the ship onto the quay wall. There was no visible damage to the concrete quay wall suggesting that the walls are strong enough to survive the tsunami of this magnitude. There were two small vessels dragged toward the harbour management building from the tsunami and evidence of small boats washed on to the surrounding area.

Figure 2.79: Cargo ship displaced on to the concrete quay qall at Galle Port

The primary function of the port is to supply clinker for the Holcim cement processing plant and distribute the cement to the market. Since the harbour structures were intact following the tsunami, it was functional within 2 days of the event after clearance of debris.

2.7.2 Trincomalee Port

Trincomalee in the northeast of Sri Lanka is one of the world’s largest natural harbours due its deep mouth of Mahaweli River flowing to the Indian Ocean. The harbour has a terminal serving the Mitsui cement plant and the Prima flour and milk powder processing facility. The harbour is used for supplying raw materials and distribution of the products. The Port is also home to the Sri Lankan Navy’s naval facilities. There were few reports available of damage to any of the docking facilities of Mitsui and Prima plants. No reports are available of any damage to the naval facilities.

2.7.3 Fishing Harbours

Fishing harbours and boat landings encountered during the EEFIT survey appears to have survived with little damage to the harbour protection structures. Figure 2.80 shows the harbour in Beruwala where the breakwater appears to be intact with no indication of displacement of the rockfill. Figure 2.16 shows the breakwater overtopped by the rising tsunami water but remaining intact. The small fishing harbour in Hikkaduwa has also survived the tsunami with a small region of slope failure within the harbour side as shown in Figure 2.81. Asian Development Bank (2005) reports that there was considerable damage to fishing harbours in Hambantota and Trincomalee districts. Many of these harbours require extensive dredging and removal of debris and sand from the basin. There were damages to the service facilities and harbour equipment including shore structures, dredgers, heavy mechanical equipment, ice plants, buildings, boat repair yards etc.

Figure 2.80: Beruwala fishing harbour with no visible damage to the breakwater

Figure 2.81: Slope failure in the harbour side of the rockfill breakwater in Hikkaduwa

2.7.4 Industrial Facilities

The Holcim cement processing facility in Galle is the only key industrial facility in the coastal region surveyed by EEFIT. The processing facility produced three different types of cement for the local cement market and use the Galle Port for transportation of cement clinker and supply the cement to the market. The facility located about 500m from the coast (see Figure 2.35) was inundated to a height of about 2m from the ground level. This resulted in damaged to the processing machinery however no structural damage was visible nor reported by the plant manager. The damaged components were replaced and repaired and the plant was back in operation about 10days after the tsunami. The Prima flour and milk powder processing facility located in the Trincomalee harbour also did not suffer significant damage (Pillai, 2005).

2.8 Design Codes and Regulations

2.8.1 Building regulations

Building regulations in Sri Lanka are applicable for buildings exceeding 2-storeys in height or 280m^2 in plan. The building regulations are enforced by the local authority departments and the construction plans have to obtain approval prior to constructions. Buildings exceeding 2-storeys are generally designed to British Standards, e.g. BS8110 for reinforced concrete buildings. Single storey buildings and residential buildings are not regulated and the quality control is left to the respective owners or the builders. However, planning permission is still required for these structures, which do not generally address the engineering issues.

The houses constructed to re-house tsunami affected people are required to comply with the building regulations. The developers are required to submit the design calculations for housing or other developments to the Urban Development Authority (UDA) and that the designs must be carried out by a Chartered Engineer. The construction is subjected to inspections by the UDA, who is also responsible for the strict implementation of the building regulations. UDA is also responsible for overseeing any construction activities within the coastal buffer zones declared by the Government of Sri Lanka following the tsunami.

2.8.2 Design of Roads and Bridges

The design of roads in the coastal areas may require review as they have been subjected to erosion and scour damage. The EEFIT survey found that many road sections were exposed to the sea without protection and suffered severe scour damage as a result. No design code exists in Sri Lanka for design and construction of roads. Guidelines possibly from British road construction practices are in use.

All the bridges with few exceptions are designed to a standard design layout set up by the Road Development Authority (RDA). Design of bridges is generally carried out to BS5400 in the absence of any local codes. The EEFIT survey found that damage to bridges was largely due to scouring of the abutments. This issue should be addressed during reconstruction of the bridges in the coastal areas.

2.8.3 Design for Seismic and Tsunami Loads

Sri Lanka does not have a seismic design code due to the absence of significant earthquakes and the historically low seismicity. Hence lateral resistance of buildings against external loads are largely based on wind loads. Some non-governmental organizations such as the United Nations accredited World Vision engaged in housing reconstruction has requested that consideration should be given to seismic loads expected in Sri Lanka although no level has been defined (Fernando, 2005). Studies on seismicity and seismic hazard of Sri Lanka has been carried out (Abaykoon, 1996, 1998) with particular reference to greater Colombo, however no guidelines or provisions exists for designers.

Design against tsunami loads was never considered in Sri Lanka as it was not anticipated to be a risk to the coastal areas. For instance the return period of a tsunami of the scale on December 26, 2004 in Sri Lanka would be around 500 to 1000years (see Section 1.2). No guidance exists on dealing with tsunami or flood loads on buildings. FEMA55 provides an aid to designing against tsunami loads. It should be noted that the tsunami that occurred on December 26, 2004 is a rare event that may have a return period of 2000years or more. Designing against such an extreme event may not be prudent since a balance must be drawn against cost of construction and importance assigned to the use of the structure. Critical facilities may be designed for such loading if they have to be sited close to the sea. The guidelines produced by the U.S. National Oceanic and Atmospheric Administration (NOAA, 2001) provides guidance on addressing the tsunami hazard from a risk management perspective. If structures have to be sited in proximity to the sea e.g. a tourist hotel within the coastal buffer zone, then guidance on designing against tsunami loads could be sought from FEMA 55 coastal construction manual.

2.9 Impact on Society and Recovery

2.9.1 Casualties and Fatality Rate of the Tsunami

2.9.1.1 Human Casualties

Sri Lanka is divided into 9 provinces (Northern, North-Central, North-Western, Central, Eastern, Western, Sabaragamuwa, Uva and Southern) and 25 districts. Four of the nine provinces (Northern, Eastern, Southern and Western) and 13 of the 25 districts were affected by the tsunami. The other provinces and districts were almost totally unaffected. A map of Sri Lanka's districts and Divisional Secretariat (DS) divisions affected by the tsunami are shown in Figure 2.82.

The Centre for National Operations (CNO) last reported the summary of the tsunami's effects on January 27, 2005. The data by province and district are shown in Table 2.4. The most recent summary of casualties (June 15, 2005) stood at 31,229 dead, 4,100 missing and 23,819 injured (8,623 added) while the number of displaced people stood at 516,130 (Relief Web 2005, NDMC, 2005), i.e. 270 fatalities were added and 1,204 missing persons have been found, compared to the detailed data of January 27. The number of completely damaged houses has come down to 63,472 while the number of partially damaged houses has gone up to 43,234. This was largely attributed to more accurate counting in the Northern and Eastern Provinces few months after the event and due to initial access difficulties.

Table 2.4: Summary damage and human casualty statistics in Sri Lanka by district (January 27, 2005)

Province	District	Deaths	Injuries	Missing	Displaced	Damaged Houses	
						Completely	Partially
Northern	Jaffna	2,640	1,647	540	40,120	6,084	1,114
	Killinochchi	560	670	1	1,603	1,250	4,250
	Mullaitivu	3,000	2,590	552	22,557	3,400	600
Eastern	Trincomalee	1,078	-	337	81,599	5,974	10,394
	Batticaloa	2,840	2,375	1,033	62,846	15,939	5,665
	Ampara	10,436	120	876	73,324	29,199	-
Southern	Hambantota	4,500	361	963	17,742	2,303	1,744
	Matara	1,342	6,652	613	12,198	2,362	5,659
	Galle	4,218	313	554	127,754	5,525	5,966
Western	Kalutara	256	400	155	27,713	2,780	3,116
	Colombo	79	64	12	31,697	3,398	2,210
	Gampaha	6	3	5	1,449	292	307
North Western	Puttalam	4	1	3	66	23	72
SRI LANKA		**30,959**	**15,196**	**5,644**	**500,688**	**78,529**	**41,097**

The worst effects were experienced in the Eastern province whose coast is lined roughly parallel to the earthquake's rupture zone and faced the incoming tsunami across the Indian Ocean. This is where 65% of the destroyed buildings were located based on data in Table 2.4. Ampara district in Eastern province was the worst affected part of the country with one third of the confirmed deaths and 37% of the destroyed buildings. In total close to 120,000 houses were destroyed or partially damaged, with 66% of the affected houses having complete damage. The numbers of injured persons by district are understandably not as accurate by January 27, 2005 with Ampara district reporting a small number and Trincomalee not having a tally of the injured. The largest displaced population is in Galle district at about 26% of the total. This is largely due to the coastal exposure of a large population in relation to the inundation distance observed in this district from Ambalangoda to Habaraduwa (see also Figure 2.10). In Sri Lanka as a whole for every injury reported there were about 1.48 fatalities and missing persons based on June 15, 2005 data. Even though the number of reported injuries is not complete this suggests that if people were caught by the rapidly moving waves they had a low chance of survival. For every damaged housing unit in Thailand there were 25 damaged housing units in Sri Lanka.

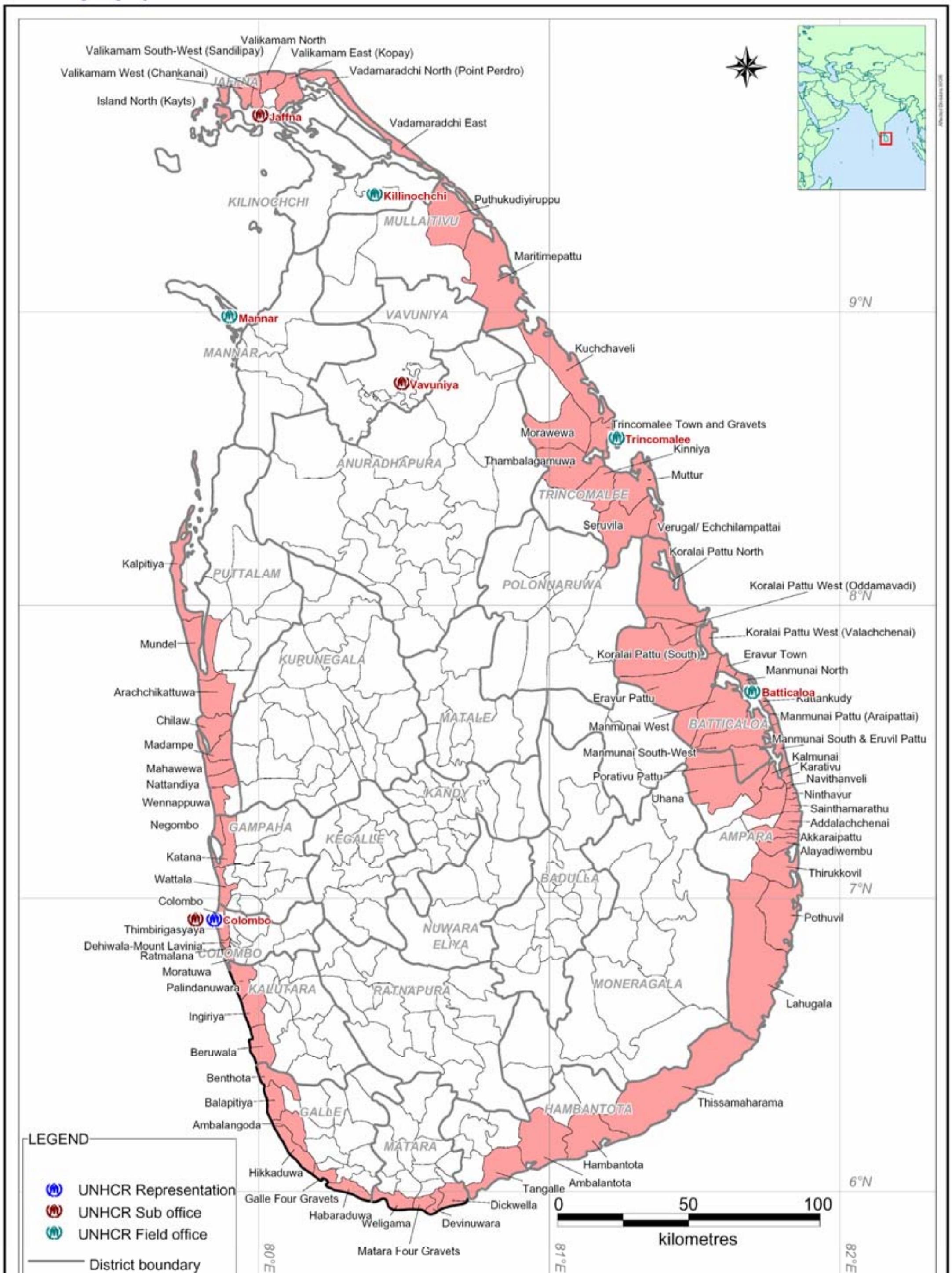


Figure 2.82: Map of Sri Lanka's tsunami affected districts and DS divisions (Source: UNHCR).

2.9.1.2 Fatality Rates by Province

An analysis was made using the CNO fatality data in Table 2.4 in order to investigate the severity of the event in several parts of the country that may have been affected differently by the tsunami waves, or that may have different building or coastal topography characteristics. The fatality and injury rates can be calculated if we have a reasonably good estimate of the population near the coast. This problem was addressed by Center for International Earth Science Information Network (CIESIN) at Columbia University in a web-based report (Balk et al, 2005) where the population in all the affected provinces and districts was estimated at 1-km and 2-km from the coast. Table 2.5 summarizes the lethality (fatalities and missing) and casualty rate relative to CIESIN's 1-km from the coast population estimates for the 3 worst affected provinces, where 98.9% of the confirmed fatalities were reported.

Table 2.5: Human casualties in Sri Lanka by province

Province	Fatalities	Missing	Injured	Population within 1-km from coast	% of regional population at 1km	Fatalities and Missing to 1-km from coast population	Human Casualties to 1-km from coast population
Northern	6,200	1,093	4,907	209,762	21.6%	3.5%	5.8%
Eastern	14,354	2,246	2,495	109,366	7.6%	15.2%	17.5%
Southern	10,060	2,130	7,326	57,789	2.4%	21.1%	33.8%
Total (3 provinces)	30,614	5,469	14,728	376,917	7.8%	9.6%	13.5%
SRI LANKA	**30,959**	**5,644**	**15,196**	**550,208**	**2.7%**	**6.7%**	**9.4%**

It is seen that the lethality rate among the population living within 1-km from the coast was almost 10.0% in the 3 worst affected provinces as a whole (assuming all deaths and missing persons are among people that lived within 1-km from the coast). If the 2-km from the coast is used then the lethality rate drops to 4.7%, however it is thought that the 1-km population is a more accurate reference for the estimation of the number of people actually facing the tsunami waves on the morning of December 26, 2004. The lethality rate among the 1-km from coast population was much lower in the Northern province (3.5%) because the Kilinochchi district does not have a coastline that was affected seriously by the tsunami (all of Kilinochchi district's coast is in the western side of Sri Lanka). Also much of the coastal population of Northern province is concentrated in and around the city of Jaffna that lies on the western shore and was not seriously affected by the tsunami. The Southern province has the highest lethality rate (21.1%) in relation to the 1-km from the coast population estimate, followed by the Eastern province (15.2%). This is somewhat surprising considering that the worst of destruction was reported in the Eastern province. The casualty figures in the Southern province contain 1,000+ deaths and hundreds of injuries related to the train disaster in Peraliya (in Galle district).

The above casualty rate estimates are dependent on the accuracy of the coastal population estimates. Considering that the average household size in Sri Lanka is 4.2 persons and that there may be on average 1.1 household per housing unit, this means that the potential occupants of the damaged buildings (completely and partially) would be around 553,000. This is close to the sum of casualties (deaths, missing and injured) and displaced from Table 2.4 and similar to the 1-km from coast population estimate in the 3 affected provinces of Sri Lanka. Hence on average the population within 1-km of the coast nationally were exposed to the tsunami of December 26, 2004. This is also reflected in the tsunami inundation map of Figure 2.10 where on average the inundation could be about 1-km from the coast. Any discrepancies between the 1-km from the coast population and the casualties and displaced population may be attributed to those who survived un-injured and damaged houses that may have been vacant at the time of the tsunami.

A good correlation exists between the human casualties and the total number of houses damaged (completely and partially) as follows:

$$\text{Log}(C) = 0.1863\ \text{Log}(D)^{2.1334}$$

$$(r^2=0.823;\ n=11\ \text{districts})$$

where C is the human casualties (total of fatalities, missing and injuries) and D is the number of houses damaged (completely and partially) and r is the correlation coefficient.

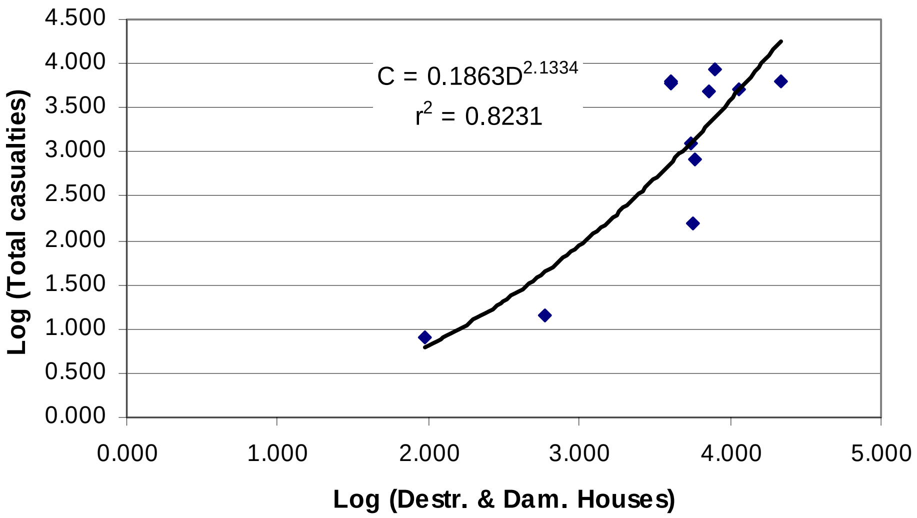


Figure 2.83: Relationship between total casualties (dead, missing and injured) and the destroyed and damaged houses in the affected DS divisions

2.9.1.3 Affected and Injured Population by DS Division in EEFIT Survey Area

The data in Table 2.6 were compiled from the detailed survey reports published by the Department of Census and Statistics of Sri Lanka. It shows the statistics for the population living in the affected census blocks in the EEFIT survey area, the percentage of people that were affected (lived in the damage housing units) and the percentage of the people disabled or injured or falling ill among the affected people. The DS divisions are listed in order of location from Colombo to Matara. It is seen that about 43.0% of the population in the affected census blocks lived in the damaged housing units and that 5.0% of them were disabled or injured or fell ill as a result of the tsunami. It is reminded that 7,229 people died or were missing in the surveyed districts (see Table 2.4), but not all were living in the damaged housing units (e.g. 1000+ people died in the Peraliya train disaster and many of the passengers may have been from non-coastal divisions).

Table 2.6: Proportion of affected and injured population by DS division in the EEFIT survey area

DS Division	Population before the tsunami in affected census blocks	% of population living in damaged units	% Disabled/Injured/Sick among the people living in the damaged units
Moratuwa	34,852	48.1%	2.3%
Panadura	15,850	53.5%	2.0%
Kalutara	16,322	52.0%	3.4%
Beruwala	22,920	36.1%	2.3%
Bentota	1,036	15.1%	3.2%
Balapitiya	22,205	45.5%	3.8%
Ambalangoda	3,738	64.5%	3.3%
Hikkaduwa	41,686	50.4%	5.7%
Galle city	28,027	29.0%	12.3%
Habaraduwa	17,841	33.3%	7.2%
Weligama	25,506	45.6%	7.5%
Matara city	25,546	37.3%	8.3%
Total in survey area	**255,529**	**43.4%**	**5.2%**

It is thus estimated that among the population living in the affected census blocks in the EEFIT survey area (Moratuwa to Matara) around 2.8% were killed or missing and around 2.3% were injured or disabled or fell ill as a result of the disaster. However the census blocks often extend more than 1.5 km inland from the coast, while most of the casualties must have occurred in the first 300m zone as evidenced by the damage statistics by distance from the coast where 91% of the damaged houses were within 300 metres from the coast (see Table 2.8 below).

2.9.2 Impact on Housing

2.9.2.1 Damage Degree Distribution to Housing in the Affected Census Blocks of the EEFIT Survey Area

The data in Table 2.7 were compiled from the reports published by the Department of Census and Statistics of Sri Lanka at the initial listing stage of their survey. It shows the statistics for the damaged housing units by their damage severity (3 degrees of damage were used: completely damaged, partially damaged that cannot be used and partially damaged that can be used, which are similar to the damage scale adopted in describing building damage in Section 2.4.2). It contains the census blocks that were affected by the tsunami but the reference is the number of housing units in the census blocks before the tsunami irrespective of height and extent of inundation within each census block. It is seen that 22.3% of the housing units in the affected census blocks were damaged beyond repair and will have to be replaced. This ratio varied significantly between the 12 visited DS divisions due to various reasons such as: the level of run-up, the extent of inundation compared to the boundaries of the affected census blocks. Figure 2.47 shows the data in Table 2.7 plotted for comparison with the observed building damage in the EEFIT survey area.

Table 2.7: Distribution of damage degrees to housing units in the EEFIT survey area

DS Division	No. of housing units before the tsunami	% of housing units in the affected census block by damage level			
		Completely damaged (%)	Partially damaged that cannot be used (%)	Partially damaged that can be used (%)	Not damaged (%)
Moratuwa	8,220	26.3%	5.1%	22.1%	46.5%
Panadura	3,826	18.3%	4.4%	31.5%	45.8%
Kalutara	662	15.5%	7.0%	27.4%	50.1%
Beruwala	3,787	16.4%	3.9%	17.8%	61.9%
Bentota	200	3.0%	0.0%	18.5%	78.5%
Balapitiya	4,917	16.3%	4.2%	27.6%	51.9%
Ambalangoda	865	37.5%	2.8%	23.5%	36.3%
Hikkaduwa	9,513	23.0%	4.9%	26.8%	45.3%
Galle city	5,440	11.9%	4.8%	19.5%	63.8%
Habaraduwa	4,116	12.4%	3.7%	20.2%	63.7%
Weligama	5,682	13.0%	5.0%	28.6%	53.4%
Matara city	5,592	10.1%	4.5%	25.9%	59.5%
Total in survey area	**50,820**	**17.6%**	**4.7%**	**24.6%**	**53.1%**

Complementing Figure 2.82, which shows the tsunami affected districts and DS divisions, Figures 2.84 to 2.87 show the affected coastal GN (Grama Niladari) divisions (lowest administrative level) in Colombo, Kalutara Galle and Matara districts respectively (Source: Department of Census and Statistics of Sri Lanka).

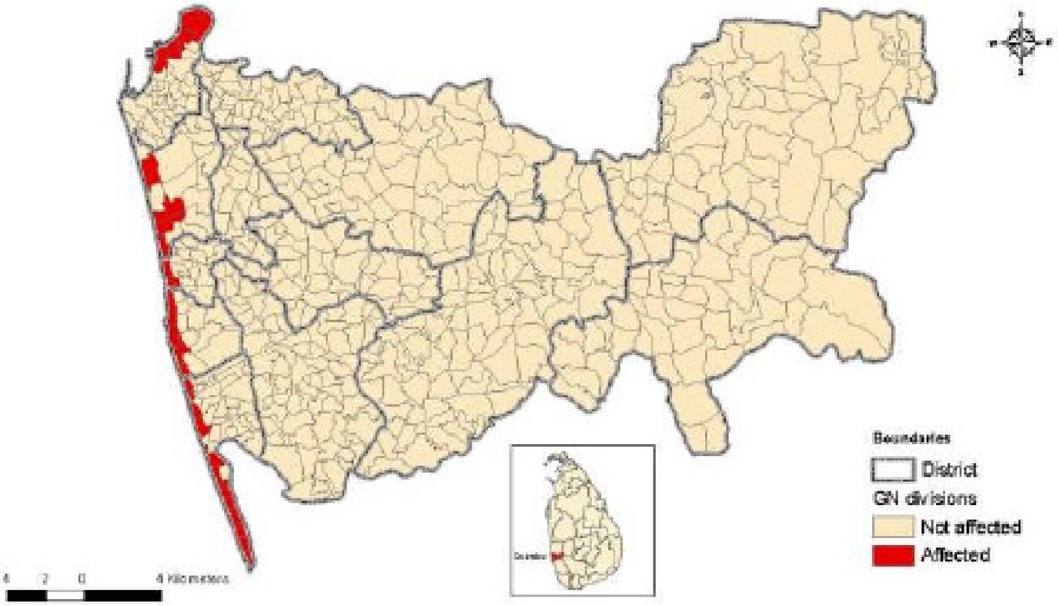


Figure 2.84: Map of Colombo district (Western province) showing the affected GN divisions

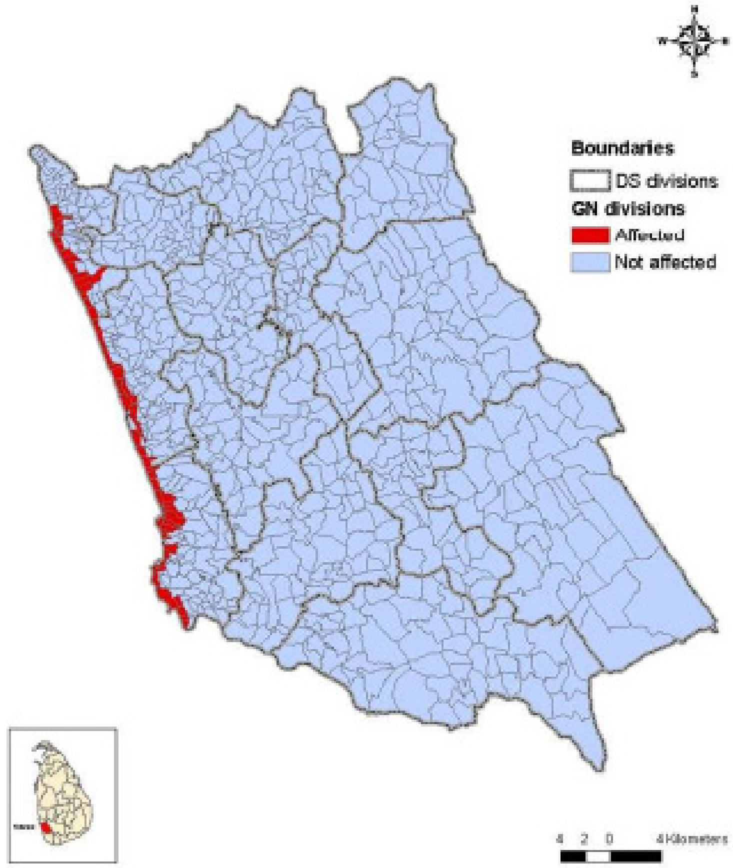


Figure 2.85: Map of Kalutara district (Western province) showing the affected GN divisions

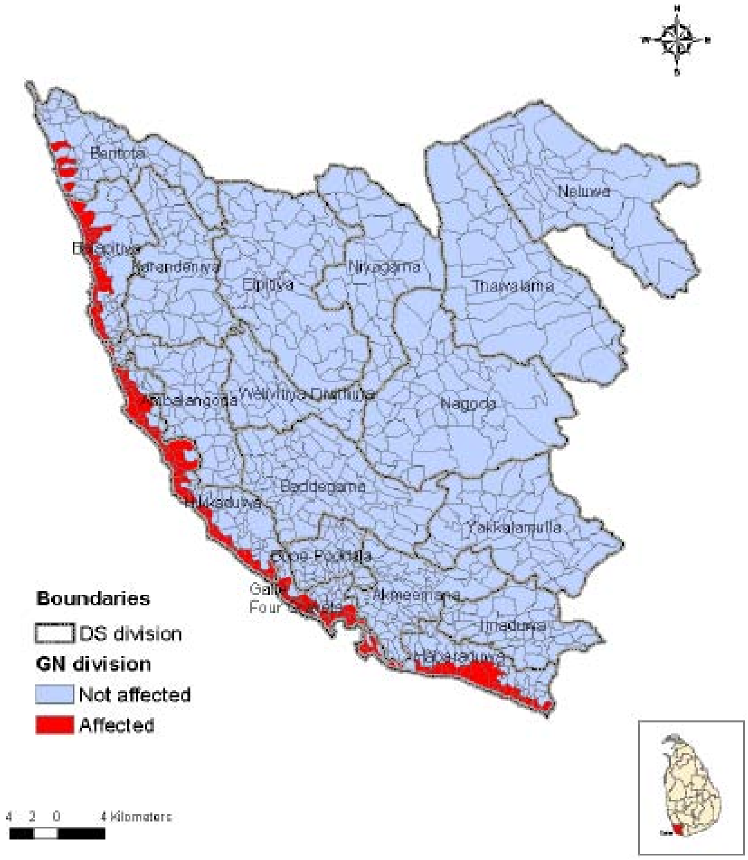


Figure 2.86: Map of Galle district (Southern province) showing the affected GN divisions

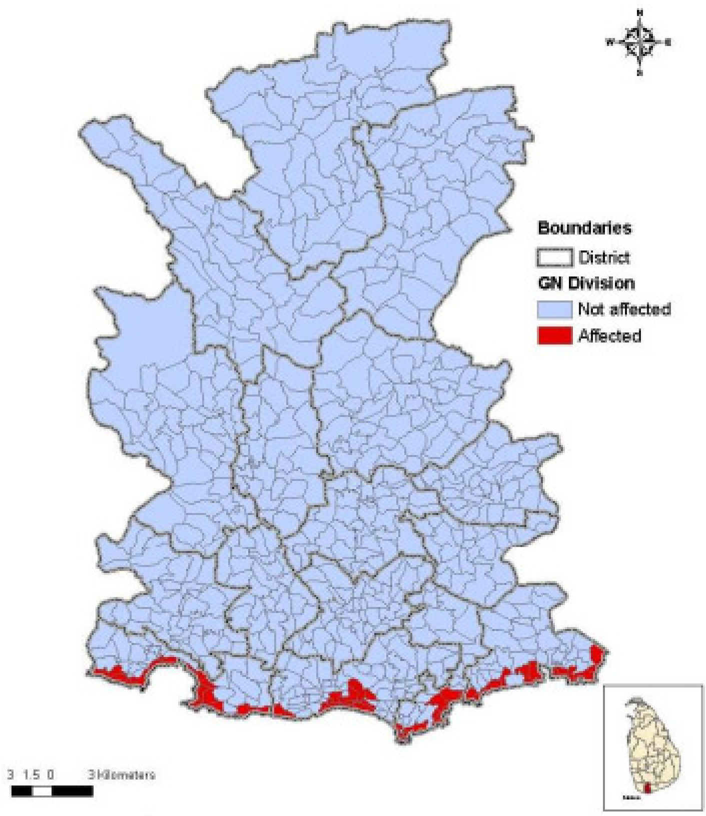


Figure 2.87: Map of Matara district (Southern province) showing the affected GN divisions

2.9.2.2 Damage to Housing in Relation to Distance from the Coast in the Affected Census Blocks of the EEFIT Survey Area

The data in Table 2.8 were compiled from the detailed survey and assessment reports published by the Department of Census and Statistics of Sri Lanka. It shows the statistics for the damaged housing units (completely and partially) in relation to their distance from the coast in most of the DS divisions visited by the EEFIT team (in Colombo, Galle and Matara districts). The distance was estimated by the enumerator at the time of the data collection. It is seen that 81% of the damaged dwellings were situated within 200m from the coast, although this ratio varied somewhat between the subdivisions (minimum in Balapitiya division where 62% of the damaged dwellings were situated within 200 metres from the coast). The biggest variation is observed in the proportion of the damaged houses that were located more than 300m from the coast. In some areas the inundation extended deeper inland and thus 15-19% of the damaged houses were beyond the 300m (in Balapitiya, Hikkaduwa and Matara) while in the city of Galle only 3.3% fell in this category perhaps due to the damping effect the dense habitation might have had on damage. The data in Table 2.8 contain around 79% of the damaged houses reported by CNO in Table 2.4 for the respective districts, either because for some of the houses it was not possible to estimate the distance from the coast or for some other unknown reason.

Table 2.8: Damage to housing units by distance from the coast in the EEFIT survey area

DS Division	District	Damaged housing units	≤ 100m from the coast	101-200m from the coast	201-300m from the coast	≥ 301m from the coast
Moratuwa	Colombo	4,019	3,529	449	24	16
Panadura	Kalutara	1,973	1,055	745	104	58
Kalutara	Kalutara	1,891	1,190	520	46	19
Beruwala	Kalutara	1,787	797	637	258	77
Bentota	Galle	38	30	6	1	1
Balapitiya	Galle	2,145	642	681	496	323
Ambalangoda	Galle	524	436	66	6	14
Hikkaduwa	Galle	4,694	1,958	1,183	664	884
Galle city	Galle	1,588	934	467	134	52
Habaraduwa	Galle	1,420	747	480	107	79
Weligama	Matara	2,487	1,188	920	291	80
Matara city	Matara	2,026	704	664	359	296
Total in survey area		24,592	13,210	6,818	2,490	1,899
Percentage by distance from coast			**53.7%**	**27.7%**	**10.1%**	**7.7%**

2.9.3 Damage to Non-Residential Buildings

The Department of Census and Statistics of Sri Lanka published the damage statistics shown in Table 2.9 for the affected non-residential buildings by district for the whole of Sri Lanka. The definition adopted for a non-residential building is a building that is wholly or partially not used as a place of dwelling. Small and medium enterprises fall into this category, which constitute most of the commercial activities in the urbanized areas. In total just over 11,000 buildings were destroyed or damaged partially with 53% needing replacement. Galle district not surprisingly had the most affected buildings due to its higher rate of urbanization, followed by the severely affected Ampara district. For every damaged non-residential building there were 11 damaged houses.

The data in Table 2.10 were compiled from the detailed survey and assessment reports published by the Department of Census and Statistics of Sri Lanka. It shows the statistics for the damaged non-residential buildings by their damage severity in the area surveyed by EEFIT. It is seen that 18.7% of the non-residential buildings in the affected census blocks were damaged beyond repair and will have to be replaced. This reflects the extent of asset loss to commercial activities carried out in buildings. This loss is smaller than 22.3% for housing in Table 2.7, which is expected owing to commercial buildings having better quality construction than houses.

Table 2.9: Damage to non-residential buildings

Province	District	No. of non-residential units damaged		
		Completely	Partially (cannot be used)	Partially (can be used)
Northern	Jaffna	181	23	146
	Kilinochchi	0	13	0
	Mullaitivu	302	52	65
Eastern	Trincomalee	328	58	232
	Batticaloa	525	167	506
	Ampara	1,173	243	683
Southern	Hambantota	289	57	243
	Matara	366	152	870
	Galle	992	321	1,857
Western	Kalutara	371	97	280
	Colombo	103	42	198
	Gampaha	19	2	42
SRI LANKA		**4,650**	**1,227**	**5,125**

Table 2.10: Distribution of damage degrees to non-residential buildings in the EEFIT survey area

Division	Non-resid. buildings before the tsunami	% of non-residential buildings by damage level			
		Completely damaged	Partially damaged (cannot be used)	Partially damaged (can be used)	Not damaged
Moratuwa	610	13.4%	5.4%	19.7%	61.5%
Panadura	450	6.0%	2.4%	16.9%	74.7%
Kalutara	311	8.7%	6.1%	17.0%	68.2%
Beruwala	1260	25.2%	5.3%	12.0%	57.5%
Bentota	77	0.0%	0.0%	13.0%	87.0%
Balapitiya	584	12.2%	4.6%	24.5%	58.7%
Ambalangoda	253	5.9%	0.0%	24.9%	69.2%
Hikkaduwa	1793	19.0%	6.0%	28.6%	46.5%
Galle city	2180	14.5%	5.2%	35.8%	44.5%
Habaraduwa	1337	18.8%	5.5%	26.1%	49.5%
Weligama	1252	9.3%	5.7%	24.6%	60.4%
Matara city	1920	6.5%	2.4%	17.0%	74.2%
Total in survey area	**12,027**	**14.0%**	**4.7%**	**24.0%**	**57.2%**

2.9.4 Impact on Healthcare and Education

The damage to health institutions and schools is summarised in Section 2.6.2. The damage to the health physical infrastructure and loss of health personnel created a breakdown of the health system where there was an inability to deal with the curative and preventative care for the tsunami displaced and non-displaced population in the coastal areas. The supply of drugs from various donors both national and international eased the shortages due to losses from the tsunami and increased demand for care. Damage was greater to hospitals in the Eastern province since the exposure to the tsunami was in these areas (see also Figure 2.74). Makeshift hospitals were set up in camps and schools undamaged from the tsunami in the short term. The prevention of communicable diseases was a priority where measures were taken to improve disease surveillance with the support from the MOH, UNICEF and WHO. This has prevented major outbreaks, which was widely anticipated following the tsunami.

Damage to 168 schools, 4 universities and vocational and industrial training centers will impact on the education among the coastal populations and those from other parts of the country attending these institutions. The majority of the damage was to primary and secondary schools (over 90%). The damage also included equipment, books, machinery, tools, furniture, teaching material and library resources, which have to be replaced (source: Ministry of Education, (MOE)). In addition to asset losses, there were physical and social losses among students, teachers, principals and administrators, which have to be addressed for proper functioning of the education system. Some schools were reopened by end of January using temporary facilities provided by the MOE and various non-governmental organizations.

2.9.5 Economic Impact and Financing Needs

The tsunami on December 25, 2005 has resulted in a direct and indirect economic impact in the coastal areas of Sri Lanka. The economic impact was largely in the fisheries and the tourism sectors as discussed below.

2.9.5.1 Impact on Fisheries

The fishery sector accounted for 2.4% of the GDP in the year 2004. The sector provides direct employment to about 142,500 active fishermen and about another 200,000 indirectly (Asian Development Bank, 2005). The death toll among fishermen was 7,222 with largest fatalities in Mullaitivu (2,524), Batticaloa (1,229) and Ampara (1,025) districts (source: Department of Fisheries and Aquatic Resources, 2005). In addition to damage reported to fishing harbours and landings about 65% (19,110) of the country’s fishing fleet of 29,700 boats was either fully destroyed or damaged to varying degrees. The damage included 594 multi-day boats (MDB), 7,996 motorized day boats and about 10,520 traditional non-motorized boats. The fisheries industry produces about 300,000 tonnes of sea fish annually at a value of $250 million. The export earnings were about $100 million in 2004, which is largely relying on catches from MDBs. The substantial damage to the fleet would affect the output in 2005 predicted to be about 200,000 tonnes resulting in an output loss of $200 million in years 2005 and 2006. The fishing sector provides the income and livelihood for the coastal communities hence loss of income and unemployment would have a severe impact on the quality of life and may increase the level of poverty in the coastal areas in the short term until relief is provided to restore the lost or damaged fleet.

2.9.5.2 Impact on Tourism

The tourism sector in Sri Lanka accounted for 2.0% of the GDP in 2004 providing employment to about 115,000 people (50,000 direct and 65,000 indirect). Of the 246 hotels islandwide, 109 are located along the coastal areas (source: Sri Lanka Tourist Board). The number of hotels closed as of January 12, 2005 was 52, which accounts for 47% of the coastal hotels (21% of the hotels islandwide). Since many of the hotels in the coastal areas are located within 100m of the sea, the exposure to the tsunami and hence damage were substantial. Typical damage to hotels was seen in the survey carried out in Unawatuna beach, just south of Galle City (see Section 2.4.6). The damage to hotels resulted in lack of availability of rooms, about 3,500 out of 14,000 rooms became unavailable in medium to large scale hotels (Asian Development Bank, 2005). The asset loss amounts to $200 million in damages to hotel rooms and another $50 million in damages to related assets such as souvenir shops, vehicles etc. The tourism sector posted foreign exchange earnings of over $350 million in 2004 due to the tourist arrivals reaching a historical record of 565,000 (source: Central Bank of Sri Lanka). The tourist arrivals are expected to fall to about 425,000 in 2005 resulting in an output loss of $130 million through to 2006.

2.9.5.3 Overview of Macroeconomic Impact and Financing Needs

The economic impact of the tsunami consists of asset losses (direct impact), output losses (indirect impact) and fiscal losses (secondary effects). Table 2.11 summarizes the losses in each sector affected by the tsunami and financing needs from a preliminary damage assessment jointly carried out by the Asian Development Bank, Japan Bank for International Cooperation and the World Bank (ADB, 2005). The total asset losses come to about US $1.0 billion, which is 4.6% of the GDP in 2004. The combined output loss largely from the anticipated slowdown in fisheries output and the decline in tourism revenue is about \$330 million (1.5% of the GDP) in 2005 and 2006. ADB (2005) estimates that the total financing needs for short and medium term operations are \$1.5 to \$1.6 billion (7.0 to 7.3% of GDP). Table 2.11 also shows the cost estimates evaluated by the Task Force for Rebuilding the Nation (TAFREN), which were reported to the office of the President within 3 weeks of the tsunami. The TAFREN cost estimates are higher than the ADB (2005) estimates of short and medium term needs, and the total estimate comes to about \$2.0 billion (10.5% of GDP).

Table 2.11: Preliminary estimates of losses and financing needs (ADB (2005) and TAFREN)

Sector	Losses (US$ million)		Financing needs (US$ million)			TAFREN cost (US$ million)
	Asset	Output	Short term	Medium term	Total needs	
Housing	306-341		50	387	437 – 487	400
Roads	60		25	175	200	353
Water and sanitation	42		64	53	117	205
Railways	15		40	90	130	313
Education	26		13	32	45	170
Health	60		17	67	84	100
Agriculture	3		2	2	4	-
Fisheries	97	200	69	49	118	200
Tourism	250	130	130	-	130	58
Power	10		27	40 – 50	67 – 77	133
Environment	10		6	12	18	-
Social Welfare	-		30	-	30	157
Excluded items	90		30	120	150	
Total (US$ million)	**970 – 1,000**	**330**	**500**	**1,000 – 1,100**	**1,500 – 1,600**	**2,089**
% of GDP (2004)	**4.4 – 4.6**	**1.5**			**7.0 – 7.3**	**10.5**

The impact on the nation's output was not considerable compared to the asset losses, however the economic and social infrastructure of the coastal areas was hit by the tsunami. The GDP growth forecast for 2005 has been revised from 6.0% to 5.4% (Central Bank Annual Report, 2005). The relatively limited impact on the GDP growth is due to the primarily affected fishing and tourism sectors together contributing only 3.0% of the national GDP. Brookshire et al (1997) describes that the nature of the pre-existing economic conditions has much to do with the degree of indirect economic loss observed after an event. Sri Lanka in the post-independence era (1948) was an agriculture-based economy. The structure of the economy experienced transformation into a manufacturing driven economy from the early 1970s largely led by the textile and garment sector from the 1980s onward (Kelegama, 2004). During this period there was a shift in the labour force from the agriculture sector (including fisheries) into manufacturing. By the 1990s the adoption of market economic policies resulted in a growing service sector led by information technology. The transformation away from the agricultural base (which includes fisheries) meant that the contribution to the GDP growth was overtaken by other sectors, namely manufacturing and service. Many of the manufacturing and service sectors are located in the Colombo and Gampaha districts and well away from the coastal areas. This meant that the contribution from the fisheries sector to GDP was not significant, hence their impact due to the tsunami was limited. Although tourism belongs to the service sector, it provides a modest contribution to the GDP (2.0%) compared to other contributors.

Table 2.12: Selected economic indicators, 2004 – 2005

	Actual 2004	Pre-tsunami 2005	Post-tsunami 2005
Real GDP growth (%)	5.2	6.0	5.4
Nominal GDP (US$ million)	19.8	23.0	23.0
Fish production (Tonnes)	300,000	300,000	200,000
Tourist arrivals	565,000	600,000	425,000
Construction sector growth (%)	5.0	6.0	9.0
Inflation (%)	7.6	10.0 – 11.0	12.0

Table 2.12 summarizes selected economic indicators (Central Bank Annual Report, 2005). It is anticipated that the construction sector will grow due to the need for short and long-term re-construction and new construction needs. Rebuilding will require a substantial rise in the imports within the next three years resulting in a widening trade balance and the overall balance of payments. The anticipated reduction in tourist arrivals and hence tourism revenue through to 2006 will further widen the balance of payments currently at a deficit. ADB (2005) estimates that there would be an external financing requirement close to $800 million in 2005 to dampen the negative impact of rise in imports and the decline in tourism revenue. The flow of external aid from foreign donors, concessionary loans and possibly debt relief is expected to ease the pressure on the external sector. The impact on the external sector and the effect of capital inflows is reflected in the exchange rate of the Sri Lankan Rupee in the currency markets. Figure 2.88 shows the effect on the exchange rate with the UK Sterling (GBP) on the days following the tsunami and during the period of the Sri Lanka Development Forum donor conference held on May 16 – 17, 2005 in Sri Lanka. The aid pledges and flow of capital appreciated the value of Sri Lankan Rupee in the currency markets hence easing the pressure on imports.

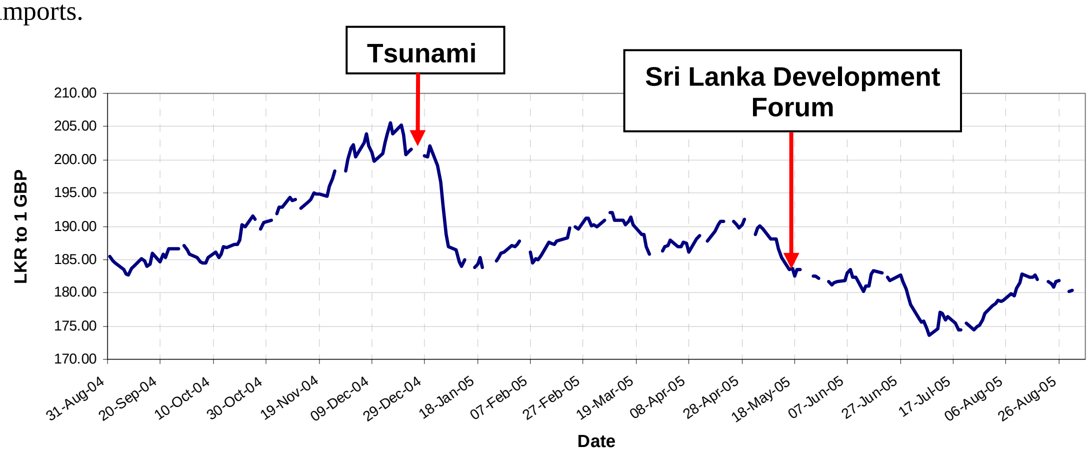


Figure 2.88: Exchange rate of Sri Lankan Rupee (LKR) with UK Sterling (GBP) and impact of the tsunami and aid flow (source: International Monetary Fund and Central Bank of Sri Lanka)

2.9.5.4 Impact on Poverty

Although the economic impact on Sri Lanka was considered to be minimal, the tsunami has raised the vulnerability of the coastal population to poverty given the loss of employment and the means of generating an income. People involved in the fisheries sector are largely expected to fall below the poverty line (see sub-section 2.9.14.1) at least in the short term. The official poverty line in Sri Lanka is defined as the per-capita expenditure of a person to be able to meet the nutritional anchor of 2030 kilocalaries. This was defined for the year 2002 since the latest Household Income and Expenditure Survey (HIES) was conducted by the Department of Census and Statistics in that year. The estimated poverty line for the year 2002 is LKR 1,423 (US $14) per month for all the districts except the Eastern and Northern province, where complete data sets were not available. Hence people living in households where the real per-capita monthly consumption expenditure is below LKR 1,423 in the year 2002 are considered to be poor. Table 2.13 shows the headcount index (percentage of population below the poverty line) and the population below the poverty line for the districts surveyed by EEFIT.

Table 2.13: Headcount index and population below the poverty line in 2002 for EEFIT survey districts

District	Poverty line (LKR (US$))	Headcount index (%)	Population below poverty line
Colombo	1,537 (15.3)	6.0	143,000
Kalutara	1,523 (15.2)	20.0	223,000
Galle	1,466 (14.6)	26.0	269,000
Matara	1,395 (14.0)	27.0	219,000
Sri Lanka	**1,423 (14.2)**	**23.0**	**3,841,000**

The data shows that 23.0% of the population of the four surveyed provinces are poor. The level of poverty (headcount index) before the tsunami in Galle and Matara districts was higher than the national average. It is likely that these figures may have increased following the tsunami thereby worsening the already alarming situation.

2.9.6 Emergency Response, Relief and Reconstruction

2.9.6.1 Government's Response

The Sri Lankan Government established the Center for National Operations (CNO) within two days of the disaster. This was a round the clock operation located in the Office of the President where all the relief operations were coordinated. The mandate of CNO was to monitor and coordinate all initiatives taken by government ministries, agencies and other institutions relating to post-tsunami relief efforts. The top most priority of CNO was to ensure that relief measures were directed to the affected people by identifying their needs and matching them with the available resources. The CNO was set up to fill the void of a think-tank, which is capable of strategy planning & overall monitoring of the disaster management programme of the Government. It was a round the clock operation located in the Office of the President and run by a team of volunteers released from various organizations.

To handle post-tsunami activities, the President on January 1, 2005 appointed 3 task forces;

- Task Force for Relief (TAFOR) – for immediate relief
- Task Force for Logistics and Law & Order (TAFLOL) – for logistics and law & order
- Task Force for Rebuilding the Nation (TAFREN) – for needs assessment and rebuilding the infrastructure

These task forces and various line ministries were geared to take over the responsibilities of CNO when it ended its operations 1 month after the tsunami.

2.9.6.2 Relief and Reconstruction

The team visited the affected areas a month after the event. Relief operations were visible along the whole length of the coast. A large number of foreign aid agencies had a presence in the area including from the UK, Italy as well as the US Army. Several camps with tents set up for the displaced persons were seen and visited. In the town of Galle, clean-up was complete and the town seemed to be recovering despite the heavy damage experienced in its port side.

The level of social cohesion in Sri Lanka proved to be beneficial in the immediate aftermath of the tsunami. Before the government's aid distribution system become fully functional, aid in terms of food, water and clothing were supplied by those not affected by the tsunami. The degree of social cohesion is evident from the number of displaced people living with relatives and friends instead of camps set up for internally displaced people. For instance data at January 27, 2005 shows that 339,984 out of the 500,668 displaced population are living with relatives and friends, i.e. 68% of the displaced population, hence easing the burden on the provision of short term shelters.

At the time of the visit the focus of the disaster management appeared to be gradually moving away from the immediate relief and beginning to address the need for reconstruction. An ongoing debate was taking place in the English printed national papers regarding the proposal from the Sri Lankan government to prohibit the reconstruction of dwellings near the shore. For example the town of Hambantota (Southern province) was so heavily damaged that the authorities are considering relocation of the town several kilometres inland. Since 1981 the Coast Conservation Act had prohibited building within the 100 metres zone from the sea, but this was not enforced and as seen in Table 2.8, close to 54% of the damaged buildings in the area visited by EEFIT were in this zone.

In some severely damaged areas, clearing of collapsed buildings had not taken place but it was common to see piles of recovered bricks neatly stacked amongst the rubble. In other areas, organised clearing was taken place, both by mechanical and manual means. This was generally carried out under the auspices of foreign agencies. No systematic reconstruction was seen. In less affected areas, house owners were carrying out repair and reconstruction of collapsed buildings, sometimes from the remaining foundations of the previous building. In total more than 90,000 houses will have to be rebuilt and more than half of these properties were originally located in the 100 metre zone. The future of these households that have also suffered extensive life losses is thus in doubt. The cost of labour in the construction industry has trebled while similar inflation was reported in the cost of building materials with severe shortages in key materials such as sand already becoming apparent. Securing state compensation for lost property is likely to be a lengthy process, with many households having lost their paper certificates during the flooding.

In the ensuing months emphasis was placed to providing reasonable temporary housing for the displaced people before the start of the monsoon season, and by June 2005, 31,000 transitional shelters had been completed, housing approximately 150,000 people. By the end of July an additional 50,000 was completed, bringing the number of people housed to 250,000 (roughly 50% of the displaced population). The UNHCR has distributed material aid to more than 160,000 people in the form of tents, mosquito nets, cooking equipment and utensils, clothing and other necessary household items. The UNHCR has also built around 3,850 temporary shelters in the Jaffna and Ampara districts.

The effects on the fishing industry were particularly severe, with damage in many fishing ports, in fish processing and storage facilities and the destruction of fishing boats. FAO has delivered 47,650 fishing nets to fishermen who lost their livelihoods, but the government’s promise to replace the destroyed boats have in large part not materialized in the 6 months following the disaster. A total of 740 special nets will be distributed through the Ministry of Fisheries and Aquatic Resources. In total 10,200 boats (around 62% of the affected fleet) have been repaired or replaced by the government and the various NGOs. FAO has repaired 3,415 boats in Sri Lanka, enabling nearly 10,200 fishers to resume their livelihoods. Local and international NGOs are active in this sector offering options in the form of loans, grants, shares in cooperatives or even replacement of damaged boats. There is concern that the recovery must take into account the long-term sustainability of the sea’s supplies, thus favouring more traditional methods and means of fishing.

A non-governmental organization (People's Action for Free and Fair Elections (PAFFREL)) said that lack of cooperation between Sri Lanka's government and the opposition parties has hampered the post-tsunami rebuilding process. PAFFREL's report released on its supervision of relief work during the six months after the tsunami says that less than 1,000 permanent houses had been completed out of over 64,000 houses required. PAFFREL recommends a mechanism to be set up at village levels to avoid delays and to increase efficiency.

2.10 Conclusions

Following the December 26, 2004 Indian Ocean tsunami, the EEFIT team surveyed the southwestern and southern coastal areas of Sri Lanka between Colombo and Dondra. The conclusions from their findings discussed in this chapter are summarized below.

1. The damage surveys conducted revealed that damage was largely in masonry residential developments, which are present along the coastal areas from Colombo to Dondra. These houses were largely of unreinforced masonry type where a mixture of semi-fired clay blocks and solid bricks are used for the load bearing walls. The low and mid-rise reinforced concrete

(RC) structures largely used for commercial purposes performed well although there was some evidence of damage to their masonry infill panels.

2. The collapse of masonry wall panels facing the sea shows that this was largely due to the pressure from the tsunami water flow exceeding the out-of-plane resistance of the wall panels. There was evidence of collapsed wall panels disintegrated into large blocks of debris flowing some distance inland. Some houses had only their ground floor slabs exposed while others had suffered structural damage beyond repair. The principal cause of structural damage appears to be that due to pressure from the tsunami flow.

3. Erosion and scouring underneath foundations appears to be another cause of structural failure for those structures that survived the direct pressure from the tsunami flow. Scouring resulted in structural collapse of masonry houses into newly formed scour holes or cracked wall sections settling due to the undermined foundations. Some reinforced concrete hotel structures experienced cracking in the RC frames and wall panels due to erosion undermining the foundations. Scouring was observed in areas where the soil was typically loose to medium dense sand with little or no clay content by visual examination. There was little evidence of surface vegetation that would have acted as a reinforcing barrier to erosion in these areas.

4. The damage surveys revealed that there was a considerable variation in the extent of damage to masonry houses along the coast even at a local level. This may be attributed to the variation in the flow conditions i.e. wave height and speed due to different bathymetries. Damage appears to diminish with distance from the coast where more houses have experienced moderate to minor structural damage.

5. The water level in the surveyed area was generally about 4-5m except in Peraliya where a 10m high water level was recorded according to post-tsunami surveys. Peraliya was in area with the highest level of collapses and heavy damages to masonry houses, extending to a distance about 300m from the coast. The derailment of the train carriages also occurred at this location. The highest tsunami intensity of VI was assigned between Ambalangoda and Hikkaduwa, which include Peraliya whereas the intensity was generally around III to IV in other surveyed areas. This correlates well with 40% of houses in the affected census blocks in this area collapsed and damaged beyond repair from the survey carried out by Department of Census and Statistics. Other survey areas had a damage level of 20%.

6. The damage to buildings in the Eastern province appears to be similar to those observed by EEFIT where the principal cause was pressure from the tsunami flow. The high water levels coupled with flat topography resulted in collapse and heavy damage extending to distances up to 1km from the coast in certain areas. The type of materials and method of construction in the Eastern province is similar to that in the EEFIT surveyed area. The percentage of collapsed and heavily damaged houses was generally at 40% in the Eastern province reaching as high as 80% in some areas.

7. The severity of damage observed in Sri Lanka appears to be related to the characteristics of the tsunami that arrived in the coastal areas. The Eastern province faced the direct impact of the tsunami waves travelling from northern Sumatra where they were in the form of a wave of considerable height and velocity resulting in significant extents of inundation. The waves that arrived in the southwest and western coastal areas were the result of refraction around the southern continental shelf coupled with localized diffraction. This has resulted in considerable variability in the nature of the tsunami where some areas experienced a massive tidal wave e.g. Ambalangoda to Hikkaduwa whereas other areas experienced a series of tidal waves with rising water level leading to inundation.

8. Sections of the coastal roads were damaged due to erosion and scouring. Bridges at road crossings in the EEFIT survey area suffered damage to abutments resulting in collapse of the structurally intact reinforced concrete deck. The abutments appear to have failed due to scouring behind the abutment wall from the receding tsunami waters. Temporary Bailey bridges were in-place at the time of the survey. The damage to road bridges in the Eastern province was so severe that some bridges were found totally destroyed. The southern railway route from Colombo to Matara suffered damage along several sections due to failed

embankments caused by erosion and scouring. Several causeway bridges of the southern railway route were also destroyed.

9. The water supply system suffered damage at locations of damaged road sections and bridges since they follow the coastal route and uses bridges at river crossings. The connections were quickly restored and water was supplied using tankers to areas where no water is available due to well contamination. The damage to electricity supply and telephone network was localized and restored within 1 week in the southern areas. Restoration took longer in the Eastern province due to access difficulties and flooding that followed the tsunami.

10. Many hospitals suffered heavy damage hence were unavailable to provide proper healthcare following the tsunami. The damage was severe in the Eastern province where many of the hospitals were located near the coast. A large number of schools and educational institutions were damaged disrupting the education for many students. Many schools that survived were used as camps and makeshift hospitals thereby delaying their re-opening for education.

11. The fishing harbours and breakwater structures in the EEFIT survey area performed well. However heavy damage was reported to fishing harbours in the southeast and eastern coastal areas. Galle Port, which serves as a supply and distribution point for the local cement plant was undamaged despite scouring of the retained soil behind a concrete quay wall.

12. The casualty figures for the entire country reveals that the death/injury ratio was about 1.5 based on June 5, 2005 data, hence a higher fatality rate with a low chance of survival. The lethality rate among the population living within 1km from the coast was at 21% in the EEFIT surveyed Southern province and 15% in the Eastern province. There appears to be a good correlation between the total casualties and the number of destroyed and damaged houses.

13. The economic impact of the tsunami consists of asset losses (direct impact), output losses (indirect impact) and fiscal losses (secondary effects). The asset losses were estimated to be US $1.0 billion (4.6% of 2004 GDP) while the output losses primarily from the fisheries and tourism sectors (two most affected economic sectors) is estimated to be $330 million (1.5% of GDP) through 2005 and 2006. Total financing needs are estimated to be about $1.6 to $2.0 billion. The GDP growth forecast for 2005 has been revised from 6.0% to 5.4%. The relatively limited impact on the GDP growth is due to the primarily affected fishing and tourism sectors together contributing only 3.0% of the national GDP. The rise in imports triggered by reconstruction and the projected loss of tourism revenue is expected to widen the overall balance of payment deficit. The flow of external aid from foreign donors, concessionary loans and possibly debt relief is expected to ease the pressure on the external sector.

14. Although the economic impact on Sri Lanka was considered to be not very severe, the tsunami has raised the vulnerability of the coastal population to poverty given the loss of employment and the means of generating an income. The level of poverty in the EEFIT surveyed districts of Kalutara, Galle and Matara were above the national average of 23% before the tsunami. It is likely that the poverty level may have increased from pre-tsunami levels at least until relief is provided so that employment is provided to the affected coastal population.

15. Six months after the tsunami, with the emergency relief phase winding down, but not yet completely over, daunting challenges lie ahead. They will require the full coordination of the government and international agencies and NGOs, and a constant ear to the views and aspirations of tsunami-affected communities. The sheer scale and complexity of the task - securing adequate land, building 90,000-plus permanent homes, and restoring livelihoods for every family – is expected to take at least 4 years in total.

16. The Sri Lankan government now has a national reconstruction plan and UN agencies and NGO's are lending their support and underpinning to it. "Get people into homes," "Get people back to work," "Ensure health, education and protection for all affected people," and "Upgrade the national infrastructure." These are the titles of the four main action programmes of the Taskforce for Rebuilding the Nation (TAFREN). In the interim, there are still pressing humanitarian needs to be met – with one of the most pressing priorities being to give full support and assistance to those people who remain in inadequate shelters until present (six months after the disaster)

17. Sri Lankan Government declared a coastal buffer zone where re-construction and new construction subject to certain conditions is prohibited with 100m in the western and southern coastal areas and 200m in eastern and northeastern coastal areas. The inundation measurements indicate that the extent of tsunami inundation were much greater than these imposed limits. The imposition of such a buffer zone was largely the enforcement of the 1981 Coastal Conservation Act, which has not been strictly enforced as the post-tsunami surveys shows about 54% of the damaged houses in the EEFIT survey area are within 100m of the coast. It may not be practical from a societal and economic view point to move people too far inland as fishing communities who make up most of the coastal population want to remain close to the sea. A more pragmatic solution would be to have an adequate tsunami warning system and an evacuation plan. Casualties could have been avoided in many areas if people had not walked toward the shore when the sea had retreated before the arrival of the tsunami waves. The importance of educating the people and having an emergency evacuation procedure is essential.

2.11 Acknowledgments

The authors of this chapter would like to express their gratefulness to the following:

Prof. Robin Spence (University of Cambridge, UK) and Prof. Sarath Abayakoon (University of Peradeniya, Sri Lanka) for reviewing the chapter.

Mr Dennis Knight (Halcrow-Sri Lanka) for providing the EEFIT team first hand information on the damage in the southwest of Sri Lanka on the day of the tsunami and supplying photographs and other data.

Anton Pillai of Arup for providing information and photographs taken during the field survey conducted in the Eastern province of Sri Lanka, which enabled the coverage of damage in eastern Sri Lanka in this chapter.

Arup, Risk Management Solutions Inc, Buro Happold and Halcorw for supporting members to go on the mission.

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3 Thailand

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3.1 Introduction to Mission to Thailand

On 26th December 2004 the Indian Ocean Tsunami hit the shores of Thailand at around 2:45GMT (9:45am local time), approximately 1 hour and 45 minutes after the occurrence of the triggering earthquake event. A trough in the wave-train encountered Thailand first, and the precise arrival time varied along the coast, with a destructive surge being reported at Phuket Island some minutes before inundation occurred at Khao Lak (Figure 3.1). The tsunami caused large loss of life and property and severe erosion of the coasts. The EEFIT Team arrived in Thailand on the 27th January 2005. During the next six days the Team visited the western coast of Phuket island, Phi Phi island and the resorts north of Khao Lak National Park (from Khao Lak Beach To Ban Nam Kaem) in the Phang Nga province. Within this report an overview of the observed tsunami damage to buildings and infrastructure in Thailand is given and the effects on coastal inhabitants are discussed. Damage surveys and tsunami water height measurements made by the Team are presented and the resistance of different structural types to the tsunami is discussed. Finally, the main conclusions of the field mission in Thailand are summarised.

Figure 3. 1 EEFIT Survey Areas

3.2 Brief damage observations

The EEFIT team visited the affected areas shown in Figure 3.1. These include the western coast of Phuket Island, Phi Phi Island and part of the coastal zone north of Khao Lak national park in the Phang Nga province (about 70km north of the Sarasin bridge that connects Phuket to the mainland). In the following sections a summary of the damage observed by the EEFIT Team in these locations is given. Although the Krabi province and to a lesser extent Ranong, Trang and Satun provinces were also affected by the tsunami, it was not possible to visit these locations due to time limitations. Damage to these areas is therefore not reported.

3.2.1 Phuket Island

Contrary to popular perception abroad, the physical impact of the tsunami on Phuket Island, (Thailand's most popular tourist resort area), was not devastating. According to data provided by the Thai Tourism Authority only 17.6% of the hotels in Phuket were affected with only 10.8% of the deaths and missing persons occurring on the island (see Section 3.6). Therefore, in terms of directly affected room capacity, Phuket temporarily lost less than 17% of its total capacity of 32,585 rooms in 573 hotels. Almost all of the affected hotels had damage to their ground floors, especially to fittings and contents. Most of these took between 1 and 6 months to re-open, and by September 2005 Phuket had recovered 98% of its hotel capacity. In the following we describe the effects of the tsunami on the Andaman Sea coasts of Phuket starting from south to north.

3.2.1.1 Southern Phuket Island – Koh Sirey to Rawai Beach

Koh Sirey is a small island just offshore to the east of Phuket town (Figure 3.1). The channel that separates the two islands is used as a main fishing port and is a busy naval route for boats travelling to the islands in the east. A bridge connects the island to Phuket town. The tsunami crest was characterised by a large swell that travelled up the channel dragging dozens of large and small fishing boats off their moorings and hurling them against the bridge. The port was fully functional on January 29, 2005 when the EEFIT team used its facilities for travel to Koh Phi Phi Don. On Koh Sirey itself, the village called Sea Gypsy located on the southernmost shore was hit hard by the tsunami with many homes destroyed but no loss of life. A couple of small hotels were also affected. Phuket town was unaffected. There are no reports of damage in Makham Bay (also called Phuket Bay) to the south of Phuket town. Chalong Bay (further south) was mildly affected with damage incurred to an old jetty (the main concrete pier was left intact) and a couple of beach front bungalow resorts. Two small hotels were affected on Koh Lon Island offshore of Chalong bay and two more on the remote island of Racha Yai to the south. Further south, Rawai beach sustained more extensive damage along its beach front wall. The Japanese survey team from the Kyoto University Disaster Prevention Research Institute measured the wave height at three locations at Chalong and Rawai to be around 2.5m (above mean sea level). Several boats were destroyed, corals were washed ashore and some loss of life occurred in Mu Ban Chao Le (another Sea Gypsy Village where the Urak Lawoi people live).

3.2.1.2 Western Phuket Island – Nai Harn beach to Karon beach

Nai Harn beach is the southernmost resort in the hardest hit area of western Koh Phuket. Here, the tsunami transported large quantities of debris onto the beach but did not inundate the land beyond the coastal road. Damage was sustained by sea front restaurants, some buildings within two major hotel complexes and several other bungalow guest houses. Just north of Nai Harn there is a small bay called Yanui beach, where three hotels suffered heavy damage and two suffered total loss. The inundation at Yanui reached several hundreds of metres inland.

North of Yanui is the Kata Beach resort, the first major resort on the western shores of Phuket with a 3,061 room capacity in 61 hotels and guest houses. Damage to sea front shops and restaurants at the south and north end of this 3-km beach resort was significant, but was mainly restricted to non-structural components (e.g. shop windows and doors). Damage also occurred in the southern part of Kata, Kata Noi. The central part of the northern side of Kata is occupied by the 300-room Club Mediteranée, which was inundated following the tsunami and was still undergoing repair at the time of the survey. Other beach front hotels along Kata Beach sustained water damage to their ground floor facilities. However, the facilities behind the first row of buildings were not seriously affected and none were closed for more than a few weeks. Some minor damage was sustained by sea walls as shown in Figure 3.3. The EEFIT team measured wave heights of 2.5m (above mean sea level) in Kata. This value corroborates the wave height data made by the Japanese survey team from the Kyoto University Disaster Prevention Research Institute (KUDPRI). Although the physical impact of the tsunami on the resorts of Kata was much less than elsewhere, the local sewerage treatment plant was rendered inoperable by the tsunami having inundated the control electrics and mechanisms (Bell et al. 2005). The Director of Public Works in Kata expressed concern to the New Zealand Society for Earthquake Engineering (NZSEE) Reconnaissance team (Bell et al. 2005) about the threat to public health and stated that the few tourists that remained or arrived in the month following the tsunami were reoccupying beaches adjacent to the sewer outfall.

Figure 3. 2: Minor damage to Club Mediteranée Resort at Kata Beach. Damage was mainly restricted to the ground floor and was not structural in nature.

(a) (b)

Figure 3. 3: Minor seawall damage at Kata Beach

North of Kata Beach is the resort of Karon, which is built along a 5km crescent shaped beach. Karon Beach has a capacity of 5,497 rooms in 77 hotels and guest houses (17.2% of Phuket's hotel capacity). On the northern side most of the big hotels are set back from the beach front and lie on higher ground, and thus were not affected by the incoming tsunami. A wide sloping swath of grass separates the beach from the coastal road and the hotels beyond. This is thought to have averted the levels of damage seen in other resorts. However, the Golden Sand Inn had 50 seaward facing bungalows that were flooded by the rushing waters and the Phuket Island View Hotel also had 20 similarly damaged bungalows. Both these hotels were operational within a month of the tsunami. Only two small hotels with a total of 44 rooms were still closed in Karon at the time of the field mission, but were operational by September 2005.

3.2.1.3 Western Phuket Island – Ban Trai Trang and Patong beach to Kalim beach

North of Karon beach there is a promontory on which lies Ban Trai Trang beach. The 415-room Merlin Beach resort is located there. This hotel sustained extensive damage to the southern part of the building, with 83 ground floor rooms being flooded despite the fact that the hotel was located at least 150m inland from the sea. Hotel managers told the EEFIT team that they planned to re-open on April 1, 2005.

Further north is Patong, Phuket's largest resort with a capacity of 9,085 rooms in 193 hotels and guest houses (28.4% of Phuket's hotel capacity). Loss of life in Patong was large and damage in Patong beach was significant with 60 facilities being flooded (damaged facilities ratio 31%) containing 3,552 rooms (39% of the room capacity temporarily lost). A coastal road runs parallel to the whole length of the 4-km crescent shaped beach. In the southern and northern parts of the beach the coastal road is located at about 30m from the sea shore and all facilities are situated on the inland side of the road. However, in a 750m stretch on the northern side of Patong, five hotels (with more than 200 room total capacity) and many shops are situated on the seaward side of the road and were subjected to the full force of the tsunami. All properties along the Patong coastal road (Thaweewong Road) sustained some degree of damage from the event, especially to the ground floors and basements (See Figures 3.4 and 4.5). The majority of the damage was flood damage, with little structural damage evident. The EEFIT team made a detailed survey of the southern half of Patong beach and took measurements of tsunami run-ups ranging between 2.2m and 4.5m (above mean sea level) along the coast (See Section 3.4.4.2).

Figure 3. 4 Heavily damaged ground floor infill walls and columns of the Patong Swiss Hotel on Thaweewong Road, located about 90m from the sea front .

One month after the event, clean-up operations were complete and repairs well under way in most coastal properties. Tourism had reinitiated at the time of the field mission but a further 4-5 months were estimated to be required before pre-tsunami levels of tourism in Patong would be restored. Recent reports from the Tourism Authority of Thailand (September 2005) state that only five hotels still remain closed and therefore 97% of the hotel capacity has been restored. However, the Thai Tourism Authority also state that tourist numbers and hotel occupancy have not yet returned to values recorded prior to the event

(a)

(b)

Figure 3. 5: Sea Pearl Beach Hotel on Thaweewong Road, Patong: (a) external view of hotel entrance and (b) internal view of the hotel. The hotel had moderately damaged infill masonry walls and columns in the basement and ground floors. Broken windows in the 1st storey of the building indicate a flood height of 5m above ground level. The hotel was under repair at the time of the field mission.

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Kalim beach and village are located immediately north of Patong. All the hotels here lie on a hillside that rises sharply beyond the coastal road and were not affected by the tsunami. Kalim village is near the sea and sustained moderate levels of damage to its masonry houses and to a primary school. In the latter, the infill panels of the classroom nearest to the coastal road were destroyed and the 150mm square columns were left exposed, damaged but still standing. Some low-rise RC buildings (including the offices of two major real estate agents) on the seaward side of the coastal road suffered heavy damage to the infill panels and were under repair at the time of the team visit.

3.2.1.4 Western Phuket Island – Kamala Beach to Bang Tao

Kamala Beach was the location most seriously affected by the tsunami in Phuket. 67 locals and 7 tourists were killed, 40 fishing boats and 173 cars were destroyed, more than 760 houses were damaged and 210 totally collapsed (Srivichai et al. 2005). Kamala is about 10-km north of Patong and is one of the smaller resorts with 27 hotels and guest houses with total capacity of 1,140 rooms. One month after the event, 23 hotels with 623 rooms were still closed (54.5% of the room capacity temporarily lost). By September 2005, all except one hotel were operational. Examples of a collapsed guest house and school are shown in Figures 3.6 and 3.8b, respectively. The EEFIT team made a detailed survey of a section of Kamala beach (see Section 3.4.4.2) and took maximum tsunami water height measurements of 5m above mean sea level. Pictures of the event (Figure 3.7) confirm this large tsunami water height at Kamala Beach. The Kamala village was well inland and was not affected.

Further north is the 6-km long Bang Tao beach, an exclusive resort with 10 large hotels and 5 smaller inns and guest houses with total capacity of 1,854 rooms. One month after the event, two hotels and three guest house with 329 rooms were closed (17.7% of the room capacity temporarily lost). These hotels were still closed in September 2005. Most of the damage in Bang Tao occurred on the southern part of the beach where the facilities and a number of beach front houses and shops were located very close to shoreline (Figure 3.9). According to local eye witnesses the surge there was at least two metres high, and the waters did not withdraw for over an hour. Measurements made by the EEFIT team at two locations showed maximum water heights of 3.7m above mean sea level. There is significant evidence of scouring alongside a road that runs 200 meters inland, with large pieces of the tarmac having been ripped up and flung further inland by the tsunami (Figure 3.41). This would seem to indicate that the wave was travelling at a high velocity at this location.

Figure 3. 6: Seriously damaged single storey house located 100m from the shore line at Kamala Beach. Example of typical timber roof system and its poor connection to the supporting structure.

(a) (b)

Figure 3.7: Pictures of traditional Thai Bhuddist temples at Kamala Beach during (a) and after (b) the tsunami (Source: Srivichai S., Chidtong Y., Supratid S., and Shuto N., Rangsit University, Thailand).

(a)

(b)

Figure 3. 8: Pictures of (a) coastal road and (b) a school at Kamala Beach. before (left) and after (right) the tsunami (Source: Srivichai S., Chidtong Y., Supratid S., and Shuto N., Rangsit University, Thailand).

The lively village of Bang Tao is situated 400 metres inland and was not seriously affected. The EEFIT team visited the area on January 30, 2005 and one of the closed hotels (Best Western Bang Tao Beach & Spa with 240 rooms) was well on the way to complete recovery. Another beach front hotel had damage to the ground floor rooms and had not yet started any significant repair work. Six hotels of international repute are situated in the central part of Bang Tao beach. These include the Banyan Tree, Laguna Beach (Figure 3.10a), Rydges Amora Beach (Figure 3.10b), which were visited by the EEFIT team. Damage to these exclusive hotels was limited to 60 out of 1,430 rooms (statistics refer to all six hotels) because their facilities were set back from the beach. They were fully operational at the time of the visit.

Figure 3. 9: Foundation failure of bungalows on Bang Tao beach front.

(a) (b)

Figure 3. 10: No damage to the Laguna Beach Hotel in Bang Tao Beach (a), which was elevated 3.5m above the shore and set back 100m from the shore. (b) Damage to window curtain walls and non-structural infill panels of the three-storey Ridges Amora Beach Resort on Bang Tao Beach were repaired. These buildings are located at approximately 120m from the coastline.

3.2.1.5 Western Phuket Island – Layan Beach to Sarasin bridges

Layan Beach is situated north of Bang Tao. Only one hotel exists in this location and it was not damaged by the tsunami. The inundation in Layan reached 400 metres inland but fortunately no habitation was located within the inundated zone. North of Layan is Nai Thon beach with two medium-sized hotels and six smaller facilities. Damage here was limited and none of the facilities closed after the tsunami. Nai Yang beach lies further north of Nai Thon. It has two big hotels and ten smaller facilities with a total of 466 rooms, of which only 14 were not in operation after the event and all were fully operational by September 2005. However, the numerous shops, restaurants and bars close to this popular beach were totally destroyed. Not far from Nai Yang is Phuket International Airport, which experienced flooding to its runway when its protective wall was breached (Figure 3.47). The airport was fully operational less than 15 hours after the event. The Japanese KUDPRI team took one measurement of wave height in Nai Yang at just under five metres.

North of Nai Yang there is a 9-km long beach leading up to the causeway that separates Phuket Island from the mainland. There are no facilities or villages on this stretch of coast and thus not much has been reported about the size of the tsunami here. The causeway is spanned by two bridges (the Sarasin bridges), one old and one new. The first is used for southbound traffic and the latter for northbound traffic. The bridges lie 1.8 km inland from the Andaman Sea. Both bridges were inspected by the EEFIT team and showed no visible signs of damage to their footings and abutments. Although the older bridge (that has a lower deck height) had been closed for inspection in the days following the earthquake, it was open at the time of our investigation. Eye-witnesses reported seeing water overtop the northern abutment of the old bridge. However only slight damage, in the form of displaced rock armour of the retaining walls of the structure, was observed by the EEFIT team at the northern side of this bridge.

3.2.2 Phang Nga Province – Khao Lak Beach to Bangsak Beach

The area worst affected by the tsunami was the stretch of coast north of Phuket between the north side of Khao Lak national park and the town of Takua Pa (Phang Na province). The Phang Nga province can be accessed from Phuket Island via the Sarasin bridges. The Khao Lak area is 70km north of the causeway on highway route 4. The coast in between is sparsely populated, but the area of Thai Muang beach, about half way to Khao Lak, was not investigated by EEFIT. The region inland is mountainous, and hence the name Khao, meaning “mountain” in the Thai language. The so-called “Khao Lak tourist region” is located on a coastal fringe of 15-20km and contains several beaches listed here according to their location from south to north: Khao Lak, Nang Thong, Bang Niang, Khuk Khak, Laem Pakarang, Pakweeb and Bangsak. In the last five years this region has grown rapidly as a tourist destination, with a capacity (according to data provided by the Tourism Authority of Thailand) of 5,533 rooms in 143 facilities. The Khao Lak Tourist Region was one of the areas in Thailand to be worst affected by the tsunami. An estimated 71% of all tsunami related deaths in Thailand occurred here. Approximately 25% of the estimated population living within 1km of the coast died, with approximately 3,000 victims among the foreign visitors (about 50% of those in the area).

The height of the waves along this stretch of coast for the most part exceeded eight metres with peak water heights of 13m above mean sea level being measured by the EEFIT team and other parties. Inundation reached up to 1.8km inland and a patrol boat was washed 1.2km inland (Figure 3.12). The large horizontal movement of water and turbulence associated with the tsunami here resulted in the entrainment of sediment and vast coastal erosion. Only rocks were seen to be left along the once sandy beaches of Laem Pakarang, where the roots of secular trees were exposed to a depth of 1.5-3m along the coast (Figure 3.13).

Figure 3. 11: Damage to a two storey resort on Bang Niang Beach in Khao Lak, situated approximately 50m from the sea.

Figure 3. 12: A Thai police patrol boat left stranded 1.2km inland at Khao Lak.

The Khao Lak Tourist Region suffered extensive loss of housing and hotel capacity. At the time of the field mission a large number of the buildings had been demolished and cleared. Some buildings were left standing possibly awaiting a decision on repair or demolition. The observations made by the EEFIT team are mainly based on these surviving buildings and on inferences from pictures taken by others of Khao Lak Beach just after the event. Timber frame structures near the shore were completely destroyed. Many of the hotel structures were sited on the beach near the shoreline and bore the full brunt of the waves. Others were sited more than 100 meters inland but still suffered extreme levels of damage due to the depth and speed of the tsunami. Hotels of the bungalow type, containing a number of single storey detached houses, suffered the most damage. During the on-site investigation those large medium-rise hotel structures that had not been cleared were observed to have survived relatively well despite the large wave heights. However, in the locations of maximum water height, damage to the infills, fittings and contents up to the third floor of these buildings was total (Figure 3.14 and Figure 3.15). It must be noted that from the point of view of life safety, even those structures that fared better would have provided limited refuge to occupants due to deep flooding of the structures (Figure 3.15).

Figure 3. 13: IKONOS satellite pictures of the Laem Pakarang Cape in Khao Lak before and after the tsunami (lower and upper right, respectively (http://earthobservatory.nasa.gov), and beach erosion (upper left) observed at the location indicated by the arrows. Water towers observed at this and all other locations generally survived intact.

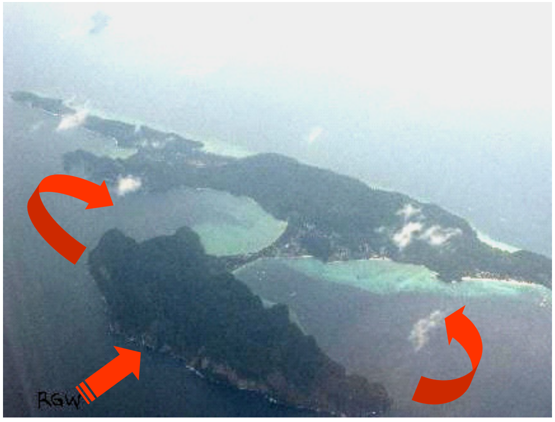
(a) (b)

Figure 3. 14: Damage to RC buildings in Khao Lak: (a) Damage to the Laguna Hotel, situated 100m from the seafront. The displaced roof tiles indicate a water height of nine metres above sea level. (b) Damage to the infill partition walls (parallel to the seafront) of a hotel situated at 120m from the seafront.

Figure 3. 15: Khao Lak Seaview Resort. Wave height was established from measurements made inside this hotel, sited approximately 150m from the beach and approximately one metre above sea level. There were only small 'bar' and pool type structures between this building and the ocean (all of which had been destroyed). Structural damage to this building was limited to windows and a few masonry infill walls, with the corner columns on the left front side also damaged presumably from debris impact.

3.2.3 Phi Phi Island

Phi Phi Island (Figure 3.16a), part of Krabi Province, lies approximately 54km east of the southernmost tip of Phuket Island. The land between Ton Sai bay to the south and Loh Dalam bay to the north is a narrow sand tombolo and was swept by the tsunami (Figure 3.16b). The tombolo is barely 200 metres wide at its narrowest and increases to a maximum of 1km at the foot of the cliffs to its east and west. These karstic cliffs are the remnants of ancient coral reefs, a geo-morphological feature common in the Andaman Sea and other parts of Southeast Asia (e.g. Ha Long bay in Vietnam), and rise steeply from the sea to form the rest of Phi Phi Island. The waves hit the land strip from both bays, first from the north and a few minutes later from the south (Figure 3.16a).



(a)

(b)

Figure 3. 16: Aerial views of Phi Phi Island and Ton Sai Bay: (a) The arrows indicate how the tsunami was refracted around the western granite cliff and hit the narrow land strip (tombolo) from both the North and South directions. (b) Ton Sai Bay four days after the tsunami.

Figure 3. 17: A collapsed timber frame and corrugated iron-clad habitation on the Southeast coast of Ton Sai bay, Phi Phi Island.

Figure 3. 18: Reinforced concrete frames with open ground stories on the south-eastern side of Ton Sai Bay, Phi Phi Island.

Only twenty years ago this strip of land was a pristine palm forest but on December 26, 2004 it was already densely developed with hotels, bungalows, inns, guest houses and other facilities to service the numerous tourists. The approach to this car-free island by visitors is made from a pier at the south (Ton Sai bay). The island had 34 facilities with 1,392 rooms, many of which suffered damage and were closed. Hotels on higher ground on the eastern cliff escaped any damage and remained fully operational. In Ton Sai the impact was more extensive on the western side of the bay, where around 10 detached bungalow buildings tilted severely, the ones at the sea front being almost completely underwater (Figure 3.21). These buildings had been removed by the time the EEFIT team visited the island, on January 29th. On the eastern side of Ton Sai bay buildings are still standing including a row of eight newly built reinforced concrete houses on stilts (Figure 3.17 and Figure 3.18). However, damage to fittings and contents is comprehensive to all sea front shops and hardly any recovery had been made at the time of the investigation.

Figure 3. 19: Major damage to a resort on Phi Phi Island. The structure is located about 50m from the north beach and has extensive damage to lower storey windows and masonry walls. Debris damage to the roof is visible.

The situation is much worse on the north side (Loh Dalam) where an extensive area of devastation was observed (Figure 3.19). One of the few structures still standing in this area was the local power station (Figure 3.20) an engineered reinforced concrete structure. To the west around the Phi Phi Cabana hotel the damage was somewhat less severe, probably due to the construction of the hotels (i.e. 3-4 storey engineered reinforced concrete structures). Many of the 1,423 dead and missing reported for the Krabi province (see section on human casualties below) occurred in Koh Phi Phi where a press report released on the 30th of December stated the recovery of 218 bodies.

Figure 3. 20: Local power station and telecommunications building extensively damaged on Phi Phi Island. The exhaust pipes for the diesel generators remain standing at left hand side of the picture.

Figure 3. 21: Collapse and transport of wooden detached bungalows by tsunami waters along the south west coast of Ton Sai Bay, Phi Phi Island (Source: Warnitchai 2005).

Figure 3. 22: The Cabana Resort on Phi Phi Island. Although this resort was close to the beach, it was at the western end and therefore probably more sheltered. Structural damage is restricted to windows on the lower two storeys and a few masonry panels on the ground floor.

3.3 Building Regulations and Typologies in the Affected Region

As in the case of earthquakes the level of damage sustained by structures is dependent both on the applied tsunami forces and on the vulnerability of the building stock to those forces. In order to better understand the vulnerability of Thai buildings to lateral loads imposed by the tsunami, the provisions in the Thai building code for seismic and wind loads are described and the degree of practical application of these provisions is discussed. The predominant building types in Thailand and their observed resistance to the 26th December 2004 Indian Ocean Tsunami are then presented.

3.3.1 Building regulations

Seismic codes were first introduced to Thailand in 1986 following a magnitude 5.9 earthquake on 22 April 1983, centred 200km from Bangkok and felt over western and central parts of the country. The latest seismic hazard map for Thailand (Warnitchai and Lisantono 1996) indicates the northern and western regions of Thailand have moderate and moderately high seismic risk, similar to those of zones 2B and 3 of the US Uniform Building Code (UBC 1985), respectively (Warnitchai 1998). However, seismic design requirements have only become mandatory for these regions since a set of ministerial regulations came into effect under the National Control Act of Legislation in November 1997. According to these regulations only public buildings, essential or hazardous facilities and buildings exceeding 15m in height located in 10 Thai provinces (seismic zones 1, 2A and 2B in Figure 3.23) are required to be designed for earthquake loading in Thailand. A map showing the design peak ground acceleration and the seismic zones of the Thai code is presented in Figure 3.23. The regulations prescribe design requirements similar to those for zone 2 in UBC 1985.

Phuket Island, Phang Nga and Krabi provinces all lie within the southern provinces of Thailand where seismic design is not mandatory (Zone 0 in Figure 3.23). Hence, the only lateral loads the buildings are designed to resist are those imposed by wind, which according to the Thai code are 0.5 kPa over the lowest 10m and 0.8 kPa over the next 10m of a structure (Lukkunaprasit and Ruangsassamee 2005).

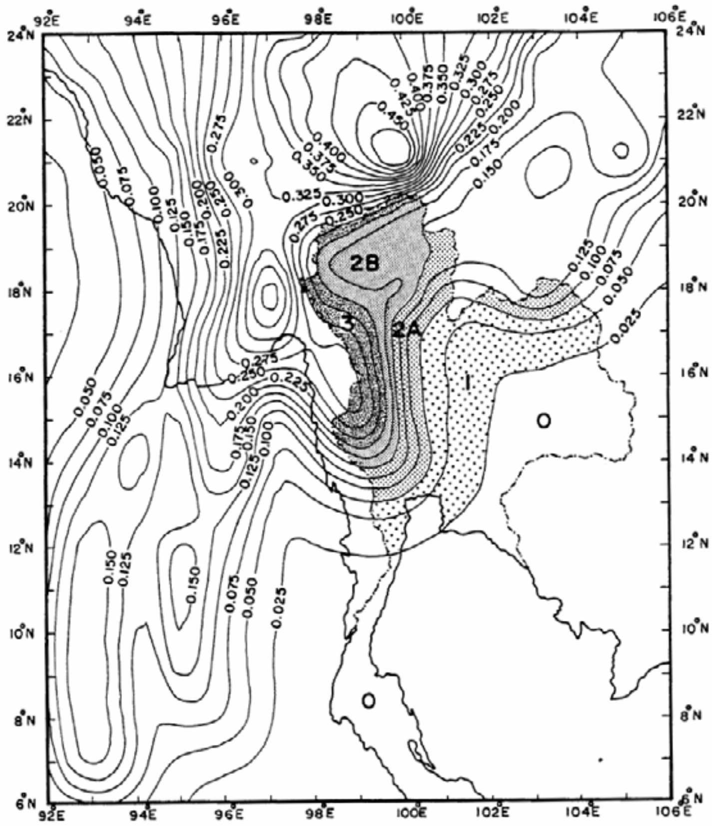


Figure 3. 23: Map showing contours of peak ground acceleration (in g) with 10% chance of being exceeded in 50 years, and the seismic zones of the Thai seismic design code, (Source: Warnitchai 1998)

3.3.2 Building typologies

The following is a description of the buildings in the region visited by the EEFIT team. The observations described below are based on the inspection of many damaged buildings or buildings under construction.

3.3.2.1 Low-rise Reinforced Concrete (RC), (Category D)

These buildings are non-seismically designed cast-in-situ RC frames of up to two (sometimes three) storeys in height. They can be residential or commercial in occupancy, and have varying standards of construction depending on their ownership. They range from 1-2 storey homes or villas to hotel beach bungalows. The quality of some of the bungalows and villas is visibly better than that of the small homes or businesses built in the numerous towns and resorts visited. Observed buildings of this type used for domestic purposes had building plan grids that rarely exceeded 5m in lateral dimension. A typical beam element used in these buildings was observed (from damaged buildings or those under construction) to have 400mm x 200mm section with 6 x 16mm deformed bars and shear reinforcement consisting of 6mm round bars at 150mm centres. A typical column was seen to consist of a 200mm square cross-section, reinforced with four round low-yield bars of 12mm to 16 mm diameter (although sometimes deformed bars were used). Column ties were commonly seen to consist of 6mm diameter round bars with 90° hooks at 200mm centres. The reinforcing steel used typically has a yield strength between 200 and 300MPa and the concrete an ultimate strength of 18MPa or less (Lukkunaprasit and Ruangsassamee 2005). On-site inspection of the concrete also suggested that badly graded aggregates are used in the concrete mix, of probable beach or river provenance. In several locations significant structural damage occurred due to poor detailing of the column-beam joints. These details had insufficient anchorage of the reinforcement which led to the failure of the connection and often total or partial collapse of the structure. A typical example of these details can be seen in Figure 3.24.

Figure 3. 24: Typical example of poor connection detail. The beam reinforcement is insufficiently anchored to the column reinforcement, leading to a lack of integrity of the connection and partial collapse of the structure shown as DC4 on the left hand side of Figure 3.32.

(a) (b)

Figure 3. 25: Damage on two sides of the same building in Khao Lak, oriented with its smaller plan dimension parallel to the shore: (a) shows that one side of the structure has suffered a soft storey failure, while (b) shows the other side of the structure has reasonable structural integrity.

The roofs are commonly pitched, with either timber or light-metal (cold formed steel) trusses covered by clay tiles or metal sheeting. The roof design varies from a simple four-way pitch to more intricate Thai architectural styles. The timber/steel roof frames were often observed to be poorly connected to the building frame leading to insufficient restraint at the tops of the columns in single storey dwellings and total loss of the roof when overtopped by the tsunami.

Infill walls were generally observed to be 100mm thick un-reinforced masonry made of clay bricks or concrete blocks on cement mortar. In the better quality construction double-skin walls are built. These infills are considered non-structural by the Thai codes. Many of these infills suffered severe damage or collapse when located close to the shoreline and oriented parallel to the sea. Masonry infill walls perpendicular to the beach were seen to significantly increase the in-plane resistance to the tsunami as shown by Figure 3.25. In this building, one side resisted the tsunami by frame action, whilst the other side of the structure had masonry infill panels contributing to its resistance. The infilled side of this building shows reasonable performance, while the other side performed as a soft storey.

Most foundations consisted of shallow footings. Scour of the sand around these foundations was often seen to be the cause of significant damage to buildings located along the coastline. In very rare occasions 400mm square reinforced pre-cast concrete piles were used. When these were used a greater resistance to scouring was observed.

3.3.2.2 Mid-rise RC Non-residential and Hotel Buildings, (Category E)

Most resorts and individual hotels visited in Thailand belonged to this category. These buildings are of superior standard compared to the low-rise RC buildings, having been designed and supervised by engineers during construction. Despite the presence of a seismic code in Thailand, these buildings are very rarely designed to withstand any earthquake loads (see Section 3.3.1). They are usually 3 to 4 storeys high (sometimes higher) and have all the characteristics of hotel structures, i.e. elongated forms, a large proportion of openings, large lobby areas on the ground floor, wide balconies, verandas and corridors. Their roofs were observed to consist of flat slab, steel trusses or less frequently timber trusses. Infill walls were typically 100mm thick unreinforced masonry panels made from clay bricks or concrete blocks on cement mortar. The column and beam dimensions were observed to be larger than those of the previous class due to the larger loads involved in their design. Typical member sizes at the larger resorts were 350mm square columns with 6 x 16mm diameter deformed bars and beams of 600mm x 300mm, (these were observed from damaged buildings or those under construction). Reinforcement in these beams consisted of 5 x 25mm diameter deformed bars for bottom reinforcement and 4 x 25mm diameter bars for top reinforcement. Shear reinforcement consisted of two legs of 6mm diameter bars at 150mm centres. Some failures of these larger resorts could also be attributed to poor detailing of beam to column connections, however, a number of such structures were seen to have performed remarkably well, even in locations where the tsunami had reached or even exceeded the third floor of the buildings (i.e. in the Khao Lak region).

3.3.2.3 Wood frame and bamboo buildings (Category A)

Very few such buildings survived the impact of the tsunami especially when water depths exceeded three metres (see Figure 3.26). The main characteristics of these structures are their light weight and their large proportion of openings (to aid ventilation in the tropical climate). Traditional Thai architecture contains numerous types of such buildings, but their contribution to the general construction activity of recent decades has decreased. They still constitute the predominant construction type in non-touristic fishing villages (e.g. Ban Nam Kaem in Phang Nga province). They were also seen in Bang Thao near waterways, supported on stilts and near the sea with some protection from wetness on the lower part of the wooden columns, and on dry land in Laem Pakarang. The roofs of these buildings are typically pitched timber and are either thatched or tiled.

Figure 3. 26: Timber frame structure in near collapse damage state located approximately 100m from the shore line at Kamala Beach.

3.4 Damage Surveys and Wave Height Measurements

In this section the tsunami water height measurements and building damage surveys made by the EEFIT Team are presented. An attempt is made to identify trends in the correlation between the observed damage and physical parameters of the tsunami.

3.4.1 Wave height measurements

Observations of the wave height were made by the EEFIT team at several locations along the Thai coast between Khao Lak and Kata Beach, and on Phi Phi Island. Mud lines on buildings, hanging debris and consistent levels of uplifted roof tiles were used as indications of the water level (Figure 3.27). The level of stripped bark on palm trees was not used as an indication of the inundation height due to the flexibility of the palm trees and the likelihood of their bending significantly during the tsunami. The geographical coordinates were obtained from GPS readings.

(a)

(b)

Figure 3. 27: Examples of the mud lines (indicated with arrow) used to measure tsunami water height above ground in (a) Phi Phi Island and (b) Bang Tao.

The Kyoto University Disaster Prevention Research Institute (KUDPRI) carried out a more detailed survey in Khao Lak, Phuket and Koh Phi Phi between the 31st December 2004 and 3rd of January 2005 (Figure 3.28). A Thai team lead by Dr N. Poovarodom (Thammasart University) carried out a survey of water heights in Ranong, Phra-Thong Island and Khao Lak. The geographical distribution of the water levels measured by this team is also shown in Figure 3.28. A comparison of the measurements obtained by EEFIT and the KUDPRI team is made in Table 3.1, where the measurements made by the latter team for the locations visited by the EEFIT team are highlighted in grey. Comparison of Table 3.1 and Figure 3.28 shows a reasonable correlation of the maximum water level measurements made by all three teams.

Table 3.1: Comparison of wave height measurements made in Khao Lak, Phuket and Koh Phi Phi by EEFIT and KUDPRI (shaded). (Note: these measurements are presented as being those before tide correction).

No	Location	Latitude (N)	Longitude (E)	Height above msl* (m)	Height above ground (m)	Shoreline Distance (m)	Comment
1	Kamala Beach	7°57'02.9"	98°16'51.1"	4.93	4.57	50	Mud trace inside 2nd storey of resort building
		7°57’14.1”	98°16’56.2”	3.85	2.15	154	Trace on side of house
		7°56’83.3”	98°16’96.1”	5.12	-	Not stated	Traces on the wall of the second floor
		7°56’79.1”	98°16’91.9”	5.72	-	Not stated	Trace on wall
		7°56’79.1”	98°16’91.9”	4.86	-	Not stated	Trace on wall
2	Khao Lak	8°38'14.1"	98°14'48.1"	13.0	11.0	262	Laguna Hotel : All roof tiles displaced below this level
		8°38'11.1"	98°14'42.6"	6.5	6.0	92.5	Simijiana Beach and Spa Resort : All roof tiles displaced below this level
		8°38'30.4"	98°14'45.5"	9.8	8.8	92.5	Nang Thong Bay Resort : Water mark measured inside hotel
		8°39'46.5"	98°14'38.7"	10.5	8.5	89.4	Mukdara Resort: Roof tiles displaced
		8°38’22.5”	98°15’04.6”	9.90	-	132.49	Height of washed roof tiles
		8°38’21.6”	98°15’15.0”	10.70	-	286.09	Edge of eaves of damaged cottage
3	Phi Phi (Ton Sai)	7°44’13.2”	98°46’12.9”	3.2	2.9	0	Watermark on front of house
		7°44’16.7”	98°46’18.3”	3.7	2.7	20	Mud trace on side of

							house
		7°44’16.7”	98°46’18.3”	2.5	1.5	108	Mud trace on side of house
	Phi Phi (Loh Dalam)	7°44’33.4”	98°46.621'	6.89	-	242.16	Trace on wall of house
	Phi Phi (Ton Sai)	7°44’89.8”	98°46’32.3”	5.32	-	62.63	2nd floor of hotel
4	Patong Beach	7°53’02.7”	98°17’10.4”	4	3	30	Sea View Hotel: Trace on wall
		7°53’04.1”	98°17’15.1”	5	4	30	Avantika Hotel : Trace on wall
		7°53’05.8”	98°17’19.4”	4.5	3.5	30	Luxury Sea View Rooms and Café’: Trace on wall
		7°53’08.5”	98°17’22.9”	2.9	1.9	60	Sea Pearl Beach Hotel : Mud trace on interior wall
		7°53’16.5”	98°17’32.3”	2.2	1.2	30	Beach Hotel Resort Horizon : Mud trace on wall
		7°53’02.9”	98°17’52.2”	6.39	-	Not stated	Trace on wall
		7°53’24.5”	98°17’74.3”	5.85-6.41	-	Not stated	4 traces on wall
		7°53’63.2”	98°17’92.2”	5.83	-	Not stated	Trace on wall
		7°53’53.2”	98°17’87.9”	5.24	-	Not stated	
		7°54’22.6”	98°18’03.3”	4.91	-	Not stated	Trace on wall
5	Bang Thao Beach	7°58’57.2”	98°16’48.5”	3.26	1.5	132	Trace on wall
		7°58’57.2”	98°16’48.5”	3.66	1.9	132	Trace on wall
		7°58’57.2”	98°16’48.6”	2.9	1.1	135	Trace on wall
		7°59’23.1”	98°17’27.9”	2.05	0.3	30	Rydges Amora Hotel: Trace on wall
		7°59’41.0”	98°17’32.3”	3.0	1.0	30	Laguna Grand Beach Resort: Trace on wall
	Bang Thao Beach	8°00’11.7”	98°17’76.2”	4.36-5.36	-	Not stated	5 readings from wall and tree traces

* mean sea level

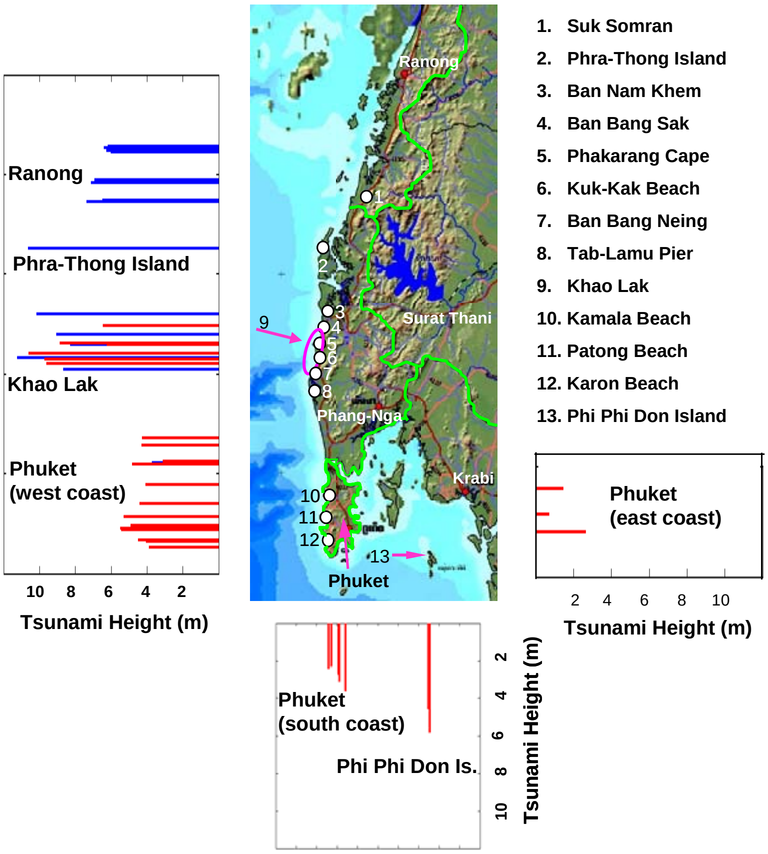
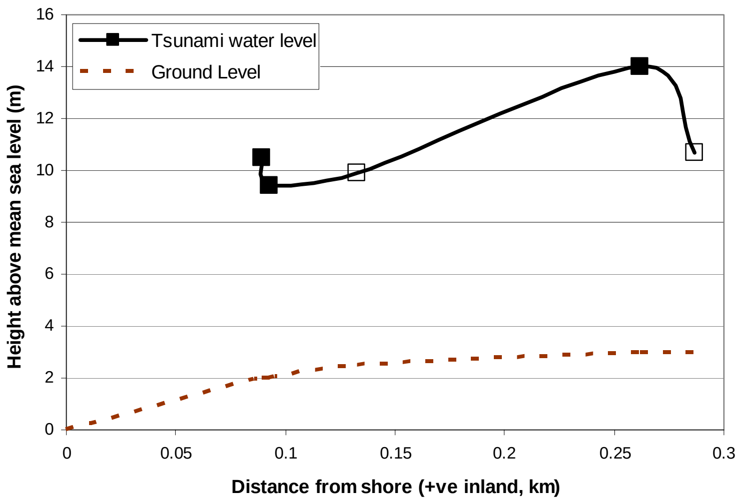


Figure 3.28: Inundation height measurements made by KUDPRI (red) and the Thai team (blue) in Thailand. (Source: Warnitchai 2005)

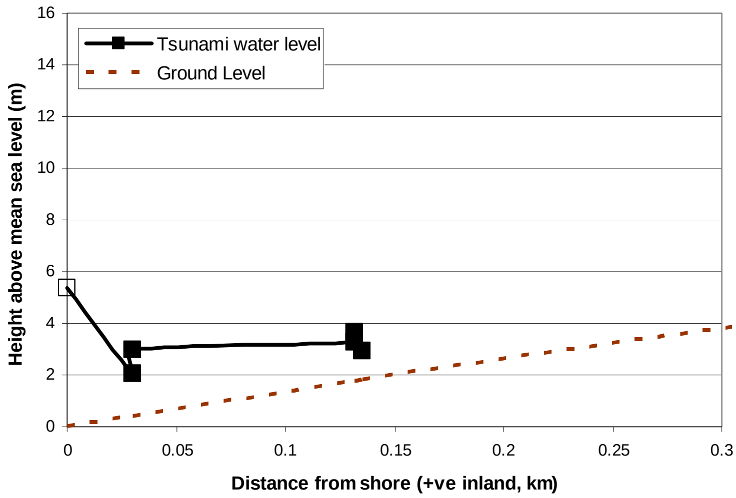
The maximum tsunami onshore water levels measured in Thailand are significantly larger than those observed by EEFIT in Southern Sri Lanka, but less than the maximum wave heights documented in northern Sumatra, Indonesia (see Section 1.7.1). Generally it was observed that high water levels were maintained over large distances in locations with gently sloping beaches, which did not have densely built up towns and dense coastal vegetation. A small inundation distance and more rapid attenuation of water height above ground with distance from shore is observed where a steeper coastal profile is present, as is the case in Bang Thao (Figure 3.29b), where the inundation distance is extrapolated to be 250m from the shore.

However, local topography was seen to play an important role in determining the water height on land. For example in the case of Khao Lak the tsunami inundated the low-lying coast and reflected from the hills behind Khao Lak beach causing water levels to rise on ground (as more waves approached the shores) and water heights above 9m to be recorded up to 1,350m inland (see Figure 3.31). Furthermore, the reflected waves met incoming waves and set up giant whirl-pool like water motions (Figure 3.30), the turbulent waters causing severe scour damage.

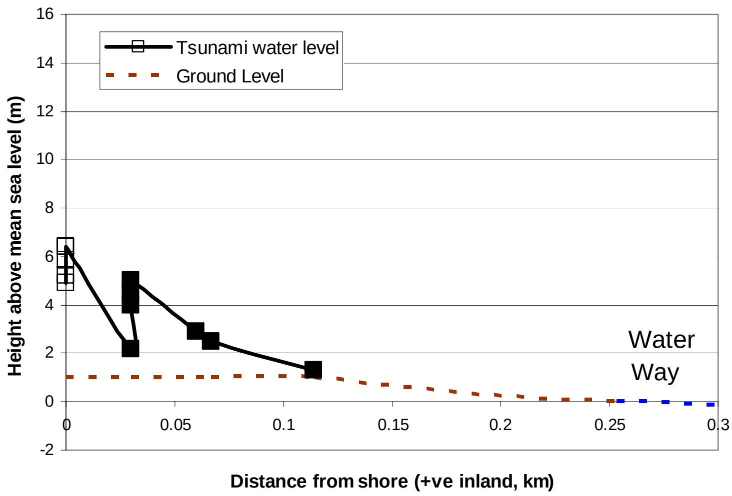
A relatively short inundation distance was instead observed at Patong, which has a high density of buildings along the coast that exerted drag on the tsunami as it flowed onshore. In Figure 3.29c, a dip is observed in the measured water height trend at a distance of 86m from the shore. All inland watermark measurements were made along Kesbab Soi, a road running perpendicular to the sea. However the dip in the water profile corresponds to a measurement made within the hotel complex of the Beach Hotel Resort Horizon, whilst all others were taken from the walls of buildings directly facing onto the road. The difference in water height is an example of the erratic path followed by tsunami onshore flow, which tends to follow the path of least resistance, i.e. a higher level of water was recorded along the road (obstacle free) than at the hotel (situated behind a series of buildings) at the same distance from the shore.



(a) Khao Lak



(b) Bang Thao



(c) Patong Beach

Figure 3. 29: Graphs of the tsunami inundation height with distance inland. The filled black squares correspond to water height measurements made by the EEFIT Team, whilst the white squares are data points obtained from the KUDPRI Team observations.

Figure 3. 30: Whirlpool-like water motion observed from the hillside above the southern end of Khao Lak beach during the tsunami surge, (Source: Chaimanee and Tathong 2005).

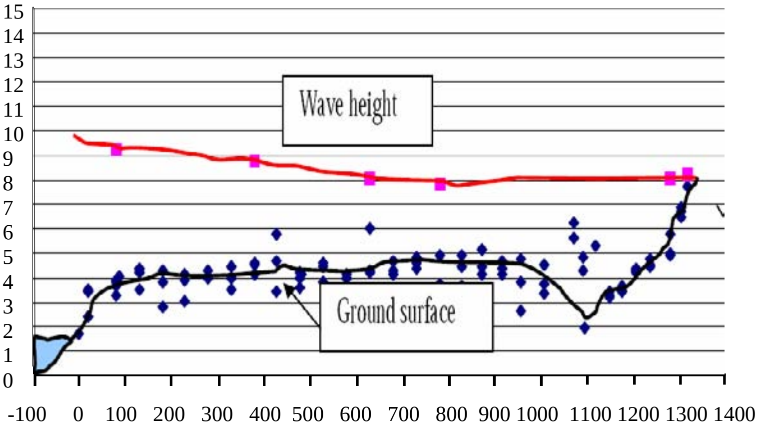


Figure 3. 31: Inundation height measurements with distance inland made in Khao Lak by the Thai team. They show inundation extending 1,300 metres from the shore, with water heights in the 6-8.5 metres (above msl) range. (Source: Chaimanee and Tathong 2005).

3.4.2 Tsunami onshore velocity and force estimation

In deep ocean waters a tsunami has small amplitude (~1m) and propagates at a velocity approximately equal to $\sqrt{gd}$ (*d* being the water depth). From satellite data the 26th December 2004 tsunami was estimated to have been travelling at a velocity of approximately 640km/hr in the Indian Ocean (NASA: http://www-misr.jpl.nasa.gov/). Generally, as the wave of a tsunami propagates into shallower waters its amplitude increases and its velocity decreases. However, modelling the variation in velocity and amplitude of the waves as they approach a shore is a highly complex process. Numerical wave propagation models require accurate bathymetric data in order to model effects such as wave diffraction around coasts of islands or wave reflection from coastlines (e.g. the waves hit the Indian Coast and were reflected back to Sri Lanka). As a wave front approaches the shore, the coastline configuration can alter its shape and direction of travel. As the tsunami inundates the shore its velocity and propagation path is erratic and may be affected by very small variations in elevation of the ground surface, the built environment and vegetation. The forces applied by the tsunami to a building onshore are greatly dependent on the wave characteristics, the water velocity and wave profile when it hits the structure, and whether or not the wave is breaking. In simple terms the main forces acting on a building during a tsunami are:

- Wave impact forces
- Hydrostatic pressure (=flow density x g x water height above ground)
- Hydrodynamic pressure (= 0.5 x flow density x velocity ^{2})
- Buoyancy
- Debris impact
- Erosion/Scouring

An accurate modelling of the onshore water velocities and applied building forces is beyond the scope of this report. However, ignoring wave impact, buoyancy and debris impact, simple and very approximate estimates of the main tsunami water pressures at Khao Lak and Kamala are made using the tsunami heights measured by EEFIT and estimates of wave velocities made from video footage by Professor Matsutomi and his reconnaissance team (the KUDPRI team) during their survey in Thailand and are presented in Table 3.2. It should be noted that these lateral pressure estimates represent an upper bound to the force, as the maximum hydrostatic pressure has been used and because many structures would have been inundated before the maximum water height was reached leading to equalisation of static pressure.

Table 3.2: Rough estimates of tsunami water pressure on buildings in Thailand.

Location	Estimated Velocity Range (m/s)[1]	Maximum Water Height Above ground (m)	Maximum Hydrodynamic Pressure (kN/m^2)	Maximum Hydrostatic Pressure (kN/m^2)	Maximum Total Lateral Pressure (kN/m^2)
Khao Lak	6-8	11	18-33	111	128-144
Kamala Beach	3-4	4.57	4.5-8.0	44.8	49.3-52.8

[1]Source: KUDPRI.

According to these rough calculations, the maximum tsunami lateral loads applied to buildings at Khao Lak and Kamala are respectively, more than 100 and 50 times greater than the design wind loads (see Section 3.3.1) for RC buildings in Thailand. Even if only the hydrodynamic forces are considered, these are seen to greatly exceed those required to fail windows and masonry panels ($5kN/m^2$ and $10kN/m^2$, respectively). The failure of windows and infill panels reduced the lateral load transmission to the frames of many buildings, which remained standing after the tsunami despite the deep inundation.

3.4.3 Damage scale

The following damage scale is adopted in order to describe the structural damage to the low (Category D) and mid-rise (Category E) reinforced concrete infilled frames that typify Thai construction at the surveyed sites (see Section 3.3.2). This damage scale describes direct structural damage and damage due to geotechnical failures.

- **No Damage (DC0)** – No visible structural damage to the structure observed during the survey. Immediate occupancy.

- **Light Damage (DC1)** – Flood damage to contents. Some non-structural (fittings, windows) damage. Damage is minor and repairable. Suitable for immediate occupancy.

- **Moderate Damage (DC2)** – Out-of-plane failure or collapse of parts of or whole sections of infill walls and windows at ground storey. Repairable damage from debris impact to structural members. No structural member failure. Scouring at corners of the structures leaving foundations partly exposed but repairable by backfilling. Unsuitable for immediate occupancy but suitable after light repair.

- **Heavy Damage (DC3)** – The structure stands but is severely damaged. Infill panels above the first storey have been damaged or have failed. Structural and non-structural members have been damaged. Failure of a few structural members which are not critical to structure stability. Roofs are damaged and have to be totally replaced or repaired. Structure requires extensive repair and hence is unsuitable for immediate occupancy.

- **Collapse (DC4)** – Partial or total collapse of the building. Collapse of large sections of foundations and structures due to heavy scouring. Excessive foundation settlement and tilting beyond repair. Damage to the structure cannot be repaired after the tsunami and must be demolished.

Figure 3.32 illustrates the typical damage associated with categories DC1 to DC4 for the two types of RC building in Thailand (Cat. D and Cat. E). Low and mid-rise RC buildings in Thailand have a significantly different resistance to lateral loads (see Section 3.3.2). As the composition of buildings is not the same at each surveyed location, in order to obtain an objective assessment of the devastating force of the tsunami a descriptive intensity scale is defined. This scale combines the damage observed in the two RC building types to assign an intensity value to a given location. Furthermore, in order to compare the damage observed in Thailand and Sri Lanka, where the tsunami affected areas have different predominant building types (see Section 2.4.2), the degree of damage (as described in Chapter 2) expected to occur in masonry buildings (Cat. B and C) and wood frame buildings (Cat. A) for each intensity level is also included. The Intensity scale used is presented in Table 3.3 and is based on the EEFIT team on-site observations and on the tsunami intensity scale of Papadopoulos and Imamura (2001). The approximate correspondence between the intensity scale adopted here and those of Papadopoulos and Imamura (2001), Ambraseys (1962) and Shuto (1993) is given in Table 3.4.

Table 3.3: Description of the tsunami intensity scale used by EEFIT.

	Intensity	Upper Level Intensity Description.
I.	Weak	Felt by all onboard small vessels. Observed by most people on the coast. Some flooding of gentle sloping coasts. No effects on objects. No damage to buildings.
II.	Light	Light sailing vessels carried on shore. Flood damage to timber structures (Cat. A) near shore. Damage level DM1 in masonry (Cat. B and C) and DC1 in RC buildings (Cat. D and E) near shore.
III.	Strong	Flooding of shore to some distance. Many people are frightened and run to higher ground. Most small vessels move violently onshore, crash into each other or overturn. Severe damage and collapse of many timber structures (Cat. A). Damage to DM2 in most Cat. B and some Cat. C masonry buildings and DC1 in most RC buildings (Cat. D and E).
IV.	Destructive	Many people are washed away. Most small vessels are destroyed or washed away. Many large vessels are moved violently ashore, few are destroyed. Extensive erosion and littering of the beach. Local ground subsidence. Damage of DM3 in many Cat. B and few Cat. C masonry buildings. Very few Cat. D RC buildings suffer from DC3, most Cat. D and E suffer damage to DC2.
V.	Very Destructive	General panic, most people are washed away. Most large vessels are moved ashore, many are destroyed. Extensive ground subsidence. Damage of DM4 in most Cat B masonry buildings. Most Cat. C masonry buildings have damage to DM3 and above. Many Cat. D and few Cat. E RC buildings suffer from DC3. Many Cat E RC buildings suffer from DC2.
VI.	Devastating	Damage of DM4 in most masonry buildings. Many Cat. D RC buildings suffer from DC4. Many Cat. E RC buildings suffer from DC3 and above.

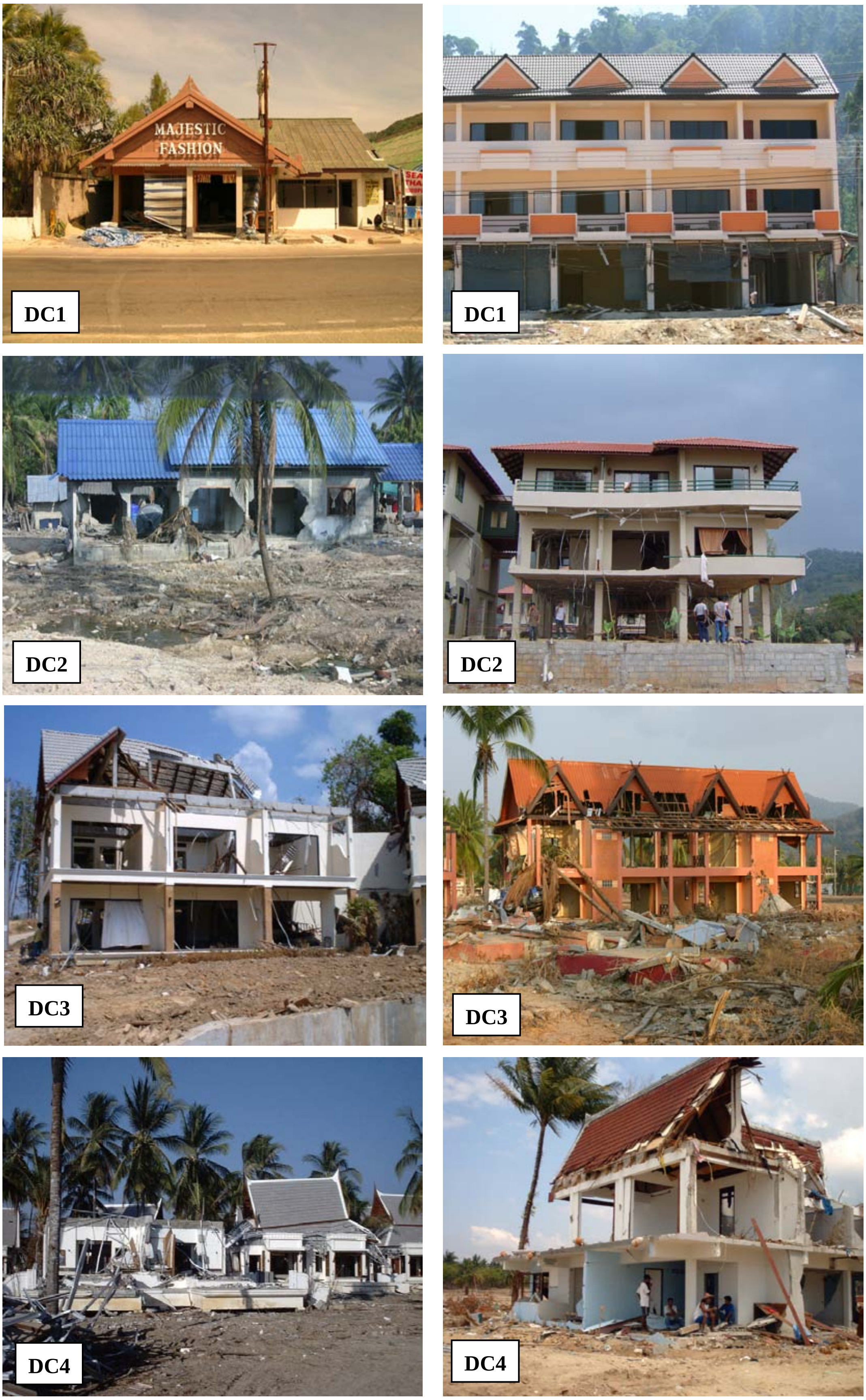


Figure 3. 32: Examples of different categories of damage DC1 to DC4 in low-rise Cat. D (left) and mid-rise (right) Cat. E reinforced concrete structures in Thailand.

Table 3.4: Approximate correspondence of the proposed EEFIT tsunami intensity scale with other existing tsunami intensity scales.

EEFIT Intensity		Papadopoulos and Imamura (2001)	Ambraseys (1962)	Shuto (1993)
I.	Weak	IV-V	II	0
II.	Light	VI-VII	III	1
III.	Strong	VIII-.IX	IV	2
IV.	Destructive	X	V	3
V.	Very Destructive	XI-XII	VI	4-5
VI.	Devastating	XII	VI	

3.4.4 Damage maps and surveys

The number of severely damaged buildings in the Phang-Nga, Phuket, Krabi, Ranong, Trang, and Satun provinces reported by the Department of Disaster Prevention and Mitigation, Ministry of Interior, Royal Thai Government, on 24 January 2005, comprised 6026, 921, 1384, 171, 6, and 6, respectively. The EEFIT team carried out a series of damage surveys at various locations along the western coast of Phuket, in Phi Phi Island (Krabi Province) and in the Khao lak region (Phang Nga Province), the results of which are presented here.

3.4.4.1 Macro-scale damage survey

Tsunami intensity (See Section 3.4.3) values were assigned to the coastal locations visited. These macro-scale damage assessments are presented in Figures 3.33 to 3.36. The first three figures show the assigned intensity levels and measured water heights (above mean sea level) along the surveyed areas of the Thai coast together with the variation in the bathymetry offshore of these sites. Figure 3.36 shows the assigned intensity level and measured water height (above ground level) together with the topographic variation along the western coast of Phuket Island. Intensity values are not assigned to locations that were not surveyed by the EEFIT Team, nor are water height recordings made by other survey teams presented in these maps.

From the macro-scale damage maps it is observed that of the sites surveyed, Khao Lak (Phang Nga Province) and Phi Phi Island (Krabi Province) suffered the worst damage. These areas also suffered the largest mortality rates and building losses. A Strong tsunami Intensity causing Light damage in RC buildings was inferred in the south of Bang Thao Beach. The tsunami had Destructive and Very Destructive Intensities at Patong and Kamala Beaches causing Moderate and Heavy damage in most RC buildings along the coast, respectively.

In order to better understand the causes of the observed variation in building damage along the coast, the assigned intensity levels are plotted against the average bathymetry, topography and measured water height profile at the surveyed locations (Figure 3.37). The bathymetry is calculated as the average gradient over a 50km distance offshore and perpendicular to the coast and topographic gradient is calculated as the average gradient between the shore line and the distance inland at which the first 50ft contour is met.

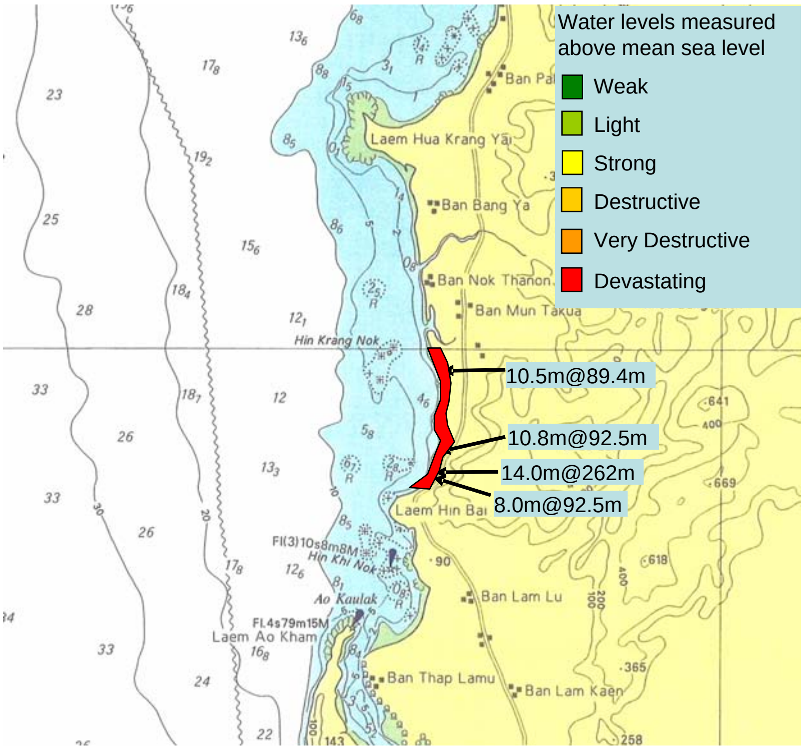


Figure 3. 33: The surveyed damage in the Khao Lak region, Phang Nga Province, Thailand. The arrows indicate locations of inundation height measurement (e.g. 10.5m@89.4m means a water height of 10.5m above mean sea level was measured a distance 89.4m from the shore).

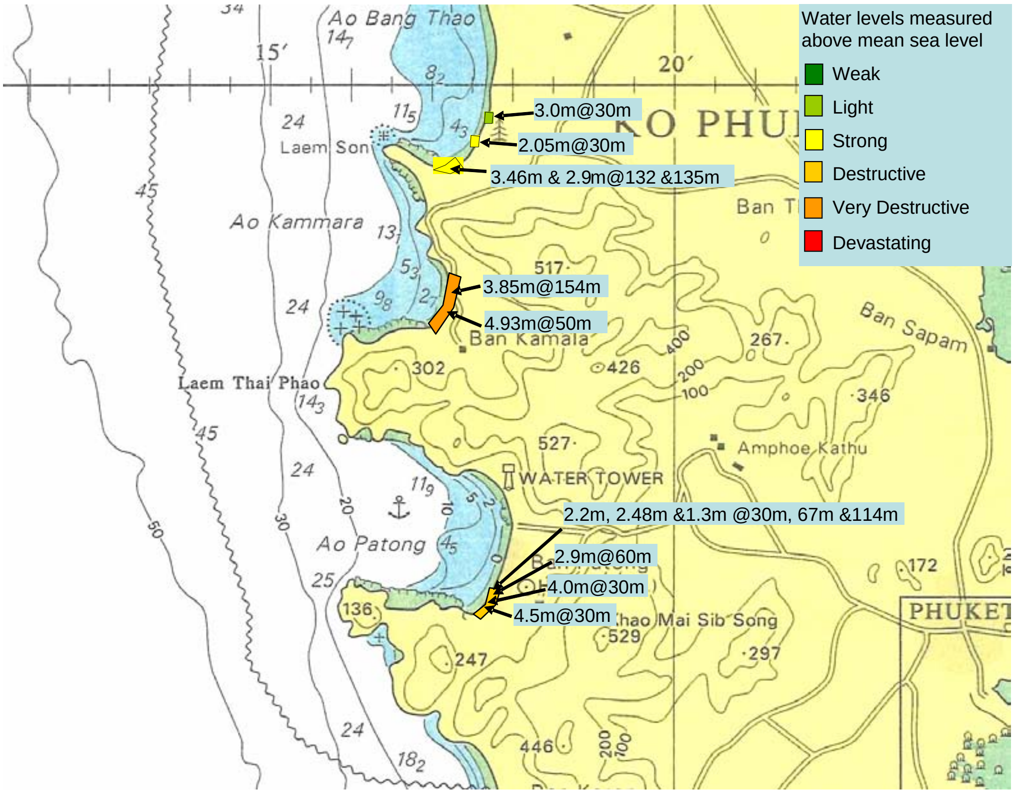


Figure 3. 34: The surveyed damage on the Western coast of Phuket Island, Thailand. The arrows indicate locations of inundation height measurement (e.g. 4.5m@30m means a water height of 4.5m above mean sea level was measured a distance 30m from the shore).

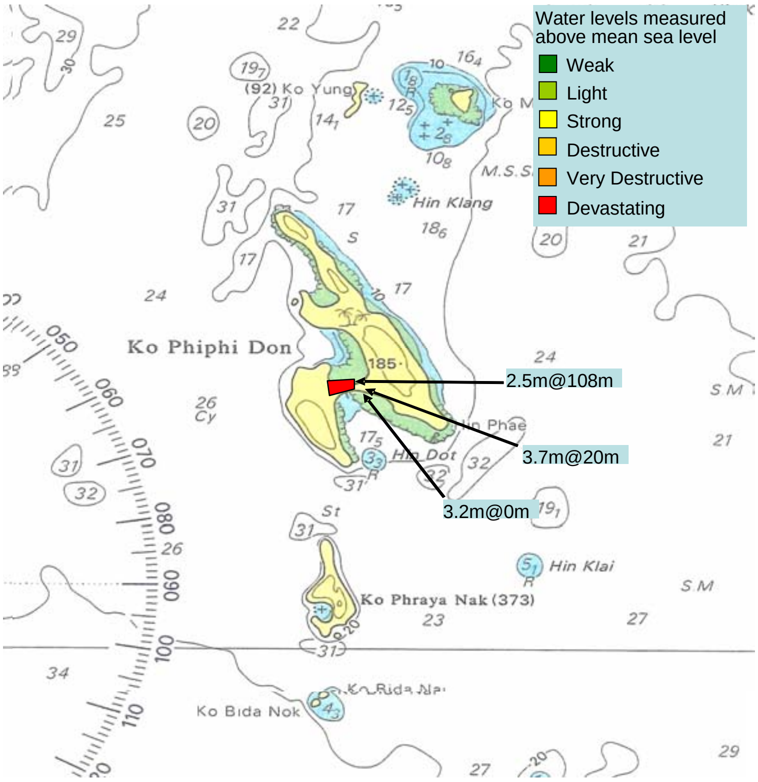


Figure 3. 35: The surveyed damage on Phi Phi Island, Krabi Province, Thailand. The arrows indicate locations of inundation height measurement (e.g. 3.2m@0m means a water height of 3.2m above mean sea level was measured a distance 0m from the shore).

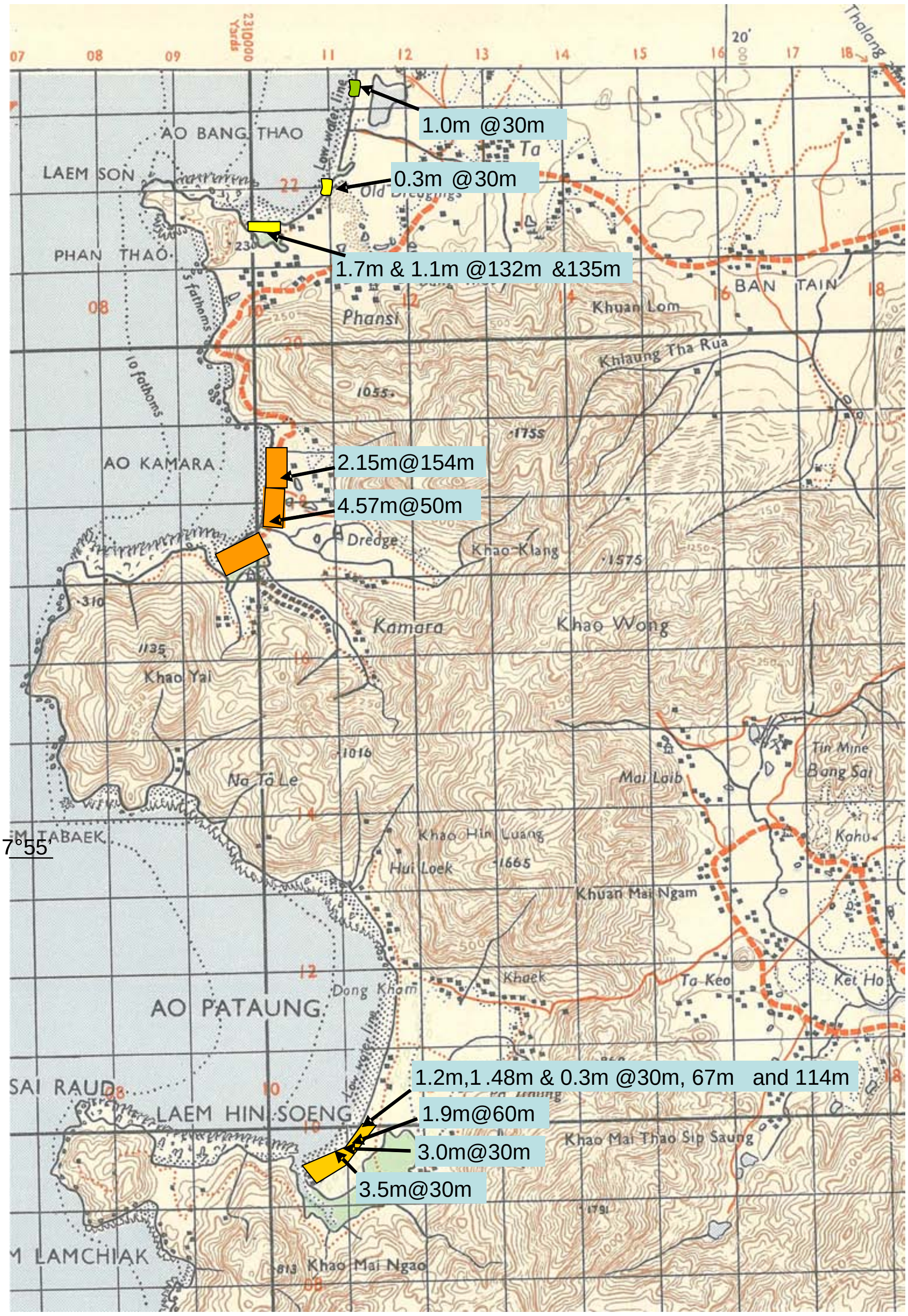
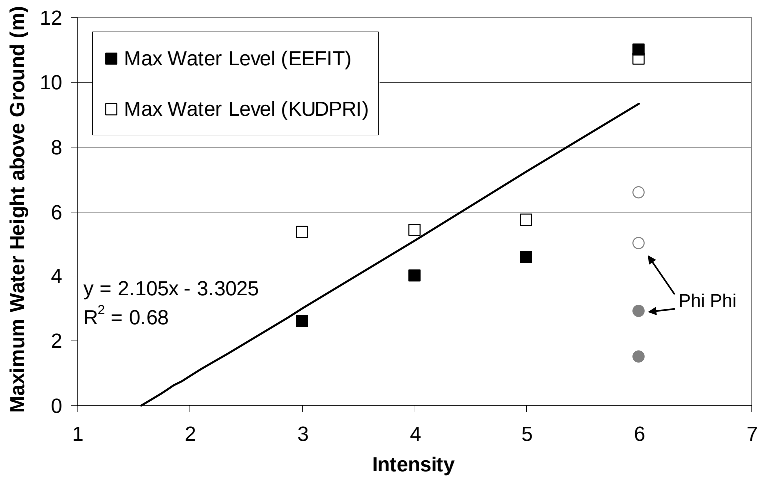
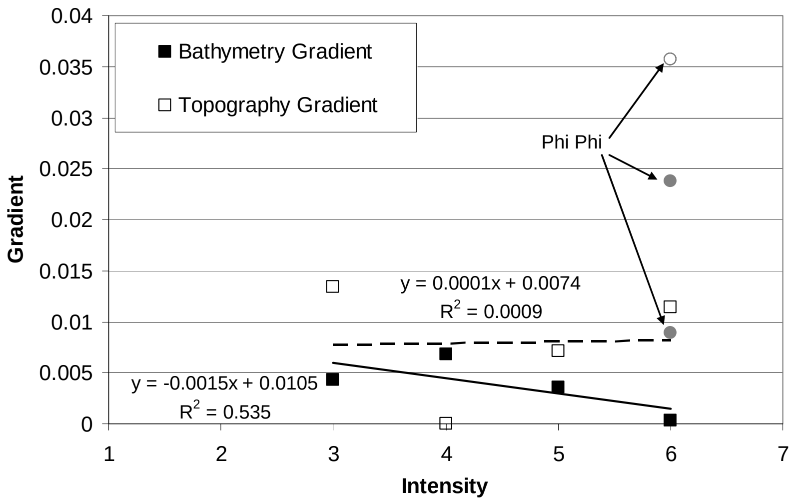


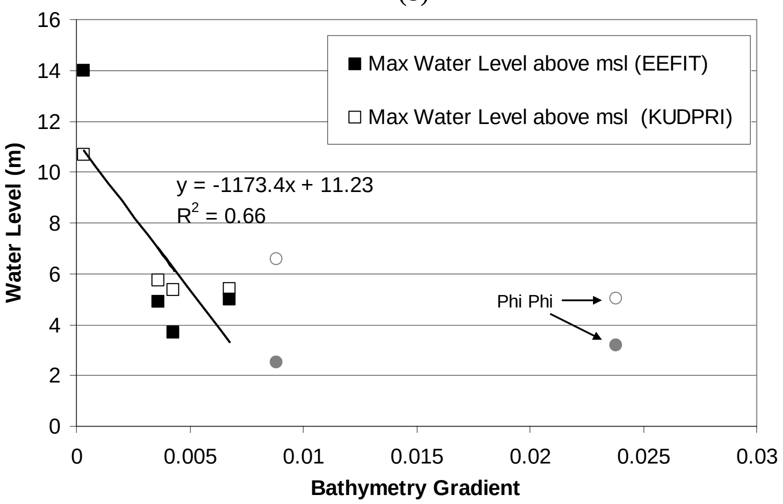
Figure 3. 36: The surveyed damage plotted on a topographic map of Phuket Island, Thailand. The arrows indicate locations of inundation height measurement (e.g. 3.2m@0m means a water height of 3.2m above ground level was measured a distance 0m from the shore). Contours are at 50feet height intervals. Each grid square is 1000 x 1000 yards.



(a)



(b)



(c)

Figure 3. 37: Plots of (a) Tsunami Intensity versus water height above ground, (b) Intensity versus the bathymetric gradient offshore (average gradient over 50km perpendicular to the coast) and topographic gradient (calculated as the average gradient between the shore line and the distance inland at which the first 50ft contour is met) of the coast at the surveyed locations, (c) Tsunami water height above mean sea water level versus the bathymetric gradient. Measurements for Phi Phi are plotted separately as damage at this site was caused by the tsunami sweeping both sides of Ton Sai Bay in quick succession.

From Figure 3.37a strong positive correlation is evident between the measured water height above ground and the assigned intensity levels at the different sites. This is not surprising as larger water heights will cause larger hydrostatic forces to act on buildings. Linear regression on the plotted points gives the following relationships between water height above ground (H in m) and Tsunami Intensity (I).

$$H = 2.105.I - 3.3025 \quad , \quad R^2 = 0.68 \tag{3.3}$$

The threshold values of tsunami water level above ground given by Equation 3.3 for the different Intensity levels are presented in Table 3.5. In this table the threshold values obtained through interpretation of the water height damage matrix in Shuto (1993), (shown in Figure 3.38) are also reported. Shuto (1993) does not include data for masonry and RC buildings for intermediate damage states, and the interpretation of the "Safe" damage state is ambiguous. Despite this, the correlation between the expressions derived here and those of Shuto (1993) is good up to intensity level IV but under-predicts the damage levels for large run-up heights in Thailand. Imamura (2005) also gives criteria for estimating tsunami damage from inundation height: Humans will be killed if the inundation height exceeds 0.5m, houses will be partially damaged for inundation heights exceeding 1m and totally damaged for inundation heights exceeding 2-3m, and better built buildings will be damaged at water heights exceeding 5m. These criteria also correlate well with the field observations made in Thailand.

Table 3.5: Threshold values of tsunami water height above ground (H) for the EEFIT Tsunami Intensities based on data collected in Thailand .

Intensity		I	II	III	IV	V	VI
Threshold H (m)	EEFIT	0	0	1.96	4.07	6.17	8.28
	Shuto (1993)	0	0	2.00	4.00	7.50	14.0

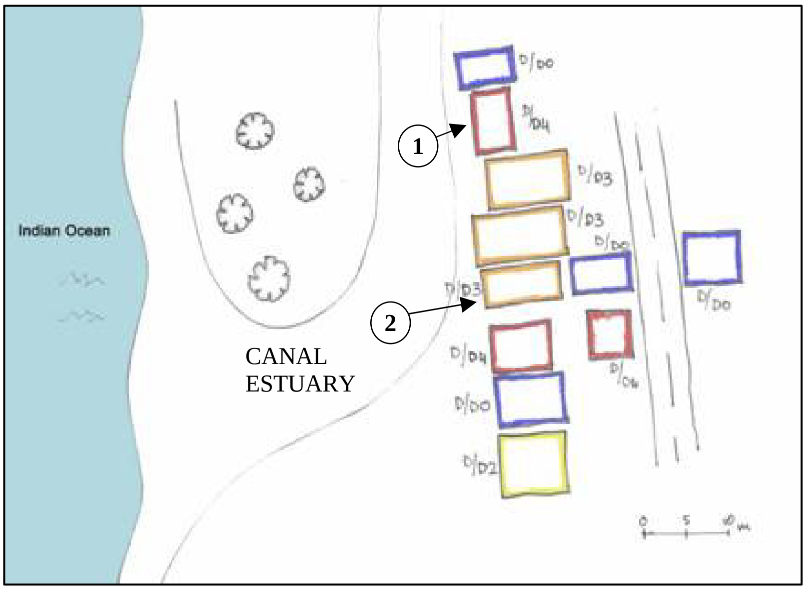
Figure 3.38: Tsunami water height over land versus damage matrix proposed by Shuto (1993).

From Figure 3.37b it is observed that the intensity is inversely proportional to the bathymetric gradient and almost independent of the topographic gradient of the coast. It must be noted here that in all areas the topographic gradient at the coast was similar and hence no real conclusion as to the effect of coastal topography on damage can be made. However, it is noted above (Section 3.4.1) that the extent of inundation inland is dependent on the topographic gradient and hence it is expected that the higher the coastal gradient, the lower the level of damage to structures inland. From water depth surveys made in Thailand (Yokoki et al. 2005), the Ibaraki University Sumatra Tsunami Survey Team concluded that the ground level, (i.e. topography) was the main factor in reducing damage inland as it effectively reduced the water height above ground. In Figure 3.37c, the bathymetric gradient is plotted against the measured height of tsunami water level above mean sea level. A strong negative correlation is seen. Hence the effect of an increasing bathymetric gradient is to reduce the tsunami inundation height and therefore reduce the intensity of its impact. It is recognised that the data used to make these statements is few and that further work is necessary to make general statements about the effect of bathymetry in other locations.

The recordings made at Phi Phi Island are observed not to give the same tendencies as the rest of the data. This is because Ton Sai Bay was swept from both sides (as described in Section 3.2.3) and the small topographical gradient gave rise to an extremely high level of damage despite relatively steep bathymetric gradients. In addition the EEFIT run-up measurements were made in the southern side of the land strip because the north side was severely devastated and there were not many places where watermarks could be measured with certainty.

3.4.4.2 Detailed surveys

The tsunami intensity at a site is not only dependent on the general bathymetry and topography of an area, but also by local topographical features, the presence of waterways, the density of buildings and vegetation, and the type of founding soil. Two detailed surveys are presented to illustrate the influence of local features on building damage and the challenge this poses to predictive modelling of tsunami damage. Our surveys were made at Kamala Beach (Intensity - V) and southern Patong Beach (Intensity - IV). The building categories and the damage levels used for the survey are presented in Sections 2.4.2, 3.3.2 and 3.4.3.



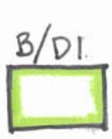
	Legend			
	Damage State			*Construction type*
D0	*no damage*		*A*	*timber*
D1	*light damage*		*B*	*poor quality masonry*
D2	*moderate damage*	*Example: Poor quality masonry, light damage*	*C*	*good quality masonry*
D3	*heavy damage*		*D*	*low rise concrete frame*
D4	*collapse*		*E*	*mid rise concrete frame*

Figure 3. 39: Detailed damage survey carried out by EEFIT at Kamala Beach. The building typologies and damage states are described in Sections 2.32 and 3.4. The circled numbers refer to the locations of the damaged building pictures shown in Figure 3.40.

Eleven buildings were surveyed along the Kamala beach front. All were low rise RC frames with masonry infill (Cat. D) of similar construction (Figure 3.39). The performance of the buildings varied with nearly 30% of buildings suffering complete collapse. The typology of the collapsed buildings is not available but is assumed to be similar to that of the standing buildings. Infill walls were found to be undamaged from the direct water impact. However, large erosion of the beaches was observed and the surveyed buildings collapsed or were damaged principally due to ground scour and sea wall failure (see Figure 3.40a). The failed structures were set on stub columns and sitting on pad foundations, formed by means of large flat stones or mass concrete. The estuary location of the survey area exemplified this type of damage as receding water flowed into natural channels and scoured the ground on which the buildings were founded.

(a)

(b)

Figure 3. 40: Photographs of building damage at Kamala Beach taken at survey locations 1 and 2 shown on Figure 3.39: (a) taken at location 1, shows the sea wall failure at Kamala caused by beach erosion, (b) the footings of the house at location 2 are left exposed by the erosion caused by the tsunami.

Eleven hotels were surveyed for overall damage from the inundation along the Thaweewong Road that runs parallel to the beach front at the southern end of Patong Beach. All were mid-rise RC frame buildings with masonry infills (Cat. E) sited about 30m inland from the shore. Onshore tsunami water heights between 2.2-4.5m were measured at the locations of these shore front buildings. Building damage ranging between DC1 and DC2 was observed, most hotels sustaining flood damage to the fittings and contents of their ground floors and basements (Figures 3.4 and 3.5). Although the proportion of flooded rooms within these buildings is estimated to lie between 10-15 %, and little non-structural damage was observed, disproportionate costs can be associated with flood damage to the basement and ground floors of hotels as most buildings services, such as electricity switching boxes or generators, are located there.

The degree of sustained building damage was generally observed to reduce with distance from the shore, some flood damage being observed up to four properties inland. However, damage was seen to extend to greater distances where roads extended perpendicular to the beach and the tsunami could enter unimpeded. Indeed, the road geometries had a major influence on the damage patterns and mortality. Locals interviewed by the NZSEE Reconnaissance team (Bell et al. 2005) attributed their survival to good fortune or split-second decisions that placed them in streets or buildings in the lee of the wave attack and perpendicular to the flow direction. This life-risk can be likened to that of a swimmer caught in a rip current, more likely to survive by swimming across the current than against it.

3.5 Lifelines

The timely restoration of lifelines after an event is critical to the provision of relief and recovery. In particular, communication and transportation networks are essential to co-ordinate and to deliver the relief effort. These in turn rely on other infrastructure such as electricity networks to function. Extended periods without water and electricity supply may increase the suffering and death toll and retard the relief effort. Furthermore, damage to large facilities may impact on local employment and slow the rate of return to economic normality. Within this section a brief overview of the observed damage to lifelines, ground retaining structures and large facilities is given and the impact of lifeline disruption on the local population is described.

3.5.1 Road and bridge damage

There was no serious damage to the main arterial roads in Phuket, Khao Lak and Phi Phi Island. However, minor damage to the road surface was observed in areas near the coastline (e.g. Figures 3.41 and 3.42). This damage was probably due to increased pore water pressure under the flexible pavement which in turn reduced the effective stress and consequently the shear strength leading to slope failure. This was visible on small areas of road surface adjacent to the beach front and especially on grasscrete surfaces (e.g. at Kamala and Laem Pakarang).

There was no apparent damage to reinforced concrete bridges. The Sarasin bridge connecting Phuket Island to mainland Thailand was undamaged and operational after the tsunami. The pile caps of the bridge south of Patong Beach were partially exposed due to the erosion of the surrounding sand (Figure 3.43), but no damage to the structure was observed. These observations suggest that the RC bridges performed satisfactorily under the tsunami impact forces. Abutment damage was observed on one minor bridge in the region of Bang Thao. At this location the unprotected abutments had scoured completely. However, since the bridge was undamaged, repair had already been completed by the time of the survey. This was achieved by simply filling in the scoured regions.

(a) (b)

Figure 3. 41: Road damage near Bang Thao Beach, approximately 120m inland.

Figure 3. 42: Damaged pavement at Patong Beach, approximately 30m from the sea.

Figure 3. 43: No damage was observed on the cross-river bridge at the south of Patong Beach, however the pile caps under the piers have been partially exposed by erosion.

3.5.2 Retaining structures

Most of the masonry walls (see Figure 3.44) and concrete gravity walls (see Figure 3.45) adjacent to the beachfront had suffered tilting, and/or partial or total collapse. It is unclear whether the incoming or outgoing waves caused this damage. Reinforced concrete retaining walls faired much better with the majority showing no apparent damage (an example is shown in Figure 3.46).

(a) (b)

Figure 3. 44: Damaged masonry retaining sea wall in Kamala Beach.

(a) (b)

Figure 3. 45: Damaged 500mm inner diameter gravity retaining sea wall with sand infill on Loh Dalam Bay in Phi Phi Island located at approximately 10m from the coastline.

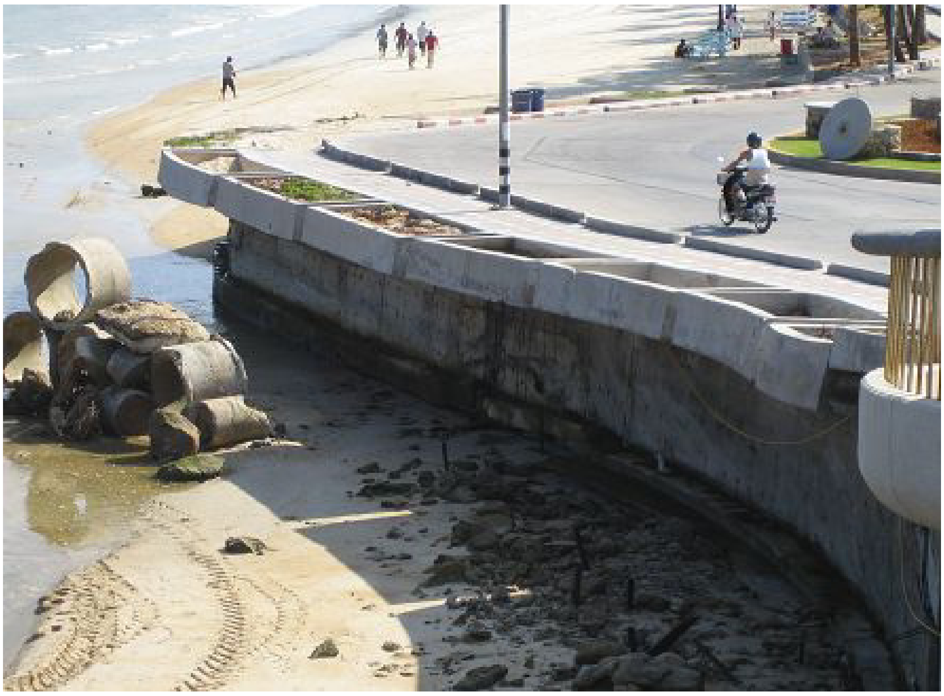


Figure 3. 46: No apparent damage on the RC retaining sea-wall at the south of Patong Beach.

3.5.3 Phuket International Airport

Flooding on the runway was reported at Phuket International Airport. The airport was closed for several hours due to high levels of sand and dust blown up by the initial shock of the wave. No significant damage was reported at the airport runway and buildings, however part of the lighting system was temporarily affected. The airport was re-opened by the Sunday evening of 27th December 2004 when flights arrived to Phuket from Bangkok containing aid workers that assisted the early stages of the rescue and clean-up efforts. Figure 3.47 shows the airport runway one month after the tsunami occurred.

Figure 3. 47: The runway at Phuket International Airport.

3.5.4 Water supply and electricity

There was no serious long term disruption to the water and electricity supply in Phuket. Minor damage to electricity distribution posts on Bang Thao Beach was observed (see Figure 3.48) as well as Khao Lak and the beachfront of Patong. Electricity supply to tsunami affected areas of Phuket was temporarily suspended for two or three days with supply restricted to inundated areas. It is assumed that in the heavily affected areas of Khao Lak both water and electricity supplies were completely damaged. However, the speed with which supply was reinstated was remarkable. One month after the tsunami complete replacement of local overhead supply along damaged sections of the network was observed in Khao Lak and in Ban Nam Kaem (Bell et al. 2005). Some damage to drainage pipes was observed at the southern end of Patong Beach at the river inlet as shown in Figure 3.48. Flotation of underground services was also observed at several points around Khao Lak

(a) (b)

Figure 3. 48: Examples of damage to water supply and electricity. Left: Minor damage to an electric power post on Bang Thao Beach located at approximately 150m from the coastline. Right: Damaged drainage pipe at the south of Patong Beach which is located at the river inlet.

3.5.5 Large facilities

Few large infrastructure facilities were located close to the affected beachfront areas. The exception was Phi Phi island where the main telecommunications and power generation building was badly damaged (see Figure 3.22). This building was of a reasonable construction standard, but seemed to suffer from either impact damage or severe wave slam. Although the unusual shape of the island resulted in the tsunami inundating Ton Sai Bay from both North and South, the powerplant is exposed to the north side and more sheltered from the southern side. The highest surge was judged by the NZSEE Reconnaissance team (Bell et al. 2005) to have come ashore from the north side. It is speculated that location of the power plant close to steeply rising ground may have made it more susceptible to a focusing of energy from incoming and refracted waves.

3.6 Impact on Society and Recovery

3.6.1 Impact on tourism industry

The Tourism Authority of Thailand kindly released the following summary table of data concerning the hotel capacity in the three worst-affected provinces of Thailand. They have also released a complete list of the affected and unaffected hotels in the three provinces along with their contact details for further investigation. The worst affected province is seen to be Phang Nga, which has 80% of its capacity affected by the tsunami, whilst Phuket and Krabi were affected to a much lesser degree with 17% of their facilities damaged. The most recent update of this data (September 2005) shows that 10, 26 and 8 hotels still remain closed in the Phuket, Phang Nga and Krabi provinces, respectively.

Table 3.6: Statistics of Hotel Damage in Thailand

Province	No. of Operational Hotels	% of Operational Hotels	No. of Operational Rooms	% of Operational Rooms	No. of Hotels before Tsunami	No. of Rooms before Tsunami	Damaged Hotels
Phuket	472	82.4%	26,762	83.3%	573	32,585	101
Phang Nga	46	32.2%	1,098	19.8%	143	5,533	97
Krabi	292	83.2%	9,042	77.2%	351	11,709	59
Total	810	75.9%	36,902	74.1%	1,067	49,827	257

Source: Office of the Tourism Authority of Thailand in Phuket Town.

The Tourism Authority of Thailand reports that affected provinces may lose more than US$ 1 billion in tourism revenue in the first quarter of 2005. The provinces of Phuket, Krabi and Phang Nga were expected to generate 3 billion US$ worth of tourism income to the Thai economy prior to the disaster, but in the first month after the tsunami tourist arrivals were down 88% compared to the previous year. The Thai government has estimated losses to the business sector of nearly US$390 million, but this total excludes losses to more than 250 affected hotels. It was reported in early March 2005 that the Thai government has approved a US$100 million fund to revive tourism in the affected provinces, including subsidised airfares, subsidies to public employees who decide to take a holiday in the region, new duty-free shops, rehabilitation of affected beaches and the creation of a remembrance museum.

3.6.2 Human casualties

According to data reported on March 24, 2005 life loss in Thailand reached 5,395 people (including 1,953 foreign tourists or residents and 1,503 unidentified persons). Many of the unidentified persons are believed to be foreign tourists plus undocumented migrant workers. The deceased were initially collected in four Buddhist temples in the Phang Nga province for detailed forensic examination, identification and repatriation. In addition, 2,932 people were listed as missing including 909 foreigners. Thus the potential life loss may total 8,327 people. The listed number of injured was 8,457, including 2,392 foreigners. The casualty statistics by province are shown in Tables 3.7 and 3.8.

Table 3.7: Fatalities and missing persons by province in Thailand

Province	Dead				Missing			
	Thai	Foreigner	Unidentified	Total	Thai	Foreigner	Unidentified	Total
Phang Nga	1,266	1,633	1,325	4,224	1,428	305	0	1,733
Krabi	357	203	161	721	329	240	0	569
Phuket	151	111	17	279	256	364	0	620
Ranong	156	4	0	160	9	0	0	9
Trang	3	2	0	5	1	0	0	1
Stoon	6	0	0	6	0	0	0	0
Total	1,939	1,953	1,503	5,395	2,023	909	0	2,932

Source: Thai Department of Disaster Prevention and Mitigation, updated as of March 24, 2005.

The casualty statistics are constantly changing as the painstaking process of finding the missing and identifying the unidentified bodies continues. The latest data released on May 19, 2005 by the Thai Department of Disaster Prevention and Mitigation are 5,396 dead (1,975 Thai, 2,246 foreigners and 1,175 unidentified) and 2,845 missing. Thus the number of potential fatalities (including the missing and unidentified) now stands at 8,241 people. Considerable frustration exists because five months after the disaster there were still more than one thousand unidentified bodies (apparently due to the lack of coordination between the various nations' forensics teams that use different methodologies). To the above life losses the number of Burmese and Laotian migrant workers must be added, which are reported by the Thai authorities to be 25 but this is believed by media sources to be larger (Section 1.8).

Table 3.8: Injuries by province in Thailand

Province	Injuries			
	Thai	Foreigner	Unidentified	Total
Phang Nga	4,344	1,253	0	5,597
Krabi	808	568	0	1,376
Phuket	591	520	0	1,111
Ranong	215	31	0	246
Trang	92	20	0	112
Satun	15	0	0	15
Total	6,065	2,392	0	8,457

Source: Thai Department of Disaster Prevention and Mitigation, updated as of March 24, 2005.

Estimates of Thai citizens directly affected by the disaster (loss of a family member or home) stood at 91,638, comprising an estimated 20,537 households, although this was later lowered to 58,550 persons and 12,017 households (this latter number concerning only those cases that had a relative killed or missing). However when the effects to the fishing and tourism industry are taken into account the number of affected people is estimated to exceed 150,000 people. UNICEF has identified around 100 orphans (lost both parents) and an additional 1,100 children that lost one parent, while the total number of affected children is around 8,000.

The number of foreign persons lost in this disaster exceeds that of Thai nationals, due to the fact that the areas affected were predominantly tourist resorts. Approximately three quarters of the foreign tourists killed were located in the Khao Lak area. The worst life loss among Thai people occurred in the coastal town of Ban Nam Kem (population 6,000) in the Takua Pa district of Phang Nga province where up to 1,950 people were killed and up to 80% of the houses destroyed. Other locations with high loss of life included: the Khao Lak resort where more than 2,000 foreign tourists lost their lives, Phi-Phi island where around 400 people died, Patong beach in Phuket island where around 150 people died, Kamala beach in Phuket island where around 75 people died, Pra Thong island where around 30 people died. The above figures may not match exactly to the ones in Table 3.7 because they group the dead, missing and unidentified Thai and foreign nationals in one single potential life loss figure per location. They are nevertheless quoted here so that a better understanding of the spatial distribution of life loss can be gained.

There is a significant difference in the proportion of missing persons compared to the confirmed deaths between the two investigated countries. In Sri Lanka the missing are 13% of those confirmed dead, while in Thailand they are 54%. Also, unlike in Sri Lanka where there were more than two dead or missing for every reported injured person, this ratio in Thailand was 1:1. In Sri Lanka there were more than seven times as many people affected than in Thailand, and for every damaged housing unit in Thailand there were 20 damaged housing units in Sri Lanka. The ratio between the dead and missing to the internally displaced (affected) population is approximately 6.5% in both Thailand and Sri Lanka, if foreign visitors are excluded from the comparison.

3.6.3 Potential lethality among the coastal population

Phuket Island is densely inhabited, with a surface area of 558 km^2 and population of 249,500 people in the census of April 1, 2000. Phuket is one of the fastest growing provinces of Thailand with an average annual population growth of around 4% during the nineties. Therefore, the population of Phuket island at the time of the disaster was close to 300,000. An estimated 899 people lost their lives or are missing in Phuket of which 407 were Thai nationals. The population within the first kilometre of the coast was estimated by the Center for International Earth Science Information Network (CIESIN) at Columbia University to be 30,649 (or 12.3% of the total). At least two thirds of the coast in Phuket was not seriously affected, which would suggest that the lethality ratio among Phuket inhabitants in the zone affected by the waves was around 3 to 5%. However, this is a rough estimate as insufficiently detailed population data is available for each of the affected areas of Phuket. The main settlements in Phuket are Phuket town with 63,000 people and Patong town with 15,000 residents. Phuket town was not affected by the waves and in any case only a small part of the town lies within 1km of the coast. Patong town was affected as described earlier in this chapter with around two-thirds of the town within the 1km coastal zone. The number of tourists on the island at the time of the event is uncertain but inferred to be around 30,000 to 40,000 people (at the time of the disaster there were 32,585 hotel rooms in operation).

In Phang Nga province the population within the first kilometre of the coast has been estimated by CIESIN at 10,331 (or 4.3% of the total) and the number of confirmed Thai inhabitants dead or missing is 2,694 to which a number of the unidentified victims must be added. This means that in the affected areas of Phang Nga the lethality ratio may have exceeded 25%. Reports from the worst affected villages suggest very few survivors. The number of tourists in the Phang Nga province at the time of the event is uncertain but is inferred between 5,000 and 10,000 (at the time of the disaster there were 5,533 hotel rooms in operation). Many of the missing foreigners were out at sea, on offshore islands, on the beach or in hotel rooms and adjoining facilities that were exposed to large forces and flooded to depths of 5-10m.

Figure 3.49 shows a photo of a small part of the Khao Lak resort area as it was just days after the disaster. It was seen that well-built engineered reinforced concrete hotel structures of three storeys withstood the force of the tsunami waves, while other lighter structures on the sea front were completely devastated. However because the waves in this area were 7-12 metres high, even rooms at the third floor of these hotels did not provide safe refuge since they were rapidly flooded to ceiling level. For example, Figure 3.50 shows the condition of the interior of a room on the second floor of the hotel in the left hand corner of Figure 3.49. This hotel did not have any serious structural damage (except for a damaged column in the left corner at the front of the building attributed to debris impact), but the windows on all three floors had failed allowing water to flood the rooms. The hotel had not yet been cleared at the time of our visit (see also Figure 3.15).

Figure 3. 49: Aerial view of tsunami damage to hotels in the Khao Lak region of Thailand, (Source: http://www.undp.org/bcpr/disred/documents/tsunami/thailand/ocha_assreport1201.pdf)

Figure 3. 50: The condition in the interior of a second floor hotel room in Khao Lak following the tsunami.

3.6.4 Impact on other sectors of the Thai economy

Damage to housing in Thailand was not as extensive as in Sri Lanka but still significant as shown in Table 3.9 below. Damage to non-residential buildings was reported at 826 destroyed and 2,430 partially damaged.

Table 3.9: Housing damage statistics in Thailand

Province	Houses Completely Destroyed	Houses Partially Damaged
Phang Nga	2,563	2,052
Krabi	338	123
Phuket	420	511
Ranong	222	127
Trang	33	133
Satun	2	47
Total	3,578	2,993

Source: Thai Department of Disaster Prevention and Mitigation, updated as of March 24, 2005.

The village of Ban Nam Kaem (Phang Nga province) lost up to half its inhabitants and more than a thousand houses were completely destroyed. The 855 families (3,450 people) who survived were re-located to a camp where they will remain for a period of 4-6 months during planning and reconstruction of permanent housing. The village will be relocated to a new site to be identified by the local authorities, possibly in Ban Pru Tiew approximately 5 kilometres inland with daily transportation for fishermen in the plans.

In Kamala village (Phuket province) where 73 people were killed, 210 houses were completely destroyed and 228 houses were partially damaged. Also destroyed were a day-care centre, a health centre and a temple, while 174 cars and 40 boats were damaged.

Further north on Phra Thong Island (Kuraburi district of Phang Nga province), all 1,074 people of 336 households were affected and were evacuated to a relief camp on the mainland. Reportedly 149 of the 151 houses in the four villages on the island were destroyed and 87 people died (including 11 tourists and 6 hotel staff). Damage included destruction of a healthcare centre and damage to concrete bridges. A resort at the northern tip of the island was completely washed away. Detailed assessments of damage, relief, casualties at the tambon level (a subdivision of the provinces) can be seen for all affected areas at: http://library.enaca.org/tsunami/modules/_tinycontent4/index.php?id=11. In the education sector at least four schools were destroyed and more than 100 were damaged or lost students and (or) teachers as a result of the tsunami. All schools re-opened on January 10, 2005, but 25% of the students did not return due to fear and distress.

An assessment conducted in the first week of January 2005 by the United Nations Development Program (UNDP), the World Bank and the Food and Agriculture Organization (FAO) found that more than 300 coastal settlements were affected by the tsunami with 47 fishing villages being badly damaged and 182 moderately damaged. In total it is estimated that 3,402 small fishing boats and nearly 1,127 large fishing trawlers were destroyed or were seriously damaged. To this estimate a further 3,000 smaller boats were added in late April 2005 (these were apparently unregistered boats). Furthermore, several thousand fishing cages were destroyed, impeding the capture of grouper and sea bass that are especially lucrative for the local fishermen supplying Thai restaurants. More than 459 rais of fish/shrimp farms (1 rai = 0.395 acres) and more than 7,000 fish/shrimp ponds were damaged. In addition, the waters flooded more than 225 hectares of productive agricultural land and killed 54,000 livestock. It is estimated that the livelihood of 100,000 – 120,000 people has been affected with 5,400 families directly affected either by life loss, injury or loss of fishing related property.

The same report outlines the socio-economic profile of the affected regions at the time of the disaster. The local communities rely on an increasingly depredated and fragile environment and are pulled by the major driving force of the rapid and expanding development of mass tourism. In the past, the rural and coastal communities of Phang Nga and Phuket for example, relied on land based activities such as forestry products, commercial agriculture (fruit orchards, copra and rubber) and tin mining. Fishing and aquaculture, although present, represented marginal activities some 30 years ago. Directly and indirectly, the boom in tourism provided new attractive sources of income and jobs for the local younger generations (up to 50% of staff employed by the destroyed major complexes of Khao Lak came from the surrounding communities).

The tourism industry has provided new markets for local production, and subsequent revenues were re-invested in services for tourists and small businesses (small souvenir shops, restaurants, guided tours) located along the coast in the vicinity of large resort complexes. All along the central portion of the coast, the fishing communities which are traditionally among the poorest in Thailand have responded to the opportunity and directed a significant part of their activity to the supply restaurants and resorts with fresh highly prized reef fish species and sea food products in general. This increased further the exploitation of marine resources (allegedly including protected areas), together with the provision of water taxi and guiding services for tourism to nearby beaches and islands. Migrant workers from Burma have become the predominant labour force in the fishing industry while young Thai nationals from fishing communities moved into the more profitable tourism-related jobs. Some sea gypsy communities have become sedentary in Phuket partly (but not only) due to the attraction of revenues from the tourism industry. This indigenous minority have also used their boats to transport tourists to the islands of the bay of Chalong and Rawai. On the other hand some other sea Gypsy communities maintain more or less their original livelihoods mostly based on fishing and harvesting seashells.

There is no doubt that the tsunami has caused large loss of income from tourism, fishing and all related activities and may continue to do so for some time. People have lost not only their productive assets such as boats, fishing equipment and business facilities (hotels, shops, rental equipment) but the drop in the demand already evident in the mid-short term will take a long time and a huge effort to restore to former levels. The Thai Ministry of Labour estimates that 56,960 people lost their means of income. An employment program will be established to provide temporary employment for up to 30,000 people. The government has taken steps to respond to these losses in the short term, but it is clear that it will take time for the more vulnerable affected communities to recover. In Phang Nga province around 4,500 families are in need of urgent support as they have lost many family members and most of their possessions. This, coupled with their dependency on revenues from the nearby tourist resorts in Khao Lak that may take several years to re-open, there is a clear danger of impoverishment.

3.6.5 Pace of recovery

On the 5th March 2005, the Deputy Prime Minister instructed state agencies to complete 33 projects aimed at rebuilding tsunami-affected areas before October, ahead of the peak tourism season. The Commerce Ministry is working closely with the Asian Development Bank (ADB) to complete a long-term master plan for the recovery and development of Thailand's six Andaman provinces.

Representatives from Asian agricultural banks met in Bangkok from 14-18 March to identify strategies to be adopted by rural credit organizations, banks, financial and micro-finance institutions for the long-term rehabilitation of fisheries and aquaculture. In Phang Nga Province, the authorities announced that the distribution of cash compensation to affected fishermen had been completed. The authorities have repaired 60 fishing trawlers and a further 400 new trawlers have been built with foreign donations and local contributions. UNDP is providing emergency assistance to tsunami-affected fishing communities, as well as community-managed micro finance, in order to aid restoration of self-sufficiency, production and livelihoods. Eight boat yards have been under construction since mid-January in Krabi, Satun and Trang provinces; an additional 18 are planned for the Phang Nga, Phuket and Ranong provinces.

The conservation of coral reef resources is key to local tourism and fisheries and the clean-up operations supported by UNDP aims to minimize long-term damage from debris and pollution. As of the 15th March, nearly 30% of the damaged coral reef has been cleaned and/or rehabilitated, while by late April it was reported by UNDP that 95% of debris had been cleared from the targeted coral reefs, thus completing the work before the onset of the monsoon season.

Housing reconstruction is progressing reasonably well, with the Ministry of Interior reporting in late May that 791 new homes were built (22% of the identified needs) and a further 2,067 were under construction (58% of the identified needs). In the worst affected village of Ban Nam Kaem 200 homes had been completed by the Army. At the same time the number of people in temporary shelters is falling (in May 2005 according to UNICEF there were 6,000 people in temporary shelters). In Phuket, a Navy task force finished constructing housing for the tsunami-affected population, and was scheduled to be handed over to beneficiaries by the end of March, once electricity and necessary household items had been installed.

3.7 Conclusions

The 26th December 2004 Indian Ocean Tsunami caused a large loss of life, homes and hotel facilities in the coastal areas of Thailand visited by the EEFIT Team: the western coasts of Phuket Island, the Khao Lak region of Phang Nga province and Phi Phi Island in Krabi province. Within this chapter the damage observed in different building types by the team has been presented and the overall severity of damage at each location visited has been qualitatively described in terms of a tsunami intensity scale. The need for a clearly defined intensity scale for the quantification of tsunami damage to different buildings, which is calibrated with observed damage data, is identified. Measurements of tsunami water levels made at the different locations by the EEFIT team have been presented and an attempt to identify trends between the tsunami characteristics and the observed tsunami intensity has been made.

In addition to the damage to buildings, the effect of the tsunami on lifelines and infrastructure has been discussed. The impact to society including effects on tourism and fishing industries, human casualty statistics, damage to housing and non-residential buildings have been presented. Some discussion is also made regarding the potential lethality of the tsunami in various locations in the survey area.

The following conclusions are made from the EEFIT Team observations in Thailand:

- The areas visited that were worst affected by the tsunami were the Khao Lak tourist area in Phang Nga province, the island of Koh Phi Phi Don in Krabi province and Kamala Beach in Phuket Island. These areas also were seen to have had the highest tsunami run-up.

- The tsunami caused large erosion of beaches in various coastal locations such as Laem Pakarang and Kamala.

- The characteristics of the tsunami flow onshore were found to be extremely difficult to predict, being affected by the local bathymetry, coastal topography, amount of entrained debris, vegetation and the location and resistance to lateral loads of objects (e.g. buildings) in its path.

- The impact of entrained debris on buildings was observed to cause extensive non-structural damage, but was only one of the causes of building collapse.

- An initial study confirms observations made in previous empirical studies and modelling by other agencies (e.g. by the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Association) that tsunami water level height above ground is inversely proportional to the coastal bathymetry gradient approaching the coast and the coastal topographic gradient. Further work would be required to confirm this conclusion at each of the affected locations.

- In Thailand, tsunami water level height above ground was observed to correlate strongly with the observed tsunami intensity. Inundation height and tsunami onshore flow velocity are seen to be the two most important parameters in the determination of tsunami potential hazard to buildings.

- Masonry and wooden houses were seen to have collapsed within 150m of the coast in most of the visited locations in Thailand. This type of construction is not seen to provide adequate resistance where tsunami water levels exceeded 2.5m.

- Despite not being designed to resist earthquake loads or any significant lateral wind loads, well-built reinforced concrete (RC) moment-resisting frames were observed to perform well and were still standing even in locations where high inundation heights were recorded. Collapse of these buildings typically occurred only when poor quality building materials were used or inadequate beam-column connection details were present.

- The majority of infill panels and windows perpendicular to the direction of the flow collapsed under the water pressure. Within moment resisting RC frames the failure of infill panels contributed to the structures ability to survive the tsunami, as they acted like a lateral pressure release, (i.e. once the panel fails the lateral load applied by the tsunami waters to the large panel surfaces are no longer transferred to the framing members).

- Despite the fact that well-built RC structures withstood the tsunami they were seen not to provide adequate life-safety to their inhabitants. The collapse of windows and infill panels allowed water to flood the buildings thus reducing the possibility of escape for the building occupants.

- Erosion of the soft soil around the typical pad foundations used for masonry and reinforced concrete houses in Thai coastal areas was seen to cause some building failures. No buildings with piled foundations were observed to have failed due to scour. Therefore piles are recommended for use in areas exposed to tsunami.

- In the case of lifelines, no serious damage was sustained by arterial roads in the affected areas except minor erosion on the road surfaces. No apparent damage to RC bridges was observed. Most of the masonry and concrete gravity retaining walls at the coastline had collapsed or were tilted by the tsunami force. No apparent damage was observed for RC retaining walls.

- There was no serious disruption to reticulated water supply and electricity in the affected areas after the tsunami, these were restored within two or three days, although waste water collection facilities were disrupted locally (Kata Beach) and underground services at individual resorts in the Khao Lak area were damaged.

- It is estimated that the costs of recovery in Thailand is US$ 0.53 billion, (approximately 0.1% of the GDP). The tsunami caused large loss of income from tourism, fishing and all related activities and may continue to do so for some time. People have lost not only their productive assets such as boats, fishing equipment and business facilities (hotels, shops, rental equipment) but the drop in the demand already evident in the mid-short term will take a long time and a huge effort to restore to former levels.

Overall the main impact of the 26th December 2004 Indian Ocean Tsunami was not to the economy of the affected countries but to life loss. Given the observation made above that good engineering is not sufficient to provide life safety in the case of a large tsunami, it is essential that the risk of life loss be reduced through the implementation of a program of tsunami preparedness, which provides education, methods of warning, disseminating alarm and evacuation and a post-event disaster management plan.

3.8 Acknowledgements

The authors of this Chapter would like to express their gratefulness to the following:

Dr Hugh Cowan (GeoNet Project Director, Institute of Geological and Nuclear Sciences, New Zealand) and Dr. Pennung Warnitchai (Asian Institute of Technology, Thailand) for reviewing the Chapter and providing some photographs.

The Tourism Authority of Thailand, Office in Phuket, for providing us with the hotel capacity and damage statistics of the affected provinces in Thailand.

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Conclusions

In concluding this report it is important to recognize that the earthquake and ensuing tsunami of December 26, 2004, was a rare event with correspondingly large consequences. This enormous tsunamigenic earthquake was initially reported by the United States Geological Survey (USGS) to have had a moment magnitude (Mw) 9.0, while later after taking into account the energy content of ultra-long period seismic waves the magnitude was increased to moment magnitude (Mw) 9.3. The December 26, 2004 earthquake was therefore the second biggest earthquake of modern times recorded, surpassed only by the Mw 9.6, 1960 Chile earthquake that also caused tsunami that affected many countries in the Pacific Ocean. The death toll, 176,706 killed and 51,168 missing, is the largest for a tsunami event in recorded history.

According to Petersen et al. (2004) the average return period of an earthquake of this magnitude in the whole of the Sumatra subduction zone is believed to be 250-300 years which would mean that the return period in the northern segment that ruptured in December 2004 would be even longer. Using the earthquake catalogue of Petersen et al. (2004), Thio et al. (2005) propose that the December 26, 2004 tsunami was an approximately 500 to 1,000 year event. Further research is needed to better determine the seismic hazard in the Sumatra subduction zone and the tsunami hazard in the various coastal regions of the Indian Ocean.

Tsunami have occurred before on the coasts of the Indian Ocean and the Andaman sea but the last significant events were on August 27, 1883, during the eruption of the Krakatau volcano; on January 4, 1907, due to an earthquake of surface wave magnitude (M_s) 7.6 with estimated epicentre near the 2004 event; and on June 26, 1941, due to an earthquake of (M_s) 8.1 in the Andaman islands. Prior to these events tsunami had occurred in November 1833 and February 1861 due to large subduction earthquakes west of Sumatra (M_s 8.2 and 8.5 respectively), but these were centred further to the south and east and are not very well documented. The 2004 and 1883 tsunami fall into the category of basin-wide events, however, the occurrence of several smaller tsunami events in the region suggests that a tsunami warning system is now a priority. Such a system when implemented must be well integrated with other risk assessment and mitigation strategies, including education and community participation, hazard mapping, coastal bathymetry investigations and planning regulations to name but a few.

This event highlighted inherent vulnerabilities that are of immediate concern to the affected countries as well as to many other countries that are exposed to tsunami risk. Coastal populations are on the increase in many parts of the world for reasons such as the exploitation of sea resources or tourism. Tsunami hazard must be taken into account in areas at risk so that adequate protection measures can be taken for infrastructure that is already in place or for works that will be carried out in the future.

In the regions of Sri Lanka and Thailand visited by the EEFIT team, the tsunami water height ranged from 2.1 to 14.5 metres in areas with significant damage. In parts of Aceh province (Indonesia) tsunami wave heights of up to 30 metres have been documented by the Japanese, and US teams visiting the area. The extent of inundation in the worst affected areas visited by EEFIT varied but was generally in the range of 300 to 1,200 metres (even greater inundations such as 3,500 to 4,000 metres in Banda Aceh (Indonesia) and in Kalmunai and Batticaloa (Sri Lanka) have been reported by other organisations. Throughout the areas visited, the variability of damage along the coasts was significant and was most likely related to differences in coastal bathymetry, coastal morphology and differences in coastal elevation profiles. However a fairly good correlation was observed between locations of highest onshore water heights, building damage and life-loss.

The lessons learnt from this disaster can be categorized into four areas:

1) tsunami behaviour
2) the structural performance of buildings and infrastructure,
3) the life-safety capabilities of buildings and
4) the post-disaster performance of lifelines and disaster relief systems.

In addition to these lessons, the human and economic costs of the disaster must be acknowledged as these are not only the best gauge of the tragedy that occurred but also an indication of what may reoccur if we do not take heed of these painful lessons.

Lessons Learnt from the Disaster

Tsunami Behaviour

- The characteristics of the tsunami flow onshore were found to be extremely difficult to predict, being affected by local bathymetry, coastal topography, amount of entrained debris, vegetation, density of habitation and the location and resistance to lateral loads of buildings and other structures in its path.
- Damage from a tsunami is unlike the type of damage that could be expected from normal waves (for example during a storm). The period of the tsunami waves is very long and if the topography is flat inundation can occur far inland (inundation up to 4 kilometres from the coast occurred in Sri Lanka and Indonesia). The inundations from the three tsunami surges that hit most coasts of Sri Lanka and Thailand lasted for up to 10 minutes each and sometimes the outwash flows clashed with follow-up inflows. .
- The most severe damage to buildings was observed when these were sited in the first row of constructions from the sea or along waterways. Damage to buildings was seen to typically decrease with increasing distance from the coast and numbers of obstacles between the assessed buildings and the shoreline.
- Buildings located beyond the immediate sea front could still suffer extensive damage especially in areas of relatively sparse habitation and vegetation.
- Preliminary work on collected data shows that tsunami onshore water height is inversely proportional to the coastal bathymetry gradient approaching the coast and the coastal topographic gradient.
- In Thailand, tsunami water level height above ground was observed to correlate strongly with the observed tsunami intensity. Inundation height and tsunami onshore flow velocity were found to be the two most important parameters in the determination of potential tsunami hazard to buildings.
- In general vegetation was able to resist the tsunami. Trees usually remained standing even in locations of large wave heights. Coastal vegetation was observed to help protect beaches from erosion, by dissipating some of the wave energy and reducing wave slam; however, vegetation was seen to reduce but not prevent damage to buildings located near the affected beaches.

Structural performance of buildings and infrastructure

- In both Sri Lanka and Thailand, there were many examples of buildings being very close to the high-water line (<50 metres and often <20 metres). In Sri Lanka these buildings were usually vernacular dwellings, while in Thailand they were often low-rise tourist accommodation or small commercial buildings. For these structures, damage from tsunami could be extreme. Unless the structure was of well designed, modern construction, when wave heights exceeded 2.5 metres, they generally suffered complete collapse. Even some buildings of reinforced concrete (RC) frame construction suffered extensive structural damage (although this was usually due to poor detailing). Damage reduced quickly as the rows of buildings from the coast increased. This was because each row of buildings both absorbed the energy of the tsunami and shielded the lee side structures.
- Damage due to the retreat of the flood waters was also observed, especially to low-rise buildings with spread footings near river channels.
- In Sri Lanka where wave heights of mostly 2.5 to 5 metres were measured by the EEFIT team most of the RC frame buildings survived with little or no structural damage, but unreinforced masonry structures were not able to survive a tsunami of this magnitude. In general the masonry houses situated on or adjacent to the shore suffered major damage or collapse (unless the wave height was not great – due to local conditions).
- Masonry and wooden houses in most of the locations visited in Thailand were observed to have collapsed when situated within 150 metres of the coast (unless other structures or natural features provided shielding from the worst of the effects). This type of construction did not provide adequate resistance where tsunami water levels exceeded 2.5 metres.
- Despite not being designed to resist significant earthquake or wind loads, well-built RC moment resisting frames were observed to perform well and many were still standing, even in locations where the height of the tsunami exceeded 5 metres. Collapse of RC buildings typically occurred

when poor quality building materials were used or inadequate beam-column connection details were present.

- The majority of windows and many of the masonry infill panels perpendicular to the direction of the flow collapsed under the water pressure. Within moment resisting RC frames, the failure of infill panels contributed to the structure's ability to survive the tsunami as they acted like a lateral pressure release (i.e. once the panel fails the lateral load applied by the tsunami to the large panel surfaces are no longer transferred to the framing members).
- Masonry infill panels perpendicular to the beach provided very good resistance to the tsunami. When these panels were well constructed, they generally survived. The in-plane stiffness of masonry is well established and this stiffness contributed to ensuring the stability of the structure; however it should be noted that a significant number of masonry infill panels placed perpendicular to the shore and located at the seaside corner often collapsed outwards (probably from a combination of negative pressure on the outside and positive pressure on the inside resulting from water entering through failed seaward facing walls and windows).
- In general, soils in Sri Lanka seemed to be far more susceptible to scour than in Thailand and damage due to scour was also greater.
- In Sri Lanka, at locations where surficial soils were loose to medium dense sand with little clay content, damage due to scour was both extensive and severe. If this was coupled with large wave heights (e.g. Kahawa and Peraliya) then very large scour holes and undermining of whole buildings could occur.
- Erosion of soils around the typical pad foundations used for masonry and reinforced concrete houses in Thai coastal areas was observed to cause some building failures. No buildings with piled foundations were observed to have failed due to scour.
- Debris impact was observed to cause damage to buildings, but was generally not the main cause of building collapse.
- Stilted structures were observed to perform very well as did water towers, unless the water height exceeded the height of the stilts. If this occurred then the stilted structures behaved poorly.
- Overtopping of roofs generally caused the complete destruction of the roof. If the roof was required to provide structural stability to the rest of the building, significant structural damage often occurred.

Life-safety capabilities of buildings

- When the tsunami wave height exceeded 2.5 metres, even well built RC frame structures that survived without major structural damage did not provide adequate life-safety to their occupants. The collapse of windows, doors and infill panels allowed water to rapidly flood the buildings, thus reducing the possibility of escape for the occupants.
- Houses were not designed to provide a safe location from the severe and rapidly rising flood and therefore anyone that could not escape by running or climbing would have been in serious danger.
- The inability for structures to provide a life-safety function, accounts for the relatively high death to injury rate in the worst affected areas (something experienced in previous tsunami disasters in Japan and elsewhere). For example the death rate Phang Nga province of Thailand was equal to the injury rate, while in Sri Lanka for every recorded injury there were more than two recorded fatalities (although injuries may have been under-reported in Sri Lanka). This is opposite to what we generally find during an earthquake event.
- For structures that may be difficult to evacuate (such as hospitals) life-safety was a much greater issue. Evidence suggests that patients may not even be able to evacuate from ground floors to upper floors in sufficient time to escape a tsunami (something experienced also in New Orleans during the hurricane Katrina flooding).

Post-disaster performance of lifelines and disaster relief

- In the case of lifelines in Sri Lanka, failure of major road sections, bridges, railway, water supply and electricity networks had occurred.
- The loss of the major road and rail links between Colombo and the South of the country prevented any aid reaching the affected areas for 3 to 4 days.

- Bridges in Sri Lanka were badly affected with many suffering major damage. Of those observed along the SW coast of Sri Lanka, the major cause of their damage was the scouring of the retained-earth type abutments leading to failure of the decks. This had a dramatic impact on electricity and water supply because many of the cables and water mains were connected to the bridges so they could span the rivers. The damage to road bridges severely hampered the distribution of disaster relief and thus delayed the recovery.
- In the case of lifelines in Thailand, where unlike the areas we visited in Sri Lanka, the variation of wave heights was greater (usually from 2 to 10 metres) the extent of damage depended on the height of the tsunami. In Khao Lak and Phi Phi Island where the waves were in most locations above 5 metres, damage to above ground lifelines was severe.
- In Thailand unlike Sri Lanka the major road arteries were mostly located away from the coast and thus suffered less damage. The exception to this was some minor erosion and scour on road surfaces nearer the sea (in Khao Lak and Phuket).
- The airport in Phuket experienced runway flooding but was able to resume operation around 12 hours later.
- In Thailand most of the masonry and concrete gravity retaining walls at the coastline had collapsed or were tilted by the tsunami. Damage to RC bridges and RC retaining walls was not severe.
- Damage to the water and electricity supply in the moderately affected areas of Thailand visited by EEFIT (mostly in Phuket Island) was not extensive and supplies resumed within a few days. In the devastated areas (Khao Lak and Phi Phi Island) damage was severe and complete recovery will take significantly longer.
- Water towers were used extensively in low-lying areas and in most cases performed very well because of their inherent design characteristics (i.e. slender stilts without infill allowing the free flow of the tsunami waters). This would suggest that in areas where the wave height did not exceed 2.5 metres, buildings on stilts might have survived better (something observed in the case of a school building in Kamala beach, Phuket). It should be noted however; that when the tsunami overtopped the stilted structure, these structures often performed poorly. This and the soft-storey effect in the case of severe earthquake shaking should be taken into account during the design process.

Human and Economic Cost

This disaster is one of the most tragic in history. The latest statistics quote 176,706 people lost their lives, 51,168 people were missing and 1,810,035 people were internally displaced in 12 countries. In addition to the human cost, the tsunami has also inflicted a high economic cost on the countries involved.

In Sri Lanka the most affected industries were that of fishing and tourism. The fishery sector accounted for 2.4% of the GDP in the year 2004. The sector provides direct employment to about 142,500 active fishermen and about another 200,000 indirectly (Asian Development Bank, 2005). The death toll among fishermen was 7,222 with largest fatalities in Mullaitivu (2,524), Batticaloa (1,229) and Ampara (1,025) districts (Department of Fisheries and Aquatic Resources, 2005). In addition to damage reported to fishing harbours and landings about 65% (19,110) of the country's fishing fleet of 29,700 boats was either fully destroyed or damaged to varying degrees. The substantial damage to the fishing fleet would affect the output in 2005 and 2006, which is expected to lead to a loss of US$200 million.

The tourism sector in Sri Lanka accounted for 2.0% of the GDP in 2004 providing employment to about 115,000 people (50,000 direct and 65,000 indirect). Of the 246 hotels countrywide, 109 are located along the coastal areas (Source: Sri Lanka Tourist Board). The number of hotels closed as of January 12, 2005 was 52, which accounts for 47% of the coastal hotels (21% of the hotels countrywide). Tourist arrivals are expected to fall in the aftermath of the tsunami to about 425,000 in 2005 resulting in an output loss of US$130 million through to 2006. Although the economic impact on Sri Lanka was considered to be minimal, the tsunami has raised the vulnerability of the coastal population to poverty given the loss of employment and the means of generating an income.

In Thailand, the hardest hit industry is that of tourism. Even though most hotels may be insured for structural and contents damage and the industry is expected to recover within a few months in Phuket there has still been a large impact on tourism. In Khao Lak and Phi Phi Island, recovery is expected to take much longer and near shore developments may be controlled. The Tourism Authority of Thailand suggests that the affected provinces stand to lose more than US$1 billion in tourism revenue in the first quarter of 2005. The provinces of Phuket, Krabi and Phang Nga were expected to generate 3 billion US$ worth of tourism income to the Thai economy prior to the disaster, but in the first month after the tsunami tourist arrivals were down 88% compared to the previous year. The Thai government estimate losses to the business sector at nearly 390 million US$ but this estimate excludes losses to more than 250 affected hotels.

The fishing industry was also heavily affected in Thailand. An assessment conducted in the first week of January 2005 by the United Nations Development Program (UNDP), the World Bank and the Food and Agriculture Organization (FAO) found that more than 300 coastal settlements were affected by the tsunami with 47 fishing villages being badly damaged and 182 moderately damaged. In total it is estimated that 3,402 small fishing boats and nearly 1,127 large fishing trawlers were destroyed or were seriously damaged. To this estimate a further 3,000 smaller boats were added in late April 2005 (these were apparently unregistered boats). Furthermore, several thousand fishing cages were destroyed, impeding the capture of grouper and sea bass that are especially lucrative for the local fishermen.

Recommendations

From the observations in the field and further research, a number of recommendations can be made. These have been grouped into three areas, namely:

1) understanding of tsunami hazard,
2) preparedness to tsunami risk and urban planning
3) structural design criteria in areas of tsunami risk

Understanding of the tsunami hazard

- Features of the tsunami propagation in the Indian Ocean need to be reassessed.
- Research is required to better understand the effects of bathymetry on the magnitude of tsunami intensity.
- Research is required to better understand the effects of local topography on the variation of damage from tsunami inundation.
- Tsunami hazard on Indian Ocean coastlines needs to be quantified and mapped

Preparedness to tsunami risk and urban planning

- Tsunami risk needs to be better understood and appropriate planning guidelines, tailored to the conditions and needs of each affected region, need to be drawn up.
- Coastal lifelines should be protected from the effects of tsunami, or should have redundancy provided by inland systems.
- A programme of tsunami preparedness needs to be implemented in Indian Ocean communities (including a tsunami early warning system and education programme).
- In areas of high tsunami risk, evacuation routes and maps need to be established and disseminated.
- Wherever possible, essential facilities (such as hospitals) should not be located on the coast.
- Future developments near to the shore should take into account tsunami hazard.
- Existing coastal settlements that have been devastated by the tsunami but are very strongly dependent on fishing activities may have to be replaced with houses that offer better protection. In addition, provision of nearby refuges such as that used in Bangladesh to protect coastal population from storm surges would be advisable.
- Principles of environmental sustainability can reduce the level of tsunami hazard. Policies related to mangrove reforestation, coral reef protection and improved fishing practices are among those that can have a mitigative effect.

Structural design criteria in areas of tsunami risk

- Structural designers need to better understand the nature of damage from tsunami , and establish minimum specifications for building and infrastructure in the larger context of other tsunami protection measures, such as evacuation strategies.
- Construction of single storey family dwellings, often of masonry construction, should be designed to larger horizontal loads. Though not offering life safety under large inundations, buildings whose structure has survived the tsunami can be reoccupied sooner, hence reducing the strain on the reconstruction effort. Cost effective improvements to traditional construction techniques should be developed and disseminated.
- Construction of RC framed buildings, whose upper storeys might offer protection from the inundation, should be designed to withstand the impact of water and debris, without causing incremental collapse of the structure. This requires a review of the detailing of beam to column connections and additional stiffening of the framing system, with either reinforced concrete shear walls or well detailed masonry infill panels placed perpendicular to the coast. It also requires that a minimum specification for masonry infill panel be developed for walls parallel to the coast.
- For engineered structures, in areas of high hazard, a minimum dimension of 300mm for columns be specified, and the placement of reinforced concrete shear walls perpendicular to the beach also be specified.
- Piles are recommended for use in areas of high tsunami hazard, especially for structures founded on loose sand.
- In regions of high tsunami hazard, the robustness of coastal lifelines should be considered.
- In regions of high tsunami hazard, the scour protection of the abutments of near coastal bridges should be considered.
- In regions of high tsunami hazard, the protection to services crossing near coastal rivers should be considered.
- The resistance of toughened glass to water pressure, and debris damage is investigated, with a view of determining if specifying toughened glass for seaward facing windows would increase life-safety.
- That all buildings within the expected inundation zone have landward facing egress and easy access to higher floors or roofs.

Acknowledgements

Any visit to a disaster zone is a challenging experience and this mission was no different. The team members would like to thank the following people and organizations for their support to the mission.

Engineering and Physical Sciences Research Council (EPSRC) for providing the funding for the academic members of the party.

Risk Management Solutions, Arup, Buro Happold, Halcrow, University of Newcastle, University College London.

Halcrow (Sri Lanka) and in particular Dennis Knight for their support to the Sri Lankan leg of the mission.

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