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Experience of the Indian Ocean Tsunami on the Sri Lankan coast

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ABSTRACT: The Indian Ocean Tsunami devastated the coastline of Sri Lanka. This paper summarises the initial efforts in understanding the tsunami wave and its hydraulic impact on the Sri Lankan coastline. It focuses attention on the hydraulic processes which led to large scale inundation, analysis of wave- current measurements recorded offshore of Colombo Harbour and describes post tsunami field investigations to assess the overall impact on the coastline. The paper identifies the need for modeling of potential tsunamis and discusses briefly issues relating to the planning of countermeasures.

1. INTRODUCTION

On 26th December 2004 the Sri Lankan coastline witnessed the devastating impact of a tsunami, hereafter to referred as the Indian Ocean Tsunami, which arose from a massive submarine earthquake 400 km west of northern Sumatra. The earthquake measured 9 on the Richter Scale and the fault length exceeded 1000km. The entire coastline with the exception of parts of the north-western coastline was severely affected. The previous tsunami to have affected Sri Lanka was on 27th August 1883, arising from the eruption of the volcanic island of Krakatoa. On that occasion, unusually high water levels were observed in several areas along the eastern and southern coastline with hardly any damage.

One of the important observations of the Indian Ocean Tsunami was that areas in the southern and western provinces that were in the shadow of the direct impact of the tsunami waves were severely affected. This led to the investigations of understanding the propagation of the tsunami wave. This paper describes important hydraulic characteristics of the tsunami wave and identifies the processes that led to the devastating impacts. It also focuses on planning of countermeasures and identifies physical interventions both artificial and natural that could be adopted.

2. UNDERSTANDING THE TSUNAMI WAVE

The tsunami wave is best understood by studying the important stages of its path from generation to the final phase of inland dissipation. The important stages are,

- Generation
  - -Geo disturbance
  - -Tsunami source
  - -Initial dissipation
- Deep-water propagation
- Interaction with the Continental Shelf
- Near-shore Transformations
  - -Reduced depth
  - -Combined influence of coastal processes
  - -Shoreline geometry
- Shoreline entry
- Inland Dissipation

3. GENERATION OF TSUNAMIS AND THE INITIAL TSUNAMI SOURCE

Tsunamis are primarily generated as a result of submarine earthquakes, volcanic eruptions and landslides moving into the oceans. Underwater explosions, for example, arising from test blasts can also generate tsunamis.

These phenomena cause the surrounding ocean to bulge and then spread out in a series of waves. In the case of tsunamis generated by earthquakes, the waves spread from the epicenter of the earthquake which causes the seabed to shift.

On account of their relative infrequency of occurrence and unpredictability much remains to be understood of the hydraulics of tsunamis. It is difficult to correlate the strengths of the earthquake and the tsunami. Estimation of the wave height at the center of the seismic disturbance is an equally difficult task.

Researchers from Japan, a country that has witnessed near and far field tsunamis, have made a significant contribution in understanding and quantifying key processes relating to the generation, tsunami source, initial dissipation and the propagation of the wave. In areas subject to tsunamis statistical data on their frequency, magnitude and impact have been collected and analyzed leading to graphical and empirical relationships among key parameters (1). Although these relationships cannot be directly applicable to other situations, it provides valuable information on the scientific basis of the quantification process, understanding of the relationships and initial estimates of key parameters.

In the case of tsunamis generated by submarine earthquakes, there has been a continuous demand to relate the strengths of the tsunami and the earthquake. The magnitude of an earthquake ***"M"*** is defined by the Richter Scale. The strength of the tsunami cannot be easily defined. Several classifications have been presented by researchers. Table 1 illustrates the classification of the strength of the tsunami expressed as a magnitude ***"m"*** (1).

Table 1: Tsunami Classification (1)

Tsunami Magnitude ***m***	Tsunami height ***H***	Damage
-1	50 cm	None
0	1 m	Very small damage
1	2 m	Coastal and ship damage
2	4 m ~ 6 m	Damage and lives lost in certain land-ward areas
3	10 m ~ 20 m	Considerable damage along more than 400 km of coastline
4	30 m	Considerable damage along more than 500 km of coastline

A linear correlation has been introduced between m and M based on available statistical data, leading to

$$m = 2.61M - 18.44 \tag{1}$$

Accordingly an earthquake of the order of $M < 6.5$ may not generate any notable tsunami. After the major earthquake on the 26th morning, in the following 24 hours there were 10 more earthquakes which recorded more than 6 on the Richter Scale, the highest being 7. These did not generate tsunami waves. Neither did the massive earthquake which took place on the 28th of March 2005, measuring 8.5 on the Richter Scale generate a tsunami.

It is recognized that the type of displacement arising from an earthquake is also important in its contribution to the formation of the tsunami. Vertical displacement of the seafloor is of primary importance for the generation of tsunamis. Usually the strike-slip motion free of vertical displacement is not a great threat. Some earthquakes tend to rupture the shallowest part of the interplate thrust near the trench, leading to tsunamis of greater strength than that is usually generated from an earthquake. However the Indian Ocean Tsunami is consistent with the size of tsunamis generated by other earthquakes of similar magnitude. It is also accepted that if the epicenter of the earthquake is shallow the magnitude of the tsunami generated is greater.

Mathematical modeling of the areas of tsunami origin has established that the shape of such regions is approximately an ellipse. This was based on historical information on earthquakes as well as recent tsunamis. The long and short axes '*a*' and '*b*' of the aftershock has been determined and related to the strength of the earthquake. This is a very important parameter because it represents the direct linkage between the fault length and the area of the ocean surface that becomes the source of the tsunami. It is argued that the orientation of the main axis of that ellipse plays a vital role in the direction of propagation of the tsunami. This is also very useful in detecting the overall extent of potential coastline subject to the tsunami impact.

It has been estimated that the Indian Ocean Tsunami had an initial tsunami intensity of around 5m going up to around 25m in some areas within the source. It is evident that the fault line and the resulting major axis of the ‘tsunami source ellipse’ were more or less parallel to the north south axis of Sri Lanka thus impacting directly on the eastern and south-eastern coastline.

4. DEEP-WATER PROPAGATION

The tsunami which devastated Sri Lanka travelled over 1400 km through the open ocean waters. In this process they can reach over 200 km in wavelength. However their height may be limited to comparatively small values of the order of 1.0 m in deepwater. The waves themselves move very fast with speeds of propagation (celerity, c) exceeding 800 km/hour (222 m/sec). The periods of tsunamis are generally in the order of several minutes to an hour. The period of the tsunami witnessed in Sri Lanka was of the order of 20-30 minutes and the maximum height in the deep water was around 0.6m to 0.8m. In this process they have the ability to propagate in deep water at very high speeds over thousands of miles without being detected.

The wave height at any point of a propagating tsunami is related to its distance from the origin, the energy content and area of the initial disturbance, and to energy losses in transit which are generally small except in the immediate locality of the disturbance.

Even in the open ocean the ratio of depth (d) to wavelength (L) is such that tsunami travels as a ‘shallow water wave’ $\left(d/L < 1/20 \right)$. Speed (c) of such waves are governed by the depth of ocean over which it passes and is estimated by

$$c = \sqrt{gd} \qquad (2)$$

5. INTERACTION WITH THE CONTINENTAL SHELF

On moving towards land the wave first interacts with the continental shelf during which process the initial transformation takes place. Depending on the physical characteristics of this shelf part of the energy is reflected and the rest is transmitted towards land. High reflections will reduce the energy transmitted. Sri Lanka has a very narrow continental shelf with a sudden drop of levels of the order of 150-200m to 3000m. Larger portion of the incoming wave energy may have been reflected from this near vertical continental shelf. The wave energy that transmitted over the shelf came directly towards land as the Sri Lankan continental shelf is not wide enough to contribute towards significant energy dissipation. Discontinuities in the shelf may cause problems as witnessed at the southern tip of the country. Waves diffracting around the southern parts of the island were further transformed by the complex wave patterns arising from these discontinuities leading to greater impacts (Figure 1).

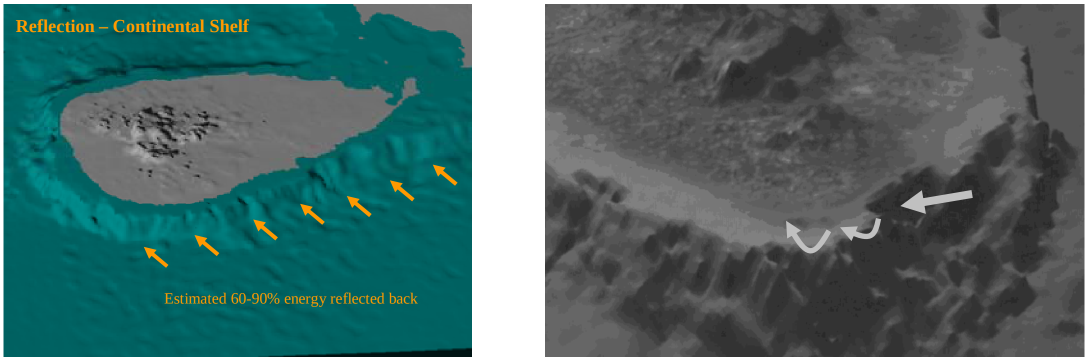

Figure 1: Reflection and Transformation from the Continental Shelf

6. NEAR-SHORE TRANSFORMATIONS

On reaching shallow water, the speed of the wave reduces but the energy in the wave remains the same due to minimum energy losses, thus increasing the wave height very rapidly and crashing inland with devastating power and destruction. It is very important to recognize that combined action of near-shore processes and local geomorphologic features influence the degree of the final impact at a given location.

In this respect the wave height prior to the entry to the shoreline is further increased by the combined influence of near-shore coastal transformation processes of refraction, diffraction, reflection, and energy concentration due to reduced crest width within bays. The near-shore transformation processes are greatly influenced by the shape of the coastline, geomorphologic features and bottom bathymetry. Depending on these features some coastal areas are more vulnerable than others against tsunamis.

The following equation provides the basic relationship between the wave heights *(H)*, depth *(h)* and bay width *(b).*

$$H \;\alpha\; b^{1/2} h^{1/4} \qquad (3)$$

From detailed studies of the tsunami wave witnessed around the island it was clearly evident that near-shore transformation processes and shoreline geometry increased the wave heights along many parts of the southern and western province which would have normally received only diffracted waves. The impacts of the combined transformation processes and the shoreline geometry contributed very heavily to the unexpected devastation at certain locations along the south west coast. The inland topography and lack of drainage facilities further enhanced the problem. Figure 2 illustrates the typical transformation processes which were effective around the island.

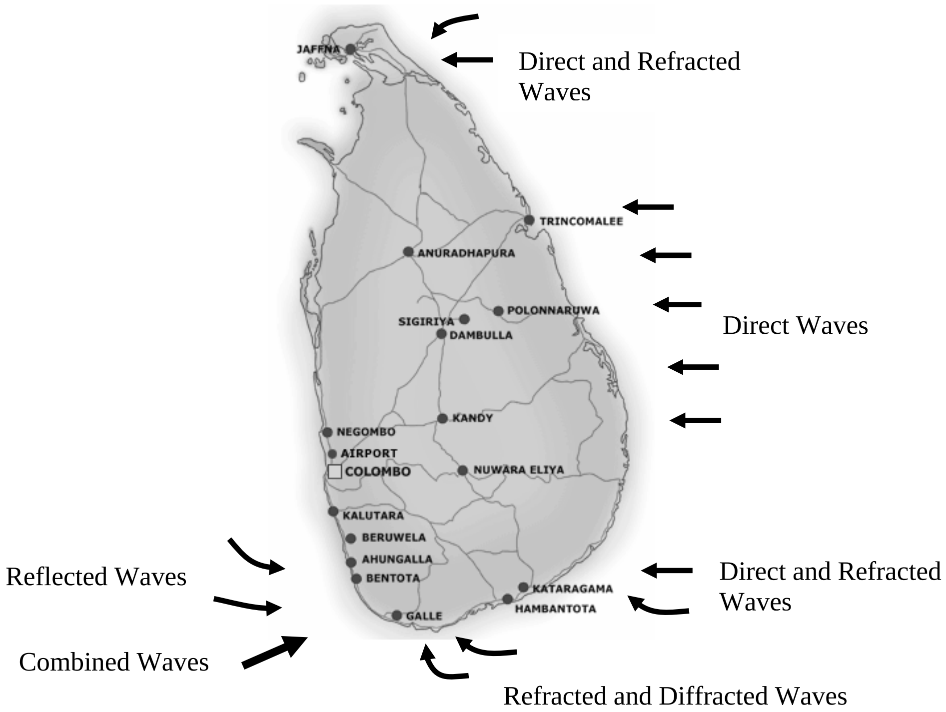

Figure 2: Coastal Processes around Sri Lanka

7. FIELD INVESTIGATIONS

Field investigations were conducted by the University of Moratuwa in collaboration with international researchers and independently, in order to assess the hydraulic impact of the tsunami wave along the affected coastal areas. Of particular interest were the inundation heights, intrusion lengths, performance of coast protection works and harbours and response of coastal eco-systems. The tsunami strikes in a series of waves whose magnitude can vary and the first wave need not be the largest in the series, as observed globally. On many occasions the second was the largest along the Sri Lankan coastline. Figure 3 illustrates the observed highest wave heights around the island.

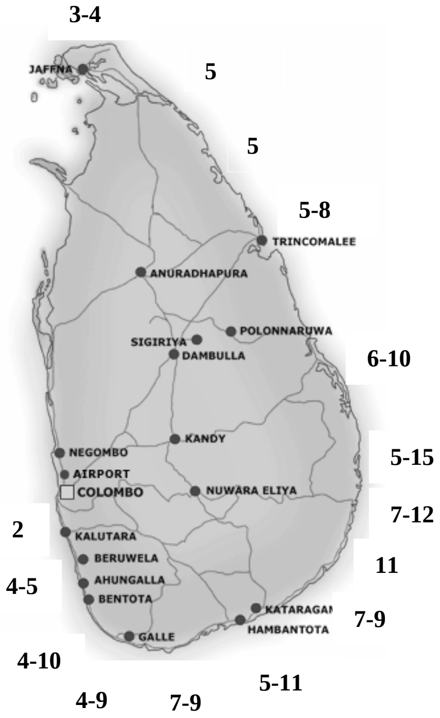

Figure 3: Testified Tsunami wave heights in meters

8. MONITORING THE TSUNAMI WAVE

Two instruments located on the western coastal waters captured the tsunami wave. The first instrument was the tide gauge of the National Aquatic Research Agency (NARA) located in the Colombo Fishery harbour that measured the water level variations. The second instrument was the S4 wave-current meter deployed by Lanka Hydraulic Institute (LHI) at 15m depth, offshore of the Colombo Port. The LHI instrument measured the water level variation, pressure variation and the magnitude and direction of the bed current leading to extensive data bank. Figure 4 gives the water level variation indicating the arrival of the tsunami. The figure also illustrates the superimposition of the tsunami wave on tide. Figure 5 gives the pressure variation for a twenty minutes period, illustrating the superimposition of wind waves on the tsunami wave. Figure 6 gives the direction of current near the bed. The influence of the tsunami wave was captured well illustrating the change of direction of the currents from alongshore to on-offshore. The magnitude and the direction of the currents heavily influenced the movement of sediments and debris along the seabed. This movement caused severe negative environmental impacts along the path of the tsunami wave.

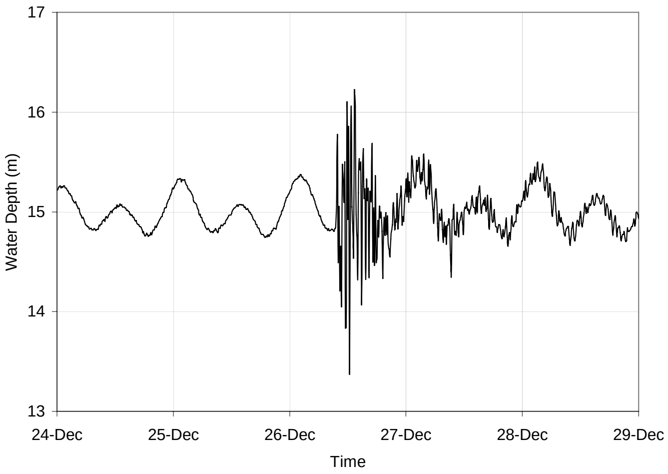

Figure 4: Water level variation showing the arrival of tsunami and the tsunami acting on the tide (LHI data)

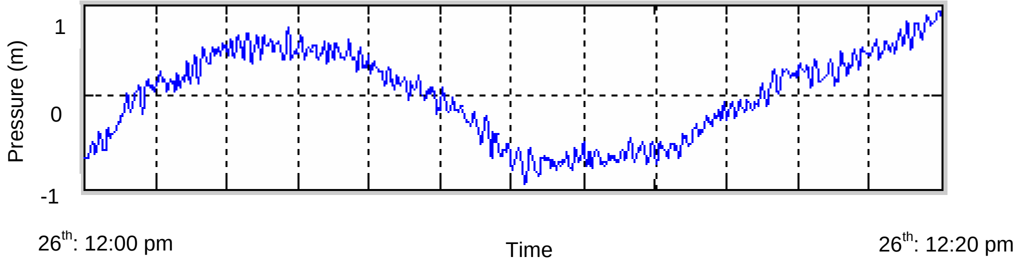

Figure 5: Pressure variation showing the wind waves acting on the tsunami (LHI data)

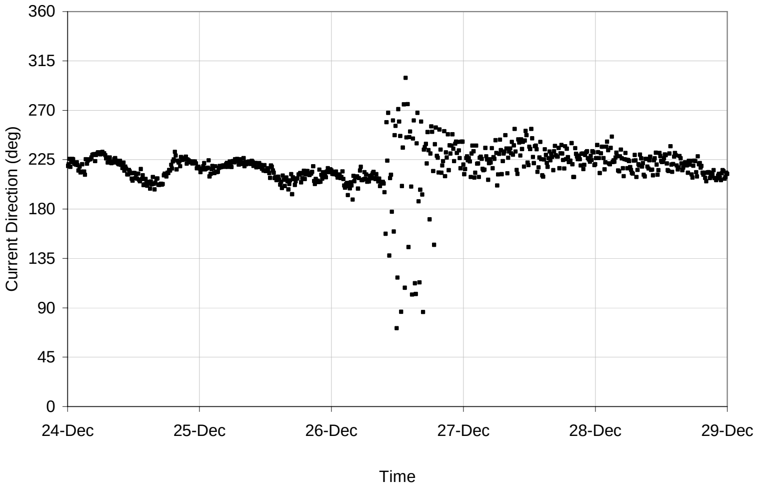

Figure 6: Current direction showing the directional change from alongshore to on-offshore (LHI data)

9. MODELING OF TSUNAMI WAVES

Tsunamis that occurred previously have been modeled successfully providing an insight to their hydraulic impact (2). Several research organisations have also modeled the impact on Sri Lanka of the Indian Ocean Tsunami. In the absence of near-shore bathymetric data the models have not covered areas closer to the shoreline. In effect the near-shore transformation processes and interactions which amplified the wave have not been incorporated. This is reflected in the comparison between the modeling results and field data which indicates poor agreement on the south western regions in which the combined transformation processes were very active.

The results from modeling have provided a reasonable understanding of the propagation of the tsunami in deep water. The fault length leading to the Indian Ocean Tsunami comprised approximately three components of 330 km (southern), 570 km (central) and 300 km (northern) having different orientation. Preliminary modeling carried out by Tohoku University, Japan, on potential tsunamis generated by the three components clearly illustrate that the tsunamis generated by the northern and central components have devastating impacts on Sri Lanka. It is a point of interest that the fault length of the earthquake which took place on the 28th March 2005 was south of the southern component of the earthquake which generated the Indian Ocean Tsunami in December 2004.

In order to understand the impact of potential tsunamis, there is a need to simulate a range of possible scenarios incorporating the combined influence of near-shore transformation processes. This could only be achieved by having near-shore bathymetric data and coastal zone topography data covering the island. Results from modeling will provide a clear understanding of the hydraulic impact of the tsunami wave and the modeling could be extended to cover inland dissipation. The distribution of the inundation water levels, length of intrusion and run-up will provide useful information for coastal zone planning (3,4).

10. PLANNING COUNTERMEASURES

It is important that post disaster planning should be undertaken in the context of overall coastal hazards one of which remains tsunamis, however remote the chances of a very extreme event taking place. In particular, when planning for reconstruction it is important to assess scientifically the basis and criteria on which such an exercise is undertaken. Planning based on observations arising from a single extreme event without scientifically analyzing the true character of its impacts and future threats and risks should be avoided.

In the post tsunami scenario, some of the issues which need to be investigated are,

1. To conduct detailed bathymetric surveys of near-shore areas and topographical surveys of the inland coastal zone covering several kilometers.
2. To assess the bathymetric changes that have taken place in the near-shore areas arising from the tsunami, and to investigate the resulting impacts on other coastal hazards such as storm wave attack, coastal erosion and long term phenomena such as sea level rise.
3. To identify potential regions in the Indian Ocean which could generate submarine earthquakes leading to tsunami waves that will reach Sri Lanka, to assess the probability of occurrence and probable locations of such potential earthquakes.
4. To numerically model potential tsunami scenarios to understand the hydraulic impact on the coastal regions, as identified previously.
5. To understand the vulnerability of our coastline against tsunamis and other coastal hazards.

The above investigations will enable the formulations of policy and management options that reflect a strategic approach for achieving long term stability for sustaining multiple uses of the coastal zone giving due consideration to the threats and risks of hazards.

There are many counter measures that could be adopted in coastal zone management, when planning for a tsunami and other coastal hazards that accompany high waves and high inundation. These include physical interventions such as protection structures and regulatory interventions in the form of extension of the existing ‘setback’ defence line. These have to be supplemented with efficient evacuation procedures, incorporating, if necessary, planned evacuation routes and structures that effectively integrate with the overall planning process.

It the above context three types of physical interventions are identified depending on their location and function in protecting the coast. These interventions may be achieved not only by artificial methods via Coastal Engineering Design but also by harnessing the full potential of natural coastal ecosystems. The types of interventions and typical examples for each category are listed below.

(i) Reduce the impacts of tsunami waves prior to reaching the shoreline.
(eg. Tsunami Breakwaters, Coral Reefs)

(ii) Protect the coastal zone by preventing the inland movement of tsunami waves.
(*eg. Tsunami Dike, Sand Dunes*)

(iii) Mitigate the severe impacts of tsunami waves on entry to the shoreline.
(*eg. Tsunami Dikes, Revetment, Mangrove Forests*)

On many occasions both methods can be adopted in parallel to develop hybrid solutions satisfying environmental concerns.

11. ACKNOWLEDGEMENTS

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