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Strategic Planning for Post Tsunami Rehabilitation and Conservation of the Sri Lankan Coastline

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Introduction

On 26th December 2004 the Sri Lankan coastline was devastated by the Indian Ocean Tsunami (IOT), which was caused by a massive submarine earthquake 400 km west of northern Sumatra. The Sri Lankan coastline with the exception of parts of the north-western coastline was severely affected. It is important to note that areas in the southern and western provinces that were in the shadow of the direct impact of the tsunami waves were also severely affected. This led to investigations to understand the full impact of the tsunami waves on the Sri Lankan coastline. On 28th March 2005, another tsunami was generated by an earthquake which took place south of the previous fault line. The tsunami which was not as strong as the IOT travelled south of Sri Lanka recording higher water levels in the south east quarter but without overtopping.

The previous tsunami to affect Sri Lanka prior to the IOT was on 27th August 1883, arising from the eruption of the volcanic island of Krakatoa. On that occasion, unusually high water levels with mild overtopping were observed in several areas along the eastern and southern coastline, but hardly any damage was caused.

Approach to the Study

The paper describes important hydraulic characteristics and processes which led to the devastating impacts on the Sri Lankan coastline, following which a strategic approach towards post tsunami rehabilitation and conservation of the coastline is presented. It focuses on planning countermeasures and identifies physical interventions both artificial and natural that could be adopted. The said strategic approach is achieved by conducting a series of investigative studies, both field and computational work within an overall framework of risk assessment which gave due consideration to all hazards, natural and man made encountered in the coastal zone. The said approach primarily achieves disaster risk reduction for which a clear understanding of hazards, exposure and vulnerability is essential. The Sri Lankan coastline has been subjected to flooding, storm attack and coastal erosion, extreme weather related events such as cyclones. In view of the close proximity of the international shipping routes the coastline is also at risk from oil spills.

A principal area of the investigative studies is the assessment of the hydraulic impact of the tsunami waves. This was achieved by adopting a three pronged approach, namely assessing the physical impact, understanding the different phases of the tsunami wave propagation from generation to inundation and the prediction of impact by the use of numerical models to simulate tsunami events which have occurred and potential events.

The physical impact was assessed by monitoring the tsunami wave where possible, conducting field investigations and making use of satellite images before, during and after the tsunami. The field investigations include the study of tsunami wave, its dissipation and resulting consequences (tsunami wave heights, inundation lengths and tsunami deposits), impact on coast protection works, harbours, housing, infrastructure and ecosystems.

The tsunami hazard and exposure could be understood *via* scenario modeling of tsunami waves and considerable field investigations are required to assess the vulnerability in the socio- economic context.

Assessing the Hydraulic Impact

Monitoring of the Tsunami Wave

Two instruments located on the western coastal waters recorded 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 the 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 an extensive data bank. The magnitude and the direction of the currents greatly influenced the movement of sediments and debris along the seabed. This movement caused severe negative environmental impacts along the path of the tsunami wave.

Field Investigations

Field investigations were conducted by the University of Moratuwa in collaboration with international researchers and independently, in order to assess the impact of the tsunami wave along the affected coastal areas. Of particular interest were the inundation heights, intrusion lengths, tsunami deposits performance of near-shore and onshore infrastructure and coastal eco-systems. A 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 wave was the largest along the Sri Lankan coastline**.** Figure 1 illustrates the observed highest wave heights around the island.

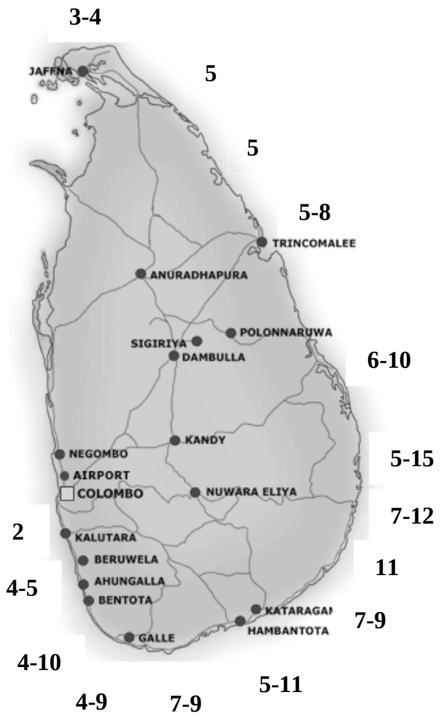

Figure 1: Testified tsunami wave heights in meters

Different Phases of Tsunami Wave Propagation

The principal phases of the tsunami wave from generation to inland dissipation are listed below. It is important to understand the physics of the phenomenon associated with each stage.

- 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

Mathematical modeling is widely used to simulate tsunami wave propagation. Deep water modeling is used until the interaction with the continental shelf and thereafter near-shore and inundation modeling are used. The latter is challenging in view of data requirements and simulation of rather complex phenomena.

Initial Tsunami Source

The type of displacement arising from an earthquake is an important parameter with respect to the initial tsunami source and the generation of the tsunami. In particular the vertical displacement of the seafloor is of primary importance for the generation of tsunamis. Usually a 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 ones that are usually generated from an earthquake. However the IOT 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 (1). This concept is very important because it represents a direct linkage between the fault length and the area of the ocean surface that becomes the source of the tsunami. The orientation of the main axis of that ellipse may play a vital role in the direction of propagation of the tsunami. This is also very useful in detecting the exposure of a given coastline to the potential tsunami impact.

The earthquake which generated the IOT measured 9 on the Richter Scale and the fault length exceeded 1000km. It has been estimated that the 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. The eastern and south-eastern coastline was directly exposed to the tsunami hazard.

Deep Water Propagation

The IOT travelled over 1400 km through the open ocean waters prior to its impact on the Sri Lankan coastline. The waves themselves move very fast with speeds of propagation (celerity, *c*) exceeding 800 km/hour (222 m/sec) and reaching 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 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.

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.

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 reduce the energy transmitted. Sri Lanka has a very narrow continental shelf with a drop of levels of the order of 150-200m to 3000m. A reasonable portion of the incoming wave energy may have been reflected from the continental shelf. The wave energy that transmitted over the shelf came directly towards land as the Sri Lankan continental shelf is insufficiently wide to contribute towards significant energy dissipation. Discontinuities in the shelf, as present at the southern tip of the country, may have contributed to interactions leading to complex wave patterns. Waves diffracting around the southern parts of the island were further transformed by such formations affecting the south-west quarter of the country and leading to greater impacts (Figure 2).

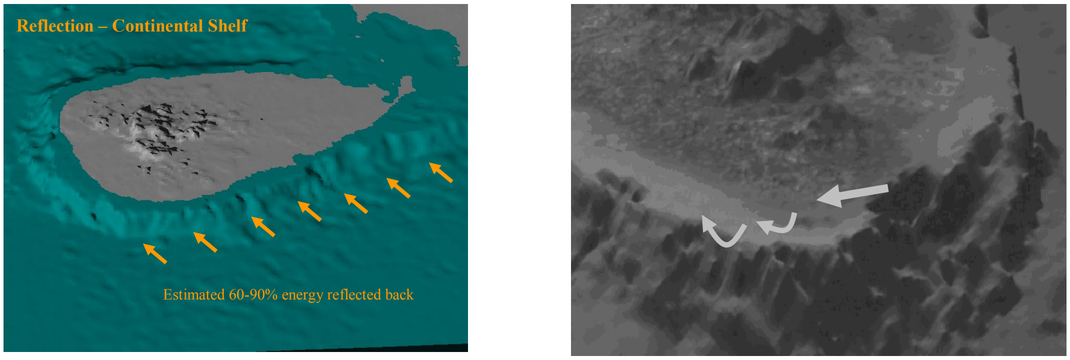

Figure 2: Reflection and transformation due to the continental shelf

Nearshore Transformations

On reaching shallow water, the speed of the wave reduces but the energy in the wave remains the same due to minimum energy loss, thus increasing the wave height very rapidly and crashing inland with devastating power and destruction. It is very important to recognize that the 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 the 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 have greater exposure than others to tsunamis.
The following equation provides the basic relationship between the wave heights *(H)*, depth *(h)* and bay width *(b)*.

$$H \ \alpha \ b^{1/2} h^{1/4} \qquad \text{--------}$$

(1)

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 greatly contributed to the unexpected devastation at certain locations along the south-west coast. Of particular interest was the enhanced wave heights observed at cities located along bays and around headlands. The inland topography and lack of drainage facilities worsened the impact. Figure 3 illustrates typical transformation processes around the island.

The high velocities of the tsunami wave caused considerable erosion of the sea bed. The eroded material were deposited in inland areas or transported to the deep ocean with the ebb velocities. Investigations conducted by Tohoku University in the deep south indicate that near-shore erosion in certain areas was of the order of 3-5 m. The erosion of near-shore areas have also resulted in wave breaking closer to the shoreline than before leading to increased coastal erosion and also causing a sense of fear among the coastal population.

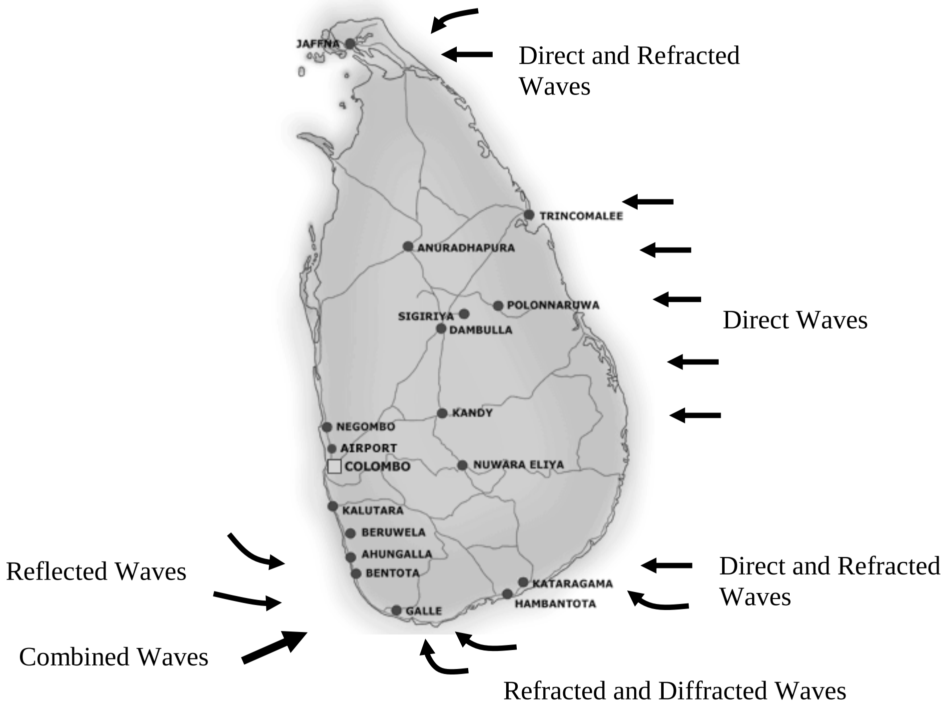

Figure 3: Coastal processes around Sri Lanka

Modelling of Tsunami Waves

Numerical simulation of tsunamis was carried out for understanding the exposure to the hazard, investigating the impact of tsunamis which have occurred, simulation of potential tsunamis for scenario modeling and for identifying locations for tsunami detecting equipment. Numerical modelling has been widely used before and provides a good understanding of the relevant processes and impacts (2).

Several research organizations have also modeled the impact of the IOT on the Sri Lankan coastline. In the absence of near-shore bathymetric and topographical data the output of the models have limitations. In effect the near-shore transformation processes and interactions that amplified the wave have not been incorporated. This is reflected in the comparison between the modeling results and the field data which indicates poor agreement with the south western regions in which the combined transformation processes were very active. In order to conduct inundation modeling it is also necessary to include hydraulic characteristics of the built environment and other phenomena such as jetting when waves travel through confined spaces. In spite of these limitations, preliminary inundation modelling provides reasonable predictions on inundation.

The results from modeling provide a reasonable understanding of the propagation of the tsunami in deep water and on the exposure of the island to the hazard. The fault length leading to the IOT comprised approximately three components of 330 km (southern), 570 km (central) and 300 km (northern) having different orientations. 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 will have devastating impacts on Sri Lanka. The fault length of the earthquake that took place on 28th March 2005 was south of the southern component of the earthquake that 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 can 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).

It is equally important to conduct probabilistic tsunami hazard analysis which provides comprehensive and consistent ways to quantify the hazard posed by tsunamis (5).

Rehabilitation and Conservation of the Coastline

Multi Hazard Risk Assessment

Planning post tsunami rehabilitation and conservation of the Sri Lankan coastline should be undertaken within a multi hazard coastal risk assessment framework giving due consideration to all the coastal hazards.

Risk is usually expressed by the notation Risk = Hazard x Vulnerability. In this expression hazard includes exposure. Risk represents the probability of harmful consequences or expected losses (in terms of deaths, injuries, property, livelihoods, economic activity disrupted or environment affected) arising from interactions between natural or human hazards and vulnerable conditions. Vulnerability can be broadly classified into several components including, structural, functional, economic, social, cultural and psychological vulnerability. Prior to the IOT, Sri Lanka had not adopted a planned approach towards preparedness in relation to disasters, an aspect which is considered vital in saving lives. Hence the notation Risk = Hazard x Vulnerability x Deficiencies in Preparedness seems more appropriate. The additional term represents certain of measures and tasks the absence of which could reduce the loss of human lives and property in the specific interval of time during which the event is taking place (6).

In particular, when planning post tsunami rehabilitation and conservation of the coastline 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 potential events, their impacts and future threats and risks should be avoided.

In the light of the investigations carried out, the following long term investigations should be implemented.

1. Conducting detailed bathymetric surveys of near-shore areas and topographical surveys of the inland coastal zone covering several kilometers. With the assistance of the Italian Government LIDAR Surveys of the landward side of the coastal zone have been duly completed.
2. Assessing the bathymetric changes that have taken place in the near-shore areas arising from the tsunami and investigating the resulting impacts on other coastal hazards such as storm wave attack, coastal erosion and long term phenomena such as sea level rise.
3. Identifying potential regions in the Indian Ocean that could generate submarine earthquakes leading to tsunami waves that would reach Sri Lanka, to assess the probability of occurrence and probable locations of such potential earthquakes.
4. Implement probabilistic tsunami hazard analysis to understand the threat posed by the tsunami hazard.
5. Numerically model potential tsunami scenarios to understand the exposure of the island, the full hydraulic impact on the coastal regions, including wave heights, inundation, velocity regimes, etc.
6. Assess the overall vulnerability of the coastal zone
7. Implementing Tsunami Risk Assessment within a multi hazard framework.

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

Counter Measures

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 early warning systems, regulatory interventions in the form of extending existing setback defense line and physical interventions such as protection structures and utilizing the full potential of coastal ecosystems. These have to be supplemented with efficient evacuation procedures, incorporating planned evacuation routes and structures that effectively integrate with the overall planning process.

In this respect the counter measures can be broadly classified into two categories and the respective measures are listed below.

- Counter measures that promote successful evacuation from tsunami
    1. Early Warning Systems
    2. Public Warning Systems
    3. Hazard Maps for Vulnerability
    4. Set Back defense line
    5. Evacuation Routes and Structures

- Counter measures that mitigate the impact of tsunami
    1. The implementation of artificial measures for protection including tsunami breakwaters, dikes and revetments
    2. The effective use of natural coastal ecosystems including Coral Reefs, Sand Dunes and Coastal Vegetation (Mangrove Forests)
    3. Tsunami Resistant Buildings and Infrastructure

Physical Interventions (Artificial and Natural)

In 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.

1. Reduce the impacts of tsunami waves prior to reaching the shoreline
   (eg. Tsunami Breakwaters, Coral Reefs)
2. Protect the coastal zone by preventing the inland movement of tsunami waves
   (*eg. Tsunami Dike; Sand Dunes*)
3. 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 well-integrated hybrid solutions satisfying environmental concerns.

Development of Guidelines for Tsunami Resistant Buildings

The coast is an area of high economic activity and it is not possible to transfer all activities to areas that are completely free from potential tsunami hazards. For some areas of the coast, safe evacuation areas may be too far away for citizens to reach on foot thus necessitating vertical evacuation structures. Therefore there is a need to develop Design Guidelines and Construction Manuals for tsunami resistant housing and infrastructure for the benefit of the public and wider usage.

In this respect two types of guidelines are required.

1. Overall Design Guidelines providing advice on location, layout, orientation, structural configuration, geo-technical considerations and other considerations relating to good design practice.
2. Detailed Design Guidelines leading to hydraulic and structural loads, geo-technical issues and detailed design information.

The Overall Design Guidelines could be developed from the experience gained from Damage Assessment from different parts of the country and such assessment should be analyzed in the context of the hydraulic regime which would have been generated by the tsunami at that location. Relevant information from other countries that have been affected by tsunamis will also be very useful for this exercise. It is important that Damage Assessment should cover infrastructure that was (i) Destroyed (ii) Damaged (iii) Survived (least affected).

Conclusions

This paper summarizes the important aspects relating to the hydraulic impact of the Indian Ocean Tsunami which devastated a major proportion of the Sri Lankan coastline, causing death and destruction. Of particular interest to Sri Lanka are the governing coastal processes which dominate the tsunami wave propagation, shoreline entry and inland dissipation. The paper presents a strategic approach for the rehabilitation and conservation of the coastline within a framework of multi-hazard risk assessment. Investigations which have been carried out have been summarized and those which have to be implemented have been identified.

The paper has identified the importance of probabilistic tsunami hazard analysis and scenario modelling in order to obtain a clear understanding of the hazard, exposure, vulnerability leading to risk assessment. The paper has focused on the planning of counter measures giving due recognition to the utilization of both natural and artificial methods, hybrid solutions and incorporating effective design guidelines for infrastructure development. In the case of Sri Lanka, tsunamis are associated as low frequency events with potential high impacts. In this respect it is economical to harness the full potential of natural methods for coast conservation and protection. The island-wide damage assessments also provided critical information on the effectiveness of such methods. Natural methods could be implemented successfully *via* a participatory approach, mobilising the community thereby improving their knowledge base on awareness and preparedness.

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