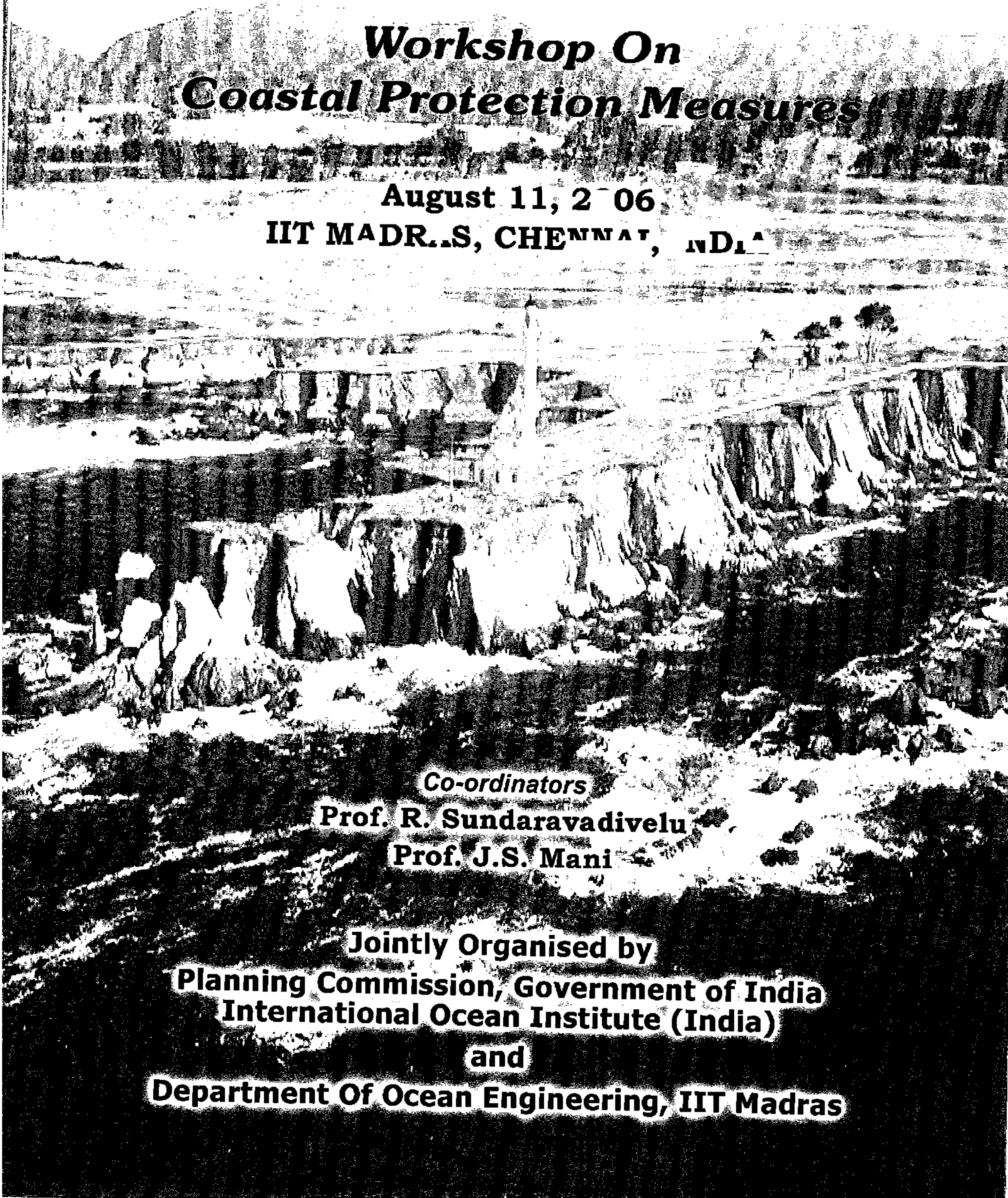
सत्यमेव जयते

Pacem in Maribus



Workshop On Coastal Protection Measures

August 11, 2006

IIT MADRAS, CHENNAI, INDIA

Co-ordinators

Prof. R. Sundaravadivelu

Prof. J.S. Mani

Jointly Organised by

Planning Commission, Government of India

International Ocean Institute (India)

and

Department Of Ocean Engineering, IIT Madras

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PREFACE

The Coastal protection works, planned and executed in the early 1960's concentrated mostly on the local requirements and the benefits were confined to a smaller region. However, as the concept of sustainable development gained momentum, the emphasis is towards broadening the benefits derived from the coastal protection measures. Extensive damage caused by the Indian Ocean Tsunami during Dec – 2004 to the coastal zone, has given additional importance to the coastal protection measures. In this direction conducting workshop on **"Coastal Protection Measures"** to discuss and share the experiences gained by various implementing agencies and academic Institutions was felt essential.

The Workshop would identity various means of Coastal Protection Measures, including benchmarking international Practices and a working group be formed with competent representatives from Planning Commission, Central Government Ministries, State Union Territory administration, Technical experts etc. The Workshop would identify various surveys and studies to be conducted for each of the coastal states for developing suitable protective measures. The workshop would also help in developing long-term relationships with International / Nation experts on the above subject.

The various studies carried out by the Department of Ocean Engineering, IIT Madras related to coastal protection measures considering the effects of Tsunami will be discussed in this workshop. The experts from the reputed organizations like NIO, NIOT, CWPRS, CESS, NIT-Surathkal, Anna University, Indomer Coastal Hydraulics, Andhra University, representatives from Planning Commission, Central Government ministries and State Union Territory administrations are invited to participate in the group discussion. The Planning of conference on 11th & 12th Dec – 2006, to be held at IIT Madras will also be discussed in the workshop.

This workshop is being organized by the Department of Ocean Engineering, Indian Institute of Technology Madras in collaboration with Planning Commission, Government of India and International Ocean Institute (India).

Coordinators

Prof. R. Sundaravadivelu
Prof. J.S. Mani

GROUP DISCUSSION

Chairman
Mr. T.V. Antony IAS
Chairman
Infrastructure development & Miscellaneous Projects (MOEF)
Govt. of India,
Chief Secretary (Retd), Govt. of Tamil Nadu.

Experts Invited For Group Discussion

1. Mr. Anandane C. Project Manager, Pondicherry Medical College, Pondicherry
2. Dr. Chandramohan P. Indomer coastal Hydraulics (P) Ltd, Chennnai
3. Dr. Hedge A.V. Professor, NIT Surathkal, Karnataka
4. Dr. Kurian N.P. Head, Marine and Science Division, CESS, Thiruvanthapuram
5. Brigadier Kaushik S. Chief Engineer, A&N Zone, Port Blair
6. Dr. Kathiroli S. Director, National Institute of Ocean Technology, Chennai
7. Dr. Narsimham M.L. Professor, Department of Civil Engineering, Andra University, Visakhapatnam
8. Mr. Purandare U.V. Central Water & Power Research Station, Pune
9. Dr. Ramachandran S. Director, Anna University, Chennai
10. Rear Admiral Raman Prabhat, Director General, Vizag
11. Prof. Subramanian SP. Department of Ocean Engineering, IIT Madras, Chennai
12. Prof. Sundar V. Head of the Department, Department of Ocean Engineering, IIT Madras, Chennai
13. Mr. Sekar K. Additional Chief Engineer & Administrator (ALHW), Port Blair
14. Mr. Sivaswamy R. Chief Administrator & Chief Engineer (Retd), Ministry of Surface Transport, Chennai
15. Mr. Saneel Kumar V. Scientist, Ocean Engineering Division, NIO Goa
16. Brigadier. Wahi A.K. Chief Engineer (Navy), Vizag Zone, Vishakapatnam

CONTENTS

Geology of Tsunamis and Precautions

SP. Subramanian
Department of Ocean Engineering,
Indian Institute of Technology Madras Chennai, India
Email: sps@iitm.ac.in

Abstract

Tsunami is one among the catastrophic tectonic Phenomena of the crustal part of the earth created mostly by a submarine earthquake. They occur at plate boundaries due to interaction of two convergent plates resulting subduction of an oceanic plate at depth of tens of kilometers in the Asthenosphere.A tsunami can cause damage upto a few thousand kilometers from its orgin, so there might be several hours between its creation and impact on a coast. Nearly three-fourths of sub marine seismic activities do not result in a Tsunami. Tsunami cannot be prevented or precisely predicted. In some Tsunami prone countries precautionary measures have been taken to reduce the damage caused on the shore and loss of life. Though Tsunami occurs more frequently in the Pacific Ocean, they are a global phenomena. Number of past occurrence of Tsunamis originating from other oceans have been reported. In the Indian Ocean one among the most disastrous Tsunami has occurred on December 26th 2004. In the light of this Tsunami UNESCO and other world bodies have called for a global Tsunami monitoring system and a consolidated effort to go in depth not only detailed research on this "secondary seismological event" but also on the measures to reduce the damage to property and loss of life by educating the people of the Tsunami prone regions.

INTRODUCTION

Tsunami is one among the most terrifying natural hazards known to man and have been responsible for tremendous loss of life and property around the world. Because of their destructiveness, tsunami has important impact on the human, social and economic sectors of our societies. Pacific Ocean where most of the tsunami are formed cause tremendous destruction. Japan, which is one of the most populated coastal regions in the world, has a long history of earthquake activity and tsunami has destroyed often the coastal populations. The most notable destructive tsunami has occurred in the Indian Ocean and was associated with violent explosion of the volcanic island of Krakatoa in August 1883. A 30-meter tsunami resulting from this explosion killed 36,500 people in Java and Sumatra in the recent Tsunami of December 26th 2004.

A tsunami can be generated by any disturbance that rapidly displaces a large mass of water, such as an earthquake, volcanic eruption, and landslide or meteorite impact. However, the most common cause is an undersea earthquake. An earthquake which is too small to create a tsunami by itself may trigger an undersea landslide quite capable of generating a tsunami. Tsunamis can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. Such large vertical movements of the earth's crust can occur at plate boundaries. Subduction earthquakes are particularly effective in generating tsunamis, and occur where denser oceanic plates slip under continental plates in a process known as subduction.

Collapses of volcanic edifices may also disturb the overlying water column as sediment and rocks slide downslope and are redistributed across the sea floor. Similarly, a violent submarine volcanic eruption can uplift the water column and form a tsunami. Tsunami waves can travel at the speed of a commercial jet plane, over 800 km per hour. They can move from one side of the Pacific Ocean to the other in less than a day. The length of the tsunami wave goes through several hundred kilometers but the height of the wave is comparatively very small.

A tsunami can cause damage thousands of kilometres from its origin, so there may be several hours between its creation and its impact on a coast, arriving long after the seismic wave generated by the originating event arrives.As the wave approaches the shore the velocity decreases and there is a amplification in the wave height. Tsunami waves can be 30 meters high as they come into shore and can rush kilometers inland across low-lying areas. Most tsunamis do not result in giant breaking waves rather, they come in much like very strong and very fast tides. Much of the damage inflicted by tsunamis is caused by strong currents and floating debris brought with it with enormous force which can lift large rocks weighing several tons, along with boats and other debris which are moved inland hundreds of meters by tsunami wave activity. All this material and water move with great force, and can kill or injure people. Tsunami can also be caused by volcanic eruptions and landslides, which are less powerful and in most cases show a local effect.

The following signs have at various times been associated with a tsunami:

- An earthquake may be felt.
- Large quantities of gas may bubble to the water surface and make the sea look as if it is boiling.
- The water in the waves may be unusually hot and the sea may recede to a considerable distance.

The earthquake of December 26 that occurred off the west coast of northern Sumatra took place at the interface between the Indian and Burma plates, where Burma plate has been referred by Andaman/Nicobar ridge that acts as a small tectonic plate. It is a typical oceanic-oceanic convergent plate boundary where the Indian plate moving at a rate of 6 cm a year relative to the Burma plate came together collided and the Indian plate dived (subducted) under the Burma plate. Volcanic eruptions are commonly seen at such convergent boundaries. "Two major plate tectonic features on either side of a narrow strip show how seismically active the region is." A lethal combination of huge magnitude and shallow depth focus led to high vertical displacement of the Burma plate that acted like a great piston deforming the sea. That in essence is the power of the earthquake that struck off the Sumatra coast. The U.S.Geological Survey has called this event a mega thrust earthquake referring to the large cracking of the plate boundary. The vast expanse of the Indian Ocean posed little challenge to the movement of the killer tsunami. Reaching a distance of 2000 km to hit the Indian coast was not difficult.

Subduction Zones are potential locations for most of the tsunamis. Subduction zone is an area where continental plates are being forced down into the mantle of the other rigid continental plate. The friction between the subducting plate and the overriding plate is enormous. Energy accumulates in the subduction zone over a period of time - decades or even centuries. This continues until the energy accumulation exceeds the frictional forces in the plates. When this happens, the overriding plate snaps back into an unrestrained position. This sudden motion is the cause of the tsunami - because it gives an enormous shove to the overlying water. The moving wave begins travelling out from where the earthquake has occurred. Some of the water travels out and across the ocean basin, and, at the same time, water rushes landward to flood the recently lowered shoreline. Tsunamis travel swiftly across the open ocean. Many people have a belief that tsunamis are single waves. Tsunamis are "wave trains" consisting of multiple waves.

PAST TSUNAMIS

Tsunamis occur frequently in the Pacific Ocean, but are a global phenomenon. Very small tsunamis, non-destructive and undetectable without specialized equipment, occur frequently as a result of minor earthquakes and other events.

The Cascadia Earthquake has been one of the largest earthquakes on record, ruptured the Cascadia offshore from Vancouver Island, Canada to northern California, creating a tsunami that logged in Japan in January, 1700. Tens of thousands of Portuguese who survived the great 1755 Lisbon earthquake were killed by a tsunami which followed a half hour later.

The island volcano of Krakatoa in Indonesia exploded with devastating fury in 1883, blowing its underground magma chamber which caused much of overlying land and seabed collapsed into it. A series of large tsunami waves was generated from the explosion, some reaching a height of over 40 metres above sea level. Tsunami waves were observed throughout the Indian Ocean, the Pacific Ocean, the American West Coast, South America, and even as far away as the English Channel.

On November 18, 1929 (Newfoundland tsunami), an earthquake of magnitude 7.2 occurred beneath the Laurentian Slope on the Grand Banks. The quake was felt throughout the Atlantic Provinces of Canada and as far west as Ottawa, Ontario and as far south as Claymont, Delaware and resulted in a tsunami in Burin Peninsula on the south coast of Newfoundland.The Aleutian Island earthquake (1946) tsunami that killed 165 people on Hawaii and Alaska resulted in the creation of a tsunami warning system, established in 1949 for Pacific Ocean area countries.

The Great Chilean Earthquake (1960), at magnitude 9.5 the strongest earthquake ever recorded, off the coast of South Central Chile, generated one of the most destructive tsunamis of the 20th century. It spread across the entire Pacific Ocean, with waves measuring up to 25 metres high. When the tsunami hit Onagawa, Japan, almost 22 hours after the quake, the wave height was 3 m above high tide.

Vajont Dam disaster (1963) in which the reservoir behind the Vajont Dam in northern Italy was struck by an enormous landslide. A tsunami was triggered which swept over the top of the dam (without bursting it) and into the valley below.

After the Good Friday Earthquake (1964) of 9.2 magnitudes, tsunamis struck Alaska, British Columbia, California and coastal Pacific Northwest towns. A magnitude of 7.9 earthquake occurred on December 12, 1979 along the Pacific coast of Colombia and Ecuador. The earthquake and the resulting tsunami caused the destruction of at least six fishing villages. A devastating tsunami occurred off the coast of Hokkaido in Japan as a result of an earthquake on July 12, 1993.

The 2004 Indian Ocean earthquake, that had a magnitude 9.0, triggered a series of lethal tsunamis on December 26, 2004 that killed over 2 lakh and wrecked economic damage of billions of Dollars. Making it the deadliest tsunami in recorded history. The tsunami killed people over an area ranging from the immediate vicinity of the quake in Indonesia, Thailand and the north-western coast of Malaysia to thousands of kilometres away in Bangladesh, India, Sri Lanka, the Maldives, and even as far as Somalia, Kenya and Tanzania in eastern Africa.

This tsunami has proved how dangerous it is, not to care for disaster preparedness by all sectors of the community and administration though the Indian Ocean has witnessed a few tsunami in the past century which were proved to be highly destructive. Disaster preparedness has to be the most important issue in mitigating natural hazards in coastal areas. From installation of early warning system to architectural and coastal planning methodology, zoning, restriction, control and physical application, structural integrity of buildings, structural and non-structural measures, all are to be explored.

Unlike in the Pacific Ocean, there is no organised alert service covering the Indian Ocean. This is in part due to the absence of major tsunami events between 1883 (the Krakatoa eruption, which killed around 360000 people) and 2004. In light of the 2004 Indian Ocean tsunami, UNESCO and other world bodies have called for a global tsunami monitoring system.

The India Plate is part of the great Indo-Australian Plate, which underlies the Indian Ocean and Bay of Bengal, and is drifting northeast at an average of 6 cm/year. The India Plate meets the Australasian Plate (which is considered a portion of the great Eurasian Plate) at the Sunda Trench. At this point the India Plate subducts the Burma Plate, which carries the Nicobar Islands, the Andaman Islands and northern Sumatra. The India Plate slips deeper and deeper beneath the Burma Plate until the increasing temperature and pressure drive volatiles out of the subducting plate. These volatiles rise into the mantle above and trigger melt which exits the earth's mantle through volcanoes. The volcanic activity that results as the Indo-Australian plate subducts the Eurasian plate has created the Sunda Arc.

WARNINGS AND PREVENTION

Tsunamis cannot be prevented or precisely predicted, but there are some warning signs of an impending tsunami, and many systems are being developed and in use to reduce the damage from tsunamis.In instances where the leading edge of the tsunami is its first peak, succeeding waves can lead to further flooding. Again, being educated about a tsunami is important, to realise that when the water level drops the first time, the danger is not yet over. In a low-lying coastal area, a strong earthquake is a major warning sign that a tsunami may be generated. Japan has implemented an extensive programme of building tsunami walls of up to 4.5m high in front of populated coastal areas. Other localities have built floodgates and channels to redirect the water from incoming tsunamis. However, their effectiveness has been questioned, as tsunamis are often higher than the barriers. Environmentalists have suggested tree planting along stretches of sea coast which are prone to tsunami risks. While it would take some years for the trees to grow to a useful size, such plantations could offer a much cheaper and longer-lasting means of tsunami mitigation than the costly and environmentally destructive method of erecting artificial barriers. Surviving a Tsunami is itself an important method for preparing the future generation to face the tsunami.

FORECASTING, PREPAREDNESS AND WARNING

History has been the witness of tsunami destruction. Historical records speak the considerable loss of life and destruction of property that have attacked various coast around the world. Japan is very vulnerable to the tsunami hazard. All the major Japanese islands have been struck by devastating tsunamis. A total of 68 destructive tsunami have struck Japan between 684 A.D and 1984 leaving thousands dead and hundreds of villages destroyed. In this century alone, at least 6 major destructive tsunamis have hit Japan. The 1983 event, although not very destructive in terms of lives lost and property damage, occurred in the Sea of Japan in an area not known before for seismic or tsunami activity. Hawaiian islands, tsunamis have been struck repeatedly, causing great loss of life and immense damage to property. Most noteworthy of the recent Hawaiian tsunami is that of 1 April 1946 which inundated and destroyed the city of Hilo, killing 159 people.

Forecasting tsunami and determine terminal run up and destructiveness, one must be able to evaluate the parameters of the tsunami source mechanism in real time, often from inadequate data. Forecasting the run up (Tsunami run-up is the vertical distance between the maximum height reached by the water on shore and the mean-sea-level surface) and potential destructiveness of a Tsunami at a distant shore will depend greatly on determining the seismic parameters of the source location such as magnitude of the earthquake, its depth, its orientation, the length of the fault line, the size of the crustal displacements, and depth of the water. Refraction and diffraction processes will affect the energy and height of the tsunami waves as they travel across the ocean. The refracted tsunami waves will usually attack the coast with less power compared to the original tsunami wave. For instance the refracted tsunami wave which hit Kerala caused by the flooding of the coastal low lying plains. These effects must also be determined. Finally, terminal height, run-up, and inundation of the tsunami at a point of impact will depend upon the energy focusing effect, the travel path of the waves, the coastal configuration, and the offshore bathymetry. Problems of communications and lack of sufficient station density, often complicate the process of forecasting the tsunami. Forecasting tsunamis requires adequate understanding of the phenomenon, good and expeditious collection of earthquake and sea level data, and accurate and expeditious assessment and interpretation of this data which is not available at present in the Indian Ocean.

Preparedness and Planning

Mankind can do very little to prevent the occurrence of natural hazards. But a lot can be done to reduce loss of life and property through proper preparedness and planning. The first initiation in this regard should be in the formulated in the form of land-use regulations for a given coastal area, which has a potential tsunami risk keeping in mind, particularly those areas which are known to have sustained damage in the past. Tsunami hazard perception should be brought into the people of a coastal area for mitigating loss of life and damage to property. Hazard perception by the public is based on a technical understanding of the phenomenon, at least at the basic level and confidence in the authority responsible for warning. Warning, based on inadequate data leads to the false prediction, which has often, brings to false alarms. Such false alarms result in a loss of faith in the capability of a warning system and result in reluctance to take action in subsequent tsunami events. The availability of good quality data has helped in better forecasting of tsunami in the recent years.

The International Tsunami Warning System (TWS) of the Pacific ocean which was established on 1948 following the disaster caused by the tsunami of 1 April 1946 in the Hawaiian Islands, to provide watch and warning information to the civil authorities throughout the Pacific and to islands in the Trust Territories. Beginning in October 1953 warning information was extended to California, Oregon and the State of Washington.

The great destruction caused by the May 1960 Chilean tsunami prompted a large number of countries and territories to Join the TWS. Another catastrophic tsunami generated by the great Alaskan earthquake of 1964 emphasized the need for an International Tsunami Warning System. In 1965, the United Nations Educational Scientific and Cultural Organization's Intergovernmental Oceanographic Commission accepted the United States' offer to expand its existing Tsunami Center in Honolulu to become the Pacific Tsunami Warning Center (PTWC). Functioning of the system begins with the detection from the seismic observatory of an earthquake of sufficient to trigger tsunami which is set at the threshold of 6.5 on the Richter Scale. PTWC collects the seismic data, locates the earthquake and computes its magnitude. When reports from tide stations show that a tsunami has been generated which poses a threat to the population in part or the entire Pacific, a warning is transmitted to the dissemination agencies for relaying to the public. The agencies then implement predetermined plans to evacuate people from endangered areas. In addition number of Regional Warning Systems have been established to warn the population in areas where tsunami frequency is high and where immediate response is necessary.

DISASTER MITIGATION PLAN

- Study the pattern of earlier events and identify the vulnerable areas with reference to risk if Tsunami, having a potential of damaging life, property and related infrastructure.

- Preparation of a Vulnerability Atlas which will show areas vulnerable to Tsunami and determination of run up level which will help in coastal zone plan.

- Formulate a strategy to manage the disaster and enforce modern construction practice and planning in coastal settlement

Pre Disaster Management Strategy

- Assessment of the risk in the entire coastal belt under the threat of the Tsunami.

- Collection of the historic earthquake data which have produced Tsunami and run-up to the inland.

- Run numerical model study for the earlier and compare it with the observed or measured tidal data to forecast tsunami in the real time mode.

- Based on the model results with hypothetical earthquake various intensities and prepare vulnerability maps which will be useful for implementing coastal zone management plan.

DISASTER MITIGATION PLAN

Based on the model study, risk maps of the vulnerable areas the disaster mitigation plan need to be charted out based on location and the distance to the coast and socio-economic status of the region.

Warning system for the vulnerable regions

- Warnings to be transmitted at regular intervals from warning stations (for example radio, television, mobile phones, public broadcasting) based on the forecast, so that it can be transmitted at local levels for the evacuation.

- The coastal region must have a monitoring station in its vicinity at safe point so that they are able to monitor the worst circumstances that may generate.

- Local centers must be established for transmitting the forecast and also these stations should be equipped with satellite phones for receiving and transmitting information.

Educating the people

Educating the people can reduce the destruction caused by natural disaster to a large extent.The people should know the actual mechanism of the monitoring system i.e what is its accuracy of prediction so that they will always take the warning seriously and should have the knowledge regarding the things that should be done when warning is issued. Above all people should be educated not to be panic after the tsunami and wait patiently until the issued warning is waved off or wait for the rescue teams to arrive.

Protection Strategy

- Construction of sea wall in the coastal region will be effective to counter the small tsunami and reduce the damage as a hard measure.

- Shelter belts comprising of a resilient trees like casuarinas must be planted in the coastal belts under the social forestry scheme to a maximum width 500 meters of coastal regulatory zone.

- Formation of block management committee in every locality to take over the charge in case of any disaster and start the rescue work before the rescue team arrives.

- The management groups must be trained to handle the disaster and must have the knowledge of safety measures that are to be adopted during the disaster.

- Mobilization of rescue team must be as early as possible after the disaster for faster relief to the affected.

- Setting up of a disaster management cell having the knowledge and expertise of the steps to be taken once the warning is issued.

TSUNAMI RISK

Preparation of data-base of historical and archival of information relevant to Indian Tsunamis, with the emphasis clearly on the December 26, 2004 event. Analyses of these data, to define the scenario Tsunamis from various earthquake sources and prepare the Tsunami hazard map.

Prepare all the existing habitations below the maximum run up level or maximum tsunami height and demarcate on a map. This will help to evacuate the people based on their vulnerability to tsunami.

Vulnerability assessment can be explained as the vulnerability of various exposed elements on the coastal, island and reef environments and in the Ports and Harbours. The vulnerability assessment is carried out based on their exposure to the disaster.

The key factors to reduce potential losses due to tsunami are awareness and preparedness. The practical applications of this tsunami risk assessment, in both quantitative and qualitative terms, for implementation into mitigation strategies for the terrestrial and marine environments include:

- Strict implementation of the coastal zone regulations (within 500 m of the high tide line with elevation of less than 15 m above m.s.l.

- Mapping the coastal area for multiple hazards, vulnerability and risk analysis up to taluka /village level. Development of Disaster Information Management System (DIMS) in all the coastal states.

- Aggressive capacity building requirements for the local people and the administration for facing the disasters in wake of tsunami and cyclone, 'based on cutting edge level'

- Developing tools and techniques for risk transfer in highly vulnerable areas

Launching a series of public awareness campaign throughout the coastal area.

- Training of local administration in forecasting warning dissemination and evacuation techniques

- Awareness generation and training among the fishermen, coast guards, officials from fisheries department and port authorities and local district officials etc., in connection with evacuation and post tsunami storm surge management activities. Regular drills should be conducted to test the efficacy of the DM plans.

- Studies focusing on the tsunami risk in India.

List of Tsunami that Affected India

Date	Remarks
1008	Tsunami on the Iranian coast from a local earthquake
1883	Karatoa 1.5 m Tsunami at Madras
1884	Earthquake in the western part of the Bay of Bengal Tsunamis at Port Blair,Doublet (mouth of Hoogly River)
1941	8.1 quake in the Andaman Sea at 12.9^{0}N,92.5° E Tsunamis on the east coast of India with amplitudes from 0.75 to 1.25 m. Some damage from East Coast was reported.
1945	Mekran Earthquake (Magnitude 8.1). 12 to 15 M wave height in Ormara in Pasi (Mekran coast) Considerable damage in Mekran coast. In Gulf of Cambay of Gujarat wave heights of 15 meter was estimated. The wave height at Mumbai was about 2 meters.
27th November 1945	8.25 quake 70 km south of Karachi at 24.5° N, 63.0° E Tsunami amplitude at Kutch was 11.0 to 11.5m
26th December 2004	Earthquake of magnitude 9.1 off north Sumatra coast generated devastated Tsunami waves affecting several countries in South East Asia.

CONCLUSION

Tsunami, triggered mostly due to a sub marine earthquake is one among the disastrous natural tectonic hazards. The fact is that it can not be prevented or predicted. With the present seismological and tectonical knowledge, the crustal parts of the earth on which these events occur is broadly known but when and where accurately these disasters take place including intensity and duration are not at the reach of the human efforts.

Precautionary and preventive measures based on detailed studies will definitely help to reduce damage too properly and loss of life. Well planned disaster management and mitigation programmes are to be strictly implemented in line with coastal zone regulations UNCLOS and UNCED as pre and post disaster strategies for the well being and livelihood of people.

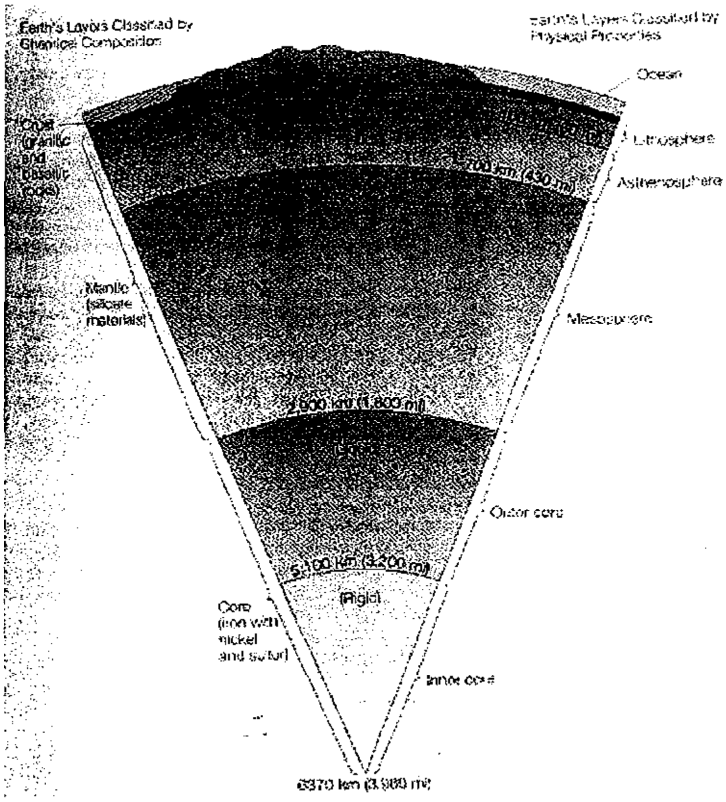

Fig. 1: Structure of the Earth

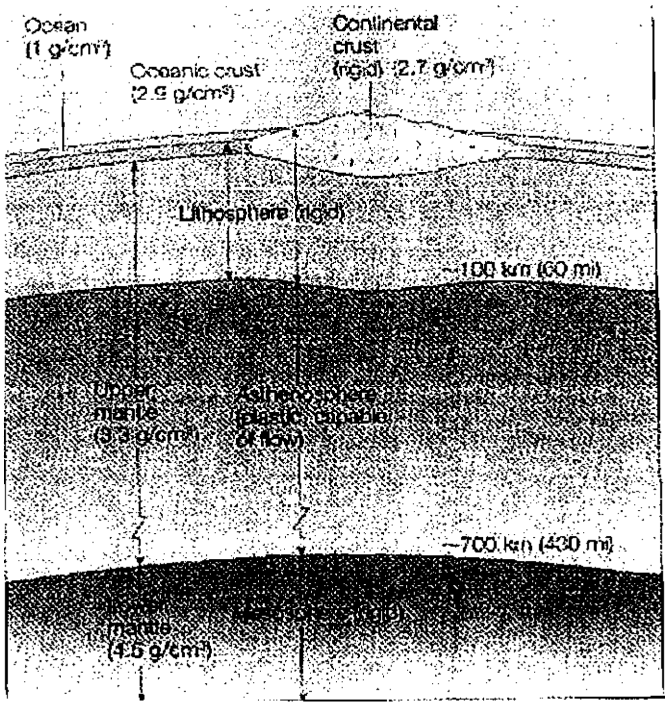

Fig. 2: Contact of Lithosphere and Asthenosphere

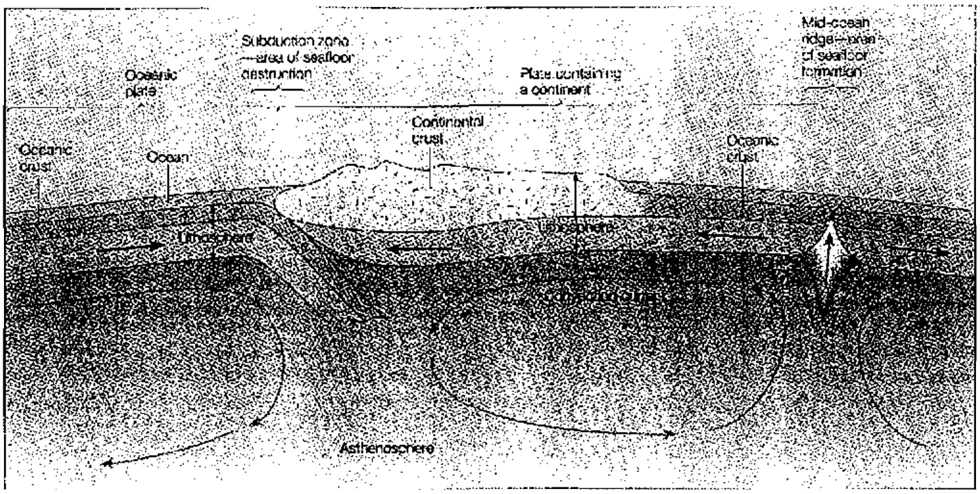

Fig. 3: Sea Floor Spreading

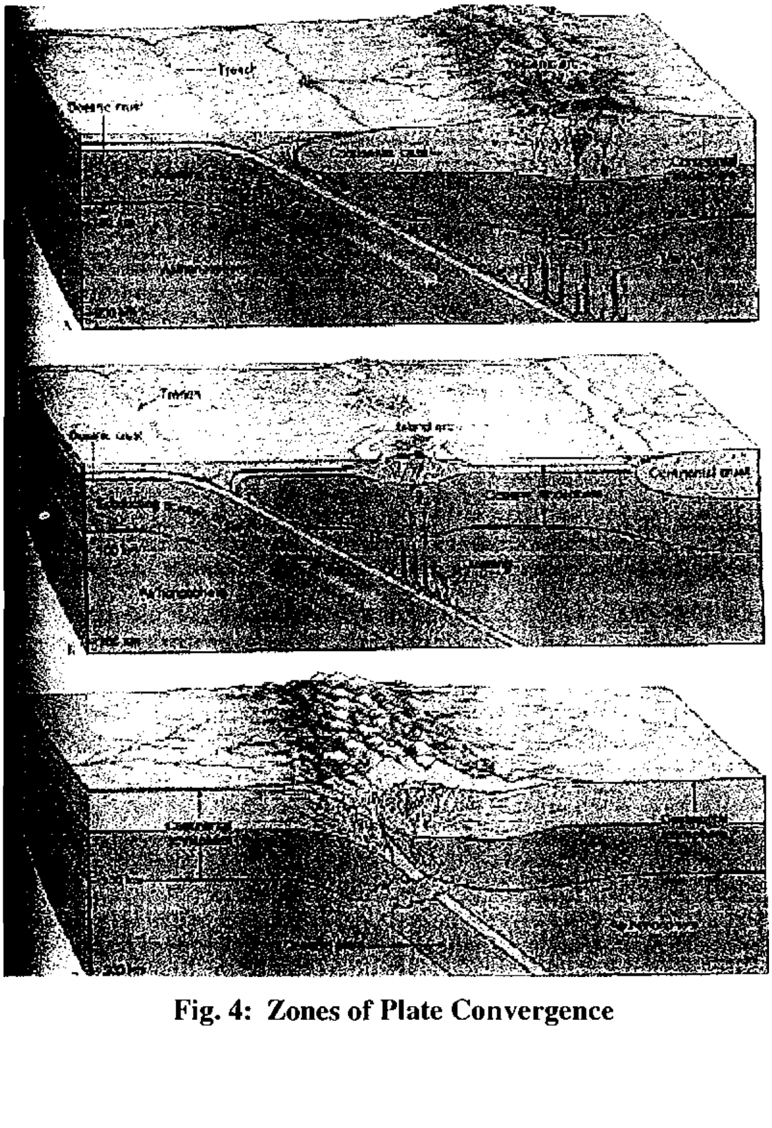

Fig. 4: Zones of Plate Convergence

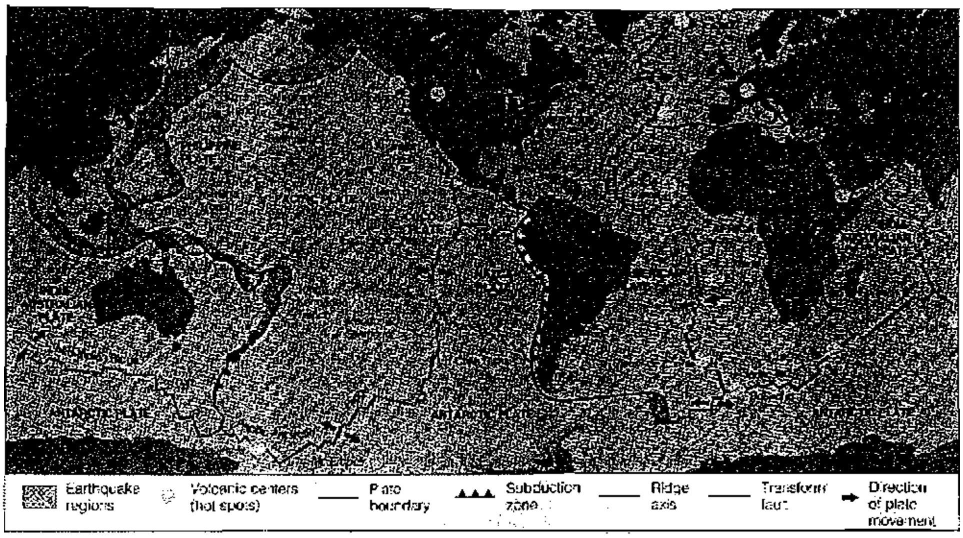

Fig. 5: Tectonic features of the Earth

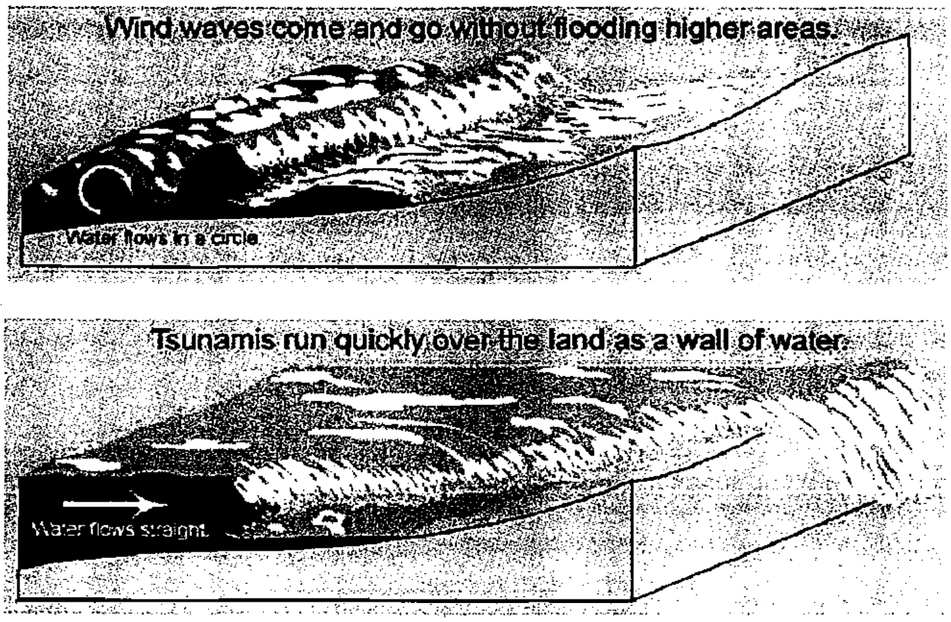

Fig. 6: Wind Waves and Tsunamis

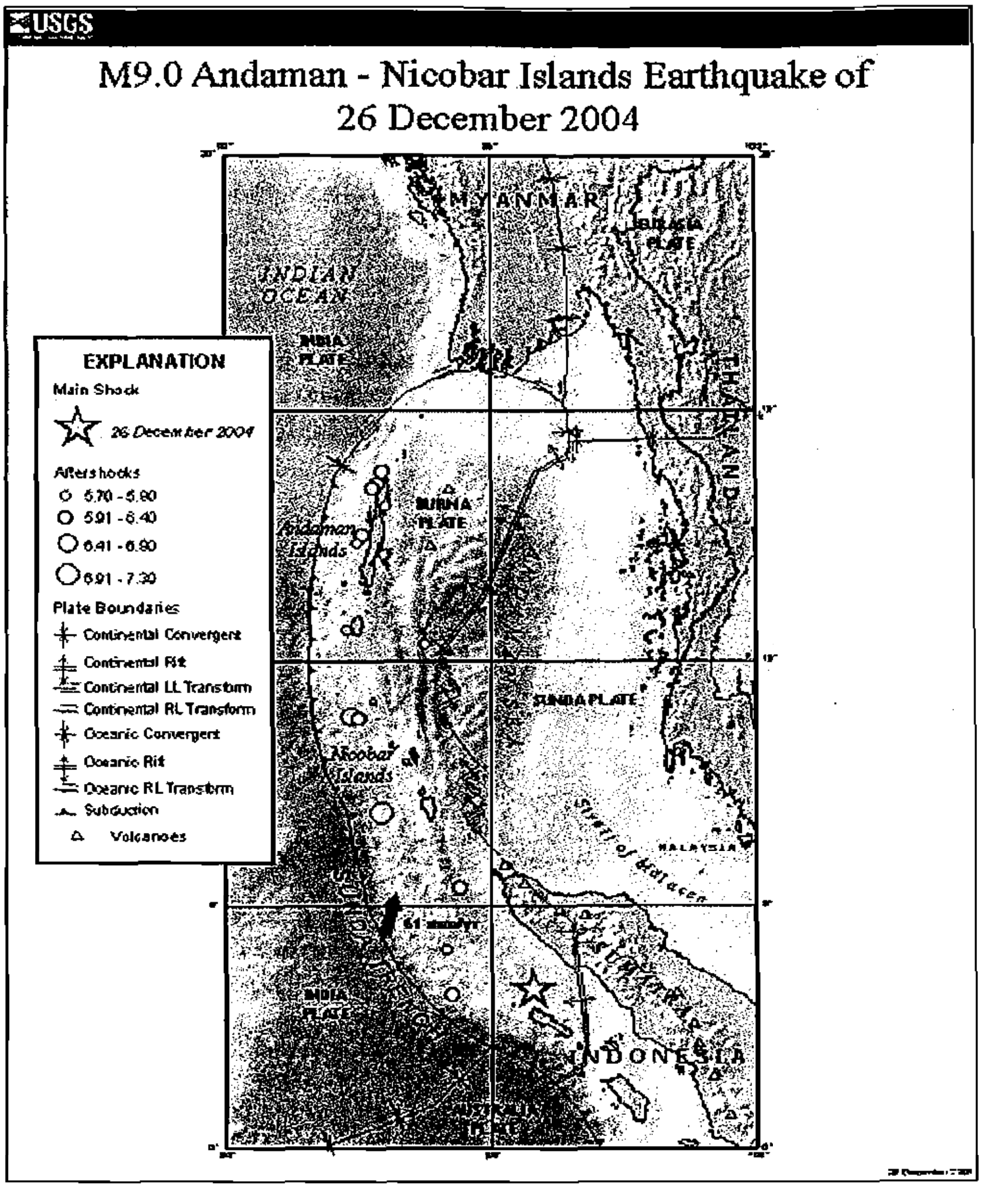

Fig. 7: Tectonic activity in the vicinity of Andaman and Nicobar December 26th 2004

Numerical Methods in Coastal Hydrodynamics and Modelling of Tsunamis

Dr.K.Murali
Assistant Professor
Department of Ocean Engineering
Indian Institute of Technology Madras
Chennai, India 600 036

e-mail : murali@iitm.ac.in

1.0 Overview

Coastal hydrodynamics is a subject consisting of a variety of physical processes. By variety, one means a range of physical and temporal scales. Typically, the physical scales vary from an order of 1 meter to an order of 100 km. Similarly, the temporal scales vary from a few seconds to days and months. These wide variations in range of physical and temporal scales are dictated by various natural forcings that influence the coastal setting. The offshore winds generate waves of lengths in the range of 100-200m and periods in the range of 5-20s. On the other hand, the gravitational balance between earth, moon and the sun causes tides that rise up and down around the globe in a predictable manner. A cyclonic swirling wind - the storms and cyclones for example - results in a surge of water mass, of the order of up to 10m, in the nearshore zone during the cyclonic landfall. On the other hand, sudden release of energy underwater, due to sub-marine landslides; earthquakes; eruptions etc., generates tsunamies that travel around the globe at speeds of sound and cause devastating effects - thanks to their high speeds and tall heights. Then there are currents generated be various imbalances in the physical setting of the ocean waters – namely temperature, salinity, density etc.

Given the variations in the scales of physical processes of coastal environment, the challenges in modeling these processes should be recognised. Once this understanding is achieved, the search of suitable modeling approach will be easier and fruitful – either physical or numerical. This course is intended for beginners in numerical coastal hydrodynamics. Based on the aforementioned discussion, the obvious objective in this course is to create an awareness in coastal modeling through introduction to **a)** basics of computing and numerics; **b)** basic of equations governing various physical processes one comes across under the umbrella of coastal hydrodynamics and **c)** development of the numerics as numerical techniques for solving the governing equations for a given physical setting.

2.0 Computers as a computing machine

"Men are from Mars. Women are from Venus. Computers are from Hell"- goes a saying. Computers, if appropriately used, can really be a wonderful tool for humankind. The above adage basically expresses the fact that it is little difficult to that. The need is to understand the functioning and utility of the machine. This section tries to drive home the important concepts in the computing mechanism thereby creating a common minimum understanding of the functioning of the machine.

Computers are machines capable of churning out numbers, the binaries, at very high speeds. Let us clarify, however, a point that very high speed means the speed of the binary operation. However, any number is represented by binaries. Hence, operation on any two numbers might take much longer than a binary operation. In simple terms, if a computer chip is designed for 3.4 Ghz (3.4 billion cycles a second), then it can do a binary operation in 1/3.4 billionth of a second. However, the time taken for an operation on two numbers is different. This is typically referred to as "compute cost". Typical ranges of computing costs are given below:

Table.1. Typical computing costs

Compute operation	Compute cost
floating point (+ , - , * , +*)	1 cycle
floating point divide (/)	15-30 cycles
square root	25-40 cycles
integer (*, /)	3, ~30 cycles
real, integer conversion	7 cycles
Intrinsic functions (sine / cosine, tan, logarithmic/ exponential, exponentiation	(60, 120, 100, 230) cycles
logical IF	300-400 cycles

In general, it is a good practice to keep the above costs in mind when writing a computer programme: A good computer programme will have the least of high cost operations. For example, a good programmer will use A**(0.5) instead of A**(1/2), and A*A instead of A**(2).

This is not a course in computing. But it is extremely important to understand how the computing cycle looks like for writing efficient computer programmes. A computer chip or processor consists of FPU (floating point units) for FSU (integer units) for operating on real and integer numbers respectively. There are also load/store (LD/ST) for transferring these numbers from/to the "Cache" memory to/from the FPUs or FSUs - there can be more than one FPU / FSU in a chip. A schematic of an IBM chip is shown in Fig.1.

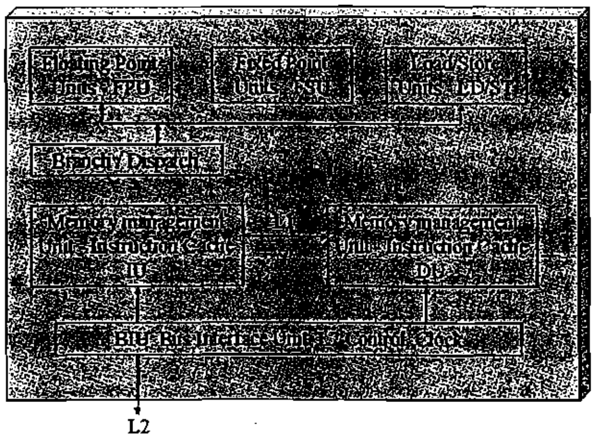

Fig.1. The PROCESSOR - an overview

The cache is a memory of small size that could fit within the chip. The bottleneck in computers is that the processor speed is much higher (in Ghz) than the memory (RAM) speed (in Mhz) - think yourself trying to cross the road with a snail. You would try to go fast but the snail will pull you back, as it could go no faster. Hence the chip has cache memories. The data is stored within the cache for getting processed by the FPU. In high-end compute servers there can be more than 1 cache memory. In such a case these are called L1, L2, L3, etc. The compute costs for data to move to/from the FPU/FSU from/to the memories are: L1-1 cycle; L2 - 7 to15 cycles; L3 - ~100 cycles and Memory (RAM) – 60 to 300 cycles.

Understanding and implementing the above concepts in the computer code is essential for writing efficient and useful computer codes for solving coastal hydrodynamic problems. Otherwise bottlenecks in compute time and compute errors are unavoidable.

3.0 Basic numerical processes

3.1 Interpolation

Let $x_i = x_1, x_2, x_3, ...$ and $y_i = y_1, y_2, y_3, ...$ be a pair of values. Under the process of interpolation, one tries to find the estimate y at a given x, with $(x_1 < x < x_N; x \neq x_N; i = 1,...,N)$. Here, x may be defined an independent variable with y being the dependent variable. If the task is to estimate y at x, with $(x < x_1 (or) x > x_N)$, then the problem may be defined extrapolation. The selected numerical technique/ algorithm should model the function between or beyond the known points, by some reasonable and realistic functional form. Typically, the following functions are used for interpolation.

1. Polynomials
2. Splines
3. Rational functions
4. Trigonometric interpolation

The task of interpolation may look similar to that of functional approximation. However, they can be differentiated with the help of the following table.

Table.2. Interpolation vs. Functional Approximation

Interpolation	Functional Approximation
▪ Evaluating 'y' at x given a set of x_i $\rightarrow$ no choice is available on selection of points.	▪ Approximation of a complex function by sampling it at chosen locations and using these samples to develop a simple function.
▪ Evaluating values. The functional relationship is implicitly defined.	▪ Evaluating function. Evaluation of values is done when needed.

The suitable choice of interpolation function depends on the nature of the function that is being approximated. In order to do this, one has to have a fair idea of the nature of the behavior of the data and understanding of the variation of the dependent variable, y, as a function of the independent variable, x. For example, let us examine the function shown in Fig.2.

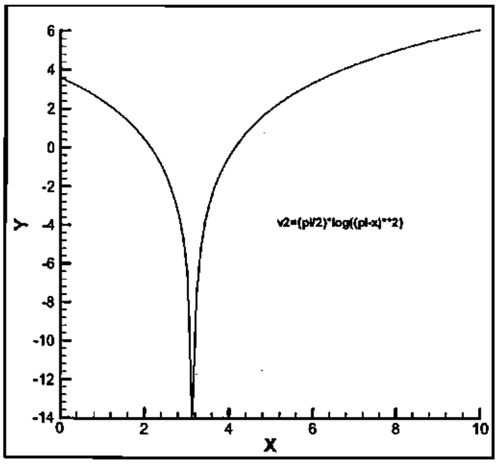

Fig.2. Example of a complex function

The function shown in Fig.2 is $f(x) = y = \frac{\pi}{2}\ln(\pi - kx)$. Let us assume that we are given the values of the dependent variable, y, at x = 0,1,2,3,4,5,..., and the task is to evaluate y at x = 3.1415. Now, a little bit of effort could indicate any of the above method would yield wrong output. With this example, it is basically demonstrated that one has to be aware of the nature of the data that is being interpolated. However, leaving alone this extreme scenario, interpolation of data is a useful way evaluating the dependent variables at any locations. In order to achieve this, methods that provide functional estimate based on the tabulated values is the need of the hour.

Order of interpolation: If the number of points used in the interpolation is N. Then the order o. int.rp.lati.n is d.fin.d as N−1. **Howe.er, increasing the order does not necessarily increase the accuracy.**

Referring to Fig.3, it could be realised that unless proper evidence exists for a function to be of higher order, one should not opt for higher order polynomials / interpolation.

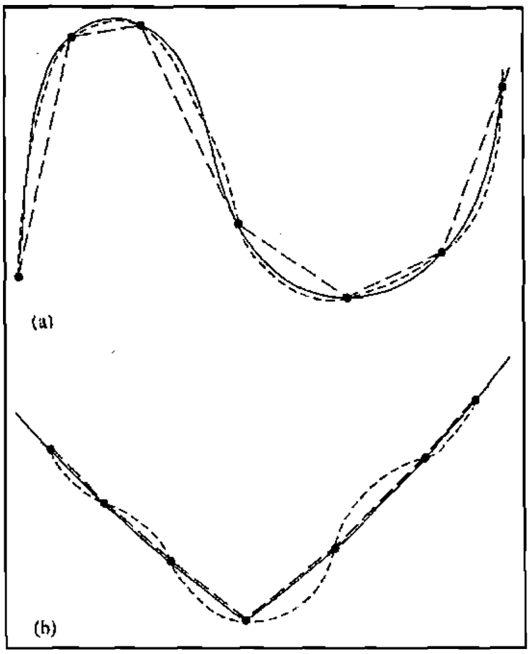

Fig.3. Order of interpolation

(a) A smooth function is more correctly represented by higher order interpolation.

(b) *A discontinuous function if wrongly represented by higher order interpolation*

3.1.1 Basic interpolation techniques

The obvious way: One starts from the nearby data points and applies corrections of decreasing order by incorporating the information from other $f(x_i)$. This involves operations of the order $O(N^2)$. If everything is well behaved, the last correction is the smallest. However, because of N^2 operations, it is usually not economical.

Polynomial interpolation: Approximating the underlying function by polynomials, the polynomial interpolation tries to directly yield the estimates.

Local interpolation: In this case only neighbors (or) nearest neighbors are used. Even though this is easy to do the derivatives of the underlying function is discontinuous. Hence, one has to be sure that this is not very important for the overall objectives of the numerical computation process.

Spline Interpolation: Ensures continuity of derivatives. A spline is a polynomial between each pair of local points, but the co-efficients of the polynomial are determined somewhat non-locally – to assume global smoothness– up to some order of derivatives. **Cubic Splines** are famous for their simplicity and effectiveness. They yield continuous second derivatives.

3.1.2 Polynomial interpolation and extrapolation

Lagrange's formula: For N data points, the polynomial of order N-1 is given by,

$$P(x)=\frac{(x-x_2)(x-x_3)..(x-x_N)}{(x_1-x_2)(x_1-x_3)..(x_1-x_N)}y_1+\frac{(x-x_1)(x-x_3)..(x-x_N)}{(x_2-x_1)(x_2-x_3)..(x_2-x_N)}y_2+......+\frac{(x-x_1)(x-x_2)..(x-x_N)}{(x_N-x_1)(x_N-x_2)..(x_N-x_{N-1})}y_N$$

eqn.(1).

There are N terms in the formula and each of them is of degree N-1. Each polynomial is zero at all i when $x = x_j$ and $j \neq i$; so that the original data value is recovered. The biggest advantage of this method is that it explicitly estimates the dependent variable. However, it remains to be difficult to program in digital computer. In addition, it provides no means of estimating the errors. Hence, this must be chosen with utmost care and evidence.

Cubic Splines: Between two data points x_j & x_{j+1}, let us say our cubic spline has the form

$$y = Ay_j + By_{j+1} \text{ or } y_j = Ay_j + By_{j+1}. \qquad \text{eqn.(2)}$$

This implies that Implies that, $A=1$ @ $x= x_j$ while $B=0$; $B=1$ @ $x=x_{j+1}$ and $A=0$. Hence, it can be shown that

$$A=\frac{(x_{j+1}-x)}{(x_{j+1}-x_j)};B=\frac{(x-x_j)}{(x_{j+1}-x_j)}. \qquad \text{eqn.(3a) \& (3b)}$$

However, with the above linear approximation, eqn.(2) only yields a zero second derivative in the interior of each interval. Our requirement is however to (a) obtain a smooth finite derivative, and (b) ensure continuous second derivative: both in the interval and boundaries between x_j *and* x_{j+1}. This can be done by simply adding a cubic polynomial, as shown below in eqn.(4), to eqn.(2) by assuming that we have tabulated values of the second derivatives.

$$Cy_j'' + Dy_{j+1}'' \qquad \text{eqn.(4)}$$

The above formulation assumes that y'' varies linearly from $j \to j+1$ and the cubic polynomial has zero values at x_j and x_{j+1} (NODAL POINTS) - so that it does not modify the original tabulated values of the dependent variable, y. After some algebra, it can be shown that

$$C=\frac{1}{6}\left(A^3-A\right)\left(x_{j+1}-x_j\right)^2, \ and \ D=\frac{1}{6}\left(B^3-B\right)\left(x_{j+1}-x_j\right)^2,$$

$$\frac{dy}{dx}=\frac{y_{j+1}-y_j}{x_{j+1}-x_j}-\frac{3A^2-1}{6}\left(x_{j+1}-x_j\right)y_j''+\frac{3B^2-1}{6}\left(x_{j+1}-x_j\right)y_{j+1}'' \qquad \text{eqn.(5)}$$

and $$\frac{d^2y}{dx^2}=Ay_j''+By_{j+1}'' \qquad \text{eqn.(6)}$$

Now, by requiring the continuity of the first derivative at x_j, i.e., $\left.\frac{dy}{dx}\right|_{x_{j-}}=\left.\frac{dy}{dx}\right|_{x_{j+1}}$; an equation to be satisfied at the nodes with the second derivatives, y'', as unknowns.

$$\frac{x_j-x_{j-1}}{6}y_{j-1}''+\frac{x_{j+1}-x_{j-1}}{3}y_j''+\frac{x_{j+1}-x_j}{6}y_{j+1}''=\frac{y_{j+1}-y_j}{x_{j+1}-x_j}-\frac{y_j-y_{j-1}}{x_j-x_{j-1}} \qquad \text{eqn.(7)}$$

Applying eqn.7 at all the interior nodes results in N-2 linear equations with N unknowns – a 2-parameter family of possible solution. Unique solution of the set N-2 equations are applied by assuming suitable values for the boundary values of the second derivatives, i.e., y_1'' or y_N''. The most commonly used approaches are:

(1) *Natural Spline:* Obtained by setting y_1'' or y_N'' or both = 0

(2) Set the boundary values y_1'' and y_N'' from first known derivative and using eqn.5.

3.2 Numerical Differentiation and Integration

3.2.1 Finite Differences

Taylor's series is the basis for modern computing. This is because the computers know only "finite" numbers and not symbolic variables. And Taylor's series exactly does the same thing. It talks about the value of a dependent variable in a neighborhood of the representative location, given the value of the variable and its derivatives at that location. Hence, everything could be represented in digital computers once the finite value of the "difference" is given. On the other hand, any differential equation has to be converted into a difference equation in order to represent it in digital language. There lies the secret of numerical solution of any physical problem. The Tailor's series representation in the neighborhood of 'x' in the +ve and -ve direction are:

$$\begin{aligned}
y(x+h)&=y(x)+\frac{hy'(x)}{1!}+\frac{h^2y''(x)}{2!}+\frac{h^3y'''(x)}{3!}+O\left(h^4\right)\\
y(x-h)&=y(x)-\frac{hy'(x)}{1!}+\frac{h^2y''(x)}{2!}-\frac{h^3y'''(x)}{3!}+O\left(h^4\right)
\end{aligned} \qquad \text{eqn.(8)}$$

Rearranging the first equation above, one could obtain the finite difference form of the first derivative as:

$$y'(x)=\frac{y(x+hx)-y(x)}{h}+O(h^2) \qquad \text{eqn.(9)}$$

The above representation of first derivative is known to be 'forward difference' formula as the forward neighborhood value is used. The term $O(h^2)$ indicates the rest of the terms are of the order h^2 and is termed as the 'truncation error' - as these terms are usually ignored by assuming to be very small. This is applicable, however, for small values of 'h' – **the step size**. Hence, the forward difference formula is **accurate** up to $O(h)$. By subtraction of the second equation from the first, one obtains the finite central difference formula for the first derivative as:

$$y'(x)=\frac{y(x+h)-y(x-h)}{2h}+O(h^3) \qquad \text{eqn.(10)}$$

The above central difference formula is accurate up to $O(h^2)$ and has truncation errors of the order $O(h^3)$. Similarly, one could obtain the finite difference representations for any derivative.

3.2.2 Numerical differentiation

Numerical differentiation is many times either very easy or impossible. The differentiation could be done using the forward difference formula (eqn.9). For example, let us examine the function given below and try to numerically differentiate it.

$$f=\frac{e^x}{x}$$

$$f'(2)=\frac{f(2+h)-f(2)}{h}$$

Now, for various values of h,

h	0.2	0.1	0.05	0.01	0.005	0.002	0.001	0.0001
$f'(2)$	2.038	1.941	1.892	1.85	1.84	1.85	1.8	1.0

The correct value for the derivative is 1.84726402 – up to eight decimal **'precision'**. The above example indicates that there are errors in the numerical computations. Also, when working with fixed number of decimal places, a stage is reached where accuracy cannot be improved by reducing 'h'. This is due to the truncation errors. Here two types of truncation are involved – one from the finite difference formula and the other from the truncation various numerical values used as the computer takes only a finite value of the numerical exact value. Hence, one has to be extremely careful while numerical differentiation even though it appears to be very easy.

Higher order finite difference schemes could be used to improve accuracy of the lower order schemes. On the other hand, the Legrange's interpolation polynomial could be used and differentiated using basic calculus.

3.2.3 Integration

Numerical Integration / Quadrature is the process of performing a definite integral where the integrand is not directly integrable. Mathematically, if $I = \int_{x_1}^{x_2} f(x)dx$, then the task is to numerically compute the value of I as accurately as possible. Obvious techniques such as Square rule (counting) and Rectangle rule are left the readers' reading. Herein the basic Simpson's rule and some of the closed-type formulae will be discussed.

Open and closed formulas: An integration formula is said to be of open type if it calculates the integration with in the data points available. On the other hand, the closed formulas compute integration including outside domains.

Closed Newton-Cotes formulas:

Consider A function $f(x)$ has known values at the x_i: $f(x_i) = f_i$ and $x_i = ih$; $i = 1,2,\ldots,N$ where N is the number of points considered for integration.

Trapezoidal Rule: The trapezoidal rule is an obvious closed type formula between to points. In considers the area between the points to be trapezoidal and calculates the area assuming linear variation of the function *f(x)*.

$$\int_{x_1}^{x_2} f(x)dx = h\left[\frac{1}{2}f_1 + \frac{1}{2}f_2\right] + 0\left(h^3 f''\right)$$

This formula is accurate up to and including polynomial order 1.

Simpson's Rule: The Simpson's 1/3 formula is one of the simplest and accurate. It is also easy to implement in the digital computers. It considers 3 points for integration – or 2 intervals – and is known as:

$$\int_{x_1}^{x_3} f(x)dx = h\left[\frac{1}{3}f_1 + \frac{4}{3}f_2 + \frac{1}{3}f_3\right] + 0\left(h^5 f^{IIII}\right)$$

This is accurate up to and including order '3' and can be applied to many scenarios in many fields of engineering and science.

Simpson's 3/8 Rule: This is a four point formula and also accurate up to and including order '3'. It is given as:

$$\int_{x_1}^{x_2} f(x)dx = h\left[\frac{3}{8}f_1 + \frac{9}{8}f_2 + \frac{9}{8}f_3 + \frac{3}{8}f_4\right] + 0\left(h^5 f^{IIII}\right)$$

As it can be used for 3 intervals, a combination of this with the 1/3 formula is applicable for many practical situations where the intervals may be odd or even.

The five point formula: Bode's Rule is a five point formula and is accurate up to order '5'. This is many times the basis for advanced integration formulas and algorithms.

$$\int_{x_1}^{x_5} f(x)dx = h\left[\frac{14}{45}f_1 + \frac{64}{45}f_2 + \frac{24}{45}f_3 + \frac{64}{45}f_4 + \frac{14}{45}f_5\right] + 0\left(h^7 f^6\right)$$

The above formulae can be extended for multiple intervals and can then be used to carrying out integration of large domains.

4.0 Basic equations of coastal hydrodynamics

Flow of oc[illegible] y [illegible] governed by the Navier-Stokes equation. H[illegible]wever, lea[illegible]ing alon[illegible] th[illegible] difficulti[illegible]s in solving the equations for a given situation, it essential to have valuable data, along wi[illegible] [illegible]m[illegible]r[illegible]c[illegible]l m[illegible], [illegible] ga[illegible] reasonable understanding of the oceans. Eventually, an understanding of the ocean-

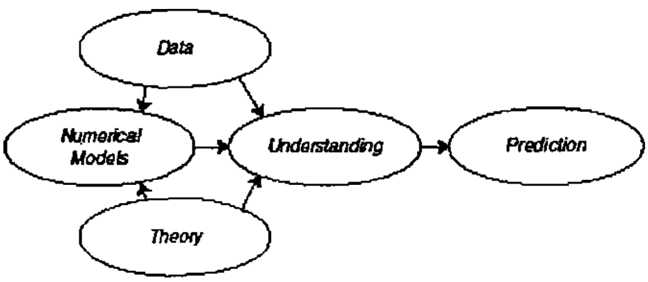

Fig.4. Data, numerical models, and theory are all necessary to understand the ocean.

atmosphere-land system will lead to predictions of future states of the system - to forecast climate change, currents, and waves. Nonetheless, the numerical equations are approximations to the continuous analytic equations that describe fluid flow, they contain no information about flow between grid points, and they cannot yet be used to describe fully the turbulent flow seen in the ocean.

Oceanic dimensions range from around 1500 km for the minimum width of the Atlantic to more than 13,000 km for the north-south extent of the Atlantic and the width of the Pacific. Typical depths are only 3–4 km. So horizontal dimensions of ocean basins are 1,000 times greater than the vertical dimension. A scale model of the Pacific, the size of an 8.5 × 11 in sheet of paper, would have dimensions similar to the paper: a width of 10,000 km scales to 10 in, and a depth of 3 km scales to 0.003 in, the typical thickness of a piece of paper. The small ratio of depth to width of ocean basins is very important for understanding ocean currents. Vertical velocities must be much smaller than horizontal velocities. Even over distances of a few hundred kilometers, the vertical velocity must be less than 1% of the horizontal velocity. The relatively small vertical velocities also have great influence on turbulence. Three dimensional turbulence is fundamentally different than two-dimensional turbulence. In two dimensions, vortex lines must always be vertical, and there can be little vortex stretching. In three dimensions, vortex stretching plays a fundamental role in turbulence.

Fluid mechanics used in oceanography is based on Newtonian mechanics modified by our evolving understanding of turbulence. Conservation of mass, momentum, angular momentum, and energy lead to particular equations having names that hide their origins. It is worth while to note that, only a few forces are important in physical oceanography: gravity, buoyancy due to difference in density of sea-water, and wind stress. Remember that forces are vectors. They have magnitude and direction.

1. *Gravity* is the dominant force. The weight of the water in the ocean produces pressure, and the varying weight of water in different regions of the ocean produces horizontal pressure gradients. Changes in gravity, due to the motion of sun and moon relative to earth produces tides, tidal currents, and tidal mixing in the interior of the ocean.

2. *Buoyancy* is the upward or downward force acting on a parcel of water that is more or less dense than other water at its level. For example, cold air blowing over the sea cools surface

waters causing them to be denser than the water beneath. The difference in density results in a force that causes the water to sink.

3. *Wind* blowing across the sea surface transfers horizontal momentum to the sea, creating currents. Wind blowing over waves on the sea surface leads to an uneven distribution of pressure over the waves. The pressure distribution transfers energy to the waves, causing them to grow into bigger waves.

4. *Pseudo-forces* are apparent forces that arise from motion in curvilinear or rotating coordinate systems. Thus, writing the equations for inertial motion in a rotating coordinate system leads to additional force terms called pseudo forces. For example, Newton's first law states that there is no change in motion of a body unless a resultant force acts on it. Yet a body moving at constant velocity seems to change direction when viewed from a rotating coordinate system. The change in direction is attributed to a pseudo-force, the Coriolis force.

5. *Coriolis Force* is the dominant pseudo-force influencing currents moving in a coordinate system fixed to the earth.

Summary of Forces in Geophysical Fluid Dynamics:

Dominant Forces

Gravity	Gives rise to pressure forces and tides.
Wind Stress	Transfers horizontal momentum into the sea.
Buoyancy	Result from changes in density, leads to convection.

Other Forces

Atmospheric Pressure	Results in inverted barometer effect.
Seismic	Results in *tsunamis* driven by earthquakes.

Coordinate System:

Coordinate systems allow us to find locations in theory and practice. Various systems are used depending on the size of the features to be described or mapped.

1. *Cartesian Coordinate System* is the one we will use most commonly in this course to keep the discussion as simple as possible. We can describe most processes in Cartesian coordinates without the mathematical complexity of spherical coordinates. The standard convention in geophysical fluid mechanics is x is to the east, y is to the north, and z is up.

2. *f-Plane* is a Cartesian coordinate system in which the Coriolis force is assumed constant. It is useful for describing flow in regions small compared with the radius of the earth and larger than a few tens of kilometers.

3. *β-plane* is a Cartesian coordinate system in which the Coriolis force is assumed to vary linearly with latitude. It is useful for describing flow over areas as large as ocean basins.

4. *Spherical coordinates* are used to describe flows that extend over large distances and in numerical calculations of basin and global scale flows.

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Recalling the fact that the vertical velocities and accelerations are much smaller than the horizontal ones, for an incompressible homogeneous fluid, the SWE with respect to Cartesian co-ordinate frame fixed to the rotating earth can be written as,

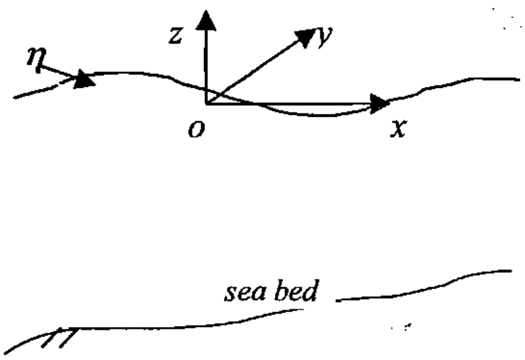

Fig.5. Coordinate system for shallow water equations

The continuity equation:

$$u_{,x}+v_{,y}+w_{,z}=0 \qquad \text{eqn.(11a)}$$

The momentum equations in the conservation form:

$$\begin{aligned} u_{,t}+(u)^2_{,x}+(uv)_{,y}+(uw)_{,z}-fv &= -g\eta_{,x}-\rho^{-1}p_{a_x}+\rho^{-1}\tau_x \\ v_{,t}+(uv)_{,x}+(v^2)_{,y}+(vw)_{,z}+fu &= -g\eta_{,y}-\rho^{-1}\tau_y \end{aligned} \qquad \text{eqn.(11b,c)}$$

and the vertical direction equation becomes,

$$p_{,z}=-\rho g. \qquad \text{eqn.(11d)}$$

In the above equations, (u,v,w) is the velocity vector, η is the free surface elevation from the still water level, g the acceleration due to gravity, ρ the density of water and p is the pressure. f is the coriolis force term and is defined as $2\Omega sin(\varphi)$; with φ - the latitude and the Ω rate of earth rotation (=7.292 x 10^{-5} rad./s). The ',' represents partial derivative with respect to the variable on the right of it. The stresses is x and y directions, τ_x and τ_y, are defined as:

$$\begin{aligned} \tau_x &= \tau_{xy,x}+\tau_{yx,y}+\tau_{zx,z} \\ \tau_y &= \tau_{xy,x}+\tau_{yy,y}+\tau_{zy,z} \end{aligned} \qquad \text{eqn.(12)}$$

Vertically integrated equations:

The vertical variation of flow is insignificant. Hence,

$\Rightarrow$ Explicit dependence of variables in the z-direction can be eliminated by vertically integrating the equations, i.e., taking the total flux in the horizontal direction only into account.

$\Rightarrow$ we will deal with vertically averaged velocities (or) volume flux across a vertical section and across an horizontal edge.

$\Rightarrow$ this approach reduces the dimensions of the problem and hence the number of variables.

Integrating the continuity equation:

$$\int_{-h}^{\eta} u_{,x}dz + \int_{-h}^{\eta} v_{,y}dz + (w_\eta) - (w)_{-h} = 0$$

But the kinematic condition at the free surface requires that;

$$(\eta_{,t} + u\eta_{,x} + u\eta_{,y} - w)_\eta = 0$$

$$(h_{,t} + uh_{,x} + uh_{,y} - w)_{-h} = 0$$

Hence,

$$\frac{\partial}{\partial x}\int_{-h}^{\eta} udz + \frac{\partial}{\partial y}\int_{-h}^{\eta} vdz + (\eta_{,t} + u\eta_{,x} + v\eta_{,y} - h_{,t} - uh_{,x} - vh_{,y}) = 0$$

$\Rightarrow \quad q_{x,x} + q_{y,y} + \eta_{,t} = 0$ eqn.(13a)

Where, $q_x = H\bar{u} = \int_{-h}^{\eta} udz \quad \Rightarrow \quad \bar{u} = \frac{1}{H}\int_{-h}^{\eta} udz$

Similarly for q_y.

Using a similar approach for momentum equation becomes,

$$q_{x,t} + \frac{q_x}{H}q_{x,x} + \frac{q_y}{H}q_{x,y} - fq_y = -\rho^{-1}Hp_{a,x} - gH\eta_{,x} + \rho^{-1}(F_{xx,x} + F_{yx,y} + \tau_{dx} - \tau_{bx})$$

eqn.(13b,c)

$$q_{y,t} + \frac{q_y}{H}q_{y,z} + \frac{q_y}{H}q_{y,y} + fq_x = -\rho^{-1}Hp_{a,y} - gH\eta_{,y} + \rho^{-1}(F_{xy,x} + F_{yy,y} + \tau_{ay} - \tau_{by})$$

Equation (13) is called the vertically integrated form of the shallow water equations. The wind and bottom stresses are defined as:

Wind Stresses: $\tau_a = \rho_a k_a W|\overline{W}|$

Bottom Stresses: $\tau_b = \rho k_b M^{-2}|q|q_x$

Internal Stresses: Usually neglected.

Linearisation of inertial acceleration: For weakly non-linear problems, the Storm surges and Tsunamis fall in this category, the linearization eliminates the inertial terms (Das,1981).

The linearized equations are,

$$\begin{aligned} &q_{x,x} + q_{y,y} + \eta_{,t} = 0 \\ &q_{x,t} - fq_y = -\rho^{-1} H p_{a,x} - gH\eta_{,x} + \rho^{-1}\left(\tau_{ax} - \tau_{bx}\right) \\ &q_{y,t} + fq_x = -\rho^{-1} H p_{a,y} - gH\eta_{,y} + \rho^{-1}\left(\tau_{ay} - \tau_{by}\right) \end{aligned} \qquad \text{eqn.(14,a,b,c)}$$

4.1 Initial and Boundary Conditions

Initial condition

For the linear form of the governing equations, the usual practice in **storm surge** simulation studies is to assume the ocean to be initially at rest, before the introduction of the wind stress at the ocean free surface, i.e η, q_x , q_y = 0 for $t \le 0$. However, for Tsunamis the initial displacement has to be given. This is caused by the submarine activity and has to be specified based on the type of submarine disturbance. The readers are advised to look into the literature for this purpose.

Boundary conditions

Numerical simulation of flow fields in ocean shelf regions requires fine spatial grids to represent the small-scale features of surge phenomenon. This requirement and the limitation of computational resources demand the use of a finite solution domain. This involves specification of artificial boundaries to the study area. In the case of a shelf along an open coast, three artificial boundaries are specified, one along the open sea-side at the shelf break and two on the lateral sides. The length scales of the phenomenon under consideration and available computational resources guide the choice of location of lateral boundaries.

5.0 Numerical methods applicable to coastal hydrodynamics

5.1 Time Stepping

A review of the governing equations, eqn.14, will help realising that our problems are non-steady and hence a time derivative is always involved. Time derivatives are usually discretised using finite differences – this is applicable any numerical methods. Let us consider,

$$\frac{dU}{dt}=f(u,t);U=\dot{u}(t)$$

- The time is usually discretised with constant Δt (adaptive time stepping is possible for specific needs)
- U^n denotes U at $t = n\Delta t$
- It is also assume $U^n, U^{n-1}, \ldots$ are available and the objective is to estimate U^{n+1}

The schemes are usually classified into two level and three level schemes.

Two Level Schemes:

1. **Euler schemes : (forward scheme-Explicit)**

$$\frac{U^{n+1}-U^n}{\Delta t}=f^n+o(\Delta t)$$

2. **Backward scheme:(Implicit scheme)**

$$\frac{U^{n+1}-U^n}{\Delta t}=f^{n+1}+o(\Delta t) \text{ where } f^{n+1}=f(U^{n+1},t^{n+1})$$

In explicit schemes, the new value of U at (n+1) level is determined explicitly by values a n level and previous levels. On the other hand the implicit scheme tries to satisfy the governing equation in the future level – hence, simultaneous equations need to be solved. However, the implicit schemes have excellent stability. The implicit schemes are impractical for large practical problems.

Three Level Schemes:

The dependent variable at (n+1) level are related to its value at x and x-1 level.

$$U^{n+1}=U^{n-1}+\int_{(x-1)\Delta t}^{(x+1)\Delta t} f(u,t)\,dt$$

1. **Leap frog Scheme:** In the leap-frog scheme, one tries to leap, at the n[th] level, from the n-1 to n+1 level. All the other variables are defined at the n[th] level. This scheme had been used by many shallow water models and is very useful for our purpose.

$$U^{n+1} = U^{n-1} + 2\Delta t\left(f^{n}\right) + o(\Delta t^{3})$$

2. **Adams Bashforth Scheme:** In this case, f in Leap frog scheme is approximated by value at the center of x to x+1 level.

$$U^{n+1} = U^{n-1} + \Delta t\left(\frac{3}{2}f^{n} + \frac{1}{2}f^{n+1}\right) + o(\Delta t^{3})$$

5.2 Discretisation of the governing equations

The ADI (Alternating Direction Implicit) scheme: Let us consider the shallow water equaitons, eqn.14.

$$\frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} + \frac{\partial \eta}{\partial t} = 0 \quad \longrightarrow \quad \mathrm{I}$$

$$\frac{\partial q_x}{\partial t} - f q_y = -gH\frac{\partial \eta}{\partial x} + \rho^{-1}(\tau_{ax} - \tau_{bx}) \quad \longrightarrow \quad \mathrm{II}$$

$$\frac{\partial q_y}{\partial t} + f q_x = -gH\frac{\partial \eta}{\partial y} + \rho^{-1}(\tau_{ay} - \tau_{by}) \quad \longrightarrow \quad \mathrm{III}$$

In the ADI method, the component equations are implicitly written alternatively in each ½ time step.

1[st] half : Implicit in x- direction for $\Delta t/2$ (coupling I & II)

$$\frac{(q_x)^{n+1/2}{}_{i+1} - (q_x)^{n+1/2}{}_{i-1}}{2\Delta x} + \frac{(q_y)^{n}{}_{i+1} - (q_y)^{n}{}_{i-1}}{2\Delta y} + \frac{\eta^{n+1/2} - \eta^{n}}{\Delta t} = 0$$

$$\frac{q_x^{n+1/2} - q_x^{n}}{\Delta t/2} - f q_y^{n} = -gH\left(\frac{\eta_{i+1} - \eta_i}{\Delta x}\right)^{n+1/2} + \rho^{-1}(\tau_{ax} - \tau_{bx})$$

$$\frac{q_y^{n+1} - q_y^{n}}{\Delta t} - f q_x^{n} = -gH\left(\frac{\eta_{i+1} - \eta_i}{\Delta y}\right)^{n} + \rho^{-1}(\tau_{ax} - \tau_{bx})$$

2nd half: Implicit in y-direction for $\Delta t/2$ (coupling I & III)

$$\frac{(q_x)^n_{i+1}-(q_x)^n_{i-1}}{2\Delta x}+\frac{(q_y)^{n+1/2}_{i+1}-(q_y)^{n+1/2}_{i-1}}{2\Delta y}+\frac{\eta^{n+1/2}-\eta^n}{\Delta t}=0$$

$$\frac{q_y^{n+1/2}-q_y^n}{\Delta t/2}-fq_x^n=-gH\left(\frac{\eta_{i+1}-\eta_i}{\Delta y}\right)^{n+1/2}+\rho^{-1}(\tau_{ax}-\tau_{bx})$$

$$\frac{q_x^{n+1}-q_x^n}{\Delta t}-fq_y^n=-gH\left(\frac{\eta_{i+1}-\eta_i}{\Delta x}\right)^n+\rho^{-1}(\tau_{ax}-\tau_{bx})$$

The above set of equations result in tri-diagonal system of linear simultaneous equations and can be easily solved in each ½ time step – alternatively. This method is most suitable for shallow water equations.

6.0 Public domain codes

Princeton Ocean Model developed by Blumberg and Mellor (1987) is widely used for describing coastal currents. It is a direct descendant of the Bryan-Cox model. It includes thermodynamic processes, turbulent mixing, and the Boussinesq and hydrostatic approximations. The Coriolis parameter is allowed to vary using a beta-plane approximation. Because the model must include a wide range of depths, Blumberg and Mellor used a vertical coordinate σ scaled by the depth of the water: $\sigma = (z - \eta)/(H + \eta)$, where $z = \eta(x, y, t)$ is the sea surface, and $z = -H(x, y)$ is the bottom. Sub-grid turbulence is parameterized using a closure scheme proposed by Mellor and Yamada (1982) whereby eddy diffusion coefficients vary with the size of the eddies producing the mixing and the shear of the flow.

The model is driven by wind stress and heat and water fluxes from meteorological models. The model uses known geostrophic, tidal, and Ekman currents at the outer boundary. The model has been used to calculate the three-dimensional distribution of velocity, salinity, sea level, temperature, and turbulence for up to 30 days over a region roughly 100–1000 km on a side with grid spacing of 1–50 km.

7.0 Referenes:

1) **Blumberg A.F., and G.L. Mellor**. 1987. A description of a three-dimensional ocean circulation model. In: *Three-Dimensional Coastal Ocean Models*. Edited by N. S. Heaps.1–16. Washington, DC: American Geophysical Union.

2) **Das,P.K.**(1981) Storm surges in the Bay of Bengal. *Proc. Indian Acad. Sci.(Engg.Sci.)*,4,3

3) **Chitra. K** (1997) Simulation of Storm surges along the east coast of India, *M.S. Thesis, Ocean Engineering Center*, I.I.T.Madras

TSUNAMI EFFECT ON COASTAL STRUCTURES

R.Sundaravadivelu
Professor, Dept. of Ocean Engineering, IIT Madras, Chennai – 600 036,
rsun@iitm.ac.in

INTRODUCTION

The Tsunami effect on coastal structures situated in Chennai Port, Andaman and Nicobar Island and coastal protection structures in Karaikal are discussed.

CHENNAI PORT

Layout of Chennai harbour showing the entrance main harbour and location of oil berth is shown in Fig.1

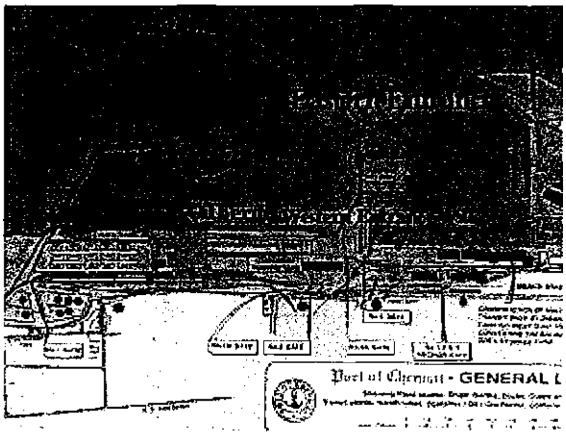

Fig. 1: Layout Of Chennai Port

In Chennai Port due to scouring, Northern and Southern block wall at entrance to main harbour basin were partially damaged. The mooring dolphin of 2nd oil jetty at Bharathi dock got fully damaged **(Fig.2)**.

Repair Scheme

The proposed mooring dolphin will have 16 number of RCC bored cast-in-situ vertical piles of dia 1250mm. The decking over the piles will be a single RCC deck slab of 2.44m thick with reinforcement in different layers.

The details of block work wall in western entrance in main harbour basin is shown in **Fig.3** and details of settlement of block work due to Tsunami waves and cracks developed in the wall are shown in **Fig.4a and 4b.**

Measures taken for Rehabilitation of block wall

A row of steel sheet piles ARBED section AZ18 will be driven around the block walls on both eastern and western end about 3m away from the face of wall. The sheet piles will be driven upto a level of (-)20.0m approx below bed level around the end portion of wall up to about 3m beyond the location of crack. The cutoff level of sheet piles will be upto existing top level of block wall.

A PCC of mix 1:3:6 using 40mm metal for a depth of 2m above bed level will be provided using Tremie method to act as a bottom plug for the wall. This concrete will be done using an admixture of chloride free, accelerating, water reducing agent viz "Conplast NC" of Fosroc Chemical or equivalent.

The inner core above this level will be filled with sea sand, well-compacted upto +2m level inside the sheet pile wall.

The top portion of core will be provided with PCC of mix 1:3:6 using 40mm metal to a thickness of 2m. So that top of this concrete will serve as top plug upto a level Of +4.0m.

The top surface of block wall with sheet pile wall around will be first provided with 150mm thick reinforced cement concrete. In this slab also, 16mm dia shear key will be provided. Finally a reinforced cement concrete of 500mm thick with reinforcement in two layeres to the full area of block wall upto sheet pile wall around will be provided.

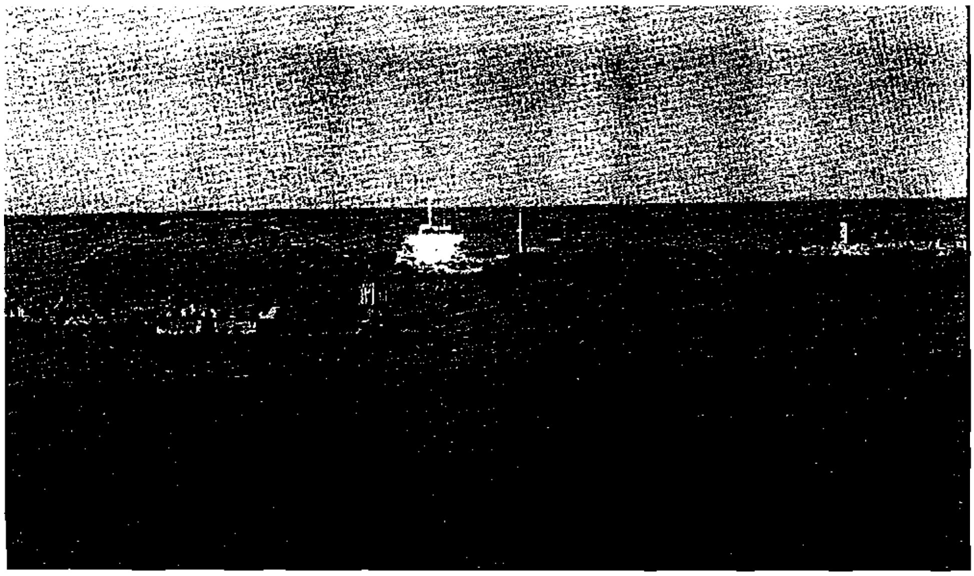

Fig. 2: Location of Oil jetty

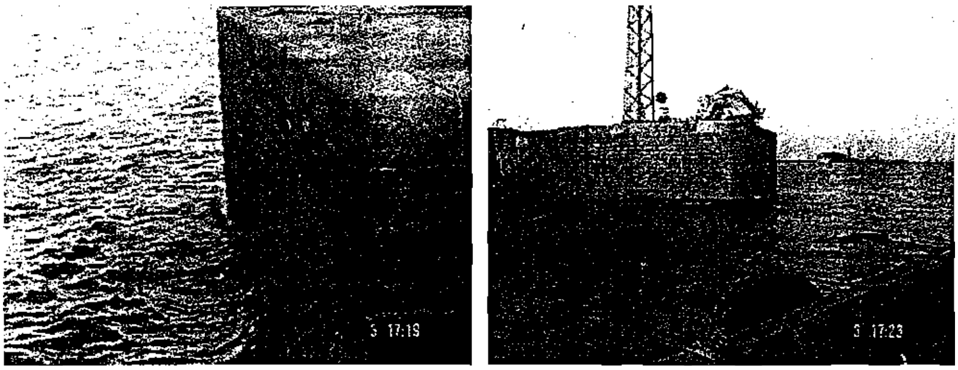

Fig. 3: Western Entrance Wall

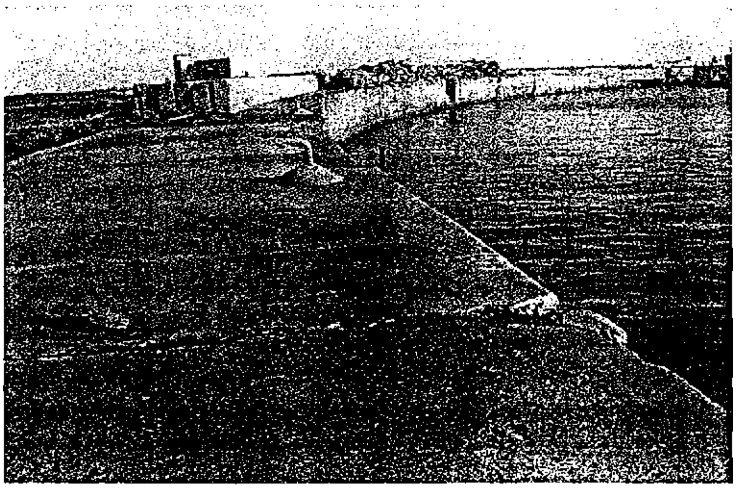

Fig. 4a: Crack In Eastern Side Entrance Wall

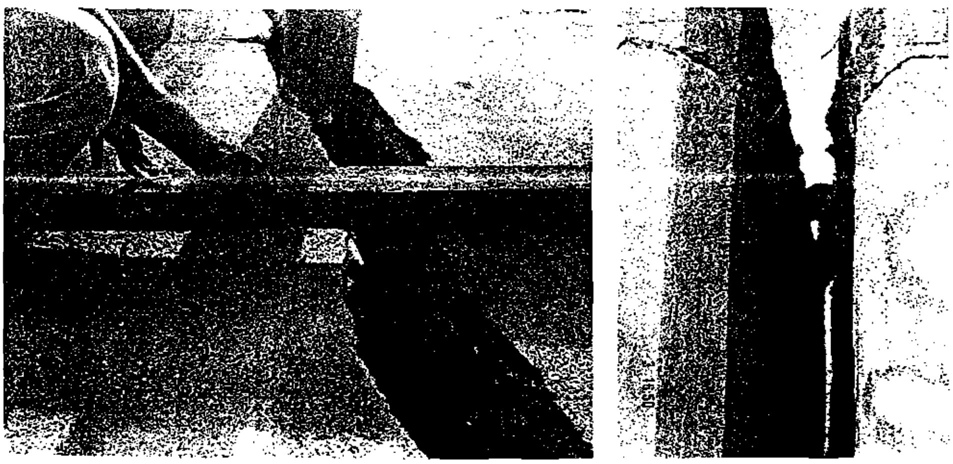

Fig. 4b: Crack In The Wall

BERTHING STRUCTURE IN PORT BLAIR-ANDAMAN NICOBAR ISLAND

The plan showing location of Andaman Nicobar Island is shown in **Fig. 5a and 5b.**

The pile supported berthing structure, pile supported berthing structures with retaining wall and monolith type berthing structure have suffered different types of damages.

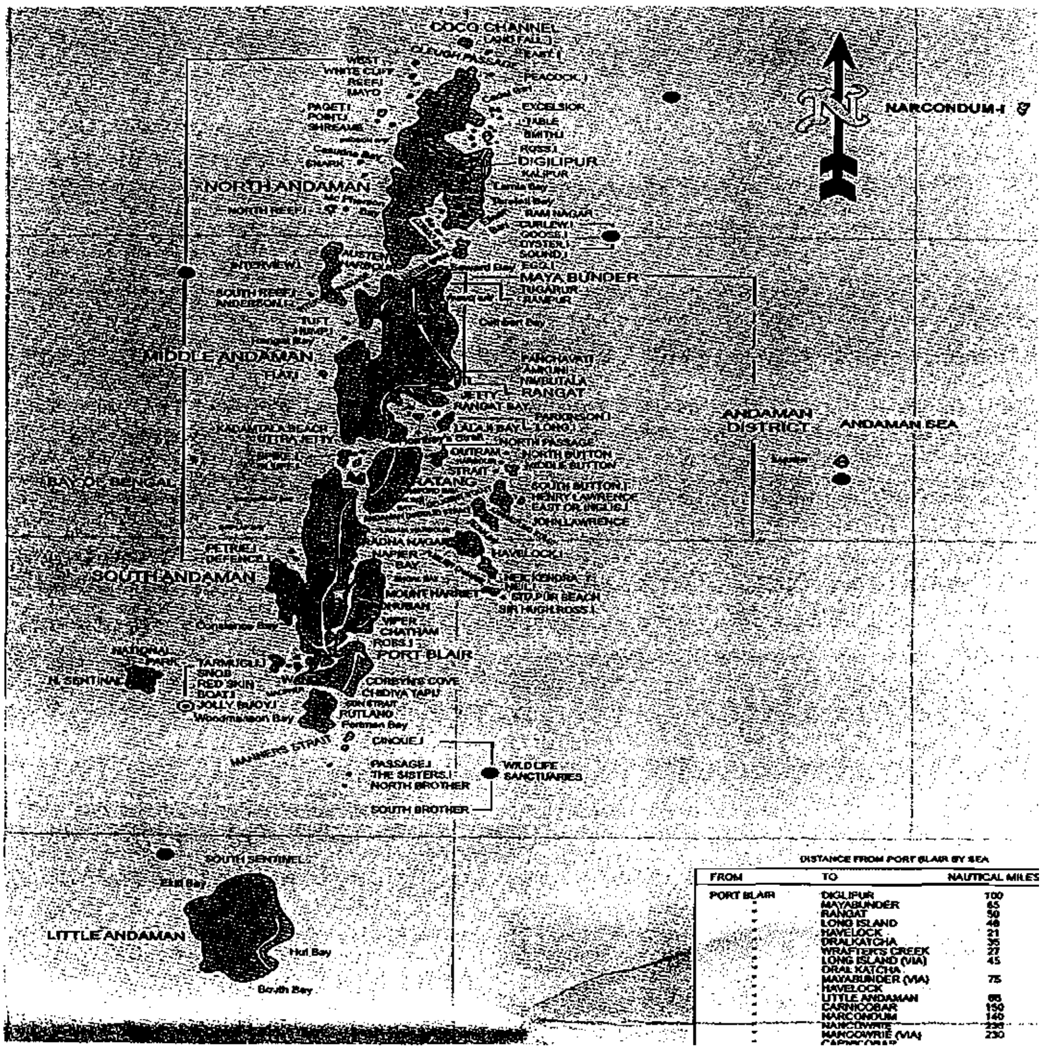

Fig. 5a: Andaman Islands

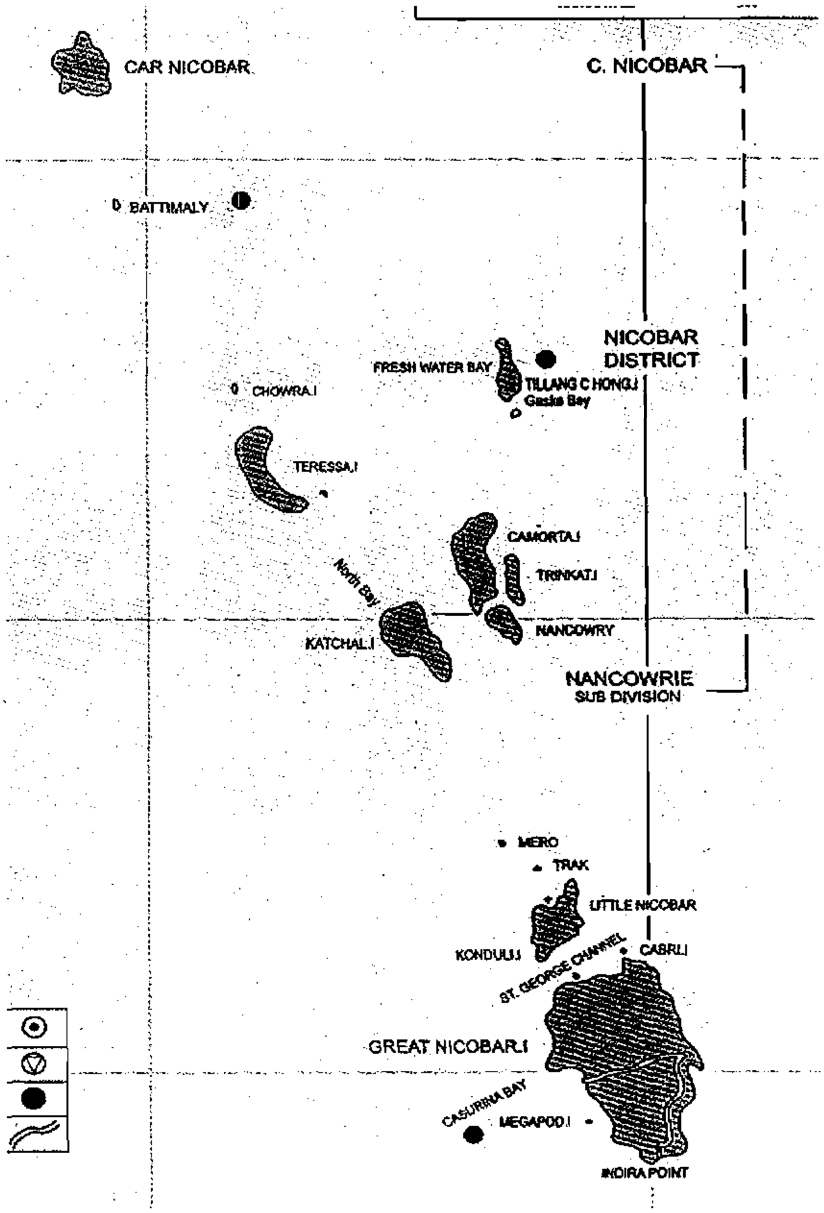

Fig. 5b: Nicobar Island

PILE SUPPORTED BERTHING STRUCTURE

The layout of Haddo wharf is shown in **Fig.6**

The haddo wharf has 4 berths. The berth no.1 is constructed in monolith, berth no.2 and 4 is constructed with vertical and raker piles and berth no.3 is constructed with vertical and raker piles and a diaphragm wall (retaining wall). The cross sectional details of Haddo wharf berth no.3 showing the position of piles shown in **Fig.7.** The pile supported berthing structures have raker piles in transverse direction with no raker piles in longitudinal direction. The 250 m long berthing structure with five blocks of each 50 m has expansion joint of about 20 mm. The founding level of piles at various depth varies because of varying rock bottom level. The soil above the rock level in silty sand and this depth of soil varies along the length of the berth. The response at the berth was in different frequencies due to varying rock level and due to liquefaction of soil. Hence the blocks collided with each other causing damage to expansion joint in deck slab.

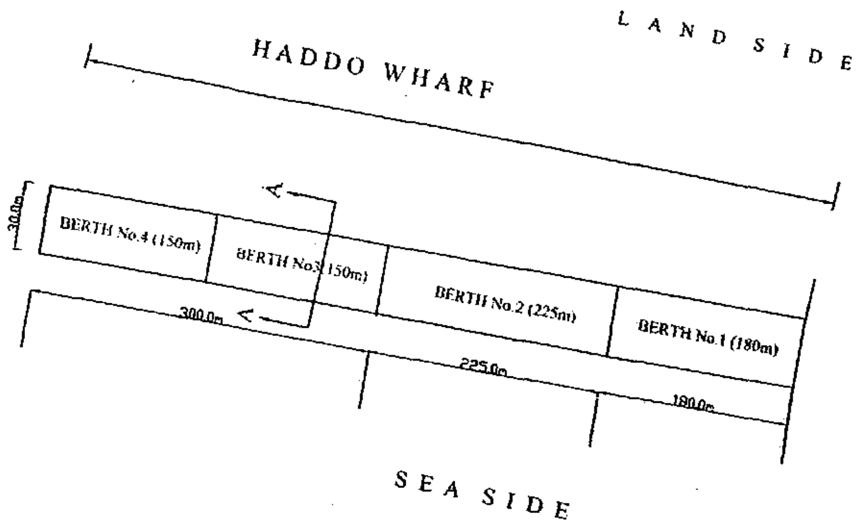

Fig. 6: Layout of Haddo wharf at Port Blair, Andaman

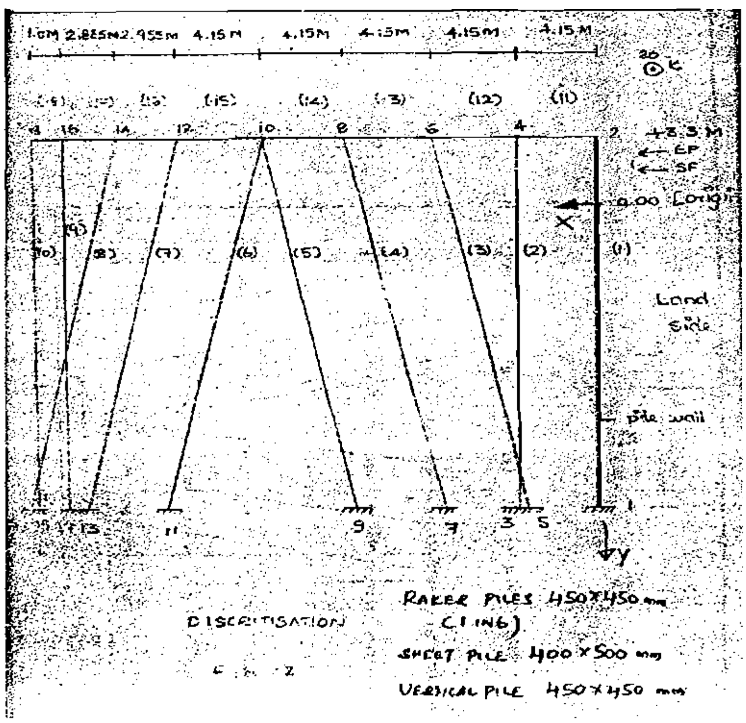

Fig. 7: Section A-A of Haddo wharf berth no.3

The structure with retaining wall in the rear is very stiff and suffered damage as it was subjected to large lateral force not only due to deck mass but also due to earth pressure at the back of diaphragm wall. The lateral earth pressure during earthquake had increased since the soil became saturated due to overtopping of water by Tsunami waves and liquefaction of soils due to more than ten of after shocks.

The settlement in Haddo wharf 3 is shown in **Fig.8.** The liquefaction of soil has also resulted in settlement near the compound wall as shown in **Fig.9.**

Fig. 8: Settlement Behind Haddo Wharf

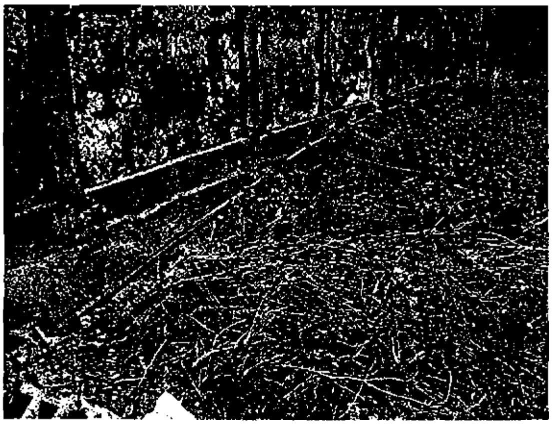

Fig. 9. Settlement Near Compound Wall Near Haddo Wharf

INTEGRITY TEST

In order to ascertain the strength of the berthing structure after Tsunami, integrity test have been carried out on the pile supported structure. Details on integrity tests for the damaged berth is shown in **Fig.10a.** Integrity test was carried out by fixing the wooden blocks positioned with accelerometers on the deck. The tugboat was tied to the structure and released it resulting in free vibration. The free vibration has concise stored in the storage. The typical response showing the historic details is given below

The natural frequency of the berth is obtained. The result indicates that berth no.2, 3 and 4 have natural frequency of 1.12 S, 0.74 S and 0.65 S respectively. The results also indicate that the berth no.3 is stiff. The finite element analysis of the structure indicates natural frequency of ______, and _______ of berth no.3 and 4.

Based on the above results it is concluded that the structure have not suffered any damage except the damage near the expansion joint.

The details showing rehabilitation of expansion joint is shown in **Fig. 11, Fig. 12 and Fig.13.**

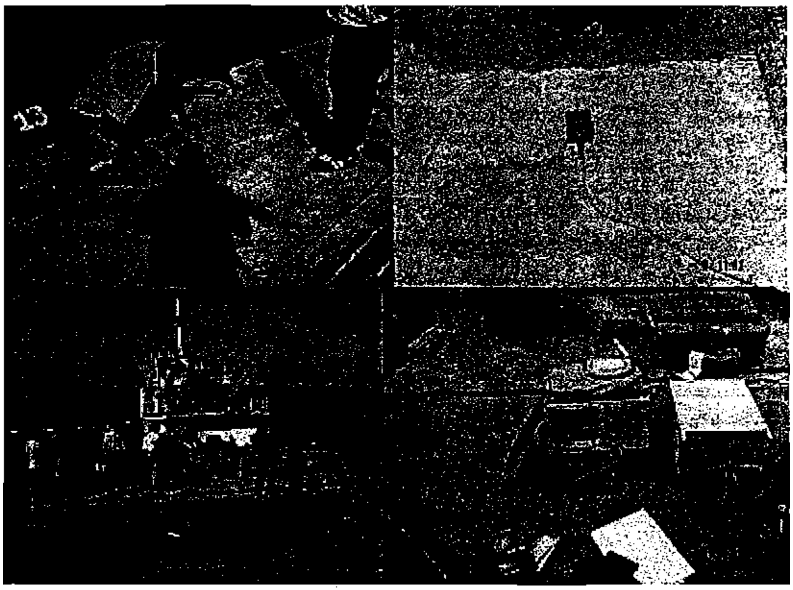

Fig. 10a: Integrity Tests For The Damaged Berth

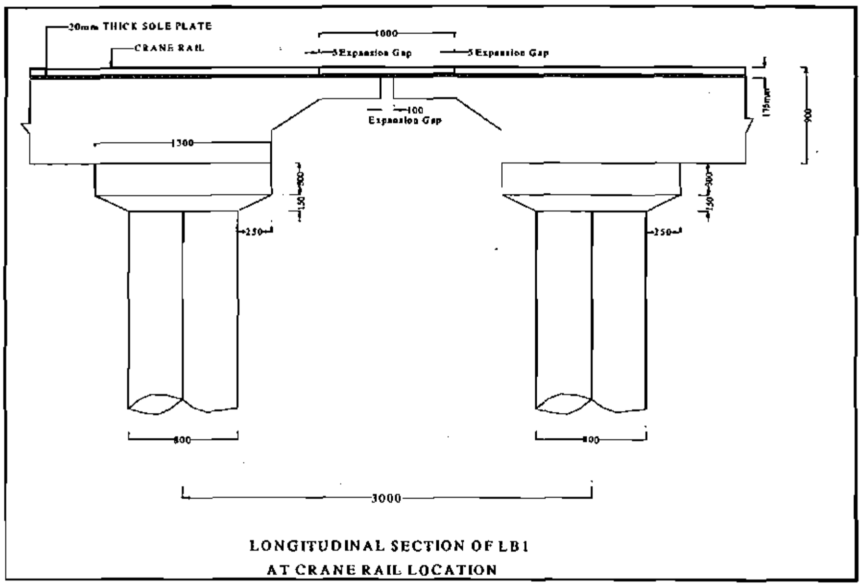

Fig. 11: Longitudinal Section At Crane Rail Location

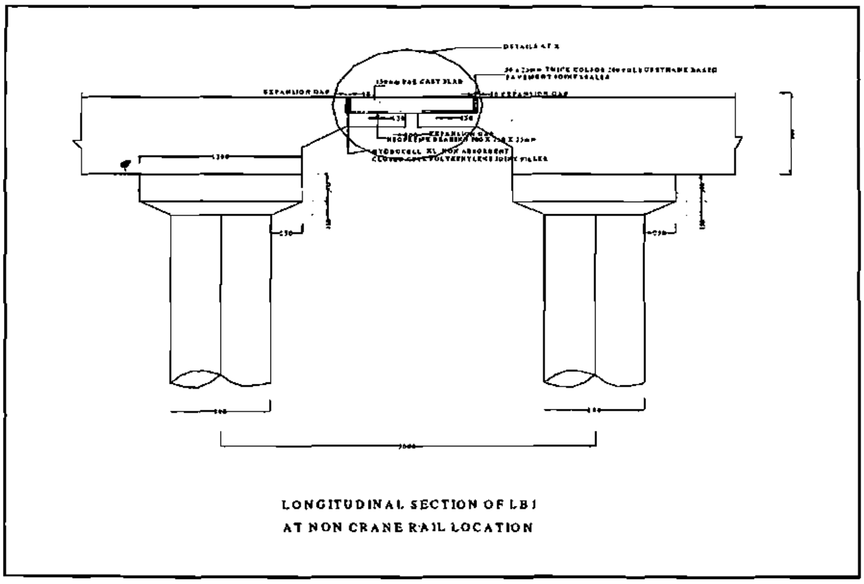

Fig. 12: Longitudinal Section At Non Crane Rail Location

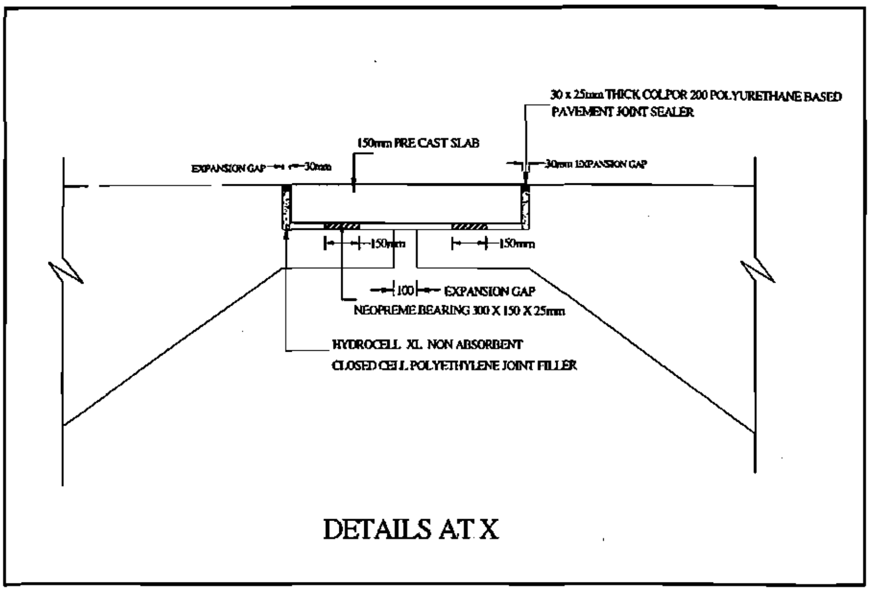

Fig. 13: Longitudinal Section At Non Crane Rail Location (Details At X)

DRY DOCK

Due to Tsunami, dry dock gate in Port Blair got damaged requiring replacement/rehabilitation. Details showing the damages in the gate and overtopping of vessel is shown in **Fig.14 and 14a**

In Andaman island, liquefaction of soil, had damaged expansion joints of deck slab of berthing structures and tilting of monolithic structure. Pile with pile cap joint failure is observed.

The Coastal protection structure with toe protected by gabions and stone groynes are observed to resist the Tsunami force and no damage was reported.

Fig. 14: Overtopping Of Vessel In The Dry Dock

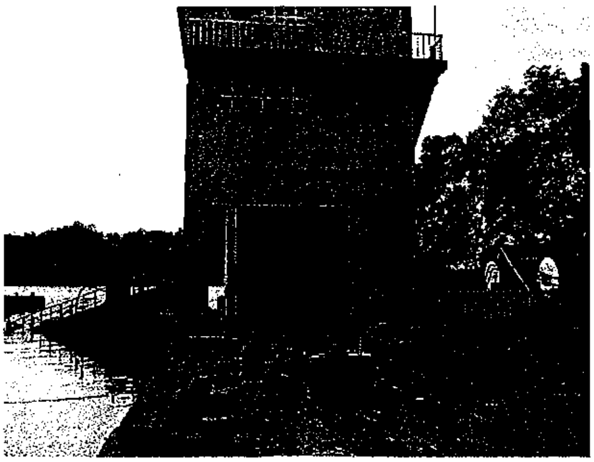

Fig. 14a: Damage In The Dry Dock Gate

RISING OF TIDE LEVELS AT ANDAMAN

Fig.15 shows the Intensity of Tsunami waves occurred in Andaman as compared to normal tide level

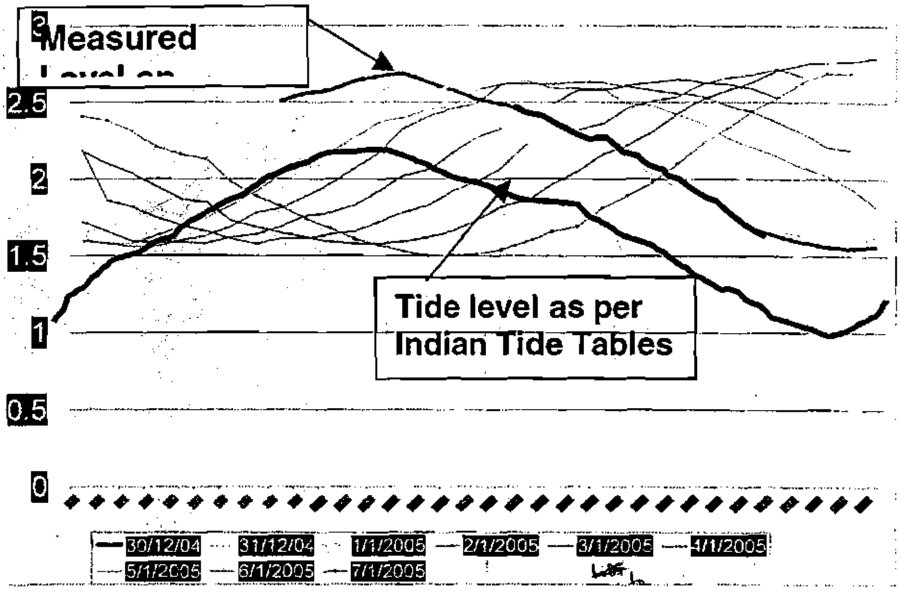

Fig.15: Tide level

OFF SHORE TRANSMISSION TOWER

The Transmission tower in off shore got damaged due to Tsunami waves. The four piles below the tower got sheared from the pile muff requiring rehabilitation. Details of damage caused to the tower are shown in **Fig.16a** and the repair measures taken in the rehabilitation of transmission tower are shown in **Fig 16 b** to **16 c.**

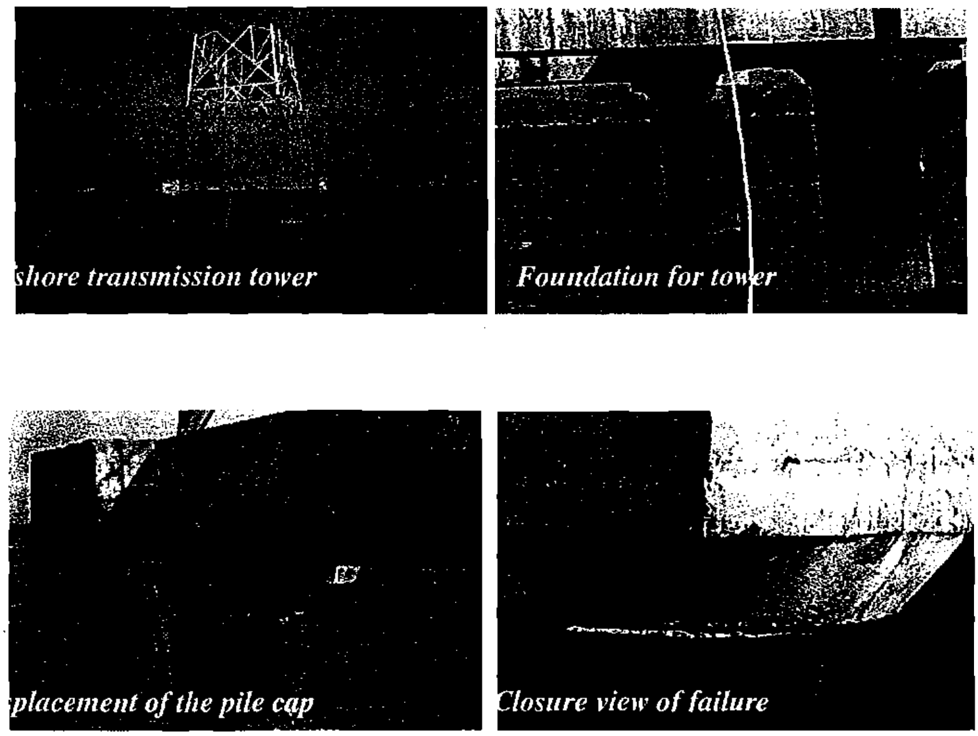

Fig. 16 a: Damage In The Transmission Tower

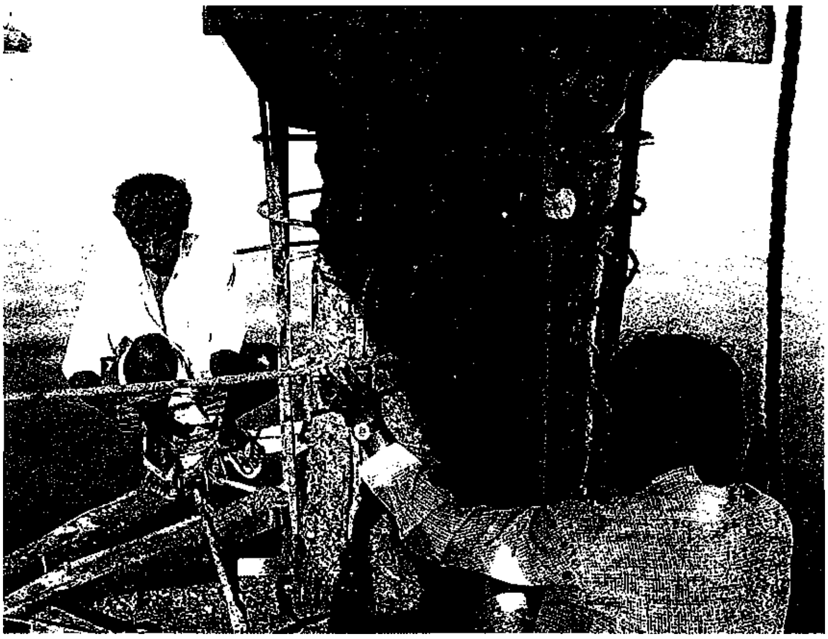

Fig. 16 b: A View Of Rehabilitation Of Transmission Tower

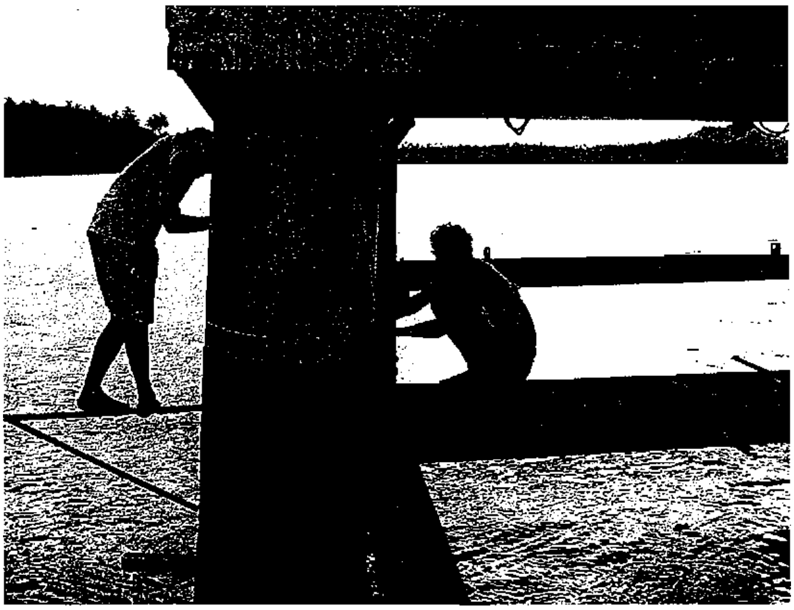

Fig.16 c. Rehabilitation Of Transmission Tower After Completion

MONOLITH WALLS IN NAVAL WHARF

The Monolith walls which are found on sandy soils are observed to have tilted towards the seaside as well as towards the pile supported approach jetty. The tilt towards pile supported jetty has caused severe damages near expansion joints.

The Monolith structure which was found on rock has not suffered any damages. The Damages of Monolith structure founded on sand may be due to the following.

- Saturation of soil behind monolith wall due to Tsunami waves.
- Liquefaction of soil behind the berth.
- The receding tsunami waves in front of monolith reduced the water level below the chart datum (CD) by more than 3 m. and would have created more than 6 m. height of differential water pressure.

The sandy soil may not have adequate strength to resist these forces.

The settlement behind monolith is shown in **Fig.17**

Fig. 17: Settlement Behind Caisson Due To Liquefaction

HUTBAY

The breakwater in hutbay got damaged due to Tsunami and a part of breakwater was washed upto the water level. The details showing damaged break water in **Fig.18a, 18b &18c.**

Fig. 18a: Hut Bay Breakwater

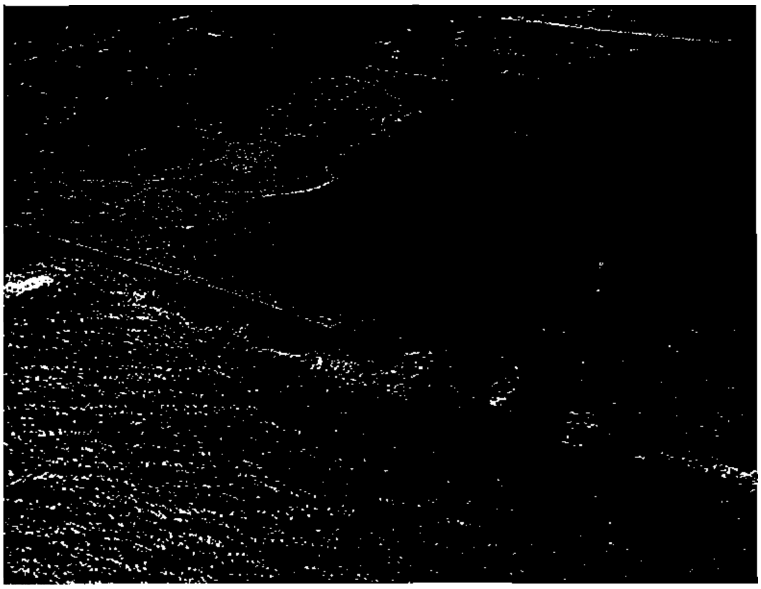

Fig. 18b: Damage Near Shore

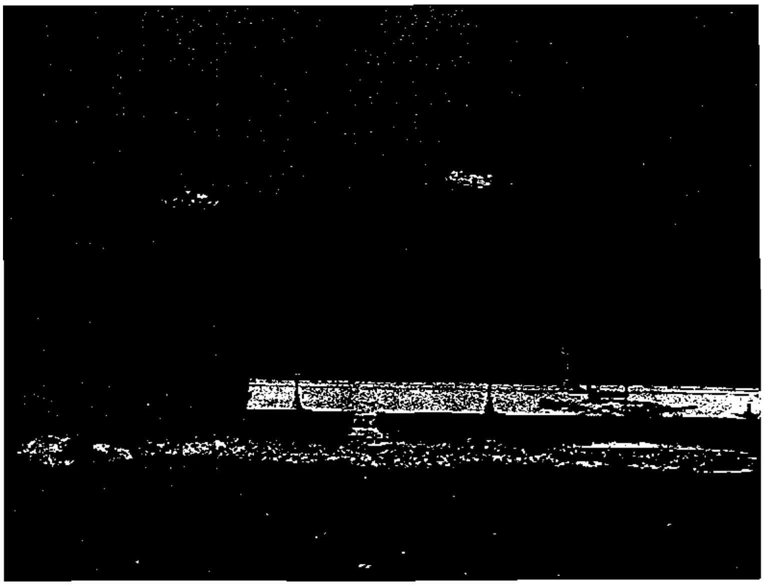

Fig.18c. Damage Near Wharf

COASTAL PROTECTION WORKS

Karaikal

A view of damaged seawall due to tsunami is shown in **Fig.19 a.**

Repair scheme: The Sand bund wall with cement concrete slabs along the coast of Karaikal got damaged fully. The Rehabilitation measures is proposed in the location of original alignment along the coast by construction of plain cement concrete sea wall near the coastal villages. The coastal protection wall comprises of M20 grade PCC with a stem of 300mm thick at top and 900mm at the bottom and a base slab of varying thickness from 900mm at center to 500mm at toe and heel. The two sides will be covered with sand filling with grass turf at sea side is provided to increase the stability and also to reduce the scour gabion box with geo textile will be provided. An expansion gap will be provided for every 30m. of length of the wall. and in other location with sand bund protected with Garmet material. The cross section of sea wall is shown in **Fig.19 b.**

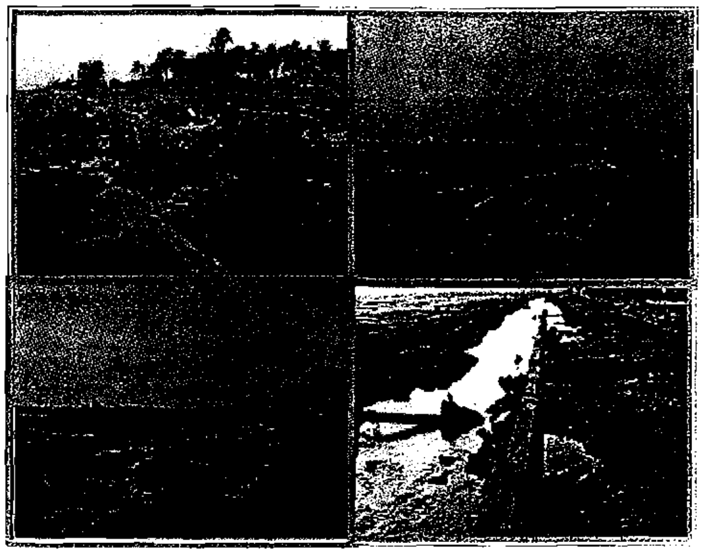

Fig.19 a. Damaged seawall due to Tsunami

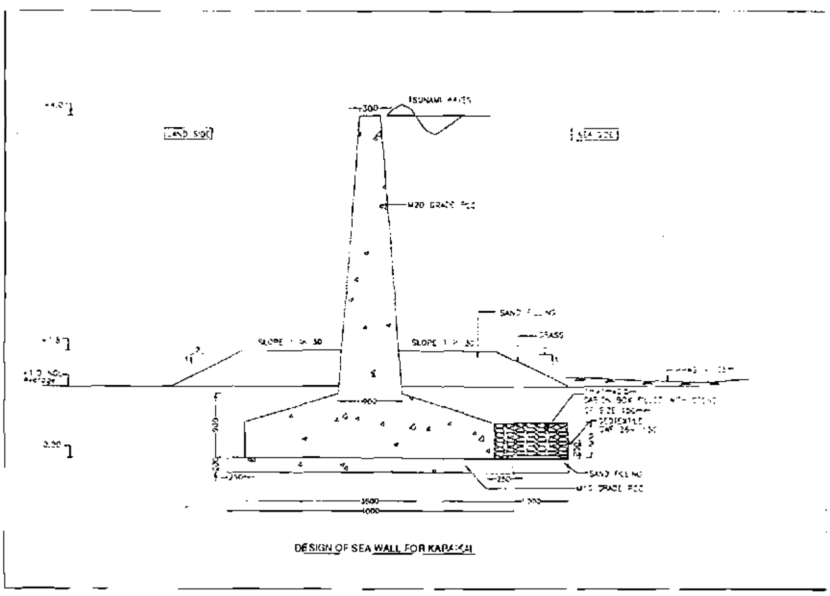

Fig. 19 b: Cross Section Of Sea Wall

Sand Bund

Rehabilitation measures is to construct sand bund in all other location where the direct attack of Tsunami to the inhabitants is not expected.

The sand bund consists of sand filling as the inner core, next a good earth of about 60cm will be provided, then Garmat, manure of 15cm thick and in the extreme outer region it will be covered with grass.

The typical cross section of sand bund with 0.0m, 1.0m and 1.5m normal conditions are enclosed in **Fig.20a– Fig.20c.**

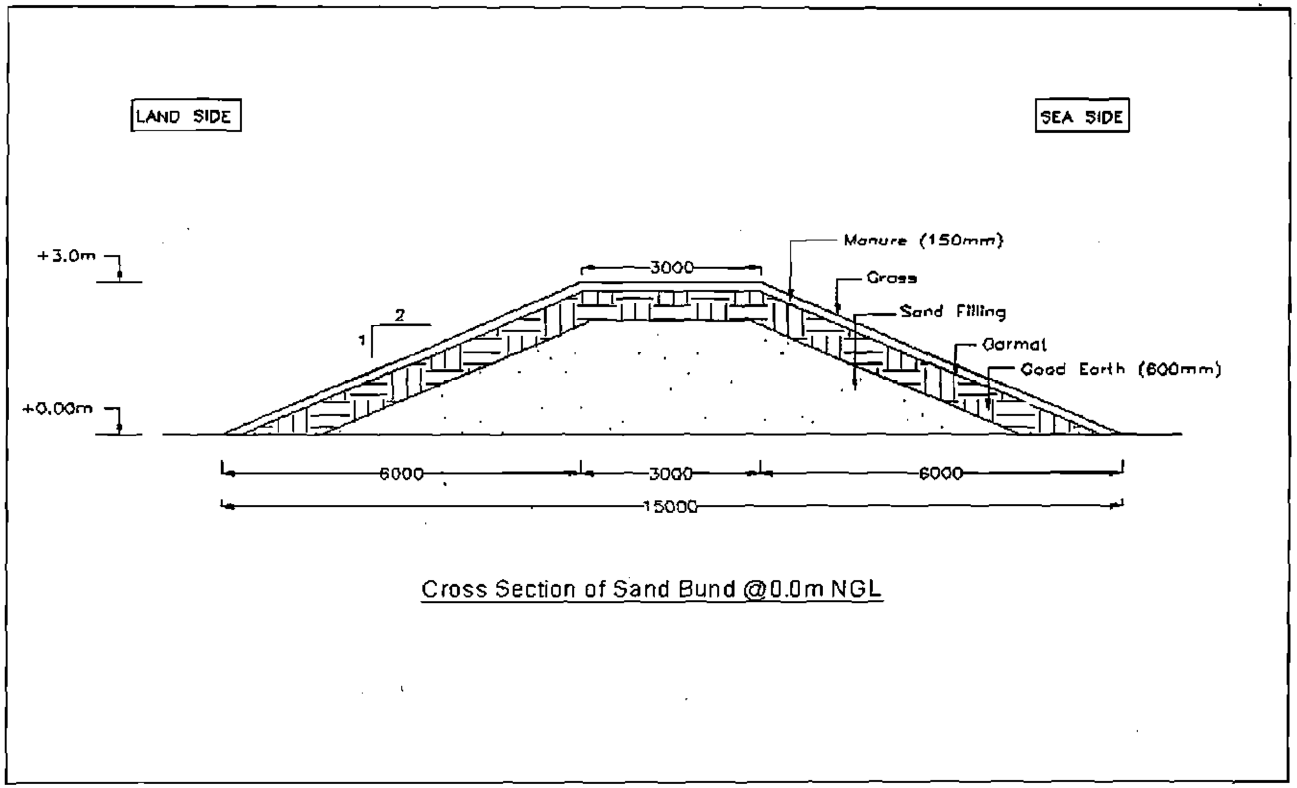

Fig. 20a: Cross Section of Sand Bund at + 0.00 m NGL

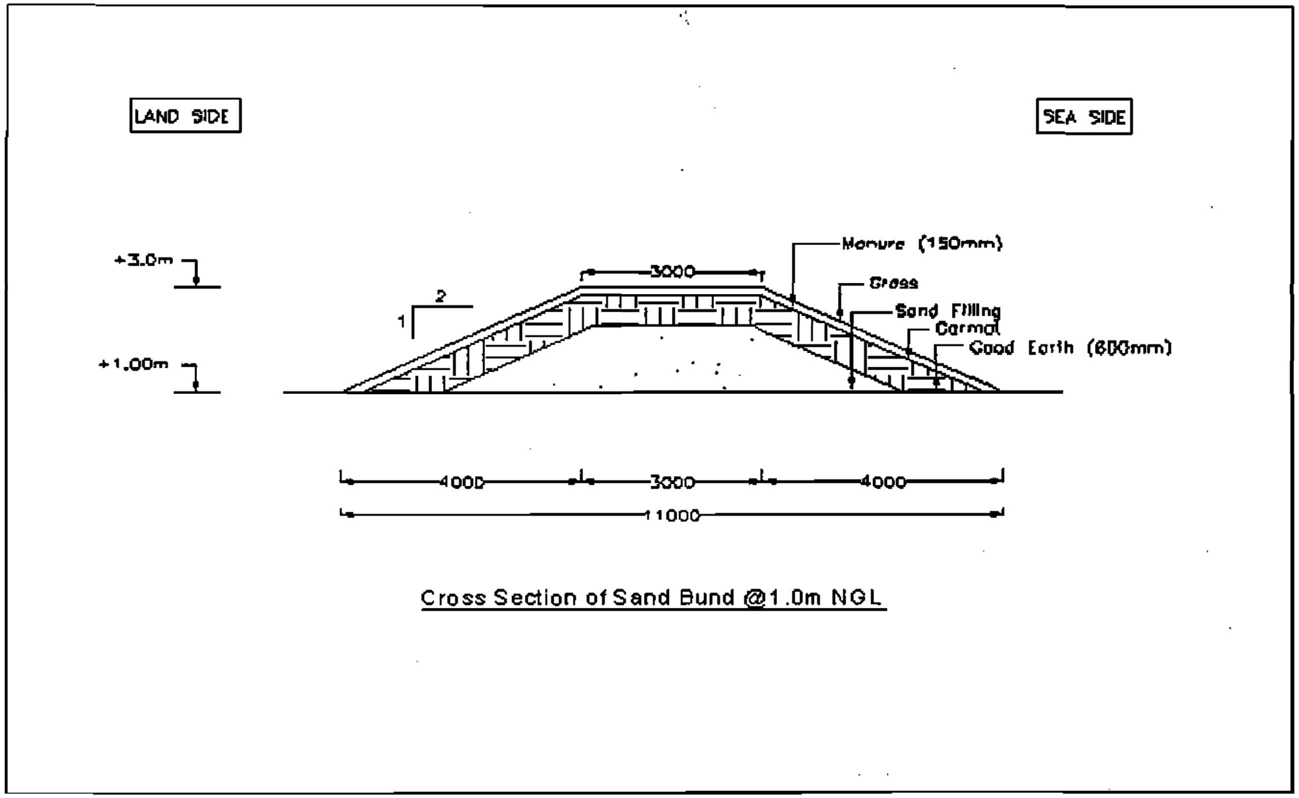

Fig. 20b: Cross Section of Sand Bund at +1.00 m NGL

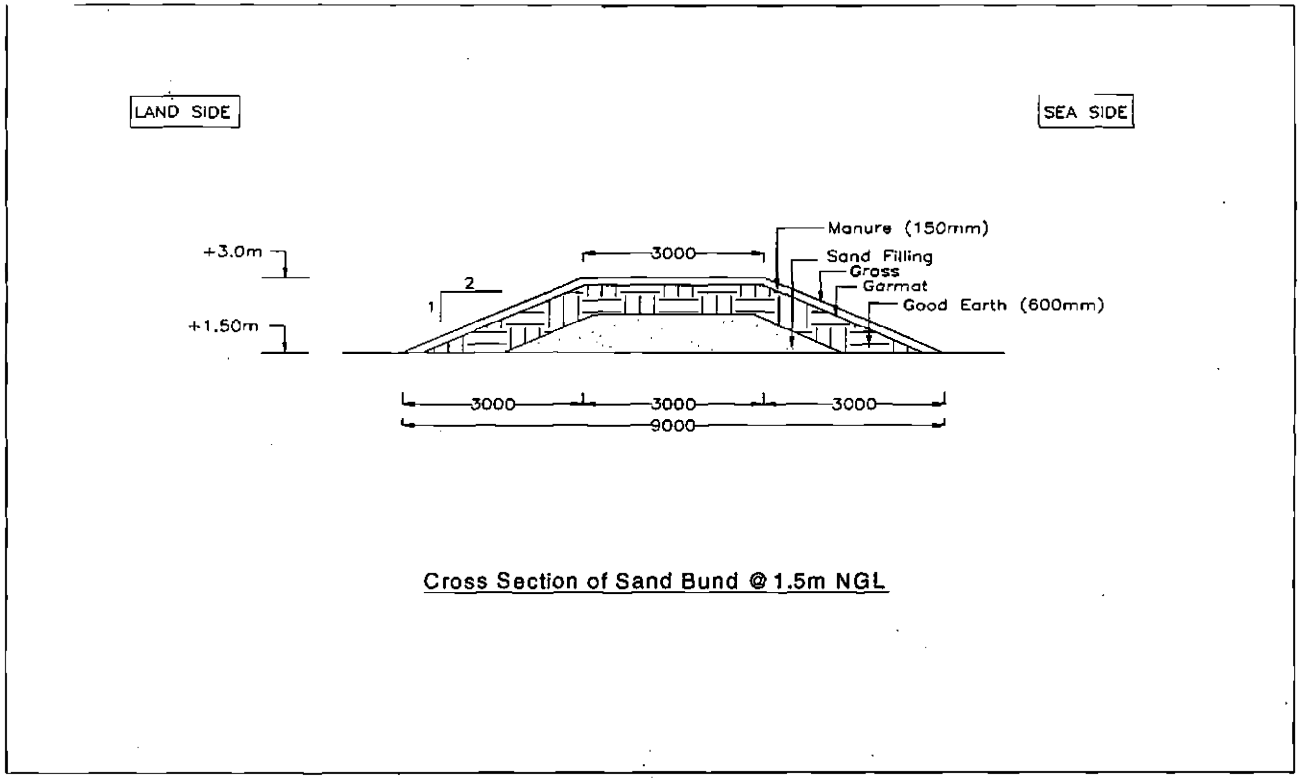

Fig. 20c: Cross Section of Sand Bund at + 1.5 m NGL

DESIGN OF SHORE PROTECTION AGAINST TSUNAMI FOR COASTAL TOWNSHIP

Dr. J.S.Mani
Professor
Department of Ocean Engineering
Indian Institute of Technology Madras
Chennai 600 036
Email : jaysmani@yahoo.com
Phone : 22574806 (Office), 22432168 (Res)

1. Introduction

A township located on south of Chennai, was affected by the Tsunami on 26th, December 2004. In order to protect the coastal township, detailed study was carried out and suitable protective measures suggested. This paper highlights on the characteristics of tsunami and various other parameters considered for the design of protective measures.

2. Tsunamis

2.1 Occurrence of tsunami in Indian Ocean region

Tsunamis are surface waves associated with large-scale seismic disturbances (more than 6.5 in Richter scale) in Deep Ocean with the epicenter located as far as 60 km below the seabed. The disturbance due to seismic activity is transmitted to the water surface, resulting in the generation of 0.6 to 1.5 m waves with periods ranging between 20 and 30 minutes. Though the height of these waves in Deep Ocean with water depth of 4 km is small, their length would vary between 300 and 400 km.

Tsunami propagating radially from the source of disturbance travels with more than 800 km/hr, in the deep ocean. As it approaches the continental shelf, the Tsunami's velocity of approach is reduced compensated by an increase in its height. Tsunami, advancing towards the coastal region, experiences further reduction in speed and wavelength whereas its height increases due to the processes known as refraction and shoaling. Thus a huge wave with substantial speed lashes the coast.

An analysis was conducted with the past data on earthquakes that occurred in Indian Ocean during 1063-1984 and from 1973 to 2005. The frequencies of occurrence of earthquakes of magnitude ranging from 1 to 9 in Richter scale were determined. Figures 1 & 2 show the frequency distribution during the periods 1063-1984 and 1973–2005 respectively. It is inferred from the above figures that earthquakes of magnitude 4 to 6 on Richter scale have larger frequency of occurrence compared to earthquakes of higher magnitude (>7 in Richter scale).

2.2 An example on the characteristics of Tsunami.

Assume that a seismic activity has occurred in deep ocean where the water depth is 5km. resulting in the generation 1m high waves with period of 30min.

Based on the following relationship its speed is estimated as 221m/s

$C_o = \sqrt{(g.d_o)}$ (d_o= water depth in metres and g=9.81 m/s^2)

The wave length is determined as 398 km from the following equation

$L_o = C_o.T$ (L_o= wave length and T wave period in seconds)

Wave height, wavelength and speed of Tsunami in 8m water depth close to the shore are obtained by equating the power of the wave in the deep ocean and in the shallow water.

$H_o^2.\sqrt{(g.d_o)} = H^2.\sqrt{(g.d)}$ (H_o = deep water wave height, H = wave height in shallow water and d= depth in the shallow water)

Thus in 8m water depth following would be the characteristics of the Tsunami

Wave height : 5m.

Speed : 8.86 m/s

Wave length : 15.95 km.

The above example illustrates the characteristics of the Tsunami near the coast.

2.3 Effect of tides on Tsunami

During full and new moon periods the water level near the coast tends to rise (tidal effect) and the water depth of 8m mentioned in the above example may become 10m. (Depending on the location). Readers can now calculate the change in the characteristics of Tsunami corresponding to 10m depth of water.

It is interesting to note that as the distance of a location from the shore (where 8m water depth occurs) remains unaltered due to rise of water level (tidal effect), one can visualize that the effect of Tsunami on the coast would be more aggressive due to tidal effects.

2.4 Dynamic wave force

Mizutani[1] and Imamura (2001) have carried out experimental studies on the dynamic wave force of tsunamis acting on a structure and have emphasized the need for accounting dynamic wave pressure and sustained wave pressure while estimating impact standing wave pressure. The authors have derived expressions for the determination of impact standing wave pressure.

Impact sustained wave pressure

The relationship between the sum of maximum dynamic wave pressure p_{dm}, maximum sustained wave pressure, p_{sm}, and maximum impact wave pressure p_{im} is given below.

$$\frac{p_{im}}{p_{dm}+p_{sm}}=0.5 \quad \text{for} \left(\frac{g(h+H)\cot\theta_1}{c^2}<1.1\right) \tag{3}$$

$$\frac{p_{im}}{p_{dm}+p_{sm}}=10\cos\theta_1-6.6 \quad \text{for} \left(\begin{array}{c} Fr=\frac{c}{\sqrt{g(h+H)}}\leq 1.13 \\ \frac{g(h+H)\cot\theta_1}{c^2}\geq 1.1 \end{array}\right) \tag{4}$$

where, F_r= Froude Number

2.5 Run up of Tsunami

Synolakis[2] (1987) has studied the run up of Solitary waves on plan beaches. An approximate theory is given by the author for the non-breaking waves and an asymptotic result is derived for the maximum run up of Solitary waves. A series of laboratory tests were conducted to support the theory and it is shown that the linear theory predicts the maximum run up satisfactorily and the non-linear theory describes the climb of Solitary waves. Maximum run up for non-breaking waves is expressed by the following run up law.

$$\frac{R}{d}=2.831(\cot\beta)^{\frac{1}{2}}\left(\frac{H}{d}\right)^{\frac{5}{4}} \tag{6}$$

where,

R = run up

d = water depth

β = Bed slope

H = wave height

With the conditions corresponding to the occurrence of tsunami design levels for the retaining wall and the associated protective system were estimated based on the maximum run up and the structural details derived based on the impact standing wave pressure involving dynamic pressure and sustained wave pressure.

3. Input parameters for the design of protective structures

3.1 Tsunami run up

For the coastal region of interest maximum tsunami run up of the order of 4.4m was estimated, corresponding to earthquake magnitude of 9.1 in the Richter scale occurring at Indonesian coast.

3.2 Wave characteristics

Refraction analysis was carried out for the coastal township. Further waves of the order of 5 m were considered corresponding to storm conditions with an approach angle of 45 deg corresponding to the Northeast monsoon. It is inferred that for the sea front, the maximum wave height during normal condition would be of the order of 1m with an approach angle of the order of 9.5 deg. However during storms the wave heights vary from 4.2 to 4.6m along the coast with an angle varying from 18 to 20 deg.

3.3 Tides

Characteristics of the tide provided by the Chennai Port Trust and are presented as follows:

Highest High Water	(H.H.W)	1.50 m
Mean High Water Spring	(M.H.W.S.)	1.10
Mean High Water Neap	(M.H.W.N.)	0.80
Mean Sea Level	(M.S.L.)	0.54
Mean Low Water Neap	(M.L.W.N.)	0.40
Mean Low Water Spring	(M.L.W.S.)	0.10

All the levels mentioned above are with respect to Chart Datum specified by the Naval Hydrographic Office, India. The tides in the region are semi-diurnal and the tidal range is moderate at Chennai.

3.4 Storm surge

The coastal stretch of interest in the present investigation is along the East Coast of India, which is frequently affected by cyclonic storms. These cyclones/storms form in the Bay of Bengal as low-pressure areas and move towards the Indian coast. Sometimes these moving low-pressure areas intensify in to cyclones. When the cyclones approach a coast, the accompanying strong onshore winds sometimes generate rapid changes in the sea level near the shore. The abnormal rise in the sea level induced by cyclonic wind field is referred to as the storm surge. Storm surge was estimated by integrating the vertically averaged form of the equations governing the shallow water flow field. For the coastal region of interest maximum surge height of 2.1m corresponding to 1 in 100 year was estimated.

3.5 Wave Set up

Wave set up were estimated corresponding to the normal and storm surge conditions which were of the order of 0.03m and 0.07m respectively for the coast under reference.

4. Details of protective structure

4.1 Retaining wall

1. Construct 4.5 m high retaining wall in place of the existing masonry wall with its top elevation maintained at +12 m with respect to MSL.
2. The position of the retaining wall should be at a distance of about 42m, from the high water level (6.596) (Figure 3).
3. The front portion (between the counterforts) of the retaining wall shall be filled with rubble stones of 0.80 m dia with a slope of 1 in 1.5. The sloping rubble fill would extend for a clear distance of 4m from the edge of the retaining wall. Suitable geotextile shall be provided between the rubble stack and the sand.

4.2 Sand dune

1. Form a sand dune with its top elevation of 9.5m and a bottom width of about 20 m with its centerline located at a distance of 14m from the HWL.

4.3 Channel

1. Form 10m wide channel with bed elevation of +7.5m with respect to HWL.

2. Channel would run parallel to the coastline with a mild slope of 1 in 1000 (Channel bed elevation would therefore vary along its length).

4.4 Embankment for the backwater

Figures 4 & 5 show the protection for the embankment against tsunami for a creek located in the coastal region under reference. The sloping surface between the retaining wall and the waterfront shall be protected by an embankment with stone size dia of 1m. The embankment would have a slope of 1 in 1.5. Suitable geotextile shall be provided between the sand and the embankment to prevent scour. This embankment has been designed to withstand flow velocity of the order of 5.5 m/sec during the occurrence of tsunami.

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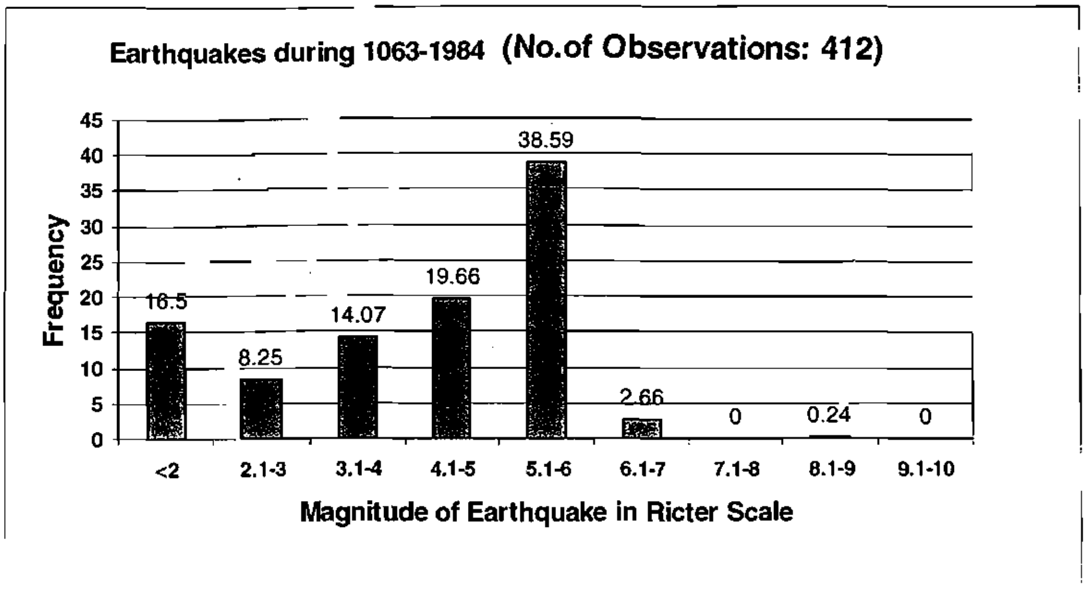

Fig.1. Frequency of occurrence of Earthquakes during 1063-1984

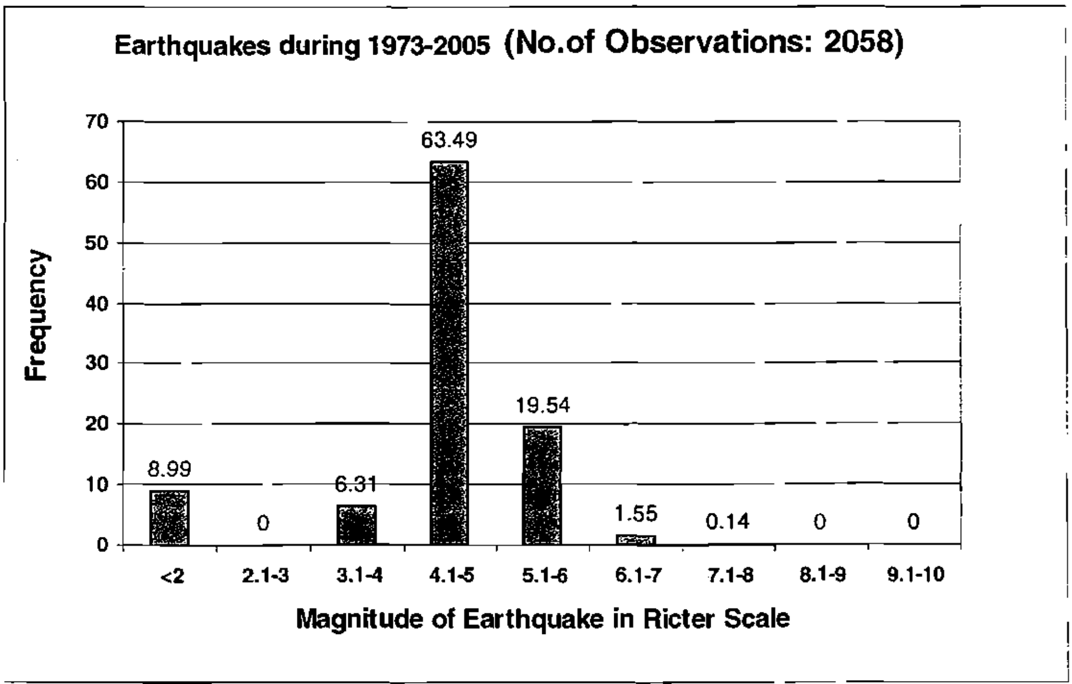

Fig.2. Frequency of occurrence of Earthquakes during 1973-2005

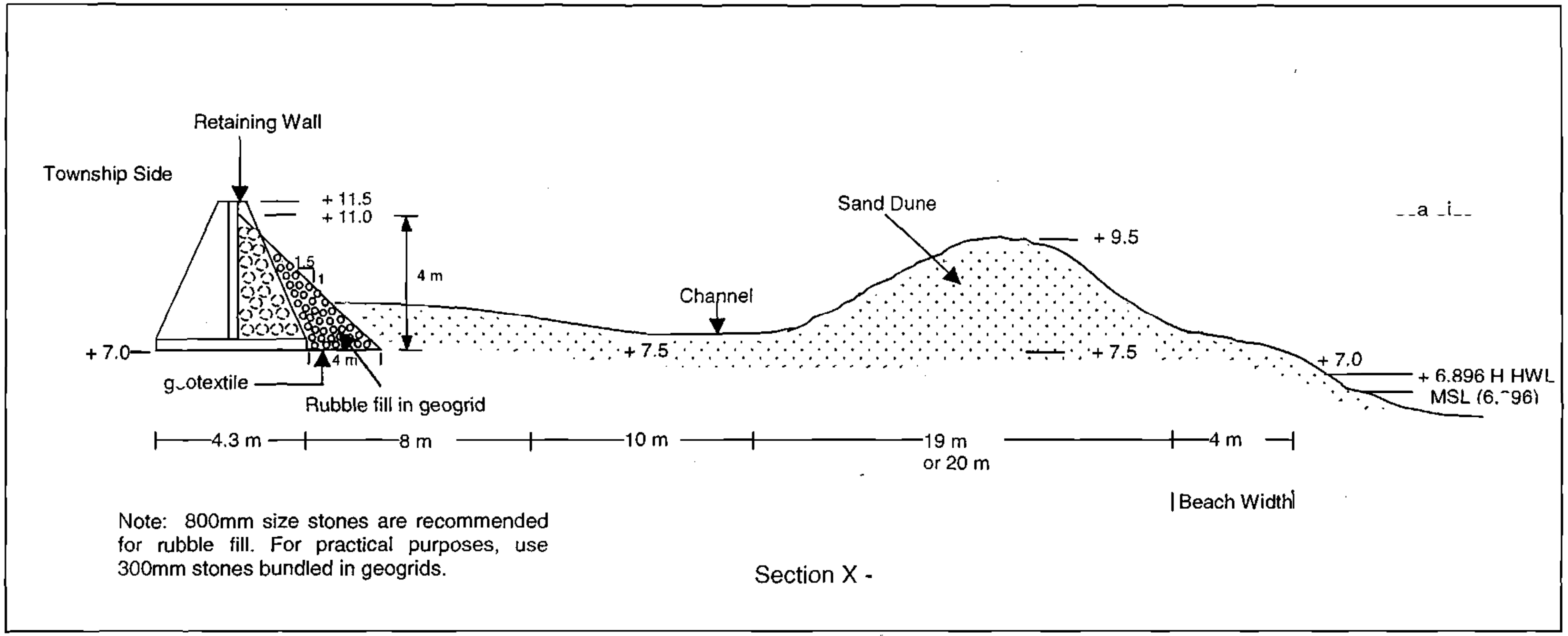

Fig.3. Cross sectional details of the proposed protective system

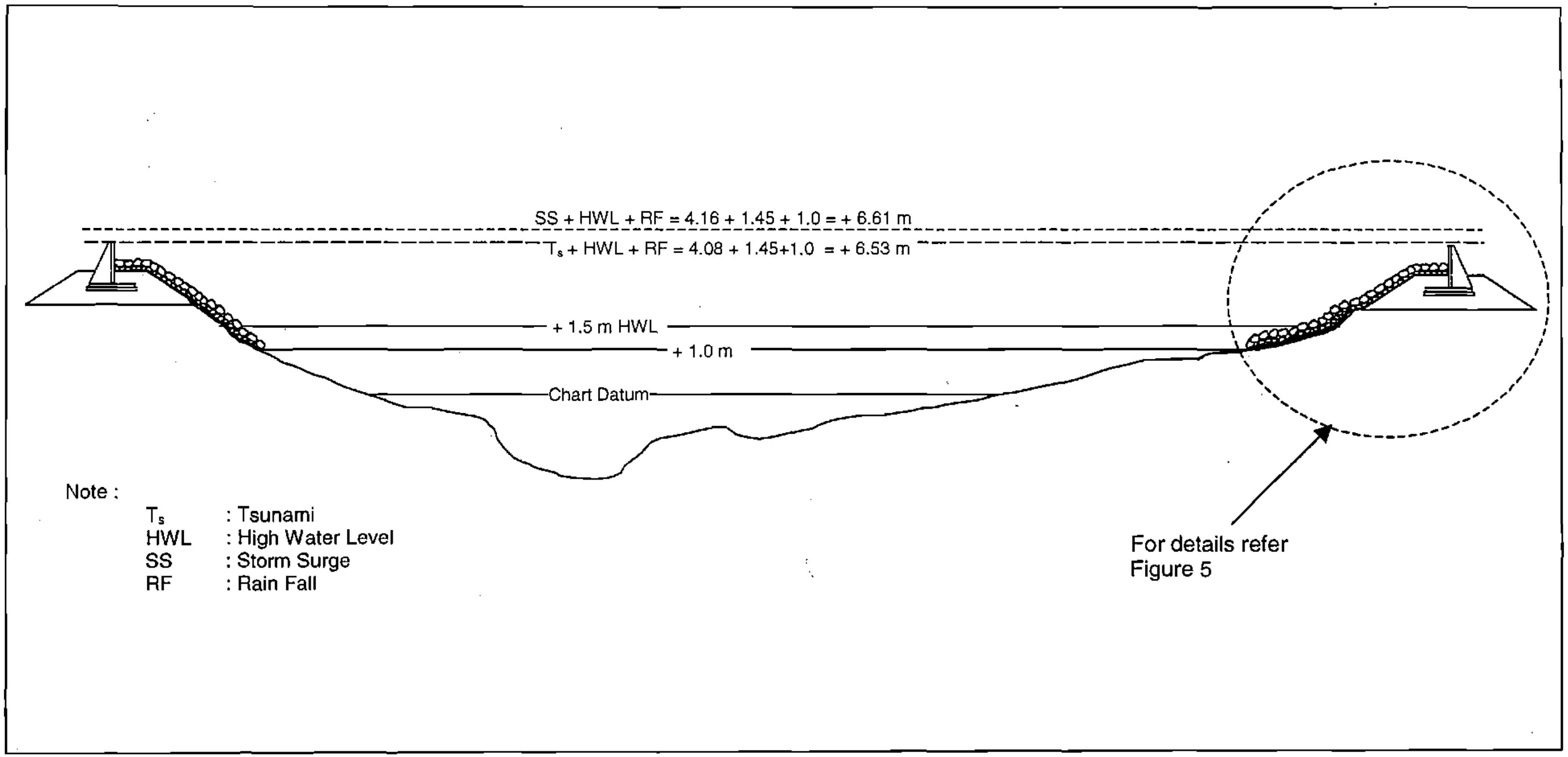

Fig.4. Typical embankment protection for Creek

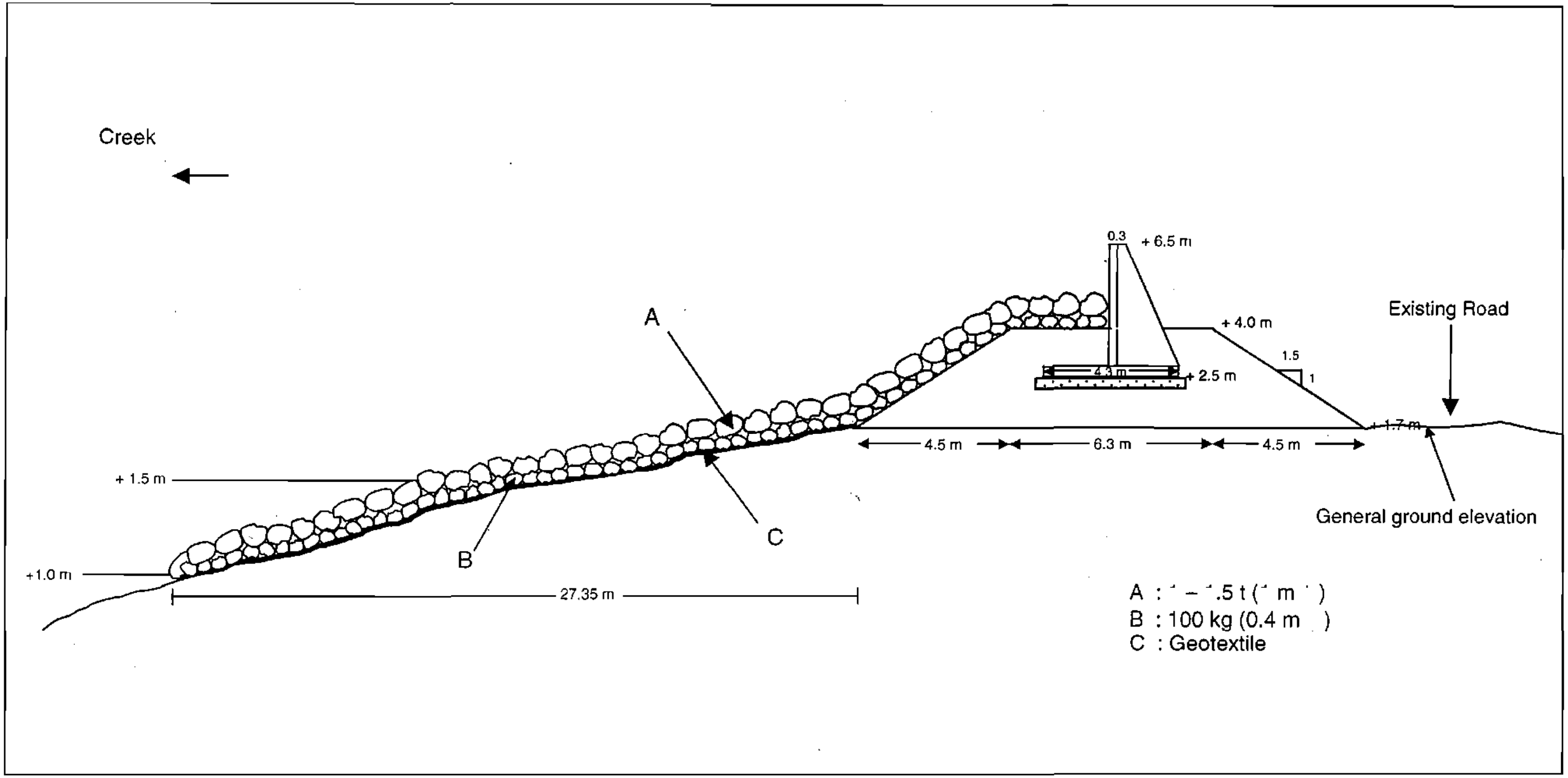

Fig. 5. Details of protection to the embankment

TSUNAMI HAZARDS ALONG TAMILNADU COAST

Dr. S.A. Sannasiraj
Department of Ocean Engineering, IITMadras

1.0 INTRODUCTION

A knowledge on the characteristics of the tsunami, their generation, propagation and on how it differ from the ocean waves observed on the beach is of great importance in the early warning in order to minimize the damages forcing scientists and engineers to focus a great deal of attention in assessing its potential of the damages. Estimating the flooding area of the coastal zone caused by the tsunami waves is essential for the tsunami hazard mitigation. In order to determine run-up of long waves, different theoretical and experimental studies have been performed.

"*Tsunami*" is a Japanese word which translates as "harbor wave". Thus, the amplification of wave energy during the propagation of tsunami is obvious. Scientists investigating the damage in Aceh, Indonesia have reported that the tsunami reached a height of up to about 24 m over large stretches of the coastline, rising to even up to about 30 m in some areas (Choi et al., 2005). The strike of tsunami along the shore has inundated particularly low-lying coastal areas leading to a mass destruction of life and property. The damages were devastating especially at locations where the beach slope is flatter. When the flooding tsunami waves retreat they tend to carry loose objects and people out into sea. The maximum vertical height up to which the water is observed with reference to sea level is referred to as run-up. The maximum horizontal distance that is reached by a tsunami is referred to as inundation.

Tsunamis are generated by four distinct mechanisms:

- The most common type being the abrupt deformation of the seabed due to tectonic earthquakes along subduction boundaries.
- Submarine landslides either triggered by earthquakes or local instability of the continental slope.
- Major volcanic eruptions which displaces sufficient mass of water.
- Underwater manmade explosions with subsequent water inrush.

It should not be imagined that earthquake induced tsunamis are confined to the subduction zones of the Pacific and Indian Oceans; the destruction of Lisbon in 1755 was the result of a North Atlantic earthquake with associated tsunami which killed 90,000 people in Portugal and produced 4metre high waves on the southern English Coast. This proves that tsunamis can travel long distances until they encounter a land mass.

A tsunami is often thought to be a large, steep wave breaking along the shore which need not be true. This may be the case if tsunami propagates over steep beach slopes, in which it has also a tendency to break. However, if it propagates at locations of flat beaches, it travels as a wall of water with out being attenuated, without a developed wave face thus, exhibiting its devastating power over life and structures.

The topography of the seafloor, the actual configuration of the shoreline, reefs, bays, river entrances and the slope of the beach dictate the appearance, characteristics and behaviour of the tsunami. Tsunamis rarely reach the shore as towering breaking waves and sometimes may break far offshore. The tsunami waves on striking headlands would result in a concentration of its energy, whereas along bays, the energy is expected to diverge. While traveling into estuaries it can penetrate through a long distance and its return flow is capable of removing sand bars that may be formed during normal periods. In the event tsunami enters into a harbour, as it is characterized by its long period, the disturbance increases and might take hours to days to get dissipated. This rare event is called as 'seiche'.

The presence of an offshore coral reef can dissipate the energy of a tsunami, decreasing its impact on the shoreline. Flooding tsunami waves tend to carry loose objects and people out to sea when they retreat.

2. INDIAN OCEAN TSUNAMIS

Tsunamis have been recorded to occur in all the major oceans of the world. However, this phenomenon is mainly restricted to the Pacific basin, an area surrounded by volcanic island arcs, mountain chains and subduction zones, as it is the most geologically active area on the planet. The amount of activity in this region makes it much more susceptible to submarine faulting and subsequent tsunami events, whereas the Indian and Atlantic oceans are far less geologically active, with some exceptions, and therefore the occurrence of tsunamis is rare. The statistics on the worldwide tsunamis until 2000 showed that about 90 tsunamis recorded in the pacific since 1900 with about one major tsunami in each decade.

The attack of tsunami on the Indian coastal waters was a great surprise even though tsunamis are not entirely unknown in India. For example, the Tsunami in 1883 generated by the Volcanoes at Krakatoa led to a surge of at least 1 m in Sri Lanka and in Chennai. The damage was much less then. Table 1 shows the details of tsunami occurrences in India and the authenticity of the data provided in this table is uncertain (www.nio.org/jsp/tsunami.jsp). In general, there are two sources of tsunami origination which could possibly affect the Indian coast. One is at Mekran coast that has in the past affected the northern west coast, particularly the Gulf of Cambay along the Gujarat coast. Gulf of Kambhat is also prone to be exposed to concentration of energy towards inner gulf. The other origin is along the fault line in between the Indian and Burmese plates along which, the great Indian Ocean tsunami originated and traveled the Andaman and Nicobar islands, parts of East Coast of India, Thailand, Sri Lanka, Maldives and West and East Africa. As the fault line of length 1,200 km affected by the quake was in a nearly north-south orientation, the greatest strength of the tsunami waves was in an east-west direction. Bangladesh, which lies at the northern end of the Bay of Bengal, had very few casualties despite being a low-lying country relatively near the epicenter because it benefited from the fact that the earthquake proceeded more slowly in the northern rupture zone, greatly reducing the energy of the water displacements in that region.

On 26th December 2004, a massive earthquake of magnitude 9.3 on the Richter scale occurred off the Sumatra coast of Indonesia. This unusually large earthquake occurred due to slipping of 1200 km of fault line by about 15 m along the subduction zone, where the India Plate, subducted under the Burma Micro Plate.

3. FIELD SURVEY ALONG TAMILNADU COAST

Following the Tsunami wave attack along Indian coast on December 26th of 2004, the Department of Ocean Engineering took steps in collecting the data of time of occurrence of waves, run-up and inundation distances along the coasts of Tamilnadu. Tsunami waves generated over the rupture zone as detailed earlier struck the Indian east coast at different intensities at different times. The reason for delay in arrival time of the Tsunami waves at different locations is due to the variation in the sea bottom topography along the coasts.

The post tsunami survey along the entire Tamilnadu coast from the Kanyakumari district to north of Chennai has been conducted from 10th to 22nd January 2005. The survey operation was divided into two phases. The instruments used were auto level, global positioning system (GPS) and audio/video recorders for interviewing the local public. Estimation of run up levels in these areas was based on numerous interviews with local public, staff of Public Works Department on duty. The key plans of the study area are shown in Fig. 1.

Northern Tamilnadu Coast

In the first phase of the survey, a total of 38 locations in the northern part of Tamilnadu were surveyed. Katupallikupam (northern most part) was the survey starting point. No initial withdrawal was observed here and the first wave reached the shore at 8.45am. A total of three waves were seen with the last wave approaching the coast at 10.45am. In Kasimedu of Chennai (north of Chennai port), twenty dwelling units were completely destroyed. However, the rubble mound groins constructed to protect this stretch of the coast which has been experiencing erosion for last four decades, (Sundar, 2005) prevented the area from the severe damages.

The marina beach on the south of Chennai harbour due to the presence of its southern breakwater is fairly wide beach to an extent of about 300m. The arrival time at this location was 9am. The cars from the parking lot were lifted up and washed out to the main road for a distance of about 50m. Waves struck thrice with the first one as the biggest. Forty people were missing who were playing or walking on the beach. In Thiruvanmiyur (South Chennai), the water surge was up to 5m and the third wave was the strongest. The waves damaged in total a 1.5m tall reinforced wall of 0.3m thick. No significant initial rundown was observed. Initial recession was only 10 m at Injambakkam. The third wave was reported to be largest at 9 am. In Muttukakdu, considerable destruction was observed. A view of the damages of a newly constructed house is shown in photo 1. Boats were washed into the land up to a distance of about

300m of a village which was completely deserted. The height of the wave run-up was about 6m. The water receded up to 1km offshore at Kovalam before the first wave advanced the shoreline. The initial recession was approximately 1km at Venpurusham near Mahabalipuram. The receding of water exposed the submerged monuments off Mahabalipuram, which has not been visible over several decades in the past as can be seen in photo 2.

The seawall along the coast of Pondichery town reduced the impact of tsunami wave, however, the return flow has resulted in its toe scour. In Periya Kalapet Kuppam south of Pondichery, accretion of sand was found after tsunami impact. Thalanguda of Cudalore district observed an initial withdrawal of about 500m before the first wave surpassed the shore. The shore region had many coconut trees and found to fall sequentially due to the erosion of sand due to the return flow and the sand deposition was seen at south in the Pennaiyar river mouth. In silver beach of Thevanampatam, Cudalore district the first wave struck at 8.45am with an inundation of up to about 1 km. The river mouth was found to be deposited with a heap of sand. There was a surge in sea level of about 3-4.5m initially. The stagnation time was for about 5 hours for a height of 1.3m above the ground level. A 2-ton roller was carried from the shore to a distance of about 200 m. A water mark left behind by stagnant pool of water was observed at 3.2m from MSL.

Annan Kovil observed two waves with first wave of height of 7-8m at 8:45am followed by the second being the largest of height of about 10m. A lamp post was bent in the southwest direction, indicating the wave direction here. The inundation was about 1.5 km inland (photo 3). In Thirumullaivasal, initial arrival time was 8:50 am with an inundation of about 700m inland. A weir built in 1950 by the Dutch which had been overlaid by a road was completely washed exposing it. A newly constructed restroom at the children's park which was 8m high was completely submerged and destroyed. At Poompuhar village, a historical place (part of city was submerged centuries back), river Cauvery joins the sea. There were four waves with the first one being the largest with an inland inundation of up to about 1 km.

The approach road of Karaikal beach was severely damaged and the river mouth was opened completely (photo 4). In Nagore, an initial withdrawal 500 m was observed in Aryanatu theru, Nagapatnam district at 9:10am and the old mini port was damaged. The coconut trees were washed away and sand deposition has newly been formed down stream south. At Nagapatnam port one of the worst affected area is just 0.6m above MSL received the wrath of the tsunami, leading to heavy causalities as the thickly populated town is adjacent to the coast. The breakwater of the Nagapatinam port was partially washed away and boats were not only severely damaged by collision experienced due to the penetration of long waves but also dragged above the jetty onto the road (photo 5). A vertical quay wall was also damaged. A sand dune near the shore was washed away completely at Velankanni and, sand deposition was found downstream (south).

At village Athiramapatnam, final location of the first phase of the post tsunami survey, the damage was only to boats and nets and an initial warning was given to the local people at 8.30 am by the officials about the strange behavior of the sea. Aliyathi plants in the sea shore reduced the damage (photo 6).

Southen Tamilnadu Coast

It was observed that along southern east coast, the second tsunami wave created a larger destruction than the first. The first one was just a bore (piling of water like a wall) and hence resulted in rise of water level and gave a warning of a tsunami. Also, receding of the shoreline ranging from 300m to 1km was reported along the South East coast. Compared to Southeast coast of Tamilnadu, the Southwest stretches felt the maximum impact of the tsunami in terms loss of both human lives and property were reported. The reason may be attributed to the protection on the eastern side created by shadow of SriLankan Island and, the directly penetrated diffracted waves hit the south-western coast. This is also clear from the numerical simulation of several agencies that were available on the internet.

Among the tsunami-affected areas in the southwest Kanyakumari coast, Colachel, Pillathoputhurai, Sothavalai beach, Melamanakudithurai and Kezhamanakudithurai were the worst affected villages in terms of casuality. From the field investigation, it was found that the beach slope in Colachel area was very mild and the beach was entirely open to the sea without any coastal protection. As the terrain is flat in nature, the tsunami inundation was up to a distance of about 750m from the shoreline. Also, it has been reported that the canal called AVM canal flowing along the coast silted up with debris and beach sand acted as a death trap. Interestingly, the jetty at colachel harbor did not suffer damage.

The fury of the tsunami waves that struck the Southwest coast can be better understood from the photo 7, which shows the remains of a bridge at Melaamanakudithurai. As the tsunami waves struck laterally, the mid spans of the bridge constructed at the river mouth, were carried to the river bed, whereas, the end spans thrown aside the riverbanks. The extent of damage caused to the seawall and to a near by church at Kezhamanakudithurai is shown in photo 8, where, it was reported that the displacement of armour stones during tsunami caused severe threat to human lives and the residential structures.

Huge loss of human life and property were reported from Pillathopputhorai and Sothavalam beach, as these places were open to sea without any protection. Further, these areas are of flat terrain and hence, the waves surged up the land and inundated up to distance of about 500 m.

The stretches of Thengapattinam, Kezhamidalam, Kovalam, Algramatha Street (Kanyakumari district) and Arokiapuram are protected either by sea walls or groin field. In the above stretches, the loss of property has been reported to be less. Further, the slope of the beach formed in between the groins was found to be relatively steeper, the land well elevated above the mean sea level, which reduced the inundation level and hence the damage was less.

The coastal stretches of Tirunelveli district were less affected by the tsunami waves compared to the neighboring Kanyakumari district. The effect of the tsunami was felt at some pockets of Kootupuli, Idinththakarai and Uvari where, the average land level was closer to the mean sea level. Along the coast, water receding after the first wave has been observed. The sequential attack of tsunami on a groin, which was in construction stage at Periyathalai during the propagation of the tsunami is shown in photo 9. It has been reported that the maximum run up reached a height of about 5.5 m from MSL, which submerged the groin which can be clearly seen in the photo.

In Veerapandipattinam, as the beach slope is mild, the tsunami waves had surged up to distance of about 220m causing destruction to residential buildings. Except Veerapandipattinam the other stretches of Tuticorin district were least affected and no major threat to both human lives and property has been reported.

The run up height and inundation distances at various measurement stations along the Tamilnadu coast are reported in Figs. 2 to 5.

Initial warning

Typically, before a tsunami, the sea receded from the coast, exposing part of the seabed. If the slope is shallow, this recession can exceed 800 m. The sea retreat is nothing but the wave trough which reaches before the crest. The shoreline configuration and the continental slope dictate the tsunami wave profile which reaches the coast. People unaware of the danger may stay at the shore, due to curiosity, but this may be a warning sign of a coming tsunami. This has lead to the exposure of one of six shore monuments buried centuries back in Mahabalipuram , which is one of the tourist attractions of south Chennai. A view of this monument during the retreat of the waterline is projected in photo 2. Similarly, the retreat of water exposing a vast land in front of Tiruchendur temple, close to Kanyakumari is shown in photo 10.

4.0 TSUNAMI HAZARDS ALONG THE COAST

The hazards due to tsunami wave along the Indian peninsula can be factored under four major categories.

- Firstly, during initial tsunami run up towards the land, the movable and loose objects such as cars, boats and people, were dragged by the water mass by the way of floatation. Fishing boats and other small vessels were found to be dragged several km upstream and many of them were left on bridges, jetties and elevated bunds (Photos 5 and 11). Considerable damage was caused by the resultant floating debris, including boats and cars that became dangerous projectiles that crashed into buildings and broke the power lines. The floatation of navigational vessels also damaged the berthing structures particularly the top coping beam and pile heads were dented. During the evacuation, people making an attempt to move out of the shore by cars were caught by the wave and those who ran towards upper floors escaped from the tsunami.

- Secondly, during the mass movement of water, an impact force acted on the shore based structures. Photo 7 shows the displacement of simply supported bridge decks from its support piers due to the impact force and the floatation effects. Photo 8 shows the completely damaged walls of a church which is located about 50m from the shoreline in the Kezhaamanakudithurai village. In fact, the shoreline here was protected against erosion by seawalls. The armour stones of weight more than 1ton were displaced by the moving mass of the water in few places and stones weighing 100kgs were thrown on the thatched roofs. The immediate property damages in this village were mainly due to the impact force of the moving water.

- The acceleration of the moving water mass into the land decelerated quickly due to the elevation of the land topography. The quick deceleration of the moving water induced the movement of the water in the opposite direction towards the sea. The reversal in the flow of water towards the sea has also been accelerated by the natural slope in the land topography. Hence, the wave had the tremendous power to drag away any loose materials on its way towards the sea which forms the third reason for the devastation. One of the severe impacts during the receding of water is the scour around foundations (Photo 12) and trees. Strong, tsunami-induced currents lead to the erosion of foundations and the collapse of bridges and seawalls. The houses were mostly damaged due to the foundation failures due to its full exposure. Many of the shore buildings were found to be in good condition except that its foundation had experienced severe scour that made the building useless. The entire harbour basin in many of the fishing and commercial harbours have been found to be deepened to an order of 0.5m to 2m. Even though, it is advantageous in terms of dredging requirements, the berthing and other associated structures posed severe threats. The only consolation due the tsunami was the opening of sand bars near the mouth of rivers. Along east coast of India, the net littoral sediment drift is towards north of the order of 0.8 to 1.0 million m^3 and hence, the river mouths are usually found to be closed during non monsoon seasons. Tsunami wave had resulted in the removal of sand bars and, some of the rivers where the mouth was almost permanently closed like Coovum River in Chennai city, south of Chennai port has seen the water circulation.

- Finally, the fourth level effects are damages aggravated due to the inundated water which did not drained out to sea. The inundation in a dry dock of a port at Portblair (Photo 13) has resulted in collapse of two boats berthed inside the dock. The inundated sea water in the lake/ ponds resulted in affecting the ground water and most of the cultivated land near the coast was polluted. The long time inundation caused most deaths due to the spread of diseases, power outages and machinery malfunction.

5.0 SUGGESTED STEPS FOR EFFECTIVE MANAGEMENT AFTER TSUNAMI WITH PARTICULAR REFERENCE TO COASTAL EROSION

- Enforcement of CRZ guidelines. Should penetrate through grass root level

- Relocate habitation from low lying coastal areas to higher levels landward

- Assess the damages to the coast due to Tsunami & perennial problem of erosion

- Vertical walls could be only for certain locations where the land property is extremely important. Further, in the case of vertical walls, although the wave run-up may be less, there are other problems like enhancement of scour leading to uncertainty in their stability. The forces exerted by waves and tsunami are high if they are directly exposed. The toes in such case of walls have to be properly protected.

- Sloping walls on the other hand will gradually dissipate the incident wave energy. Against tsunami, it is suggested to provide crown walls (vertical or other shapes) at landward end of such walls.

- Identify the locations along the coast where casuarinas or mangroves (bio-shields) can be planted and efforts to be taken for their preservation (Long term solution) [Soft Measure]

- At locations, where beach width is narrower, artificial beach nourishment (pumping in sand from location of sand deposition like sand dunes & bars to the eroding areas) along the coast. This is however is not possible always [Soft Measure]

- Only in case, any of the above two cannot be implemented, need arises for Measures with structures [hard measure]

- Hard measures are construction of seawalls (with or without a berm, preferably the second option), groin field or offshore detached breakwaters. The last option is comparatively costly and difficult to construct. Only after careful assessment of the coast, the final remedial measure needs to be considered. At location of densely populated stretches of the coast that has suffered damages due to tsunami, immediate steps as a crisis management need to be taken up

6.0 SUMMARY

The impact of tsunamis is very limited geographically, affecting only land mass at the edge of some of the world's oceans. However, where they do strike they can be with a destructive force greater than the other types of disasters. Protecting lives and property from such losses begins with good land planning, placing high economic investments out of reach of a potential tsunami and implementing a warning/evacuation system that will maximize the safety of persons living and working near the coastlines.

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Table 1. Tsunamis recorded in India (NIO, Goa, India)

Date	Cause	Impact
326 B.C.	Unknown	Unknown. Noted from the history Alexander the Great
April-May 1008	Earthquake along Iranian coast	Unknown
31 Dec 1881	A 7.9 Richter scale earthquake beneath Car Nicobar	Entire east coast of India and Andaman & Nicobar Islands; 1m tsunamis were recorded at Chennai.
27 Aug. 1883	Explosion of the Krakatoa Volcano in Indonesia	East coast of India was affected; 1.5m tsunamis at Chennai; 0.6m at Nagapattinam; 0.2m at Arden
26 June 1941	A 8.1 Richter scale earthquake in the Andaman archipelago at 12.9°N, 92.5°E.	East coast of India was affected with 0.75 to 1.25m tsunamis. Some damages were reported.
27 Nov. 1945	A 8.5 Richter scale earthquake at a distance of about 100km south of Karachi	West coast of India from north to Karwar was affected; 12m tsunami was felt at Kandla.
26 Dec 2004	A 9.1 Richter scale earthquake at Sumatra coast	East coast of India, Andaman & Nicobar islands, Laksdweep islands, Kerala coast were recorded 1-7m tsunami. 9700 people lost their lives and 6000 people were reported to be missing. Minor damages to coastal and harbour structures.

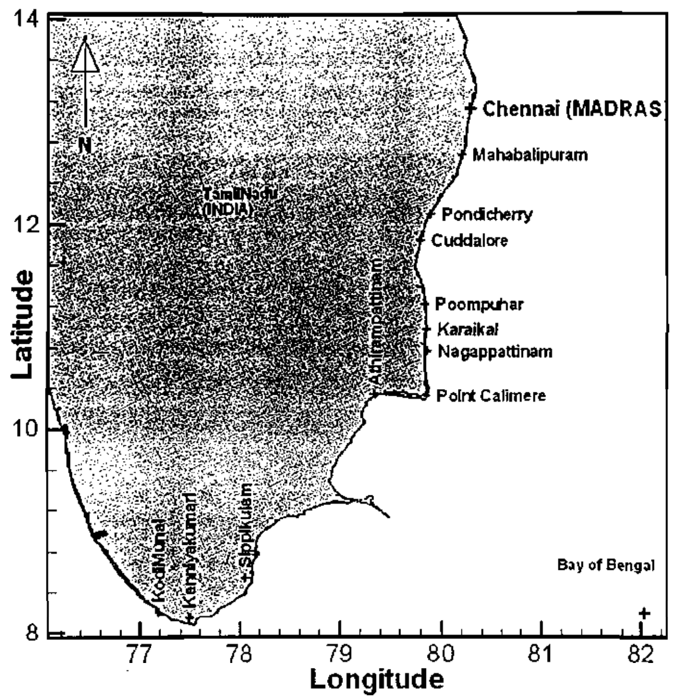


Fig. 1. Key map of the study area depicting Tamilnadu coast and Andaman & Nicobar islands

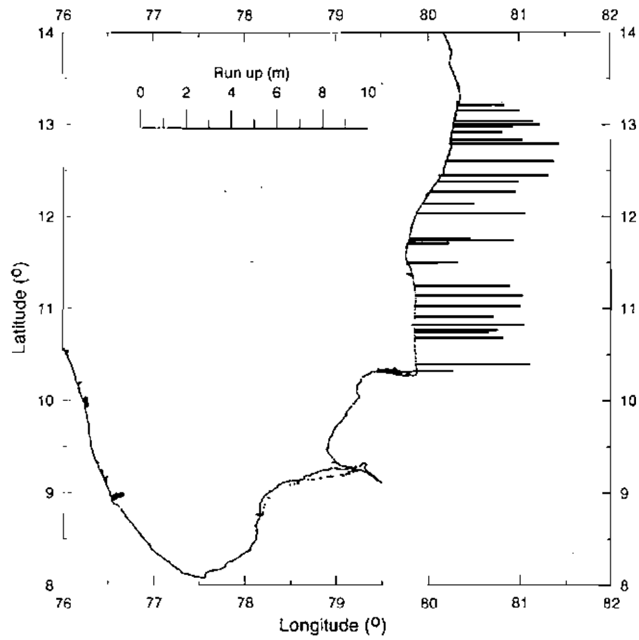


Fig. 2. Measured run up height along northern coast of Tamilnadu

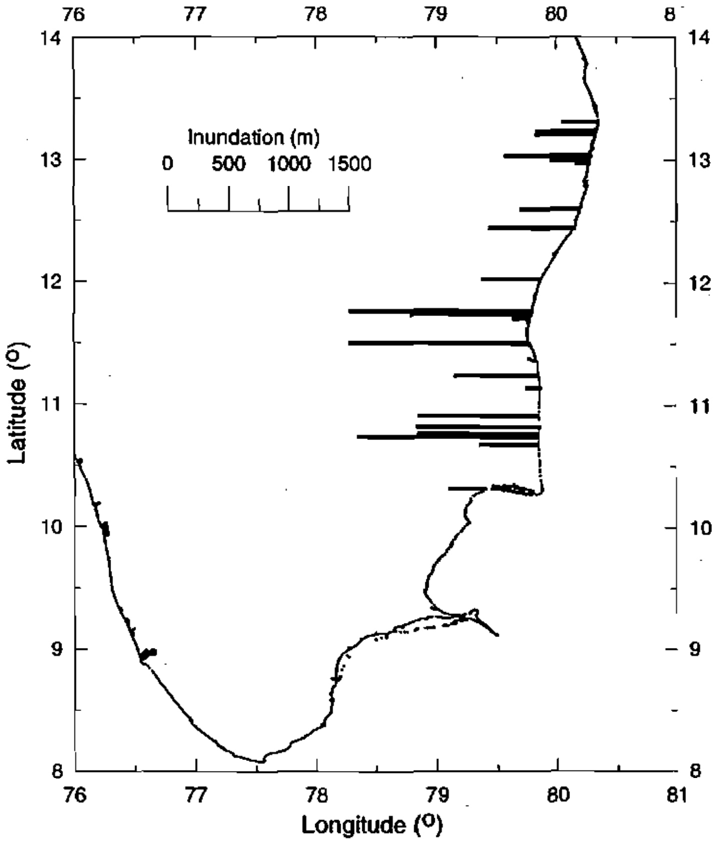


Fig. 3. Measured inundation distance along northern coast of Tamilnadu

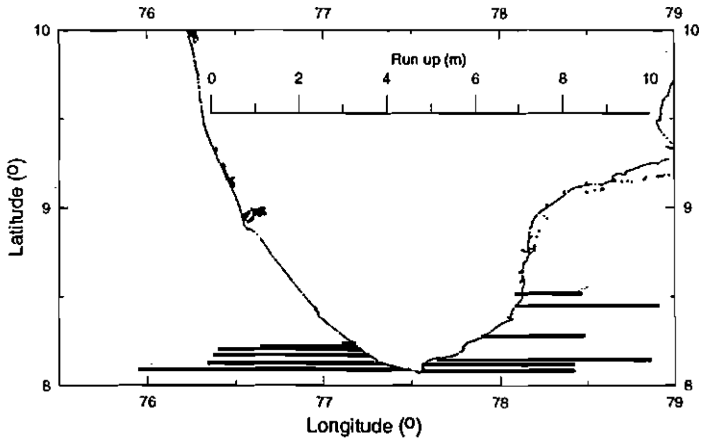


Fig. 4. Measured run up height along northern coast of Tamilnadu

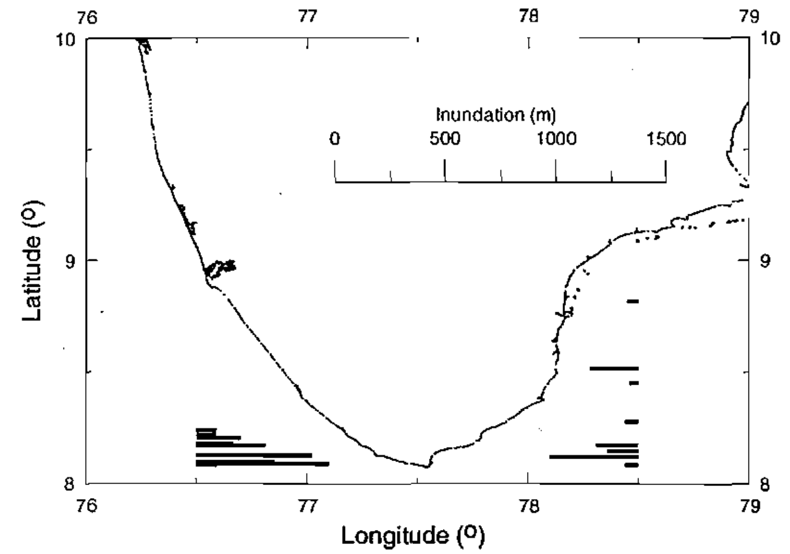
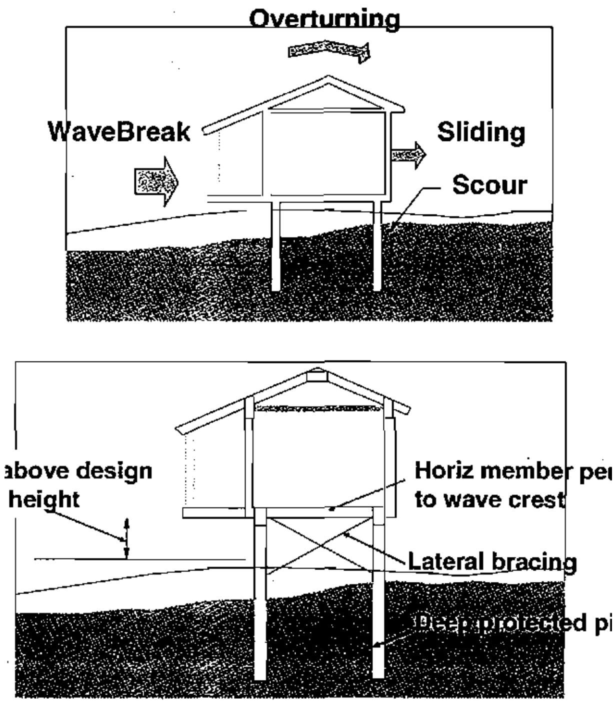


Fig. 5. Measured inundation distance along northern coast of Tamilnadu



a. Forces on structures **b. Design concepts**

Fig. 6. Forces on structures created by tsunami and probable design solutions

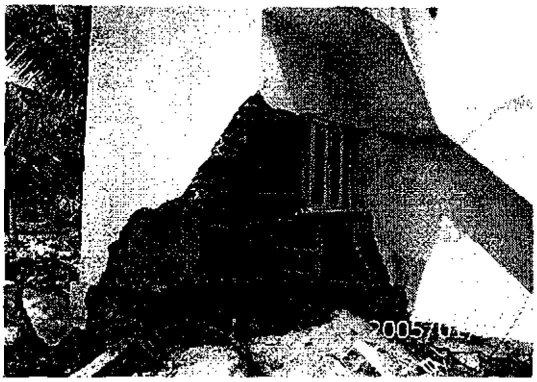


Photo 1. Structure failure due to scouring of foundation at Mutukadu

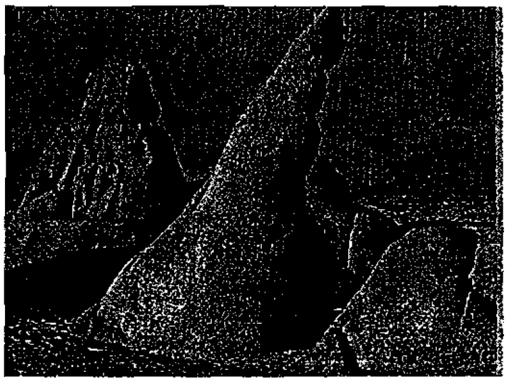


Photo 2. Exposed monument at Mahapalipuram

Photo 3. Picture taken from light house, Annankovil.

Photo 4. River mouth opened at karaikal

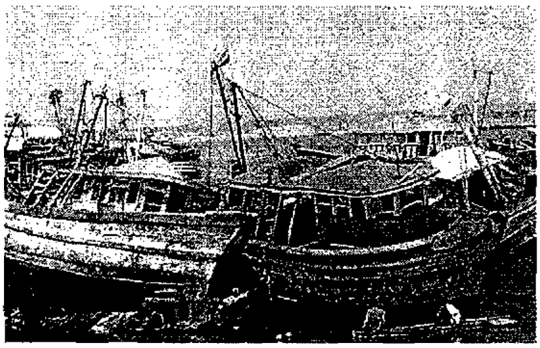


Photo 5. Collapsed boats at Nagapattinam port

Photo 6. Aliyathi plants in Athiramapatnam

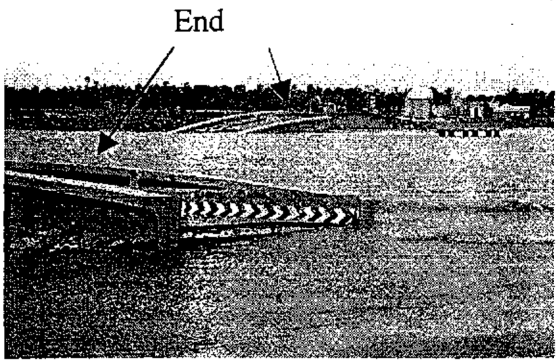


Photo 8. Damaged Seawall and Church Kezhaamanakudithurai

Photo 7. Remains of a bridge at at Melamanakudithurai

Photo 9. The sequential attack of tsunami on the groin at Periyathalai

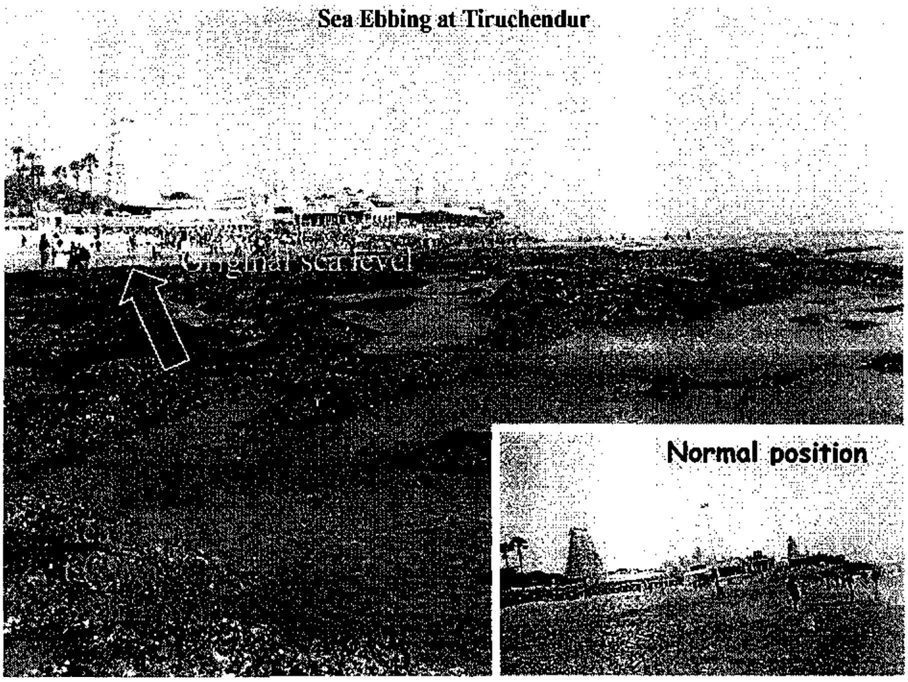


Photo 10. Sea ebbing at Tiruchendur

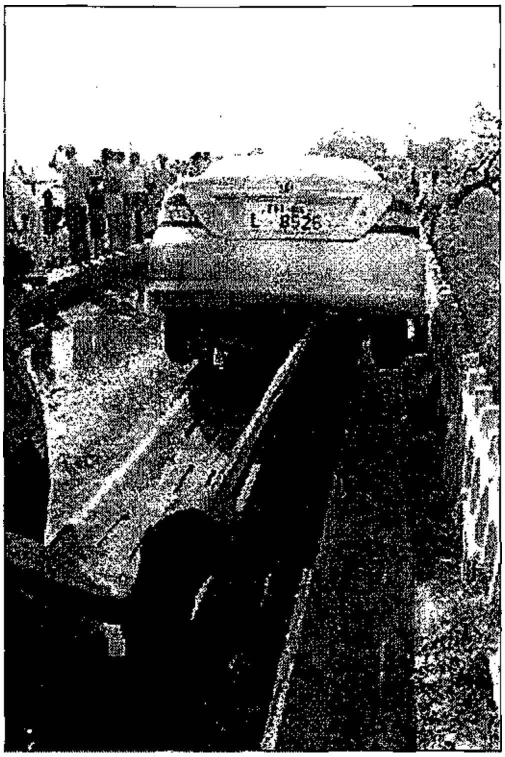


Photo 11. Damages due to floatation

Photo 12. Damages to residential buildings due to scour

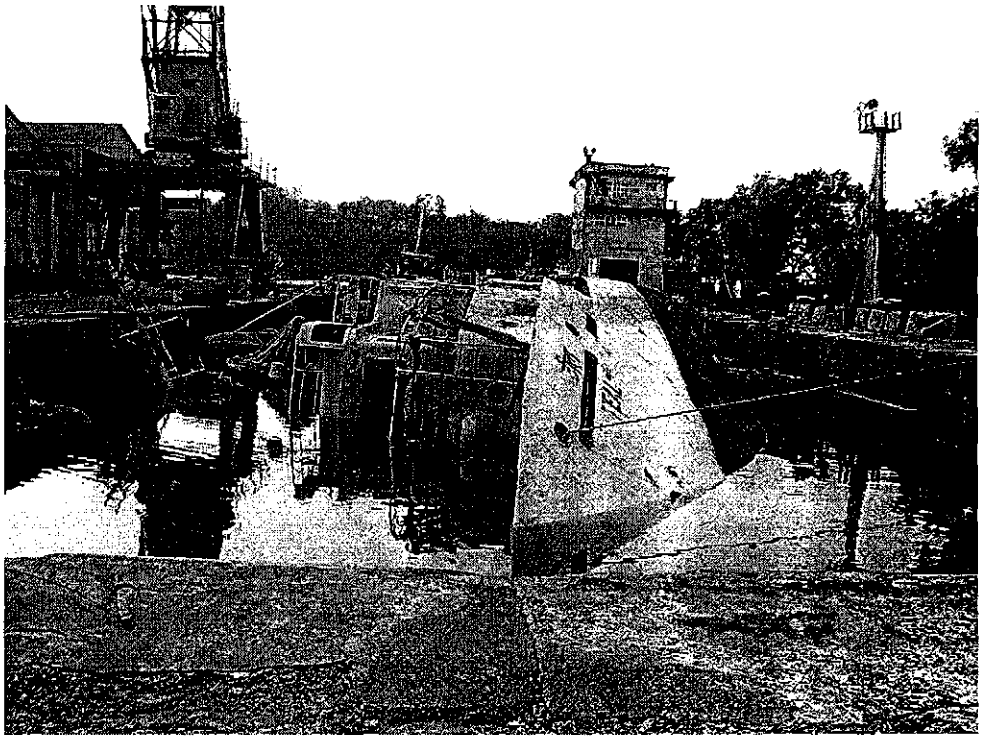


Photo 13. Damages caused inside a dry dock by inundation and continuous submergence

Planning of Coastal Protection Measures Considering The Effects of Tsunami Along The Coast of Tamilnadu, India

Prof. V. Sundar
Head & Professor
Department of Ocean Engineering
Indian Institute of Technology Madras
Chennai – 600036, India, vsundar@iitm.ac.in

Abstract

Planning of Coastal structures against extreme events (storms, tsunami, etc.) is necessary to reduce its affects on the coastal communities. The present paper aims at the planning of coastal structures taking into account the effects of the aftermath of the tsunami, triggered due to the earthquake off Sumatra, of magnitude 9.1 on Richter scale, on 26th December, 2004. In India, the state of Tamilnadu situated on its south east coast is the worst affected accounting for a huge loss of both life and property. The effect of tsunami was severely felt along the coastal stretches of Nagapattinam, Cuddalore and Kanyakumari districts of Tamilnadu for which, the coastal structures proposed are discussed in this paper. The different types of coastal protection structures considered in the above proposal include seawalls, groins, combination of groins and seawalls, artificial beach nourishment, buffer blocks, plantations, etc. Apart from the structural measures to be discussed in this paper, the roots and stems of plants are natural traps for sand particles that would otherwise be carried away by wind, currents and waves. A flat beach is more favourable for such plantation. In addition marsh vegetation acts as a buffer against wave action and tsunami to some extent. Vegetation as a protection can both reduce loads and increase strength which has a relatively large resistance to waves and currents, thus reducing the loads. Roots can increase the strength by protecting the grains on a micro scale or by reinforcing them. ***Mangrove forests*** *are the natural vegetation of many tropical coasts and tidal inlets; they form a highly productive ecosystem, a nursery for many marine species Schiereck G.J., (2001). The protection measures are selected based on the factors such as littoral drift, beach characteristics, and coastal features like estuaries, bays and tidal flats. Planning of coastal protection structures for tsunami waves is economically not viable. Hence, the structures proposed here are to gain beach, which will act as a buffer zone facing the brunt of the tsunami waves and thus minimizing the inundation distance of sea water. The protection measures suggested only for typical locations are herein reported.*

BACKGROUND

Tamilnadu situated on the south east of Peninsular India has a coastline of length of about 1050 km with its significant portion on the east coast bordering the Bay of Bengal. The coast line starts from Pulicat along the east coast and extends up to Erayamanthurai in Kanniyakumari District and consists of Estuaries of ecological importance, Major and Minor ports, Fishing harbours, Monuments of international heritage, Tourist locations, Pilgrimage centers, etc. The Tamilnadu state map is shown in **Fig.1**. There are 46 rivers draining into the sea along the coast of Tamilnadu.

LITTORAL DRIFT

The wave induced net sediment transport, 'littoral drift' is along the east coast is about $1.2*10^6$ m^3/ year directed towards the North. Northward of the Tamilnadu coast, the net drift reduces due to the interception of its movement by the breakwaters of Visakhapatnam and Paradeep ports and is also altered due to the imbalance in the sediment supply from rivers. The said quantity is probably one of world's highest rates of sediment transport. The P.W.D [----------, IHH (2002)] based on the continuous monitoring of the levels of the crest of berm have found that the stretch of the coast north of Chennai harbour is being eroded at an average rate of about 6.5m/year. The details of these results are reported in **Table.1**. Due to the great Indian Ocean tsunami, as almost the entire coast of Tamilnadu was affected, a study was undertaken to identify the zones of erosion and plan for protection measures as a primary goal taking into account the effects of tsunami. In order to accomplish the objectives set in the study, the discussion is based on the three regions namely Chennai, Trichy and Madurai. The problem and suggested remedial measures are accordingly reported in the subsequent sections.

COASTAL PROTECTION MEASURES

Chennai Region

Ennore (N 13°13'56.9" E 80°19'51.7") to Royapuram (N 11°54' 59.03" E 79° 49'51.7")

The stretch of about 15km from Ennore towards its south upto Royapuram comprise of a number of fishing hamlets. Even though, the reach from Chinna Kuppam (about 3km from South of Ennore creek mouth) to Ennore mouth has been protected by a seawall, this stretch is liable to be eroded in future. Hence, this should be strengthened by a groin field, by which additional beach width can be gained. The benefit also will be the reduction of sand entering the Ennore river mouth and harbour leading to lesser quantity of maintenance dredging of the approach being carried out by the Ennore port. The number of groins for this stretch will be about 10, wherein, the average length of the groin will be 150m. The tentative proposed remedial measure for this stretch of the coast is shown in **Fig.2.** The coast north of Chennai harbour for a distance of 9km has already been protected by groin fields designed by IITM, which has served as an effective measure against coastal erosion [Sundar(2005)]. Further strengthening is planed with seawall to reduce the run-up during the new moon and full moon days, phenomena which is experienced in the very recent past after the occurrence of the tsunami.

Stretch between Chennai port (N 13°02'24.9" E 80°16'47.5") to Foreshore estate (N 13°02'04.9" E 80°16'35.3")

This stretch of the coast (**Fig.3**) has the Marina beach one of the World's longest beach. The net littoral drift being towards north has resulted in the sand bar formations at the mouth of rivers Cooum and Adyar. A pair of groins as training walls is suggested for training of the mouth of cooum river with that on the south of the Cooum mouth extending up to a water depth of about 6m, whereas, that on its north extending up to a water depth of about 4m. The reason for longer groins is to trap the sediments for 1.5 to 2 times the surf width. In the case of Adyar, regular maintenance dredging of the mouth is recommended. The stretch in between these two river mouths need to be considered for plantations.

Meyyur Kuppam (N 12°31'44.5" E 80°10'00.8") and Sadras kuppam

This village lies south of Kalpakam Atomic Power Station. The tsunami was quite vulnerable in this stretch. In the immediate south of this village, the presence of coconut plantations had given slight relief. The sea water during the tsunami has penetrated which has risen up to 3 m. Further south, the flat beach and the less elevated region has enabled the tsunami to exhibit its might. Based on the behavior of the tsunami and also due to the elevation of ground level being less, it is recommended that this stretch of 1.5km be protected with a combination of groin field (about six with an average length of about 200m) and seawall, the crest of which should be fixed higher 2 m above Ground Level in order to protect the coast and also to serve as a buffer to handle natural hazards in future. The suggested coastal protective measure is shown in **Fig 4.** Almost a similar measure is suggested for Oyyalikuppam, which is south of Meyyur kuppam. As a secondary effort, plantations can be done as a long-term solution.

Thazhanguda Village (N 11°46'08.1"E 79°47'37.4") and Devanampatinam (N 11° 44'40.4"E 79°47'16.6")

This stretch of the coast along with the suggested protection measures are shown in **Fig.5**. The river (pennaiyar) training works would consist of a pair of training walls of lengths of about 250m. On the southern side of the mouth, a long groin is proposed followed by a groin field for a distance of about 3km upto Devanampatinam. This would consist of 8 groins with an average length of about 150m and training walls of about 250 m at the mouth of river Gadilam. Only the concept of the protection measure to be adopted for the stretch of the coast between Thazhanguda Village and Devanampatinam are shown in the above figure. Initially the groins should be constructed, followed by the seawall after monitoring the performance of the groins in shoreline build up.

Pudukuppam (N 11°31'34.9"E 79°45'47.8")

During the tsunami, water penetrated about 1km into the land. The houses are located at a distance of about 500m from the shoreline. The barren land in this stretch of the coast has not offered any protection from the tsunami run-up. **Hence, dense plantations are proposed.** As dwelling units are located mostly about 200m away from the shoreline and as the seabed is quite flat, without much shoreline oscillations as per the information gathered by local public and PWD officials, conventional hard measures like seawalls or groin field would not serve as coastal protection measure. In the event of tsunami, the aim of the protection measure should be to reduce its speed, for which masonry buffer blocks (4mx0.5mx0.5m) and can be constructed in two rows at a distance of 200m from the shoreline and in between these blocks and shoreline plantation as already mentioned could act as front line soldiers to reduce the speed. The priority in this case would be plantations followed by the buffer blocks. The details of the concept are projected in **Fig. 6.**

Madurai Region

A few stretches of the west coast of Tamilnadu has been protected with groin field and sewalls designed by IITM which have withstood the tsunami and has also been very effective in reducing the inundation particularly due to beach formation in between the groins. The most affected stretch of the coast under this coastal region are

Colachel Jetty (N 8°10'18.4"E 77°15'18.2")

The beach is found to be very flat on either side of the jetty which can be used for plantations. A pair of groins with a crest elevation of about 6.0 m from MSL locally called as thoondil valaivu can serve as a protection measure against severe waves particularly during cyclones. This proposal will also serve as a landing facility for boats and catamarans, the concept of which is projected in **Fig. 7.** The existing jetty can more effectively be used if the above proposal is implemented. The length of the coast that should be covered under this proposal will be about 1km.

Kottilpadu Colachel (N 8°10'09.9"E 77°15'47.4")

This is one of the worst affected villages of the coast of Kanyakumari district due to tsunami and has resulted in a number of casualties about 200. The local public have reported that the canal, which is running parallel to the shoreline has acted as a death trap, as the people trying to escape from the attack of the tsunami should have got stranded and drowned as the number of bridges or escape routes available are less. The measurements of certain important area were made and the plan showing these details is shown **Fig. 8.** This area needs to be protected against wave run-up during cyclone and tsunami. Local public have to be strongly recommended to move towards landward side of the canal. In addition, one more bridge adjacent to the existing one, with a higher deck slab of atleast about 1m above the present level and of greater width is recommended. A seawall with a crest level of +6m with a berm and a strong toe of width of about 3m along with a crown wall upto an elevation of +7.0m is recommended. In the portion between crown wall and seawall, plantations are strongly recommended. The scheme proposed is shown in **Fig.9.** The details are to be worked out after measuring the levels at the site. A distance of about 9 km from Pozhikarai to the western tip of Palayar river should be protected by 8 groins with an average length of about 200 m each of which would extend upto a water depth of 1.5 to 3 m. The western and eastern tip of this river mouth will have groins extending up to a water depth of 5 m in order to avoid the siltation near the mouth of river Palayar. A pair of groins (river training works) or a groin field has been suggested for locations at Pallanthurai (N 8°5'57.1" E 77°25'51"), Mezhamanakudithurai (N 8°5'36.3" E 77°27'36.4"), Keezhamanakudithurai (N 8°5'16.7" E 77°29'17.5"), Idinthakarai (N 8°10'40.5" E 77°44'46.8"), Alanthalai (N 8°27'53.7" E 78°06'2.5"), Punnakayal (N 8°38'12.8" E 78°07'19.9"), Threspuram (N 8°48'55.4" E 78°09'47.6") of the Madurai region

Trichy Region

The Nagapattinam coastal district map is shown in **Fig. 10.** The different stretches **A** (Pattinacheri, Nagore to Keechankuppam), **B**(Velanganni to Vellapallam) and C(Tharangampadi to Palayur) of the above coast are indicated in this map. During the tsunami, the water has penetrated upto a distance of about 1 Km and a run-up height of about 8.0 m with a great velocity mainly because of the flat beach that exist in this stretch of the coast. The barren land North of Nagapattinam port is an excellent place for dense plantations.

Keechankuppam (N 10°45'16"E 79°50'57.8")

This is the worst affected area with in the **stretch 'A'** due to tsunami. The tsunami has resulted in uprooting of several bridges and houses along this stretch. Dense plantations as a long-term measure for a distance of about 9 Km is recommended (Nagoor to Keechankuppam) protecting about 6 villages with in this stretch of the coast. The recommendation is made for the two stretches namely, (between Kallar and Kaduvayar river mouths) and (Nagore to Kaduvayar river mouth). As littoral drift in this stretch is more towards the North and the coast is of sandy type, T – shaped groins would certainly trap the sediments and also retain the same with in them. In order to minimize the inundation of sea water into the land, a seawall is recommended. As the coast is just 0.6 m above MSL as per the P.W.D, Govt. of Tamilnadu, a seawall is also recommended for the entire stretch of the coast. The details of the proposed layout for the stretch between the rivers Kaduvayaar and Kallar to protect the stretch of the coast in Keechankuppam are shown in **Fig. 11a and 11b.** The average length of the groin including the T portion for estimation purpose would be about 250 m. or the stretch (Nagore to Kaduvayar river mouth), it is recommended to construct fifteen number of T-shaped groins with an average length of about 250 m as shown in **Fig. 12.** If in case the suggested remedial measure does not accelerate the beach formation, only then the construction of the seawall should be considered the cross-section of which, will be decided at the appropriate time after detailed studies. In addition to the above, the rivers Kaduvaiyar and Kallar need to be provided with two training walls each with an average length of about 300 m. The complete protection measures for the entire **stretch 'A'** are shown in **Fig. 13.**

Velankanni (N 10°40'48.6"E 79°51'09.2")

For this location in **stretch 'B'**, it is recommended to dredge the mouth of river Vellayar and nourish the beach on its Northern side as well as to construct a sand dune. Plantations backed up with sand dunes and masonry buffer blocks are recommended for this stretch of the coast as shown in **Fig. 14.** The buffer blocks may also serve as a relaxing facility for the pilgrims and locals. After monitoring the shoreline for a period of about 2 years, a decision can be taken up on the necessity of a hard measure. ***Vellapallam (N 10°31'20.7" E 79°51'37")*** near the confluence point of the Nallar Straight cut can be taken up for dense plantations. Two long training walls for the improvement of the mouth of Nallar Straight cut should be taken up.

Tharangampadi (Tranquebar) (N 11°01'32.4"E 79°51'23.1")

This stretch of the coast **(Stretch 'C')** at Tharangampadi comes under the protection of monuments and places of National heritage. The existing old groins are ineffective in trapping the sediments. It is recommended to rehabilitate the groin A-A with a proper head with a top elevation of +3.35 m. Also, an extra groin of length 70 m at a distance of 50 m South of A-A is recommended. The existing two groins on the South of A-A should be rehabilitated and the length should protrude to a distance of 50 – 60 m from shoreline with a top level of +3.35 m. Plantations on the leeside of the existing seawall is recommended as a long-term measure. The proposed scheme is shown in **Fig 15.** The village Sathankudi (N 11°01'52.7" E 79°51'19.6"), located North of the fort has suffered huge loss of life and dwelling units. The water has penetrated about a distance of about 750 m from the shoreline. The PWD has a proposal for construction of a seawall for a distance of about 850 m from the existing seawall. While, the construction of the seawall is recommended, the crest level has to be at + 4.35 m. In addition to the seawall, a groin field consisting of 5 transition groins of average length of 100 m, with one or two groins to be bent to be formed as 'Thoondilvalivu' as it is called by the locals.

Poombuhar (N 11°08'37.8"E 79°51'27.8")

The beach south of the above location is protected by a seawall. The tsunami has penetrated to a distance of about 75 m from shoreline with a run-up of about 1.5 m. The performance of the existing seawall is found good as beach has formed. However, the seawall has to be rehabilitated with a crest elevation of + 4.3 m. The North of this village has to be protected by a seawall for a distance of about 650 m. The large extent of barren land in this area is to be developed with plantations. The stretch of the coast near ***Vaanagirikuppam (N 11°07'50.4"E 79°51'28")*** is an ideal location for plantations. The beach can be protected by groin field and rubble mound seawall with cross-section similar to Tharangambadi. Only plantation is recommended for the stretch of the coast ***Pudukuppam (N 11°10'07.4"E 79°51'18.2")***.

Palayur (N 11°21'14.6"E 79°49'44.5")

A number of casualties and damages to the property have taken place in this stretch of coast during the tsunami. As the village is right on the banks of river Coleroon, **one suggestion is to retain the dunes already constructed by the local people** and the top level of the dune may be further raised. The ditch in front of the dune should be shifted to rear side of the dune. The dune should take the shape as shown in Fig. **16** for a distance of about 1 Km. Plantations on the seaside and on the dune are recommended. **As a long term measure, the dunes can be converted to revetments or with Geo-tubes with its top level of + 6.0 m above MSL.** For this purpose, the shallow regions can be dredged and the dredged spoil can be used for the creation of the dune. A portion of the bank can also be planned for landing jetty in future after the protection of the river bank with spurs. The details of the proposed scheme are shown in **Fig. 17.**

Thirumalaivasal (N 11°14'31.5"E 79°50'37.9")

This stretch of the coast is at the confluence point of the river Vellapallam Uppanar. The entire stretch needs to be dredged and a bund has to be created using this dredged spoil for a distance of about 1 Km from the mouth. Two training walls, at the mouth of the river Vellapallm Uppanar as shown in **Fig. 18**, are recommended. A few spurs along the banks of this river need to be provided in order to divert the flow into the ocean. Plantation along the banks of the river is recommended.

SUMMARY

A general survey of the coast of Tamilnadu after the great Indian Ocean Tsunami was conducted during Feb-March 2005 in order to assess the vulnerable areas being affected by the perennial problem of erosion. The effect of the recent tsunami was considered in the said exercise. As the state is divided into three coastal regions namely, Chennai, Madurai and Trichy, the sections were accordingly organized. Only the concepts of the different coastal protection measures are projected that consist of Seawall, Groin field, Combination of seawall and groins, Training walls, Plantations, Buffer blocks, Curved groins (Thoondil Valaivu), Geotubes.

The protection measures are site specific and are dictated by the direction and magnitude of the littoral drift. As a detailed knowledge of the host of parameters like the beach profile, bathymetry, shoreline changes over the past few years, behaviour of already existing protection measures, etc control the magnitude and quantity of Littoral drift has not been carried out; the contents of this paper should serve only as a guideline for the planning process. The implementation of the measures should be taken up only after detailed investigations.

ACKNOWLEDGEMENT

The author wish to record his thanks to the Public Work Department, Govt. of Tamilnadu for entrusting the responsibility for carrying out the study as well as to permit the author to present the salient parts of the comprehensive report in the form of a publication. The support of his colleagues and students as well as PWD sengineers is greatly acknowledged with out whose help, the study would not have been possible.

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Table 1. Rate of Erosion along the Tamilnadu Coast (PWD, Tamilnadu, 2002)

S.No	Location	Length in m	Accretion/Erosion	Rate in m^3/year
1	Pulicate	0.71	------	3.20
2	Ennore	3.27	====	1.30
3	Royapuram	5.38	------	6.60
4	Marina	2.97	====	1.7
5	Foreshore	2.3	====	1.09
6	Elliot / Astalakshmi temple site	2.08	------	1.28
7	Kanathur	0.24	------	1.4
8	Kovalam	3.15	------	0.81
9	Mahabalipuram	5.45	====	0.25
10	Pondicherry	1.19	------	0.15
11	Cuddalore (North)	1.538	====	8.00
11 a	Cuddalore (South)	0.483	====	2.98
12	Poombuhar	1.905	------	0.65
13	Tranquebar	0.76	------	1.80
14	Nagapatnam	4.25	------	0.11
15	Point Calimere	0.966	====	3.40
16	Ammapattinam	3.6	====	0.72
17	Keelakarai	2.9	====	029
18	Mandapam	2.19	------	0.25
19	Rameswaram	3.3	====	0.06
20	Tiruchendur	1.53	====	0.33
21	Manappadu	1.6	------	1.10
22	Uvari	2.6	------	0.86
23	Kanyakumari	0.7	------	1.74
24	Manakkudi	3.65	====	0.57
25	Pallam	2.6	------	0.93
26	Muttom	3.0	====	0.17
27	Manavalakunchi	3.5	------	0.60
28	Colachel	1.75	------	1.20
29	Midalam	2.5	------	0.84

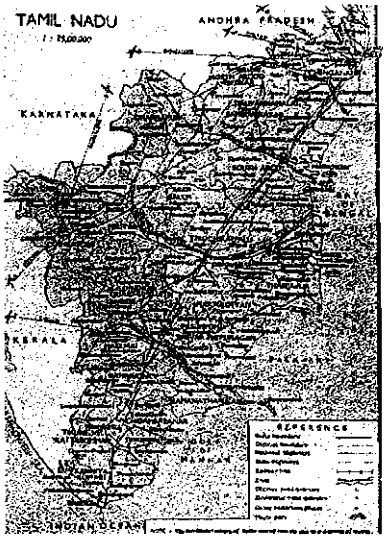


Fig. 1: Tamilnadu State Map

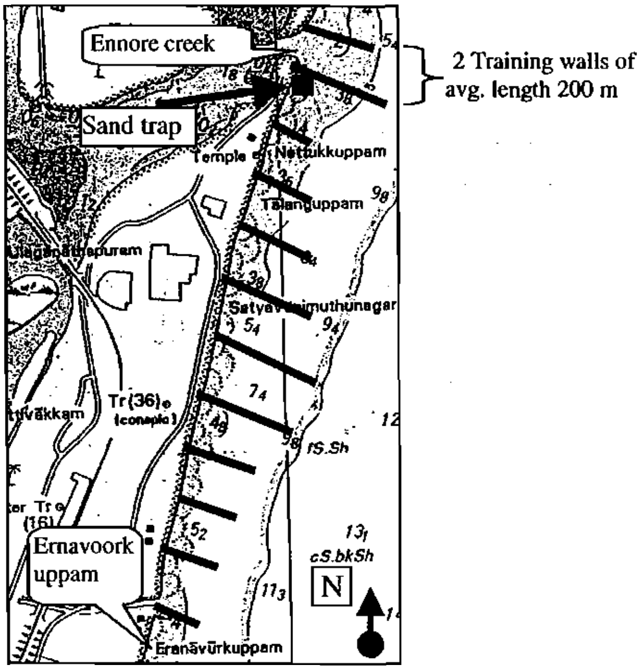


Fig. 2. Groin Field of 10 Transition Groins of Avg. Length 150m at the Stretch of the Coast In Between Ernavoorkuppam and Ennore Creek

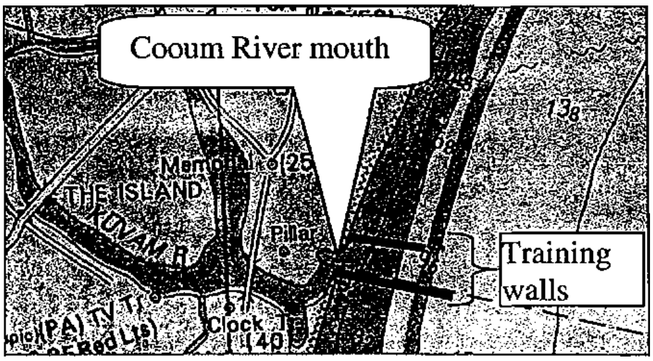


Fig. 3: Training Walls At The Cooum River Mouth

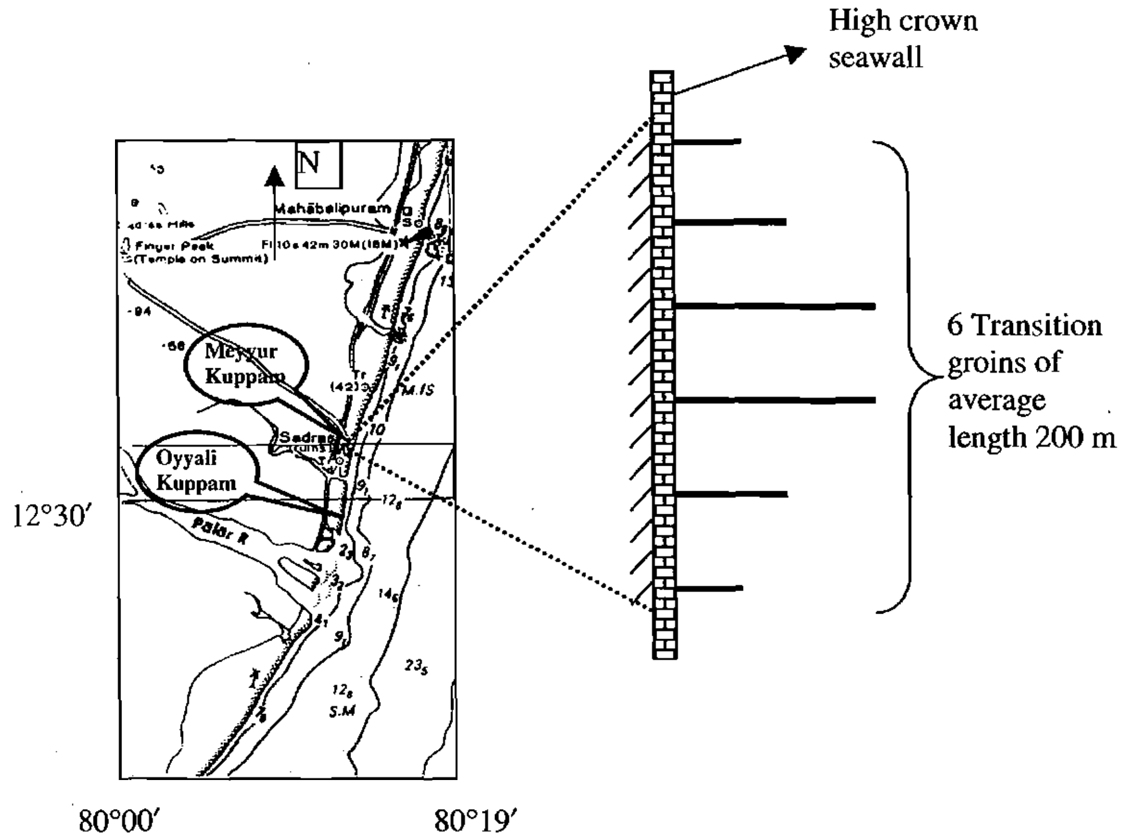


Fig. 4: Combination of Groin Field and Seawall at Meyyurkuppam

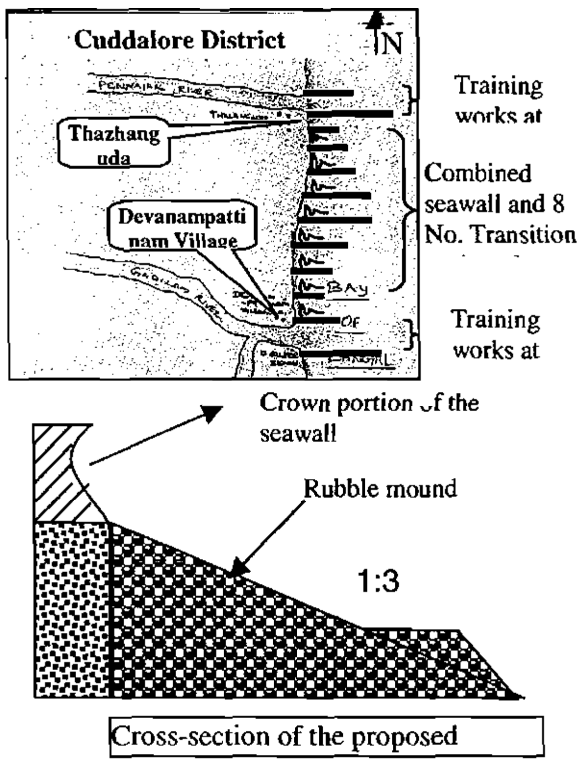


Fig. 5: The Combined Groin Field And High Crown Seawall Along The Stretch Of The Coast Between Thazhanguda And Devanampattinam

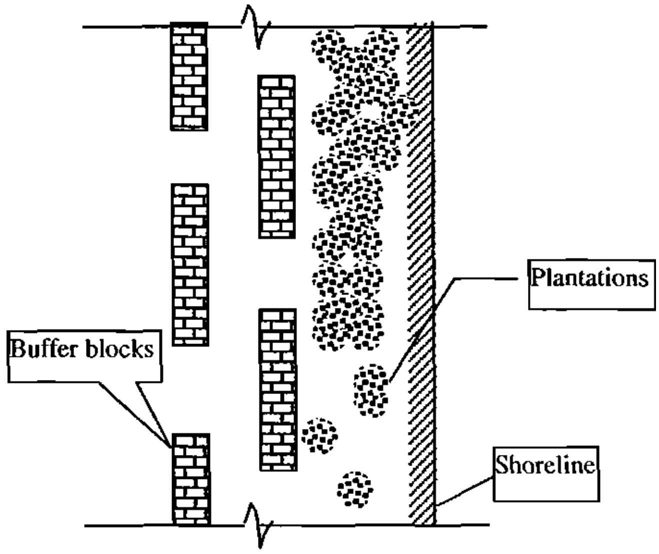


Fig. 6: Suggested Protection Measure For The Stretch Of The Coast At Pudukuppam In Parangipettai

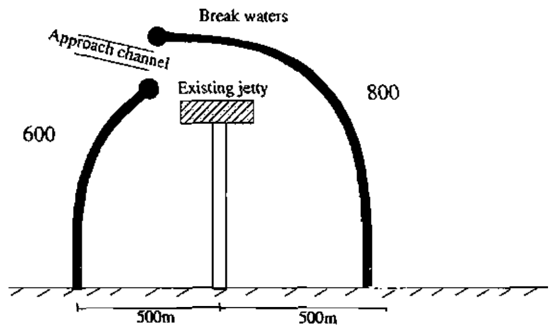


Fig. 7: Proposed Groins (Thoondil Valivu) At Colachel Jetty

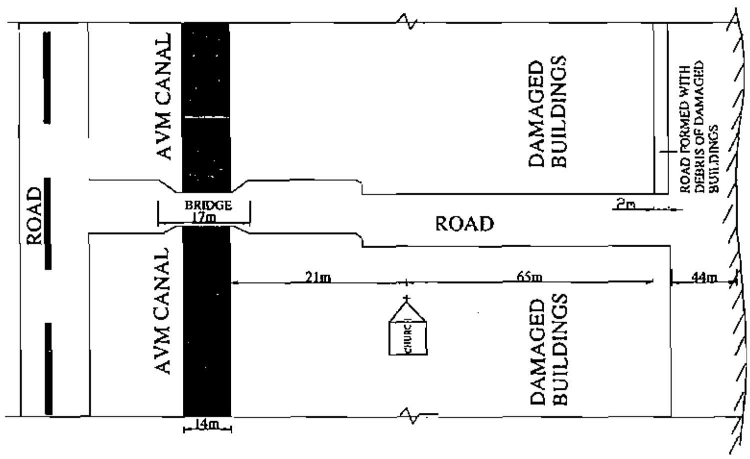


Fig. 8: Plan Of A Damaged Area Kottilpadu Colachel

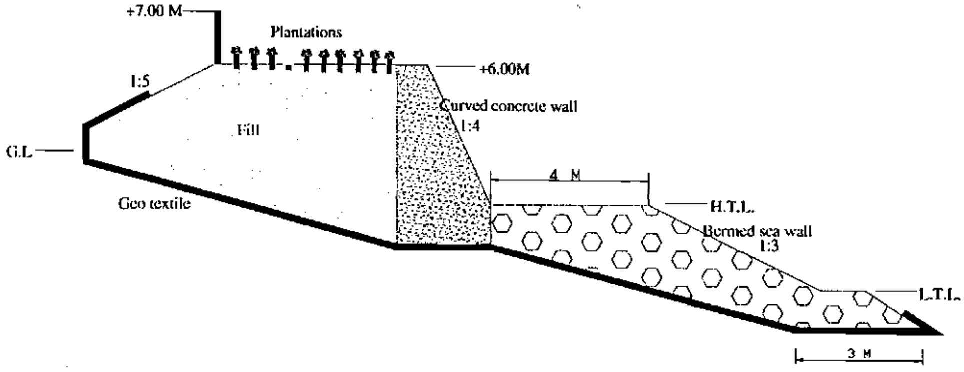


Fig.9 Proposed Seawall for a distance of 1 Km at Kottilpadu Colachel

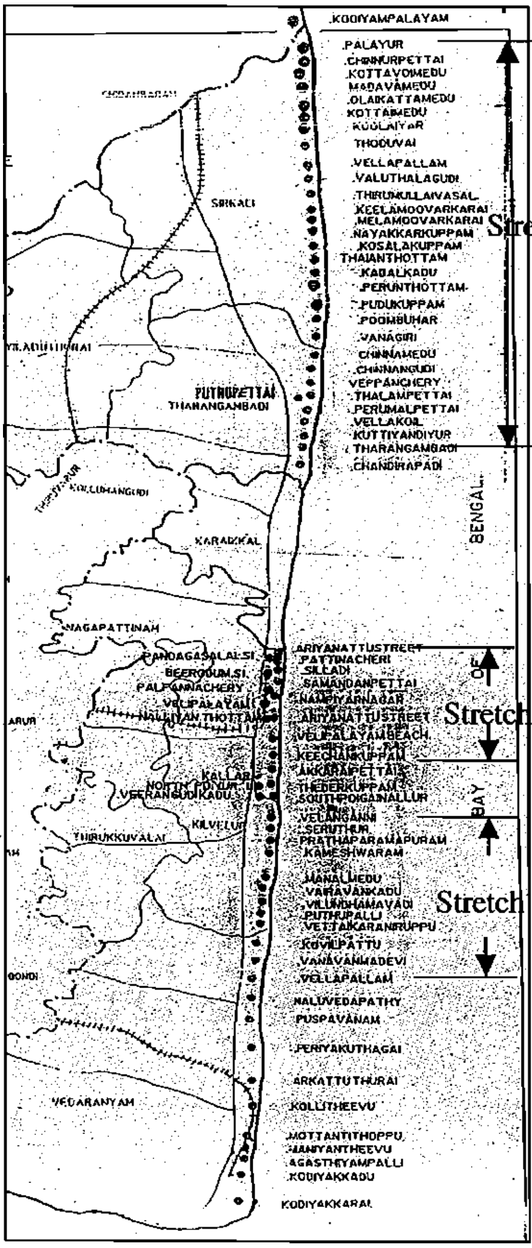


Fig. 10. The Nagapattinam Coastal District Map

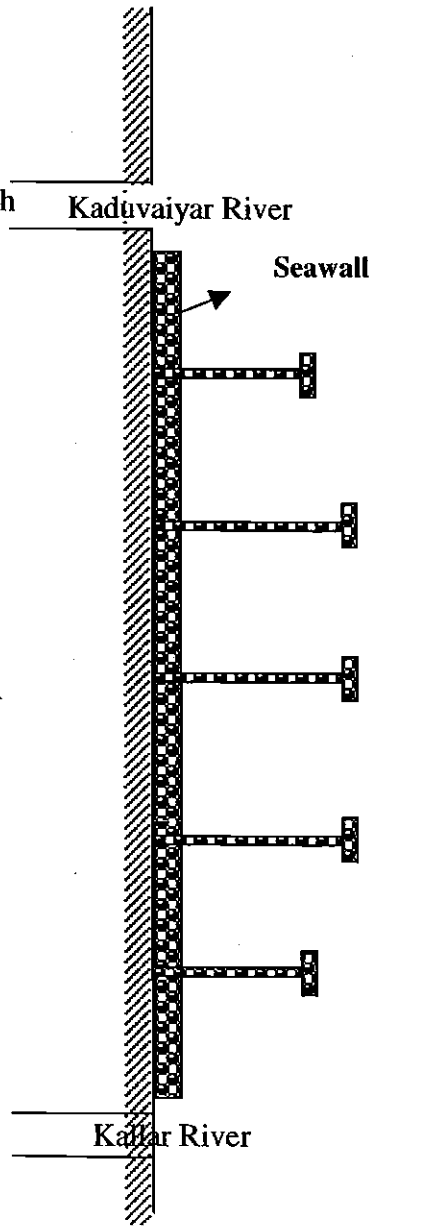


Fig. 11 a. Proposed Layout Of Groins From Nagoor To Keechankuppam

Section A – A is shown in fig. 11b

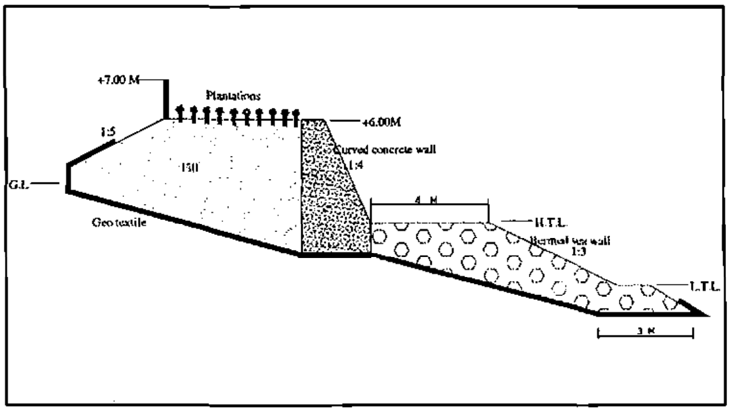


Fig. 11 B Cross-Section of Seawall

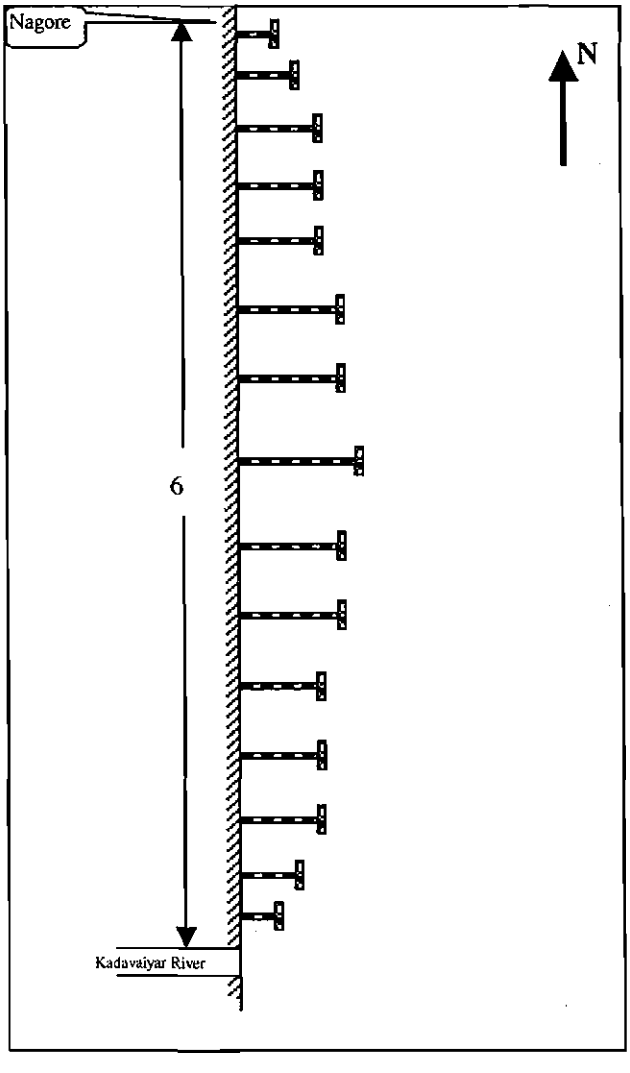


Fig. 12 Transitional T-Groins in Between Nagore and Kadavaiyar River.

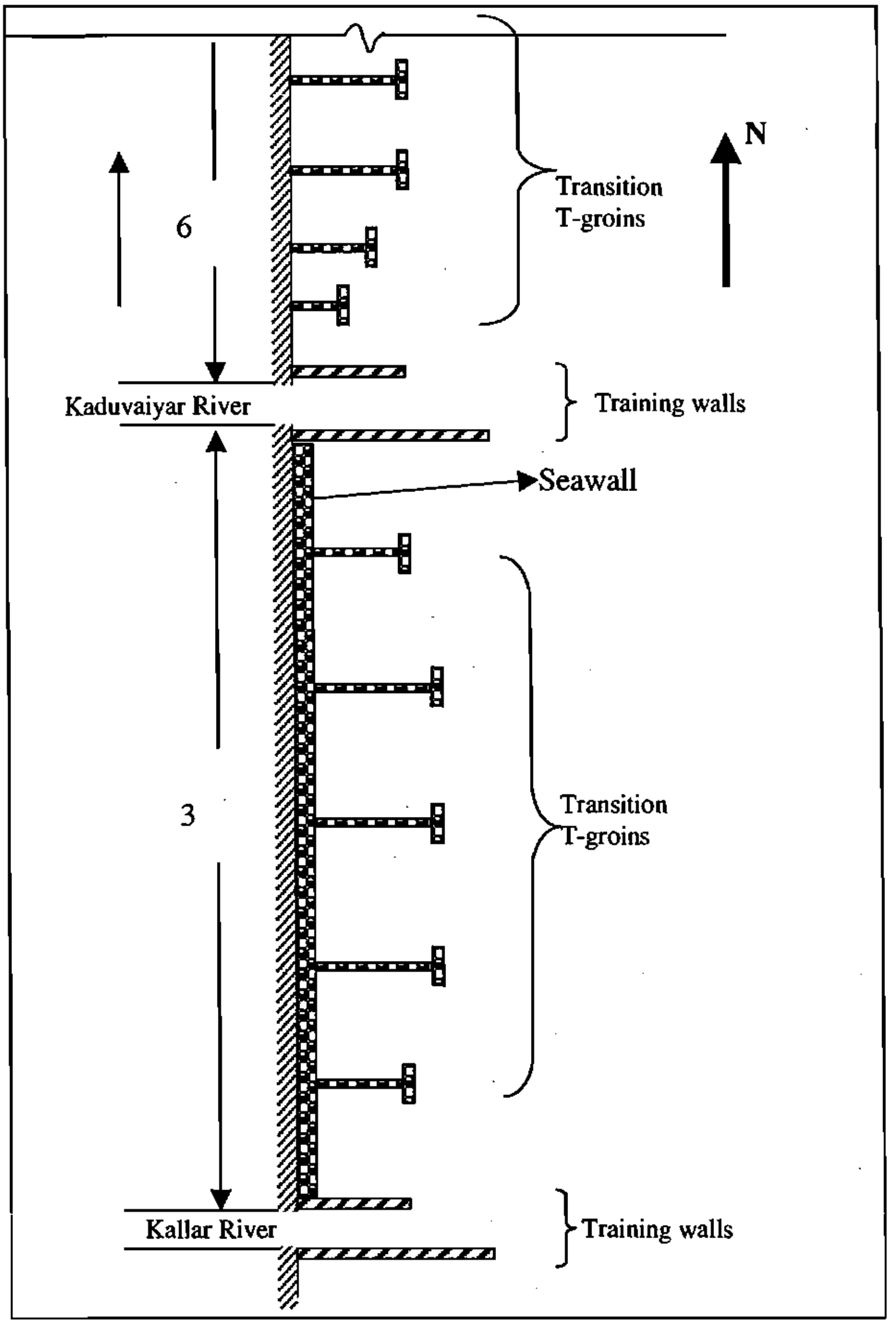


Fig. 13. The Stretch of the Coast from Velankanni to Vellapallam

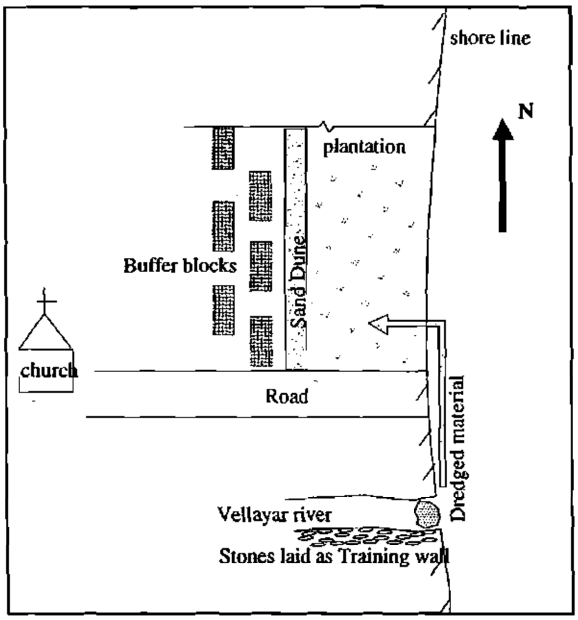


Fig. 14 The Protection Measures for Velankanni Stretch 'B'

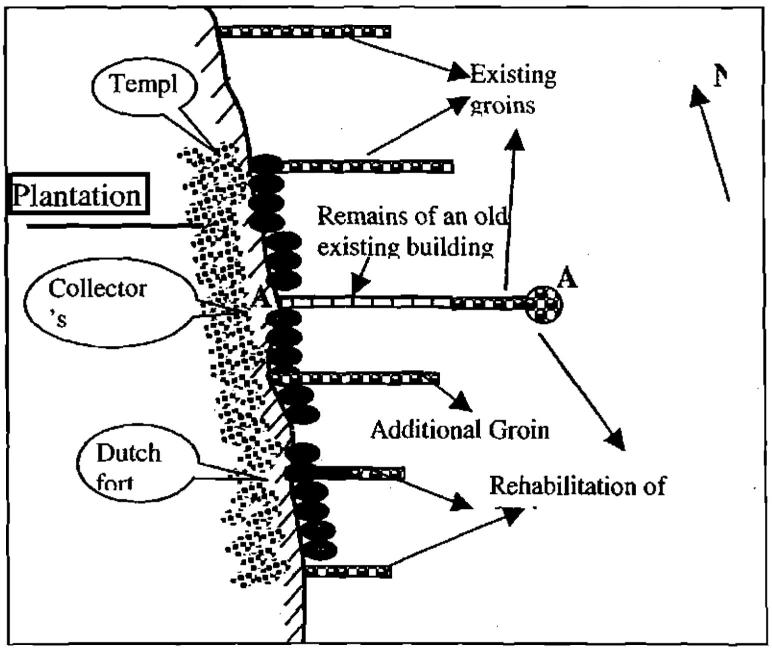


Fig.15. Rehabilitation of Existing Groins at Tranquebar Coast

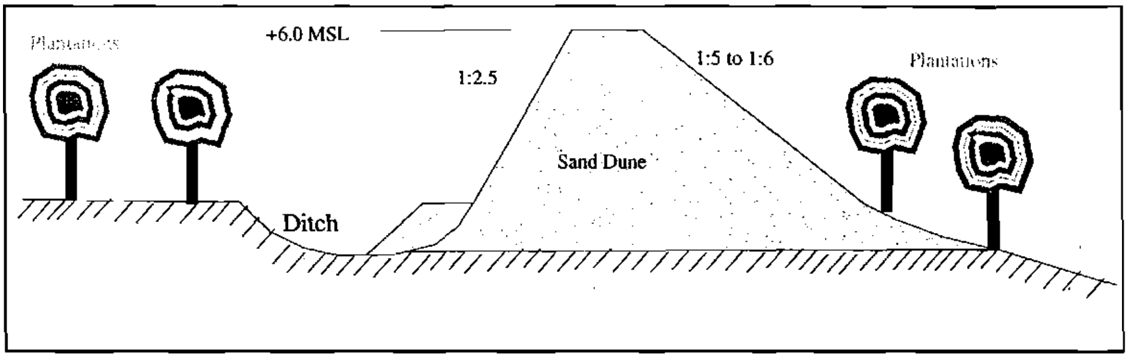


Fig. 16. Proposed Shape of the Sand Dune at Palayur

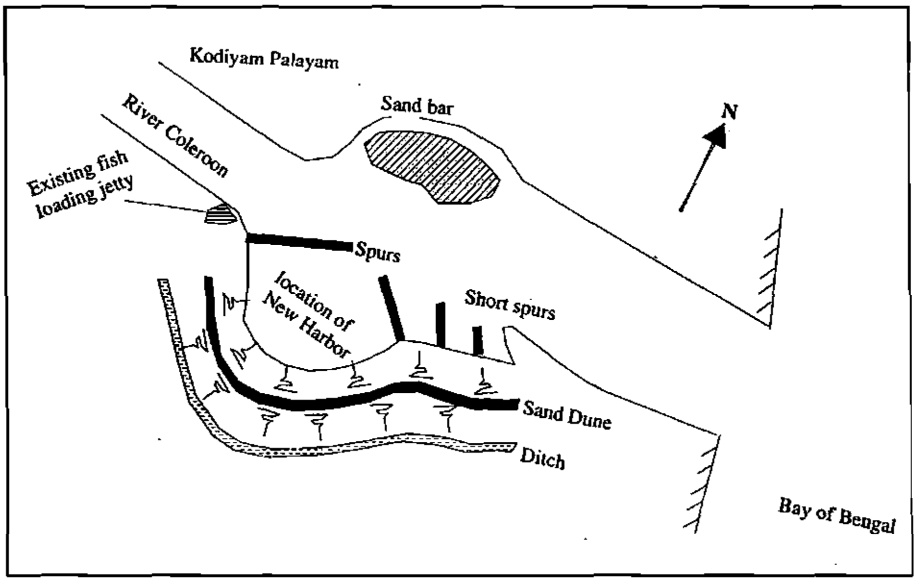


Fig. 17. Proposed Coastal Protection Measure at Palayur

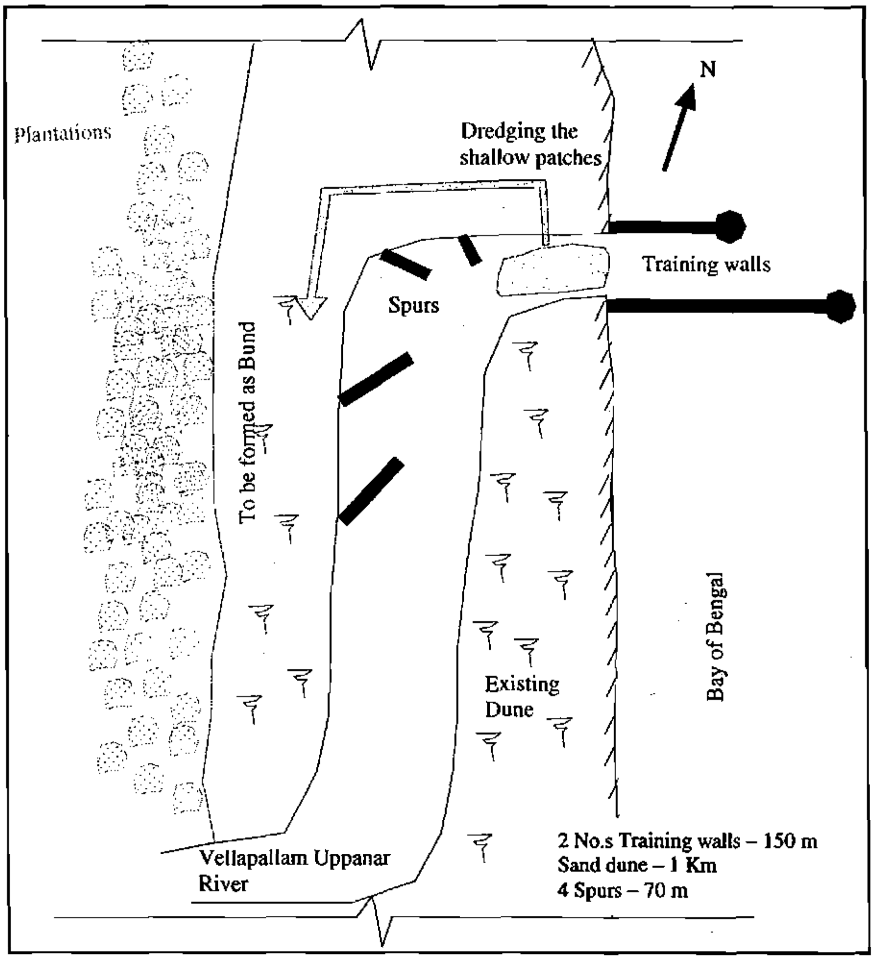


Fig. 18. Proposed Coastal Protection Measure at Thirumullaivasal

Planning of Coastal Protection Measures Considering the Effects of Tsunami along the Coast of Karaikal, India

Dr.R.Sundaravadivelu
Professor
Department of Ocean Engineering
IIT Madras, Chennai – 600 036

Abstract

Karaikal formerly a French territory located on the coramandel coast of Bay of Bengal located 300 Km south of Chennai. Historically Karaikal has been severely affected by the cyclones that have made landfall close to Karaikal or Nagapattinam. These cyclones not only affected the coastal structure with the high-speed wind but also, the induced surge flooded the coastal low lands. As a mitigation measure to prevent the coastal inundation during cyclone the then French government constructed coastal wall with sand as core material and covered it with precast concrete blocks covering the full coast length of Karaikal region.

The 26th December 2004 earthquake 9.0 on Ritcher scale was experienced off the west coast of Northern Sumatra, has created tsunami waves with high speed. As this wave entered the shallow coast its speed diminishes, its wavelength decreases and the wave height gradually increases with the piling up of water. Similar waves of 5m high, which hit the coast of Karaikal during tsunami destroyed every thing up to 150m from the shoreline and inundating upto a length of 1.5 km from the shore. The sand bund wall was not able to withstand the force of the tsunami and got fully damaged.

This paper briefs the protection measure that was suggested to reduce the impact of Tsunami and providing location specific structures in form of groin field adjacent to training walls and breakwaters, Rubble Mound Wall near the groin field, Cantilever Wall near populated settlements and sand bund with geomat and grass at other locations.

Introduction

Indian landmasses have been vulnerable to various forms of natural disasters because of its unique geo-climatic conditions. About 8% of its total landmass is vulnerable to the disasters that are caused by cyclone induced storm surge and Earthquake induced Tsunami.

Karaikal has a gentle topography varying from 1.5 to 2 meter above the Mean Sea Level and this makes it highly vulnerable to the flooding caused by the cyclone induced storm surge and Tsunami. Karaikal falls on the belt that is frequented by cyclones.

The entire 17 Km length of Karaikal coast was protected with the coastal sand bund against the flooding that was caused by the cyclone surge frequently. This system of coastal protection was planned and executed by the French government during their occupation of the territory. The structure comprised of sand bund as core material covered with Precast concrete blocks. The top and bottom width of the coastal bund was 1.5 m and 5.5m respectively with side slopes of 1. This wall was completely washed out during the 26th December 2004 Tsunami waves.

Four major rivers are draining into the Bay of Bengal in Karaikal coast. Fishing harbour in Arasalar river and one major port in Parvanar have already been approved and for both this projects training wall/breakwaters are planned. These structures may create erosion/accretions. IIT Madras has carried out the bathymetric survey and PWD Pondicherry has carried out topographic survey based on this data IIT has suggested an integrated coastal protection method by a combination of transition groin field near the training walls of fishing harbour and breakwaters of major port, Rubble Mound Seawall, Plain Cement Concrete cantilever wall and sand bund.

Proposed Protection Measures

The topography of the coastal zone in the Karaikal region is gentle flat and hence the French government has constructed a sand bund all along the coast to protect against storm surges that frequented the Karaikal Coast. These sand bunds have protected the agricultural lands from the ingress of seawater during storm surge. The sand bund wall with cement concrete slabs got damaged fully due to overtopping of Tsunami waves **(Fig-1)**.

Fig-1 Damaged seawall due to Tsunami

Hence the reconstruction of sand bund with Rubble Mound Seawall near the proposed groin field adjacent to the rivers and Plain cement concrete cantilever wall near populated settlements are proposed. The area where the direct impact from Tsunami to the inhabitants is insignificant, it is suggested to reconstruct the sand bund along the same alignment. Instead of protecting the sand bund with cement concrete slabs, it is proposed to protect the sand bund with geomat and grass.

Rubble mound seawall

The typical cross section of rubble mound seawall used in Kanyakumari District (Fig-2) for shore protection is proposed adjacent and in between the groins. The rubble mound sea wall with geotextile filter for providing, separation & filtration and gabion box for providing the protection is found to be efficient to protect the shoreline from storm waves of Tsunami waves.

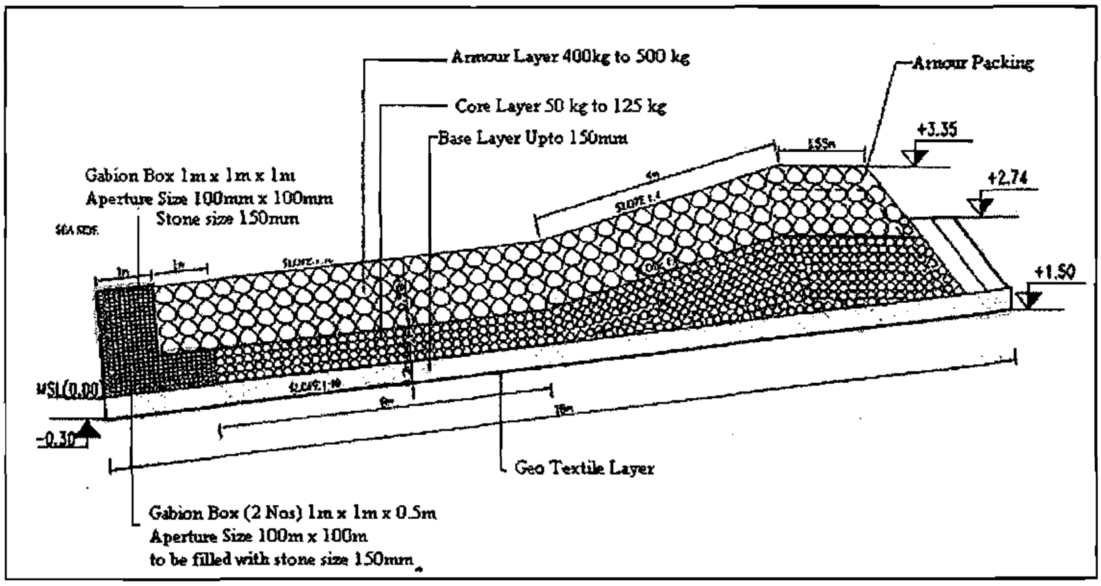


Fig-2 Typical Cross Section of Rubble Mound Sea wall

Cantilever Seawall

The cantilever type sea wall will be provided at location of population settlement.The coastal protection wall comprises of M20 grade Plain Cement Concrete with a stem of 300mm thick at top and 900mm at the bottom and a base slab of varying thickness from 900mm at center to 500mm at toe and heel. The two sides will be covered with sand filling with grass turf at sea side to increase the stability. In order to reduce the scour, gabion box with geotextile filter will be provided. An expansion gap will be provided for every 30m length of the wall. The cross section of sea wall is shown in Fig-3.

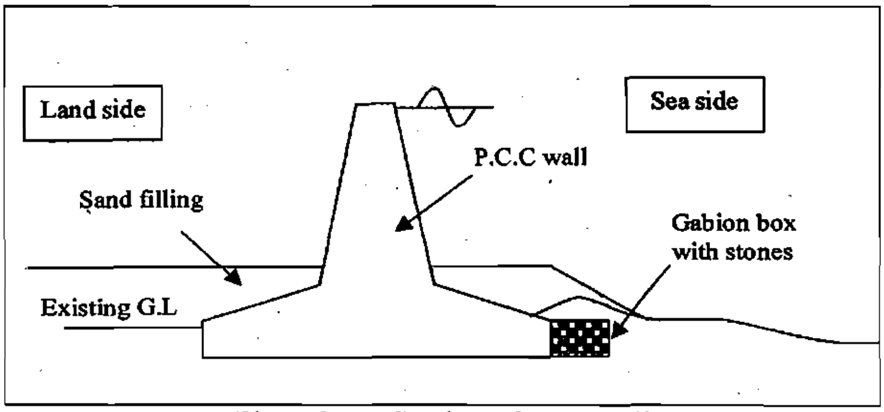


Fig-3 Cross Section of Sea Wall

Sand Bund

The sand bund consists of sand filling as the inner core, good earth of about 600mm as intermediate layer and geomat with manure of 150mm thick and grass as the extreme outer region.

It is proposed to construct sand bund in the region where the direct attack of Tsunami to the inhabitants is not expected. This will reduce the cost, since the construction of the seawall is about one fourth the cost of cantilever type sea wall. Therefore a combination of seawall and sand bund will provide an economical solution for coastal protection. The typical cross section of the sand bund with in shown in Fig-4 and Fig-5

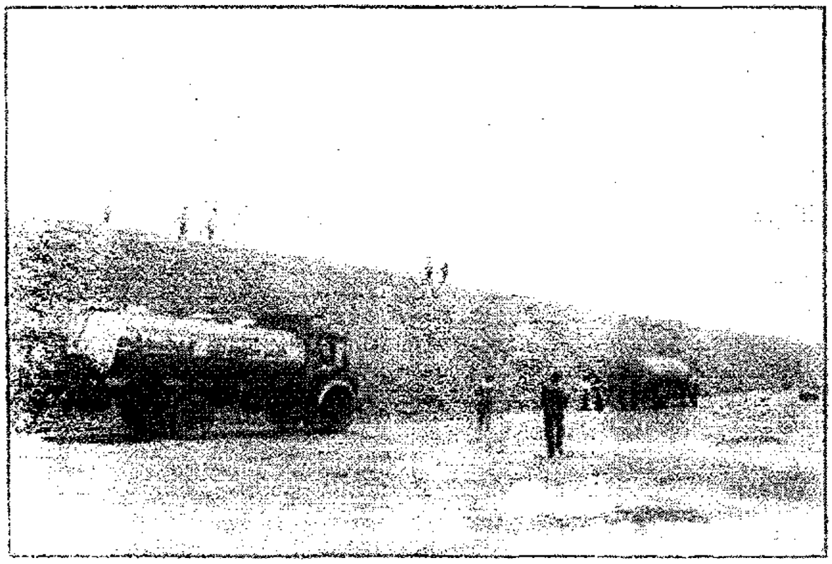


Fig 4 Typical embankment covered with grass

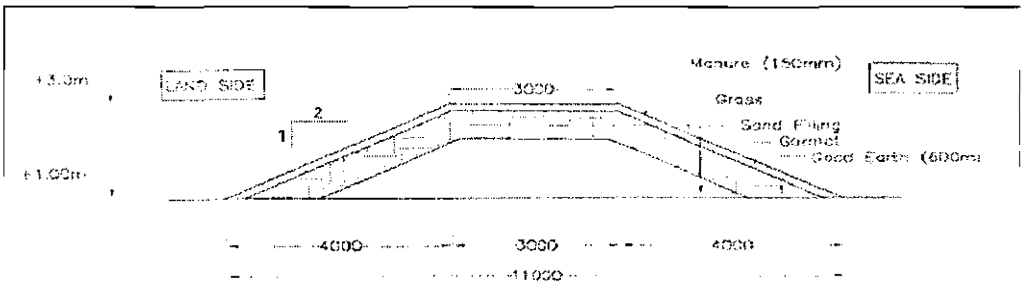


Fig-5: Cross section of Sand Bund

Groins / Training Wall

In addition to the Coastal wall, construction of training wall / groins are also proposed at the mouth entrance of Tirumalarajanar, Arasalar, Pravadyanar rivers. The length and spacing of the groins are decided based on bathymetry survey and numerical modal study. The wave data has been extracted from the wave atlas published by National Institute of Technology (1990) for Arabian sea and Bay of Bengal (Latitude: $0^0 - 25^0$ N and Longitudinal: $60^0 - 95^0$ E) compiling the ship observed wave data for 19 years. The wave atlas divides the coastal region around India into 10 grids. The present study area comes under the grid located at $10 - 15^0$ and $80 - 85^0$E in the wave atlas-representing grid number four. The details of the wave heights, wave direction and wave direction have been provided in Table – 1.

Month	Most frequently occurring wave height (m)	Mean wave height (m)	T (sec)	Deep water direction w.r.t North	Wave direction w.r.t X-axis
January	1.29	0.89	9.0	60	138
February	1.05	0.77	9.0	60	138
March	0.76	0.70	9.0	90	108
April	0.87	0.90	9.0	150	48
May	1.2	0.88	9.0	180	18
June	0.87	0.84	9.0	180	18
July	0.7	0.79	9.0	180	18
August	0.69	0.80	9.0	180	18
September	0.76	0.75	9.0	180	18
October	0.73	0.88	9.0	60	138
November	0.69	1.16	9.0	60	138
December	1.20	1.18	9.0	30	138

Table.1 Wave Characteristics for Shoreline Evolution

When a training wall is constructed normal to the shore at the river mouths it intercepts free passage of long shore sediment transport, which results an imbalance in the quantity of sediment transport, which results an imbalance in the quantity of sediment in the near the structure. This leads to accretion on the up drift and erosion on the down drift side of the structure. To prevent the erosion on the down drift groins are arranged up to a point where there will be no significant effect of erosion on the coast. The layout of the groin / training wall system along with alignment of coastal protection wall is given in fig 5.

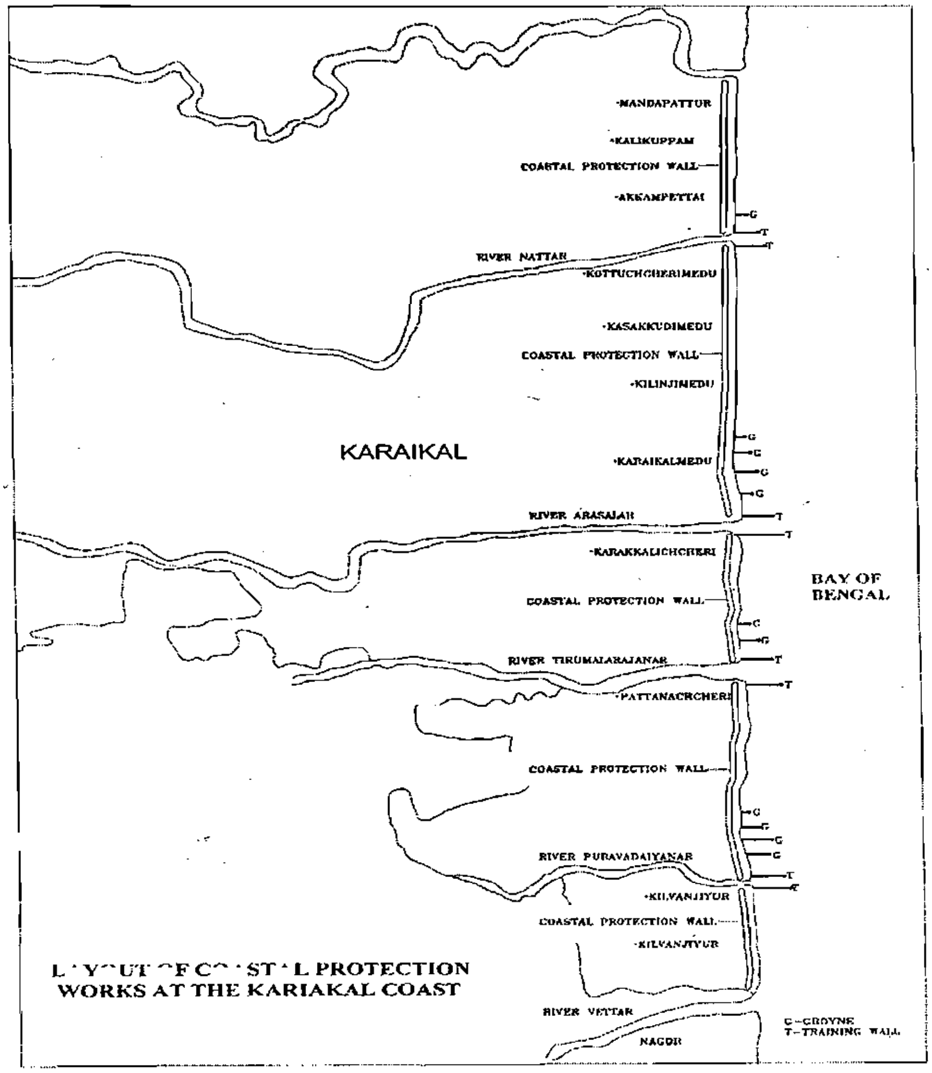
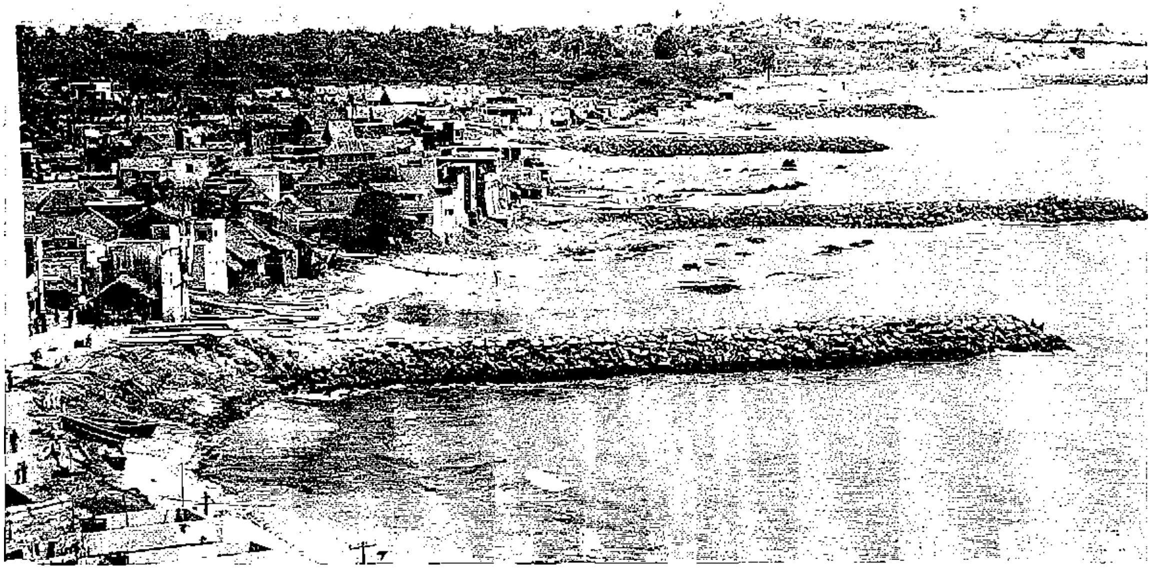
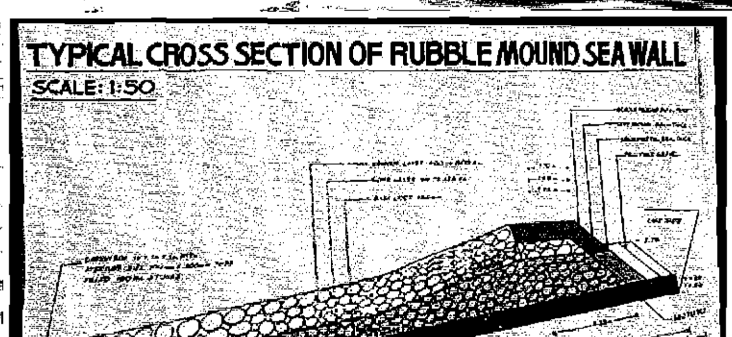


Fig 5 Layout of the coastal protection works at Karaikal coast

Conclusion

The groins will be suitably placed at the major river mouths. The provision of groins will help to control erosion further and the river mouth could be expected to be open during a major part of the year. In addition to the groin fields, a combination of rubble mound seawall, cantilever type seawall and sand bund are dry the old alignment of coastal sand bund constructured by the French government.




TYPICAL CROSS SECTION OF RUBBLE MOUND SEA WALL
SCALE: 1:50