12-2017

Resilient Housing Design for Tsunami Prone Andaman and Nicobar Islands in India

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Recommended Citation

Das, Sabyasachi, "Resilient Housing Design for Tsunami Prone Andaman and Nicobar Islands in India" (2017). Thesis. Rochester Institute of Technology. Accessed from

RESILIENT HOUSING DESIGN FOR TSUNAMI PRONE ANDAMAN AND NICOBAR ISLANDS IN INDIA

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A thesis submitted in partial fulfillment of the requirements for the
Degree of Master of Architecture

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Rochester, New York
December 2017

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ACKNOWLEDGMENTS

First, I would like to thank my thesis committee members, Mr. Nana-Yaw Andoh, Dr. Gabrielle Gaustad and James Yarrington for their guidance and review of this document, and for devoting their time and attention during their busy schedule. I would also like to thank the Head of Department of Architecture Mr. Dennis Andrejko for his support through this process. Sir, I am deeply grateful for your feedback. I would also like to express my gratitude to the other architecture and sustainability faculty for their assistance and support, and for being a constant source of motivation. Thank you for sharing your experiences, visions and analysis, which have contributed to my growth as an architecture student.

I would also like to thank my parents for their endless support and encouragement. Last but not the least, I would like to thank Rochester Institute of Technology (RIT) for providing me with the facilities and giving me a platform to purse my dream to become an Architect.

PREFACE

Over the first twenty years of my life I visited Andaman and Nicobar islands numerous times. When the 2004 Tsunami struck and caused major destruction to life and property on these islands, I developed a vision to provide a resilience solution which could sustain such natural disasters in the future. As a student of Masters of Architecture with a Bachelor's degree in Mechanical Engineering, I found the opportunity to draw light to my vision and was drawn to designing resilient buildings.

With increased changes in the physical world around us owing to development, globalization and other factors, there has been an increase in the number of natural and man-made disasters. This understanding has motivated me to contribute to the society through my knowledge of engineering and architecture.

The goal of this thesis is to act as a guide for architects, planners and builders to develop resilient designs for houses in coastal areas prone to Tsunami, hurricanes and flash floods. The motive is to develop a house which is habitable by regional population with better comfort levels and has the ability to survive a natural disaster. This thesis will discuss strategies to influence and inform the field of resilient model housing to keep the populations living in the disaster prone areas safe.

This thesis is based on logical decision making to inform the development of houses, which are resilient to natural disasters described above. The aim of this thesis is to provide solutions to develop resilient houses with better comfort levels in Andaman and Nicobar Islands, India as an adaptation measure for people inhabiting this area.

ABSTRACT

Human settlement along coastal areas has grown dramatically over the last two decades. Unfortunately, coastal areas are prone to natural disasters caused by climate change and tectonic shifts underwater in the adjacent water bodies, resulting in loss of life and property. Tsunami is a form of natural disaster which occurs because of earthquakes under oceans and seas creating large waves which flood or wash out any coastal cities or islands located in the area impacted.

In 2004 the Indian Ocean Tsunami had an enormous impact on the coastal cities in Southeast Asia causing loss of thousands of lives and making millions homeless. One region that bore the worst impacts of this tsunami was the Andaman and Nicobar Islands in India, located in the Bay of Bengal. Rehousing for those who lost their houses was the biggest post disaster issue as these islands were completely washed out. People built temporary housing until they moved to permanent houses, which took about two years to develop. The temporary houses built by the disaster stuck population were unsustainable. Being an island town, natural disasters such as tsunami due to tectonic shifts or rising water levels globally could reoccur bringing even more damage.

This thesis addresses the development of a resilient house as a solution for preventing homelessness caused by coastal natural disasters and act as an informative guide for houses that are to be built to make them resilient to similar natural disasters. Resilient housing is a viable solution to reduce the loss of housing post a disaster and to protect human lives through the disaster. This proposed prototype design of the core and shell of the house which is resilient and based on the characteristics of the region is based on studying and analyzing existing research in the field of tsunami's and their impact. This thesis takes into account the climate of the region and has features that ensure better comfort levels. The development of this thesis involved a study of Tsunami and its impacts, social aspects of the study area, relationship between structures and their resilience to Tsunami, the regulatory requirements of the government regarding incorporation of resilience in building design, a climate characterization of the region. This was followed by an analysis of the information gathered, based on which a prototype design of a house resilient to impacts of Tsunami has been proposed.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

NOAA	National Oceanic and Atmospheric Administration
Mt	Metric Tonne
Mph	Miles per hour
FEMA	Federal Emergency Management Agency
IPCC	Intergovernmental Panel on Climate Change
NIDM	National Institute of Disaster Management
RC	Reinforced Concrete
CGI	Corrugated Galvanized Iron sheets

TABLE OF CONTENTS

PART 1: OVERVIEW

1.1 INTRODUCTION

Water is a key element for human survival and its presence along land has fostered the growth of some of the largest civilizations. Water covers 71% of the earth's surface and 96.5% of this water is in saline form found in oceans and seas; and only the remaining 3.5% is fresh water [47]. Ironically water which is essential for the wellbeing of humans also takes human lives through natural disasters. Tsunamis are comprised of series of large waves of ocean or seawater, which flood into adjoining coastal areas causing flash floods and destruction of properties with their smashing thrust [48]. They are a result of geological changes namely tectonic shifts, underwater volcanic eruptions or combination of both. These large tidal waves are generated by vertical motion among tectonic faults. As illustrated in Figure 1.1 below, an earthquake displaces volumes of water pushing them up and thereby triggering the oscillation of water at great speed. The water is pulled back from the nearest shore which is observed as receding tides, and then as the water returns to the surface it creates a series of strong high speed waves which increases in height as the water becomes shallower near the shore and its speed reduces from 450-500 mph to 18mph near the coastal line [49].

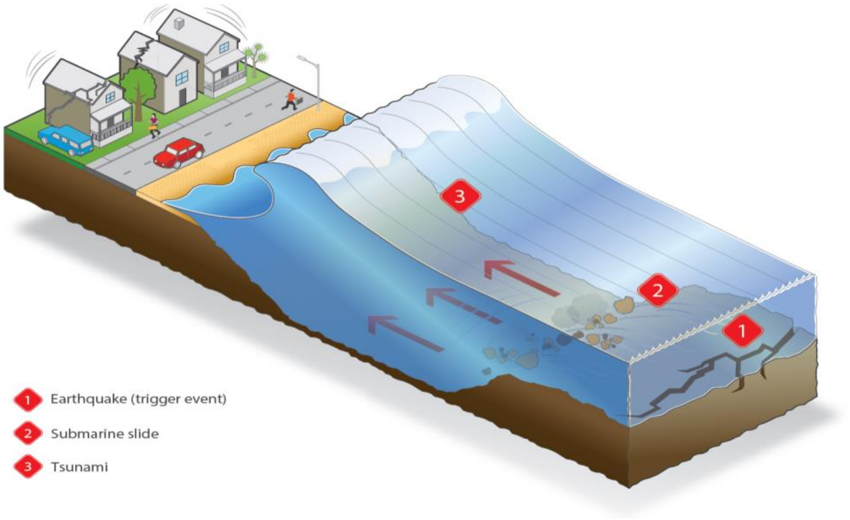


Fig. 1.1 Generation of a Tsunami

Source: Taranaki Emergency Management, Government of New Zealand [63]

These waves can destruct the shore even in when they have heights like 5 meters. According to the National Oceanic and Atmospheric Administration (NOAA), the occurrence of tsunamis around the world has been accountable for over 420,000 lives lost and billions of dollars in economic damage in the form of destruction of coastal structures and habitat since 1850 [1]. These casualties were mostly caused by local tsunamis that occur occasionally once a year somewhere around the world.

One of the largest Tsunami disasters in recent times was the Indian Ocean Tsunami that struck on December 26, 2004. This tsunami originated under the Indian Ocean near Banda Aceh, Indonesia, caused by an earthquake of 9.1-9.4 on Richter scale [2]. The tsunami waves from this earthquake, also called Sumatra-Andaman earthquake travelled long distances in different directions. Eleven countries were affected by this natural disaster. A total of 280,000 people lost their lives and more than 1.5 million people were left homeless. According to the Asia Disaster Preparedness Center, the damages were close to 6 billion US dollars [3].

Andaman and Nicobar Islands is an archipelago, which are Indian Union Territories in the Bay of Bengal near the eastern coast of the country (See Figure 1.2 below). These islands were closest to the epicenter of the Indian Ocean 2004 Tsunami and were among the most affected zones in the disaster stuck area. These islands that had a small population of 350,000 people bore highly intense damage [34]. The death toll of the island exceeded 12,800 and 50,000 people were affected in the 38 islands hit by the tsunami. 14,000 dwelling units were damaged by it, as waves up to 9 meters high reached the shores and flash floods were traced to at least one mile inland [4]. According to the local government reports, a total of 9,565 intermediate shelters were made for the survivors and an estimated 15,000 Metric Tons (MT) of construction material was transported to the islands [42]. Housing became a major issue after the disaster as most people had lost their houses. It took long periods of time to create shelter for the people as these were island towns where shipping ports and airstrips had got damaged due to Tsunami. It had become immensely difficult to make relief reach the affected areas from the mainland country, as the island generally relies on mainland imports. The damage caused prolonged economic damage on the islands as the fishing and the agriculture industries which are the predominant industries in the islands were greatly affected. The Andaman and Nicobar Islands houses a strategically important defense port for India in the Bay of Bengal, which also got disrupted [70]. Agricultural fields were either washed out or salinized due to temporary inundation of seawater as some saline water remained in the island in natural depressions and man- made topographic changes.

Fig. 1.2. Location of Andaman & Nicobar Islands in Subcontinent of India
Source: Maps Open Source Website [64]

As these islands are very close to the tectonic plate faults of the Indian, Australian and the Eurasian plate [50], and a similar even in this region is highly possible in the future, that may cause recurring damasge. As per the Intergovernmental Panel on Climate Change (IPCC 2001), global sea water level will rise between 110 and 880 mm by the year 2100 [71]. The rise in sea water level can lead to saline water inundating inland surface causing flooding [46]. Considering that these islands are prone to a tsunami in the future and globally rising seawaters, it is very important to make buildings in these islands that are resilient to these foreseen disasters.

The damage to residential buildings on the islands was large. Numerous buildings with reinforced concrete construction did not survive the impacts of the Tsunami as they didn’t have any seismic code incorporated in their design [4]. The buildings which had seismic detailing in their column structures survived better. During the Tsunami some ground shaking occurred in particular areas of the islands that lead to liquefaction and cracking of floors in houses. The houses which were made with lighter construction materials such as wood and tin sheet metal roofs, or a combination of wood and masonry survived the impacts of the shock better. Even the old masonry structures on the islands survived better in response to the ground shaking of the impact. In Port Blair, the main town of the islands, owing to a lack of open space around buildings that aids in lateral deformation during the Tsunami, the buildings suffered cracks in their building shell.

The houses constructed post the 2004 tsunami are mostly built on higher plinths, with masonry walls, RC isolated footings, steel structures. Bamboo boards are also used as a building material [86]. Sloping roofs are made of tin sheet metal or Corrugated Galvanized Iron sheets (C.G.I.) [86]. These houses have more open spaces around them that would support lateral deformations during a Tsunami.

As per Resilient Design Institute’s definition, “*resilient design is the intentional design of buildings, landscapes, communities, and regions in order to respond to natural and manmade disasters and disturbances*” [51]. The development of resilient houses that can withstand disasters is a viable solution to areas prone to natural disasters. The purpose of this thesis is to propose a housing prototype along coastal areas that is resilient against future natural disasters and can be used by the users for a prolonged time with enhanced comfort levels in context to climate of the region. This thesis involved a literature review to understand the science behind the causes of Tsunami, social norms of infrastructure on the islands. The literature review was followed by an analysis and a proposal of a resilient house design. The aim of this thesis is to develop a resilient housing design, which can be used by people as a guideline in the area to help them adapt to the impacts of future Tsunamis and create a design which could be accepted socially for regular habitation.

1.2 PROBLEM STATEMENT

Tsunamis are a series of tall waves with large amount of energy and water contained in them [48]. These waves cause mass destruction by their smashing force due to their high-speed and large voluminous wall of water travelling towards the shore and washing it away. Tsunamis occur, at very little warning, by the movement of the tectonic plates which is felt as an earthquake. It is difficult to predict tsunamis well in time to provide time for evacuation as according to the NOAA, "*neither seismometers nor coastal tide gauges provide data that allow accurate prediction of the impact of a tsunami at a particular coastal location*" [5]. Tsunamis have led to the loss of more than 420,000 lives across the world since 1850 [1]. The Indian Ocean 2004 tsunami has been cited to be the most damaging with 280,000 deaths in the 11 affected countries and 1.5 million people left homeless. The area of this study, the Andaman and Nicobar Islands, which were closest to the epicenter of the earthquake that caused the Tsunami, suffered a death toll of 12,800 and 50,000 people getting affected. The waves moved at high speeds of 500mph across the Indian Ocean and took the form of destructive high waves of 10m height travelling at a speed of 20mph along shallow coastal waters. 14,000 dwelling units in the islands were damaged by the waves that reached shores and caused flash floods up to one mile inland [4]. There was damage to the jetties, trade and transport links, power infrastructure and water supply systems. This left the people living in the islands homeless and making them live in makeshift tents for months before they could move into semi-permanent shelter. Being island towns which are dependent on the mainland for regular import supplies, even reach of relief supplies and new construction materials got delayed due to logistic delays and damages to its jetties. The tsunami led to the caused severe damage to the local economy especially the islands fishing and agriculture industries as lands were salinized or submerged. Considering that the islands are close to the Indian, Australian and the Eurasian fault plates, there are chances that an earthquake underwater triggering Tsunami could reoccur. The population of the islands is 380,000 observed in 2012, an increase of 8% from the 350,000 population of the island in 2004 [34]. Considering the fact that a tsunami may reoccur, the risk of number of people losing life and property is higher. In precedence to the delay caused in the reach of relief supplies to these islands after the disaster from the mainland due to possible logistic delays, a possible disaster situation would affect them similarly even today.

In order to address this problem, it is important to develop housing for the people who inhabit such tsunami prone regions that is resilient to the impacts of a Tsunami as an adaptation method to protect human lives and their property in case of a disaster. This thesis is based on the study of literature and Design guidelines of building infrastructure in Tsunami affected areas of Andaman and Nicobar Islands by Government of India and proposes a concept resilient design prototype of houses. The purpose of this research is to inform architects, planners and builders through the development of a tsunami resilient design of a house as a guide for building new houses or retrofitting houses in areas prone to Tsunami, hurricanes and flash flooding.

1.3. AIM & OBJECTIVES

In view of the background and problem statement mentioned in the sections above, this research had the following aim:

To propose the design of a house that is resilient to impacts of a Tsunami as an adaptation measure in Tsunami prone areas of Andaman & Nicobar Islands, India while accounting for the climate of the region to provide better comfort levels.

To achieve the above state aim, following objectives were developed:

1. To conduct a study of Tsunami and its impacts.
2. To study the relationship between buildings structure and its resilience to Tsunami.
3. To conduct a background study of Andaman and Nicobar Islands.
4. To review the regulations and guidelines for design criteria for Tsunami resilience in buildings in India.
5. To do a Climate Characterization of the region.
6. To create the house design based on analysis of information gained in Objective No. 1. to 5 using *Revit 17* as a design tool.

1.4. LITERATURE REVIEW

Natural disasters have become recurrent in coastal areas across the world in the last two decades. Along with storms and floods, tsunamis have caused enormous damage in the regions of occurrence over the years. The 2004 Indian Ocean tsunami caused damage to 11 countries, with Banda Aceh, Indonesia and Andaman & Nicobar Islands, India suffering the most damage. Hock Lye Koh in his paper "Earthquake and Tsunami Research in Universiti Sains Malaysia (USM): The Role of Disaster Research Nexus**"** [6] talks about the impact of tsunami and methods to reduce its impact in the different studied simulated Tsunami conditions. The paper also discusses methods that can be implemented to cope with soil salinity changes due to water inundation and assisting vegetative rehabilitation, and a model for estimation of tsunami forces on coastal structures. The paper analyses all of these with an objective to encourage researchers to collaborate further in the development of resiliency to face future earthquakes and tsunamis better.

Thorne Lay's paper on the 2004 Indian Ocean Tsunami titled "The Great Sumatra-Andaman Earthquake of 26 December 2004" [2] discusses the earthquake that caused the tsunami in the region. In this paper, Lay has talked about the two most powerful earthquakes in the past 40 years that ruptured a 1600 km stretch of the boundary between Indo- Australian and South-Eastern Eurasian plates and also a slip occurred north of the Andaman and Nicobar Islands over a period of fifty minutes. He has further discussed the impact of this on the neighboring countries and Andaman and Nicobar Islands. This paper supported this thesis by building an understanding of qualitative and quantitative impacts of a tsunami.

In "Natural Disaster, Mitigation and Sustainability: The Case of Developing Countries" [7] the authors Souheil El-Masri & Graham Tipple have discussed the method of applying sustainable development principles to natural disaster mitigation in developing countries. Land-use planning and policies; building materials, shelter design and methods of construction; and institutional organization at local, provincial, national and international levels have been considered. These aspects have been described based on the knowledge of settlement of humans in reference to particular disaster situations and housing for the underprivileged in developing nations. The paper discusses a spectrum of conditions and the problems associated with them along with the respective solutions. It further says that transforming ideas into implementable strategies requires creative combinations of solutions with customization to a particular disaster situation. A detailed study of the circumstances and the disaster type is essential for the proposed adjustments and changes to accommodate human user better.

“Understanding and Applying the Concept of Community Disaster Resilience: A capital-based approach” by Joseph S. Mayunga [8] speaks about the limitation of understanding of the concept of Resiliency. The paper discusses the limitation of operation and understanding of the concept of resilience. In this study, Mayunga has developed a conceptual and methodological framework for the analysis, measurement, and mapping of community disaster resilience. His method involved first an examination of the definition of the concept followed by a review of the currently used framework to measure resilience of the community. He has further proposed a method for community disaster resilience.

In the paper “Simulated Tsunami bore impact on an onshore structure” by Al-Faesly, et al [9] motivated by the recent disasters investigate the effects of Tsunami waves in order to propose an appropriate formulation to analyze tsunami loads better. The paper involves a great deal of practical experimentation through a fabricated model structure that was subjected to hydraulic bores in a simulation of rapidly advancing broken tsunami waves. The experiments generate evident data which could be used to aid further understanding and development of resilient structural systems.

Folke et al. in their paper “Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations” [10] have emphasized that natural resource governance policies have been built on two major errors and that the world needs to recognize these errors and work to correct them. The first error is the assumption that human use causes ecosystem responses that are linear, controllable and predictable. The other is that humans and nature and its systems are independent, which is not the case. The authors have proposed resilience as a method to understand how to build and develop adaptive capacity in this world constantly marked by transformations. They have further discussed two tools that can be used for building resilience in socio-ecological systems. These include active adaptive management and structured seniors. The aim of the tools according to the authors is to facilitate a social context among system structures to allow learning of adaptive methods without affecting development in the future.

Adger et al in their article “Social-Ecological Resilience to Coastal Disasters” [11] speak about the necessity to build socio-ecological resilience into social systems to limit the vulnerability of coastal economies/regions. The authors state that large scale processes like economic activities affect resilience capacity and anthropogenic activities only worsen the risk that disasters pose. Building this resilience would require both people and the governance system to contribute. According to the authors, efforts need to be made at multiple social networks with inter-level cooperation and interaction to aid in building resilience.

Terry Canon in chapter titled “Vulnerability Analysis and the explanation of ‘Natural’ Disasters’ of his book “Disasters Development and Environment” [12] has argued that vulnerability of people to impacts of a natural hazard is affected by social and economic factors. If a group of people have the economic means to prepare for a disaster, they can become resilient to the effects of that hazard. He added how social systems like social institutions such as unions, NGOs and cooperatives allocate resources to reduce impacts of a disaster are important. He further states that the aim of preparedness for a disaster should be to reduce impact of the hazard by reducing vulnerability of the people that may be carried out by constructing buildings that are disaster resilient.

Theo Schilderman in his study “Building Research and Information” [13] speaks about the adaptation of traditional shelters for disaster mitigation and reconstruction. He states that development affects vulnerability of people to a disaster and occurrence and scale of disasters. If development goes wrong, vulnerability of poor people increases. In addition, if a disaster strikes it sets back development. The author has emphasized the importance of community based disaster mitigation stating that it can help reduce vulnerability by involving local knowledge, popular approaches, and social capital while addressing their weaknesses. Some community based mitigation examples mentioned by the author include encouraging participation, learning from past, building local capacity, influencing formal education, associating with communities, working with local artisans and builders, and documenting and sharing lessons.

The Hyogo Framework for Action 2005-2015 adopted at the World Conference on Disaster Reduction in Hyogo Japan 2005 [14], urged governments to integrate assessment of disaster risk into urban planning activities and management of human settlements that are disaster prone. In addition, it asks governments to incorporate considerations for disaster risk in planning activities for key infrastructure projects, including but not limited to "criteria for design, approval and implementation of such projects and considerations based on social, economic and environmental impact assessments." The Framework further calls out governments to include disaster risk concerns in planning and management for rural development, especially in coastal flood plain areas, by efforts such as identifying land zones, revising existing building standards, codes, rehabilitation and reconstruction practices, with the overarching objective of making them more suitable to local requirements.

The role of construction professionals in contributing to disaster resilience has been emphasized by Bosher et al., 2007 [15] where they have stated that construction professionals who have the experience and knowledge to design, build, retrofit and operate buildings that essentially bespoke assets into the Disaster risk management framework should be included in the design process. The paper further discusses taking an integrated approach in completion of a building project.

In his book "The Environment as Hazard" Burton [16] has categorized human responses to natural hazards into short-run and long actions. They discuss that short run actions focus on adjustment and long-run actions involve adaptation. They categorize the method of designing a disaster resilient house as an adjustment. An example of adaptation would be locating a community in a way that the houses are in an area that is away from most impact of disaster.

The paper "Geotechnical and structural damage in Tamil Nadu, India, from the December 2004 Indian Ocean tsunami" by Maheshwari et al. [4] talks about the inspection of the scenario after the 2004 Indian Ocean Tsunami. The team came to conclusion of determining the major cause of the devastating circumstances and determined it was not particularly only by earthquake but more from the waves of tsunami. The main aspects identified by the authors were incidents of collapsing of rural houses, damage to columns and roof damages. The summarized analysis discussed the damages being much more drastic by a tsunami when compared with an earthquake situation.

Shaw et al in their work “Resilience from Climate Disaster Focusing on Coastal Urban Cities in Asia” [17] have discussed five resilience dimensions, namely, Natural, Physical, Social, Economic & Institutional. The study is limited to cyclones, floods, heat waves, droughts and incidents of heavy rainfall. The authors have advised that the local government should take part in building resilience against a climate disaster. Several methods for such engagement have been suggested in the article including engagement in cist services and various other investments. In addition, the authors suggest that resilience as an agenda should be not ignored at present keeping in mind our future generations.

Heracles Lang in his paper "Community Housing in Post Disaster Area on Nias Islands, Indonesia: Responding to Community Needs" [18] discusses the widespread damages in the Nias Islands in Indonesia due to the Indian Ocean Tsunami. He talks about rehousing and redevelopment issues that came up after the disaster as the rehousing and redevelopment process became ineffective due to the disputes among the beneficiaries and the concerned agencies because of low construction quality with the concerned agencies. In order to solve this, the government developed a community based approach towards redevelopment of the affected zones. The paper discusses the importance of community satisfaction and also how the extent of redevelopment is customized to community requirement and allowance of this makes the process smooth and harmonious. The community based redevelopment process enhances the bonding in the community after the disaster as people work towards a targeted approach towards the satisfaction of their housing needs.

C.V.R. Murty in his paper “Performance of Structures in the Andaman and Nicobar Islands (India) during the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami” [19] discusses in detail the damage caused to buildings and structures in the islands by Tsunami’s impact. The paper discusses the different impacts in varying types of structures in the islands with Reinforced Concrete Construction (RC) and Traditional Wood Construction. He has further talked about how many building structures with wood construction survived the impact and a number of new RC structures collapsed where on investigation it was observed that they were missing ductile detail features for earthquake impact resistance.

Sustainable building technologies and construction are gaining momentum throughout the world. In "Sustainable building technologies" Reddy, Venkatarama BV [20] speaks about the energy consumed in manufacturing and transporting of some common and alternative building materials and the implications they have on the environment. Construction is responsible for 22% of greenhouse gases. He has talked about the impacts of alternative building technologies on environment and recycling techniques to meet the need of building construction in a sustainable manner. The qualitative and quantitative analysis carried out in this study using real life examples of efficient building construction elements proves its point well.

Availability of materials required to implement a technology affects the technology’s reach. In the study "Light transmitting roof/floor system” Taylor, John R [21] have discussed a technology that involved light transmitting plate assembly, which is formed by simple gluing of glass plate laminated to a plastic plate of lower thermal conductivity by a silicone adhesive which is secured by a perimeter frame. These may sometimes include a grid of divider members for aesthetic and light transmitting purposes or for supporting the glass blocks. These panels, which are made on-site, can be used as one of a building exterior wall, roof, floor and skylight. It is highly load resilient and waterproof in nature to be used in the above ways creating a structural lightning feature. The consideration of possible innovative building methods should not go unnoticed and these should rather be implemented strategically to our concepts local to the region. This technology which can be made in-site conditions and doesn’t need to be assembled at a factory thousands of miles away could be utilized in housing around the world. Similarly, local material sourcing if utilized in building projects in developing resilient housing can support the mission of sustainable housing better.

The paper on “Building damage in Thailand in the 2004 Indian Ocean tsunami and clues for tsunami-resistant design” by authors Panitan Lukkunaprasit & Anat Puangrassamee [22] conducted a field study of the buildings in Southern Thailand affected by the 2004 Indian Ocean Tsunami to understand what features are necessary to make tsunami resilient buildings. They found that openings in walls and low seawalls are two features that can help reduce impact of such disasters. They have stated that openings in walls helps decrease unbalanced pressure that builds on the walls of buildings during such a disaster. On the other hand, low seawalls partially help disperse the energy of attacking waves. A large number of such buildings survived which suggest that it is possible to design buildings that are tsunami-resistant and can survive with damage that can be offset by repair, incur least economic loss and can recover quickly.

The paper on “Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites” by Harry Yeh, Ian Robertson, and Jane Preuss [23] builds a foundation to help standards and guidelines to be made for buildings in Tsunami prone areas. Earthquakes can be felt in large areas but areas that get inundated by the large waves and are more close to the shore area bear the most impact of a Tsunami. The authors have emphasized the importance of evaluating design requirements of buildings in order to make them resilient to seismic activity and tsunami waves. They have further stated that while design requirements for the former are affected by the redundancy, flexibility, and ductility of the system in consideration, tsunami resistance requires a structure to be rigid and have enough strength, especially at the structure’s lower levels.

In the paper “Tsunami wave loading on coastal houses: a model approach”, Lukkunaprasit et al [24] have tested a model house developed in USA called ‘tsunami-resistant house’ and constructed a 1:25 model in simulation to Sri Lankan coastal line and placed their tsunami resilient house model in the tank along with regular coastal houses to test their resilience to Tsunami waves. The results showed that the Tsunami waves didn’t cause any damage to the model house while a regular coastal house was brutally damaged. The idea behind the design of the model house was to allow the tsunami waves to pass through the house’s central area without causing much hydrodynamic loading. Hence, instead of a typical coastal house in Sri Lanka that comprises of four solid walls each with small openings for windows and doors, the doors in the model house were centrally placed and faced the sea, while reinforced concrete was used to build the corner walls of the house.

In the paper “Tsunami loading of buildings with openings” [24] Lukkunaprasit et al have explored effects of openings in buildings on their capacity to resist impacts of Tsunami waves. In this study, square shape building model of one to one hundred scale were tested against a hydraulic flume. A slope was 0.5degree representative of sea shore in Phuket, Thailand was simulated. Two different opening configurations with 25% and 50% openings of the front and back walls were investigated. Pressure sensors and high frequency load cell was placed in the model to measure pressure distribution and record the tsunami forces in the model. The result of the experiment demonstrated the benefits of openings in reducing the effect of tsunami on buildings. As the openings allowed water to enter the building, creating counteracting pressure on the inside of the upstream panel and reducing the force acting on the rear panel. According to the tests building 25% opening configuration had a reduction of 15-25% of wave force and 25% reduction for a 50% opening configuration.

The authors of “Built-in resilience to disasters: a pre-emptive approach” [25] state that Disaster Risk Mitigation can be of two types. First is structural mitigation which involves strengthening of infrastructure and buildings that may be exposed to hazards. This can be achieved through engineering design, building codes, and construction practices. Secondly is Non-structural Mitigation which involves ensuring that any new development activities are allowed only on areas that are away from hazard prone areas by the way of land-use plans and regulations, moving prevailing developments to areas that are safer and ensuring that features of natural environment that guard against impacts of hazards are maintained. These natural environment features could include forests and vegetated areas, sand dunes etc. that have the capacity to act as buffer in order to decrease the magnitude of impacts.

The authors Edris Alam and Andrew E. Collins of “Cyclone disaster vulnerability and response experiences in coastal Bangladesh” [26] have discussed construction practice adopted by local communities in cyclone prone areas of Bangladesh where people make houses with higher plinths using mud in hazard prone areas. The more vulnerable an area is; a practice of higher plinth is made with the base of the house on it. As observed by the authors, higher the height of plinth the more successful it has been in increasing the probability of saving people during times of tidal surges.

Kason Hoku Pacheco in “Evaluation of Tsunami loads and their impact of reinforced concrete buildings” [27] studied various structures that bared Tsunamis and found that only those structures with engineered structural steel, reinforced concrete which were raised above the tsunami water flow could survive the forces of tsunami waves without either substantial damage to the structure or without collapsing. The author performed experiments where three prototype multi-story reinforced concrete buildings having different structural systems were designed for varied levels of seismic ground quaking or winds with subjection to 3, 5 and 10m tsunami flow. Tsunami flow equations were derived from current codes and the buildings were evaluated. It was found that the prototype building with “moment-resisting frame or dual system” could resist the force of tsunami. The prototype building with “shear wall-frame systems designed for high seismic design categories” could also resist the force of tsunami waves however, the shear walls that were perpendicular to the tsunami flow could fail and cause a the building to collapse in a progressive manner. In addition, the prototype building that had a “bearing wall system” could not take the impact of tsunami forces and should not be adopted in areas where Tsunami flooding may occur.

Gautam et al in their study “Disaster resilient vernacular housing technology in Nepal” [28] have discussed about resilient housing in disaster prone areas of Nepal. In the Terrai region of Nepal, people primarily seek to build flood resistant housing. These houses which are constructed over raised platforms are mostly one to two storied and have less weight. People use locally made partitioning materials to help maintain thermal comfort and timber is used as construction material. In addition, features like high ductility, symmetrical construction, proper binding of housing units that make the houses resilient to earthquakes are also incorporated. Another type of housing described is those adopted in hills where the housing comprises one-two storeyed structures and where symmetrical rounded configuration is adopted and these structures are made resistant to earthquakes. The roof is properly connected with other structural system. The structural walls have mainstreamed cantilevered load and subsequently there is lesser load on upper storeys.

In "Tsunami loadings on structures: Review and analysis" Yeh et al [29] discusses about the consequences after the Great East Japan Tsunami. In 2011 after the Great East Japan Tsunami the belief that reinforced concrete structure would withstand tsunami actions was debated. The paper discusses the design and major actions adapted to minimize the damages. The concept of Buoyancy force is introduced in building structures to reduce structural body weight. The concept of increasing the pore-water pressure in the soil by excess water is used for the buoyancy in the structural build up. Since Buoyancy force is an upward pressure force under the structure, it has less chances of sliding and overturning effects after the impact. Due to the elongated process even though the build-up time is increased significantly, the process proves stability when the building interior is submerged in water as the weight increases and reduces the chance of structural collapse.

R.L.Mayes, A.G.Brown & D.Pietra in their study "Using seismic isolation and energy dissipation to create earthquake-resilient buildings" [30] have discussed the function of seismic isolation. Seismic isolation means the process of collective structure element being substantially decoupled from the main structure which is resting on the shaking ground, thus protecting the building from collapsing. The authors state that the technique was initially designated for only those buildings which were historic or of high value. The technique has been a success for the Earthquake-resilient buildings and so all the structures the community would require to build. Since the Canterbury earthquake, this isolation technique has been commonly used throughout the country of New Zealand. The authors also discuss further in the paper the cost effectiveness of this technology and how its benefits better may prevent problems that could be faced in the near future.

The paper "Slotted bolted connections in aseismic design for concentrically braced connections" by Fitzgerald et al [31] discusses the need to achieve Lateral Force stability as a design practice in buildings, which are in seismic prone zones. The method of using concentrically braced steel frames allows efficient development of an earthquake resistant design with the dual purpose of damage control and prevention of the structural collapse. The properties of the steel braces that give it high tensile yield and inelastic buckling allows absorption of the impact energy under multiple cycles of inelastic deformations. The paper also states that the slotted bolted connection may also provide inelastic energy dissipation. This technique of lateral force resisting system can be a viable alternative solution for the cases of both new construction and upgradation of existing structures in the tsunami prone zones which are close to seismic epicenter zones.

PART 2: THE METHOD

2.0 METHODOLOGY

To achieve the above stated aim of *proposing the design of a house that is resilient to impacts of a Tsunami as an adaptation measure in Tsunami prone areas of Andaman & Nicobar Islands, India while accounting for the climate of the region to provide better comfort levels*, the methodology of this research comprised of three phases: Investigation, Analysis and Design proposal, that covered the 6 objectives of the study.

The investigation phase covered the first 5 objectives of the research. First, a broad understanding of Tsunami and its impacts was developed via a review of literature on Tsunami. Next, the relationship between building structures and their resilience to Tsunami were studied, followed by a background study of study area. To understand the relationship between building structures and their resilience to Tsunami, the case study of Japan 2011 Tsunami was studied along with a review of Tsunami Resilience Building Design Guidelines in the US and a study of associated Hydrodynamic forces of Tsunami. The forces involved in Tsunami were studied by review of two experiments on these forces from the literature and their simulated impact on simulated structures. The first experiment gives an understanding of the force exerted by the series of Tsunami waves. The second experiment helped understand the distribution of these forces on a structure and studying the consequent response in different structural conditions. Next, a background study of Andaman and Nicobar Islands was conducted where location & geography, history, flora, people, agriculture, livelihood, and housing aspects were studied. Next, the various regulatory provisions/ guidelines of the Indian government regarding incorporation of tsunami resilience in building design were studied. Next, a Climate Characterization of the region was conducted using the software tool *Climate Consultant 6.0.*

Towards the objective No. 6 of this study, analysis phase of the methodology was conducted. This involved an analysis of the information gathered by the above explained literature review and the climate characterization.

Next, the results of the analysis were used as an input to the development of a prototype design for housing that is resilient to Tsunamis. Autodesk Revit was used as a design tool for the development of the prototype.

2.1 Tsunami

The Sumatra-Andaman earthquake on 26 December 2004 was one of the most devastating natural disasters with the highest death toll in the world history since the 1960 Chilean earthquake [2].

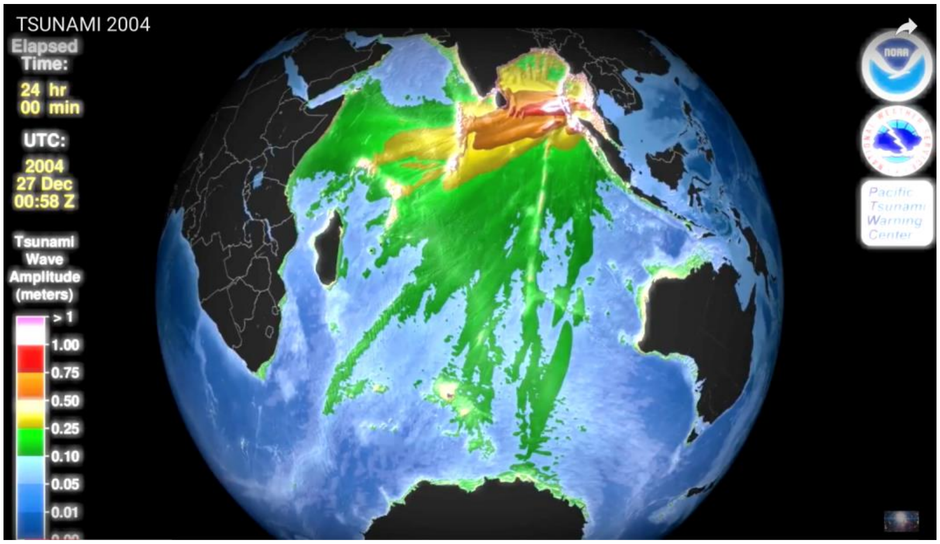


Fig. 2.1 Tsunami Wave Amplitude Source: NOAA

The aftershock area travelled from northwest of Sumatra Island to Andaman Islands (Fig. 2.1). The total area that the aftershocks covered was more than 745.64 miles [53]. The principal of the earthquake indicates thrust type faulting (strike = 329◦, dip = 8◦, rake = 110◦) [53]. The subduction of the Indian-Australian plate beneath the Eurasian plate led to an earthquake under thrusting plate boundary [52]. An enormous slip happened along a 373 miles' section of the boundary of the plate which is offshore of south Nicobar Islands and north-west Sumatra. This was caused by a rift that expanded at the rate of 1.6 miles/s. There were some slips in the northern parts of about 250 to 300 miles of the aftershock zone which occurred on a time scale beyond the seismic band [73]. The earthquake had a magnitude of 9.15 on Richter scale with rupture duration of 600 seconds [53]. This earthquake generated large tsunamis that severely damaged coastal communities in countries around in Indian Ocean, including Indonesia, Thailand, Sri Lanka and India. The waves were recorded around the world. The documented death toll exceeded 283,000, with the heaviest loss along the west coast of Sumatra where more than 1 million people were displaced [72]. There was damage to houses, infrastructure and loss of livelihood.

2.1.1 Generation of a Tsunami

What causes a Tsunami?

Reverse faults among Tectonic Plates in the earth are the main cause of Tsunami waves. Reverse faults involve the collision of two tectonic plates where one of the plates is lifted over the other [1]. Tectonic plates are always in motion. A Reverse Fault involves collision of tectonic plates where as a result one of the plates is lifted over the other. Tectonic plates are locked together along their boundaries. These junctions are where a reverse fault occurs due to building up of stress between the plates. Tectonic plates comprise the earth's mantle. The occurring of a reverse fault is shown been two tectonic plates as No.1 in Fig. 2.2.

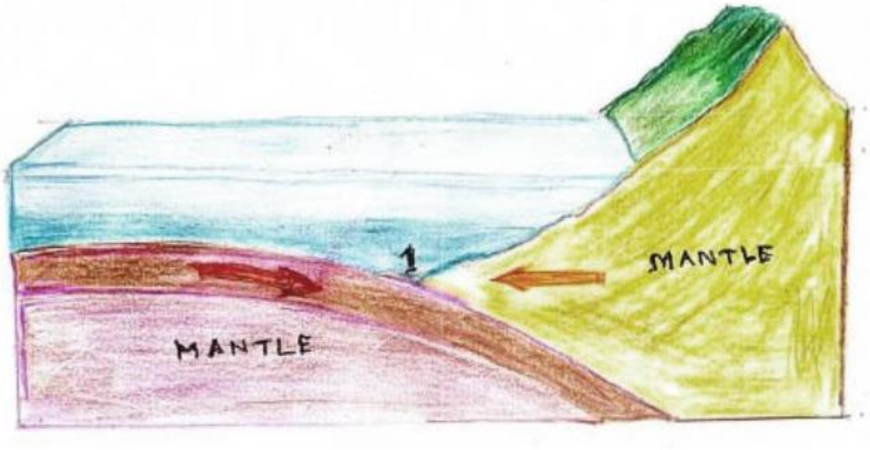


Fig. 2.2 Generation of a Tsunami (1)
Source: Drawn by Sabyasachi Das

How does a Reverse fault cause Tsunami?

As stress continue to build in a reverse fault, as shown in the condition No. 2 in Fig. 2.3 below, the tectonic plate below the sea floor is pulled down, while the continental side tectonic plate rises up [74]. This is shown as No. 3 in Fig. 2.3.

Fig. 2.3. Generation of a Tsunami (2), (3)
Source: Drawn by Sabyasachi Das

The stress between the two plates keeps building up and as shown in condition No. 4 in Fig. 2.4, this increasing stress pushes down the sea floor further and pulls up the continental side of the reverse fault [74]. This is described as condition 5 in Fig. 2.4 below.

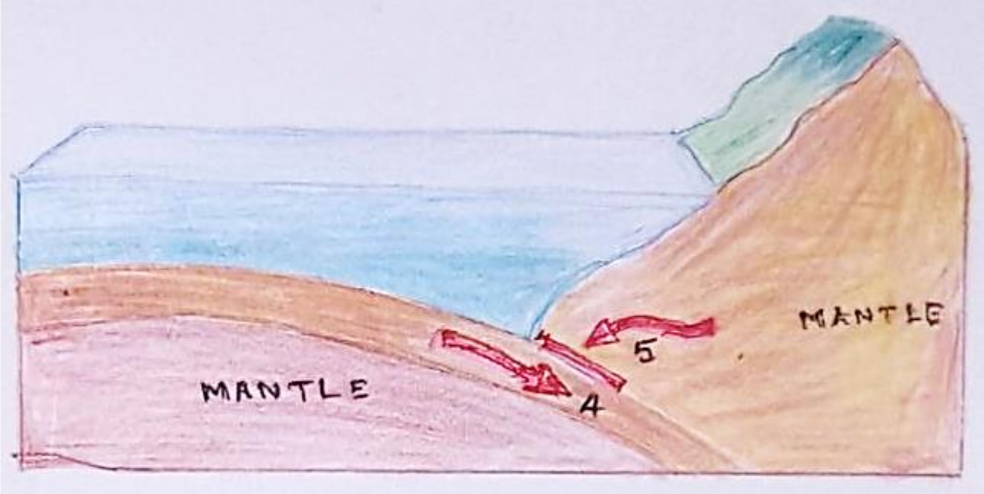


Fig. 2.4. Generation of a Tsunami (4), (5)
Source: Drawn by Sabyasachi Das

As this stress between two plates builds up even further, the earth area between these two plates moves which causes this pressure to get released. This movement No. 6 in Fig. 2.5 below causes an earthquake [1].

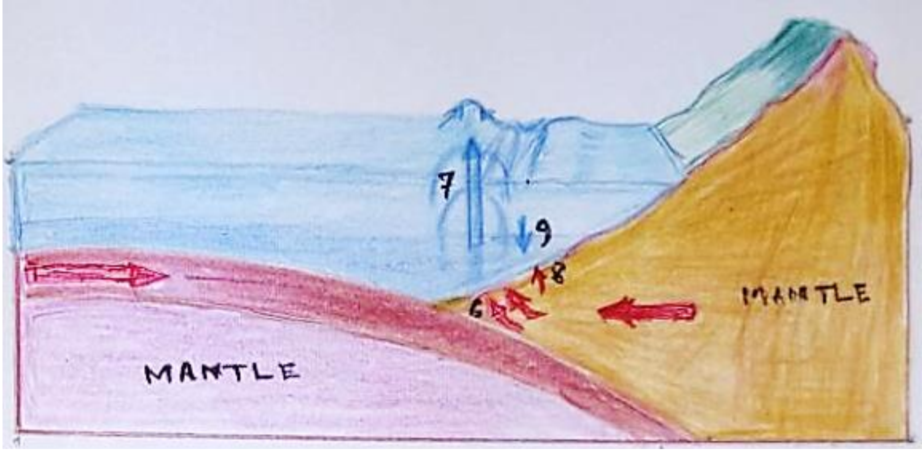


Fig. 2.5. Generation of a Tsunami (6), (7), (8), (9)
Source: Drawn by Sabyasachi Das

As the earthquake causes the earth to rise up, as shown in No. 8 in Fig. 2.5, in turn lifts up the water column that lies above the fault. The continental side bump of the reverse fault on the other hand subsides. This represented as No. 8 in Fig. 2.5. This dipping of the continental plate pushes down the water column which is depicted as No. 9 in Fig. 2.5. This phenomenon is deceiving and often people venture farther into the sea endangering them as when the tsunami waves' crest approaches these people find it difficult to escape.

Now, as the water tries to return to a mutual level, it leads to formation of a series of waves of different heights, from the origin of the earthquake through the column of water [1]. These waves constitute the Tsunami. The higher is the depth of the water, higher is the wavelength of the waves and the faster they move.

As Tsunami waves enter shallow water, their velocity reduces and height increases. No. 10 in Fig. 2.6 depicts this phenomenon. When these waves reach the seashore, they might look like briskly falling or rising tides. It is not essential that the first wave would be the largest in the series of waves that comprise the Tsunami.

Reefs, bays, undersea features and the slope of the beach all contribute to the modification of the tsunami as it approaches the shore. A particular coastal area may have lesser damaging wave activity compared to other areas where destructive waves can be large and violent. Fig 2.7 shows the map of India with earthquake prone zones [50].

Fig. 2.6. Generation of a Tsunami (10)
Source: Drawn by Sabyasachi Das

Like the north eastern part of India, Andaman and Nicobar Islands also come under Zone V [50]. The islands are classified to be in the most intense seismic zone among them, increasing the possibility of a reoccurrence of an earthquake in the near future. A reoccurrence of an earthquake in the region may trigger a tsunami considering these islands are surrounded by the Bay of Bengal and also near the Indian ocean. Fig. 2.7 below shows the seismic map of India where the country is classified in four seismic zones.

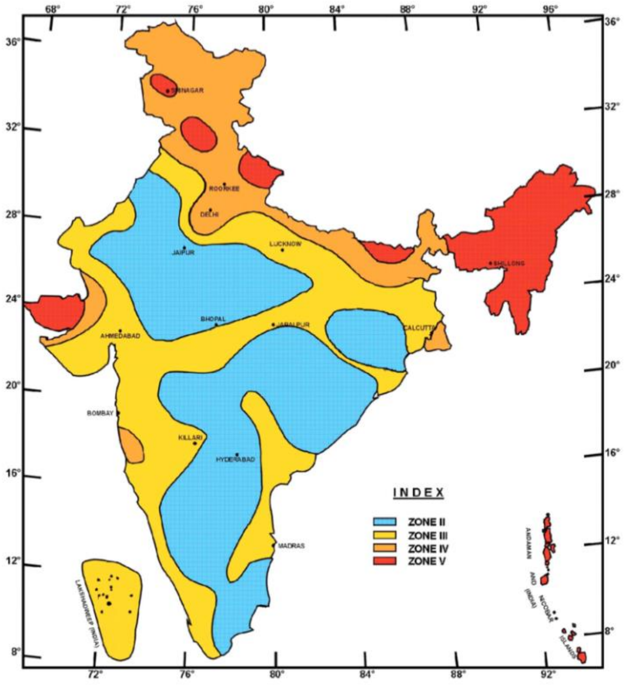


Fig. 2.7. Seismic Zones in India
Source: National Institute of Disaster Management

2.1.2. Characteristics of Tsunamis

Tsunami is comprised of a series of waves. Characteristics of Tsunamis are described below:

Cause: Tsunami waves differ from regular tidal waves which are caused due to factors like gravitational force of moon and other celestial bodies. Tsunami waves are causes due to factors like earthquakes, volcano etc. [77].

Water Movement: As explained section 2.1.1 above, water that forms Tsunami waves may move to seafloor as well unlike regular waves which stay only around ocean surface.

Wavelength and Time Period: Tsunami waves have long wavelengths with values going upwards of 100 km [75], which is much longer than wavelengths of regular waves like wind driven ones whose wavelengths may be around 100-200m. The time waves have time periods ranging from 10 minutes to 2 hours while wind driven waves have time periods of around 5-20 seconds [76]. This makes Tsunami waves comparatively way more destructive. That means that these waves be this much time apart.

Impact of water depth on wave size: As distance to land decreases, size of tsunami waves magnifies. As a result, these waves that are generated in deep ocean may often go unobserved by vessels in the sea due to their small size on water surface. What actually happens is that the major chunk of the wave remains below the ocean surface and the rest in above it. Consequentially, when the wave reaches shallow region of the ocean its size increases with the wavelength getting decreased and height increasing [1].

Velocity: While regular waves have speeds around 55mph, the Tsunami waves on the other hand travel at speeds up to 590 mph making them comparable to jetplanes [76].

Energy: Tsunami can retain their energy while travelling and can therefore ravel across entire oceans [55].

Path: The direction of Tsunami waves is like radiation from the source. Their path is unsymmetrical and is affected by factors like extent of earthquake, the alignment of the "subduction zone" where the earthquake is born, among others.

Severity: The size of the Tsunami waves decides its impacts. Small sized Tsunamis cause impact to only small extent like affecting swimmers, or stationery boats, or inundating land to a small extent. Large Tsunamis can cause devastating impacts like the 2004 Indian Ocean Tsunami or the Japan Tsunami of year 2011.

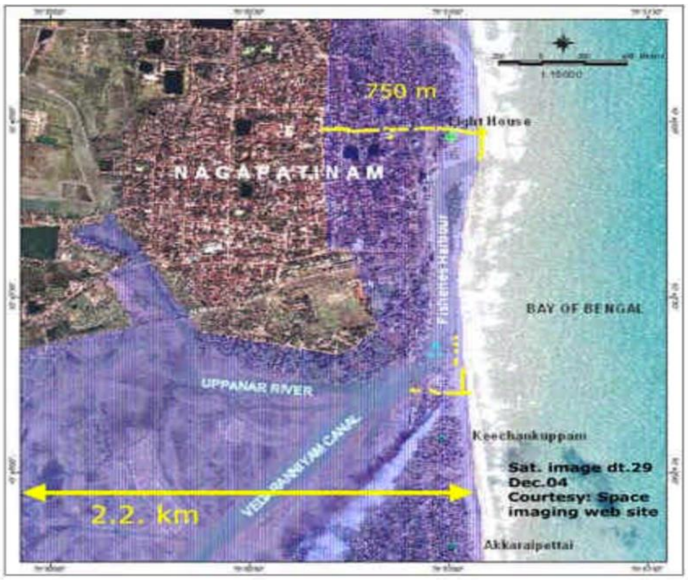
2.1.3. Impacts of tsunami

Inland surface and ground waters are salinized by tsunami in the inundated areas. As a consequence of the Indian Ocean Tsunami, saline water contaminated ground water supplies and shallow wells especially those on small islands that bore the impact of the Tsunami. Septic tanks got damaged and pit toilets destroyed causing fecal bacteria to infiltrate the ground water and the surface water that were the main sources of water for the local people and the tourists [58]. In the Province of Phang Nga, Thailand nearly 190 out of 530 wells became unsafe for use as got contaminated with sewage water [59]. Contamination by other agents such as Arsenic and infiltration of saline water into groundwater by the short duration flooding and saline infiltration by water that remained in pools, lakes or depressions after the tsunami impacted the ground water [58]. Fig. 2.8, 2.9 and 2.10 contain images of impacts of 2004 Indian Ocean Tsunami.

Fig. 2.8. Impacts of Tsunami

Source: http://antagonf.blogspot.com/2014/12/tsunami-10-years-later-is-world-better.html

The destruction of the beach resorts along the Andaman Sea, as well as the massive tourist death-toll, led to a massive decrease in the tourism industry in Thailand, Sri Lanka and Andaman Nicobar Islands. Tourism industry in these countries suffered damages in upward tune of half billion dollars [60]. Immediately after these events, thousands of hotels, resorts and independent business located on these small islands lost their business, as tourists were afraid to travel to Thailand, Sri Lanka and Andaman Nicobar Islands [61]. In the months that followed however, the Thailand government, the Sri Lankan Government and also the Indian government with the help of investors and outside funds were able to re-open all hotels and began advertising heavily in an attempt to lure visitors back into these tourist destinations.



Sat. image dt.29 Dec.04 Courtesy: Space imaging web site

Fig. 2.9 Satellite image of a zone inundated by tsunami

Source: http://www.scidev.net

Source: http://www.ibtimes.co.in

Source: Happyheartsfunds.org

Source: www.livemint.com

Fig. 2.10. Images of Impact of Indian Ocean Tsunami 2004, Andaman and Nicobar Islands

2.2. Relationship between Structure Design and its resilience to Tsunami

From the study conducted so far, we understand Tsunami is a natural disaster that can occur due to unpredictable ruptures in tectonic plates underwater. The severity of the impact of Tsunami can be varying depending on the speed of the waves, the water depth, wave size generated by the earthquake. A severe tsunami like the 2004 Indian Ocean Tsunami can cause damage to structures near the shore of occurrence. The objective of this section is to develop a better understanding of the forces that affect a building structure when it is struck by a tsunami. This section studies the impact of the 2011 Japan tsunami which was similar in magnitude to the 2004 Indian Ocean tsunami, and the guidelines developed consequentially by the countries near it to create structures with resilience. Hydrodynamic forces which are responsible for damage to structures in case of inundation of water are also studied. The other two experiments studied in this section as a part of this research were studied with the objective of gaining a better comprehension about the forces that affect a structure during Tsunami and also response of the structures to them.

2011 Japan Tsunami

The north-east coast of Japan was hit by a tsunami on March 11, 2011. An earthquake of magnitude 9.0 on Richter scale which triggered the tsunami happened at a depth of 19.89 miles under the surface of the Pacific Ocean. The epicenter of this tsunami was at an approximate distance of 43.49 miles in east direction of the Oshika Peninsula of Tohoku, Japan [62]. The death toll caused by this event was 15,148. The economic damage exceeded 300 billion dollars, making it the most expensive natural disaster ever to occur in history of mankind [78]. This tsunami is discussed here since it was similar in nature and extent of damages to the Indian Ocean Tsunami of December 2004, which accounted for the highest number of death toll in history.

Even though tsunamis are commonly known in Japan, only a handful of the infrastructures had the design codes and engineering guidelines which have the capacity to sustain tsunami loads. The study in the regions affected by tsunamis states that the present guidelines for building infrastructure are almost Stone Age or are obsolete in nature as they are unable to withstand the present disaster.

Tsunami Resilience Design Guidelines in United States

Soon after the March 2011 Japan Tsunami disaster several measures were taken by the United States to protect the Hawaii islands which are on the Pacific Ocean, and are close to Japan. Tsunami Resilient design guidelines were incorporated as a measure into the building design guidelines of the region. The current building codes and design guidelines procedures provide for methods to calculate the tsunami design loads as a function of the tsunami wave height and the slope of the beach.

American Society of Civil Engineers document (ASCE07/2005) gives engineers plans in relation to the minimal load required for the design of the structural process. The document states the use of hydrodynamic loads based on the principals of fluid mechanics [79].

In 2008, the FEMA published the procedures for Design of Structures named as FEMA P646 for Vertical Evacuation from Tsunamis with an objective to provide procedures for building tsunami refuge infrastructures which are competent of withstanding the ultimate forces of tsunamis and earthquakes. The method of formation of the design guidelines are based on the addressing of tsunami-induced loading and underlying concept of the approximation of the hydrodynamic forces which affect coastal properties when there is an occurrence of Tsunami [80].

Federal Emergency Management Agency's (FEMA) publication FEMA55 Coastal Construction Manual advises designing and constructing building of one and two storeys only. This manual specifically addresses seismic loading and it also contains steps or procedures that are relevant for river floods and wind wave loads. It also provides load amalgamation for some structural parts and also gives knowledge on tsunami risk and danger [81].

2.2.1. Hydrodynamic Forces

According to FEMA, "Hydrodynamic forces are imposed on an object, such as a building, by water flowing against and around it" The understanding of the elementary fluid forces acting on a given body is important in design of offshore structures, underwater and surface vehicles [66]. The drag-force on the body is caused by the viscous rubbing of the layers of the fluid which adheres to the body due to the adhering property of water [67]. During the process of adhesion, the net force of the layers of the viscous fluid converges into the adhered body [67]. Hydrodynamic forces occur in the form of high velocity waves hitting stationary bodies or moving bodies on the impacted shore. As the wave breaks with initial thrust on the shore bodies and inundates the land at great pace, and then pulls back the water back to the shore, hydrodynamic forces act against the structure creating frontal pressure and drag effect by the bodies.

2.2.2. Experiment 1

Originally conducted by four researchers Taofiq Al-Faesly of University of Ottawa, Ioan Nistor of University of Ottawa, Dan Palermo of York University, and Andrew Cornett of National Research Council Canada as a part of their study *Simulated Tsunami bore impact on an onshore structure* presented in 20th Canadian Hydrotechnical Conference, this was the first experiment that was studied in this research. The objective was to understand the velocity, pressure and force of the tsunami waves when they reach the shore to have a better understanding of these physical aspects of Tsunami waves while creating the proposed building design. This experiment is explained in detail in *Appendix Part: A* of this document. The experiment involved the simulation of a tsunami model and is explained below [9]. Fig. 2.11 below shows the square model details used in the experiment.

- A one meter high plexiglas model was made with a metal structure and a flume was made with two high discharge electrical pumps.
- The experiment was performed under high discharge flume applying force on the simulated structure with forces of a hydraulic bore identical to a broken tsunami approaching land.

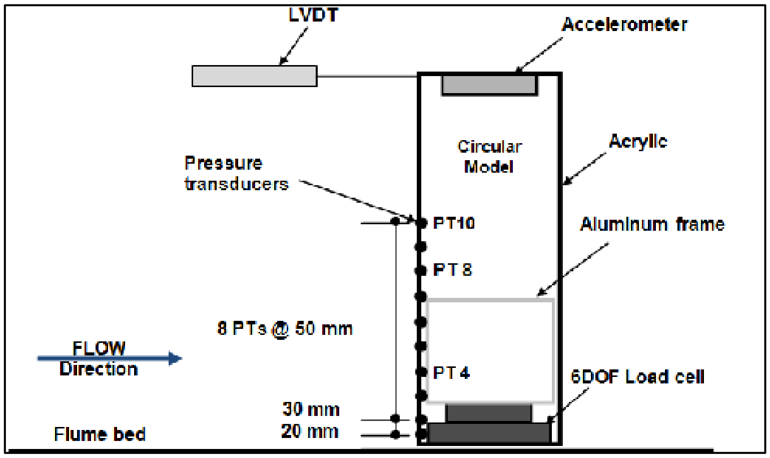


Fig. 2.11: Square model details (side view)
Source: Al Faesly et al. (2011) [9]

- During this experiment force the following were recorded “*forces and moments with a six degrees of freedom load cell (6DOF), structural displacement, structural acceleration, bore depth and bore velocity*”
- The experiment was conducted under two conditions of wet bed and dry bed conditions.
- In the first stage of the experiment tests were conducted using hydraulic bores to obtain a bore profile and the bore velocity (velocity of the discharged water which tends to gain some velocity due to the acting gravity on the flow of water)
- The high speed camera installed in the model tracked the bore front individually by frame which was used to derive bore front velocity at multiple successive sections of the flume’s longitudinal axis. The data obtained was used to calculate the bore velocity.
- The bore velocity was also calculated using the time required for the bore to document a particular inundation depth between two consecutive couples of wave gauges (WG).
- The existing formulas for calculations of bore velocity were used to calculate theoretical bore velocity value and compared to experimentally derived data.

In the wet bed condition the impact force was smaller than the run up force, and for dry bed condition the impact force had the biggest magnitude in comparison to run up and quasi-steady hydrodynamics. With the determination of the bore velocity, bore force and the bore pressure we can determine the velocity, force and the pressure exerted by a series of waves (Tsunami). The data collected by the said researchers in this experiment indicates a correlation between the bore pressure, pressure and associated force of Tsunami waves. The bore force profile in the experiment demonstrated three major components of hydrodynamic force, which are: impact, run up and quasi-steady hydrodynamics. The experiment develops a correlation between bore velocity (m/s) and water bore height (m) and on comparison to data calculated through FEMA55 and CCH formula it generated results similar in magnitude and trend to the experimental data [9].

Keeping in mind these points and values, we can design as well as create a procedure to build infrastructure which can withstand both flood as well as Tsunami's damage to infrastructure. This will make the houses resilient and provide better quality of shelter after and during such damaging calamities keeping people's lives safer.

2.2.3. Experiment-2

This experiment was conducted by Tiecheng Wang, Tao Meng, Hailong Zhao in Japan, published as their study titled *"Analysis of Tsunami Effect and Structural Response"* in Tehnicki vjesnik/Technical Gazette 22, no. 6 in year 2015. The purpose of studying this experiment is to learn how to improve structural performance of the proposed design to resisting tsunami disaster casualties and economic losses. This experiment is explained Appendix Part B of this document.

The purpose of studying this experiment in this thesis was to better understand the magnitude and distribution of tsunami forces on a structure with mathematical simulation and studying response of different simulated structural conditions under impact of tsunami forces.

As per the experiment's simulation process, in order to compare the influence of tsunami wave on a structure with and without wall on the upstream face at the bottom of the structure, two different scenarios were simulated. In Case 1, the upstream face on the bottom floor of the building was constructed with walls, as is shown in Fig. 2.12 (a), and in Case 2, the upstream face on the bottom floor of the building didn't have any walls and floors from 2 to 5 were constructed with walls as is shown in Fig. 2.12(b) [32].

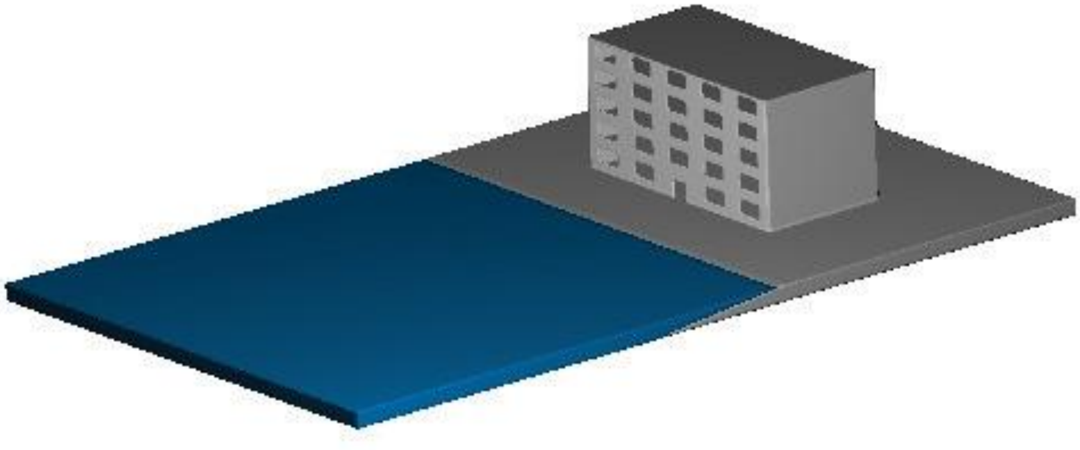


Fig. 2.12. (a) Case 1
Source: Wang et al (2015) [32]

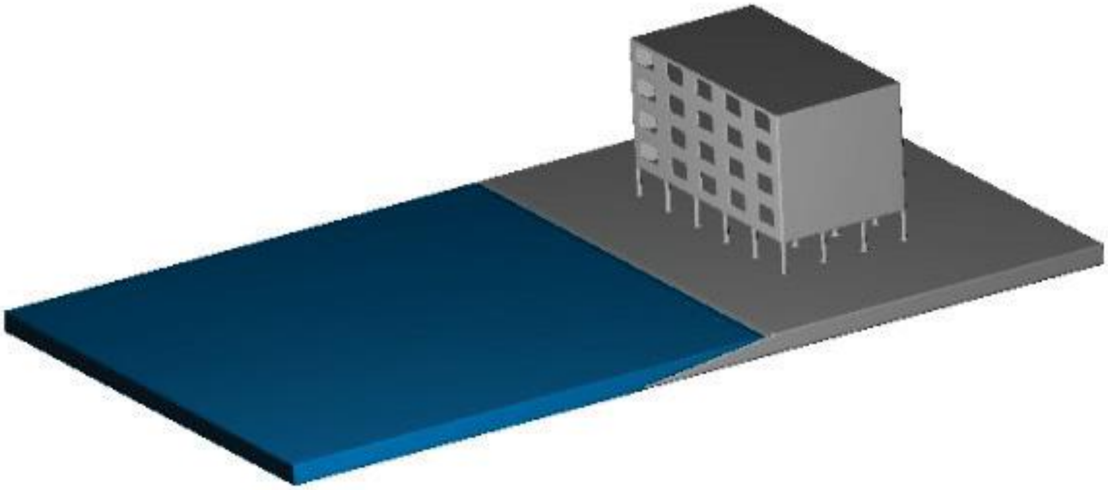


Fig. 2.12. (b) Case 2
Source: Shuto (1993) [32]

In Case 2 of this experiment, since the bottom of the structure were not constructed with upstream walls, the impact from the tsunami waves was borne by the columns on the bottom floor. Therefore, in Case 2, the surface area of the structure impacted by Tsunami was considerably small. Whereas on the other hand, in Case 1 due to the presence of walls that lead to the building have larger surface area the forces left more impact in this case [32].

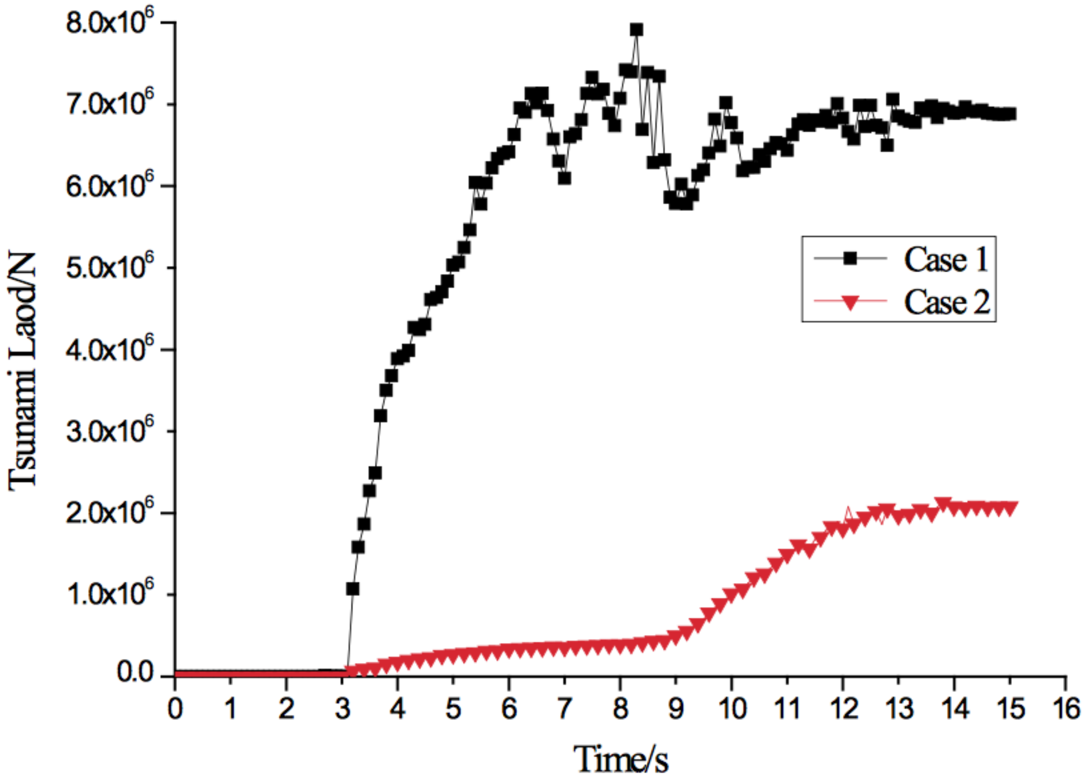


Fig.2.13. Comparison of Tsunami Load on Case 1 vs. Case 2
Source: Wang et al (2015) [32]

The graph of the data generated from the experiment, given in Fig. 13 above shows that the maximum tsunami wave force impacting the structural condition in Case 2 is lesser compared to condition of Case 1. Moreover, the occurrence time of maximum tsunami wave force on the structure is later than that in Case 1. Considering the fact that in case 2, there is no in-filled wall constructed on the upstream face of the bottom floor of the structure and the bearing bottom floor has only columns, the reason that the impact from tsunami waves is comparatively lesser is because the resistance of water passing through the columnar structure is less [32]. Hence the structure in Case 2 is more effective in resisting tsunami waves, and also considering the fact that people in such a structural condition would have more time to escape to the top or other higher positions. The study of this experiment helps in contributing to the proposed resilient housing design by guiding technical structural design factors and served as an important precedence in development of the design.

2.3 Social Study of Andaman and Nicobar Islands

Location & Geography

The Andaman and Nicobar Islands are located on the south-east of mainland India. They are a part of India that was closest to the 2004 earthquake epicenter. The islands' capital is Port Blair. They consist of a thin chain of 572 scenic rocks, islets, and islands that extend along a north-south direction between 14° N and 6.5° N latitude and stretching over a narrow arc of 800 km in the south-eastern part of the Bay of Bengal [33]. Fig. 2.14 shows location of the islands in South East Asia.

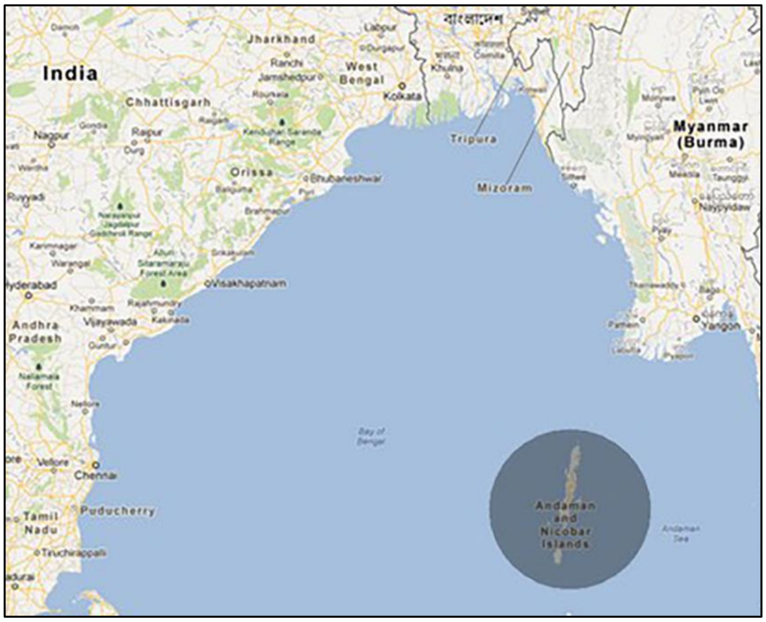


Fig. 2.14. Location of Andaman and Nicobar Islands in South East Asia

Source: Internet

Only 36 of the said 572 islands are inhabited. These islands are grouped into two sets, with the 10°N latitude international shipping channel running through them. The islands above this latitude are called the Andaman Islands and those below it are called the Nicobar Islands. **Fig. 2.15** below is a map of the islands. South, North, Middle, and Little Andaman Islands are the most populated among the Andaman islands. The most populated islands in the Nicobar group are Car Nicobar, Great Nicobar, Katchal, and Kamorta islands. According to the 2011 census, the total population in the Andaman & Nicobar Islands is about 380,581 while in the in Census 2001 it was 356,152 [34].

Fig. 2.15. Map of Andaman & Nicobar Islands
Source: Incredible India, Ministry of Tourism, India

History of the islands

The islands were colonized as British India territories to Britain. During British rule in India, the islands served primarily as a colony for criminal convicts from the Indian subcontinent. The Cellular Jail in Port Blair was used to house the prisoners. The jail is now a popular tourist destination and is listed by the UN as a UNESCO World Heritage Site. Since 1980s, the islands serve as an important defense base facilities for India. They play a key position in India’s strategic role in Bay of Bengal and Malacca strait [35].

Flora

The Andaman and Nicobar Islands are a tropical rainforest which are made up of a mixed type of flora with similarity to neighboring countries flora varieties. 2,200 varieties of flora have been recorded in the islands with 86.2% area covered by forests. The islands have a wide variety of flora ranging from deciduous forests, grasslands and mangroves [36]. These mangroves act as seawalls in many of the islands thereby protecting them from erosion.

People

The indigenous people of the island are known as Andamanese - the Jarawa and Sentinelese tribes who live in the Andaman Islands and the Nicobarese - Nicobari and the Shompen islands who live throughout the islands [82]. The population of the indigenous people of the islands are sparsely distributed throughout the islands. The majority of the population are immigrants from the different states of mainland India [83].

The official languages in the islands are Hindi and English. Bengali being the most dominant most spoken languages with Hindi, Tamil, Telugu, Malayalam and Nicobarese as other languages, according to the Census of India. Other minor spoken languages are Kurukh/Oraon, Munda and Kharia. Andaman Creole Hindi is widely used as a trade language in the Andaman's.

Agriculture

Agriculture is one of the predominant occupations of the residents of the islands [37]. A total of 48,675 hectares of land is used for agriculture purposes. Rice is one of the most cultivated crops in the Andaman group of islands. Coconut and arecanut are the cash crops of Nicobar group of islands. Pulses, oilseeds, vegetables, along with tropical fruits such as mango, banana, pineapple etc. are also grown. Spices such as pepper, clove, nutmeg and cinnamon are cultivated in multi-tier cropping practices in the island where agriculture is practised [84].

Livelihood

The primary occupation of people residing in the islands is agriculture and fishing. Forestry for the production of sawn wood for the use in domestic purposes is a common occupational practice for the people. The excess timber production is sometimes exported to the mainland. Furniture industry is also one of the livelihood sources for the people in the islands. In recent times processed foods and garment industry are growing trades. Port Blair, an island town and the capital of the island territories which has historic importance attracts tourists throughout the year from mainland India and foreign countries. The other parks, sanctuaries and island resorts on other islands help promote the growing tourism industry of the islands [85].

Housing

The indigenous people of the islands live in huts and temporary houses constructed with bamboo, wood having thatch roofs made with materials like hay and mud. The other residents of the islands live in one to three storey houses that have concrete construction structure and walls with sloping metal roofs or flat concrete roofs. People belonging to lower economic strata live in houses made using wood walls construction and tin metal roofs. These were the predominant style of housing that people resided in when the Indian Ocean Tsunami struck in year 2004.

The houses occupied by the indigenous people of the islands were located at higher elevations i.e. hilly areas on the islands and bore little or no impact of the Tsunami. Owing to the higher elevations in the location of these houses, Tsunami waves couldn’t impact them.

The other dwellers of the islands that lived in the kind of houses described above, and resided closer to the shoreline of the islands bore the most impact of the Tsunami getting damaged as a result.

2.4. Regulatory Requirements of Government of India to inculcate Tsunami Resilience in Structures [38]

2.4.1. Design Criteria

According to the National Institute of Disaster Management (NIDM) report “Design Criteria for reconstruction of Houses in Tsunami affected areas in India” [68], latest construction in such areas must consider multi-hazard climatic problems of a coastal-area and the design criteria should consider certain aspects. These include: Wind Speed in cyclonic conditions; Continuous wind pressure at sea coast; Height of storm with height of tide level; effects of Tsunami, including (i) height of the tsunami wave, ii) Dynamic pressure of the tsunami waves; effects of Earthquakes; Fire Hazards and safety; Flood flow and flood height; Building aspects like Shape, size and height of buildings; importance of the buildings and choice of material and the technology used to construct it.

The said NIDM report also lists certain factors that must be considered in design stage of constructing buildings in coastal regions. These include pressure factors, seismic coefficients, storm surge, etc. These are given as Table A.C.1 in Appendix: Part C of this thesis.

The said report also mentions the characteristics that Reinforced Concrete (RC) used in construction in coastal areas should have. These are mentioned in Appendix: Part C.

The National Disaster Management Authority (NDMA) published a report “National Disaster Management Guidelines: Management of Tsunamis” in year 2010 where they have given guidelines for mitigation of impacts of Tsunami, one of which is incorporating safety in design and construction of buildings in Tsunami prone areas. In this document, they state that impact of hydrodynamic forces can be avoided by elevating buildings, anchoring buildings to their foundation, and designing buildings for dynamic water forces on the walls of buildings and other building elements [38]. The Bureau of Indian Standards has published “Draft Indian Standard Guidelines for Risk Reduction of Structures Against Tsunami” where they have discussed design solution for many factors. For hydrodynamic forces, they state that to evade hydrodynamic pressures, buildings should be elevated on stilts [69].

One of the other draft guidelines talks about are hydrostatic forces where they state that with the objective to allow water to be at equal elevation outside and inside buildings, adequate openings like louvres should be provided [69]. Regarding buoyancy floatation or uplifting forces caused due to buoyancy, the guidelines state that in order to avoid flooding arising due to such forces, buildings should be elevated. In addition, to avoid floatation buildings should be anchored to their foundation [69].

2.4.2. Specific Recommendations for Andaman & Nicobar Islands

2.4.2.1. Structural measures:

Since, as mentioned earlier, Andaman & Nicobar Islands fall in Seismic Zone V, the report advises that buildings in these islands should incorporate features that make these structures earthquake resistant. These include:

- Stilts made of Steel and RC columns should be used for erection of buildings at higher elevations from sea shore grade level. Houses should have earthquake resistance features like anchoring of structural elements with the main structure, etc.
- Use of Pre-engineered, pre-fabricated, and modular composite structures should be made popular.
- Readily available materials like hollow concrete blocks (also called CMUs), steel etc. should be used as Transportation costs are high and demand for materials is also high.
- Roofs should have feature for water harvesting.
- Roofs should be sloping and should be used along with sheeting made of Galvanized Iron (CGI)
- The first floor elevation of the building should be at a minimum height of 3m above the seashore grade.
- Steel Corrosion resistance measures has to be given priority in all RC and steel constructions

Houses should be able bear wind speeds of 44 m/s [68]. Housing developed for earthquake resiliency having a ductile RC frame should have an earthquake coefficient of 0.09, R = 5.0 [68]. Any load bearing walls in such buildings should a category D earthquake coefficient [68]. Wall construction in these buildings should have a fire rating of 1.5 hours. For Andaman Islands the minimum height of stilts should be at least 2m and in case of Nicobar Islands this height should be 3m at least [68].

2.5. Climate Characterization

According to NASA the climate of a region or city is its typical or average weather over a long-time order. One of the key determinant factors of climate of a region is its latitude which controls the degree of warming [39]. The tilt of the earth's axis is accountable for degree of warmness at different latitudes as angle of sun rays contact varies with the latitudinal location on earth [40].

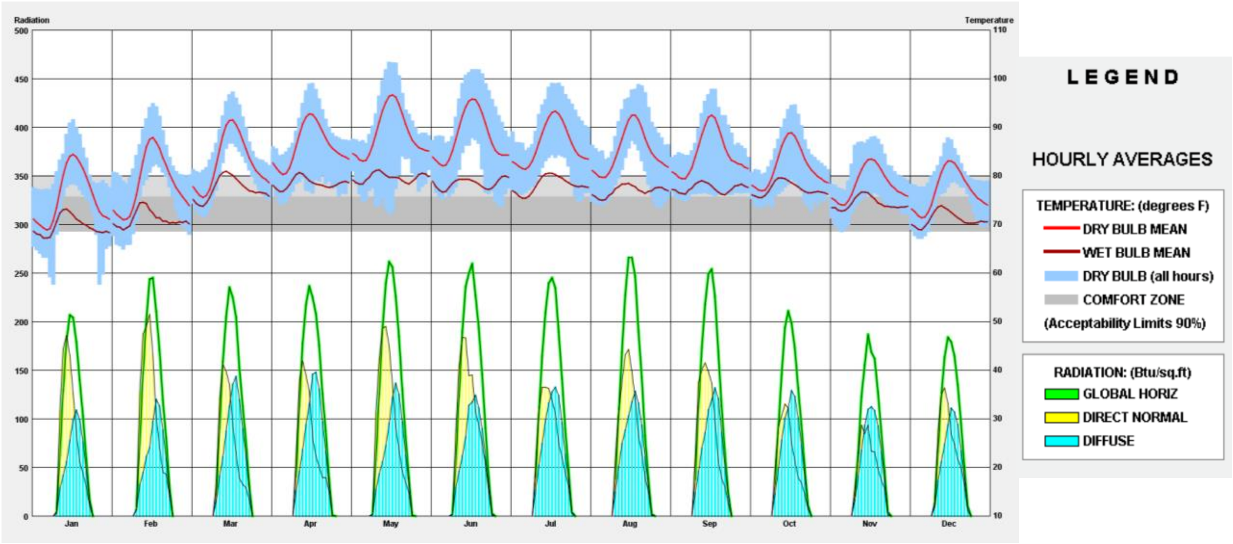


Fig. 2.16. Monthly Diurnal Averages. Source: Climate Consultant 6.0

The further the latitude is from the equator the sun rays spread broader and those latitudes receive lesser heat [41]. The purpose of climate characterization of Andaman and Nicobar in this study is to better understand the local climate of the region and use it as a design tool to influence the design proposal process of the tsunami resilient house for the islands. The software Climate consultant 6.0 has been used as a tool for climate characterization of the islands. Data for Chennai, India which is the closest city in mainland India to these islands with very close latitudinal proximity of 13.0827° N compared to Andaman and Nicobar Islands 11.7401° N was used for the Climate Characterization. Chennai's close proximity to the islands and the originating epicentre led it to suffer massive damage due the Tsunami in 2004. It is assumed the islands are in the similar latitudinal zone as Chennai and the availability of Chennai's weather data allows proper running of the software to determine the regions climatic conditions.

ASHRAE Standard 55 has been used as a basis of comfort levels in generating the data through the Climate consultant 6.0 Software.

The Monthly Diurnal Averages shown as Fig.16 above show temperatures in the zone as mostly constant throughout the year with an annual average of 90°F. The temperature range as per the figure refers to it mostly above the comfort zone. In general, the climate is constantly humid through the year as the dry bulb and the wet bulb temperature maintain a similar average relation as per the figure. The precipitation during the winter months is emphasized by the dry bulb temperature being closer to the wet bulb temperature. The climate maintains a fairly high constant amount of global horizontal radiation throughout the year. The wind in the zone is distributed in almost all directions, however prevailing winds come from the Southern direction from the Indian ocean below towards North in the Bay of Bengal which is shown in the wind wheel given in Fig. 2.17.

The psychrometric chart in Fig. 2.18 shows that climate in the zone is in the comfort zone as per ASHRAE Standard 55-2010 for only 0.7% of the hours of the year. The data are concentrated highly on the upper part of the graph in the figure where the weather is too hot and humid for comfort standards. The main passive design strategies that can be applied for the islands in this zone are sun shading of windows to reduce the effect of the constant amount of global horizontal radiation and oriented towards prevailing breezes for cooling, good cooling systems, features can regulate the high temperatures, and good natural ventilation could improve dehumidification. The Sun Shading Chart in Fig. 2.19. is for the summer months, it shows that considering the zones radiation if a shade is oriented at an angle of 30° it will be successful in creating proper shade to the opening throughout the day for the seasonal period.

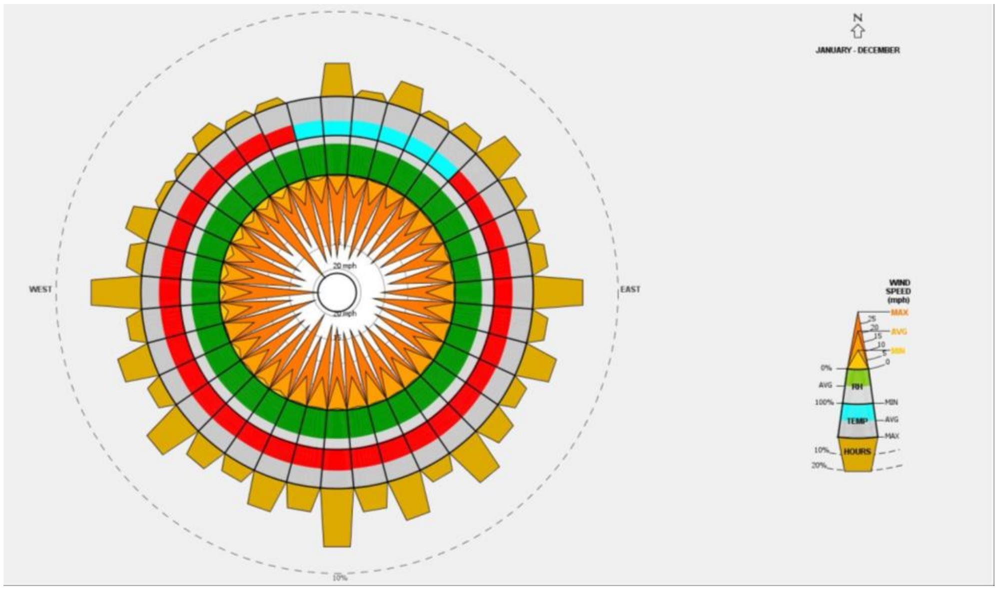


Fig. 2.17. Wind Wheel.
Source: Climate Consultant 6.0

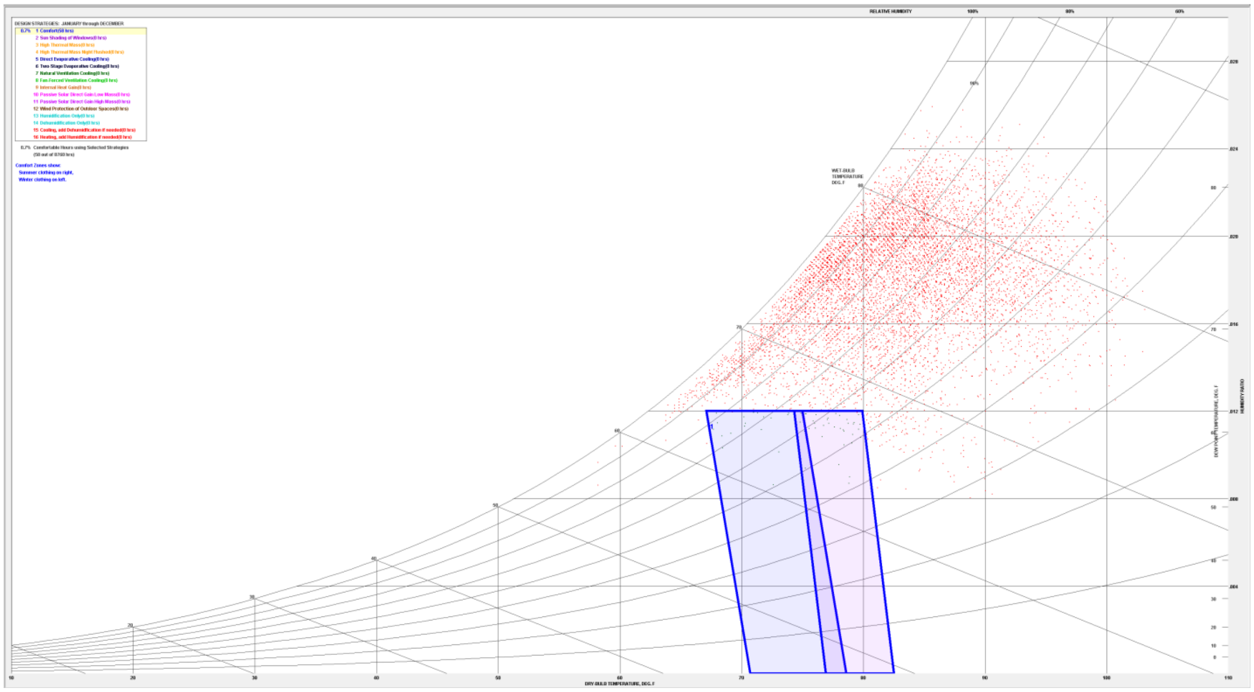


Fig. 2.18. Psychrometric Chart
Source: Climate Consultant 6.0

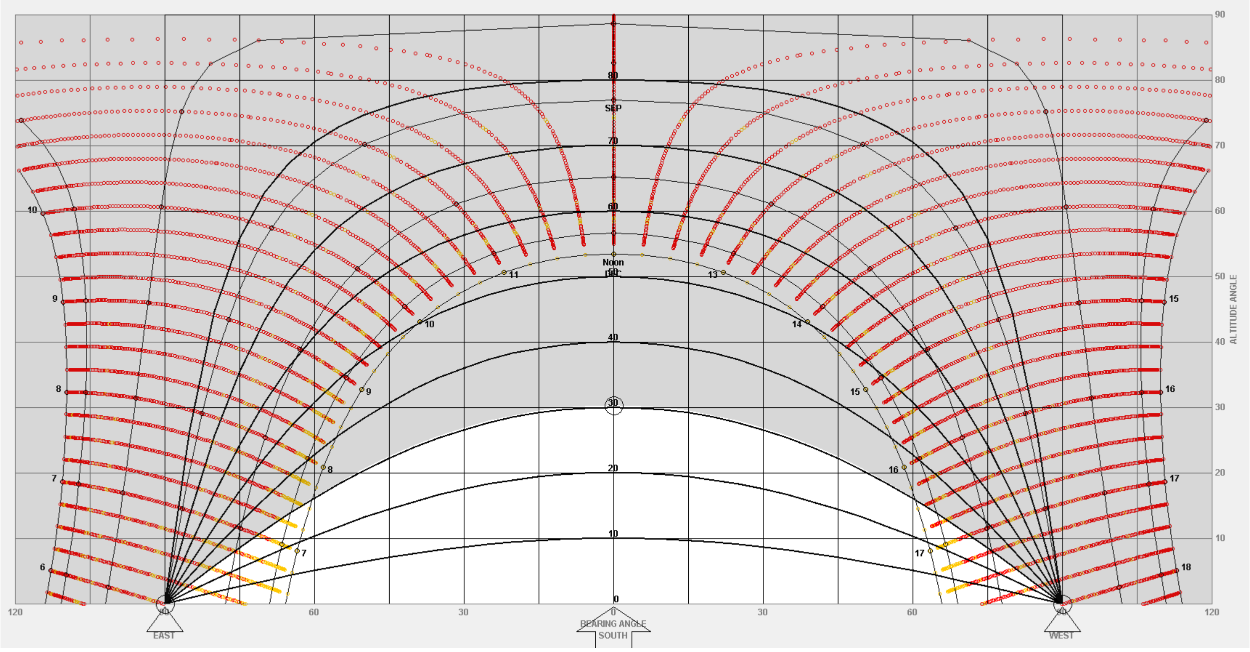


Fig.2.19. Sun Shading Chart
Source: Climate Consultant 6.0

2.6. Analysis and Strategies

The study of Experiment 1 gives us an in-depth knowledge about the forces that are responsible for the impact of a Tsunami on life and property. It also sheds light on velocity, force and the pressure exerted by the Tsunami waves, a study of which was essential owing to the fact that a building's shell design adds to its endurance capacity. The study of Experiment 2 also gives us a better understanding of the magnitude and distribution of tsunami forces on a building's structure through case studies of simulated structural conditions under similar impact of tsunami forces. The results of the experiment suggest that buildings with no infill walls on the upstream face of the bottom floor of the structure will suffer impact of much lesser magnitude compared to buildings with walls in the lower level. When no infilled wall is constructed in the bottom floor and there are only columns on the bottom floor bearing the impact from tsunami waves, the endurance of the building to passing water is smaller. This also allows people in the building more time to escape to the top or other areas as higher elevations.

The culture and history of the island shows that the island is inhabited by people from a mix of regional and cultural backgrounds from all over mainland India giving the islands a mix Indian cultural identity.

The housing system in the island has sloped gable roof in reinforced concrete (RC) construction or wood construction being the most predominant styles.

The National Institute of Disaster Management (NIDM) recommends that the performance of buildings having a circular shaped structure increases its resilience during a Tsunami as water is able to easily flow around [42].

The impact of damage on the houses constructed with RC was large even though they were new permanent constructions, as they didn't involve any seismic code in their design. So these houses couldn't withstand the tsunami's seismic force impact [4]. The traditional wood houses and even old masonry structures on the island survived better in response to the ground shaking [4]. The recently constructed RC housing and buildings which didn't have ductile detailing in their column construction didn't survive the tsunami well compared to the ones that did have them in their columns [4]. In response to the zoning of the coastal area of the islands, the law of the land now requires that all new permanent settlements should be located a minimum of 10 meters above contour levels or 3 meters above high tide line, whichever is higher to prevent inundation of water near the seashore area. The roofs are recommended to be sloping in nature.

As discussed in the design guidelines in Tsunami affected areas, the design criteria for infrastructure in the zone should keep the hazardous climatic conditions in mind. Along with continuous wind pressure along the coast, the height of tide levels should be considered [43]. The guidelines also advise that dynamic pressure of waves should be factored in structural calculation, as discussed above in reference to the experiment. Building aspects such as shape, size and height of buildings should be aptly decided in relation to location of the building near the coast line.

According to the Indian government’s design guidelines, following should be followed for housing buildings in Andaman and Nicobar islands: Wind speed - 44m/s; Factor of Pressure K1-1.0, K2-1.05, K3- 1.00; Fire Safety- 1.5 hr rating; Earthquake coefficient: Ductile RC Frame-0.09 (R=5.0), Load Bearing Wall Building- Cat. D. The guidelines also recommends that houses be built on stilts with RC/steel columns having features that make them earthquake resistant. They also emphasize on use of prefabricated, pre-engineered and modular structural composite structures.

In climate characterization of the region, it was found that the region is hot and humid in nature with constant amount of direct horizontal radiation on the islands. The wind prevails more from the Indian Ocean lying below them and towards the North in the Bay of Bengal. Owing to the fact that these islands are in a zone where the climate is in comfort levels in only 0.7% of the hours of an year, it is important that passive techniques of cooling and ventilation are integrated in design of these Tsunami resilient housing for human comfort. As having substantial comfort levels will allow the houses to be better habitable during the period of residence. Since disasters comes once in a while in a region but along with human lives safety through them we need to keep in mind about the long-term viability of the usage of the space during the users residency period.

PART 3: APPLICATION OF STRATEGIES

3.0 APPLICATION OF STRATEGIES - CONCEPT DESIGN

The study of the methods and the analysis of the information obtained contributed to the development of the concept design which is illustrated below. Refer Figure 3.9 for 3D Perspective view of proposed design.

3.1. Building Mass and Form

Process Study: During the process study various forms were studied before the development of form as per Fig. 3.1. The analysis was applied in developing the options and based on the facts of impact of tsunami forces and economic viability they were evaluated. Option one is viable in terms of the angular impact of forces but they are only case specific to conditions if the tsunami comes in a particular orientation. The option two stepping of the faced was helping in breaking the waves but at the same point of time the center portion would be substantially weak due to the deep step in the impact forces will be concentric. The third option of a regular circular building helps to solve impact issues as water can glide along it and move in a fluid manner but it is not economically viable to construct round permanent houses as circular construction is comparatively expensive and also leads to loss of usable interior area. The fourth option was chosen and is described in detail below. It was designed with a balance between force and economic factors.

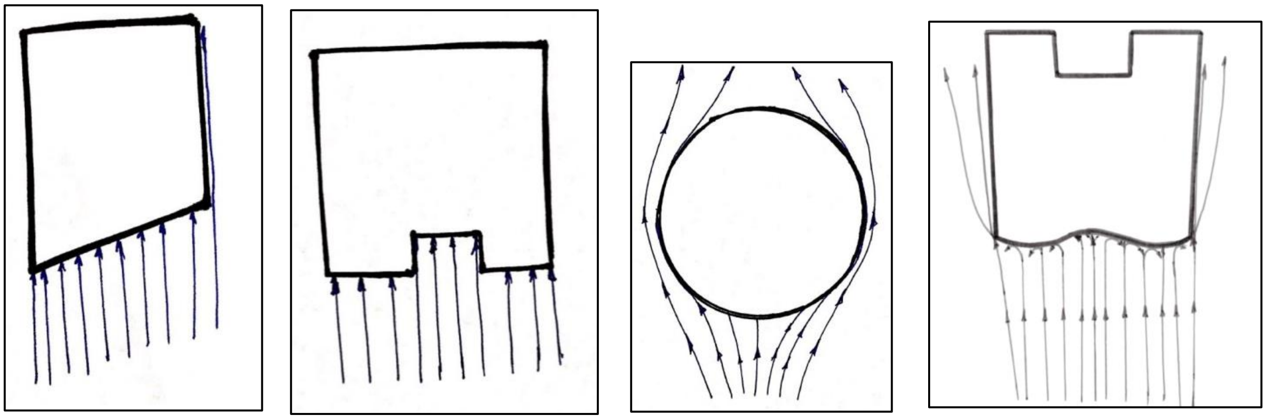


Fig. 3.1 Process Study sketches

Source: Drawn by Sabyasachi Das

The elevation of the building facing the seaward or coastal side is shaped as an arched wall. The hydrostatic forces from waves of the tsunami when acting on a flat surface, for example as in the Figure 3.2 (a) below tends to apply their total concentrated vertical load on it as the acting forces don't have any horizontal component. In case of a curved wall as in the case in Figure 3.2 (b), the hydrostatic forces acting on a curved wall surface tend to have distribution of forces along the surface as there is proportionate magnitude of both horizontal and vertical force components in the condition and there is dissipation of force energy in the process [44]. The proposed building mass widens from the coastal facing end towards the inland side to create a tapering affect.

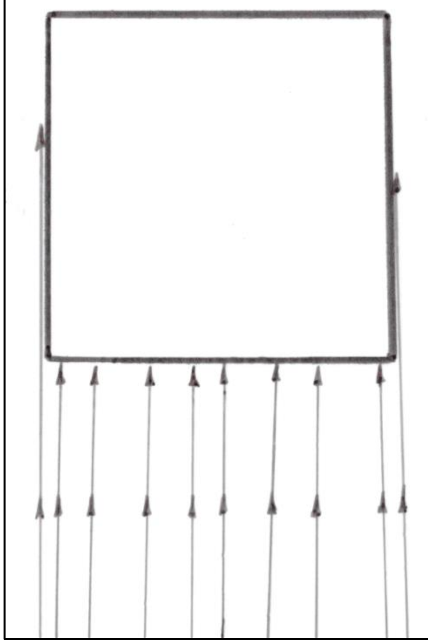


Fig. 3.2 (a) Building Mass & Form in a rectangular house
Source: Drawn by Sabyasachi Das

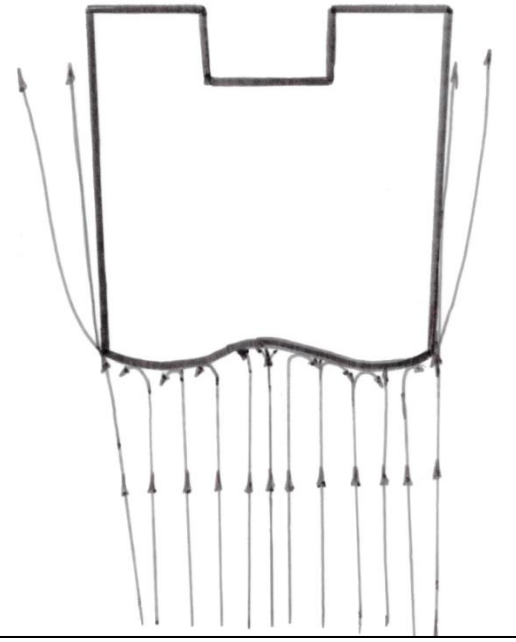


Fig. 3.2 (b) Building Mass & Form in proposed design
Source: Drawn by Sabyasachi Das

Water moves by the method of adhesion to a surface. The widening of the mass towards the land allows the water to glide along it and widens the direction of waves hitting the building. This would help in reducing the intensity of the waves reaching the area behind the building. The developed mass is made symmetrical in construction to promote proper binding of the unit.

The developed form has nautical feature to act in simulation of a boat in water. This would allow the building to survive through a flash tsunami wave condition as well as its fluidic shape will allow for better survival through a wind storm. The seaward façade of the house has a combination of convex and concave arcs in consideration of the fact that tsunami waves are unpredictable in path. Smaller arcs will increase the chance of dissipation of energy of the waves from the different directions. A larger single convex arced façade would also have dissipation of energy but as it would be a relatively larger arc it would also have longer linear tangents compared to the proposed case with multiple arcs. An increase in the amount of possible linear tangent would also increase the effect of vertical forces depending on the direction of the wave but lesser compared to a flat wall under given conditions. In development of this form economic aspects have been also kept in mind, as the vision is to also make it economical to a higher mass of people and bring safety to their lives. The seaward sides façade with multiple arcs allows easier buildability as circular construction or arced construction is relatively more expensive than regular straight wall constructions. Therefore, in consideration of the fact that Tsunami would come from the sea ward side of the island towards which this house is oriented only the seaward side is shaped so and the lands' end is more functionally made of regular linear walls. The waves after the impact on the front façade of the building reduce in height and inundates into the land. The height of the waves generally reduces on the way backward but do carry debris with them which can flow thought the open space below.

In consideration of the fact that housing in islands are clustered along the coast it is important that this proposed design acts in a model cluster along the coast with one side of the houses facing seaward.

The proposed design is repeated as blocks and analyzed in context. The elevation with the arced walls are oriented the sea. As waves approach the shore the water would flow though the set of houses or through below them as it inundates into the land. On the way backward from the land toward the sea the water level heights being lesser comparatively to the impact waves can flow through the buildings. The figure 3.3 below represents the same.

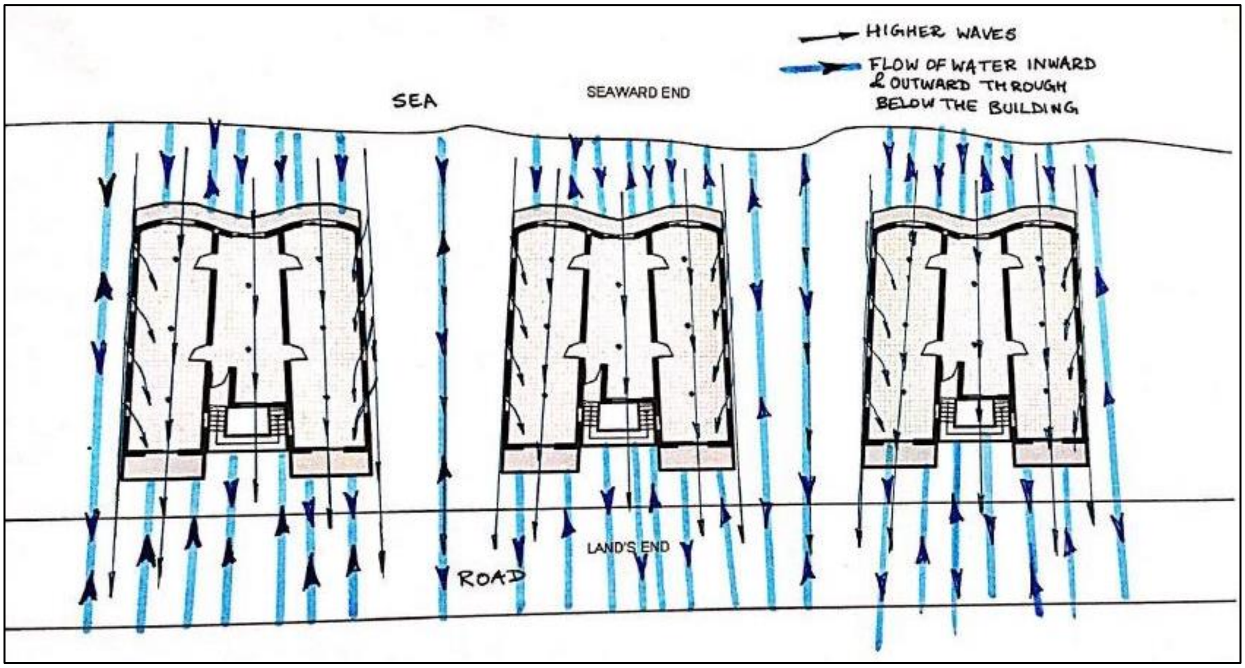


Fig. 3.3. Source: Drawn by Sabyasachi Das

3.2. Columns

Based on the recommendations of the analysis, the proposed design is to be made at a plinth height of at least 3 meters. Circular columns are proposed in the design considering the fact they have higher resistance to bending or deflection compared to a square column of the same cross section area [45]. Circular columns are symmetrical in nature about any centroidal axis. Their characteristic omnidirectional strength under influence of seismic and wind loads have made them popular for use in bridge pier design. Refer to Figure 3.5.

3.3. Building Core

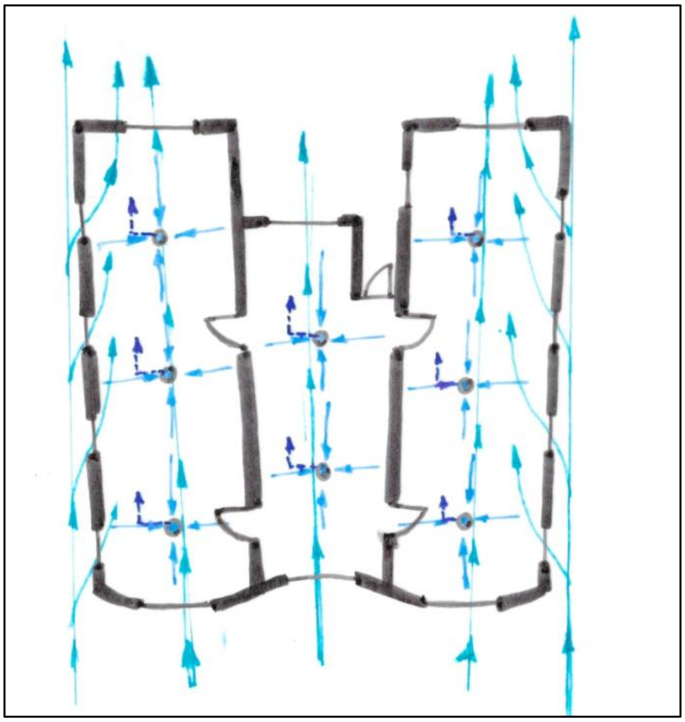


Fig. 3.4. (a) Building Core layout Source: Drawn by Sabyasachi Das

The core of the building is divided into three narrow zones to promote water to flush out through the centrally aligned door openings on either end of the house. The developed mass has ten windows and six sliding doors, which account for 50% openings in the shell of the building, this will help in reducing the impact of the tsunami as it helps in better pressure distribution during an impact. The centrally aligned linear openings allow the impact water to flow through the building under such conditions. The three zones in the core of the house have drainage as shown in the figure, which will allow water to drain out through the floor in to the space below in the case a tsunami happens (Figure 3.4. (a)). As often after flooding or tsunamis, the collected water inside buildings damages the interior of the space. This drainage system will have covered openings, which would open on inundation of water and allow it to drain down. See Figure 3.4(b) below for floor plan of proposed design with drainage plan. The house has balconies on either ends which could be made of temporary construction materials that could be possibly rebuilt after an impact at comparatively lesser costs.

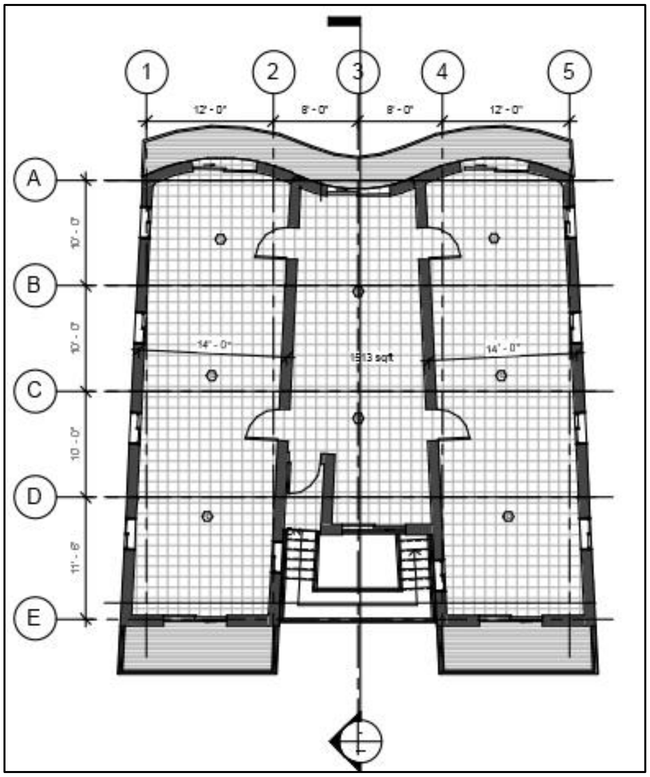


Fig. 3.4. (b) Floor Plan of Proposed Design with drainage plan
Source: Drawn using Revit 17 by Sabyasachi Das

3.4. Lateral Support

In reference to the literature review about the benefits of concentrically braced connections for dual purpose of damage control and prevention of structural collapse, steel rods of circular shape are used as cross bracing in between the columns to provide lateral support. This lateral support system will allow the structure to resist the impact when waves of Tsunami move from the coast towards the land through this building as well as when the water travels back to the sea after the flash flooding has happened. Refer Figure 3.5 below.

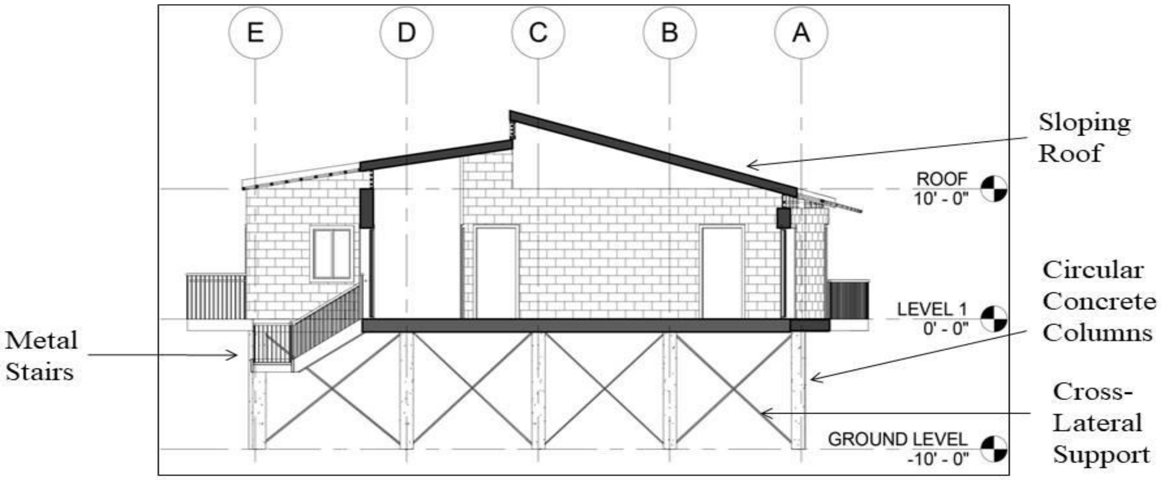


Fig. 3.5. Building Section
Source: Drawn using Revit 17 by Sabyasachi Das

3.5. Cooling and Ventilation

As discussed earlier, Andaman and Nicobar Islands have a hot and humid climate throughout the year, and cooling is mostly required to provide comfortable conditions. Passive cooling methods are applied in the proposed design. The core of the building being narrow with centrally aligned openings along with benefits from impact of tsunami also acts as cross ventilation for the designed house in principal application of the Bernoulli effect. The figures 3.6 (a) and 3.6 (b) below shows the cross ventilation of air through the building and are precedent sketches. Figures 3.6 (c) and 3.6 (d) below represent the application of strategies based on the precedence of sketches as above. High roofs and stack ventilation technique has been used to promote process of ventilation and dehumidification of the spaces. Figure 3.6 (d) represents the same.

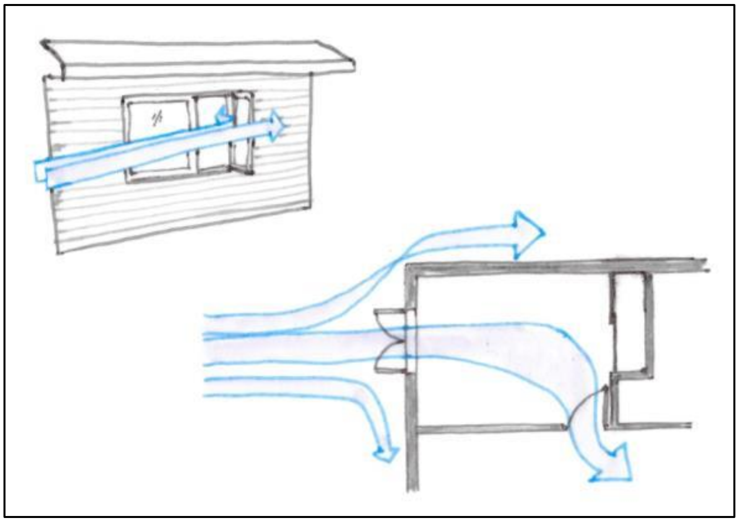


Fig. 3.6 (a) Airflow
Source: Drawn by Sabyasachi Das

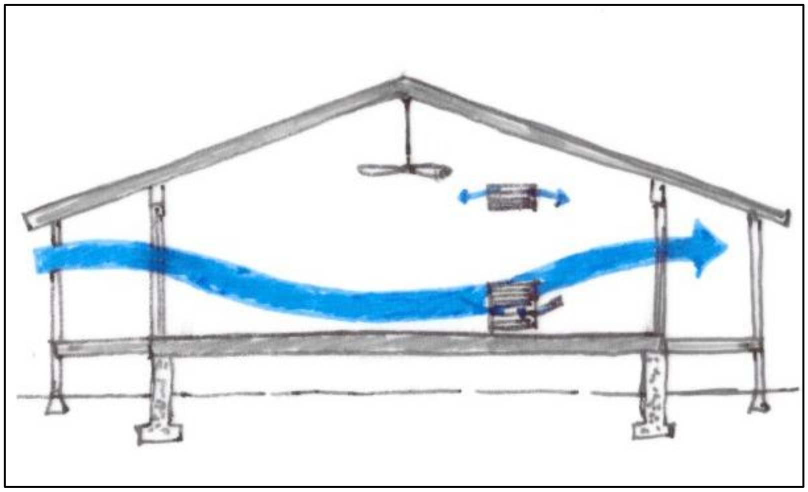


Fig. 3.6 (b) Airflow
Source: Drawn by Sabyasachi Das

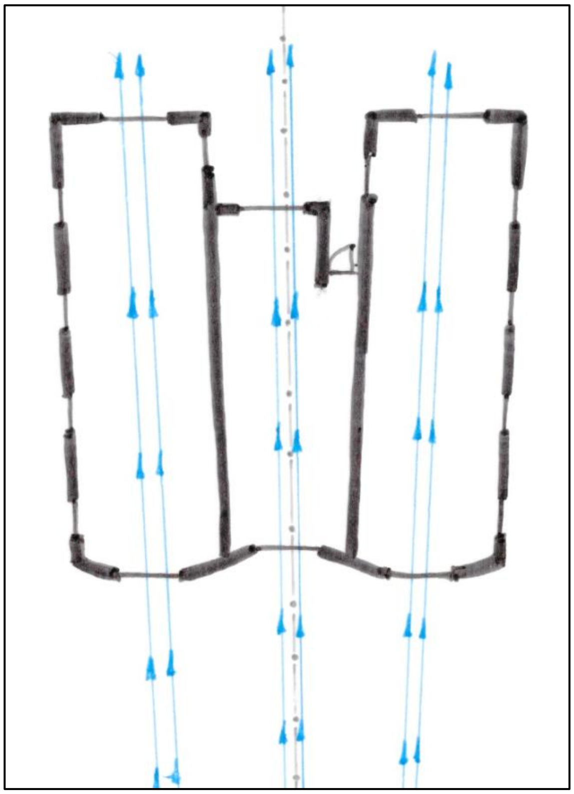


Fig. 3.6 (c) Application of Bernoulli effect via narrow core layouts
Source: Drawn by Sabyasachi Das

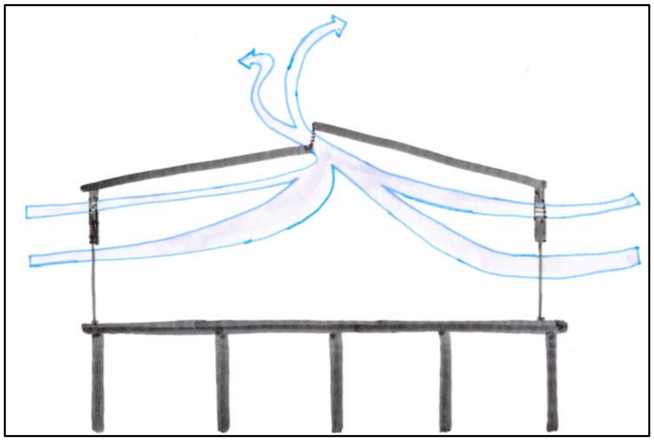


Fig. 3.6 (d) Ventilation Cooling
Source: Drawn by Sabyasachi Das

3.6. Roofing and Shading

The seaward facing of the building which has curved walls have an extending shade from the roof created by bamboo which is an available material in the region. This helps in shading of the balcony as evident from the Climate consultant tool that there is constant distribution of global horizontal radiation throughout the year. This bamboo shade which is made of a relatively temporary material as they are easily available also has a combing effect to the impact waves. And after impacts they could be easily replaced. Similarly, in the land end of the building there is a gazebo like structure over the stairs near the entrance created by a grid of bamboo to give shading. The proposed design has two roofs which are sloping in nature and is in combination with stacked ventilation to allow proper movement of air. As per the sun shading chart generated by the climate consultant software tool, the shades for the windows have been oriented at a 30-

degree angle to provide optimum shade throughout the day in the warmer summer season and allowing better comfort to the users of the building. Refer Fig. 3.7. below.

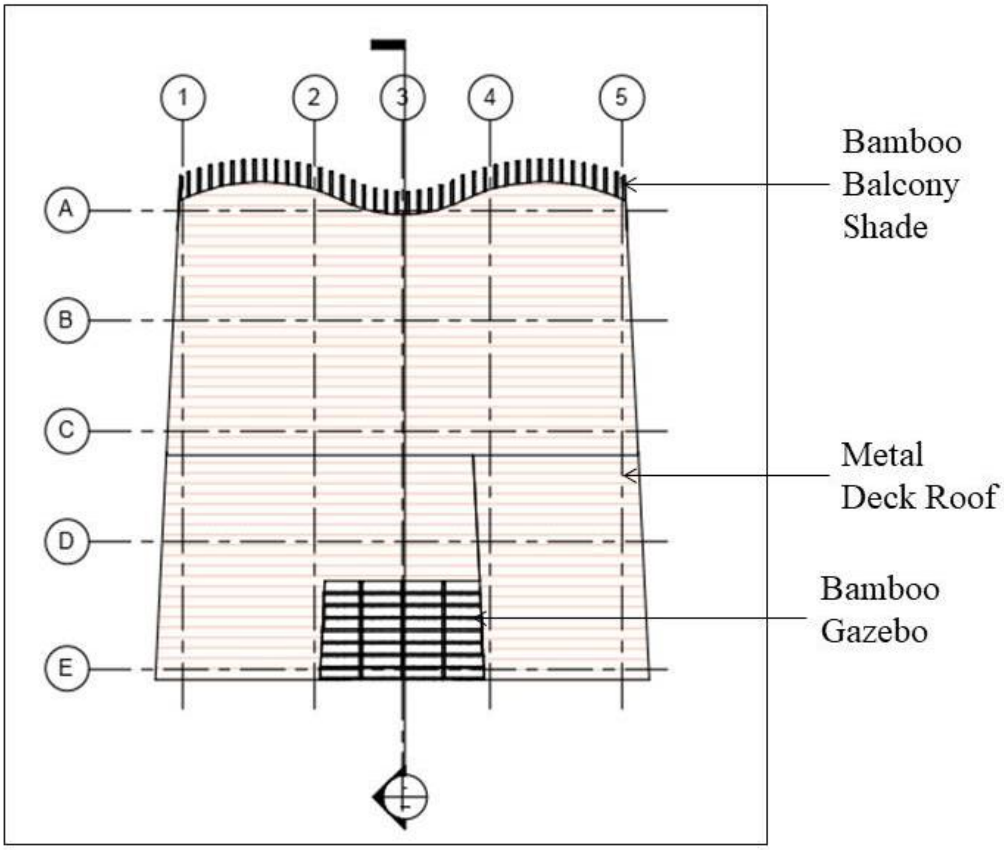


Fig. 3.7. Roof Plan
Source: Drawn using Revit 17 by Sabyasachi Das

3.7. Suggested materials for Proposed Design:

The materials suggested are based on their easy availability in the area. For the exterior and interior walls hollow CMU blocks are suggested. These CMU blocks are easily available in the region as well as have high compressive strengths compared to conventional bricks. The hollow CMU block also helps in cooling and breathability of the building as it has air in between them and will allow the building to cool off in the evenings [65]. Even though hollow concrete blocks are lighter in comparison to regular brick or solid CMU there is always a chance of them getting cracked with the impact of a tsunami. This CMU blocks being a cheap construction material in the region will allow the easy replacement of them in such events when a particular portion of the building gets damaged. The circular columns are suggested to be made of reinforced concrete construction with earthquake resistant ductile detailing in them. The lateral bracings connected to them are circular steel rods with anti-rust protection coating. This lateral bracing is to be installed in between the columns as in Fig.3.8 (b).

The installed windows and doors are hurricane rated. Since in India there isn’t any available storm rating system yet, but major companies do sell hurricane rated windows and doors which can resist winds up to 125mph. The shading features in the sea facing and the land facing end are made of bamboo which is cheap and available in the region. Bamboo being a tensile material will be able to better withstand the first impact forces on the face of the building. And in case of their damage it is comparatively inexpensive to rebuild using bamboo. The stairs are to be made of steel and connected well to the foundation. So that in event of a tsunami the stair steel structure is retained in place as the inundated water goes back to the sea. The roofing material is suggested to be made of industrial metal decking system which is also available commercially as an import material to the area. Metal decking is long lasting and lighter in comparison to concrete roof systems and easier to install. Metal decking is imported into the island by various manufacturers for other commercial purposes. The proposed stack ventilation systems for better cooling comfort in the building are generally made of aluminum. The floor area inside the house is suggested to be made of concrete cast in place. The balconies which are added features to this resilient design for human comfort can be made of cheaper wood construction which could be replaced even if they get damaged by an event of a tsunami.

Fig. 3.8. (a) Sea Facing Elevation
Source: Drawn using Revit 17 by Sabyasachi Das

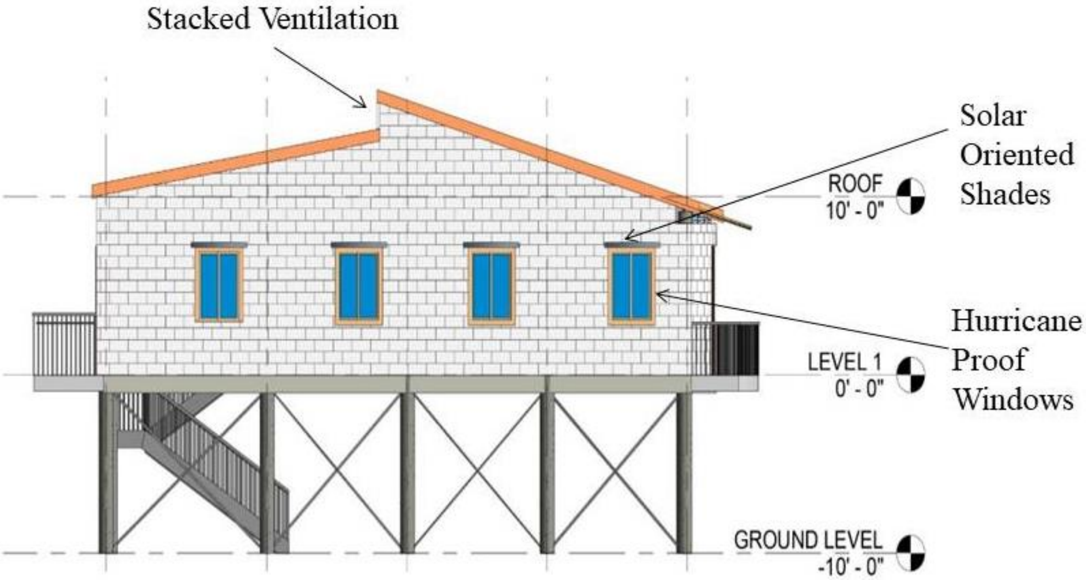


Fig. 3.8. (b) Side Elevation
Source: Drawn using Revit 17 by Sabyasachi Das

Fig. 3.8. (c) Land-end Elevation
Source: Drawn using Revit 17 by Sabyasachi Das

Fig. 3.9. 3D Perspective view of proposed design
Source: Drawn using Revit 17 by Sabyasachi Das

3.8. Cost of Construction of Proposed Design

The area of the proposed house design is 1500 sqft. The total estimated material cost of making this building is 14,180 USD (Rs. 9,50,000). This excludes land costs and interior development .

The cost of the foundation is 2,238 USD (Rs 1,50,000)and structural costs is 5970 USD (Rs 4,00,000) .The cost of the building the core and shell of the proposed design with walls is 2985 USD (Rs 2,00,000). Doors, windows, roofing and other wood work is estimated to cost 2985 USD (2,00,000). The estimation of cost of making this house in Andaman and Nicobar Islands is made in consideration of I materials market and construction service costs in India.(Note: 1 USD= 67 Rupees)

3.9. Psychrometric Results on application of Passive techniques

On application of the passive design techniques of sun shading, ventilation and dehumidification methods there is an increase in the comfort levels in the proposed design from the baseline condition of the region which only has 0.7% comfort levels. The increased comfort levels as per the chart is 29.2%.

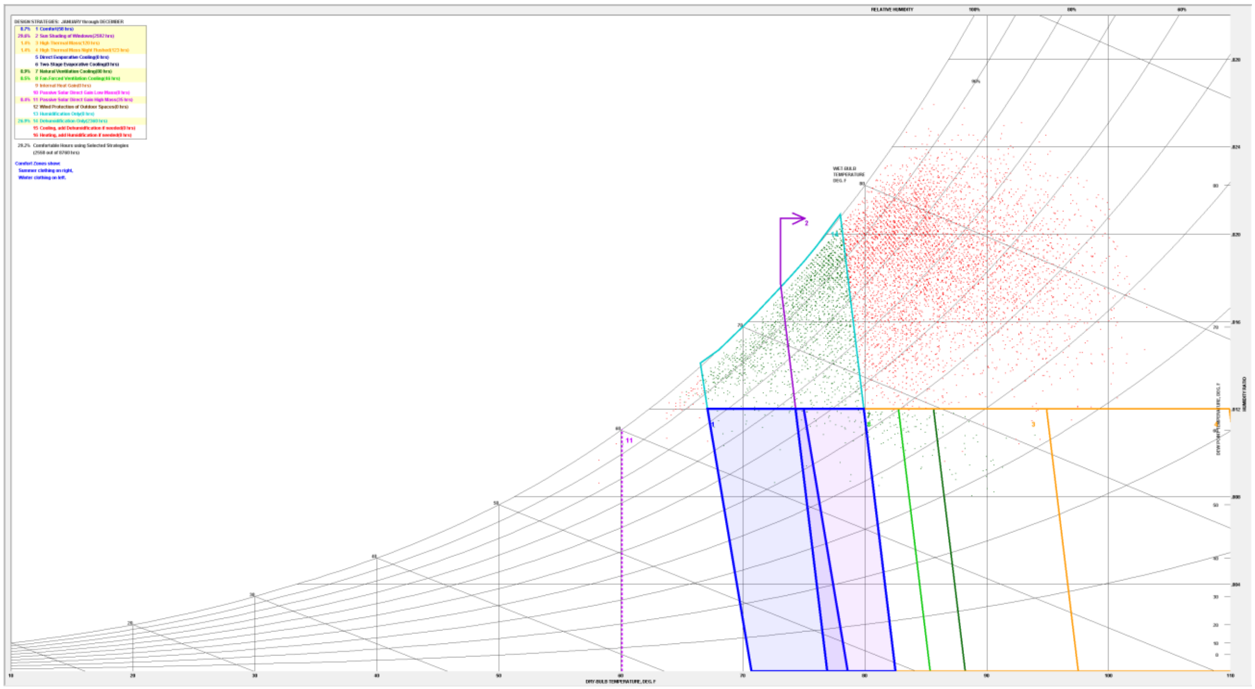


Fig.3.10. Psychrometric Chart
Source: Climate Consultant 6.0

3.10. Thesis Way Forward

- In the way forward a detailed structural calculation can be done in addition to the research to properly size the structural elements based on the loads.
- A simulation of the proposed design could be done in fluid tunnels
- Actual development of the prototype in the islands

PART 4: CONCLUSION

4.0 CONCLUSION

With a growing trend of human settlement along the coastal areas, more fraction of the population is getting vulnerable to natural disasters caused by climate change and tectonic shifts in the coastal regions with flooding, storms and Tsunamis being the primary forms of natural disasters hitting these regions. Resilient housing is a proposed solution to reduce the loss of housing post disaster and to protect human lives during the course of a disaster. This thesis discussed in depth about the natural disaster caused by the Indian Ocean Tsunami, 2004 with the Andaman and Nicobar Islands, India, as a case study to understand the characteristics and impacts of tsunami through a literature study driven approach with the objective to create a resilient design prototype based on the methodology of investigation and evaluation of strategies in the research.

Keeping in perspective the words of the NOAA “achieving resilience requires understanding environmental threats and vulnerabilities to combat issues like sea level rise” this thesis research work started with the understanding of Tsunami as a form of natural disaster and its forces which affects the structures in affected area. This research has developed a design prototype with resilient features which could be adapted by people in the area to create better resilient housing for protection of their lives from future disasters. The features of the proposed design can also be used as retrofitting techniques in the existing houses in the region.

Being able to create and dwell in resilient houses makes its users stewards of sustainability as they are being socially, economically and environmentally responsible. This approach could also be possibly used by people around the world in areas which are prone to Tsunami or by other coastal natural calamities to create resilient housing in areas where the climatic conditions are similar. In regions that have different climate, different materials and construction methods specific to the location may be applied.

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APPENDIX - PART A: EXPERIMENT 1

The experiment was conducted by four researchers Taofiq Al-Faesly of University of Ottawa, Ioan Nistor of University of Ottawa, Dan Palermo of York University and Andrew Cornett of National Research Council Canada [9].

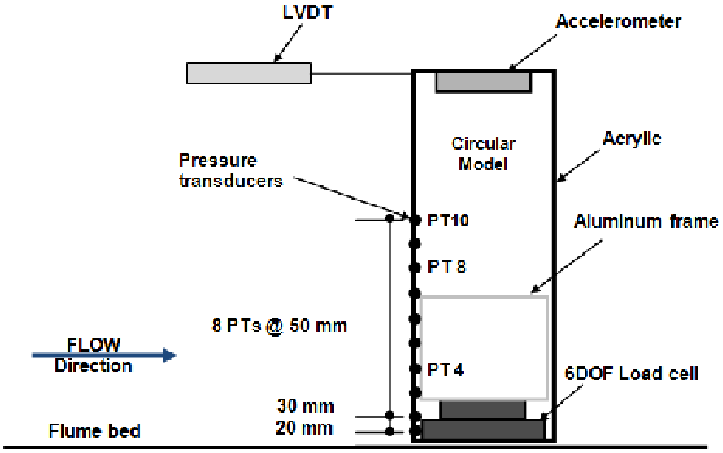

Fig. A.A. 1: Square model details (side view)

Source: Al Faesly et al. (2011) [9]

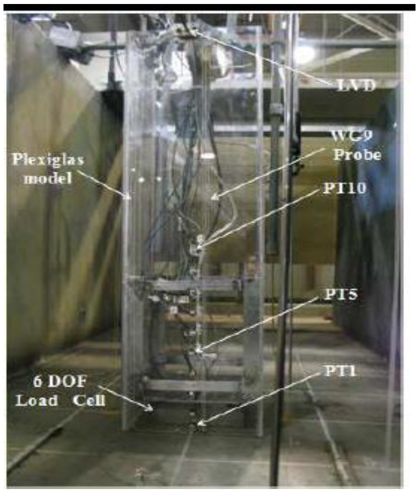

Fig. A.A.2 Testing instrumentation details

Source: Al Faesly et al. (2011) [9]

A.A.1. Construction of Experiment 1:

In this experiment the researchers had built a one-meter height square model. The model was one meter in height and was made of Plexiglas. A metal structure was designed and fabricated so as to connect the structural model to the six degrees of freedom with high frequency load cell. The flume was made using two high discharge electrical pumps, one pump with 75HP constant discharge while the second one (100HP) provided controlled, variable discharge. The construction of the structure was rigid enough to transfer the hydraulic bore-induced forces from the outside model to the support load cell. A square aluminum plate of 5mm thickness was used as a base for the structure. A detailed skeleton side view structure is shown in Figure 1. In figure 1 the notations PT, LVDT, and 6DOF refer to the pressure transducer sensor, the linear variable differential transformer, and the six degree of freedom dynamometer, respectively. The experiment was performed in High Discharge Flume (HDF) at the Canadian Hydraulic Centre (CHC) in Ottawa, Ontario. The experiment involved applying force on the structure with hydraulic bore equivalent to a broken tsunami approaching inlands and following parameters were recorded: forces and moments with a six degree of freedom load cell (6DOF), structural displacement, structural acceleration, bore depth and bore velocity.

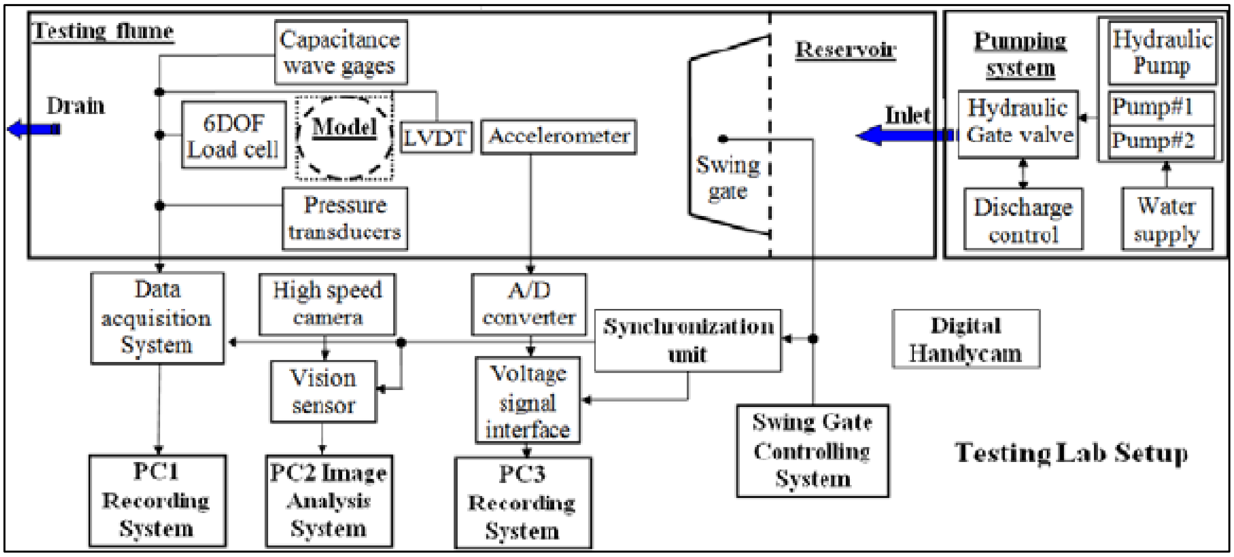

Fig. A.A.3 Flow diagram of the experiment test lab setup of the simulated tsunami experiment
Source: Al Faesly et al. (2011) [9]

A.A.2. Terminologies of Experiment 1

Hydrostatic Pump: A hydrostatic pump is a mechanical device that converts mechanical power into hydrostatic energy. It generates flow with enough power to overcome pressure induced by the load.

Bore velocity: It is the velocity of the water that flows out of the hydraulic pump into the tank with the help of gravity due to which the flow of water tends to gain some velocity.

Bore Pressure: It is the pressure that is exerted by the water at equilibrium at a single point of the flow of water due to the force of gravity. This pressure increases in proportion to depth measured from the surface. This increase is due to the increasing mass of water exerting downward force from the hydrostatic pump.

Bore Force: It is the force exerted by the water into the walls of the bore of the hydrostatic pump keeping the water at rest.

Hydrodynamic Force: the motion of water flow and the force acting on solid body (the aluminum frame model in the experiment) immersed in fluids and in motion relative to them.

A.A.3. Principle of the experiment

Bore Velocity: There were many formulations that were proposed by many organizations and researchers. FEMA 55 presented a formula $U\ max= 2(gh)^{1/2}$ whereas CCH 2000 assumed that U=h (ft/s), researchers such as Brian proposed $U= (1.67h)^{0.7}$, Murty proposed $U=1.83(gh)^{0.5}$. But the formula that is most widely used is $U= (2gR)^{0.5}$ where U is velocity, g is gravitational constant and R is the ground elevation.

Bore Velocity Tests: In the first stage of the experimental work, tests were conducted using hydraulic bores generated by the sudden release of impounding water depths of 400mm, 550mm, 700mm, 850mm, and 1150 mm in the absence of the structure model. The data recorded was used to obtain the bore profile as well as the bore velocity. The data was then used to calculate bore velocity. To capture slow-motion videos of the advancing bore, a high speed camera was installed in the model. By tracking the bore front frame-by-frame and based on the geometry of the grid lines, the authors were able to derive the bore front velocity at different successive sections along the flume longitudinal axis. As seen in Figure 2, three pairs of wave gauges were installed in the flume for this particular test series.

Spacing between successive pairs of gages was 1 meter. Bore velocity was also calculated using the time interval required for the bore to travel between the wave gauges while reaching a specified water level (30 mm, 40 mm, 50 mm, and 60 mm). To determine the time for a specific water level at a given location of a wave gauge, a cross correlation function was used for the data recorded by each pair of wave gauges position on the same transversal row.

A.A.4. Results and Discussion of Experiment 1

Bore Velocity

The bore velocity of the water was calculated in two ways: (1) Using high speed video recording camera as it helps to capture the flow of water even at a greater speed, and (2) by using the time needed for the bore to record a given inundation depth between two successive pairs of wave gauges (WG's). Also, the formulas of bore velocity were used to calculate the theoretical value of bore velocity and the results were compared with those experimentally determined from the experiment. Figure A.A.4. shows that the FEMA 55 and CCH formula provide the upper and lower bound of the envelope of the estimated bore velocity, respectively. The figure also shows that the results obtained in this study using the high speed video recordings and the wave gages are similar in magnitude and trend.

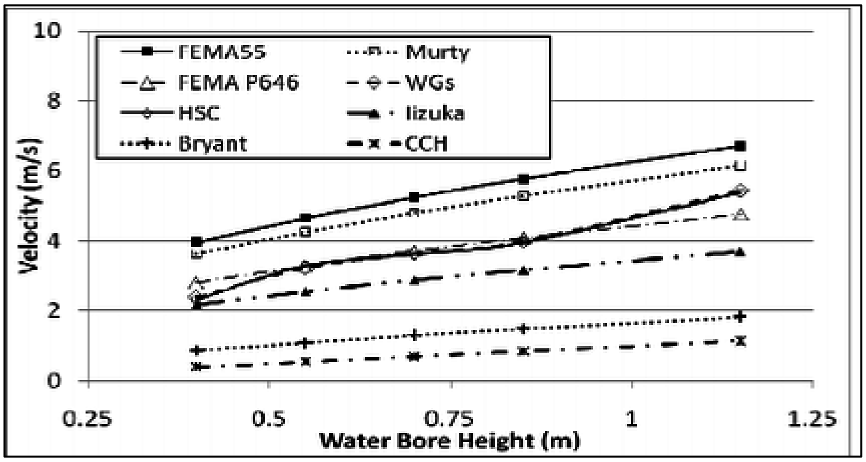

Fig. A.A.4. Bore front velocity data: experimental VS existing formula
Source: Al Faesly et al. (2011) [9]

The bore front velocity was calculated starting from 1.5 meter upstream from the model location onwards at intervals of 0.3 meter. Figure 6 shows the bore velocity profile for three different impounding water heights. The graphs corresponding to the bores generated by the 550 mm and 850 mm impounding depths showed that the bore front velocity towards the downstream of the distance analyzed increased in magnitude by 20% compared to its initial value while it is decreasing with about 4% for the 1150 mm impounding height.

The experiment was conducted in two conditions: wet bed and dry bed conditions. For the wet bed condition the impact force was smaller than the run up force and for dry bed condition the impact force had the biggest magnitude in comparison to run up and quasi-steady hydrodynamics. With the determination of the bore velocity, bore force and the bore pressure we can determine the velocity, force and the pressure exerted by a series of waves (Tsunami).

APPENDIX - PART B: EXPERIMENT-2

Another analysis was made by three researchers namely Tiecheng Wang, Tao Meng, Hailong Zhao in Japan where structural response to effects of Tsunami was analysed [32]. Tsunami is mainly triggered by strong sea quake, underwater volcano eruption, as well as large-scale underwater or coastal landslide. However, among the causes leading to tsunami, the sea quake is the most primary reason especially the dip-slip type quake that staggers up and down along the fault surface. The last decade has been witness to a number of major tsunamis that have resulted in catastrophic human and economic losses to coastal communities. (Indian Ocean 2004, Chile 2010 , and Japan 2011). As for this, to analyse the magnitude and distribution of tsunami forces on the structure and to study the response of structure under the impact of tsunami forces has an important meaning in improving the performance of structure, resisting tsunami disaster, as well as reducing casualties and economic losses.

It is an important theoretical research method to numerically simulate and analyse the interaction between tsunami waves and structures, so as to figure out the response of structures under the impact of tsunami waves. This method is effective in complementing the defects of some experimental researches. In this paper, based on the computational fluid dynamics software of FLOW-3D, the method of Volume of Fluid (VOF) is utilized to capture free interface, and the ideal solitary wave model is applied to simulate tsunami waves. Through simulating and analysing the three-dimensional numerical model of reinforced concrete frame structure under the impact of tsunami waves, the magnitude and distribution of tsunami forces can be ascertained.

A.B.1. Numerical simulation of tsunami forces

Tsunami waves are of long period gravity wave, and gravity is a restoring force. Gravity has the tendency to restore the disturbed sea water back to the undisturbed state. When the gravity waves are propagating in the seawater, gravity can transfer wave energy from the excessive regions to the insufficient regions. Moreover, as sea water is incompressible, tsunami waves are also considered as an incompressible viscous fluid motion. FLOW-3D takes the continuity equation and the Navier-stokes equation for incompressible viscous fluid motion as the control equation for fluid motion. The equation expressions are listed as follows:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Momentum Equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g$$

A.B.2. Model of tsunami impact on the structure

When waves travel into near shore shallow water areas, the shape and motion of tsunami waves closing to breaking is quite similar to the solitary wave. By researching the propagation of tsunami waves, Hammack and Segur pointed out that under the circumstance with positive net volume variation, some solitary waves with stable shapes could be generated. As for this, the ideal solitary wave is employed to simulate tsunami wave in this paper. The propagation velocity of ideal solitary wave and tsunami wave in the ocean can be calculated by

$$C= [g\ (H+d)]^{0.5}$$

Where g refers to the gravitational acceleration, H represents the height of solitary wave, and d indicates the depth of still water, in which the solitary wave travels.

$$C= (gh)^{0.5}$$

Where h refers to the depth of sea water, in which the tsunami wave spreads. Similar to the ideal solitary wave, tsunami wave also has very long wave length and relatively small wave height.

The propagation velocity may be calculated from the above two equations, which are determined by the depth of water.

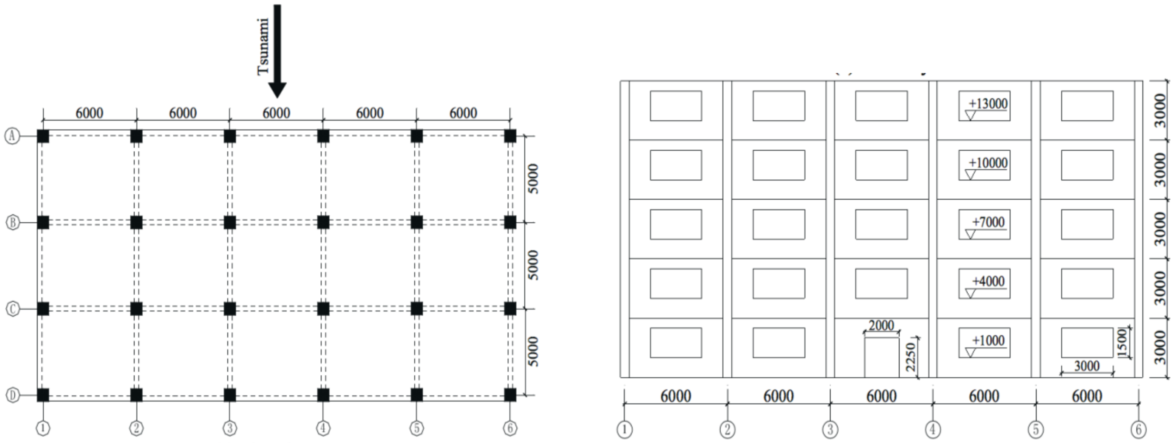

Figure A.B.1: Plane and elevation layout of the structure (in mm)
Source: Wang et al (2015) [32]

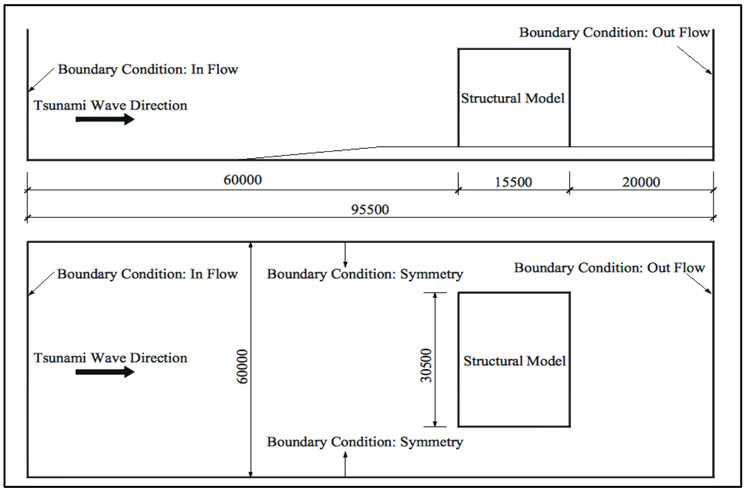

Figure A.B.2. Model Boundary conditions and geometric dimension
Source: Wang et al (2015) [32]

The model constructed in this experiment was an incompressible and viscous flow model, and Newtonian viscosity with renormalized group (RNG) k-ε turbulence model was adopted. The boundary conditions and geometric dimension of the model are shown in Fig. A.B.2.. The left side is the entrance border (In Flow) of the incident wave. It is set as H is equal to 2 m and the incident wave height *d* is equal to 3 m, therefore, the velocity of the incident wave is 7 m/s. The right side of the figure shows the exit border (Out Flow) of tsunami wave, which allows water to flow out freely. The up and down side of the figure were set as symmetry boundary condition. At the symmetry boundary, the flow flux of the fluid was zero and the tangential stress was 0, i.e., the fluids at two sides of the symmetry boundary were continuous. In order to better simulate the motion of tsunami wave before impacting the structure, the influence of seaside slope on propagation of the tsunami wave is comprehensively considered. As for this, a 10 % slope is set at the front side of the structure to simulate the coast.

In the simulation process, in order to compare the influence of tsunami wave on the structure separately with and without walls conditions at the upstream face at the bottom of the structure, the paper conducts simulation in two different cases. Case 1: The upstream face on the bottom floor of the building is constructed with walls, and the area ratio between holes and walls is 1:4, which is shown in Fig. 1(b). In the impacting process, the walls are not damaged, while the connection with the main structure is intact, as is shown in Fig. 3(a). Case 2: The upstream face on the bottom floor of the building has no walls. Floors from 2 to 5 are constructed with walls, and also the ratio between holes and walls is 1:4. In the impacting process, only columns on the bottom floor are bearing load from tsunami waves, as is shown in Fig. 3(b).

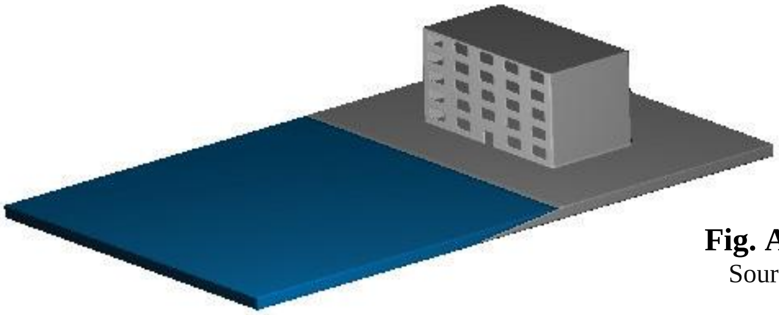

Fig. A.B.3. (a) Case 1
Source: Wang et al (2015) [32]

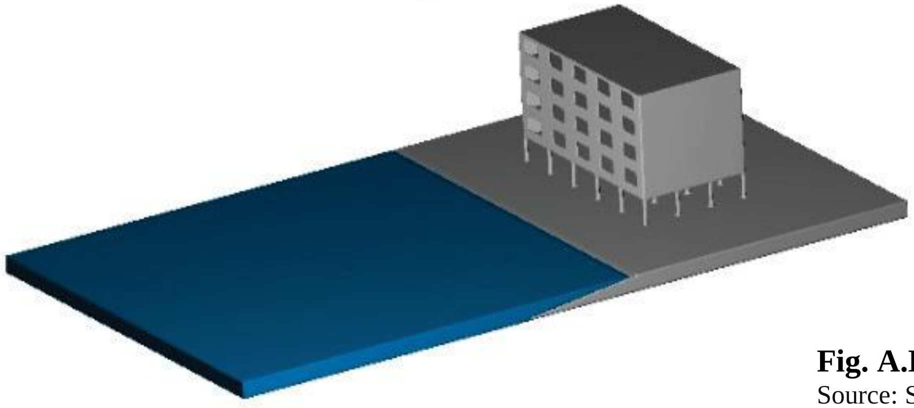

Fig. A.B.3. (b) Case 2
Source: Shuto (1993) [49]

A.B.3. Tsunami wave forces simulation results

Based on simulation, Fig. 4 shows the time-history curves of tsunami wave horizontal thrust on the frame structure in Case 1 and Case 2. During the time period from 3.0 sec to 6.5 sec in Case 1, the horizontal thrust of tsunami wave impacting on the structure presents a tendency of linear increment. After that, blocked by the upstream walls, local tsunami waves are reflected so that tsunami load on the structure is reduced in a short period. Then, as the reflected wave gradually decreases there is gradual increase in the load on the structure which reaches its maximum value of 7909.6 KN at 8.3 sec. At the moment the tsunami wave reaches the largest run-up height and is strongly instable. After the tsunami wave reaches the largest run-up height, the load on the structure decreases sharply, this finally stabilizes at 12 sec. At the moment, the structure is in a stable state of being impacted by tsunami waves.

In Case 2 as the bottom of the structure is not constructed with upstream walls, there are only columns on the bottom floor to bear the impact from tsunami waves, so that the impacting area of the structure with tsunami waves is quite small. Before 9 seconds, all loads generated from tsunami waves are impacting on columns of the bottom floor, and tsunami load on the structure increases gradually. Afterwards the run-up height of tsunami waves increases continuously and the upstream walls of the second floor start to come contact with the tsunami waves. As for this, tsunami load on the structure takes on a rapid increment tendency which is stabilized after 12 seconds and reaches the maximum value of 2129.2 KN at 13.8 seconds. When impacting with the structure in Case 2, tsunami waves encounter quite limited resistance, with small wave reflection. Thus, when compared with the situation in Case 1, the variation in amplitude of tsunami wave impacting on the structure in Case 2 are much gentler.

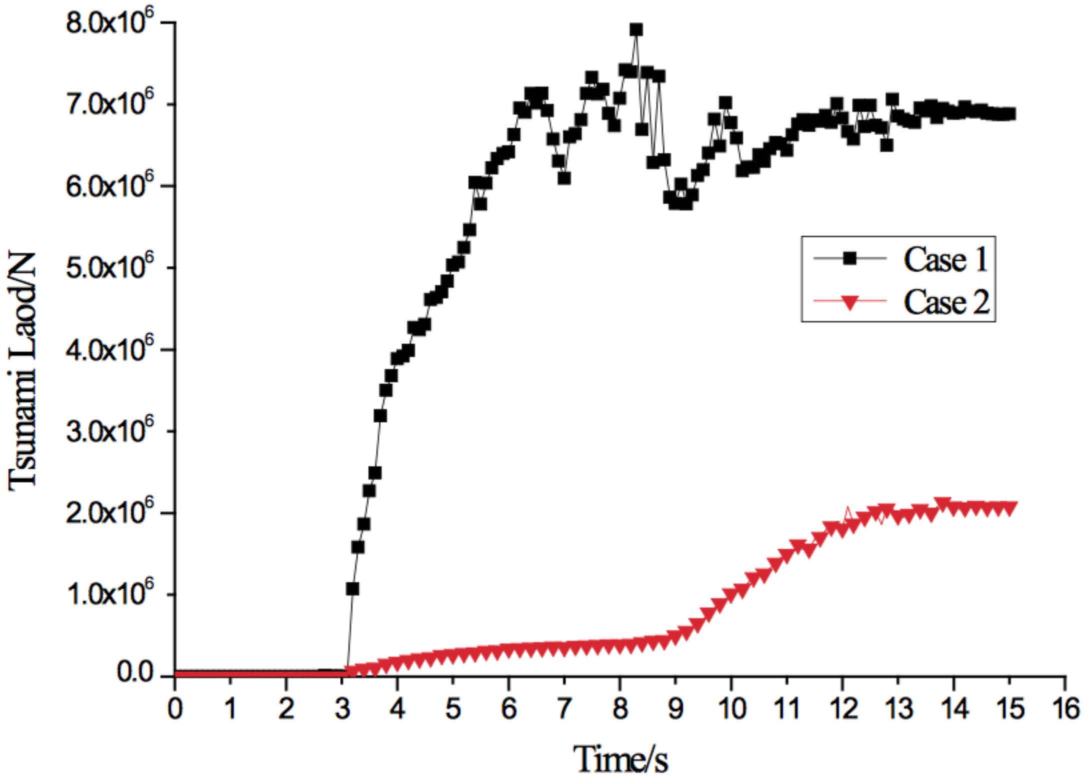

Fig.A.B.4. Comparison of Tsunami Load on Case 1 vs. Case 2
Source: Wang et al (2015 [32]

The maximum tsunami wave force impacting the structure in Case 2 is much less than that in Case 1. Moreover, the occurrence time of maximum tsunami wave force on the structure is later than that in Case 1. When no in filled wall is constructed on the upstream face of the bottom floor of the structure, there would be only columns on the bottom floor bearing the impact from tsunami waves, so that the resistance as water passes through the structure is smaller. Therefore, the structure in Case 2 is more effective in resisting tsunami waves.

APPENDIX – PART: C

A.C.1. General Design factors to construct buildings in coastal areas as proposed by National Disaster Management Authority

		Housing	Important Building	Cyclone Shelter/Very Important Installation
Wind Speed		IS:875(3)	1.15 X IS:875(3)	1.3 X IS:875(3)
Factor of pressure	**K1**	1.0	1.08	1.08
	K2	1.05	1.05	1.05
	K3	1.00	1.00	1.00
Seismic coeff. IS:1893 (1)		I=1.0, R as per code	I=1.5, R as per code	I=1.8, R as per code
Storm Surge		As per Vulnerability Atlas of India, 1997 riding over maximum astronomical tide level		
Fire safety		1.5 hr rating	2 hr rating	≥ 2 hr rating
Flood safety		Plinth height at recorded high flood level or corresponding to 10 yr flood	50 yr flood	100 yr flood

Table A.C.1. General Design factors to construct buildings in coastal areas as proposed by National Disaster Management Authority. Source**:** NIDM [38]

A.C.2. RC design criteria for all coastal areas

Concrete used to build structures that are exposed to coastal Environments should have following characteristics:

(i) Plain: Min M20, Cement: min 250 kg/m3

(ii) RC: Min M30, Cement: min 320 kg/m3 Max aggregate: 20 mm Min cover for slabs: 20 mm Min cover for beam: 30 mm 3 Min cover for column1: 40 mm Reinforcement: TMT – HCR Fe 415 for up to 2 stories. Use Fe 500 for frames in taller buildings

(iii) HCB: To be casted using M 20 concrete with fly ash. Reinforcement TMT – HCR Fe 415 bars, concrete filling M 20 grade

	Parameter	**Housing**	**Imp. Building**	**Very Imp. Installation**
Wind	Wind speed factor for cyclonic winds	44 m/s	51m/s	57 m/s
	k1	1.0	1.08	1.08
	k2	1.05	1.05	1.05
	k3	1.00	1.00	1.00
Earthquake Coefficient	Ductile RC Frame[IS:1893(1)]	0.09, R=5.0	0.135, R=5.0	0.162, R=5.0
	Load bearing wall Bldg. (IS:4326)	Cat.D	Cat.E	Cat.E+ (to be elaborated)
Fire safety	Fire rating	1.5 hr	2 hr	≥2.0 hr
Storm surge with max. astronomical tide1	Andaman District	1.0 m	1.0 m	1.0 m
	Nicobar District	1.0 m	1.0 m	1.0 m
Tsunami Nicobar1	Height, minimum	3 m	4-5 m	5-6 m
Tsunami Andaman1	Height, minimum	2 m	3 m	4 m

Table A.C.2: Specific design values/factors for Andaman & Nicobar Islands