David Miguel Marques Chaves

Licenciado em Engenharia Civil

Flood Resilient Housing Recovery Models: A Theoretical Case Study in Maldives

Dissertação para obtenção do Grau de Mestre em
Engenharia Civil – Perfil de Construção

Orientador: Miguel José das Neves Pires Amado,
Professor Auxiliar, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

Júri:

Presidente: Prof.ª Doutora Maria Paulina Faria Rodrigues

Arguente: Prof. Doutor Corneliu Cismasiu

Vogal: Prof. Doutor Miguel José das Neves Pires Amado

Maio, 2015

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

“Copyright” David Miguel Marques Chaves, FCT/UNL e UNL

A Faculdade de Ciências e Tecnologia e a Universidade Nova de Lisboa tem o direito, perpétuo e sem limites geográficos, de arquivar e publicar esta dissertação através de exemplares impressos reproduzidos em papel ou em forma digital, ou por qualquer outro meio conhecido ou que venha a ser inventado, e de a divulgar através de repositórios científicos e de admitir a sua cópia e distribuição com objectivos educacionais ou de investigação, não comerciais, desde que seja dado crédito ao autor e editor.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Professor Miguel Amado for giving me insight and direction to my work.

I thank my family who showed me extraordinary amount of support and encouragement throughout my academic life.

I would like to thank my girlfriend Neia, partner of all joys and hardships, for all the continuous support throughout my work in this thesis.

My sincere thanks to my colleagues and friends, particularly Paulo Oliveira, Gonçalo Rocha and Vera Novais for the friendship and for backing me up. Cheers!

Many thanks to Conselho Português para os Refugiados, an NGO devoted to refugees who provided important information to the making of this thesis.

My most felt thanks to Dra. Maria João Moutinho for providing me with support throughout my academic life.

My thanks also go to Carla Figueiredo and Maria da Luz for all the patience and care.

Finally I'm deeply grateful to my grandparents for shelter and love. Though gone from sight they remain in my heart forever.

ABSTRACT

Natural disasters are events that cause general and widespread destruction of the built environment and are becoming increasingly recurrent. They are a product of vulnerability and community exposure to natural hazards, generating a multitude of social, economic and cultural issues of which the loss of housing and the subsequent need for shelter is one of its major consequences. Nowadays, numerous factors contribute to increased vulnerability and exposure to natural disasters such as climate change with its impacts felt across the globe and which is currently seen as a worldwide threat to the built environment.

The abandonment of disaster-affected areas can also push populations to regions where natural hazards are felt more severely. Although several actors in the post-disaster scenario provide for shelter needs and recovery programs, housing is often inadequate and unable to resist the effects of future natural hazards. Resilient housing is commonly not addressed due to the urgency in sheltering affected populations. However, by neglecting risks of exposure in construction, houses become vulnerable and are likely to be damaged or destroyed in future natural hazard events. That being said it becomes fundamental to include resilience criteria, when it comes to housing, which in turn will allow new houses to better withstand the passage of time and natural disasters, in the safest way possible.

This master thesis is intended to provide guiding principles to take towards housing recovery after natural disasters, particularly in the form of flood resilient construction, considering floods are responsible for the largest number of natural disasters. To this purpose, the main structures that house affected populations were identified and analyzed in depth. After assessing the risks and damages that flood events can cause in housing, a methodology was proposed for flood resilient housing models, in which there were identified key criteria that housing should meet. The same methodology is based in the US Federal Emergency Management Agency requirements and recommendations in accordance to specific flood zones.

Finally, a case study in Maldives – one of the most vulnerable countries to sea level rise resulting from climate change – has been analyzed in light of housing recovery in a post-disaster induced scenario. This analysis was carried out by using the proposed methodology with the intent of assessing the resilience of the newly built housing to floods in the aftermath of the 2004 Indian Ocean Tsunami.

Keywords: Resilient Housing, Natural Disaster, Housing Recovery, Maldives, Climate Change, Floods

RESUMO

Os desastres naturais são eventos que causam a destruição generalizada do ambiente construído. O desastre natural é um produto da vulnerabilidade e da exposição das comunidades aos perigos naturais que por sua vez gera problemáticas a nível económico, social e cultural para as quais não existem soluções lineares. Uma das mais complexas questões é a perda da habitação e a subsequente necessidade de abrigo para as populações afetadas por essas ocorrências. Atualmente inúmeros fatores contribuem para maior vulnerabilidade e exposição da população aos perigos naturais, sendo as alterações climáticas um deles e os seus impactos sentidos em todo o planeta, o que faz deste fenómeno uma ameaça à escala global.

O abandono de áreas afetadas pelos desastres naturais pode igualmente forçar populações a estabelecerem-se em locais onde os perigos naturais são proeminentes. Apesar de várias entidades auxiliarem no sentido de mitigar a emergência de abrigo e oferecerem programas de recuperação habitacional, a habitação é tipicamente inadequada e incapaz de resistir aos efeitos de futuros perigos naturais. A habitação resiliente não é tida em conta ou imperativa devido à urgência em abrigar as populações afetadas. Ao serem negligenciados os riscos de exposição da habitação aos futuros perigos, os edifícios tornam-se pontos vulneráveis para a população e tendem a ficar danificados ou destruídos em eventos futuros. Daqui decorre a enorme importância de incluir, em matéria de construção habitacional, critérios que incluam a noção de resiliência, permitindo às habitações uma durabilidade longa e segura, quando expostas a desastres naturais.

Esta dissertação tem o propósito de fornecer princípios orientadores para a recuperação habitacional com foco na resiliência da habitação às cheias, tendo em conta que estas são o desastre natural mais comum. Para este propósito, foram identificadas e analisadas as estruturas que atualmente abrigam as populações afetadas após um desastre natural e fornecidos requisitos para mitigação das consequências de situações de cheia. Depois de investigados os riscos e danos provocados pelas cheias em edifícios, foi desenvolvida uma metodologia para a conceção e desenvolvimento de modelos de habitação resistentes às cheias, na qual são nomeados critérios a que a habitação deve responder. A mesma metodologia é baseada em requisitos e recomendações da Agência Federal de Gestão de Emergências dos Estados Unidos da América e é feita em concordância com zonas específicas de cheias.

Por fim, foi analisado um caso de estudo nas Maldivas – um dos países mais vulneráveis à subida do nível médio das águas do mar devido às alterações climáticas – que é representativo da recuperação habitacional após desastre natural. A análise foi conduzida com a intenção de avaliar a resiliência da habitação construída para mitigar os efeitos da situação de cheias no contexto do pós-Tsunami do Oceano Índico, assegurando assim um contributo para a prevenção e redução de perdas.

Palavras-chave: Habitação resiliente, Desastres naturais, Recuperação habitacional, Alterações climáticas, Cheias

ACRONYMS AND ABBREVIATIONS

ALNAP	Active Learning Network for Accountability and Performance in Humanitarian Action
ASCE	American Society of Civil Engineers
BFE	Base Flood Elevation
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
EPA	United States Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GRP	Glass Reinforced Plastic
$GtCO_2$	Gigatonne of CO_2
HDI	Human Development Index
HDRO	Human Development Report Office
IASC	Inter-Agency Standing Committee
IDMC	Internal Displacement Monitoring Centre
IDP	Internally Displaced Person
IFRC	International Federation of Red Cross and Red Crescent Societies
IPCC	Intergovernmental Panel on Climate Change
LiderA	Liderar pelo Ambiente para a construção sustentável
LDPE	Low-density polyethylene
LEED	Leadership in Energy and Environment Design
MDPE	Medium-density polyethylene
NFIP	National Flood Insurance Program
NGO	Non-Governmental Organization
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Program
UNDRO	United Nations Disaster Relief Office

UNEP	United Nations Environmental Program
UNHCR	Office of the United Nations High Commissioner for Refugees or United Nations Refugee Agency
UNISDR	United Nations Office for Disaster Risk Reduction
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
USA	United States of America
USD	United States Dollar
WHO	World Health Organization
WRR	World Risk Report

INDEX OF CONTENTS

Chapter I – INTRODUCTION

1.1. Initial considerations 1
1.2. Thesis objectives 1
1.3. Methodology of thesis 2
1.4. Structure of thesis 3
1.5. Limitations of thesis development 3

Chapter II – STATE OF THE ART

2.1. Housing throughout time 5
2.2. Energy and Resources 10
2.3. Population growth and urbanization trends 12
2.4. Climate change 14
2.5. Sustainability 17
2.6. Natural disasters 19
2.7. Fundamental requirements for housing 23
2.8. Housing recovery after natural disaster 24
2.8.1. Tents 28
2.8.2. Prefabricated shelters 30
2.8.3. Permanent housing 33
2.9. Resilient Housing Recovery 34
2.9.1. Floods 34
2.9.2. Tents in flood prone areas 35
2.9.3. Prefabricated shelters in flood prone areas 36
2.9.4. Permanent housing in flood prone areas 37
2.9.4.1. Flood effects in permanent housing 37
2.10. Chapter overview 43

Chapter III – PROPOSED METHODOLOGY FOR FLOOD RESILIENT HOUSING

3.1. Conceptualization of the methodology 45
3.2. Determination of flood factors 48
3.3. Identification of flood zone 48
3.4. Flood resilience criteria 50
3.4.1. Site Selection 50
3.4.2. Design 51

3.4.3. Foundations 57
3.4.4. Materials 61
3.5. Chapter overview 69

Chapter IV – CASE STUDY IN MALDIVES

4.1. Introduction 71
4.2. Climate change in Maldives 72
4.3. Flood risks in Maldives 72
4.4. The 2004 Indian Ocean tsunami in Maldives 74
4.5. Housing recovery following the Tsunami in Maldives 75
4.6. Dhuvaafaru housing project 77
4.7. Dhuvaafaru housing project analysis 78
4.8. Discussion of results 82
4.9. Final considerations and predicted consequences 85

Chapter V – CONCLUSIONS

5.1. General contributions 87
5.2. Conclusions 88
5.3. Future Developments 89

BIBLIOGRAPHY 91

ANNEXES

Dhuvaafaru Landuse Plan 101
Front elevation of housing unit 103
Floor plan and site plan of housing unit 105
Section X-X and technical details 107

LIST OF FIGURES

Figure 2.1 – Reconstructed structures in Choirokoitia, Cyprus 6
Figure 2.2 – Roman Insulae 7
Figure 2.3 – World energy consumption by fuel type 10
Figure 2.4 – Global energy buildings consumption by energy source and direct CO_2 emissions 11
Figure 2.5 – Distribution of cities by population size in 2011 and risk of natural hazards 13
Figure 2.6 – Concentration of greenhouse gases over time 15
Figure 2.7 – Evolution of temperature anomalies 16
Figure 2.8 – Regions of the world vulnerable to sea level rise 17
Figure 2.9 – Number of reported disaster types by year 20
Figure 2.10 – Economic damages per disaster type by year 21
Figure 2.11 – Pombaline Cage 22
Figure 2.12 – Cottages of the San Francisco 1906 earthquake 23
Figure 2.13 – Housing recovery distribution over time 26
Figure 2.14 – Three-stage housing recovery 27
Figure 2.15 – Two-stage housing recovery 27
Figure 2.16 – A tent camp in the aftermath of the Van earthquake in Turkey, 2011 28
Figure 2.17 – Description of main types of tents used in emergencies 29
Figure 2.18 – Prefabricated shelter developed by IKEA 31
Figure 2.19 – A flood resilient building remains standing after the 2011 Tõhoku Tsunami 37
Figure 2.20 – Main geotechincal failure modes 39
Figure 2.21 – Erosion and scour effects in buildings 40
Figure 3.1 – An example of a digital flood insurance rate map of the state of Georgia, USA 46
Figure 3.2 – Methodology for flood resilient housing 47
Figure 3.3 – Relationship between BFE, flood zones and wave heights 50
Figure 3.4 – Dry and wet flood proofing 52
Figure 3.5 – Typical enclosures with flood openings 53
Figure 3.6 – Relationship between BFE and elevation in accordance to flood zones 54
Figure 3.7 – Requirements for shape and orientation of the building 55
Figure 3.8 – Compliant housing design with requirements for V zones 57
Figure 3.9 – Compliant housing design with requirements for A and Coastal A zones 57
Figure 3.10 – Adequate foundation types for V zones 61
Figure 3.11 – Adequate Foundation types for A zones 61
Figure 4.1 – Latitudinal variations of major natural hazards across the Maldives 73
Figure 4.2 – Longitudinal variations of major natural hazards across the Maldives 73
Figure 4.3 – Number of IDPs by type of temporary accomodation 75
Figure 4.4 – Safer Island concept and cross section 76
Figure 4.5 – Kandholhudhoo Island prior to being destroyed by the 2004 Tsunami 77
Figure 4.6 – Dhuvaafaru Island 77
Figure 4.7 – Housing units in Dhuvaafaru Island 78
Figure 4.8 – Erosion and houses in close proximity to the sea in Dhuvaafaru Island 79
Figure 4.9 – Flood factors and considered BFE 80
Figure 4.10 – Plan view and typologies of housing units 83

LIST OF TABLES

Table 2.1 – Measures to minimize flood effects in tents 36
Table 2.2 – Considerations for prefabricated shelters in risk of flooding 36
Table 2.3 – Damage to houses according to flood depths 38
Table 3.1 – Flood zones 49
Table 3.2 – Site selection Requirements for permanent housing 51
Table 3.3 – Design requirements and recommendations according to flood zones 56
Table 3.4 – Foundation requirements and recommendations according to flood zones 60
Table 3.5 – Class description of materials 62
Table 3.6 – Types, Uses, and Classifications of Materials 64
Table 3.7 – Types, Uses, and Classifications of Materials 65
Table 3.8 – Types, Uses, and Classifications of Materials 66
Table 3.9 – Types, Uses, and Classifications of Materials 67
Table 3.10 – Types, Uses, and Classifications of Materials 68
Table 3.11 – Requirements for materials according to flood zones 69
Table 4.1 – Storm surge heights, average tide heights and storm tides for diferent return periods 74
Table 4.2 – 100-stillwater height, wave height and considered BFE 80
Table 4.3 – Site selection, design, foundations and materials recommendations and requirements 80
Table 4.4 – Identified materials for housing units 84

Chapter I

INTRODUCTION

1.1. Initial considerations

This master thesis aims to offer guiding criteria for flood resilient housing recovery after natural disaster, with particular emphasis on permanent housing solutions. Natural disaster is seen in contemporary literature as consequential events that are set in motion by natural hazards resulting in loss of life, damage to existent infrastructure and destruction of housing.

There can be two main outcomes after the loss of housing due to natural disaster:

- Abandonment of affected areas leading displaced populations towards unaffected areas that can be equally exposed to adverse natural hazards and therefore contribute to vulnerability of new constructed housing;
- Reconstruction in the same sites as the previous settlements.

For both different scenarios, housing recovery programs must address not only the needs of population but also the effects of natural hazards that are predicted to exist in the future.

It is known that several key factors contribute to exposure and vulnerability of housing to floods such as demographics, land scarcity, climate change and lack of appropriate housing solutions to resist the effects of future natural hazards. Population growth and land scarcity may pressure communities to establish in zones prone to recurring natural phenomena. One of today's worldwide threats – climate change – can intensify frequency, duration and intensity of natural phenomena that can potentiate inundation of land.

Because of this, even after all the tragic results of natural disasters, there is an opportunity to build back safer and better, to break the cycle of destruction and reconstruction by addressing and anticipating the effects of floods into the housing solutions. By establishing key criteria for flood resilient housing, structures are expected to resist floods by diversified ways incorporated in their construction.

1.2. Thesis objectives

It is intended with this master thesis to address two fundamental issues within the current world which are closely linked: housing recovery after natural disaster and resilient housing considerations that should be incorporated in shelter and housing structures to resist upcoming natural events.

Although the scope of this master thesis is outside the usual civil engineering subjects, civil engineering should have a central role in housing recovery following natural disaster and implementation of resilient elements in shelter and housing structures. Housing recovery is a long, complex and multilayered subject involving several specialized fields in which civil engineers should take part, considering they are essential to reconstruction and to ensure housing is provided with resistance to future natural events. As part of a world facing great dangers and taking into consideration civil engineers have vital skills and

expertise, civil engineers are key elements in participating in the reconstruction of areas devastated by natural disaster to guarantee the same scenario does not happen again.

As natural disasters are increasing in frequency and intensity, it is imperative that strategies should be implemented to mitigate and reduce the effect of natural hazards, particularly in the housing sector since it is a central aspect of human life. This thesis concentrates on floods because they are proven to be the most common of all natural disasters and response should be given to this specific subject.

To provide resilient measures for shelter and housing, it was required first to identify and study the main structures that house affected populations by natural disaster. Tents, prefabricated shelters and permanent housing were determined to be major groups of the housing recovery process in the post-disaster scenario. After these three main groups were identified and analyzed in depth, measures and requirements were given for tents and prefabricated shelters to safeguard their structures in the face of flooding. Although tents and prefabricated shelters are supposed to be temporary structures while reconstruction of housing and infrastructure is being made, many times these structures house populations several years, increasing vulnerability and exposure to floods. To reduce the impacts of flooding in tents and prefabricated shelters a number of measures were established.

Since permanent housing should be the final stage of the recovery process after natural disaster, emphasis was given to permanent housing solutions and resilient measures were explored with more depth. To that end, the following investigation questions were asked at the beginning of this thesis:

1. What is the main current natural threat to housing?
2. What main structures are used for shelter and housing of targeted populations by natural disaster?
3. Is housing recovery taking into consideration future natural hazards?
4. What methodology for resilient housing can be implemented?

1.3. Methodology of thesis

Firstly, it was necessary to study and analyze the numerous factors which contribute to natural disasters and the main structures destined to shelter and house populations after the event. An in-depth study of permanent housing was conducted by studying the various ways that flood events affect housing in order to identify guiding criteria that flood resilient housing should address. Furthermore, it was needed to differentiate between flood zones since housing should respond and resist to flooding according to predicted flood characteristics. To that effect, this master thesis proposes a methodology based on the Federal Emergency Management Agency (FEMA) system which identifies several flood zones in accordance to the levels of flood risk. The FEMA flood zone classification system is currently being used in USA and associates requirements and recommendations for residential housing and construction to an area's attributed flood zone.

Once the guiding criteria for flood resilient housing were identified and flood zones established, requirements and recommendations were grouped into each one of the guiding criteria for flood resilient housing according to flood zones.

Lastly, a case study in Maldives, more specifically in Dhuvaafaru Island, was chosen to assess the flood level resilience of permanent housing following the 2004 Indian Ocean Tsunami. Throughout the thesis, bibliographic references and statistical data were used to provide direction and substantiate the initial investigation questions.

1.4. Structure of thesis

The structure of this master thesis is divided into five chapters:

- Chapter I provides initial considerations, aims, methodology, limitations and thesis structure, contextualizing the scope of the work;
- Chapter II explores the state of the art regarding major global threats to which the construction and housing sector should respond and identifies the main structures that house communities following natural disaster;
- Chapter III proposes a methodology for flood resilient permanent housing;
- Chapter IV analyses a case study in Maldives to assess the resilience of the permanent housing solutions, in the Island of Dhuvaafaru, Maldives, following the 2004 Indian Ocean Tsunami;
- Chapter V establishes the conclusions of the thesis, general contributions for resilient housing and future developments.

1.5. Limitations of thesis development

As no studies were conducted specifically to assess the flood level risk of Dhuvaafaru, some of the relevant factors are based in data from other islands of Maldives or in the country as whole. Additionally, a major element in determining the level of flood risk in Maldives was established since no reference was found. This option constitutes a limitation to the correct assessment of the housing unit's flood resilience because some of the data for other islands can prove to be different from Dhuvaafaru. However, no other option was available for obtaining the accurate flood factor.

The accurate description of the housing solution in Dhuvaafaru also constitutes a key limitation since this work is based in available online information without possibility of a field study in Dhuvaafaru. The case study is therefore conceptualized as theoretical.

Chapter II

STATE OF THE ART

2.1. Housing throughout time

Since the dawn of mankind, shelter has been one of humans' main concerns. Archaeological findings place the first reliable traces of human dwellings somewhere in the Upper Paleolithic (Danin et al, 2004). It is a common misconception that early humans in their nomadic days were cave-dwellers – most of them were not, opting instead to roam freely for the purpose of hunting and gathering. When in need for shelter, humans would make rings of stones to support the branches of a tree and use local materials for a tent-like roof. The materials could differ significantly, from reeds daubed in mud, in damp areas, to mammoth bones and tusks tied together, in open plains, to support a covering for shelter and concealment, as evidence from the findings in Dolni Vestonice, in Czech Republic, from about 25 000 years ago (Svoboda, 2001). While these early structures would serve for early humans to spend the night and protect themselves from weather and wild animals, they still lack resemblance to the modern idea of home.

After the Ice Age, around 10 000 BC, the Natufians, an ancient semi-sedentary people who lived in the Fertile Crescent area, dwelled in huts that were semi-subterranean, often with a dry stone foundation with its superstructure probably made of brushwood. These round houses were between three and six meters in diameter and contained a central round or rectangular fireplace. The dwellings of this kind were generally grouped into villages that would have housed nearly 150 inhabitants (Watkins, 1990).

Once the Neolithic Revolution prompted, mankind became sedentary due to the development of agriculture and animal domestication and dwellings evolved drastically. It is thought that Jericho is at least one of the earliest towns coming into existence, in 8000 BC. Jericho's houses kept the circular shaped appearance but not the same materials; by this time, bricks shaped from mud and hard-baked in the sun were being used. They were then placed on top of each other, each brick being curved in its outer edge. The roof of these houses was made from branches and mud in a conical shape, and most of the dwellings only had one room. However, hubs were found that had as many as three rooms, which is an indicator of the beginning of socioeconomic distinctions. These round structures were also found in Choirokoitia, Cyprus, dating from 6500 BC, bearing innovations such as ladders inside the dwellings, with upper sleeping platforms and seats built inside the walls (ICOMOS, 1996).

Figure 2.0.1 – Reconstructed structures in Choirokoitia, Cyprus
(theheritagetrust.wordpress.com)

Around that time, rectangular houses appeared with windows, but no doors, each one adjacent to the other in a honeycomb-like structure where its inhabitants would access through the roof. Since then housing has largely been developed in order to follow the needs of human societies, creating anew the way people live in. In Ancient Egypt, for instance, the need to celebrate gods and pharaohs led to the construction of large structures as pyramids that are still today regarded as truly engineering feats. Houses of the poorest in Ancient Egypt used one row of straw and mud-made bricks dried in the sun, while social upper classes used two or three rows. Most houses had at least three rooms and all of them had flat roofs which were used as part of the living area (Spence, 2012).

Ancient Greece is seen as the birth of Western civilization due to its political, artistic, and social ideals reflected in ancient Greeks everyday lives. Their housing at this time was designed to keep the house cool in the summer and warm in the winter; they were small, with a walled garden or yard in the middle. Houses were made of sun-dried mud bricks and stone. Mud houses often crumbled down after a few years, and had to be rebuilt. Architecture was largely developed with the introduction of fluted columns and capitals which supported horizontal lintels (www.historyworld.net).

During the Roman period, urbanism was further developed in order to organize cities, establishing both private and public properties, with many inventions such as the arch and concrete. These improvements became key elements in later developments in Western construction and architecture. Cement had already been used in Ancient Greece, being made of clay, water and lime. Romans, however, would make cement out of finely-ground volcanic lava from the region of Pozzuoli. For that reason, this type of cement became known as pozzolanic cement, being the strongest mortar in History until the arrival of Portland cement in the 19th century (Deocampo et al, 2010).

Romans were indeed deeply influenced by the Greek but, as their Empire expanded, the need to quickly establish military camps, strong enough to last throughout the course of their campaigns, led them to develop the castra, well-known camp-sites that could later evolve into administrative hubs and even towns. Castra had an orthogonal design displayed in grid and served practical purposes as they were easy to build and administer. At this time, poor Romans lived in a kind of apartment building named insula that consisted of multiple-story apartment blocks, grouped around a central courtyard. The ground floors were used for shops and businesses, while the upper floors were rented as living spaces. Insulae, plural for insula, were made of wood, mud bricks and later concrete. They would often collapse or catch fire (http://humweb.ucsc.edu/gweltaz/courses/techno/papers/insulae.html).

The living quarters of the insula were smaller in the building's uppermost floors. Due to safety issues and extra flights of stairs, the upper floors were the least desirable and the cheapest to rent. These floors would have no running water, heating or toilets, resulting in residents dumping all the indoor generated trash out in the streets. Insulae housing was sometimes constructed at minimal expenses for speculative reasons, thus resulting in lack of appropriate construction where people could not have adequate insulae (http://humweb.ucsc.edu/gweltaz/courses/techno/papers/insulae.html).

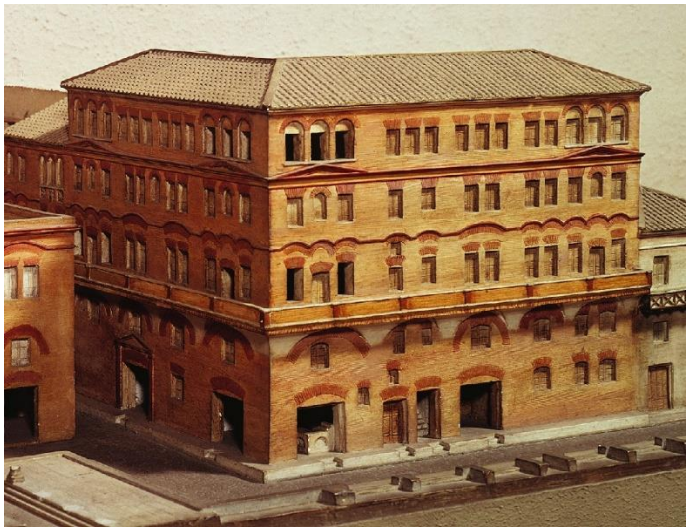


Figure 2.0.2 – Roman Insulae
(www.artemaestre.blogspot.pt)

The wealthiest Roman elite lived significantly better than the plebe in a single-story dwelling called domus that was much more than a place to live in for Romans. It also served as a place of business and worship. The domus included multiple rooms, indoor courtyards, gardens and carefully laid out walls (Halles, 2003).

When the Western Roman Empire fell, circa AD 400, many of the improvements they had made in housing were lost for several hundred years. During this time, German and Scandinavian tribes Romans considered barbarians dominated Europe constructing buildings they addressed as "ham", from which the word "home" was later derived. Most of the tribes' houses were made of wood, with roofs thatched in straw, and were built facing the sun to get as much light and heat as possible. Each dwelling had only one room where its inhabitants ate, cooked and slept. Villages were very small and built near natural resources. There were fences all around the villages meant to protect villagers of other tribes and wild animals. Homes for the average feudal vassal were made of wood; in fact, they were mostly made of oak sticks woven together, forming a type of mesh, meant to face different kinds of weather, providing insulation during the winter season. Daub was made from mud, clay and other materials. When applied to the wattle, it would seal and make it waterproof (www.historyworld.net).

As History progressed, so did houses, with new designs, materials and techniques emerging. The Industrial Revolution in the 19th century lowered house value, making houses more affordable and contributing to urban expansion. Wood was replaced for coal for being a more abundant, less expensive and a more efficient energy source fuel.

Housing expansion was rapidly growing, even if living conditions of the poorer classes were still harsh. There were few building regulations then and the existing ones were frequently ignored. Builders were putting houses up as quickly as possible, and profit became their main motivation. The Industrial Revolution saw the start of what became known as back-to-back terrace housing; these houses had no garden and the only part of the building not connected to other houses would be the front – its only

entrance. The building materials used were the cheapest a builder could find and houses were damp as none was built with damp-proof courses. People who could only afford cellar dwellings lived in the worst possible conditions as damp and moisture would seep to the lowest part of the houses. Throughout the course of the 19th century, and into the early 1900s, houses became more complete, safer and efficient, as iron stoves replaced fireplaces and kerosene lamps took the place of candles – both later then replaced by gaslight. Indoor toilets also became common improving hygiene greatly (Nevell, 2011).

Leaping in time towards the late 20th century and the era of globalization, many advances were made in construction methods, execution and materials availability, making construction possible, for instance, in previous inaccessible or inhospitable areas. Human societies have witnessed numerous architectural movements rise in the last century, and modern construction techniques come to life. Nevertheless, any given house maintains its fundamental shelter functions, even if it offers, nowadays, new functionalities and added potential qualities.

Humans can thrive in many different parts of the globe, in extremely diverse climates. Given the proper technology, they can endure extreme cold or heat, and still find a way to persevere. Human population can be found world over, from ice caps near the poles, to the hottest deserts; even in diverse climates and under unequal weather patterns, construction can be reliable and enduring. Over time, mankind has used a variety of construction materials and technologies, showing how far human ingenuity can go, and how the ongoing quest to make long-lasting structures to meet human ever-changing needs is still being perfected. If present and future construction is ever to thrive, it should bring into the equation how human beings are ever more vulnerable to its surroundings, especially anticipating future hazards. If the evolution of civil engineering is to keep on happening, it ought to take into account new challenges and needs, which are surely to be linked to climate changes.

Residential buildings can be extremely diversified ranging from rudimentary structures to complex constructions which incorporate numerous systems. Houses protect their residents from climate and provide shelter to later ensure livelihood. While houses are a fundamental part of everyday life in societies, a home can be much more.

A home is a location of life. Although the term house and home are connected, they can mean different things. While the term house is use as an object, part of the environment, the term home may refer to the meaning and experience that a home provides, more specifically it can be seen as a relationship between people and the built environment. Furthermore, a house is linked to a conceptual space – a space that is abstract, geometric and that can be objectively measured – while a home is associated to a lived space, a meaning-centered bodily experience. A home can be seen also as a temporal orientation, embedded with familiarity of past experience, making a house a place of routines until it becomes granted and is unselfconscious. A home is also linked to sociocultural norms and provides temporal and spatial identity connecting its residents with past, present and future while they simultaneously attribute an identity to the place but also draw identity from the place itself (Dovey, 1985).

For its inhabitants, houses are not structures meant to be imperatively enjoyed from the outside; they are mainly part of an inner world deeply connected to the longing for peaceful and secure living conditions, connected to the wish for a life free from risks and uncertainties (Figueiredo, 1995).

According to Bachelard (1964):

> "the house shelters day-dreaming, the house protects the dreamer, the house allows one to dream in peace."

A place of residence and ownership, the house is the location of intimate routines of everyday life. It is the physical environment that anchors human beings.

Fundamental to human life, houses have undergone a transformation process time and time again, allowing for different kinds of human existence worldwide. Thus, the loss of a home constitutes a major drawback in the lives of people. When natural disasters happen, people are often forced to leave their native places due to the destruction of their homes or the impossibility to simply remain living there. As

housing constitutes an essential part to the well-being and development of most societies, its loss is one of the most critical and visible effects of natural disaster. The loss of a home represents not only a physical deprivation but a loss of dignity, privacy and identity (Barakat, 2003).

If forced migrants cross borders due to persecution and have to leave their homes behind, they are considered to be asylum seekers, until a request for refuge has been accepted. This makes them become refugees, falling under the refugee law, allowing them to have rights and protection. If displaced people do not seek refuge in other countries and stay where they were, they become Internal Displaced Persons (IDPs) and are subject to feeble international protection (UNHCR, 2011).

In accordance to a global view that housing is seen as fundamental to human life a spectrum of laws exist recognizing its importance. Knowledge of the legal context is essential as human rights law can be used as an advocacy tool, to understand the specifics of local and national laws and to maximize the chances of affected groups to make claims for resources and demand accountability from governments and other organizations. The housing and construction sector should not only have an awareness of the legal framework in which they can operate but also a responsibility to help affected populations by natural disaster.

By the end of the Second World War, the international community reacted against the atrocities of the conflict by creating the United Nations, an intergovernmental organization destined to ensuring peace worldwide, supporting economic and social development, providing global humanitarian aid whenever needed and promoting previously established human rights. In 1946, the Universal Declaration of Human Rights was commissioned and drafted for the next two years, culminating in the final form of the Declaration consisting in thirty articles. The Universal Declaration of Human Rights was adopted by the General Assembly of the United Nations in December 1948 and the right to housing is recognized in Article 25, which states (UN General Assembly, 1948):

> "Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control."

The right to housing is not only recognized in the Universal Declaration of Human Rights but also in the International Covenant on Economic, Social and Cultural Rights, a multilateral treaty that was adopted by the United Nations in 1966. In this treaty, the right to an adequate standard of living is contemplated in Article 11:

> "The States Parties to the present Covenant recognize the right of everyone to an adequate standard of living for himself and his family, including adequate food, clothing and housing, and to the continuous improvement of living conditions. The States Parties will take appropriate steps to ensure the realization of this right, recognizing to this effect the essential importance of international co-operation based on free consent."

Many national constitutions recognize the right to housing. Portugal being no exception exhibits the right to housing of adequate dimensions, in conditions of hygiene and comfort that preserve the personal intimacy of its occupants and the family privacy, under Article 65 of its national constitution.

The Pinheiro Principles, also known as UN Principles for Housing and Property Restitution for Refugees and IDPs, were developed to address the technical and legal issues surrounding housing, land and property restitution and also provide guidelines in order to protect displaced people:

> "All refugees and displaced persons have the right to have restored to them any housing, land and/or property of which they were arbitrarily or unlawfully deprived, or to be compensated for any housing, land and/or property that is factually impossible to restore as determined by an independent, impartial tribunal."

Once housing is established as essential to human life, it is necessary to study current trends and challenges of the contemporary world that affect the housing sector and threat the built environment, contributing to exposure and vulnerability to natural disasters. Furthermore, it is also fundamental to explicit concepts that housing should address. The following chapters will examine the most dangerous threats worldwide to the built environment, their inter-relationships and how the construction and housing sector should adapt to them.

2.2. Energy and Resources

By the end of the 19th century and the beginning of the 20th century, the world saw the fast expansion of electricity and technology on which it relied upon, improving homemade tasks. In this period the world saw a need for more energy that in consequence demanded more fossil fuel. Coal was still the most important source of energy until the mid-1950s when oil took over due to its high energy density, easy transportability and relative abundance. Since then our fossil-fuel based economy is dependent on oil that it is likely to run out in the near future. Nowadays, most of the energy used worldwide comes from coal, oil or natural gas.

The process of formation of coal, natural gas and oil takes thousands to millions of years to happen under very specific conditions which makes it extremely rare and finite. Despite this fact, consumption of energy has been growing ever since, due to increasing demand.

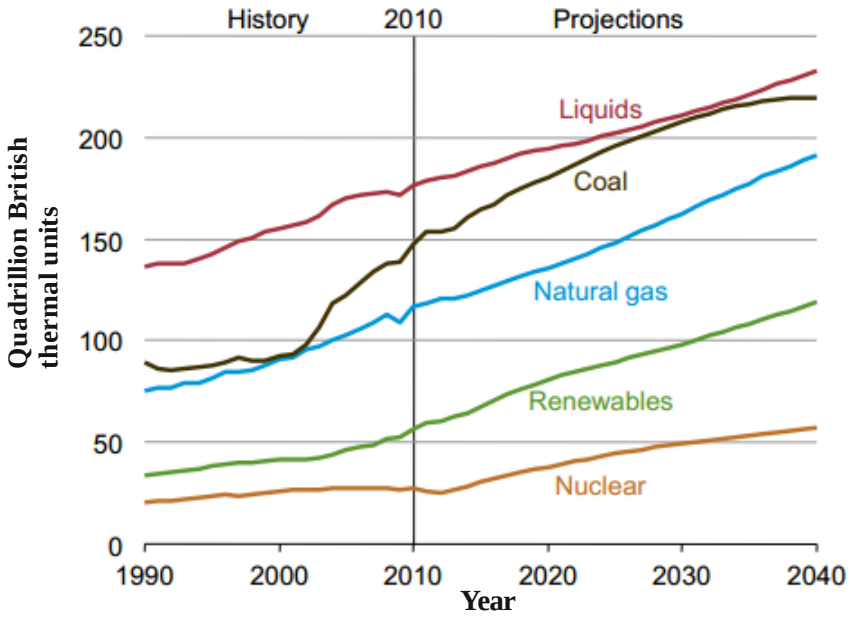


Figure 2.3 – World energy consumption by fuel type
(EIA, 2013)

Not only fossil fuel are the most consumable fuel type worldwide, but the trend is likely to maintain for the next decades. According to Figure 2.3, consumption of liquid fuels – mostly petroleum-based – will continue to grow and bear the largest numbers of consumption worldwide. In 2013 alone, fossil fuel – coal, oil and natural gas – accounted for 86,7% of worldwide energy consumption, whereas renewable sources – including solar, wind, biomass, hydropower and waste – accounted for 8,9 % of the world energy consumption (BP, 2014).

In this scenario, the construction industry – a fossil fuel based industry – from production to operation is known to be responsible for consuming numerous resources and producing large quantities of waste and emissions, therefore threatening the environment. By 1995, buildings accounted for one-sixth of the world fresh water withdrawals, one-quarter of the world's wood harvest and two-fifths of its energy and material flows (Lenssen et al, 1995).

Evolution of global buildings energy consumption by energy source and direct carbon dioxide emissions can be seen in Figure 2.4:

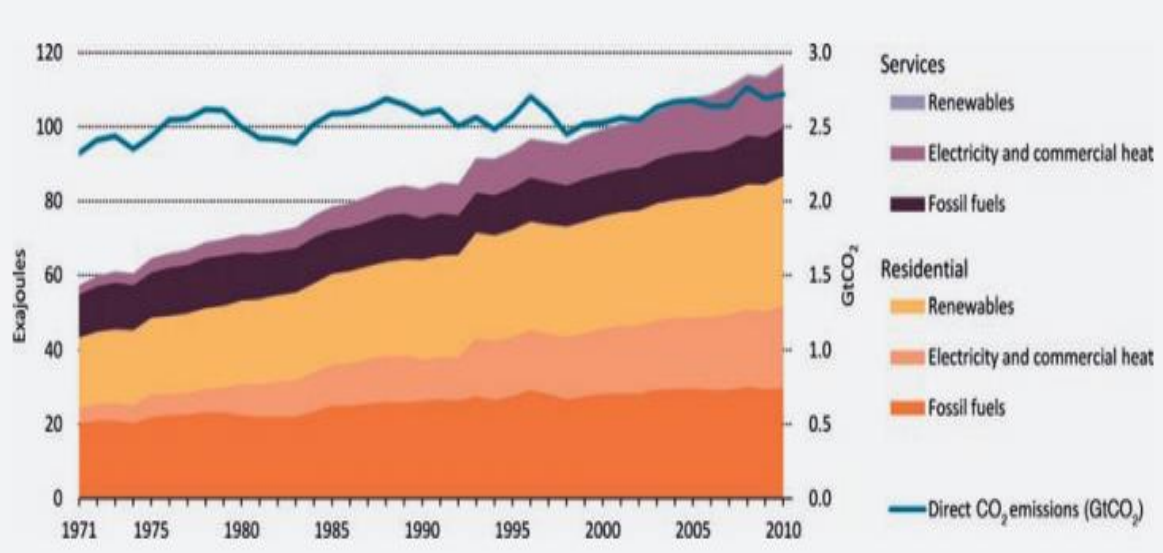


Figure 2.4 – Global energy buildings consumption by energy source and direct CO_2 emissions (IEA, 2013)

In 2013, buildings were consuming nearly one-third of global final energy consumption and accounted for about one-third of total direct and indirect energy related to carbon dioxide emissions. Energy demands in buildings are also predicted to rise by almost 50% between 2010 and 2050 (IEA, 2013).

It is therefore evident that buildings have a major key to play in the reduction of emissions and can provide main contributions for the reduction of energy consumption, resources, while integrating sustainable measures.

With the evolution of engineering, modern houses come in different shapes, sizes, and materials. New questions arise today more than ever; the depletion of Earth's natural resources sends humanity on a dangerous path of self-destruction. The understanding that resources are finite and the need to build without damaging the environment leads us to search for more efficient ways to produce energy, reduce waste and damaging gas emissions, and search for realistic alternatives for high-energy consumption in the building sector.

2.3. Population growth and urbanization trends

World population has continuously grown since the XIV century and estimates acknowledge that world population has reached 7,2 billions in 2014. It is expected to increase up to 9,2 billion people in 2050 (UN, 2014a).

Projections suggest a decline in world population growth. However, according to low, medium, and high-fertility variants projections, a growth in the near future is expected to happen and world population is likely to reach astonishing figures between 8,3 and 10,9 billions by 2050; world's population will be increasing by 49 million people each year, more than half living in the least developed countries. Since 2014, of the 82 million people added to world's population, 54% are from Asia and 33% from Africa. In the future, more than 80% of global increase in population growth will occur in Africa and only 12% in Asia (UN, 2014a).

Between 2014 and 2050, most of the population growth is expected to occur in nine countries, accounting for more than half of the world's projected growth: Ethiopia, Indonesia, the Democratic Republic of Congo, India, Nigeria, Pakistan, the United Republic of Tanzania, Uganda and the United States of America. India is expected to overthrow China as the most populated country by 2028. Human population growth rates occurring in what the UN have considered to be least developed countries is projected to double between 2014 and 2050. This fact means that in order to provide high quality services in the least developed countries, additional pressure is put on the environment and its resources, which results in a straining of national governments' resolutions (UN, 2014a).

While population growth does not have a significant relationship with climate change since the growth occurs mainly in developing countries, with little contribution to global greenhouse gas emissions, population growth puts pressure on resources, increases the demand of energy and contributes to environmental degradation. However, it is a common view in literature that population growth can be supported by economic development and growth (Satterthwaite, 2009; Cropper et al, 1994).

The issue associated with population growth has to do with the fact that it is in developing countries that it is occurring the most, meaning that in many sectors, including the building sector, which will not be prepared to address global issues such as resistance to hazards and energy and resource efficiency. However, since demand and supply for residential buildings is driven by economic factors which include population growth, there are many opportunities for this sector to innovate in a sustainable way. Most of the strategies for the building sector should be concentrated in cities, given that cities can provide for greater opportunities.

Only 3% of the world's population lived in cities in 1800; this proportion had risen to 47% by 2000, and reached 50.5% by 2010. In 2014 the world's urban population was of 3,9 billions and it is projected to increase up to 6,3 billions by 2050. In the opposite direction, the numbers of the rural world population remained constant and are anticipated to drop in the next decades, resulting in less 0,3 billion inhabitants in 2050. Large urban agglomerations of 10 million people or more – also known as megacities – became more numerous and substantially larger in size, with Tokyo, Delhi, Mexico City, New York and Shanghai housing over 20 million people (UN, 2014a).

Although urban centers cover only a small portion of the world's surface, 0,51%, they are held accountable for ecological and physical footprints far greater than their physical areas. It is estimated that urban centers are responsible for 50 to 70% of the decline of wild and semi-natural areas of resulting in a decrease of biodiversity and fragmentation of wild natural habitats. This decrease ends up by threatening ecological services that sustain urban and natural areas. If expansion of urban centers continue to happen in this manner, loss of vital habitats of diversity is likely to ensue and ruin most of

the green infrastructure. The existence of such infrastructure is fundamental in making possible adaptation to climate change impacts. It also lowers human population exposure to higher risk levels of climate adversities (Seto et al., 2012).

By 2011, urban areas over one million residents, of which 60% – approximately 890 million people – live in high risk areas in terms of exposure to at least one type of natural disaster: flooding, drought, cyclones and earthquakes. The case is particularly stressful in urban areas situated in Latin America and Caribbean, Asia and North America (UN, 2014a). The world map for hazards exposure according to distribution of cities can be seen in figure 2.5.

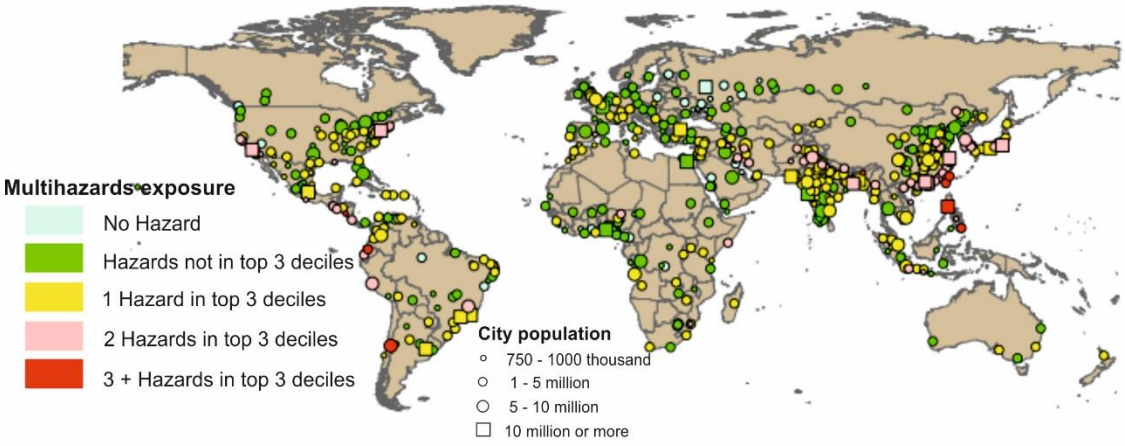


Figure 2.5 – Distribution of cities by population size in 2011 and risk of natural hazards (Adapted from UN, 2014b)

Additionally, most of urbanizing trends are happening in developing countries, as two-fifths of the world's total population, three quarters of the world's urban population and most of its largest cities are located in low and middle income nations. It is considered that about one in seven people in the world live in poor quality, overcrowded accommodation in urban areas with no adequate provision for basic infrastructure and services, typically in informal settlements (IPCC, 2014). This fact represents additional challenges on many levels, such as political, social, environmental and economic, leading to major issues such as lack of legislation, pollution, and particularly persuading populations to live in vulnerable areas without proper disaster mitigation strategies.

Furthermore, urbanization is considered to be a major factor in the growing vulnerability to natural disasters, as overcrowded cities pressure communities to establish in areas exposed to hazards and unsafe environments. (Blaikie et al, 2004). Recent analyses of disaster impacts show that a high proportion of the most affected population by extreme weather events is concentrated in urban centers (UNISDR, 2009; UNISDR, 2011). A high proportion of these urban centers lack both local governments capable of reducing disaster risk, and much of the necessary infrastructure. Their low-income households may require particular assistance because of greater exposure to hazards, lower adaptive capacity, more limited access to infrastructure or insurance, and fewer possibilities to relocate to safer accommodation, compared to wealthier residents.

Population growth and city growth puts additional pressure in finding more fossil fuel reserves and thus increasing the rate of its consumption, while much of key aspects and emerging global climate risks are known to be concentrated in urban areas (IPCC, 2014).

The increasing concentration of the world's population in urban centers also means greater opportunities for adaptation but more concentrated risk if they are not acted on. Many national governments lack the capacity to do so, especially those in low and low-to-middle income nations, which results in large

deficiencies in infrastructure and services. Urban centers in high income nations, although better equipped in comparison to lower income nations, may also face challenges – for instance, the need to adapt energy systems, building stock, and infrastructures to divergent scenarios that climate change will bring (IPCC, 2014).

It is established that vulnerability of buildings in urban areas is increasing and that building resilience to natural hazards should be a long-term concern to avoid future natural disaster devastating impact. To determine what can be done in the building sector, it is necessary first and foremost to understand the climate dynamics that the building sector is exposed to. Nowadays, one of the global scale threats to human and natural environments is climate change and the following subchapter will develop this subject.

2.4. Climate change

Climate on Earth has always been dynamic throughout millions of years alternating between lasting episodes of cold climate – glacial periods or ice ages – and significant intermittent warm periods – the interglacial periods. Climate change is the name given to global climate alterations that can potentially affect all life on the planet, reshape landscapes and introduce new climatic events that were previously inexistent in specific areas. Although not yet fully understood, it is established that the main causes for climate change, also called forcing mechanisms or climate forcings, include variations in solar radiation, Earth's regular variations in its orbit around the Sun, volcanism, continental drift and changes in greenhouse gas concentrations. There are a variety of climate change feedbacks that can either intensify or diminish the initial forcing. While some elements of the climate system, such as oceans and ice caps, respond slowly in reaction to climate forcings, others react more quickly (www.ipcc.ch).

Forcing mechanisms can be either internal or external. Internal forcing mechanisms are natural processes within the climate system itself, such as the thermohaline circulation. External forcing mechanisms can be either natural, as changes in solar output, or anthropogenic, such as increased emissions of greenhouse gases. Greenhouse gases comprise several gases such as water vapor, carbon dioxide, methane, nitrous oxide and ozone present in the atmosphere that are responsible for the greenhouse effect – the effect of absorbing thermal radiation emitted by the land and ocean and reradiating it back to Earth (www.ipcc.ch).

In the context of the current climate changes, anthropogenic forcings are man-made activities which are responsible for contributing to climate change. While climate change is an extremely challenging field in particular when it comes to studying, analyzing and determining which factors account for it, the scientific consensus on climate change is that changes can be attributed largely to human activities, most of which are likely to affect climate irreversibly (IPCC, 2014; Friedlingstein et al, 2008).

This cause-effect relationship is already established with greenhouse gas concentrations attributed to human activity. Greenhouse gas concentrations have largely increased since the pre-industrial period and are at their maximum concentrations in today's atmosphere (IPCC, 2014).

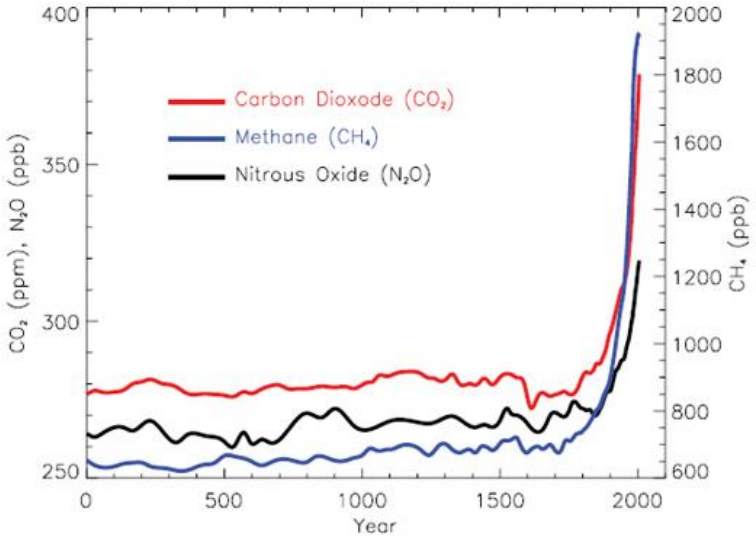


Figure 2.6 – Concentration of greenhouse gases over time (www.ipcc.ch)

What concerns the most is the increase in CO_2 levels in the atmosphere due to emissions from fossil fuel combustion, followed by aerosols – particulate matter in the atmosphere – and the CO_2 released by cement manufacture. The Intergovernmental Panel on Climate Change accounts in its latest report that human influence on the climate system is unequivocal, being that widespread impacts on human and natural systems are already occurring and can actually be observed (IPCC, 2014).

Climate change has a profound and a large scale effect on the planet although it is felt differently from region to region. While climate change progresses, its impacts will become more intensified, testing human adaptability to changes. While developed regions contribute the most in terms of gas emissions and are expected to suffer some consequences, the regions that contribute the least in terms of greenhouse gas emissions are the ones likely to suffer the most when it comes to climate change greatest impacts (van Haalst, 2006). Climate change impacts both natural and human environment in diversified ways by increasing average and extreme temperatures, inducing extreme weather events such as hurricanes, rainfall hazards, droughts, heat waves and sea level rise. Potentially severe global impacts due to climate change include ill-health and disrupted everyday life, which results from flooding, periods of extreme heat, food and water mistrust, and loss of ecosystems (IPCC, 2014).

Warming of Earth's surface has already been confirmed; each of the last three decades have been successively warmer than any preceding decade since 1850. The period from 1983 to 2012 is also likely to be the warmest thirty-year period of the last 1400 years. The combined average surface temperature of land and ocean surface show a rise in warmth of 0,85ºC between 1850 and 2012 which may not seem substantial but has proven to be a source of impact to both natural and built environment (IPCC, 2104).The warming trend of the planet due to climate change is particularly alarming when visualizing graphic data on observed global temperatures over time. The following figure displays annual mean and five-year mean temperature anomalies. A temperature anomaly is the difference between the highest or lowest registered temperatures and reference values (http://www.ncdc.noaa.gov).

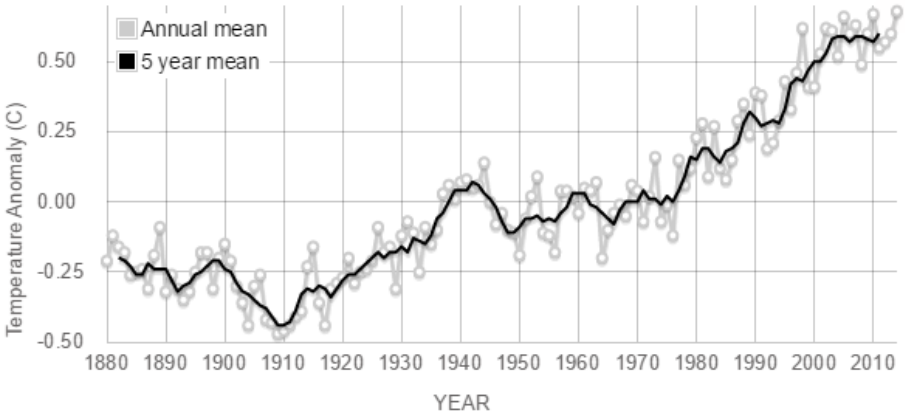


Figure 2.7 – Evolution of temperature anomalies
(climate.nasa.gov)

Projected global mean surface temperature changes from 2016 to 2035 will likely be in the range of 0,3ºC to 0,7ºC; the Arctic will continue to warm up and more quickly (IPCC, 2014).

Due to climate change, warming of the ocean is occurring, accounting for more than 90% of the energy accumulated within Earth's climate system, from 1971 to 2010. The impacts of ocean warming result in high salinity levels of ocean waters and acidification of the ocean due to CO_2 absorbance. Changes in the cryosphere are also happening with glaciers exhibiting a trend to shrink in most areas of the planet (IPCC, 2014).

Of particular interest to this thesis is the effect of sea level rise due to climate change. Although there are several factors and complex interactions that contribute to sea level rise, the two main causes for sea level rise are identified, as the loss of land-based ice due to increased melting and thermal expansion. Thermal expansion is a process in which oceans increase in volume as a result of ocean warming and density decreases. The loss of land-based ice is another major element contributing to sea level rise, since, as a result of global warming, ice sheets, glaciers and polar caps melt, contributing to higher sea levels (www.ipcc.ch).

From 1901 to 2010, average global mean sea levels rose by 0,19 m, being that the average rate of sea level rise was of 3,2 mm/yr from 1993 to 2010. Glacier mass loss and thermal expansion are responsible for 75% of the observed global mean sea level rise. Predictions for sea level however can elevate the numbers of global mean sea levels to a range of 8-16 mm/year during 2081-2100. Furthermore, sea level rise will not be uniform, varying from region to region, but 70% of coastlines worldwide are predicted to experience sea level change (IPCC, 2014).

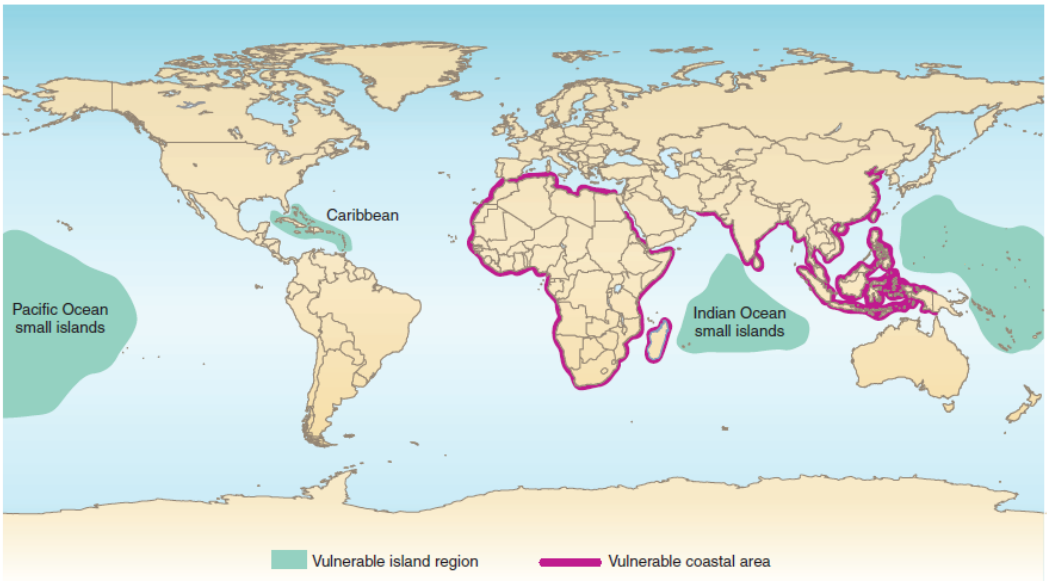


Figure 2.8 – Regions of the world vulnerable to sea level rise
(Cazenave et al, 2010)

For small and low lying islands countries such as Tuvalu, Vanuatu and Maldives the perspectives are particularly menacing. These islands currently face ongoing risks from climate-related hazards but are expected to suffer from new ones derived from climate change as a result of their enormous vulnerability.

Sea level rise predictions confirm the potential to flood and submerge small islands as well as subject them to coastal erosion. Impacts reported within small and low lying islands due to climate change include the loss of livelihoods, infrastructure, coastal settlements, ecosystem services and economic stability. Although the risk level is currently Low, it is predicted to rise to Medium, from 2030 to 2040, and will reach High or Very High from 2080 to 2100. It is determined that only 4ºC warming, sea level could rise to numbers of 0,5 m to 2,0 m, thus resulting in the displacement of between 1,2 and 2,2 million people in the Caribbean, Indian Ocean and Pacific Ocean. When temporary displacement resulting from these factors becomes permanent, small islands may be rendered inhabitable due to loss of economic and social assets (Climate and Development Knowledge Network, 2014).

To reduce the effects of climate change on small islands, adaption is viewed as the only option, demanding societies and communities alike should adapt to current or expected climate and its effects by minimizing socio-economic vulnerabilities, strengthening capacities to adapt, enhancing disaster risk reduction and contribute to long-term resilience (Climate and Development Knowledge Network, 2014). The construction and housing sector particularly have the capacity to adapt by provisioning adequate and resilient structures to coastal flooding that can withstand extreme events by anticipating the effects of flooding and incorporating resilient measures in their construction.

2.5. Sustainability

To contradict the effects of a non-renewable energy based economy, in a world that is in quick need of alternatives, during the 1980s one of the most important concepts of the contemporary world comes to life: the concept of sustainability. The search for solutions and mitigation of issues related to social and environmental issues have led to the making of the "Our Common Future" report, also named Brundtland report, published in 1987. It is in this report that the concept of sustainable development appears for the first time as the key that matches economic development with social and environmental development. Sustainable development should guarantee the well-being of present and future generations while providing greater social justice and equity. It aims to reduce poverty, social exclusion,

improve health and lead to environmental protection. Supporting this process is a social, economic and ecologically framework which aims to avoid unnecessary consumption of non-renewable resources, and advocates a policy involving both official entities and citizens (WCED, 1987).

In the report, sustainable development emerges as:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

It contains within two key concepts:

- The concept of needs, in particular the essential needs of the world's poor population, to which overriding priority should be given;

- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

Another important development for a sustainable future was the United Nations Conference on Environment and Development (UNCED), held in 1992, which became known as the Rio Summit, Rio Conference or Earth Summit. The Earth Summit gathered 172 governments and 2400 representatives of non-governmental organizations, in the city of Rio de Janeiro, to help rethink economic development while avoiding the destruction of finite natural resources and aiming to reduce pollution. New strategies were planned to change the course of further damaging actions to the planet which led to a plan on sustainable development entitled Agenda 21. This plan began to take form in 1989 with the approval of the Earth Summit and, after four years of negotiations and consultation, the final version of the Agenda 21 became public at the mentioned summit. Agenda 21 drew a plan of action in four sections in order to prevent poverty, by changing consumption habits, promoting health, protecting Earth's atmosphere, stopping deforestation, controlling pollution and managing waste. Agenda 21 aimed to achieve such goals by strengthening the roles of major groups/entities and also relying heavily on the implementation of better education, science and financial mechanisms. This plan was a global effort to contribute to a better world, although it was non-binding and voluntarily implemented action.

Since then, there have been additional attempts, and even progress, in order to not only develop but implement strategies regarding sustainable development. Today having sustainable construction means to have added a vital step in decision-making that has direct consequences on environment, budgets and high-quality construction. To address these issues the Green Building (also known as green construction or sustainable building) came into being. This type of structure uses processes that are environmentally responsible and resource-efficient throughout any building's life cycle: from site selection to design, construction, operation, maintenance, renovation, and demolition. The Green Building concept expands and supplements the classical building design concerns of economy, utility, durability, and comfort, directing its efforts to also reduce building environmental impact (Cullen, 2010).

The Green Building makes use of new technologies and reduces natural impact by efficiently using energy, water, and other resources, protecting occupants' health, improving productivity and reducing waste, pollution and environmental degradation. For its implementation, there are a number of green building rating systems, some of which are used more locally, while others are used worldwide such as CASBEE (Japan), BREEAM (United Kingdom), LEED (Canada and United States) and LiderA (Portugal). The majority of the rating systems for sustainable construction include credits earned for including building attributes that are considered beneficial for the environment.

Furthermore, in the area of urban planning, can also provide an opportunity to meet sustainable development and address clean alternative energy sources such as solar power. For instance solar urban planning can be integrated into urban planning in order to maximize building solar exposure, allowing for as energy consumption as little as possible, thus reducing emissions (Amado and Poggi, 2012).

2.6. Natural disasters

Natural disasters are defined as a result of events triggered by natural hazards that overwhelm local response capacity and seriously affect the social and economic development of a region (IASC, 2006). By definition a natural disaster does not necessarily result from hazard exposure but from a combination of factors which include physical and social vulnerabilities. Natural disasters do not occur for instance when adequate and resistant built environment exist and proper strategies of disasters preparedness and mitigation are delineated. Only vulnerable built environment and its vulnerable communities can be targeted by natural disaster, meaning that often low-income and developing countries bear larger numbers of natural disasters and endure their impacts the most.

There are five main groups of natural disasters (www.emdat.be):

- Geophysical disasters are events originating from solid earth such as volcanic eruptions, earthquakes;
- Meteorological disasters are caused by short-lived and small scale atmospheric events such as storms;
- Climate-related disasters are the product of long-lived and large scale processes such as droughts, wildfires;
- Hydrological disasters are events created by deviations in the normal water cycle such as floods;
- Biological disasters are disasters caused by the exposure to toxic substances or pathogens such as epidemics.

Natural disasters have short-term impacts and long-term impacts, producing multiple issues which can be co-related for which numerous and tailored strategies for recovery should be applied. In the short-term, natural disasters devastate infrastructure, housing sector, damage natural environment and leave large numbers of population displaced. On the long-term, natural disasters can affect economies, human health and render inhabitable previously populated areas.

Once the natural disaster hits, it produces a state of emergency which should trigger an emergency disaster preparedness response. Humanitarian emergencies are considered situations of calamity in which targeted communities or societies are severely disrupted, causing suffering and material loss that exceeds the affected population's ability to cope using its own resources. Complex emergencies are humanitarian emergencies that emerge from complex social, political and economic origins, and even government authority breakdown and often include human rights abuses (IASC, 1994; ALNAP, 2003).

Additionally, emergencies can be categorized according to their speed of onset:

- Sudden onset emergencies can be both caused by natural disasters such as earthquakes, tsunamis, man-made actions or complex disasters that result in a sudden deteriorating situation in which there is little to no warning (UNOCHA, 2011). Sudden-onset emergencies produce a large influx of displaced people, therefore becoming refugees or IDPs, in a short period of time (Corselis et al, 2004).

- Slow-onset emergencies comprise a gradually deteriorating situation, often based on a confluence of different events, where warning signs exist that should trigger disaster mitigation strategies. Droughts are examples of slow-onset emergencies, but contemporary issues such as climate change, overpopulation and macroeconomic trends can contribute to an increasing vulnerability (UNOCHA, 2011).

In 2013 alone, the reported 330 natural disasters produced 21 610 deaths, affected a total of 96,5 million people and caused economic damages of 118,6 billion USD. From 2003 to 2013, the most frequent countries hit by disasters were the United States, China, Indonesia, Philippines and India (Below et al, 2014).

Furthermore, since 1970, the risk of displacement due to natural disasters has doubled. In 2013, there were 22 million people displaced due to natural disasters in 119 countries; most displacements took place in populous Asian countries (IDMC, 2014).

Floods and storms are among the most common natural disasters registered in recent decades. Storms generated 14,2 million displaced, ranking as the first type of hazard that displaced populations in 2013, followed by floods – responsible for displacing 6,2 million. However, the trend between the period of 2008-2013 is the opposite, as floods were responsible for 93,8 million displaced and storms for 44,9 million.

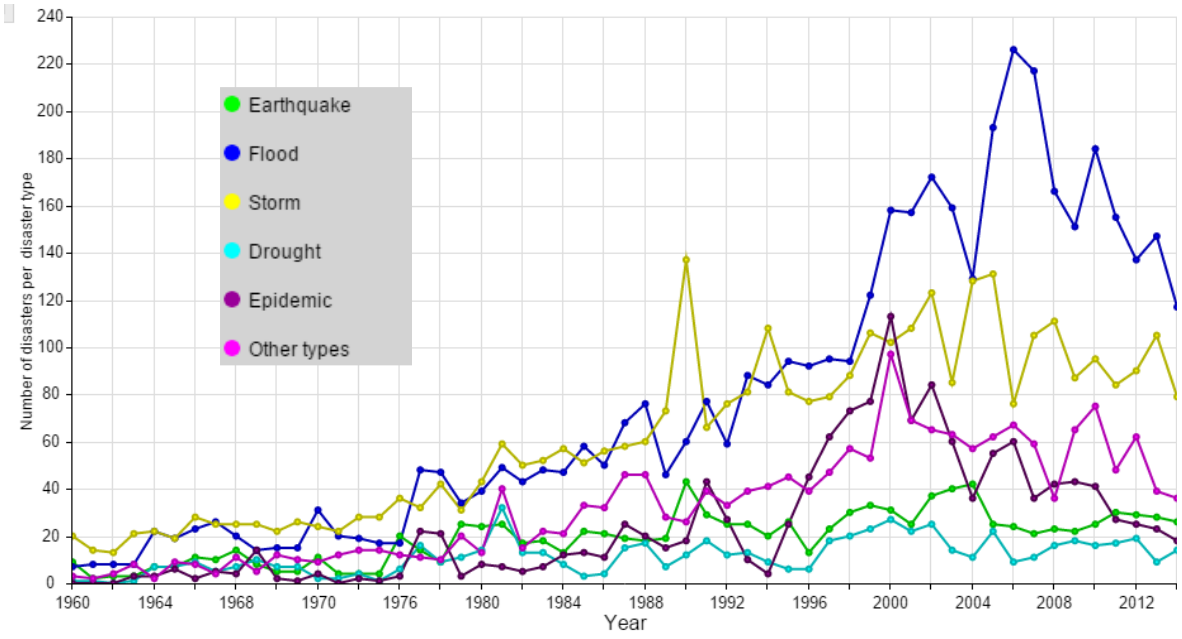


Figure 2.9 – Number of reported disaster types by year
(http://www.emdat.be)

As it can be observed in Figure 2.9, floods are currently the most common of all natural disasters, with almost 120 natural disasters resulting from floods in the year 2014. Figure 2.10 also shows that floods caused the greatest economic damage in the same year along with storms accounting for more than 50 billion USD.

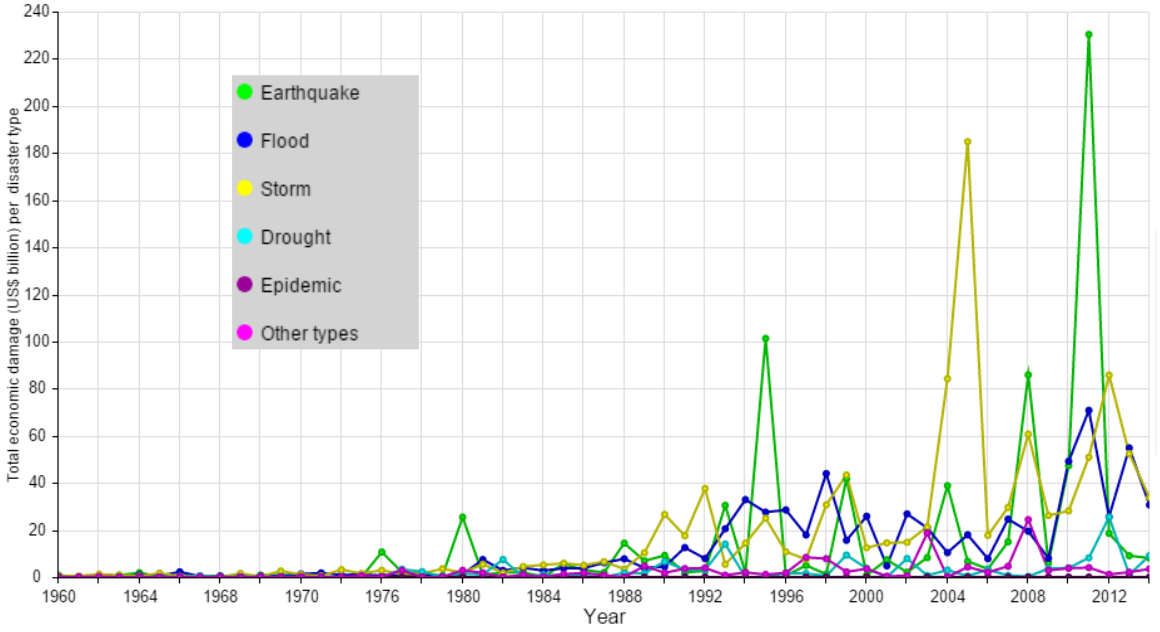


Figure 2.10 – Economic damages per disaster type by year
(http://www.emdat.be)

Following natural disaster, the scenario is usually chaotic with key actors such as the affected community, the private sector, local authorities, national government and NGOs addressing immediate shelter needs that may not lead to sustainable housing reconstruction. Typically key actors' aims are intended to shelter the affected population in the immediate future while housing reconstruction is neglected. Post-disaster housing can have distinct approaches such as providing temporary housing, repairing and building new housing. However, when housing reconstruction is attempted, planning is poor and coordination between entities becomes difficult. Housing interventions after natural disaster are usually planned and implemented quickly, without regard to political, economic or social environments. While other relief items such as food, water or aid medicine are intended to be short-term assistance, housing is a significant long-term asset and a fundamental part of the long-term recovery process (Barakat, 2003).

Furthermore, after natural disaster, fundamental assets for reconstruction such as land, human resources, institutional resources, financial resources, technology, community resources and building materials may become scarce and highly expensive. While assessments are usually carried to identify the damage to infrastructures, buildings and communities they often do not provide relevant information and may lead to housing projects that are impractical or inappropriate. Consequently, reconstruction projects become unsustainable and can be rejected or abandoned (Barakat, 2003).

Moreover, climate change can potentiate natural disasters. Although climate extremes are an intrinsic part of the natural climate system, climate change leads to variations in the frequency, intensity, special extent, duration and timing of extreme weather and climate events. These changes in the global climate system can indeed induce natural disaster as there is evidence from observational data that weather and climate extremes have become more common since 1950 due to the human impact on the climate system. While attributing an extreme event as a result of climate change can only provide answers in the probability realm, there is scientific evidence that the changing likelihood of extreme events is a result of human activity and it affects climate change. Studies and analysis performed to attribute the causes of extreme events resulted in concluding that human influence on the climate system played a role in natural disasters such as the flood in the United Kingdom, in 2000, and the drought in Somalia, in 2011 (Banholzer et al, 2014).

As it was established, natural disasters constitute undoubtedly a major loss event. However the post-disaster scenario can be regarded as a key occasion to recreate the built environment by addressing the needs of the present society, protecting the environment and especially considering future risks that new structures will face. No other circumstance provides the context to build entirely new structures – sometimes even new settlements or cities – as in the aftermath of natural disaster. Failing to see a natural disaster as an important chance to build adequately leads to developing structures that are not prepared to upcoming damaging events.

In this context, throughout History, natural disaster served to reshape cities and its infrastructures and prepare the built environment to resist future hazards. One of the most emblematic and still remembered European catastrophes was the 1755 Lisbon earthquake targeting not only Portugal but many other parts of Europe and North Africa. Lisbon alone faced the most damage caused by the earthquake and consequent tsunamis and also fires that ravaged the city. Estimates place the death toll between 30 000 and 40 000 people. Described as the first modern disaster, the earthquake marked the birth of seismology and the first requirements for urban disaster mitigation and anti-seismic building design such as the Pombaline Cage seen in Figure 2.11 (Dynes, 2003; Čermák et al., 2010).

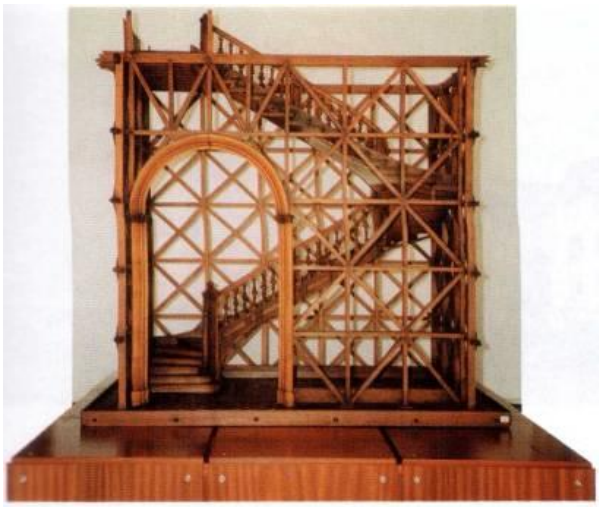


Figure 2.11 – Pombaline Cage
(Pinho, 2008)

In the aftermath, the population was sheltered in tents and huts and measures were taken in order to deal with the loss of life, economic impacts and the lack of shelter for the city's population. In the long run, the 1755 earthquake left Lisbon profoundly different as Portuguese leaders opted for a pioneer urban planning reflecting new core values intended for the city. Prohibitions of construction outside the old city walls were made to stop uncoordinated urban planning as well as inside the city, where owners were rebuilding their houses as rapidly as possible without any regard for safety, site planning and other requirements (Mullin, 1992).

Another powerful event was the 1906 San Francisco earthquake which left almost the whole city destroyed in combination with the following fires that consumed it. The earthquake resulted in the death of 3000 people and 225 000 residents were left homeless; 75 000 left the city. Makeshift camps composed of shacks and barracks were built in park areas or among the ruins of buildings, but as fires continued to burn and conditions in camps worsened, many of the homeless migrated towards the Presidio and Golden Gate Park where the Army housed nearly 20 000 of the displaced in military-style tent camps (UNHCR, 2010).

Interestingly enough, the government realized makeshift shacks and tents would not withstand the arriving winter rains and low temperatures, reaching 6˚C on that very winter. Being so, the government

itself established contracts for the construction of 5610 cottages to house 15 000 people, which began being built six months after the earthquake. These cottages were made of timber with pup-tent-like cedar-shingle roofs, redwood walls and fir floors. The cottages functioned as temporary shelters by bridging the gap between the tents and emergency housing and permanent housing, so that the homeless could be sheltered while the city was being rebuilt. The nominal rent of 2 USD a month by cottage was charged in order to avert a culture of dependency and the disruption of economic conditions, while options for buying the house were also available. Residence in the cottages happened for about two years until the camps were closed, which by then people were required to move out and owners could move their cottages to their own lands. While most of the houses do not exist anymore, there are some scattered throughout San Francisco, and more surprisingly, few still serve as homes (UNHCR, 2010).

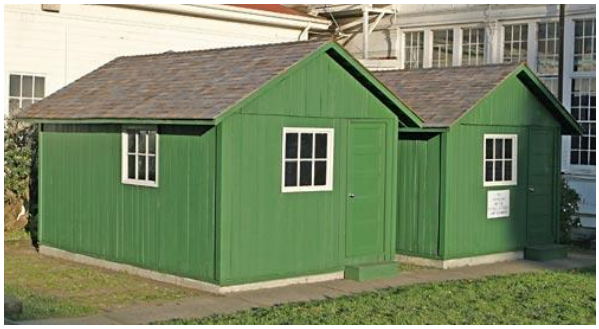


Figure 2.12 – Cottages of San Francisco 1906 earthquake
(www.nps.gov)

Although only more than a decade after the earthquake building codes in United States became more restrictive, the 1906 San Francisco earthquake is considered to be a main event which pushed anti-seismic building design in the construction sector. It is also a case where a temporary housing structure became an opportunity to be transformed into long-lasting permanent structures that are considered valuable assets decades passed.

2.7. Fundamental requirements for housing

Even though a spectrum of laws exist to ensure the permanence of population on their land and guarantee adequate housing solutions and protection, frequently human rights are violated in many emergency situations, forcing not only people to become displaced and homeless, but to lose most of what they own.

To address the specifics of housing in an emergency context, several organizations engaged in providing a characterization of adequate housing solutions. Identifying the characteristics and aims of a suitable house is the first cornerstone towards a solution. UN-HABITAT states that adequate housing is more than four walls and a roof. It lists seven fundamental criteria that have to be met in order to provide minimum proper housing (UN-HABITAT, 2008):

- Security of tenure: housing is not adequate if its occupants do not have a degree of tenure security which guarantees legal protection against forced evictions, harassment and other threats.
- Availability of services, materials, facilities and infrastructure: housing is not adequate if its occupants do not have safe drinking water, adequate sanitation, energy for cooking, heating, lighting, food storage or refuse disposal.

- Affordability: housing is not adequate if its cost threatens or compromises the occupants' enjoyment of other human rights.
- Habitability: housing is not adequate if it does not guarantee physical safety or provide adequate space, as well as protection against cold, damp, heat, rain, wind, other threats to health and structural hazards.
- Accessibility: housing is not adequate if the specific needs of disadvantaged and marginalized groups are not taken into account.
- Location: housing is not adequate if it is cut off from employment opportunities, health-care services, schools, childcare centers and other social facilities, or if located in polluted or dangerous areas.
- Cultural adequacy: housing is not adequate if it does not respect and take into account the expression of cultural identity.

In the *Handbook for Emergencies* (UNHCR, 2007) shelter is expressed as to be one of the most fundamental determinants of universal living conditions and also one of the major items of non-recurring expenditure. Although the necessity for shelter is similar in most emergencies, the type of needed housing materials and design to be employed, as well as the duration of housing, can vary in each situation. Shelter is described as having to meet the following criteria: to provide protection from the elements, a space to live and store belongings, privacy and emotional security, to be culturally and socially appropriate and familiar (UNHCR, 2007).

The Sphere Project is another important voluntary initiative of a group of humanitarian agencies aimed to improve the quality of humanitarian assistance and the accountability of humanitarian actors to their constituents, donors and affected populations, which resulted in a set of principles and minimum standards in the Handbook of the Humanitarian Charter and Minimum Standards in Disaster Response. Shelter is described as (Sphere Project, 2004):

> "Beyond survival, shelter is necessary to provide security and personal safety, protection from the climate and enhanced resistance to ill health and disease. It is also important for human dignity and to sustain family and community life as far as possible in difficult circumstances" (Sphere Project, 2004).

Some organizations also tackled the issue and delivered an answer to what a shelter must have in order to be successful. Some of them exposed the same idea that a shelter is required to have three main objectives:

- To provide protection against elements and airborne vectors;
- To provide a sense of security and privacy;
- To provide a place with sufficient space for group needs.

Obviously, accomplishing these aims does not necessarily result in an idea of home. A shelter is not only a place where people can be protected from weather, store belongings or rest. In situations of emergency, a shelter can be the very first step to recover from natural disaster. Shelter sets the foundations of a new life and possible recovery from trauma.

2.8. Housing recovery after natural disaster

Housing recovery is defined as a process starting in the aftermath of disaster in which communities who lost their house in the event regain accommodation and restoration of their daily lives through various stages of recovery.

When housing is rendered destroyed or uninhabitable, there are six options for housing populations in the post-disaster scenario (UNHCR, 2007):

- Host families – When families, neighbors and individuals provide shelter to displaced populations within their property or household;
- Urban self-settlements – When displaced populations shelter in buildings or property in urban settings that remain unaffected by disaster;
- Rural self-settlements – When displaced populations settle on collective owned rural lands;
- Collective centers – When displaced populations settle in mass shelters such as community centers, gymnasiums or town halls;
- Self-settled settlements – When a displaced community opts to settle in camps without assistance from the aid community or local government;
- Planned settlements – When displaced populations are sheltered within an area built on purpose for their needs with full services infrastructure including water supply, food distribution and health care.

While these six options can be used to shelter populations targeted by natural disaster, many times only new settlements – self-settled camps or planned camps – remain a viable option since there is widespread destruction of the built environment. This thesis addresses the structures chosen and built in planned camps to house the homeless population.

To identify the physical structures that shelter population in the aftermath of natural disasters it is necessary to describe the types of housing recovery approaches that take place. Housing recovery following a natural disaster is a complex and long process that can take many forms.

Four-Stage Housing Recovery

Quarantelli (1982) offered a typology of four distinctive forms of housing that displaced people go through following a disaster. The author divides the stages between sheltering and housing, in which the former consists in the action of staying in a place in the immediate aftermath of a disaster with disruption of daily activities, while the latter means to resume the same activities. The four stages do not refer to necessarily four different physical housing types, although that situation can occur.
The first stage, emergency shelter, is composed by abandoning permanent homes and finding refuge in unplanned and spontaneously sought sites which are intended to provide protection from elements for short periods, usually ranging from hours to overnight. Emergency shelter may take the form of public shelter, tents or tarpaulins, or accommodation in nearby houses from relatives, friends and neighbors (Paul, 2011).

Temporary shelter is the second step that displaced victims go through. Temporary shelter refers to housing into quarters destined as sleeping facilities, with expected short or temporary stay, typically of few weeks. It includes provision of food, water, sanitation and medical treatment.

Temporary housing marks the return of the residents to household routines in non-preferred structures and locations. While resuming their lives, most of the residents still wish to return to a form of permanent housing. Available resources and other constraints may affect the form of temporary housing that can take the form of rented apartments in prefabricated structures (Paul, 2011). Temporary housing can be considered both a stage in the process of housing after a disaster, and a physical type of housing stock used by families during the post-disaster period (Johnson, 2007).

Finally, permanent housing is the final stage of housing recovery, re-establishing the daily activities of disaster victims within the former reconstructed home or resettlement in a new one, where families are expected to live permanently.

Although typology allows for a global perspective on housing recovery it cannot be regarded as a mere sequence of phases where households are expected to progress linearly, even if it can happen sometimes (Rodríguez, 2009).

The four stages of housing recovery may or may not be used and typically disaster victims in developing countries use only temporary and permanent housing, taking into account that some stages can be avoided, while others can even go backwards. That being said, it is possible to find, in disaster aftermath, families living in all kinds of forms of shelter or housing simultaneously. Furthermore, there the blending of the stages can occur, considering that more often than not it is not fully clear when permanent housing begins, following temporary housing, or when emergency shelters transition to temporary shelters (Paul, 2011; Quarantelli, 1982).

By applying probabilities for transitions through time between the four stages of housing recovery, the following distribution over time has been generated and shows post-disaster housing status for impacted populations (FEMA, 2010a).

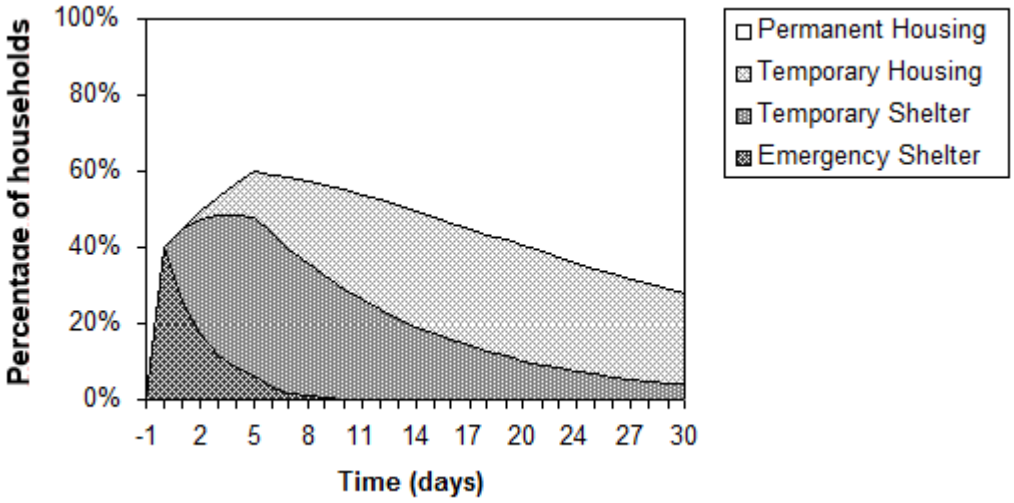


Figure 2.13 – Housing recovery distribution over time
(FEMA, 2010a)

Three-Stage Housing Recovery

There are other housing recovery procedures that do not necessarily include that many stages. Depending on many factors including economic availability, geographic situation, number of displaced persons and material availability, among others, the stages of housing recovery when dealing in the post-disaster can be reduced. A three-stage recovery plan for reconstruction is very common, consisting in:

- Tents as an immediate aftermath relief response;
- Prefabricated temporary shelters bridging the immediate and final stages;
- Permanent housing as the last stage of housing recovery.

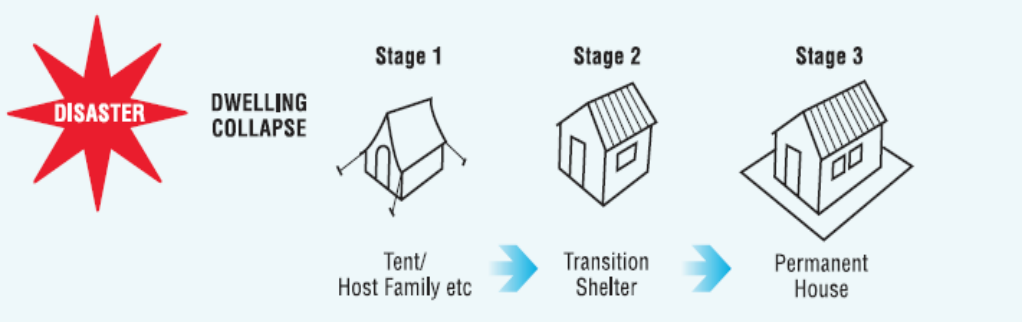


Figure 2.14– Three-stage housing recovery
(Davis, 2012)

This strategy was used for instance by the government of Turkey in the aftermath of the 1999 earthquakes in the Marmara and Bolu regions, with tents being provided by the Red Crescent and the military, prefabricated housing being built by NGOs and the government, and permanent housing built with the aid of the World Bank (Johnson, 2007).

This type of three-step approach is at times considered as a phase/product approach that is best to avoid, since by providing prefabricated temporary housing or transitional shelters as an intermediate phase it generates issues that can, for instance, delay the building of permanent homes.

Two-Stage Housing Recovery

Two-stage housing recovery is composed of only two steps – tents followed by permanent housing, eliminating stage two altogether. This is achieved by prolonging the emergency options right after the loss of housing and advancing the stage of permanent housing by rapid construction (Davis, 2012).

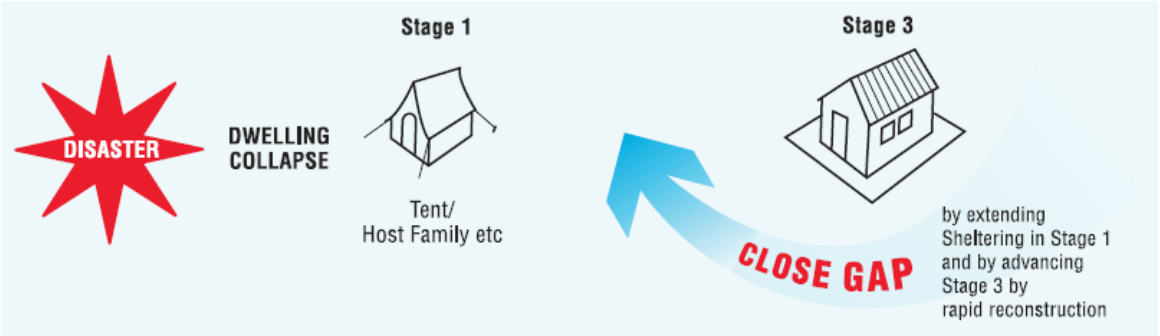


Figure 2.15 – Two-stage housing recovery
(Davis, 2012)

Regardless of the approach, three main physical structures destined to house populations affected by natural disaster were identified – tents, prefabricated shelters and permanent housing. Each one of these options will be discussed in detail below.

2.8.1. Tents

Tents are used in the immediate response relief aid. They are portable, possessing a structure and a cover. The priority in sheltering people is to have the inside of the shelter covered and dry including all the personal belongings of the people using it and keeping the temperature at comfortable levels. In terms of very basic needs, tents succeed to a degree. Tents are used in many emergency scenarios due to being portable, light weighted and have low volume. They are also easy to replicate and assemble and are generally culturally accepted.

Figure 2.16 – A tent camp in the aftermath of the Van earthquake in Turkey, 2011 (www.upi.com)

Tents can protect people from airborne diseases helping to preserve the health of the people using it. By having walls and a roof, tents provide a feeling of security and allow people using to have a sense of some privacy and dignity. Also, by having a place where to live, it guarantees that people can conduct other essential activities.

Tents are one of the possibilities within the realm of temporary shelter, but tent camps should be considered a last-resort solution only to be implemented when every other solution fails to fulfill the needs of people.

Tents can be considered for sheltering populations in the aftermath of natural disaster when (Ashmore, 2005):

- Nearby structures are not fit to be used even with quick repairs;
- Resources, skills and capacity for construction or repair are restricted;
- Basic structures made from plastic sheeting and other available materials cannot address the needs of users in specific environments and climates;
- The delivery time of tents is appropriate.

In an emergency context tents can shelter either displaced people who leave their native lands for a new location or non-displaced people who remain in their lands but who no longer have homes. For non-displaced people temporary structures able to shelter them and their belongings such as tents are particularly helpful in staying on their lands instead of moving to camps.

Tents are made from a variety of materials. The sheets can be made of polyester, nylon, polycotton or coated-cotton; groundsheets are made mostly of sturdy PVC. For the structure, the poles of the tent can be made of glass reinforced plastic (GRP), steel or aluminum alloy (Axelsson, 2012).

Usually a standard family tent with a flysheet and groundsheet has approximately 70 m² of fabric. The tent may be composed of several different types of fabric often three – flysheet, lining and valances/mudflaps – designed for each part of it. Outer tent fabrics can be made of cotton canvas or synthetic materials such as plastic sheeting, PVC coated polyester or polyester (Ashmore, 2005).

Cotton canvas is made of plain weave which is the easiest to replicate in production. Ripstop canvas is used in military tents, but is more expensive. Heavier canvases are usually more durable than lighter ones, although weight has implications on costs and transportation (Ashmore, 2005).

Mudflaps are valances used at the near bottom of the tent consisting of at least 40 cm wide intended to be rot-proof allowing tents to be dug into the ground. Mudflaps also help the tent to stabilize and reduce air droughts at ground level. The material used for mudflaps can be polyester canvas, PVC-coated canvas or woven polypropylene (Ashmore, 2005).

Groundsheets can be either separated from the inner tent or stitched as part of the tent. While the first option allows for people to use groundsheets with more freedom, it does not give water or wind proofing, whereas the sewn groundsheet can stop wind and water from leak in. However, groundsheets that are sewn in the tent leave little space for adaptations so users resort to cutting tents to make their own changes. Groundsheets can be made of canvas covered with PVC, woven polypropylene covered on both sides with LDPE, waxed cotton canvas and PVC (Ashmore, 2005).

The following figure provides detailed information on the four main types of tents used during emergencies:

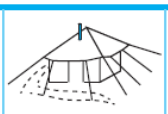
					
type of tent	**ridge tent**	**centre pole tent (tall wall)**	**centre pole tent (low wall)**	**hoop tent**	**frame tent**
description	traditional relief tent. Poles: 2-3 vertical, 1 ridge pole	centre pole tent with high walls. Walls held up by poles	tent with centre pole and low walls	tunnel-shaped tent	tent built on a rigid frame from flat poles
covered area	12 m^2 - 16 m^2	16 m^2- 24 m^2	12 m^2-16 m^2	12 m^2-18 m^2	16 m^2
advantages	tried and tested design	good headroom	relatively lightweight	good headroom, small footprint	good headroom throughout
dis-advantages	limited head-room at sides	can suffer in strong winds. Heavy	limited headroom	requires many poles. Technology in development	requires many poles. Often expensive
weight with flysheet	75-120 kg	120 kg	50-100 kg	40-80 kg	100-120 kg

Figure 2.17 – Description of main types of tents used in emergencies
(Adapted from Ashmore, 2005)

Tents function as a protection against weather such as rain, snow, wind and sun. In hot dry climates tents should block sunlight, create shades and provide enough ventilation so residents feel cooled and sheltered from the sun. Flysheets spread above the tent that generate an air gap can effectively keep the inside of the tent cool and ventilated (Ashmore, 2005).

In hot humid climates, tents are needed to function mainly as a good ventilated space for protection from the sun. Tents also need to be rot-proofed as in these climates cotton canvas tents are predisposed to rot.

In cold climates, when better shelter solutions are not available, the appropriate tent to be used is the winterized. Still, tents are difficult to be kept warm as they lose heat quickly by radiation into the air and ground, by infiltration – air leakage – and by conduction through the tent's material to the ground or its surroundings. The floors of tents can be different as the needs of their residents. It is common for tents to be distributed along with plastic sheeting that residents complement to floor their ground by using blankets, cardboards and other available materials. Many tents use adobe floors making use of clay and other ground materials (Manfield, 1999).

Tents can be improved and upgraded in order to provide more space and better quality life. In order to support people to adapt freely their shelter it is desirable that agencies keep a stock of spare parts, tools, tents and other items for repairs such as welding equipment for broken poles and sewing machines. If major modifications occur, agencies should interpret it as a sign that the shelter is not adequate and more appropriate ones should be considered in the future. As upgrading of tents take place, impacts on local environments are to be expected as some of the resources to adapt the tent are wood and foliage. If the demand is too much and exceeds the possibilities of local resources, it is important to distribute poles to avoid the consequences of deforestation and erosion (Ashmore, 2005).

More often than not, internal frames are built in order to create a more rigid and better superstructure inside the tent made by available materials like wood. The demand for wood can put pressure on native resources. Mud walls can be constructed around the tent to improve its thermal performance making the shelter cooler when high temperatures rise and warmer when temperatures drop. Mud walls also make the shelter more solid and provide draught proofing if tents are excavated downwards. Using sticks and poles to hold up eaves or building an internal frame can result in a more rigid shelter and enlarge the area inside the tent (Manfield, 1999).

Although tents are easy to ship, fast to distribute and easy to assemble and disassemble, successful in creating cover for people in need of shelter and helping non-displaced people to stay on their land, the tent does not provide for all shelter needs. Tents are expensive when comparing to other family relief items. Adding to this, tents do not create any significant long-term value and only last in average six to twelve months. Regarding logistics, tents tent to be difficult to store, as canvas tents will rot when overexposed to dampness. Canvas tents also degrade quickly when exposed to UV (ultra-violet) radiation. Stored tents need to be protected from sun and rain, from vermin and they need to be in a ventilated space. (Axelsson, 2012).

2.8.2. Prefabricated shelters

Prefabricated shelters are used as temporary housing to accommodate populations after a natural disaster. Typically these shelters are an intermediate phase of the housing recovery process and can involve aid agencies, local and international NGOs, governments, landowners, private contractors, manufacturers, and community leaders. Coordination between all entities is extremely difficult in the usually chaotic and sometimes even corrupt environment that follows natural disaster. Most of the solutions for prefabricated shelters are mass-produced and standardized and can be placed within two groups: ready-made units and kit supplies (Branco, 2013).

Ready-made units face more complex challenges in transportation because they come totally constructed from factory, just needing transport to the location where they will be placed. Heavy transport systems are therefore needed, resulting in higher costs. That is one of the reasons why so many projects opt to divide the unit into parts to be later assembled on site.

Kit solutions draw their strength from the fact that prefabrication of small elements are easy to handle and constitute the final product. When the elements arrive onsite assemblage can include the participation of the benefiting communities, thus creating know-how on housing solutions (Branco, 2013).

There are many designs for prefabricated shelters, which results in highly differentiated shelter units. Often they do not contemplate the needs of population, considering they are standardized and mass-produced. Prefabricated shelters can be built in a variety of materials.

Figure 2.18 – Prefabricated shelter developed by IKEA (ikeafoundation.org)

While some communities have pre-disaster preparedness for the emergency phase, reconstruction is often made by using tactical decisions lacking a wider perspective and temporary housing suffers from the same strategies that do not contemplate long-term relief.

Prefabricated shelter is a highly controversial subject within the scope of housing recovery. While some research has proceeded from the perspective that prefabricated shelter is needed based on the fact that families can live many years in tents, many authors and organizations adopt the elimination of this stage, mainly UNDRO, maintaining that accelerated reconstruction of permanent housing is preferable to the use of temporary housing (UNDRO, 1982).

The need for prefabricated shelters cannot be determined beforehand due to specific damage and availability of alternative forms of housing after a natural disaster. Therefore, a variety of contingency of sheltering programs is needed, meaning most of the decisions must take place after the disaster. Since many organizations and contractors are not used to supplying large quantities of temporary houses, lack of experience takes its toll on the finished products enhanced by time pressure (Comerio, 1998).

Some of the issues associated with prefabricated shelters are (Bolin and Standford, 1991; UNDRO 1982; Davis, 1977):

- Poor location;
- Delays in the completion of the projects;
- Social problems within the temporary settlements;
- Deficiencies in organizational capacities;
- Finding suitable sites;
- Cultural and climate inappropriateness.

Costs of prefabricated shelters, although varying significantly from country to country, are always too high in relation to their lifespan. At times, they can cost three times more than a permanent one. Expenses associated with temporary settlements such as water, sanitation, electricity and roads imply massive investments in settlements that are intended for a short period of time. Even after removing the units from the site, pollution can still occur, meaning cleaning works have to be performed to remove all infrastructure, resulting in additional costs for the project. Nevertheless, recycling, reusing or selling the units, or its pieces, may largely reduce costs (Johnson, 2007; Hadafi & Fallahi, 2010).

Temporary housing also consumes limited human, financial and machinery resources that are meant for other stages such as permanent housing. Prolonged accommodation can also indicate inability of residents to afford rents in permanent houses, incapability of residents to qualify for permanent homes or choice of individuals to remain in temporary housing. By prolonging staying of residents in temporary housing, these settlements can potentiate situations of crime, poverty and marginalization. Conditions permitting, failing to upgrade units to full permanent houses, which may result in sub-standard dwellings and an example of unfortunate legacy in years to come (Johnson, 2007; Davis, 2012).

As for cultural and climate appropriateness, the sector for temporary housing frequently adopts universally standardized models ready to be deployed throughout the world, disregarding variations of specific needs of future residents, climate and temperatures, cultural values and house designs and family size among other relevant factors. When housing units do not address the needs or expectations of residents, they can perform modifications in order to meet their needs, ending up damaging or exposing the unit to future harmful events. In extreme circumstances, there are cases where people leave their units because they cannot live in them (UNDRO, 1982; Barakat, 2003).

Many researches on prefabricated shelters have offered recommendations and approaches to avoid the problems previously described. Research has emphasized strategies such as community participation, usage of local resources and by prolonging the life of the unit beyond the temporary housing stage. By using local materials and manpower, the communities can participate on building the units and therefore local economy improves. Since there is no need to rely on imported materials or specialized technicians, the houses are built much more quickly and are much cheaper. Subsequent modifications or maintenance benefit from the community expertise (Barakat, 2003).

Future usage of temporary housing can be addressed by trying to incorporate opportunities for users after the transition for permanent houses. In order to prolong the use of the units, flexibility of the solutions is a fundamental characteristic to allow modifications and to accommodate multifunctional spaces (Barakat, 2003, UNDRO, 1982).

Since prefabricated shelters do not possess climate appropriateness and tend to become permanent structure, they are highly vulnerable to upcoming natural hazards.

2.8.3. Permanent housing

Permanent housing may take many forms but remains as the critical and final step of the housing recovery process. Although housing repair is the cheapest and quickest method of providing adequate housing it is dependent on the damage extent to houses and may not be possible. Many times the only option is to construct new housing which involves a great amount of effort and requires the highest investments when comparing this option to the ones previously shown. Construction of new settlements is time-consuming, and requires the full participation of local authorities (Barakat, 2003).

Among various factors, the most fundamental considerations when planning new housing and settlements in a post-disaster scenario are the choice options of (Barakat, 2003):

- Location, site selection and settlement planning;
- Construction method and materials;
- Design.

The choice of location, site selection and settlement planning is the most relevant consideration of all. The selection of a suitable site for construction of new settlements is very time-consuming and must be chosen according to land use plans, property rights, hazard exposure, infrastructure, environmental impacts among other relevant factors. Although settlements can be built in self-settled locations, this choice can generate some issues with host communities, have legal implications, and produce a lack of appropriate infrastructure. New housing settlements on the other hand should be considered to ensure housed populations have access to local employment markets, livelihood opportunities that in the end can result in self-sustainable communities. To that effect, most local planning authorities have settlement expansion plans and land use concepts that should be looked into and considered since they will provide relevant information to pursue appropriate site selection (Barakat, 2003).

Construction materials and methods for construction should be in accordance to local construction knowledge and skills, allowing for greater levels of sustainability and maintenance since communities can upgrade and repair structures which are familiar to them. By building on existing skills and traditional housing, the affected population by natural disaster will find jobs, strengthen the community and provide continuity of housing. Even when hazard exposure becomes a concern in new settlements, many communities have the knowledge of building houses that are resistant to local hazards, although new technologies and construction techniques can be introduced.

Finally, the choice of design of new houses should be a fundamental aspect of housing construction in the aftermath of natural disaster. New houses should be designed considering better ventilation and water and sanitation provision (Barakat, 2003). Cultural adequacy should be incorporated into permanent housing to meet the community aspirations as it is reported that affected population by natural disaster can abandon permanent housing due to being culturally alien or require maintenance skills that the community does not possess (Prinz, 2014).

Permanent housing is different from region to region, dependent on the building codes of each country and cannot be profoundly addressed in this subchapter. Nevertheless, as permanent housing should ensure durability, the risk of upcoming hazards must be considered to ensure a resilient housing recovery.

2.9. Resilient Housing Recovery

It has been established that as climate change intensifies, both frequency and intensity, flooding increases due to sea level rise, high intensity rainfall and strong winds and some of its effects are or will be in the near future irreversible. As floods constitute the most common natural disaster of today, construction and housing should address adaptation and mitigation strategies to increase resilience of buildings against flood events. Although local permanent resistance can be achieved by construction of low walls, mounds, dikes and sealed gates, this thesis has focused on the measures to be incorporated in residential construction.

In light of what has been previously said, resilience is defined as a set of sustainable measures and considerations to incorporate into the housing units, from site selection to the choice of building materials, in order to ensure structural and functional performance outcomes as expected before floods. By integrating resilient measures into the buildings, impact of the floodwaters should be nullified or at the very least reduced. Flood resilient construction does not address temporary measures to mitigate the effects of floodwaters, opting instead to considerate permanent measures integrated in the new construction.

The purpose of the following subchapters is to provide:

- Practical guidance on resilient measures that should be incorporated in the previously identified structures – tents, prefabricated shelters and permanent housing – in order to minimize impacts of future floods;
- Propose a methodology for flood resilient permanent housing which can also be used to assess the flood resilience of existing construction.

2.9.1. Floods

Floods are currently the most frequent natural disaster, responsible for economic damages over 50 billion USD, in 2014, and displacing 6,2 million people worldwide, in 2013. With additional future risks associated with population growth, city growth and climate change it becomes evident that strategies and response should be given to this specific issue. The housing and construction sector must be a fundamental part of a multi-sector response by integrating measures and approaches in building construction aimed specifically to mitigate and reduce the flood effects in buildings. To that effect, this master thesis intends to be a contribution to flood resilient shelter and housing in the context of a post-disaster scenario since after natural disaster occurs, it provides unique opportunities for building back better.

Flooding consists in a usually dry area becoming inundated for a period of time. Flooding can result in extensive damage to property and infrastructure and loss of life. Floods can destroy buildings, and may carry people and their belongings away, disrupting roads and rail lines and making access to flooded lands difficult. Floodwaters aren't composed only by water but can contain debris and contaminants that cause damage and destroy housing contents and pollute the environment. Water and the forces created by floodwater damage buildings and increase as water depths and water velocity increases which may result in a weakened building due to damage to foundations, walls and geotechnical failure. Vulnerability to floods exists whenever buildings are located in flood plains or in the probable path of flash floods, which means that avoiding flood prone areas is the most effective way to avoid flooding.

Land clearance and deforestation may lead to flood events since the path of floodwaters becomes unblocked. Furthermore, floods can be slow-onset and rapid-onset and have long duration periods that can cause continual disruption and health problems.

There are several types of floods according to the cause of the phenomenon (IFRC, 2011):

- Coastal flooding happens in coastal areas due to cyclones and hurricanes which create tidal surges elevating sea levels to a point that seawater covers dry land.
- River flooding is caused by rivers that become saturated with water due to extreme precipitation. River flooding is usually an issue in rivers with great flow of water situated in flat valleys.
- Flash flooding happens whenever there is a sudden release of water during intense rainfall, particularly where river catchments have a low capacity to ease surface flow. Steep valleys in high areas are prone to this type of flooding which may result in landslides.
- Urban flooding exists in urban areas where the water cannot be absorbed into the soil due to man-made impermeability. Existent natural and artificial drainage systems are insufficient or blocked leading to water accumulation.

The most relevant factors associated to floods are considered to be (Bowker, 2007):

- Potential sources of flooding;
- Flood duration;
- Frequency of flood events;
- Flood depths.

Although all of the above factors are relevant to ensure the any given structure resists flood events, flood depth is considered to be the main factor (Bowker, 2007).

2.9.2. Tents in flood prone areas

Tents are highly vulnerable to inundation and destruction of its structure, even with minimal water depths. Once flooding reaches tent settlements, tents and other infrastructure can be rendered beyond repair, in some cases forcing communities to once again, abandon the settlement.

The most important considerations for tents to reduce damage derived from flood events are based on avoidance of flood prone areas when selecting sites for tent settlements. Although tents have little flexibility to address flooding, there are some measures to maximize flood performance.

Tents mustn't be pitched in areas prone to flooding, particularly floodplains, coastlines, or lakes that are expected to overflow. However, flooding can exist due to heavy rainfall which can affect all available sites for tent settlements in a post-disaster scenario.

To counter the effects of ponding and flooding due to surface water drainage it is best to avoid putting tents in site gradients between 1 and 6 per cent maximum. Nonetheless, shallow slopes aren't a guarantee that the land isn't affected by flooding, meaning draining ditches are to be excavated upstream of tents. If steep slopes are the only available land, leveling of the floor is required and steeper drainage ditches are to be dug around the tents to prevent flooding. Drainage ditches depend on the expected quantity of rain, the type of soil and its infiltration capacity and the slope of the site and may reach 50 cm deep in worst case scenarios. Deep ditches can be unstable and need to be filled with stones in order to avoid collapse and injury or to be blocked by debris present in floodwaters. Drainage ditches must be connected from each tent to a site drainage solution (Ashmore, 2005).

Table 2.1 – Measures to minimize flood effects in tents

Measures to minimize flood effects in tents
Pitching tents in areas prone to flooding such as floodplains, coastlines and near lakes where flood events are predicted to happen should be avoided
Pitching tents in slopes between 1 and 6 per cent maximum should be avoided
Leveling of ground is required if the only available area for tents consists in steep slopes
Draining ditches need to be dug around tents in order to keep water from entering the tent

2.9.3. Prefabricated shelters in flood prone areas

Prefabricated shelters can be used to shelter affected populations by natural disaster, as discussed previously, and are often used to bridge the emergency phase and the last stage of the recovery process that comes in the form of permanent housing.

Although regarded as a temporary structure to house targeted communities by natural disaster, prefabricated shelters have the tendency to become permanent solutions. If these structures are in flood prone areas, it becomes critical that flood resistance measures are used to avoid and reduce the effects of flooding in prefabricated shelters. Much research has been conducted throughout this thesis in order to find as much detailed information as possible on this subject. However, no guiding principles for prefabricated shelters were found. For that reason, considerations in Table 2.2 have been determined so that prefabricated shelters resist the effects of flooding.

As prefabricated shelters possess little flexibility, measures for flood resilience must be based in site selection and the selection of the prefabricated unit because after the selection of the prefabricated system is done there is little room for adaptation.

All types of prefabricated shelters during the recovery response should be built in flood-free zones, far from coastlines, riverine settings and known sources of flooding. Choosing the adequate prefabricated unit should fall under characteristics that are resistant to water and its effects. This means that materials should be resistant to water and the unit itself should not allow water to enter inside. Raised prefabricated shelter systems provide better results in areas prone to flooding and should be procured. Additionally, rainwater drainage solutions can be implemented to drain rainwater flow and prevent water from accumulating near the unit.

Table 2.2 – Considerations for prefabricated shelters in risk of flooding

Considerations for prefabricated shelters in risk of flooding
Prefabricated shelters should be built in zones which are not prone to flooding
All materials of prefabricated units should resist water
Prefabricated units should prevent water from entering inside
The choice of elevated prefabricated units should be prioritized
Rainwater drainage solutions should be procured and implemented

2.9.4. Permanent housing in flood prone areas

Permanent housing should be the last step in the housing recovery process that should be built in order to achieve long-term durability. To do so, it is fundamental that building construction addresses upcoming hazardous events that can damage its structure and disrupt livelihoods of its residents, thus meaning that all types of permanent housing located in flood prone areas should be resistant to its effects. A flood resilient building should not only protect its residents from floodwaters but also resist the effects of flood by maintaining structural stability and remain functional. Although it is unrealistic to expect buildings don't become damaged to a degree from the event of floods, it is possible to anticipate flood factors and incorporate measures onto the buildings so that they have greater levels of resilience to floods. By doing so, not only lives can be saved but also economic damages that greatly surpass public and private possibilities of investments following a natural disaster. Displacement of populations affected by floods can also be avoided when infrastructure remains functional and buildings are flood resilient.

Figure 2.19 – A flood resilient building remains standing after the 2011 Tõhoku Tsunami (jenniferbruce.org)

2.9.4.1. Flood effects in permanent housing

To determine how a building should resist flood events, it is necessary to study how floods affects buildings and to define its related effects and mechanisms.

Typically, during a flood event water can enter the building via (Bowker, 2007):

- Brickwork and blockwork;
- Joints between slabs and walls or in zones where distinct construction materials meet;
- Suspended timber floors;
- Airbricks and vents;
- Seals between windows, doors and frames;

- Cracks and openings in walls due to poor construction;
- Inadequate damp proof course;
- Services entries such as utility pipes and ventilation ducts.

The extent of the damage to the building can be associated to the flood depths. The common flood damages for a residential building are provided in the following table according to the depths of floodwater.

Table 2.3 – Damage to houses according to flood depths
(Bowker, 2007)

Depth of floodwaters	Damage to the house
Below ground floor level	Corrosion in metal components Moisture absorption in timber causing warping Cracking of the ground floor due to buoyancy Accumulation of silt Loss of structural performance and material resistance due to wet and dry periods Erosion beneath foundations causing structural instability Rot and mould
Ground level to 0,5m above floor level	Accumulation of water and silt in cavity walls causing reduction in insulation Insulation of floor reduced and debonding of screeds Plaster linings and wall coverings damaged Timber materials damaged beyond repair Damage to internal and external doors
Above 0,5m	Wall instability due to hydrodynamic and hydrostatic loads Structural damage Debris impacts Erosion of the ground surface due to high-speed hydrodynamic forces

Furthermore, damage done to buildings due to a flood event can be grouped in three main groups according to the type of damage (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006):

a) Movement of foundations as a result of geotechnical failure;
b) Forces created by water, water flows and debris on the components of the house;
c) Building materials in contact with water.

a) Movement of foundations as a result of geotechnical failure

Foundations are the most vulnerable and exposed part of the house to floodwaters. They are also critical in structural stability since they are responsible for transmitting the loads of the structure to the ground. Even if foundations contemplate flood events in its design, soil stability can lead to damage – in the worst case collapse of the residential building. Soil can be grouped in two categories; coarse-grained if 50% of the soil or more is retained on or above no. 200 sieve, or fine-grained soils, if 50% of the soil or more pass the no. 200 sieve. Coarse-grained soils are considered better for building foundations since

water doesn't have a great effect on coarse-grained soils. On the opposite, fine-grained soils have much more properties that are chemical and mineralogical than coarse-grained soils causing soil to behave differently (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

The main modes of geotechnical failure associated to flood events are considered to be (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006):

- Erosion and scour of soil as floodwater advances and recedes;
- Soil piping;
- Batter slumping;
- Swelling and shrinking of soil after inundation and drainage;
- Collapse of soils after inundation and saturation.

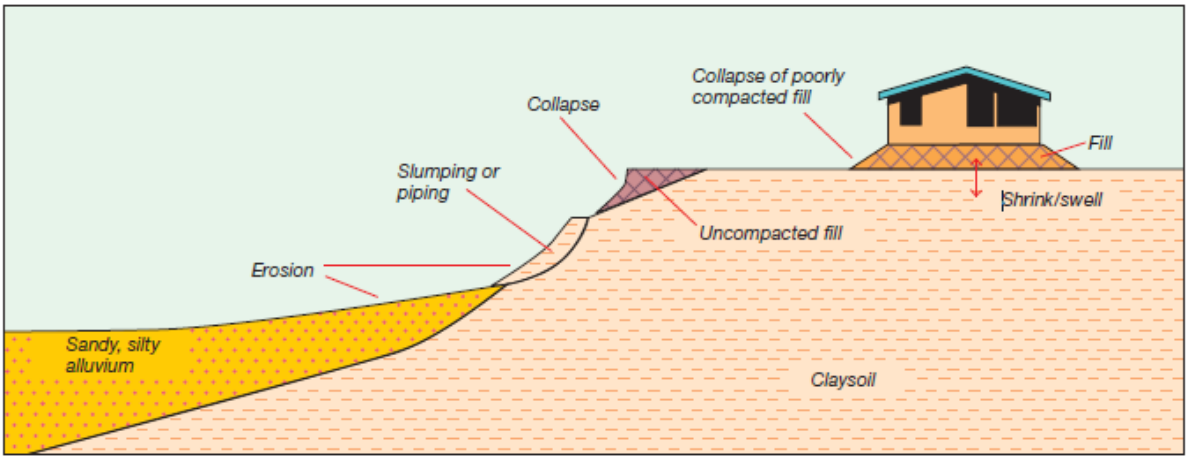


Figure 2.20 – Main geotechincal failure modes (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006)

Erosion and scour

Erosion can occur gradually over a long period of time such as many years, in a short period of time such as weeks, or can be episodic, occurring in a matter of days due to storm events.

The susceptibility to soil particles to detach and travel by the action of erosion agents is named soil erodibility and is based on the physical characteristics of each soil. Water can move through and over the soil, picking soil particles to deposit elsewhere, leading to lack of soil where foundations are supported in the ground. Typically, soils with higher levels of organic matter, faster infiltration rates and better soil structure are more resistant to erosion, meaning fine sand and silt are more erodible than gravel (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006). Hydrodynamic forces also play a part in eroding the soil and given the right amount of velocity, virtually any soil can be eroded.

Scour happens when floodwater travels around obstructions in the water column and changes direction leading to acceleration of the water. When scour happens the soil is dislodged and is carried away leading to localized depressions around piles, columns and foundations. Scour effects are dependent on flow velocity, turbulence and soil erodibility, and therefore increasing as any of these factors increases.

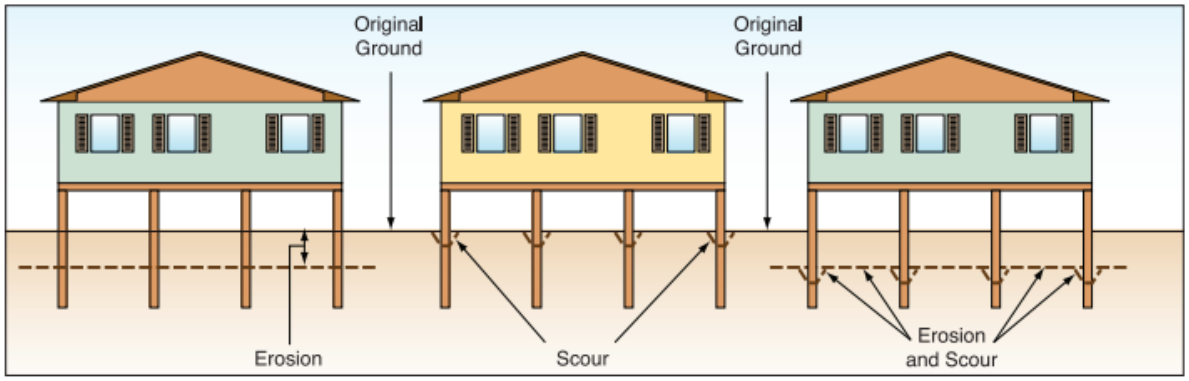


Figure 2.21 – Erosion and scour effects in buildings
(FEMA, 2010b)

Erosion and scour are known threats to foundations particularly in coastal areas where buildings are subjected to flood events and soil is fine-grained and consequently easier to transport by moving water. Scour and erosion reduce the embedment of the foundations to the soil, causing structural instability and leading to collapse in buildings resting in shallow foundations or causing buildings resting in deep foundations to become more prone to settlements, lateral movements or overturning from lateral loads. Foundations of buildings will also be more exposed to hydrostatic and hydrodynamic lateral loads. Moreover, by reducing the embedment of pile foundations the piles become overstressed due to the increase of the bending moment.

To construct permanent houses in areas prone to erosion due to floods must be avoided since long term durability isn't achievable. If building in these areas cannot be avoided, it is recommended the use of deep foundations in order to carry the loads to stronger substracts.

Piping

Soil piping is a phenomenon of internal erosion where water travels inside the soil picking up particles to deposit away, leading to tunnels where water percolates. Piping can cause geotechnical failure due to progressive increasing of width and depth of the water passages below the surface of the ground. Dispersive soils which contain high percentage of sodium ions are more susceptible to piping failure than others since they are erodible in nature and have a tendency to segregate in the presence of water. Special attention needs to be given to soils of clays with low-to-medium plasticity that contain montmorillonite since many geotechnical failures have been observed in these type of soils (Dinesh et al, 2011).

Construction located in these types of soils and in areas prone to flooding is dangerous and must be avoided.

Slumping

Presence of water in the soil can result in the slumping of the slope with consequences for buildings settled in the area. Slumps are defined as being made up of more-or-less intact blocks of soil which slide downslope above a circular shear of underlying substract. The moving soil mass is dislodged from the higher slope by a high vertical rupture or headwall, breaking into an uneven surface of backward-tilted segments separated by lower ruptures or scarps.

Slumping can develop in areas of clay soils when a quick drainage of the flooded area creates the presence of high pore water pressures in the soil which can lead to slope instability in the form of slumping. Slumping is expected to occur specifically in steep river banks and therefore, construction in these areas must be avoided.

Swelling/Shrinking of soil

Swelling and shrinking of soil is expected to occur particularly in expansive soils where there is significant presence of clay, since this phenomenon is dependent on the amount and kind of clay present in the soil.

Following a flood event, expansive soils can increase their volume up to thirty percent resulting in lifting of the building during periods of high moisture. As the water is removed from the ground, the soil shrinks pulling away from the building's foundations, leading to settlements. These types of soils will also exert pressure on the vertical face of the foundation or basement producing lateral movement. Soil strength is also lessened as the soil shrinks and swells, resulting in slope instability and geotechnical failure.

Floor slabs built on expansive soils may crack and occasionally heave if concrete design is not adequate. Walls can arch due to shrinking and swelling of the soil leading to diagonal cracks to form under the windows or above doors.

If possible, building on expansive soils is to be avoided, if not there are some measures to take when to address this issue while constructing. Pre-wetting of the ground before building foundations will cause the soils to expand with the notion that further expansion will be minimized. Further reinforcement of concrete elements, deeper foundations and thicker slabs are also ways to counter the damaging effects of shrink/swell soils (Chen, 1975).

Collapse of saturated soils

Collapse of soils can happen once soil is inundated and absorbs water. Cohesive soils or clays have been known for holding water and by action of particle attraction function as a whole which holds together and deforms plastically. For cohesive soils, shear strength can be reduced up to 50% due to saturation and may result in failure of shallow foundations. For this reason, the use of fill made of cohesive soils is discouraged for supporting buildings in flood prone areas. If fill is to be used, it must be adequately compacted since when subjected to inundation collapse of the soil can occur and lead to distress and failure of the building (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

b) Forces created by water, water flows and debris

Although buildings must be designed to resist horizontal forces such as wind and seismic action, they often aren't designed to deal with forces created by still or moving water. Therefore, in order to design flood-aware buildings, there has to be considered hydrostatic and hydrodynamic forces and forces created by the debris.

Hydrostatic forces

Hydrostatic forces are associated with hydrostatic pressure that increases as the depth of water increases. Pressure exerts forces or loads that are a function of the product of the water pressure and the surface area in which the pressure acts. Hydrostatic loads can be vertical loads which act vertically downwards and can cause the collapse of horizontal components such as floors, lateral loads that result in sideways displacement of the building and overturning, and uplift loads that act vertically upwards in horizontal surfaces and may damage floors or result in buoyant forces that cause houses to be tear apart from the ground.

Uplift forces during floods can cause buildings to float resulting in most of the times, total destruction of the building. To counter buoyant forces, allowing water to come inside the house is beneficial to stop the house being swept away by the flood. Some materials such as timber have a tendency to float and

are needed to be tightly secured to the structure and its foundations. Lightweight cladding systems also exhibit the same behavior and it's fundamental they are anchored to unmoving structure.

Hydrodynamic forces

Hydrodynamic forces are caused by moving water which result in pressure that increases as water velocity increases. The hydrodynamic pressure isn't the same on all surfaces of the house; façades facing the flow are subjected to higher water levels that results in greater pressure than other facades. Suction and outward loads are formed on the side walls as water flows along as well as on façades that are faced away from the flow. The upward loads can be greater than downward loads and may dislodge framing structure of the walls and cause damage to floors.

Hydrodynamic forces are especially harmful in cases where the water is channeled between houses resulting in greater velocities that may cause the house to fail in sequence and finally collapse.

Although residential buildings are designed to withstand dynamic forces such as the wind, water possesses much more density than air, leading to much greater destructive forces at the same velocity as the wind. Another major difference from the wind is that while wind doesn't result in upward forces in the building, hydrodynamic forces can develop at the base of the house creating buoyancy that opposes the weight of the immersed house.

In order to designing buildings to be resistant to hydrodynamic forces, it's important that it's assessed the velocity of the water where the building is located and design the house structurally to resist the forces related to the water velocity. While estimation of hydrostatic forces are dependent on few factors, hydrodynamic forces are related to many which are more difficult to calculate. This means, as a precautionary measure to avoid building where moving water can gain a very high velocity such as at the base of an accentuated downhill sloping site.

If historical values of water velocity do not exist, it is necessary to perform a flood modelling to determine water velocities. Models can be 1D, 2D grid and 3D particle-based fluid dynamics and can provide detailed information on water velocities in fully integrated flow dynamics in coastal lines, river and underground flows, as well as urban settings scenarios.

Debris impact

Finally, debris impact is the product of single objects that are carried by the water or accumulation of debris such as vegetation that cause an increment of loads to form as more debris is dragged to the facades.

Debris impact is difficult to assess and predict but it can be grouped into three categories (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006):

- Normal impact loads – are caused by singular impacts of objects in the waters. It's considered that normal impact loads are the equivalent of 454 kg travelling at the velocity of the floodwater acting in an area of 0,1 m^2;
- Special impact loads – are related to larger objects or group of objects striking or resting against a building. Special impact loads are the equivalent of 148,9 kg/m acting horizontally over a wide horizontal strip of 0,3 m;
- Extreme impact loads – are caused by large objects with greater masses than normal and special impact loads such as collapsed buildings. Addressing extreme impact loads is proven unrealistic and impractical.

c) Building materials in contact with water

Building materials in contact with water can be damaged and decay therefore lose their properties. While some materials are resilient to water, others will rapidly degrade and can result in the loss of structural integrity of the building. The magnitude of the damage will depend on the depths of the water, period of immersion, substances in the water and construction details among other factors. Usually, if good building design is made to ensure building resistance to floods, water levels below floor level create limited damage, much lesser than if the water rises above floor levels.

Construction details often lack consideration for floodwaters, increasing vulnerabilities of the house to the waters. Constructive details must aim for minimizing flood damage by reducing cavities where the water can infiltrate and damage the materials, but also by allowing for rapid cleaning and drying of the building after the flood.

It is important to acknowledge that floodwaters are not only composed of water. Many times, water carries substances that will affect the properties of building materials. If coastal floods happen, water will carry salt that will lead to sulfate attacks to metal components with devastating results for reinforced concrete houses. Reinforced concrete, if in contact with seawaters is subjected to corrosion of steel due to the presence of chloride ions in the water that travels inside the concrete through capillary action and by diffusion through the pores. Once in contact with steel bars, chloride ions destroy the passive film that coats the steel bars and initiate steel corrosion if oxygen and water are also available to sustain the reaction. As steel comes in contact with air and water, it will oxidize to form rust that has much more volume than the steel consumed in the reaction leading to more cracks to form due to low tensile strength of concrete. Corners will start to spall and delamination of the surface will occur as concrete cover will become dislodged and fall off. The failing of the steel can and will – if not properly addressed – result in structural deficiency. To avoid the risk of corrosion, increasing of the nominal cover of the element can be made by identifying the right class of exposure which is related to standardized values for resisting the action of deicing salts in many building codes worldwide.

When floodwater is moving it can drag silt that can be deposited in concealed areas of a house and lead to extended and ongoing wetting and drying. Building materials will deteriorate in contact with wet silt, and mould growth can occur.

2.10. Chapter overview

It is established that population growth and city growth puts pressure on fossil fuel reserves to meet the increasing demands of worldwide population. However, fossil fuel as non-renewable resources are finite and with the prospect of depletion of the reserves, their rate of consume makes its use unsustainable. Additionally, fossil fuel consumption is closely linked to global CO_2 emissions which is one of the primary greenhouse gases in Earth's atmosphere that are responsible for one of the greatest contemporary threats to the planet – climate change. Although climate change is already happening to an extent, the predictions for future scenarios are distressing with changes in the climate systems expected to occur such as an increase of the air temperatures, extreme precipitation events becoming more common and the rising of the mean sea levels which in extreme cases can lead to total submergence of low lying islands. As already some climatic adversities are or will be irreversible, the construction sector should provide solutions for resisting their effects.

The concept of sustainability was generated to provide response to these issues by identifying and implementing three main goals for sustainable development; economic development, social development and environmental protection.

In this context, the construction sector is held accountable for large quantities of energy consuming activities and great amounts of emissions from production of its materials to operation. Despite this reality, buildings have the ability to create major contributions to a more sustainable future by integrating elements of economic efficiency, social responsibility and environmental performance.

In sum, the construction sector must address two fundamental principles:

- To adapt to future hazards and to climate change effects by incorporating resilient measures in construction;
- To contribute for climate change mitigation by developing sustainable strategies.

In the aftermath of natural disaster destruction can be widespread and leave populations without a home. Housing recovery is a complex issue that cannot be addressed in a unilateral approach and there are many options to restore housing in a post-disaster scenario. While natural disasters are considered a loss event, they also provide an opportunity to build back better and safer.

Despite this fact, most of the times the reconstruction process in neglected and the risks of future hazards ignored. By doing so, the buildings become vulnerable and the disaster scenario is likely to repeat again.

In 2014, floods resulted in approximately 120 natural disasters – accounting for the greatest recorded number of natural disaster in the same year – produced more than 50 USD billion dollars as economic damages and displaced 6,2 million people, in 2013. It therefore becomes evident that housing should address flood events when sited in flood prone areas.

Three main physical structures destined to house populations who lost their houses following natural disasters were identified: tents, prefabricated shelters and permanent housing, all of which have advantages and disadvantages and can be used throughout the housing recovery process.

Tents are used as immediate shelter relief since they are easy to transport, assemble and generally accepted. Prefabricated shelters are intended to provide better conditions but cannot address all the residents' needs.

While tents and prefabricated shelters are a form of temporary shelter, these structures tend to become permanent and are unable to resist future flood events. The often result is that once flooding of these structures happens, they are rendered destroyed and leave once again the population homeless. It therefore becomes relevant to address the effects of floods in these structures if they are settled in an area which is expected to become inundated. Tents and prefabricated shelters provide little to no flexibility, consequently most flood resilient measures were based on avoidance of areas that are prone to flooding. Flood resilient measures for tents and prefabricated shelters are summarized in tables 2.1 and 2.2.

The last step of the housing recovery process is permanent housing where families are expected to live permanently and the structures are designed to be durable. Permanent housing takes many forms, but once again tend to neglect future hazards that are likely to impact. It is of high priority to address flood resilient housing when establishing settlements in flood prone areas.

In conclusion, floods are the most occurring natural disaster of all and building construction should be resilient enough to resist its consequences, by incorporating a set of key measures and considerations into the housing. The following chapter provides a proposed methodology to address flood resilient housing.

Chapter III

METHODOLOGY FOR FLOOD RESILIENT HOUSING

3.1. Conceptualization of the methodology

Since often permanent solutions fail in the event of flooding and do not contemplate the upcoming hazards, engineering should have a central role in contributing for a greater resilient response. To do so, it is necessary to develop a methodology for achieving flood resilience in permanent housing.

While the best way to achieve durable solutions for housing is to avoid building in flood prone areas, many times it is not possible to do so, meaning permanent housing should address flood events. Therefore, the methodology for flood resilient housing should be applied when building permanent housing in an area in risk of flooding.

The proposed methodology for flood resilient houses is composed by six steps and it is based in the Federal Emergency Management Agency (FEMA) system. FEMA is an USA agency created in 1978 for the purpose of coordinating responses to disaster that surpass the resources of local and state authorities. With a vast array of capabilities and programs created to manage disaster from mitigation to the emergency stage, FEMA is also responsible for managing the National Flood Insurance Program (NFIP).

The NFIP was designed to reduce the impact of flood events on public and private structures by allowing affordable insurance for property owners and encouraging communities to adopt and enforce management regulations in flood prone areas. To understand which areas of USA are prone to flooding, several studies are conducted periodically by FEMA, which culminate on the creation of National flood insurance maps. These same maps display flood prone areas within the country divided into flood zones according to the risk of flooding that the area is subjected to. While in the past national flood insurance maps could only be accessed by requiring the maps to FEMA, since 2004 FEMA began a process of digitizing the maps which depict flood zones and supporting data. Nowadays, many regions have digital national flood insurance maps which can be used to determine flood zones of a specific area. FEMA's flood maps can be used in urban planning, by the insurance industry and by communities to understand how to protect their property.

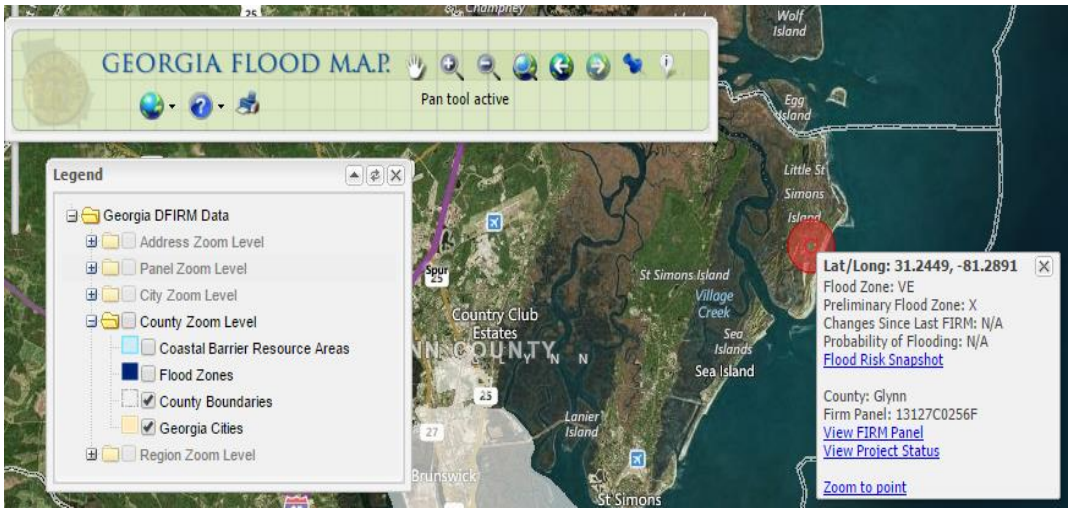


Figure 3.1 – An example of a digital flood insurance rate map of the state of Georgia, USA (map.georgiadfirm.com)

To the effect of adequate construction in flood prone areas, FEMA provides requirements and recommendations that residential buildings should address according to the respective flood zone. The FEMA system was adopted as a methodology for flood resilient housing because the requirements and recommendations for construction should be implemented according to the flood risk of an area.

After using FEMA's designation flood zone system, four main criteria that are fundamental to flood resilient housing were identified: Site selection, Design, Foundations and Materials. Throughout FEMA's available documents, requirements and recommendations for flood resilient housing were gathered under the same criteria in accordance to flood zones so that implementation of said methodology can be systematized. As NFIP is uses United States customary units, all values relevant to this methodology were converted to International system of units and rounded up to the second decimal place in order to obtain conservative values.

Although the methodology for flood resilient housing uses FEMA flood zones and many requirements and recommendations for construction in flood zone areas, it differs from the US system in its use of resilience criteria, its systematization throughout the project and its inclusion of requirements that were found to be fundamental in literature, but absent from FEMA's system. For instance, the site selection criterion is composed of several requirements that are not included in FEMA's system, but were found to of high value to achieve resilient housing.

The following figure illustrates the six steps that should are considered in this methodology for flood resilient housing:

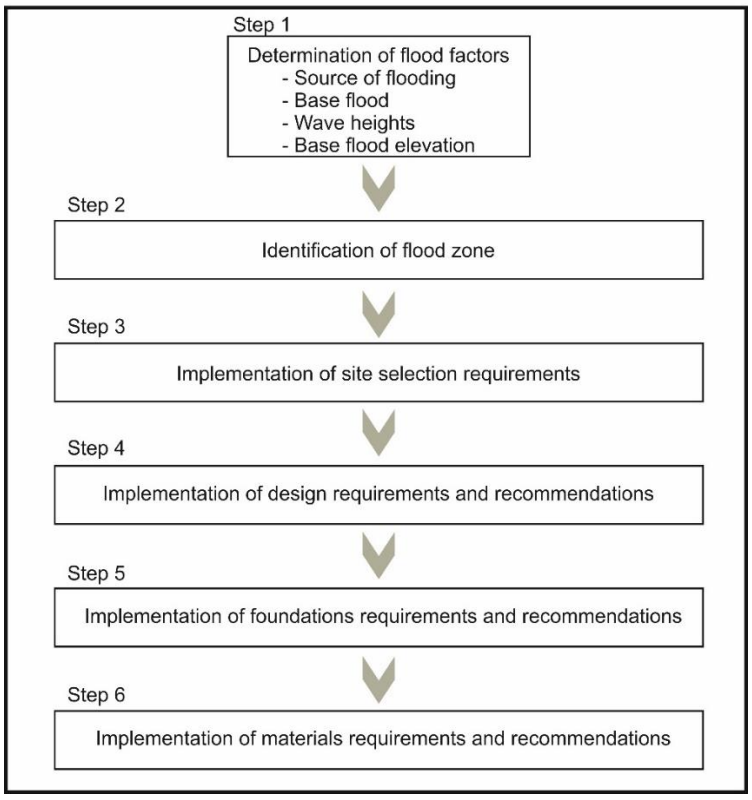


Figure 3.2 – Methodology for flood resilient housing

The methodology for flood resilient housing requires as a first step to determine flood factors that will constitute fundamental information about what the future building in a flood prone area will be subjected to.

After determined all the relevant flood factors, step 2 consists in the identification of the flood zone on which the building will be located. All the following steps will be largely influenced by the correct attribution of the flood zone.

Step 3 marks the implementation of site selection requirements in order to avoid or reduce the effects of floods in buildings.

Step 4 consists in the implementation of design requirements and recommendations in accordance to the previously established flood zone.

Step 5 requires the implementation of foundation requirements and recommendations in accordance to the previously established flood zone.

Step 6 consists in the implementation of building materials requirements and recommendations in accordance to the previously established flood zone.

3.2. Determination of flood factors

Data relevant to flood characterization can be assessed by analyzing the historic of a region and projections for the same area. To identify in which flood zone the region is under, it is necessary to determine:

- Source of flooding;
- Base flood;
- Heights of potential waves;
- Base flood elevation.

The base flood is defined as the 100-year flood or the flood having a one percent chance of being equaled or exceeded in any given year. Base flood elevation or BFE refers to the computed elevation above mean sea level to which floodwater is anticipated to ascend during the base flood (FEMA, 2008).

BFE therefore addresses several important flood factors at once such as flood frequency, flood depth and flood sources. Although BFE is a major factor in determining the flood zone of an area, its calculation is not addressed due to being a complex process that is dependent of several elements that cannot be easily determined. However in regions subjected to wave action such as coastal zones, BFE should be the sum of 100-year-stillwater elevation and the anticipated maximum wave heights (FEMA, 2007).

3.3. Identification of flood zone

Once flood factors for an area are collected, it is possible to attribute a flood zone. Currently FEMA labels several flood zones according to flood factors, but only five were considered relevant since recommendations and requirements are provided for the same five – V zones, Coastal A zones, A zones, B or X (shaded) zones and C or X (unshaded) zones. Based on the flood factors previously established, flood zones are differentiated according to the level of risk in high risk areas, moderate risk areas and minimal risk areas. The following table provides for the description of flood zones from high risk areas to minimal risk areas.

Table 3.1 – Flood zones
(www.fema.gov)

High Risk Areas	
V ZONES	Areas along coasts subject to inundation by the 1-percent-annual-chance flood event where BFE surpasses ground elevation by more than 1,83 m and with additional associated hazards such as storm-induced waves greater than 0,92 m.
COASTAL A ZONES	Areas subjected to inundation by the 1-percent-annual-chance where the principal source of flooding will be astronomical tides, storm surges, seiches or tsunamis and not riverine flooding. During base flood conditions, the potential for breaking wave heights between 0,46 m and 0,92 m will exist. In Coastal A zones, the difference between BFE and ground elevation is between 0,92 m and 1,83 m.
A ZONES	Areas subject to inundation by the 1-percent-annual-chance flood event generally determined using approximate methodologies. In coastal zones, A zones are areas with shallow flooding only where potential for breaking waves and erosion is low and wave heights have less than 0,46 m. In A zones, BFE surpasses ground elevation by less than 0,92 m.
Moderate Risk Areas	
B or X ZONES (shaded)	Areas of moderate flood hazard, usually the area between the limits of the 100-year and 500-year floods. These zones are also used to designate base floodplains of lesser hazards, such as areas protected by levees from 100-year flood, or shallow flooding areas with average depths of less than 0,31 m or drainage areas less than 2,59 km².
Minimal Risk Areas	
C or X ZONES (unshaded)	Area of minimal flood hazard, usually depicted on Flood maps as above the 500-year flood level. These zones may have ponding and local drainage problems that don't warrant a detailed study or designation as base floodplain. Zone X is the area determined to be outside the 500-year flood and protected by levee from 100-year flood.

Whenever an area is located in between flood zones it is considered to be within the flood zone of higher risk. The following figure illustrates the differentiation of flood zones according to BFE, wave heights and stillwater depths.

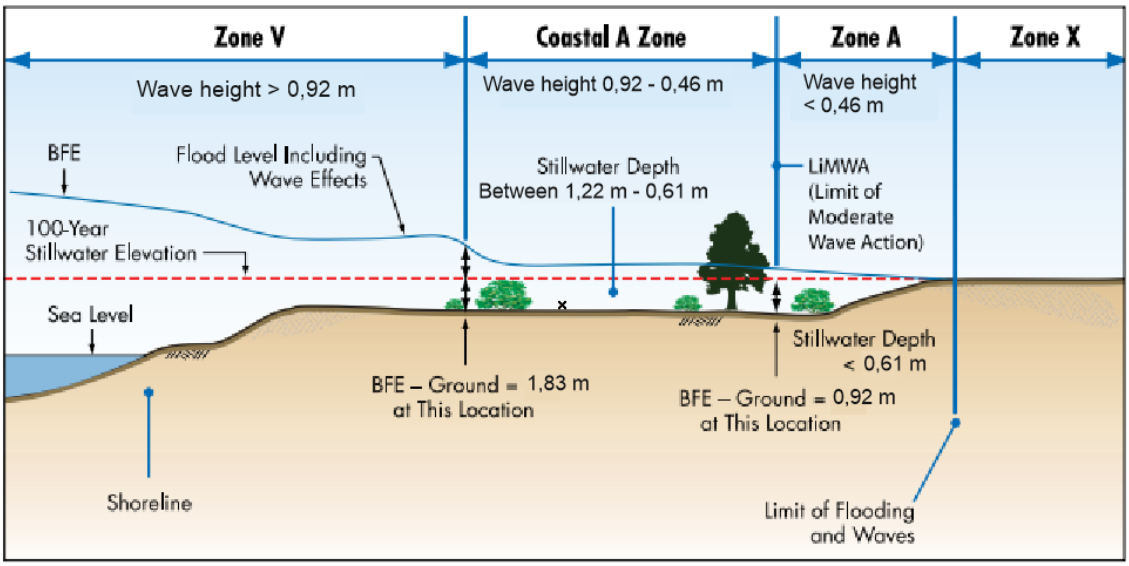


Figure 3.3 – Relationship between BFE, flood zones and wave heights
(Adapted from FEMA, 2008a)

3.4. Flood resilience criteria

Based on the flood impacts and mechanisms that affect buildings, there were identified four main criteria that should be addressed in order to provide for flood resilient housing:

1. Site Selection - Suitable sites for construction of houses have to be chosen anticipating flooding
2. Design – Approaches for the resilient design ought to be taken to minimize the consequences of floods.
3. Foundations – Foundations must be consistent with the soil where the house is settled to avoid geotechnical failure and address the damaging effects of the floodwaters and related phenomena.
4. Materials – Building materials have to be carefully selected so that in case of flooding they don't underperform and lose their resistance or properties.

These four main criteria should be used as consecutive guiding steps for maximum resilience of housing, starting from site selection to building materials. The following subchapters will expand further the criteria for flood resilient housing.

3.4.1. Site Selection

Site selection is the only criterion that isn't associated with the flood zones previously established since it is based in flood avoidance measures. Site selection is also composed of several requirements that aren't associated with FEMA requirements.

Site selection is the critical factor in order to avoid flooding. Building in an unlikely place to be flooded is the most important way to protect the dwellings. Housing and settlements should therefore be built above the highest recorded flood level or as high as possible, avoiding land depressions and sites of probable flooding.

Embankments consisting in a raised structure made of earth or gravel can also be made near the settlements in order to hold back the waters.

Buildings should not be located in sites at risk of landslides, rockfalls or any other debris that is likely to slide and result loss of life and structural damage. Being able to construct shelter and settlements on stable ground means reducing the chances of the risk of a building to collapse during flooding (IFRC, 2011).

When establishing a settlement in a flood-prone site, it's important to have information about the areas that are susceptible to an overflown of water, in order to avoid those sites. Flash flooding particularly occurs in a short amount of time with disastrous outcomes, meaning it's important to predict where it is its likely path.

Settlements should be established so that access is easy and fast for evacuation and rescue. Drainage systems are another important factor in guaranteeing resistance to flood events. Settlements should have adequate, efficient well-designed and well-maintained drainage systems to convey rainwater, and avoid flooding derived from storms or heavy precipitation (IFRC, 2011.

In shores, coastal lines or in areas near rivers, planting groundcover plants acts against erosion and is an effective way to protect shelters and settlements (IFRC, 2011).

Planting bushes and trees as a wall of defense between settlements and river banks or coastlines helps to create a barrier to hold back the water from entering the settlement zone (IFRC, 2011).

Collective buildings such as schools or hospitals – which can be used as collective centers during emergencies – should be easily accessible, flood-resistant and have higher performance for strains and stresses created by moving waters. Collective buildings should also be located above anticipated flood levels (IFRC, 2011).

Table 3.2 provides the requirements within the site selection criterion that should be met so that buildings have maximum resistance to flood events.

Table 3.2 – Site selection Requirements for permanent housing

Site Selection Requirements
Building in areas in high risk of flooding must be avoided
Building in sites or near locations at risk of landslides must be avoided
Building in areas at risk of geotechnical failure due to piping, batter slumping, erosion and swelling and shrinking of the soil must be avoided
Trees, bushes and groundcover plants should be planted in coastlines or in riverine settings
Settlements must be established in a way to make it easier for evacuation
Houses sited in flood prone areas should be near collective buildings which should be above flood levels

3.4.2. Design

The design criterion comprises a set of measures that should be incorporated in buildings in order to mitigate and reduce the effects of floods. By anticipating flooding and implementing the same design

measures housing is left less vulnerable to floods. Design criterion therefore addresses design-related characteristics that the building should possess or avoid so that it becomes flood resilient in accordance to the previously established flood zone.

Wet and dry flood proofing

When building in flood prone areas, houses can be wet or dry flood proofing. While dry flood proofing is an approach that involves building permanent or temporary barriers such as levees, door seals or using sandbags, leaving the house intact and dry in the event of floods, dry flood proofing requires maintenance, can draw issues and is an overall expensive measure that often isn't possible in the context of emergency housing. Dry flood proofing isn't also appropriate where the flood depths can be high.

On the opposite, wet flood proofing allows the water to enter the house while avoiding water loads to build in the external walls which can cause structural damage and collapse of the house. After inundation, flooded buildings that anticipate flooding only need quick repairs and cleaning, and can be reused in a short period of time after the flood. Designing walls, doors and windows to resist hydrostatic forces that eventually can increase due to the rise of the water level is costly, particularly when flood events are rare. The best option for this scenario is to allow the water to come inside the house, balancing the hydrostatic forces in a wet flood proofing approach. If the building is using brick as a construction material for walls, without any additional measures, brick walls can collapse because of sideways forces since the mortar bonding in the brickwork has low strength in tension. Both load bearing or external cladding brick walls have to address to flood events since they are the weakest link in the wall system (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

That being said, wet flood proofing only remains practical in a limited number of situations and in accordance to NFIP can only be used in A zones or lower risk zones and limited to use in enclosed areas below predicted BFE, for the sole purposes of parking, building access or limited storage (FEMA, 1993).

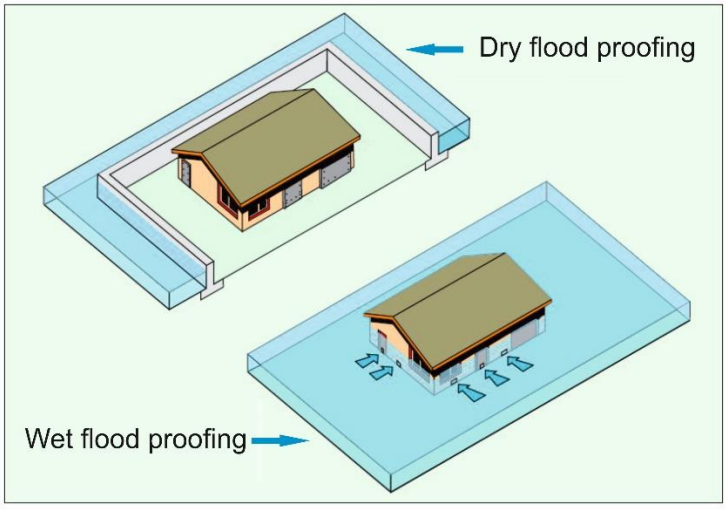


Figure 3.4 – Dry and wet flood proofing
(Adapted from Hawkesbury-Nepean Floodplain Management Steering Committee, 2006)

To that effect, it is important to design flood vents or flood openings which are openings in the building walls to allow the free passage of water automatically in both directions without the need for intervention. Flood vents are designed to balance the water levels sufficiently quick to limit a difference between the inside and outside water levels. Among several options that can be used as flood vents, are concrete blocks turned sideways, insect screening, air vents and brickwork (FEMA, 1993).

Building codes may exist on the country for calculating flood openings, otherwise and to comply with NFIP it is required (FEMA, 1993):

- There is 6,45 cm² of net open area for each 0,09 m² of enclosed floor;
- Each enclosed area should have a minimum of two openings; if there are several enclosed areas, each must have openings in its respective exterior walls;
- The bottom of each opening must be no more than 30, 5 cm above the higher of the interior or exterior grade;
- Screen, grates, fixed louvers or other covers or devices must not block the flow of floodwaters into and out the enclosed area.

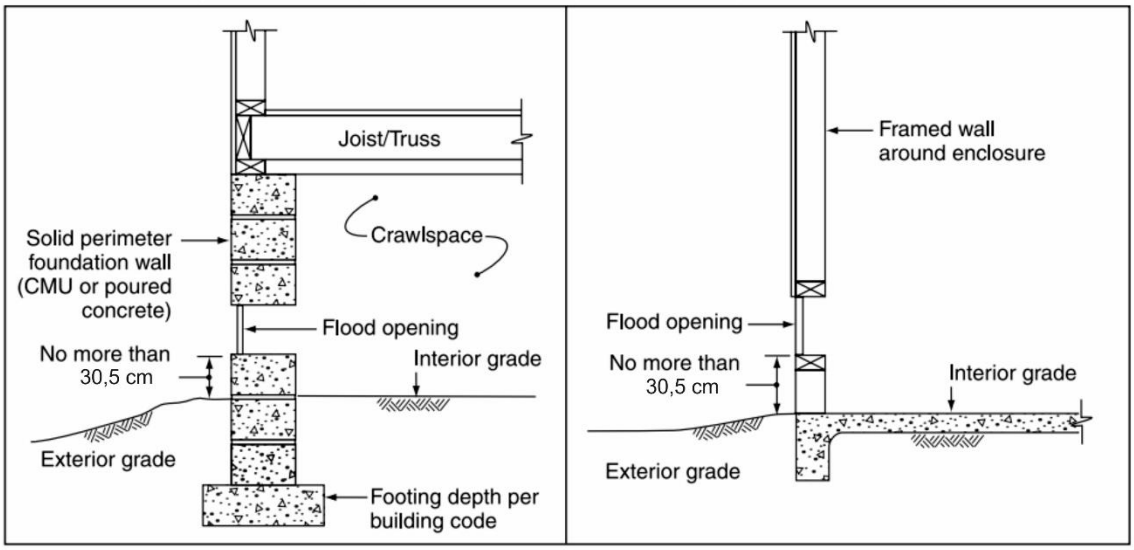


Figure 3.5 – Typical enclosures with flood openings
(FEMA, 2008c)

Flood vents aren't the only option for openings. Weepholes can be provided at the base of the walls in brickwork construction, as well as external doors with openings at the bottom known as hinged pet doors. Internal wall vents can also be considered in cases where houses have many divisions and differential of water levels in them is a concern.

Floor levels

When building permanent housing in the emergency scenario, single story-houses are often designed to accommodate residents, particularly in developing countries, mainly due to budget constraints. However, if buildings are situated in flood-prone areas, this means the ground floor is exposed to the flood hazard without the possibility of occupiers to store their belongings and retreat to higher levels within their own homes. Single-story houses have little flexibility for residents to give priority in saving their own assets during a flood event, particularly when water depths can be high. However, if the roof used is pitched, single-story houses can be designed to make use of the roof space to store valuable content (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

Double-story houses or multi-level houses have the advantage of providing a flood free area to store belongings located in the upper floor level, therefore reducing damage costs after flooding. While costly, one of the best options for building a two-story house is using full brick masonry with a concrete ground slab and a suspended concrete slab on the first floor. A more affordable possibility is to combine the flood resistant materials in the first floor and use less expensive and less resistant flood materials in the upper level, this means for example using concrete slab-on-ground and a suspended timber first floor

with upper floors consisting of clad frame or brick veneer (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006).

Floor levels requirements were added to the methodology since they provide greater levels of flood resilience, becoming mandatory in high risk areas: V, A and Coastal A zones.

Elevated Buildings

Elevated houses are typically buildings designed to address flooding raised off the ground in foundations made of timber, concrete or steel. The building is raised so that floodwaters can't access the internal living space of the house. The ground level which is open reduces the damage to the house by lessening the impact of the floodwaters on the structure. Elevated houses can be considered whenever floodwater velocity is a threat to a standard single-story house.

Elevation of houses is an important factor for buildings to achieve resilience to floods. NFIP stipulates that in A and Coastal A zones, the top of the lowest floor should be at or above the BFE. In V zones, NFIP requires the lowest horizontal structural member of the building to be at or above the BFE. Horizontal structural members are considered to be obstructions that can transmit the force of wave impacts to the rest of the structure such as the lowest beam, joist or other horizontal member that is a structural member of the building.

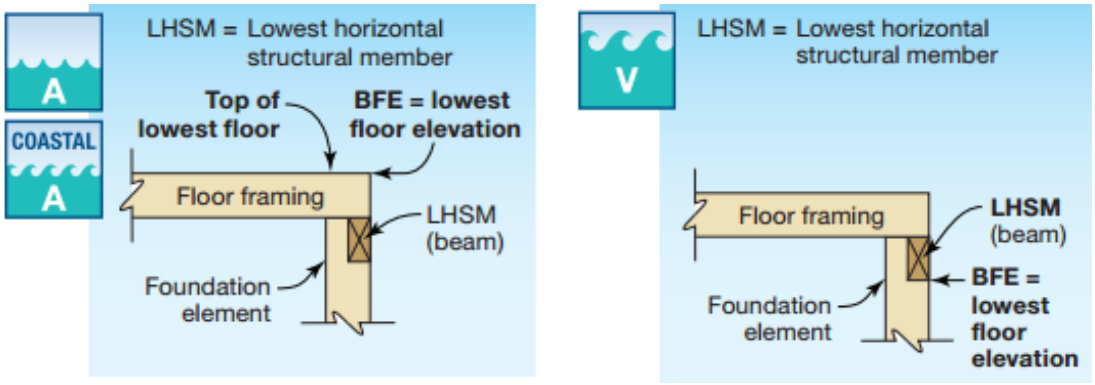


Figure 3.6 – Relationship between BFE and elevation in accordance to flood zones (FEMA, 2012)

Moreover, for V zones, NFIP requires that enclosed areas beneath the building should have breakaway walls. Breakaway walls are walls that collapse under specific lateral forces without causing damage to the building since they aren't structural. As an alternative for breakaway walls, louvers or lattice can be used.

Shape and orientation of the building

Shape and orientation building are design criteria that will affect how the building performs under a flood event. Square shaped buildings offer maximum resistance to horizontal loadings than other shapes. As water velocities become a concern, it's necessary to avoid building long walls because the building acquires a higher degree of vulnerability not only due to horizontal hydrostatic and hydrodynamic loads but also due to debris loading impact. By building houses that have side ratios less than 1:2 without long and narrow designs, the building becomes more resistant to water movements. It is also important that "L" shaped houses possess legs that aren't substantially different in length – a maximum difference of 1:1,5 is recommended.

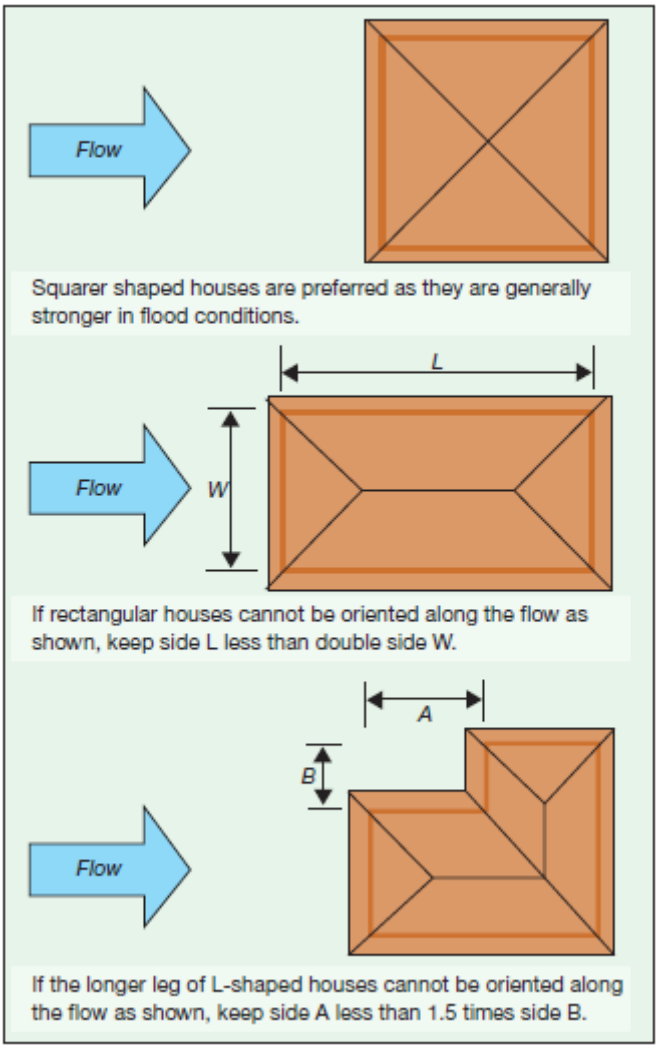


Figure 3.7 – Requirements for shape and orientation of the building
(Hawkesbury-Nepean Floodplain Management Steering Committee, 2006)

If the building is designed to be wet proof, orientating the house across the flow with openings inside the walls, designed to allow the water to flow without collapsing the structure can be considered and implemented. Although NFIP doesn't provide minimum requirements for shape and orientation of the house, these factors were considered to be important and were included in the requirements for A, coastal A zone and V zones.

The following table displays the requirements and recommendations for the design of resilient buildings in relation to the flood zones previously established.

Table 3.3 – Design requirements and recommendations according to flood zones
(Adapted from FEMA, 2010)

Risk Areas	Design Requirements
V ZONES	Bottom of the lowest horizontal structural member of the lowest floor must be at or above the BFE. Space below the lowest floor must be free of obstructions such as building elements, equipment, or other fixed objects Double-story or multi-level houses should be preferred to single-story structures It is recommended that shape of buildings respects minimum side ratios (Figure 3.7) Elevating buildings higher than the required lowest floor elevation is recommended Enclosures areas below elevated lowest floors are only permitted for parking of vehicles, building access and storage and it is recommended to minimize its use. Walls of enclosure areas below elevated lowest floors must be designed to collapse under flood loads Minor quantities of non-structural fill can be used as long as it doesn't prevent the free passage of floodwaters Tanks must be located above-ground on the landward side of buildings, if tanks are built underground, they must be below of the predicted eroded ground elevation Basements are not permitted Utilities must be designed, located, and elevated to prevent flood waters from entering and accumulating in components during flooding. Utility lines must not be installed or stubbed out in enclosures below BFE unless flood proofed to the extent practicable.
COASTAL A ZONES	Top of floor must be at or above BFE. Elevating buildings higher than the required lowest floor elevation is recommended Double-story or multi-level houses should be preferred to single-story structures It is recommended that shape of buildings respect minimum side ratios (Figure 3.7) Basements are not permitted Enclosure areas below elevated lowest floors are only permitted for parking of vehicles, building access and storage and must be equipped with openings Minor quantities of non-structural fill can be used as long as it doesn't prevent the free passage of floodwaters Tanks must be elevated or anchored to be stable under flood loads, whether above-ground or underground. Utilities, including electrical, heating, ventilation, plumbing, air-conditioning equipment (including ductwork) must be elevated above the BFE, or specifically designed to prevent water from entering or accumulating within the components during flooding
A ZONES	Top of floor must be at or above BFE. Elevating buildings higher than the required lowest floor elevation is recommended Double-story or multi-level houses should be preferred to single-story structures It is recommended that shape of buildings respect minimum side ratios (Figure 3.7) Basements are not permitted Enclosure areas below elevated lowest floors are only permitted for parking of vehicles, building access and storage and must be equipped with flood openings Encroachments are permitted only if will not result in any increase of the flood levels Tanks must be elevated or anchored to be stable under flood loads, whether above-ground or underground. Utilities, including electrical, heating, ventilation, plumbing, air-conditioning equipment (including ductwork) must be elevated above the BFE, or specifically designed to prevent water from entering or accumulating within the components during flooding
B or X ZONES (shaded)	It is recommended that lowest floor is at BFE for the nearest higher risk zone.
C or X ZONES (shaded)	It is recommended that lowest floor is at BFE for the nearest higher risk zone.

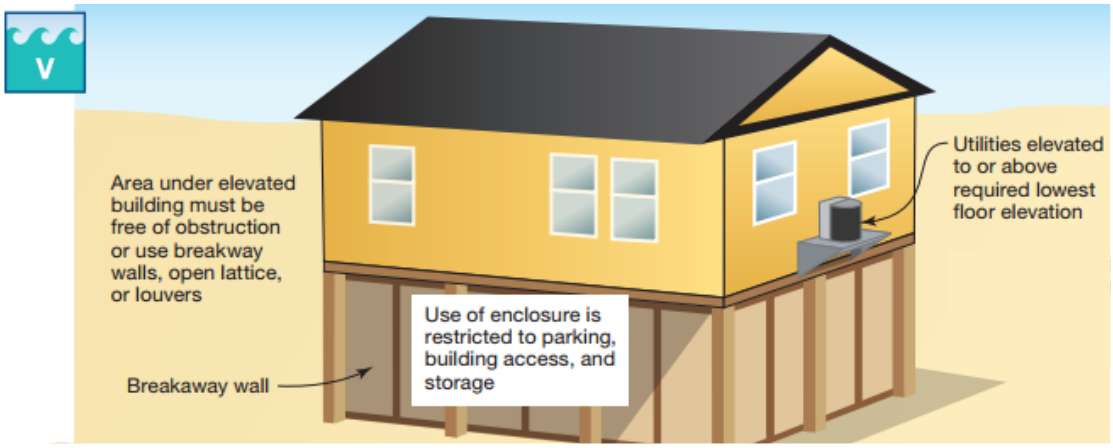


Figure 3.8 – Compliant housing design with requirements for V zones
(FEMA, 2012)

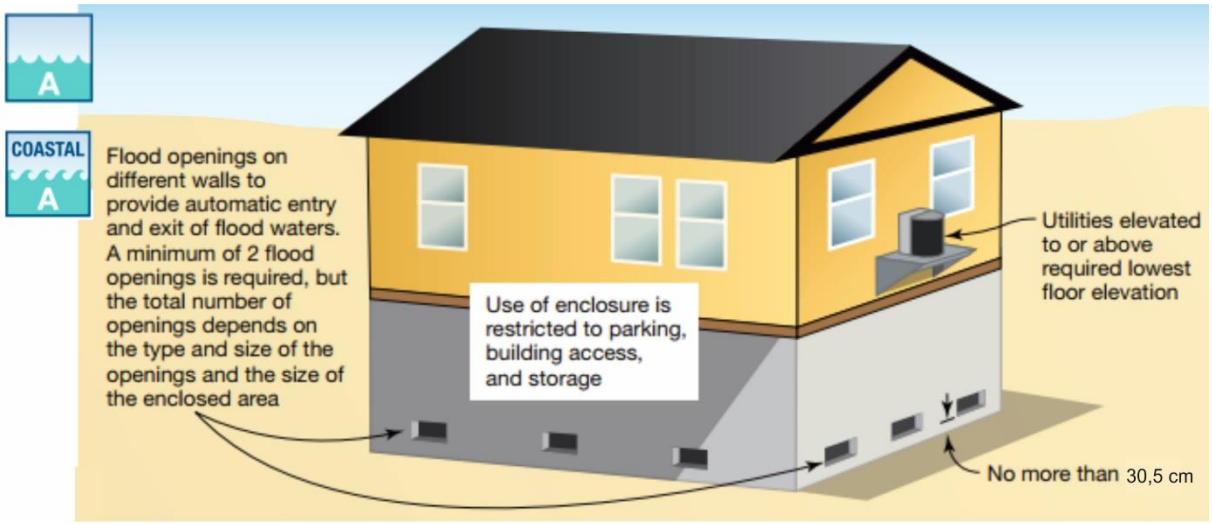


Figure 3.9– Compliant housing design with requirements for A and Coastal A zones
(FEMA, 2012)

3.4.3. Foundations

Foundations were identified as a main guiding criterion for flood resilient housing because foundations are critical elements of the building, subjected to flood forces and its effects and should be selected and built adequately according to the predicted flood conditions. Failure of foundations can result in structural instability that can have as consequence the collapse of the building.

To address flood events, foundations can be grouped in closed or open foundations. Although typically houses have only one type of foundation, some have both (FEMA, 2008a),

Closed foundations have foundation walls – which are usually load-bearing walls – extending from the footing to the first floor of the building around its perimeter. Below the first floor, foundation walls are

generally made of concrete or masonry and enclose an area that can serve as basement, crawlspace or consists in soil below a floating slab.

Closed foundations should be used in circumstances where flood depths and flood forces are low. Examples of closed foundations for flood resilient housing are given below with brief information about the types of foundations and requirements and recommendations.

Crawlspace foundations

Crawlspace foundations are designed to raise buildings over an enclosed area below the first floor, allowing for ground floors to be elevated above the base flood elevation. Crawlspace foundation is similar to pier and beam foundation since they consist in piers and beams supporting the house but include a closed and continuous wall foundations from the ground to the first floor, trapping an empty area below the first floor. This type of foundation is susceptible to erosion and to wave forces, therefore, the use of crawlspaces are prohibited in V and isn't recommended in coastal A zones. Crawlspaces can be used in A zones and should be designed to have flood openings to equalize water pressures as discussed previously in the design subchapter.
Since crawlspaces are closed foundations, hydrodynamic loads can cause structural damage to the building, therefore crawlspace construction should be used in circumstances where predicted water velocities don't exceed 1,52 m/s (FEMA, 2011).

Stemwall foundations

Stemwall foundations are closed and typically shallow foundations that also elevate the building on foundation walls running across the perimeter of the house, while the area below the first floor is backfilled with structural fill or sand supporting the floor slab. Stemwalls are usually constructed with the use of reinforced concrete or masonry after which they are filled with engineered compacted fill.
Stemwall foundations have been observed to resist storm events better than crawlspace foundations and its use reduces the issues that crawlspaces frequently have.

However, stemwall foundation have some disadvantages because during periods of high level depths, backfill soil may become flooded and result in damage to the slab. Capillary action may be also an issue in some soils such as sand, causing water and moisture to ascend and damage the slab. Stemwall foundations can be used in A zones and are prohibited in V zones. While stemwall foundations are permitted in coastal A zones, its use is discouraged and open foundations are recommended (FEMA, 2010).

Open foundations are foundations composed of piles, piers or columns made of concrete, masonry, steel or timber, supporting the building, where the first ground floor is usually higher than in the case of closed foundations. Enclosed areas below the first floor should be constructed so that they collapse and allow the free passage of water in situations of high loads resulting from flooding. To that end, breakaway walls, which are non-structural walls, should be built in enclosed areas below the first floor of houses that have open foundations. Open foundations should be used whenever predicted flood depths are high, water velocity is high and potential for erosion and scour exists (FEMA, 2010). Examples of open foundations for flood resilient housing are given below with brief information about the types of foundations and requirements and recommendations.

Pier and beam foundations

Usually piers are shallow foundations made of reinforced concrete and grouted masonry which are placed on footings to resist lateral, uplift and downlift loads.
For low-depth flooding, where flood forces and erosion potential are small, pier and beam foundations are recommended (FEMA, 2005). Pier and beam foundations raise the floor above the ground while providing for an open area below where the water can flow freely. In coastal areas, discrete footings

supporting piers are to be avoided since they are highly subjected to lateral loads resulting in rotation of footings and the collapse of structure.
Traditional pier and beam foundation is generally cheaper than other options designed for elevated buildings. Footings have to be designed for the specific soil conditions, with strong connections between the pier and its footings. Footings should be below the anticipated scour and erosion depth to maintain embedment. In coastal zones, in cases where pier is made of grouted masonry, careful application of mortar must be ensured to prevent saltwater to invade the core of bricks and corrode the rebar.

Piers can be used as foundations in A, B or X (shaded), C or X (unshaded) zones. Despite this, piers can be used in very specific circumstances in Coastal A zones and V zones if potential for erosion and scour is very low and water levels aren't considered a threat to the integrity of the house (FEMA, 2010)

Pile foundations

Pile foundations consist in long and slender structural elements that are used for elevated buildings usually constructed of steel, precast concrete or treated timber. Pile foundations are considered to be deep foundations since they are built deep in the ground so that they resist vertical and lateral loads by using the deeper layers of soil's resistance.

Pile foundations are used in situations where flood depths and velocities can be high, allowing the floodwaters to move below the elevated floor without damaging the building. Some of the fundamental aspects of pile foundations are the pile size and spacing between single elements, embedment depth, installation method, bracing and connections to the building.

When using piles in combination with grade beams, greater resistance to rotation of the building is achieved, although in flood prone areas, grade beams should be designed to resist lateral flood loads resulting from hydrostatic, hydrodynamic forces and debris impacts and shouldn't support any vertical load carrying elements such as floor slabs (FEMA, 2013).

Micropiles foundations

Micropiles are foundations that function similarly to deep pile foundations although micropiles are typically smaller in diameter than traditional piles and are designed to resist compressive, tensile or shear structural loads in diversified situations. Micropiles can be bored, grouted-in-place and incorporate steel pipes as well as steel reinforcement.

Micropiles foundations can be appropriate for flood resilient construction since they can be associated with columns or piers, elevating the building while providing for scour and erosion protection by transferring loads to deeper and more stable strata (FEMA, 2013).

The small diameters of micropiles reflects in its limited resistance to lateral loads when compared to piles foundations, and may require grade beams or bracing to resist flood loads. Micropiles can be used in all types of flood risk zones (FEMA, 2013).

The following table systematizes the foundation requirements and recommendations and provides examples of adequate foundation types according to the flood risk areas (FEMA, 2013).

Table 3.4 – Foundation requirements and recommendations according to flood zones (Adapted from FEMA, 2010)

Risk Areas	Foundation Requirements	Adequate Foundation types
V ZONES	Open foundations are required and closed foundations are not permitted Foundation materials should be resistant to water and its effects Nonstructural fill is allowed for minor landscaping and site drainage as long as fill doesn't interfere with free passage of floodwaters and debris or cause turbulence Foundations should be properly anchored to resist lateral movement, flotation and collapse Deep foundations are recommended to improve the building performance Use of piers isn't recommended unless bedrock is near surface and potential for erosion and scour is low	piles foundations pier and column foundations columns and micropiles
COASTAL A ZONES	Closed foundations aren't recommended It is recommended that foundations should be designed and constructed with V zone type foundations Use of piers isn't recommended unless bedrock is near surface and potential for erosion and scour is low When structural fill is used, compactation of fill is required Protection against scour and erosion must be provided when necessary	piles foundations pier and column foundations columns and micropiles
A ZONES	Closed and open foundations are permitted Closed foundations below elevated houses must have flood openings Foundations should be properly anchored to resist lateral movement, flotation and collapse Foundation materials should be resistant to water and its effects When structural fill is used, compactation of fill is required Protection against scour and erosion must be provided when necessary	slab on compacted fill slab cap on filled stemwall crawlspace foundations piles foundations pier and beam
B or X ZONES (shaded)	It is recommended to provide for deep foundations where erosion and scour are possible Foundation materials should be resistant to water and to its effects	crawlspace foundations slab on compacted fill
B or X ZONES (shaded)	It is recommended to provide for deep foundations where erosion and scour are possible Foundation materials should be resistant to water and to its effects	crawlspace foundations slab on compacted fill

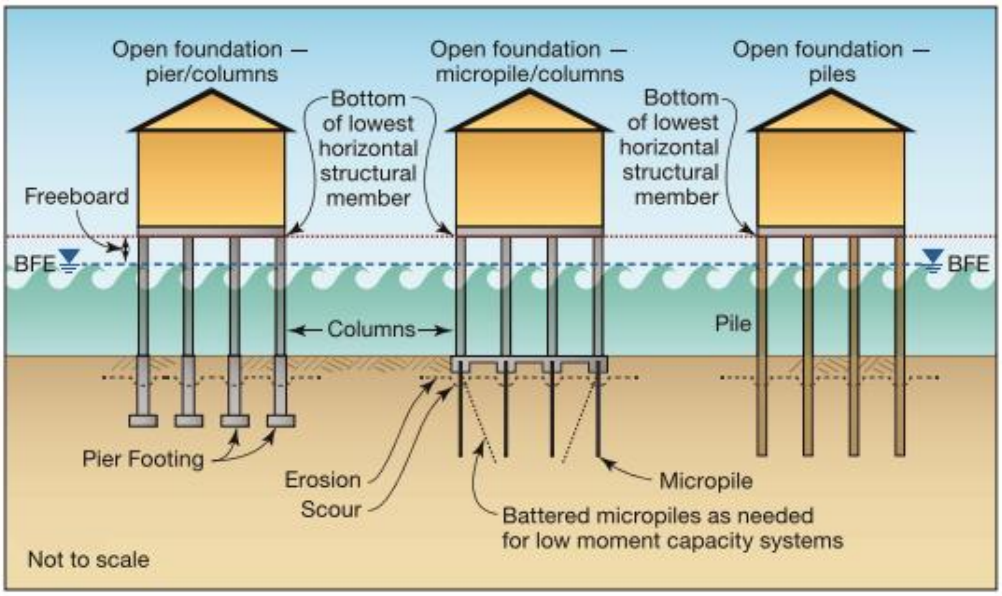


Figure 3.10 – Adequate foundation types for V zones
(FEMA, 2013)

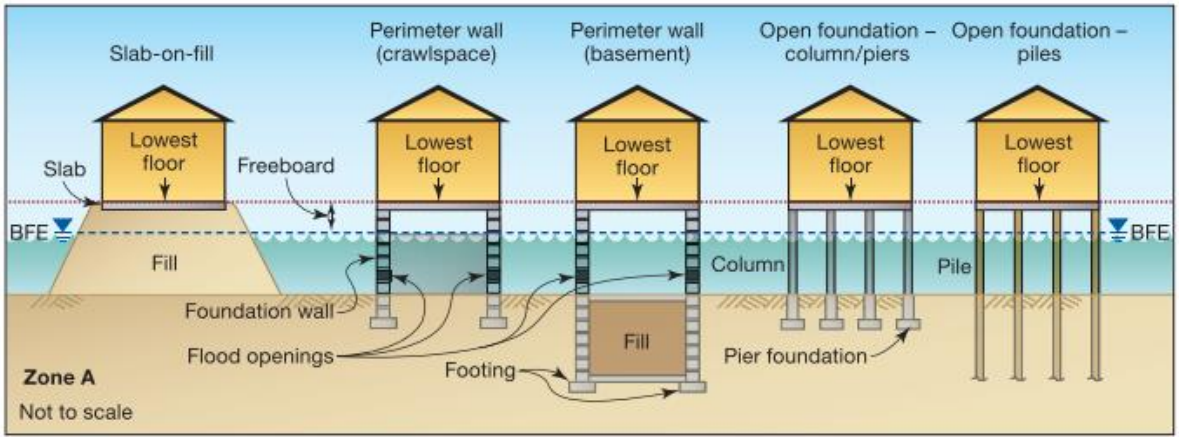


Figure 3.11 – Adequate Foundation types for A zones
(FEMA, 2013)

3.4.4. Materials

Materials criteria were found to be a fundamental factor in flood resilient construction because flood events can damage construction material in numerous ways, affecting structural and non-structural building properties.

Materials criteria are compliant with the NFIP and are systematized according to the flood zones previously established. According to NFIP, flood damage-resistant materials are construction materials, components or systems that are able to resist direct and prolonged contact – at least 72 hours – floodwaters and its contaminants without sustaining damage requiring more than cosmetic repair such

as cleaning and sanitizing. To that effect, NFIP has organized building materials into 5 classes and divided classes between acceptable for flood prone construction and unacceptable (FEMA, 2008).

Table 3.5 describes the five classes of construction materials from those who are highly resistant to floodwaters to those who don't have any resistance to floods.

Table 3.5 – Class description of materials
(FEMA, 2008b)

	Class	Class Description
Acceptable	5	Highly resistant to floodwater damage that may contain pollutants such as sewage, chemicals, heavy metals and other toxic substances. Resistant to damage caused by moving water up to 1,52 m/s. These materials can survive wetting and drying and may be successfully cleaned after a flood to render them free of most harmful pollutants. Materials in this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure.
	4	Resistant to floodwater damage that may contain pollutants such as sewage, chemicals, heavy metals and other toxic substances. 4 Class materials resist to wetting and drying, but are less durable when exposed to moving water up to 1,52 m/s. These materials can resist to wetting and drying and may be successfully cleaned after a flood to render them free of most harmful pollutants. Materials in this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection.
Unacceptable	3	Resistant to clean water damage, but not floodwater damage. Materials in this class may be submerged in clean water during periods of flooding. These materials can survive wetting and drying, but may not be able to be successfully cleaned after floods to render them free of most harmful pollutants.
	2	Not resistant to clean water damage such as potable water or wastewater collected from normal uses such as laundry, bathing, etc. Materials in this class are used in predominantly dry spaces that may be subject to occasional water vapor and/or slight seepage. These materials cannot survive the wetting and drying associated to floods.
	1	Not resistant to clean water damage such as potable water or wastewater collected from normal uses such as laundry, bathing, etc. Not resistant to moisture damage. Materials in this class are used in spaces with conditions of complete dryness. These materials cannot resist the wetting and drying associated with floods.

Only acceptable materials – classes 4 and 5 – are permitted for use below the BFE regardless of the expected or historic flood duration.

Classes 1, 2 and 3 are defined as unacceptable for areas below BFE since these materials are dimensionally unstable, they absorb or retain excessive moisture and water, they contain wood or paper products that decay or lose structural integrity, they restrict drying of materials they cover as in the cases of linoleum or rubber tiles, or they are water soluble and not resistant to alkali, groundwater seepage and vapor.

Tables 3.6, 3.7, 3.8, 3.9 and 3.10 list commonly used types of construction materials, its uses and classifications. However, the same tables do not list all available structural and finish materials, which means that materials not listed should be specifically evaluated to determine if they are able to withstand flood events.

Moreover, the combination of acceptable materials can generate construction solutions that aren't resilient to floods such as vinyl tiles with chemical-set adhesives placed over a plywood floor that result in the inability of plywood to dry. Careful consideration should be given when selecting construction materials which shouldn't be only compliant with the following tables, but also in combination with other materials.

Table 3.6 – Types, Uses, and Classifications of Materials
(Adapted from FEMA, 2008b)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls and Ceilings	5	4	3	2	1
Structural Materials (floor slabs, beams, subfloors, framing, and interior/exterior sheathing)							
Asbestos-cement board		X	X				
Brick							
Face or glazed		X	X				
Common (clay)		X		X			
Cast stone (in waterproof mortar)		X	X				
Cement board/fiber-cement board		X	X				
Cement/latex, formed-in-place	X			X			
Clay tile, structural glazed		X	X				
Concrete, precast or cast-in-place	X	X	X				
Concrete block		X	X				
Gypsum products							
Paper-faced gypsum board		X			X		
Non-paper-faced gypsum board		X		X			
Greenboard		X				X	
Keene's cement or plaster		X			X		
Plaster, otherwise, including acoustical		X				X	
Sheathing panels, exterior grade		X			X		
Water-resistant, fiber-reinforced gypsum exterior sheathing		X		X			
Hardboard (high-density fiberboard)							
Tempered, enamel or plastic coated		X				X	
All other types		X					X
Mineral fiberboard		X					X
Oriented-strand board (OSB)							
Exterior grade	X	X				X	
Edge swell-resistant OSB	X	X				X	
All other types	X	X					X
Particle board	X						X
Plywood							
Marine grade	X	X	X				
Preservative-treated, alkaline copper quaternary (ACQ) or copper azole (C-A)	X	X		X			

Table 3.7 – Types, Uses, and Classifications of Materials
(Adapted from FEMA, 2008b)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls and Ceilings	5	4	3	2	1
Structural Materials (floor slabs, beams, subfloors, framing, and interior/exterior sheathing)							
Preservative-treated, Borate	X	X	X				
Exterior grade/Exposure1 (WBP – weather and boil proof)	X	X		X			
All other types	X	X					X
Recycled plastic lumber (RPL)							
Commingled, with 80-90% polyethylene (PE)	X		X				
Fiber-reinforced, with glass fiber strands	X		X				
High-density polyethylene (HDPE), up to 95%	X		X				
Wood-filled, with 50% sawdust or wood fiber	X				X		
Stone							
Natural or artificial non-absorbent solid or veneer, waterproof grout	X	X	X				
All other applications		X				X	
Structural Building Components							
Floor trusses, wood, solid (2x4s), decay-resistant or preservative-treated	X	X		X			
Floor trusses, steel	X		X				
Headers and beams, solid (2x4s) or plywood, exterior grade or preservative-treated		X		X			
Headers and beams, OSB, exterior grade or edge-swell resistant		X				X	
Headers and beams, steel		X	X				
I-joists	X					X	
Wall panels, plywood, exterior grade or preservative-treated		X		X			
Wall panels, OSB, exterior grade or edge-swell resistant		X				X	
Wall panels, steel		X		X			

Table 3.8 – Types, Uses, and Classifications of Materials
(Adapted from FEMA, 2008b)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable			Unacceptable	
	Floors	Walls and Ceilings	5	4	3	2	1
Structural Materials (floor slabs, beams, subfloors, framing, and interior/exterior sheathing)							
Wood							
Solid, standard, structural (2x4s)		X		X			
Solid, standard, finish/trim		X			X		
Solid, decay-resistant	X	X	X				
Solid, preservative-treated, ACQ or C-A		X		X			
Solid, preservative-treated, Borate		X		X			
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Asphalt tile							
With asphaltic adhesives	X				X		
All other types	X						X
Cabinets, built-in							
Wood		X				X	
Particle board		X					X
Metal		X		X			
Carpeting	X						X
Ceramic and porcelain tile							
With mortar set	X	X					
With organic adhesives	X	X				X	
Concrete tile, with mortar set	X		X				
Corkboard		X				X	
Doors							
Wood, hollow		X				X	
Wood, lightweight panel construction		X				X	
Wood, solid		X				X	
Metal, hollow		X		X			
Metal, wood core		X		X			
Metal, foam-filled core		X		X			
Fiberglass, wood core		X		X			
Epoxy, formed-in-place	X		X				

Table 3.9 – Types, Uses, and Classifications of Materials
(Adapted from FEMA, 2008b)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls and Ceilings	5	4	3	2	1
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Glass (sheets, colored tiles, panels)		X		X			
Glass blocks		X	X				
Insulation							
Sprayed polyurethane foam (SPUF) or closed-cell plastic foams	X	X	X				
Inorganic – fiberglass, mineral wool: batts, blankets, or blown	X	X			X		
All other types (cellulose, cotton, opencell plastic foams, etc.)	X	X				X	
Linoleum	X						X
Magnesite (magnesium oxychloride)	X						X
Mastic felt-base floor covering	X						X
Mastic flooring, formed-in-place	X		X				
Metals, non-ferrous (aluminum, copper, or zinc tiles)		X			X		
Metals							
Non-ferrous (aluminum, copper, or zinc tiles)		X			X		
Metals, ferrous		X		X			
Paint							
Polyester-epoxy and other oil-based waterproof types		X		X			
Latex		X		X			
Partitions, folding							
Wood		X				X	
Metal		X		X			
Fabric-covered		X					X
Partitions, stationary (free-standing)							
Wood frame		X		X			
Metal		X		X			
Glass, unreinforced		X		X			
Glass, reinforced		X		X			
Gypsum, solid or block		X					X

Table 3.10 – Types, Uses, and Classifications of Materials
(Adapted from FEMA, 2008b)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls and Ceilings	5	4	3	2	1
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Polyurethane, formed-in-place	X		X				
Polyvinyl acetate (PVA) emulsion cement	X						X
Rubber							
Moldings and trim with epoxy polyamide adhesive or latex-hydraulic cement		X		X			
All other applications		X					X
Rubber sheets or tiles							
With chemical-set adhesives	X		X				
All other applications	X						X
Silicone floor, formed-in-place	X		X				
Steel (panels, trim, tile)							
With waterproof adhesives		X	X				
With non-waterproof adhesives		X				X	
Terrazo	X			X			
Vinyl asbestos tile (semi-flexible vinyl)							
With asphaltic adhesives	X		X				
All other applications	X						X
Vinyl sheets or tiles (coated on cork or wood product backings)	X						X
Vinyl sheets or tiles (homogeneous)							
With chemical-set adhesives	X			X			
All other applications	X						X
Wall coverings							
Paper, burlap, cloth types		X					X
Vinyl, plastic, wall paper		X					X
Wood floor coverings							
Wood (solid)	X						X
Engineered wood flooring	X					X	
Plastic laminate flooring	X					X	
Wood composition blocks, laid in cement mortar	X					X	
Wood composition blocks, dipped and laid in hot pitch or bitumen	X					X	

Finally, Table 3.11 provides requirements, recommendations and adequate material classes according to flood zones.

Table 3.11 – Requirements for materials according to flood zones
(Adapted from FEMA, 2010)

Risk Areas	Materials Requirements	Adequate material classes
V ZONES	Structural and nonstructural building materials below the BFE must be flood damage-resistant It is recommended that flood-damage resistant materials are used above the BFE It is recommended the use of lattice, insect screening or louvers instead of solid breakaway walls in enclosed areas below the elevated floor. It is recommended the use of corrosion resistant materials below BFE	Above and below BFE: classes 4 and 5
COASTAL A ZONES	Structural and nonstructural building materials below the DFE must be flood damage-resistant It is recommended that flood-damage resistant materials are used above the BFE It is recommended the use of lattice, insect screening or louvers instead of solid breakaway walls in enclosed areas below the elevated floor	Above and below BFE: classes 4 and 5
A ZONES	Structural and nonstructural building materials below the BFE must be flood damage-resistant It is recommended that flood-damage resistant materials are used above the BFE	Above and below BFE: classes 4 and 5
B or X ZONES (shaded)	It is recommended the use of flood resistant materials below nearest high-risk BFE	Below nearest high-risk BFE: classes 4 and 5
C or X ZONES (unshaded)	It is recommended the use of flood resistant materials below nearest high-risk BFE	Below nearest high-risk BFE: classes 4 and 5

3.5. Chapter overview

Established previously the main structures destined to house and shelter population affected by natural disaster – tents, prefabricated shelters and permanent housing – this chapter focused on a methodology that should be taken in order to mitigate the effects of flood events in permanent housing.

Furthermore, it became clear that flooding can damage houses in different ways according to its own characteristics and permanent housing should be in accordance to the same characteristics.

To that effect, the proposed methodology for achieving flood resilient housing was based in the FEMA classification system that differentiates between flood zones according to flood risk. Five flood zones were identified and their description can be observed in table 3.1:

- V zones constitute higher risk zones due to being in close proximity to the sea and its related hazards;
- Coastal A zones are areas that are subjected to coastal flooding to a lesser degree;
- A zones are zones have are subjected to limited wave action;
- B or X (shaded) zones consist in areas subjected to moderate flood risk;
- C or X (unshaded) zones have minimal risk of flooding.

Additionally four major criteria that a building located in a flood zone should respond to were identified:

- Site selection;
- Design;
- Foundations;
- Materials.

Site selection is not a criteria that FEMA addresses in its requirements and recommendations system, however site selection is of fundamental importance and was included in the methodology because the best way to achieve durable solutions is by avoidance of levels of risk.

Since FEMA provides for requirements and recommendations for flood resilient buildings in conformity with flood zones these guiding principles were procured and organized under each criteria so that once established a flood zone, the requirements and recommendations within each criteria can be recognized and implemented. This systematization process results in several tables according to the flood zones except for site selection requirements – Table 3.2 – that should be implemented regardless of the flood zone.

Other tables provide for requirements and recommendations flood resilient housing:

- Table 3.3 provides design requirements and recommendations according to the flood zone where the house is located.
- Table 3.4 provides foundation requirements and recommendations according to the flood zone where the house is located.
- Table 3.11 provides materials requirements and recommendations according to the flood zone where the house is located.

Chapter IV

CASE STUDY IN MALDIVES

4.1. Introduction

The case study chosen for the scope of this thesis was the housing project of Dhuvaafaru, situated in the Raa atoll in the Maldives that took place following the Indian Ocean Tsunami of 2004. The Dhuvaafaru housing project comprised of new construction in a previously uninhabited island which currently faces not only flood events from sea related hazards but is also vulnerable to future ones due to the rising of the sea levels.

The Maldives are an island nation located in the Indian Ocean and the smallest country in Asia in terms of land area and population numbers. The Republic of Maldives is composed of 1192 islands with a population of 380.000 inhabiting only 192 islands (Arnall et al, 2015). The islands are part of a double chain of twenty six atolls varying in shape and size which were formed through coral reef building and therefore, the islands are entirely sustained by the ecological and physical processes related to the coral reef ecosystem (Jameel, 2007).

Islands of Maldives consist in small sandbanks with little to no vegetation to elongated circular strips with a large cover of vegetation. The islands are scattered over a distance of 850 km, making the country one of the most geographically dispersed countries in the world (Luetz, 2013).

Maldives has a humid and warm climate with two monsoon events; the southwest monsoon, in which Madives experiences heavy rainfall, happens from May to November and the northeast monsoon happens from January to March. Temperatures along the year average between 31ºC and 23ºC (Ministry of Environment, Energy and Water of Maldives, 2006).

All soils in the Maldives are derived from weathered coral formations which are typically not more than 50-70 cm deep and are composed of medium sized calcium carbonate sand grains A characteristic soil profiles consists of topsoil made of thin sandy layer with a layer of organic matter 15-40 cm deep, followed by a layer of 30-50 cm deep of hardpan before reaching unweathered bedrock. Soil in Maldives has a very high vertical permeability with rainwater infiltrations occurring without generating run-off (UNDP, 2007; Ministry of Environment, Energy and Water of Maldives, 2006).

Natural environment of the Maldives is highly resilient to natural phenomena such as swell waves and storm surges since it has been suffering its effects since the creation of the islands. Flooding of the islands may have been a common event over hundreds of years, but damage to the physical environment is usually minor and adaptation is quick. However, natural recovery is quick only if the natural environment is maintained meaning that with the need for human settlements in the islands, biophysical changes occur resulting in the progressive product of vulnerable territories that can induce natural disaster (UNDP Maldives, 2008).

4.2. Climate change in Maldives

The Maldives is one of the most vulnerable countries in the world to the effects of the rising of the sea level due to climate change (UNEP, 2005). This happens not only because of the vulnerable inherent nature of the islands, but also as consequence of the country's topography as the Maldives is one of the lowest lying countries in the world, with more than 80% of the land area below 1 m high tide level and the highest natural elevation point of the country being 2,4 m above sea level (Jameel, 2007; Park, 2011).

Measurements in Hulhulé, one of the islands of the country, show there is a long term trend in relative sea level of 1,7 mm/year. However, the maximum hourly sea level is growing by approximately 7 mm/year with an hourly sea level of 70 cm above mean sea level likely to happen once in 100 years, but expected to become an annual event by 2050 (Ministry of Housing, Transport and Environment, 2009).

As the chances of flooding increases due to the rising of the sea level, Maldives face a real prospect of submergence and forced abandonment (Church et al. 2007).

4.3. Flood risk in Maldives

By 2006, 44% of the settlement footprints of all combined islands were within a range of only 100 m of the coastline, increasing the settlements vulnerabilities to the hazards related to the sea and to sea level rise (Ministry of Environment, Energy and Water, 2006).

From 2000 to 2006, over 90 inhabited islands have been flooded at least once and 37 islands have been flooded regularly or at least once a year. As for residential buildings, there seems to be inadequate solutions in terms of resilience to floods, since housing design, structures and materials are not prepared to address flooding and they fail to guarantee any protection to the residents and to prevent damage produced by flood events. Critical components of buildings such as floors haven't got proper elevation from the ground and the poor construction techniques and materials exacerbates the consequences of floods. Because of this fact, episodes of flooding can be progressively devastating (Ministry of Environment, Energy and Water, 2006).

By 2001, 33 inhabited islands had a land area greater than 1 km^2 with only 4 surpassing 4 km^2, presenting land scarcity issues and leading to very high values of population density. Urbanization trends which are currently expanding are expected to continue with cities growing to unsustainable numbers in a very limited land area. Additionally, as population increases and land area decreases, permanent infrastructure is progressively built in vulnerable areas, near shorelines where damaging phenomena related to the ocean are more prominent. Beaches of Maldives, which represent 5% of the country's total area are unconsolidated and dynamic producing coping mechanisms in the local communities to deal with erosion, but as population grows and construction is being made in close proximity to the shorelines, erosion is becoming a growing hazard to the country (Jameel, 2007).

In 2004, more than 97% of inhabited islands reported beach erosion, of which 64% reported severe beach erosion. Human intervention in coastal areas, changes in climatic conditions, rise of the sea level and storm surges are known to worsen the issue of erosion.

Although the Maldives are outside of a cyclone belt and the country isn't affected directly by cyclones, some historical records show that cyclones which passed hundreds of kilometers away from the Maldives caused flooding in the islands (Jameel, 2007).

Tropical cyclones and their subsequent storm surges and droughts prevail in the north of Maldives. Udha, which refers to annual rise in the water surface during the southwest monsoon that causes limited coastal flooding is a local phenomenon, still poorly understood, is prevalent to the west of the country (UNDP, 2008).

Swell waves are waves produced by wind fields and distant weather systems that travel long distances with direction of propagation not necessarily the same as the wind direction. Swell waves can cause flood of the coastal area and are less predictable than storm surges. Swell waves are a known threat to Maldives, since the country has been suffering periodic events of flooding due to swell waves, such as in 1987 and in 2007, where a series of swell waves hit most of the habitable islands and flooded land up to 600 meters from the coastline (reliefweb.int/report/maldives/maldives-coastal-flooding-ocha-situation-report-no-3)

Rainfall and its impacts can be felt more to the south of the country, due to the presence of wetlands. Rainfall induced floods have a maximum water depth of 0,5 m which doesn't produce structural damage to houses, but affects the contents within the housing units (UNDP Maldives, 2008).

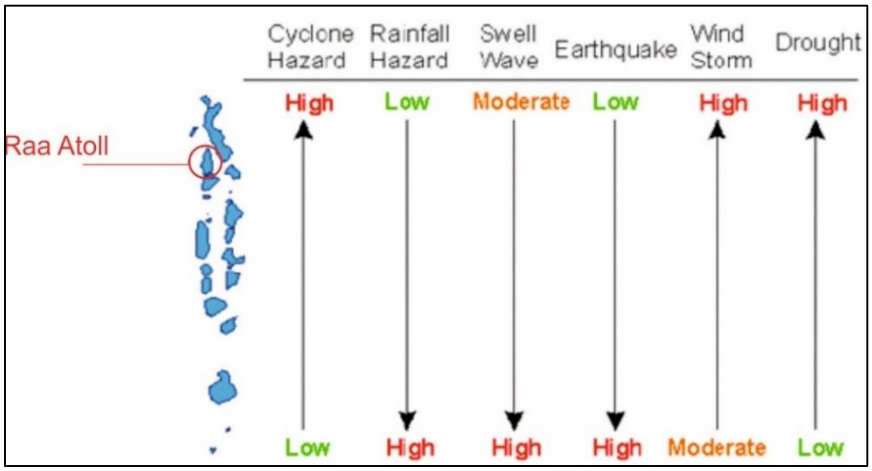


Figure 4.1 – Latitudinal variations of major natural hazards across the Maldives (UNDP Maldives, 2008)

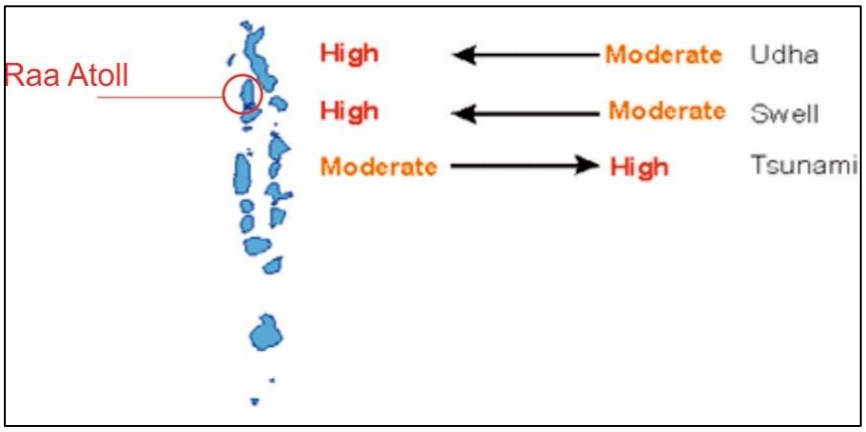


Figure 4.2 – Longitudinal variations of major natural hazards across the Maldives (UNDP Maldives, 2008)

According to the figures 4.1 and 4.2, the Raa atoll, where is located the island of Dhuvaafaru is likely to suffer the effects of floods due to:

- Sea level rise;
- Erosion;
- Cyclones;
- Wind storms;
- Udha:
- Swell waves.

The quantification of all flood-related hazards in the Raa atoll isn't possible since there aren't literary sources that provide data regarding that aspect. Although udha, swell waves, the effect of erosion and cyclones should be considered for predicting future flood levels that islands of the Maldives may face, there is only available data regarding storm tide heights associated to return periods of 100 and 500 years. Storm tide heights are the sum of storm surges and astronomical maximum tides in relation to the mean sea level.

Table 4.1 – Storm surge heights, average tide heights and storm tides for different return periods (UNDP, 2006)

Return period (years)	Storm Surge Height (m)	Average Tide Height (m)	Storm Tide (m)
100	0,84	0,98	1,82
500	1,32	0,98	2,3

As it can be observed, storm tides are 1,82 m high for a return period of 100 years and 2,3 m high for a return period of 500 years.

4.4. The 2004 Indian Ocean tsunami in Maldives

The Indian Ocean tsunami of 2004 highlighted the environmental vulnerabilities of the Maldives. On 26 December 2004, the tsunami reached Maldives with maximum tidal waves reaching 4,57 m high and causing the worst nation-wide disaster the Maldives experienced in recent history producing a sudden-onset emergency. Impacts of the tsunami resulted in the death of more than 83 people and a total damage estimate of 470 million USD which does not include the additional costs of financing the environmental recovery due to the damages generated by the tsunami (WB & ADB & UN, 2005).

Following the tsunami, fourteen islands were destroyed and had to be evacuated, 56 suffered major physical damage and 121 reported moderate damage resulting from flooding (UNDP, 2006). The seawater invaded dry land all across the country, contaminating fresh water resources and carrying away top soil and vegetation from agricultural land. Impacts ranged from complete island submergence to inundation in around margins of the islands. Shorelines faced widespread erosion as the waves and floods formed erosional scarps ranging from 0,3m to 0,5m high As the tsunami is thought to be coming from the east, islands located in the eastern rim facing the direction of the tsunami suffered the most changes in coastal morphology (UNEP, 2005).

The impacts of the tsunami were exacerbated by the chronic shoreline erosion and the inadequate design of coastal infrastructure with many coastal buildings collapsing due to shallow or improperly reinforced foundations that suffered scour and erosion before and during the tsunami event. Factors that affected the variability of the impacts include the heights of the beach bunds as they provide physical barriers against the action of the waves, the width of the reef flat as they dissipate more wave energy and coral

reef locations relative to the position of the islands as they are responsible for breaking the waves further from the coast (UNEP, 2005).

In the aftermath of the tsunami, demolition waste was of 290 000 m³ and was composed of not only vegetation, soil and debris from the buildings, but also oil, asbestos, and wastes from dump sites (Jameel, 2007).

The housing sector was affected with over 2500 houses destroyed and 3500 severely damaged. Entire settlements, hospitals, clinics and schools, were destroyed, as well as much of the transport and communications infrastructure (Jameel, 2007). As for the factors that influenced the impact on the buildings they include location of the island, angle of the tsunami wave, building location and the construction standards used (UNEP, 2005).

Due to loss of housing and destruction of infrastructure, 12 000 people were displaced from their islands, while 8500 were temporarily relocated to other areas within their islands resulting in 7% of population of the Maldives being displaced (WB & ADB & UN, 2005).

4.5. Housing recovery following the Tsunami in Maldives

Following the disaster, the Government of the Maldives mounted a dynamic relief and rehabilitation project with the aid of UN agencies, NGOs, and other development partners. The National Disaster Management Center of the Maldives was created to facilitate coordination and response.

The immediate response for many of the IDPs were accommodations in host families or the provision of tents in camps. 855 temporary shelters and 396 individual rooms were constructed in 22 islands in 8 atolls after a few months since the tsunami to house the IDPs in order to provide relief for communities who have lost everything (Department of National Planning Ministry of Finance and Treasury Republic of Maldives, 2009).

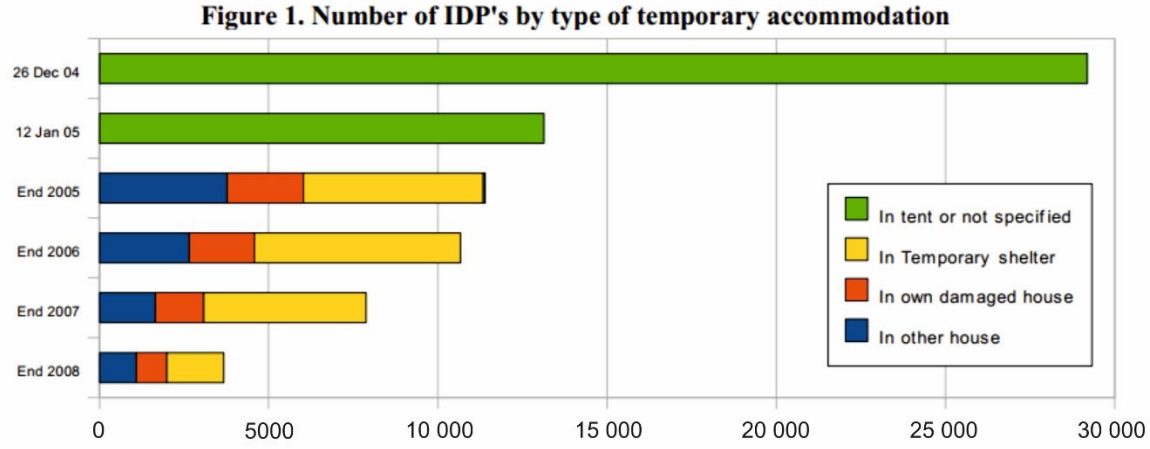


Figure 4.3 – Number of IDPs by type of temporary accommodation
(Department of National Planning Ministry of Finance and Treasury Republic of Maldives, 2009)

Some of the temporary shelters constructed by the Government of Maldives with funding from the IFRC and advice from the Internal Displacement Division of UNOCHA met Sphere standards, with family units made of plywood and zinc roofing, while repair and reconstruction of buildings and infrastructure was on its way (Ministry of Planning and National Development of Maldives, 2005b).

For circumstances where houses were damaged beyond repair, the Government of Maldives chose to provide a 3 bedroom permanent housing made from durable materials, built in a way that was easy to

adapt to meet the future needs of the family in a "build back better" approach (Ministry of Planning and National Development of Maldives, 2005a).

Government of Maldives and their partners also understood that the lack of coping mechanisms and preparedness strategies could prompt another nation-wide disaster due to exposure to future natural hazards. In response, it was launched a long-term disaster mitigation program – The Safer Islands Development Programme – addressed to increase the safety of island communities by developing physical features and integrating wider environmental protection zones and building elevated zones designed for vertical evacuation in the event of flooding (Ministry of Planning and National Development, 2005a).

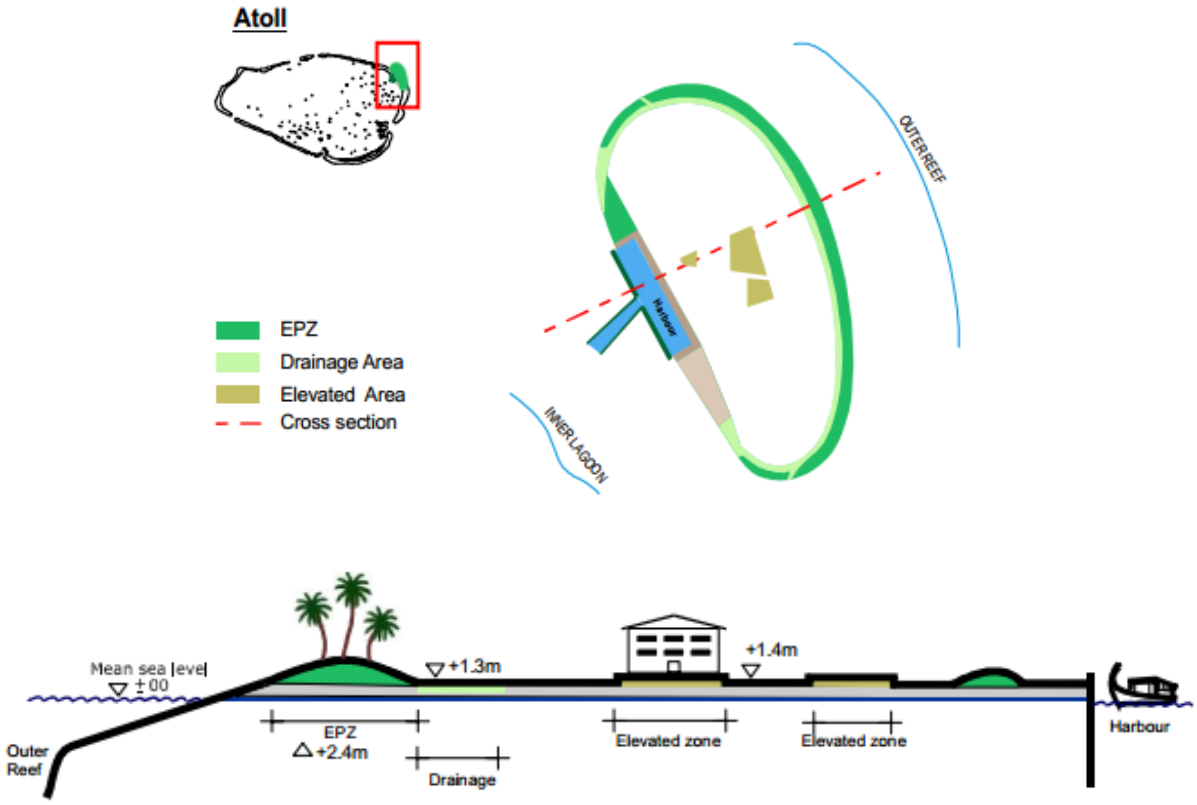


Figure 4.4 – Safer Island concept and cross section
(Ministry of Planning and National Development, 2005a)

The Safer Islands concept was established to incorporate the factors of extreme vulnerability in community settlements and mitigate ecological disasters and to adapt to climate change. The Government of the Maldives identified 11 islands which were developed as safer islands within the country. One of these islands, was the unpopulated island of Dhuvaafaru in the Raa atoll.

The scope of this case study is to assess the resilience and preparedness of the permanent housing units built on Dhuvaafaru Island to resist floods. The next subchapter will provide details on this project.

4.6. Dhuvaafaru housing project

One of the islands of the Maldives rendered without repair following the tsunami, was the island of Kandholhudhoo in the Raa Atoll, where aside the destruction of the settlement, seawater contaminated the freshwater lens – the layer of freshwater below the ground that must not be in contact with saltwater – of which the community depend which made the island inhabitable. The population of Kandholhudhoo composed of more than 3600 people was evacuated to other islands, becoming IDPs and never to return to the island of Kandholhudhoo as the Government of the Maldives and their partners chose to resettle the community in a new safe and sustainable settlement. (IFRC, 2010).

Figure 4.5 – Kandholhudhoo Island prior to being destroyed by the 2004 Tsunami (www.bluepeacemaldives.org)

Figure 4.6 – Dhuvaafaru Island (IFRC, 2010)

To that effect, the unoccupied island of Dhuvaafaru in the Raa atoll was chosen to resettle the displaced community due to many factors including location, natural ground level, size, reef characteristics and community preference (IFRC, 2010).

Dhuvaafaru, is integrated within the Safer Island Programme and is composed of a 40 m wide Environmental Protection Zone (EPZ) and accessible evacuation points. Detailed information on the land use plan for Dhuvaafaru is given in Annexes.

The project for Dhuvaafaru Island comprised of 600 housing units to accommodate the displaced population, and other relevant infrastructure which include roads, a pre-school, a community administration building, water and sewage provision, electricity network, power station, and health center, a harbor, a sports stadium and a telecommunications tower (IFRC, 2010). The construction of the 600 housing units was funded by the IFRC in the largest project taken by IFRC to that date (Saleem, 2009).

On April of 2005, Government of Maldives released a document with the requirements and design for the housing units to be built in Dhuvaafaru of which detailed information and technical drawings are available in Annexes. The works for the residential buildings in Dhuvaafaru started in June 2006 and relocation of the displaced families started in the beginning of September of 2008 (IFRC, 2010).

Housing units built on Dhuvaafaru island have the following construction characteristics (IFRC, 2010; Government of Maldives, 2005):

Foundations:

- Foundation pad at a minimum depth of 600 mm, blinding layer and damp proof membrane
- Reinforced concrete foundation beams

Structural frame:

- Concrete reinforced columns
- Concrete reinforced beams

Internal and external walls:

- Cement blocks for external and internal walls
- Plastering for external and internal walls
- Wall ventilation/Louvers

Floor:

- Reinforced concrete

Roof:

- Roof frame: battens, rafters, wall plate, fascia
- False ceiling
- Roof covering: sheeting, ridge capping, flashing, gutter, downpipes

Fit out:

- Ceramic floor for house and bathroom
- Wall tiles for bathrooms
- Timber doors: external and internal
- Windows
- Painting: exterior walls, interior walls, fascia board, down pipes, false ceiling

Figure 4.7 – Housing units in Dhuvaafaru Island
(www.bluepeacemaldives.org)

4.7. Dhuvaafaru housing project analysis

The previously mentioned methodology in Chapter III was used to analyze flood resilience of housing units in Dhuvaafaru Island. Firstly, it is necessary to determine in which flood zone within FEMA classification system that was previously established, the settlement in Dhuvaafaru belongs to. It is also fundamental to apply the flood zone rating system according to the predicted hazards that Dhuvaafaru Island will face in the future. As there are no studies for Dhuvaafaru Island in specific, measurements and predictions related to flood events are based on other islands of the country or in the country as a whole.

Effects of protective natural barriers such as the house reef of the Island or artificial barriers such as concrete barriers built in some parts of the island's shores weren't considered since its effects weren't measurable. Although lack of this data can result in exacerbated effects to housing due to flood predictions, this also means that construction or assessment of flood resilience of the housing units guarantees the estimation of solutions are conservative.

Coastal flooding has been established as the main source of flooding that can affect the island. Topography of Dhuvaafaru Island is unavailable, but it is known that the island is less than 1 m above the mean sea level. Furthermore, it's reported that one third of a meter was removed from the top soil due to the works of leveling the surface of the island after reclamation, resulting in lowering the island height. Has a consequence, the Island of Dhuvaafaru is currently above 0,67 m maximum the mean sea level (http://www.bluepeacemaldives.org/blog/2009/02).

Furthermore, the Building Codes of Maldives determines that the life of a building must have a duration of a minimum of 50 years, therefore housing units of Dhuvaafaru should resist flood events for a minimum of 50 years, i.e. until 2058 (Ministry of Construction and Public Infrastructure, 2008).

It was established previously that the Raa atoll, where is located Dhuvaafaru is prone to suffer effects of flooding due to sea level rise, erosion, wind storms, cyclones and swell waves.

Figure 4.8 – Erosion and houses in close proximity to the sea in Dhuvaafaru Island (www.bluepeacemaldives.org)

While all this factors should be considered for the determination of the base flood elevation, most of them aren't available in the literature, thus constituting a major limitation to the correct identification of the base flood elevation that buildings in the island are exposed to. For attributing a number to BFE, were considered the heights of the 100-year flood – which already accounting for predicted changes in the sea level – and the storm tide height with a return period of 100 years. While BFE calculation cannot be determined with a degree of confidence it should still be the sum of the 100-year stillwater height and maximum predicted wave height.

Considering a 100-year stillwater height of 0,7 m – based in the flood with a return period of 100 years for Hulhulé – and considering storm tide heights with a return period of 100 years as the maximum wave heights, the considered BFE for Dhuvaafaru was 2,67 m, in order to provide ground floor elevation that can reach 2 m and accounting for other uncertainties.

Table 4.2 – 100-stillwater height, wave height and considered BFE

100-stillwater height (m)	Wave height (m)	Combination of 100-stillwater height and wave height (m)	Considered BFE (m)
0,7	1,82	2,52	2,67

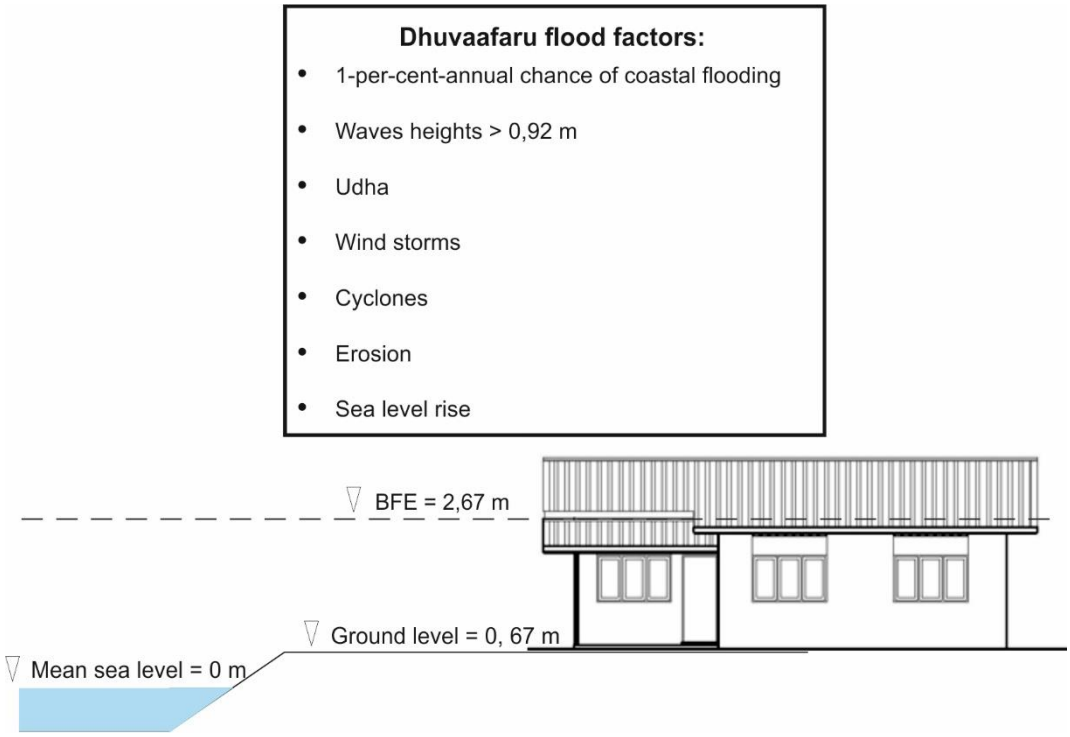


Figure 4.9 – Flood factors and considered BFE

Based on this factors, Dhuvaafaru is determined to be a high risk area flood zone, particularly a V zone since the primary source of flooding is coastal flooding, with additional sea-related hazards and waves higher than 0,92 m.

Given that Dhuvaafaru is designated as a V zone, requirements and recommendations for each of the criteria previously discussed – site selection, design, foundations and materials – should be met. The following table provides for requirements and recommendations for construction in Dhuvaafaru Island and the compliance of studied housing units according to the requirements and recommendations.

Table 4.3 – Site selection, design, foundations and materials recommendations and requirements

1 - Site Selection Requirements

Building in areas in high risk of flooding must be avoided	X
Building in sites or near locations at risk of landslides must be avoided	✓
Building in areas at risk of geotechnical failure due to piping, batter slumping, erosion and swelling and shrinking of the soil must be avoided	X
Trees, bushes and groundcover plants should be planted in coastlines or in riverine settings	✓
Settlements must be established in a way to make it easier for evacuation	✓
Housing in flood prone areas should be near collective buildings which should be above flood levels	✓
2 - Design Requirements	
Bottom of the lowest horizontal structural member of the lowest floor must be at or above the BFE.	X
Space below the lowest floor must be free of obstructions such as building elements, equipment, or other fixed objects	N/A
Double-story or multi-level houses should be preferred to single-story structures	X
It is recommended that shape of buildings respect minimum side ratios	X
Elevating buildings higher than the required lowest floor elevation is recommended	X
Enclosure areas below elevated lowest floors are only permitted for parking of vehicles, building access and storage and it is recommended to minimize its use.	N/A
Walls of enclosure areas below elevated lowest floors must be designed to collapse under flood loads	N/A
Minor quantities of non-structural fill can be used as long as it doesn't prevent the free passage of floodwaters	–
Tanks must be located above-ground on the landward side of buildings, if tanks are built underground, they must be below of the eroded ground elevation	–
Basements are not permitted	✓
Utilities must be designed, located, and elevated to prevent flood waters from entering and accumulating in components during flooding. Utility lines must not be installed or stubbed out in enclosures below BFE unless flood proofed to the extent practicable.	–
3 - Foundation Requirements	
Open foundations are required and closed foundations are not permitted	X
Foundation materials should be resistant to water and its effects	✓
Non-structural fill is allowed for minor landscaping and site drainage as long as fill doesn't interfere with free passage of floodwaters and debris or cause turbulence	–
Foundations should be properly anchored to resist lateral movement, flotation and collapse	X
Deep foundations are recommended to improve the building performance	X
Use of piers isn't recommended unless bedrock is near surface and potential for erosion and scour is low	✓
4 - Materials Requirements	
Structural and nonstructural building materials below the BFE must be flood damage-resistant	X
It is recommended that flood-damage resistant materials are used above the BFE	X
It is recommended the use of lattice, insect screening or louvers instead of solid breakaway walls in enclosed areas below the elevated floor.	N/A
It is recommended the use of corrosion resistant materials below BFE	–

✓ Meets the requirement/recommendation

X Doesn't meet the requirement/recommendation

– Unable to assess

N/A Non-applicable

4.8. Discussion of results

The results of the analysis for the case study are discussed in the following subchapters providing for information and considerations under each of the criteria. Final considerations and anticipation of results are discussed further in order to examine the consequences of flooding that housing units in Dhuvaafaru may be facing in the future.

Site Selection

Site Selection for the permanent housing can be divided in two sections:

- The selection of the island of Dhuvaafaru of all available islands as permanent resettlement
- The selection of localized sites for new construction within the Dhuvaafaru Island

The option for selection of Dhuvaafaru as permanent resettlement of the displaced communities isn't discussed in this work, since there isn't enough data to evaluate the other options for resettlement in other islands. While islands of the Maldives can have diverse levels of resilience towards flood events, all of them are low-lying with a flat topography which makes them highly vulnerable to flooding, thus resulting in inability to build in flood-free zones.

Surrounding the island of Dhuvaafaru, near the shorelines is the Ecological Protection Zone, part of the Safer Island Programme that comprises a green belt and a lower drainage area designed to function as a protection to erosion and mitigation of flooding, while the housing units are located within that belt. This is the adequate option for all construction within the island as housing is sheltered from the floodwaters, and their onset velocity.

In the island of Dhuvaafaru, there aren't any risks of landslides, rockfalls or soil movements that can slide during floodings and result in damage to the settlement. Consequently, avoiding land zones where erosion and rising of the sea levels is prominent is the main concern to guarantee the building isn't affected by floodings.

However, residential buildings are not that far from the shorelines where erosion affects land and makes it vulnerable to the rising of sea levels that could eventually reach the houses. Although land of Dhuvaafaru is scarce, all new construction should be within a lesser perimeter than the actual, farer from the shorelines to safeguard flood damages.

Because Dhuvaafaru is integrated within the Safer Island Programme, which means points for vertical evacuation have been established for the island in case of flooding, it is considered compliant with the evacuation requirement.

Collective buildings such as schools and the hospital have are more than one story and therefore are able to provide refuge to residents in case of flooding of the island.

Design

According to the Building Codes of Maldives the life of the building must have a duration of a minimum of 50 years. With flood levels resulting from the rising of the sea levels that can reach over 30 cm in 2058, combined with erosion effects and other possible threats such as swell waves and udha that also result in flooding, it is safe to say that construction in Maldives is always prone to floodings and should address it in its design.

Design of houses in Dhuvaafaru Island fails to meet many fundamental requirements that all new construction in V zones should respect.

Residential buildings in Dhuvaafaru, are single story houses without elevated ground floors to avoid floods. Considering a BFE of 1,67 m, the lowest horizontal structural member of the lowest floor – which in this case is the ground slab – should be 2 m high above the ground. However, the slab of the housing units is not raised, therefore failing to elevate the ground floor 2 m high. Due to the lack of elevation of floors, requirements and recommendations related to enclosure areas and usage of space beneath the floor are non-applicable.

The use of non-structural fill, placement of tanks and design and location of utilities are unable to be verified and assessed.

Shape of the housing units can't be properly assessed without knowing the main flood direction. However, because of the inherent nature of small islands such as Dhuvaafaru, it can be theorized that flow can be perpendicular to the four façades of the house. Furthermore, the housing unit can be perceived as combined by two different typologies and by two set of "legs". Figure 4.10 illustrates this point.

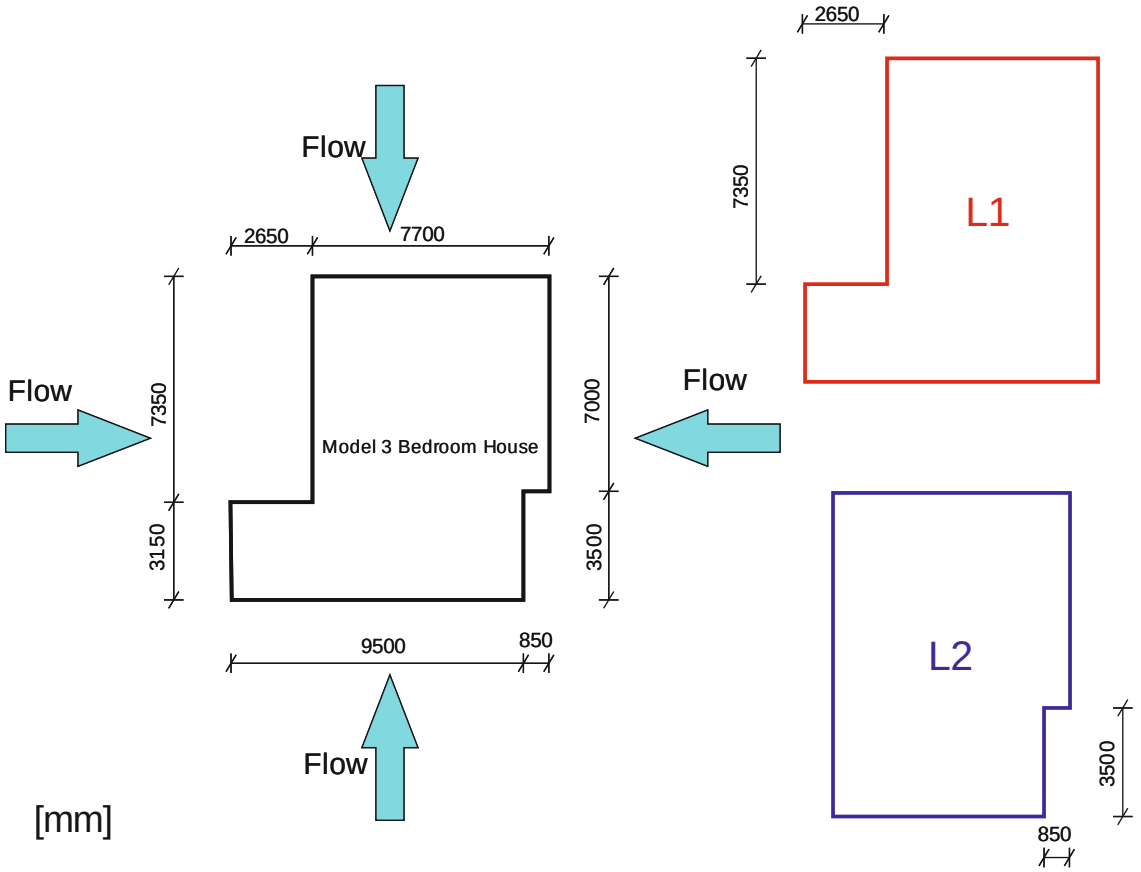


Figure 4.10 – Plan view and typologies of housing units

In doing so and as the housing unit typologies possess "legs", it's important to have length side ratios with a maximum difference of 1,5 therefore:

$$L1: \frac{7350}{2650} = 2{,}77 > 1{,}5$$

$$L2: \frac{3500}{850} = 4{,}12 > 1{,}5$$

Both L1 and L2 typologies of the housing unit don't fulfill the recommended maximum side ratios.

Foundations

The foundations used for the housing units were pad foundations at a depth of 600 mm minimum, with reinforced concrete beams above a blinding layer and protected from dampness through a damp proof membrane.

V zones require open foundations to avoid flooding of the household while allowing movement of floodwaters below the floor. In V zones, pile foundations, micropile foundation associated with columns or pier foundations associated with columns would all be appropriate foundations for this specific flood zone. However, residential buildings in Dhuvaafaru Island make use of pad foundations, without any elevation and therefore failing to meet the open foundation requirement.

Materials of foundations are required to be class 4 or 5 according to Table 3.5. Concrete is considered to be acceptable and reinforced concrete on the house foundations is appropriate for use in coastal construction in situations where wood piles cannot be readily driven and the superstructure is made of concrete which is the case.

Pad foundations are shallow foundations, failing to meet the recommendation to use deep foundations in V zones. Pad foundations alone aren't adequate in V zones because they fail to guarantee structural stability since they can overturn or result in settlements as a consequence of flood events and erosion. In this case pad foundations are associated with ground beams, thus providing greater rigidity and achieve better results of stability. Despite of this fact, pad foundations fail to meet the requirement of avoiding floatation and collapse because only deep foundations should be considered for the housing unit to provide stability.

Afterwards the construction of the housing units, bathroom tiles of some of the houses built showed signs of moist that result from capillarity action, meaning fixings or quality of damp proof membrane aren't adequate. This situation is particularly stressful under probable flood events in which waters can ascend through the ground floor into the household. Although replacement of the damp proof membranes wouldn't be feasible due to demolition of the ground floor and concrete slab, greater attention should have been given while fixing or selecting the damp proof membrane.

Materials

Structural and non-structural materials in V zones are required to be 4 or 5 class materials below the BFE. However, they are also recommended to be 4 or 5 class materials above the BFE and therefore, all construction materials used for the housing units of Dhuvaafaru should be designed to be acceptable.

Not all of the construction materials used are listed, but there are many that are listed in Government of Maldives' documents and IFRC documents which include structural materials which are considered to be the most important. The following materials were identified and grouped into acceptable and unacceptable materials using Table 4.4 and other sources.

Table 4.4 – Identified materials fof housing units

Construction materials	Acceptable	Unacceptable

Reinforced concrete slab	X	
Concrete columns and beams	X	
Plastering for internal and external walls		X
Cement blocks for internal and external walls	X	
Ceramic tiles for floor and walls	X	
Timber doors		X
Galvanized iron (GI) roofing sheets		X

Although structural materials make use of acceptable materials required for construction in V zones, some finishing materials are designated unacceptable. Reinforced concrete slab, concrete columns and beams and walls making use of cement blocks are considered to be acceptable. Timber doors are unacceptable since wood is affected by water and can warp and crack. Plaster is also considered to be unacceptable as well as galvanized iron due to being a ferrous metal that is inappropriate for coastal construction.

Since all construction materials used for Dhuvaafaru housing units should be acceptable, this specific requirement fails, taking into consideration that some of the materials used are not adequate. The requirement to make use of materials for enclosure areas beneath the floor is non-applicable considering residential buildings of Dhuvaafaru are not elevated.

Corrosion resistance of all materials below BFE is unable to be verified and assessed.

4.9. Final considerations and predicted consequences

Regarding positive aspects, site selection was found to have enhanced mitigation features due to the integration of Dhuvaafaru island within the Safer Islands Development Programme with Ecological Protection Zones shielding the settlement against the effects of floodwaters.

As exposure of the settlement of Dhuvaafaru to several flood-related phenomena is already an issue, adaptation measures of houses to floods should be a high priority of housing resilience in order to avoid and overcome its effects. However Dhuvaafaru residential houses don't address many of requirements and recommendations associated to V zones. As it can be observed in Table 4.3 housing units of Dhuvaafaru fail to meet several requirements and recommendations. The most fundamental aspects that houses of the island fail to meet are considered to be:

- **Failure to elevate ground floors 2 m above the ground level;**
- **Use of closed foundations instead of open foundations;**
- **Use of unacceptable building materials.**

Failing to comply with the required elevation of ground floors is perceived as a major vulnerability, leaving the housing units susceptible to floodwaters. During major flood events, high hydrostatic and hydrodynamic forces will subject the houses to high stresses that can result in structural failure and collapse of the building.

By using closed foundations for houses of the settlement, floodwaters cannot move freely below the house and will impact walls and structural elements of the building. Even if the houses remains stable, water will inundate the interior, damaging building materials – which are not resistant to water – and the contents of the house, ensuing economic damages.

While building 600 elevated houses in an island where there is unavailability of resources, equipment and manpower seems unrealistic fewer houses could have been built by providing more floor levels that could accommodate various families.
The adoption of one-story housing units is especially puzzling since the Maldives has major issues regarding land scarcity. As population will increase in a limited amount of area, it can be conjectured that new residential housing will be built in progressively vulnerable areas of the island, towards the shorelines, thus exposing the houses to greater effects of floods. If two-story houses or multi-level buildings were adopted, not only the upper floors could provide to the ground level residents a place of refuge from floods, but future housing wouldn't be exposed to its risks.

Nevertheless, construction of housing units in the Dhuvaafaru Island should still address the concept of sustainability and responsible construction, meaning that constructive solutions and materials should be energy efficient with minimal contributions for greenhouse gas emissions. As local resources and materials for construction are scarce in Maldives, concrete, steel and other materials for the Dhuvaafaru Project had to be imported with high contributions to emissions due to transportation and manufacture of the same materials. One option to address this particular issue was to explore the possibility of construction of reinforced concrete solutions in the ground level of the housing units with upper floors using more sustainable materials with lesser concerns of being resilient to floods.

Other options regarding sustainability involve the use of renewable energies such as solar and wind power systems which can be incorporated onto the housing units. Since the weather in Maldives is favorable to the use of solar energy, solar panels should be procured and implemented in the houses of the island as an alternative clean energy source.

Chapter VI

CONCLUSIONS

5.1. General contributions

At the beginning of the thesis, four questions were introduced that would largely influence the scope of the work. By providing answers, efforts to contributing to the development of resilient housing were expected and came in the form of the previously methodology for achieving flood resilience. Below, these answers are forthwith enumerated and answered.

1. What is the main current natural threat to housing?

In 2014, floods were the most common of all natural disasters, accounting for nearly 120 recorded natural disasters resulting in more than 50 USD billion dollars and displacing 6,2 million people, in the previous year. This has been the general trend as floods have been continuing threatening the built environment. As more and more settlements are established in zones prone to flooding, settlements become vulnerable and vulnerable communities become in risk of losing their houses. Furthermore, in accordance with the predicted consequences of climate change, sea level can rise to a range of 8 to 16 mm per year during 2081 to 2100, causing 70% of worldwide coastlines to experience sea level change. This scenario is particularly alarming to small and low lying islands which already are prone to flooding due to exposure to natural hazards, but will also face new flood events related to the sea level rise. Based on these findings, floods are considered to be the main natural threat to housing and it therefore becomes evident that housing should address this particular issue.

2. What main structures are used for sheltering affected populations by natural disaster?

Following natural disaster, there can be many approaches for housing recovery, depending on numerous factors. While some approaches can work better than others, three main structures were identified that shelter populations affected by natural disaster. Tents function as an immediate shelter relief throughout the emergency due to their versatility, relative easy transportation and low cost. However tents do not provide for all shelter needs and while they are intended for a short term-period they often remain sheltering communities for many years. Prefabricated shelters are also one of the main structures that house people after disaster and are typically used to establish a transition between the emergency shelter and more permanent solutions. Prefabricated shelters are designed to be temporary but they tend to become permanent, housing people over longer periods and failing to guarantee basic housing needs. Since both tents and prefabricated shelters often remain as permanent solutions they should anticipate future hazards that are likely to damage them, but due to their inflexibility they fail to address this fundamental aspect.

Permanent housing is the last stage of the housing recovery where families are expected to live permanently. Permanent housing may take many forms and it is impossible to address them all, but it should provide suitable conditions to daily life while guaranteeing resistance to natural hazards.

3. Is housing recovery taking into consideration future natural hazards?

The scenario following natural disaster is typically chaotic with several key actors such as NGOs, the government and local authorities providing uncoordinated shelter and housing programs. Additionally,

the urgency to shelter the affected population by disaster speeds the reconstructions process without considering population needs and neglecting future hazards. Of all types of recover

Moreover, many projects achieving permanent housing do not account for local and regional threats to housing that are likely to damage housing. Since natural disaster should be seen as an opportunity to build back better, it is imperative that measures should be implemented into the housing sector to address upcoming natural hazards.

4. What methodology for resilient housing can be implemented?

Resilient housing should be seen as a priority in a post-disaster scenario and should provide engineering solutions to mitigate the effects of hazards.

Since floods were identified as the main natural threat to housing, a methodology for achieving flood resilience in permanent housing was proposed based on how flooding affects the building integrity. Additionally, housing should respond to predicted flood characteristics, so the flood classification system of the Federal Emergency Management Agency was employed. After establishing four fundamental criteria that housing should incorporate, a set of requirements and recommendations were grouped into each one in order to provide guiding principles for housing to each of the flood zone previously established.

5.2. Conclusions

Natural disasters are historic episodes of destruction of the built environment that will continue to happen as exposure of communities and populations increases towards natural hazards. Following natural disaster, housing recovery is ensued by various housing approaches but limited to three major groups of physical housing structures: tents, prefabricated houses and permanent housing. Typically tents are provided as the initial shelter response, prefabricated shelter systems as the intermediate stage and permanent housing as the last stage of housing recovery. All of three group structures have advantages and disadvantages according the specificity of the situation, although permanent housing remains as the only viable exit strategy for housing recovery. While tents and prefabricated shelters are used as temporary, they tend to become permanent.

Moreover, the post-disaster scenario is usually chaotic, with several aid entities addressing short-term shelter needs of affected populations without long-term perspective of challenges that settlements and housing will face in the future. By failing to integrate resilient measures into housing recovery models to address future damaging events, housing will become vulnerable to its effects and is likely to be affected whether in its structure or functionality.

In sum, despite overall housing destruction, the aftermath of natural disaster should be seen as an opportunity to build new housing that responds to local and global challenges such as climate change, while resisting to present natural hazards.

This master thesis addresses in particular the consequences of floods – responsible for the largest worldwide number of natural disasters – their effects on housing, measures and considerations that can be incorporated into the three types of shelter and housing recovery structures, with emphasis on permanent housing. For that purpose, fundamental guiding flood resistant criteria were identified: site selection, design, foundations and materials. These same criteria comprise a set of key requirements and recommendations that have to be taken into consideration, so that housing becomes resistant to floods. These same requirements and recommendations can function as principles prior to new construction or as an assessment of the level of the building's flood resilience.

In regards to the case study, an analysis of the level of flood resilience of the housing units of the island of Dhuvaafaru, in Maldives, it seemed to be pertinent since it was a housing project that required new construction in a previously unoccupied island. The construction of the housing units in the island were made after the Indian Ocean Tsunami of 2004 that devastated the country and as a way to resettle a community. As Maldives have tradition of coastal floods and is one of the most vulnerable countries to the threat of the sea level rise due to climate change, housing resistant to floods should be a necessary step towards disaster mitigation and resilience.

Although the resettlement of population in the island of Dhuvaafaru can be considered a success, the primary entity responsible for the project – the Government of Maldives – failed to address some of the requirements for building in flood prone areas.

While the future seems uncertain for Maldives and the Dhuvaafaru Island, there are still some measures that can provide for greater levels of resilience to flood events implemented locally and into housing units. Retrofitting solutions in buildings for flood risks can be procured and implemented, while barriers can be placed in coastal areas to stop floodwaters from entering dry land. Nevertheless, as resilience of Maldives is tested by being on the front line of the targeted zones of sea level rise, the world should focus its attention to these small islands in the Indian Ocean and acquire knowledge of disaster preparedness, mitigation strategies and resilience that are likely to become useful in the future.

5.3. Future Developments

As future developments regarding flood resilience of permanent housing it is proposed the application of the methodology for flood resilient housing to a practical case study and its study of the effect of waters in differentiated housing models to assess the better options for flood resilient housing.

Although the fundamental aspects of flood prone construction are addressed in this thesis, some were not such as building connections and maintenance. A study to address these issues in accordance to flood zones can result in incorporation of flood resilience measures contemplating these elements in requirements and recommendations tables.

As site selection is the most important criterion, identifying the level of risk an area is exposed to is of high priority. Along the case study it was noted that although Maldives has been suffering periodic flood events and will be subjected to future ones derived from sea level rise, studies on flooding of the country are very few. Full-scale studies of predicted water levels accounting from present natural hazards such as swell waves, storms and the effects of erosion should be performed so that flood factors are determined with accurate precision. Flood related studies should also be made for each inhabited island of the country in order to assess the specific flood risk of each island. Among the most fundamental factors that future studies should determine is the base flood elevation.

Finally a flood map of the country can be considered after determining flood factors so that all new construction and housing is provided of adequate resilient strategies to the effects of flooding.

BIBLIOGRAPHY

ACTIVE LEARNING NETWORK FOR ACCOUNTABILITY AND PERFORMANCE, ALNAP – *Annual Review 2003: Humanitarian Action: Improving monitoring to enhance accountability and learning*, 2003.

AHVLIN, R. G. – *Construction Guide for Soils and Foundations*, 2nd edition, John Wiley & Sons, 1988.

AMADO, M.; POGGI, F. – *Towards solar urban planning: A new step for better energy*, Science Direct, Energy Procedia, Vol.30, pp. 1261-1273, 2012.

ARNALL, A.; KOTHARI, U. – *Challenging climate change and migration discourse: Different understandings of timescale and temporality in the Maldives*, Global Environmental Change Vol. 31, pp. 199-206, 2015.

ASHMORE, J.; CORSELLIS, T.; MANFIELD, P. – *Design of humanitarian tents for use in cold climates*, Shelterproject, The Martin Centre, University of Cambridge, 2004.

ASHMORE, J. – *Tents: A Guide to the Use and Logistics of Family Tents in Humanitarian Relief*, United Nations, 2005.

AXELSSON, F. – *The Emergency Housing Project: Product development of shelters for displaced people, based on field studies in Haiti and Kenya*, Chalmers University of Technology, 2012.

BACHELARD, G. – *The Poetics of Space*, Beacon Press, 1964.

BANHOLZER, S.; DONNER, S.; KOSSIN, J. – *The Impact of Climate Change on Natural Disasters, Reducing Disaster: Early Warning Systems For Climate Change*, Springer Netherlands, pp. 21-49, 2014.

BARAKAT, S. – *Housing reconstruction after conflict and disaster*, Humanitarian Policy Group, Network Papers 43, pp. 1-40, 2003.

BELOW, R.; GUHA-SAPIR, D.; HOYOIS, P. – *Annual Disaster Statistical Review 2013 - The numbers and trends*, 2014.

BLAIKIE, P.; CANNON, T.; DAVIS, I.; WISNER, B. – *At Risk: Natural hazards, people's vulnerability and disasters*, 2nd edition, Routledge, 2004.

BOLIN, R.; STANFORD, L. – *Shelter, housing and recovery: a comparison of U.S. disasters*, Disasters, Vol. 15, Issue 1, pp.24-34, 1991.

BOWKER, P. – *Improving the flood performance of new buildings: Flood resilient construction*, RIBA, 2007.

BRANCO, J.; FEIO, A.; FÉLIX, D. – *Temporary housing after disasters: A state of the art survey*, Habitat International 40, pp. 136-141, 2013.

BRITISH PETROLEUM, BP – *BP Statistical Review of world energy*, 2014.

CAZENAVE, A.; NICHOLLS, R. J. – *Sea-level rise and its impact on coastal zones*, Science 328, No. 5985, pp. 1517-1520, 2010.

ČERMÁK, V.; KOZÁK, J. – *The illustrated history of natural disasters*, Springer, 2010.

CHEN, F. H. – *Foundations on Expansive Soils - Developments in Geotechnical Engineering Vol. 12*, Elsevier Scientific Publishing Company,1975.

CHURCH, J. A. – *Understanding Sea-Level Rise and Variability*, Wiley-Blackwell, 2010.

CLIMATE AND DEVELOPMENT KNOWLEDGE NETWORK – *The IPCC's Fifth Assessment Report What's in it for Small Island Developing States?*, 2014.

COMERIO, M.C. – *Disaster Hits Home: New Policy for Urban Housing Recovery*, University of California Press, 1991.

CORSELLIS, T.; VITALE, A. – *Transitional settlement displaced populations*, University of Cambridge, 2004.

CROPPER, M.; GRIFFITHS, C. – *The Interaction of Population Growth and Environmental Quality*, The American Economic Review Vol. 84, No. 2, Papers and Proceedings of the Hundred and Sixth Annual Meeting of the American Economic Association, pp. 250-254, 1994.

CULLEN. J.H. – *Overview of green buildings*, National Wetlands Newsletter 33.1, pp. 3-14, 2010.

DANIN, A.; NADEL, D.; KISLEV, M.; SIMCHONI, O.; TSATSKIN, A.; WEISS, E. – *Stone Age hut in Israel yields world's oldest evidence of bedding*, University of Michigan, 2004.

DAVIS, I. – *Emergency shelter*, Disasters, Vol.1, Issue 1, pp. 23-39, 1977.

DAVIS, J.; LAMBERT, R. – *Engineering in Emergencies: A practical guide for relief workers*, 2nd edition, IDTG, 2002.

DAVIS, I. – *What is the vision for sheltering and housing in Haiti*. *Summary Observations of Reconstruction Progress following the Haiti Earthquake of January 12th 2010*, 2012.

DEPARTMENT OF NATIONAL PLANNING MINISTRY OF FINANCE AND TREASURY REPUBLIC OF MALDIVES – *Maldives - 4 Years After the Tsunami - Progress and remaining gaps*, 2009.

DEOCAMPO, D.; JACKSON, M.; MARRA, F.; SCHEETZ, B. – *Mid-Pleistocene pozzolanic volcanic ash in ancient Roman concretes*, Geoarchaeology Vol. 25, pp. 36-74, 2010.

DINESH, S. V.; SIVAPULLAIAH, P.V.; UMESH, T. S. – *Characterization of dispersive soils*, Materials Sciences and Applications 2, No. 6, 2011.

DOVEY, K. – *Home and homelessness*, Home environments, Springer, 1985.

DYNES, R. R. – *The Lisbon Earthquake in 1755: the First Modern Disaster*, 2003.

ENERGY INFORMATION ADMINISTRATION, EIA – *International Energy Outlook - World Petroleum and Other Liquid Fuels - With Projections to 2040*, 2013.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – Coastal Base Flood Elevations in Mississippi: Before and After Katrina, 2007

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Foundation Requirements and Recommendations for Elevated Homes - Hurricane Sandy Recovery Fact Sheet No. 2*, 2013.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Fundamentals of Emergency Management*, 2010a.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Floodplain Management Regulations Building Codes and Standards*, 2008a.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in Accordance with the National Insurance Program*, 2008b.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Home Builder's Guide to Coastal Construction - Technical Fact Sheet Series*, FEMA P-499, 2010b.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Openings in Foundation Walls and Walls of Enclosures Below Elevated Buildings in Special Flood Hazard Areas in accordance with the National Flood Insurance Program*, Technical Bulletin 1, 2008c.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Quick reference guide – Comparison of Select NFIP and Building Code Requirements for Special Flood Hazard Areas*, 2012.

FEDERAL EMERGENCY MANAGEMENT AGENCY, FEMA – *Wet Floodproofing Requirements for Structures Located in Special Flood Hazard Areas in Accordance with the National Insurance Program*, 1993.

FIGUEIREDO, L. C. – *Foucault e Heidegger: A ética e as formas históricas do habitar (e do não habitar)*, Tempo Social - Revista de Sociologia da USP, n.º 7, 1995.

GOVERNMENT OF MALDIVES – *Permanent housing concepts and sample designs for tsunami disaster recovery*, 2005.

GOVERNMENT OF THE REPUBLIC OF MALDIVES; UNITED NATIONS DEVELOPMENT PROGRAMME, UNDP; GLOBAL ENVIRONMENT FACILITY, GEF – *Building Capacity and Mainstreaming Sustainable Land Management in Maldives*, 2007.

HADAFI, F; FALLAHI, A. – *Temporary housing Respond to disasters in developing countries - Case Study: Iran-Ardabil and Lorestan Province earthquakes*, World Academy of Science, Engineering and Technology, Vol. 66, pp. 1536-1542, 2010.

HALLES, S. – *The Roman house and social identity*. Cambridge University Press, 2003.

HAWKESBURY-NEPEAN FLOODPLAIN MANAGEMENT STEERING COMMITTEE – *Reducing vulnerability of buildings to flood damage: Guidance on Building in Flood Prone Areas*, Parramatta, N.S.W., 2006.

HAY, J. E. – *Climate Risk Profile for the Maldives*, Ministry of Environment Energy and Water of Maldives, 2006.

HEILIG, G. K. – *World urbanization prospects: the 2011 revision*, United Nations Department of Economic and Social Affairs, DESA, Population Division, Population Estimates and Projections Section, 2012.

HUMANITARIAN PRACTICE NETWORK AT OVERSEAS DEVELOPMENT INSTITUTE – *Gender-based Violence in Emergencies*, Humanitarian Exchange Magazine No. 60, 2014.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, IPCC – *Managing the risks of extreme events and disasters to advance climate change adaptation - A special report of working groups I and II of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2012a.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, IPCC – *Summary for policy makers - A Special Report of Working Groups, I and II of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2012b.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, IPCC – *Climate Change 2014 - Impacts, Adaptation and Vulnerability - Part A: Global and Sectoral Aspects*, Cambridge University Press, 2014.

INTERN-AGENCY STANDING COMMITTEE, IASC – *Working Paper on the Definition of Complex Emergencies*, 1994.

INTERN-AGENCY STANDING COMMITTEE, IASC – *Protecting persons affected by natural disasters – Operational Guidelines on Human Rights and Natural Disasters*, 2006.

INTERNAL DISPLACEMENT MONITORING CENTRE, IDMC – *Global Estimates 2014: People displaced by disasters*, 2014.

INTERNATIONAL COUNCIL ON MONUMENTS AND SITES, ICOMOS – *World Heritage List - Choirokoitia (Cyprus)*, No. 848, UNESCO, 1996.

INTERNATIONAL ENERGY AGENCY, IEA – *Transition to Sustainable Buildings - Strategies and Opportunities to 2050*, 2013.

INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES, IRFC – *Dhuvaafaru Safe Island Project - Evaluation Phase I*, 2010.

INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES, IFRC – *Shelter safety handbook - Some important information on how to build safer*, 2011.

JAMEEL, A. – *A model to integrate the management of hazards and disasters in the national sustainable development planning of Maldives*, University of Canterbury, 2007.

JOHNSON, C. – *Strategic planning for post-disaster temporary housing*, Disasters 31.4, pp. 435-458, 2007.

LINDELL, M. K.; PRATER, C., S. – *Assessing Community Impacts of Natural Disasters*, Natural Hazards Review 4.4, pp. 176-185, 2003.

LUETZ, J. M. – *Climate migration - preparedness informed policy opportunities identified during field research in Bolivia, Bangladesh and Maldives*, University of New South Wales, 2013.

MANFIELD, P. – *Emergency Shelter for Humanitarian Relief in Cold Climates: Policy and Praxis*. The Martin Centre for Architectural and Urban Studies, Cambridge University, 1999.

MINISTRY OF BUSINESS, INNOVATION AND EMPLOYMENT OF NEW ZEALAND, *Guidance for building in toe slump areas of mass movement in the Port Hills (Class II and Class III)*, 2013.

MINISTRY OF CONSTRUCTION AND PUBLIC INFRASTRUCTURE OF MALDIVES – *Maldives National Building Code - Handbook*, 1st Edition, 2008.

MINISTRY OF ENVIRONMENT, ENERGY AND WATER OF MALDIVES – *National Adaptation Plan of Action, NAPA*, 2006.

MINISTRY OF HOUSING, TRANSPORT AND ENVIRONMENT OF MALDIVES – *National Adaptation to Climate Change - A background paper prepared for the Maldives Partnership Forum (MPF), in March 23*-24, 2009.

MINISTRY OF PLANNING AND NATIONAL DEVELOPMENT OF MALDIVES – *National Recovery and Reconstruction Plan - Programmes and Projects*, 2005a.

MINISTRY OF PLANNING AND NATIONAL DEVELOPMENT OF MALDIVES – *The Maldives - One Year after the Tsunami*, 1st edition, 2005b.

MULLIN, J. – *The Reconstruction of Lisbon following the earthquake of 1755: a study in despotic planning*, Planning Perspective v. 7, pp.157-179, 1992.

NEVELL, M. – *Living in the Industrial City: Housing Quality, Land Ownership and the Archaeological Evidence from Industrial Manchester, 1740–1850*, International Journal of Historical Archaeology, pp. 594-606, 2011.

OFFICE OF THE UNITED NATIONS HIGH COMMISSIONER FOR HUMAN RIGHTS, OHCHR; UNITED NATIONS HABITAT – *The right to adequate housing*, Fact Sheet No. 21, 2008.

PARK, S. – *Climate Change and the Risk of Statelessness: The Situation of Low-lying Island States*, Legal and Protection Policy Research Series, Division of International Protection United Nations High Commissioner for Refugees, UNHCR, 2011.

PAUL, B. K. – *Environmental Hazards and Disasters: Contexts, Perspectives and Management*, John Wiley & Sons, 2011.

PERROT, M.; BOTTMANN, D.; JOFFILY, B., *História da vida privada - Da Revolução Francesa à Primeira Guerra*, Vol. 4, 1991.

PINHO, F. – *Paredes em Edifícios Antigos em Portugal*, LNEC, 2008.

PRINZ, G. S.; NUSSBAUMER, A. – *On Fast Transition between Shelters and Housing after Natural Disasters in Developing Regions*, Technologies for Sustainable Development, Springer International Publishing, pp. 225-235, 2014.

QUARANTELLI, E. L. – *Sheltering and housing after major community disasters*, Ohio State University Disaster Research Center. 1982.

LENSSEN, N. K.; PETERSON, J. A.; ROODMAN, D. M – *A building revolution: how ecology and health concerns are transforming construction*, Worldwatch Institute, 1995.

RODRÍGUEZ, H.; KENNEDY, P. J.; QUARANTELLI, E. L.; RESSLER, E.; DYNES, R. – *Handbook of disaster research*, Springer Science & Business Media, 2009.

SALEEM, M.; SATTAR, S. A. – *Study on Post-Tsunami Restoration and Conservation Projects in the Maldives,* International Union for Conservation of Nature, IUCN, 2009.

SATTERTHWAITE, D. – *The implications of population growth and urbanization for climate change*, Environment and Urbanization 21, Vol.2, pp. 545-567, 2009.

SETO, K. C.; GÜNERALP, B.; HUTYRA, L. R. – *Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools*, Proceedings of the National Academy of Sciences 109, No. 40, pp. 16083-16088, 2012.

FRIEDLINGSTEIN, P.; KNUTTI, R.; PLATTNER, G. K.; SOLOMON, S. –*Irreversible climate change due to carbon dioxide emissions*, Proceedings of the National Academy of Sciences 106, No. 6, pp. 1704-1709, 2008.

SPENCE, K. – *Houses, Housing, Household Formation, Pharaonic Egypt*, Encyclopedia of Ancient History, John Wiley & Sons, 2012.

SPHERE PROJECT – *Humanitarian Charter and Minimum Standards in Disaster Response*, 2004.

SVOBODA, J. – *Gravettian mammoth bone deposits in Moravia*, La Terra degli Elefanti - The World of Elephants: Proceedings of the 1st International Congress "The World of Elephants", Rome 16-20 October, 2001.

UN GENERAL ASSEMBLY – *Universal Declaration of Human Rights*, UN General Assembly, 1948.

UNITED NATIONS, UN – *The World Population Situation in 2014 - A Concise Report*, 2014a.

UNITED NATIONS, UN – *Risks of exposures of world's cities to natural hazards*, 2014b.

UNITED NATIONS DEPARTMENT OF INTERNATIONAL DEVELOPMENT - SHELTER CENTRE – *Shelter after disaster: Strategies for transitional settlement and reconstruction*, 2010.

UNITED NATIONS DEVELOPMENT PROGRAMME MALDIVES – *Developing a Disaster Risk Profile for Maldives, Volume 1 and 2*, 2006.

UNITED NATIONS DEVELOPMENT PROGRAMME MALDIVES, UNDP MALDIVES – *Detailed Island Risk Assessment in Maldives - Natural Hazard and Physical Vulnerability Assessment Report (Final version) - Volume I: Executive Summary*, 2008.

UNITED NATIONS ENVIRONMENT PROGRAMME, UNEP – *Maldives Post-Tsunami Environmental Assessment*, 2005.

UNITED NATIONS DEVELOPMENT PROGRAMME, UNDP – *Developing a Disaster Risk Profile for Maldives Volume 1: Main Report*, 2006.

UNITED NATIONS DISASTER RELIEF OFFICE, UNDRO – *Shelter after disaster: Guidelines for assistance*, 1982.

UNITED NATIONS HIGH COMMISSIONER FOR REFUGEES, UNHCR – *Handbook for Emergencies*, 3rd edition, 2007.

UNITED NATIONS HIGH COMMISSIONER FOR REFUGEES, UNHCR – *Shelter projects 2010*, 2010

UNITED NATIONS HIGH COMMISSIONER FOR REFUGEES, UNHCR – UNHCR Resettlement Handbook, 2011

UNITED NATIONS INTERNATIONAL STRATEGY FOR DISASTER REDUCTION, UNISDR – *Global Assessment Report on Disaster Risk Reduction 2009 – Risk and Poverty in a Changing Climate: Invest Today for a Safer Tomorrow*, 2009.

UNITED NATIONS INTERNATIONAL STRATEGY FOR DISASTER REDUCTION, UNISDR – *Global Assessment Report on Disaster Risk Reduction – Revealing Risk, Redefining Development*, 2011.

UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, OCHA – *OCHA and slow-onset emergencies*, Occasional Policy Briefing Series Brief No. 6, 2011.

VAN AALST, M. K. – *The impacts of climate change on the risk of natural disasters*, Disasters Vol. 30, pp. 5-18, 2006.

WATKINS, T. – *The origins of house and home?*, World Archaeology 21, No.3, pp. 336-347, 1990.

WORLD BANK; UNITED NATIONS, UN; ASIAN DEVELOPMENT BANK, ADB – *Maldives Tsunami: Impact and Recovery*, Joint Needs Assessment by World Bank, ADB, UN System, 2005.

WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT, WCED – *Our Common Future*, 1987.

Websites

www.bluepeacemaldives.org – Accessed 20 September 2014

http://www.ncdc.noaa.gov – Accessed 4 April 2014

climate.nasa.gov – Accessed 8 August 2014

theheritagetrust.wordpress.com – Accessed 15 February 2014

www.historyworld.net – Accessed 15 February 2014

www.artemaestre.blogspot.pt – Accessed 16 February 2014

www.ipcc.ch – Accessed 23 August 2014

www.emdat.be – Accessed 5 October 2014

www.nps.gov – Accessed 20 September 2014

jenniferbruce.org – Accessed 4 October 2014

map.georgiadfirm.com – Accessed 3 January 2015

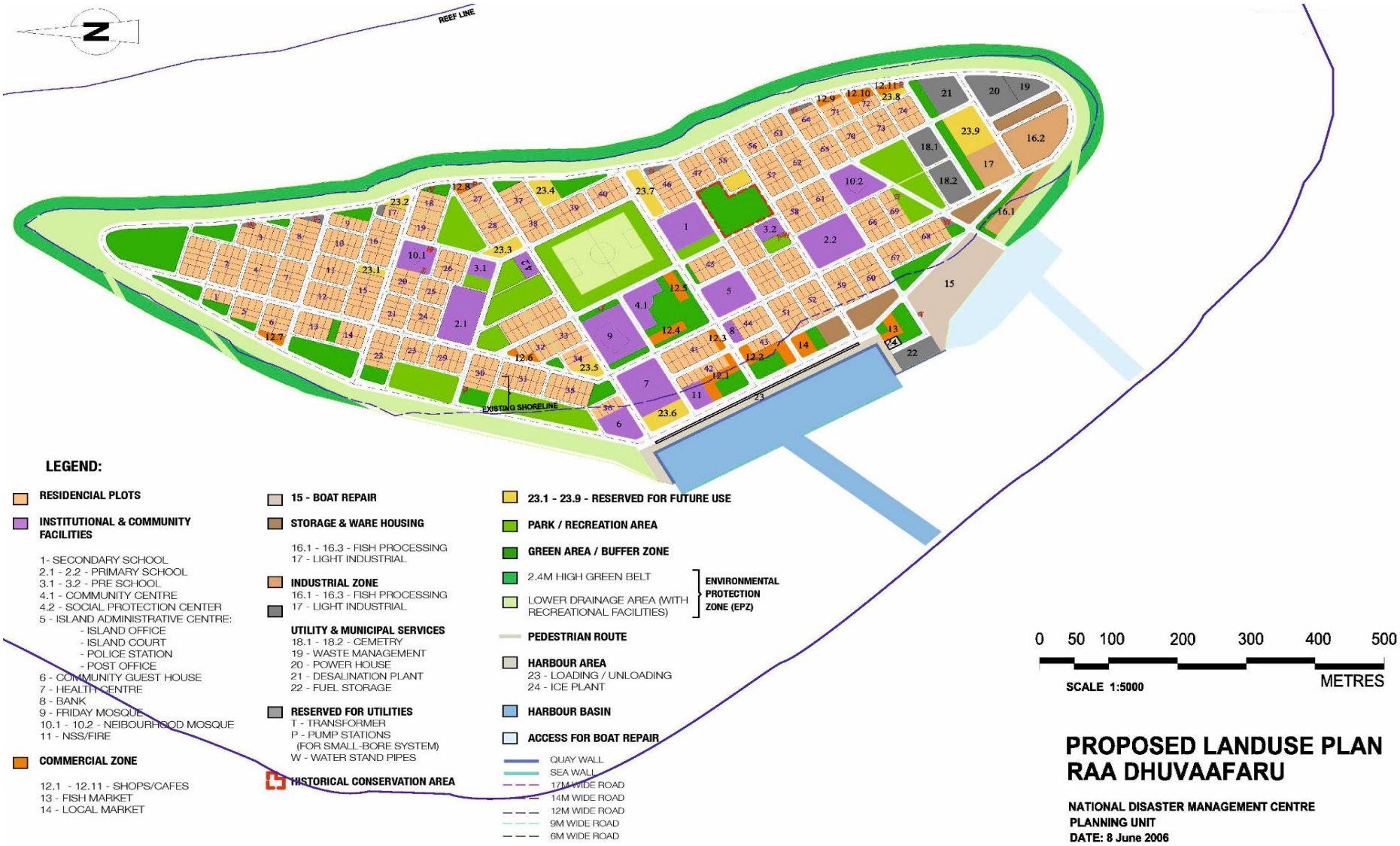
http://humweb.ucsc.edu/gweltaz/courses/techno/papers/insulae.html – Accessed 29 April 2014

www.fema.gov – Accessed 5 November 2014

ikeafoundation.org – Accessed 19 April 2014

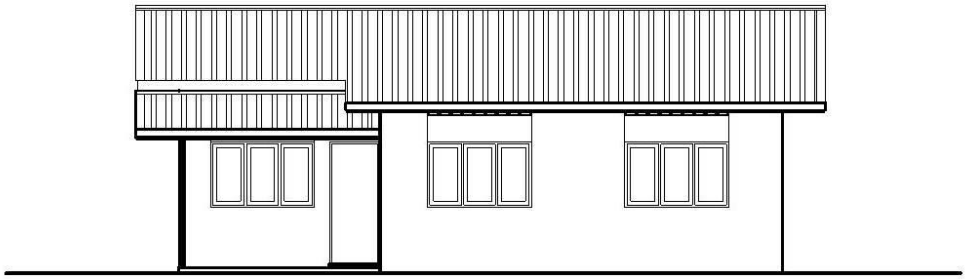
ANNEXES

ANNEX – Dhuvaafaru Landuse Plan



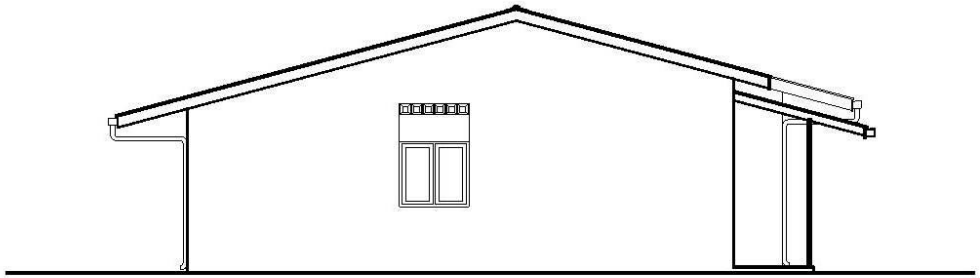
(National Disaster Management Center Planning Unit, 2006)

ANNEX – Front elevation of housing unit



FRONT ELEVATION

0 1 2 3 4 5m



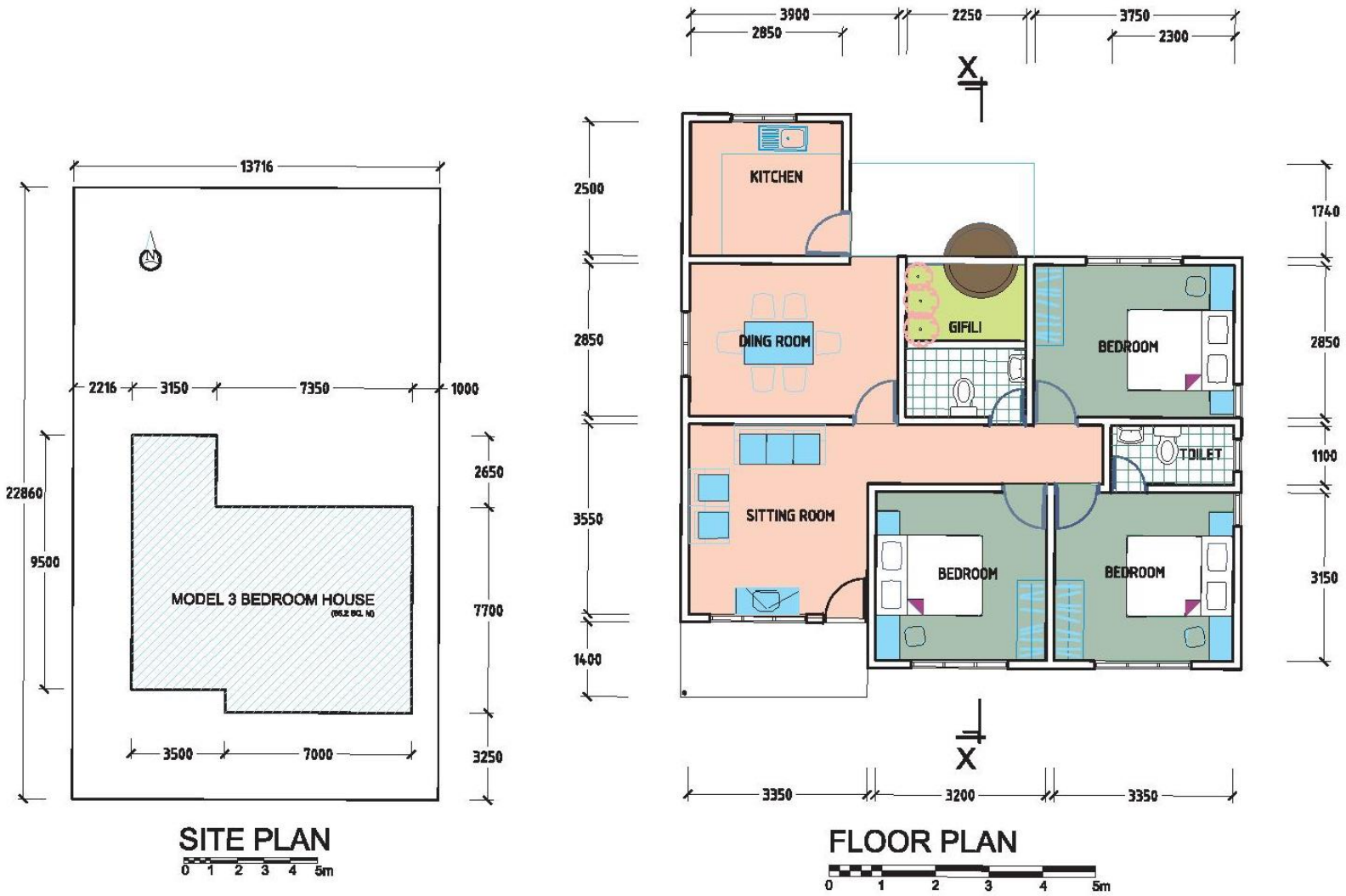
SIDE ELEVATION

0 1 2 3 4 5m

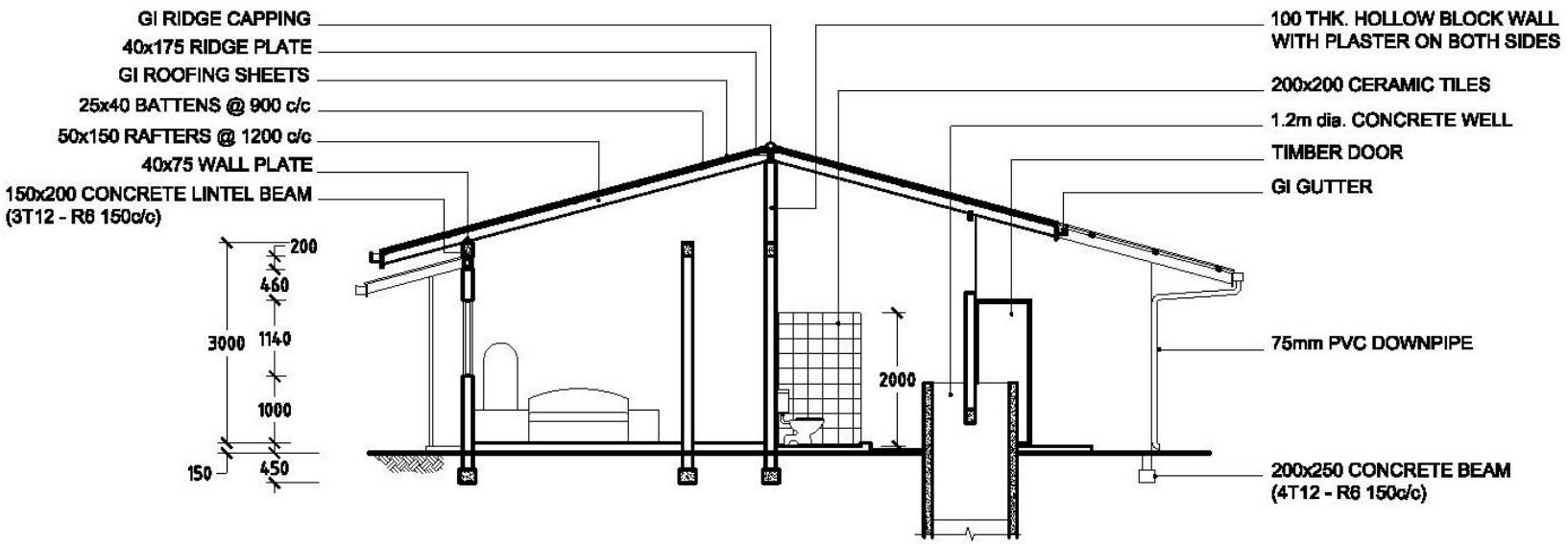
MODEL 3 BEDROOM HOUSE

(Government of Maldives, 2005)

ANNEX – Floor plan and site plan of housing unit



(Government of Maldives, 2005)



SECTION X-X

0 1 2 3 4 5m

MODEL 3 BEDROOM HOUSE

(Government of Maldives, 2005)