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SUMMARY

The informal settlements are encountered frequently in the urban texture of African cities. These buildings are often constructed without formal engineering criteria and the living conditions of their inhabitants are generally poor. The most recurrent construction types in the informal settlements in Africa can be classified as, adobe, rammed earth, mud and wood and cement-stabilized brick houses. The number of inhabitants of informal settlements in urban areas is showing an upward trend as an effect of the high rate of urban growth in Africa. This, paired together with the undesirable effects of climate change, renders the informal settlements particularly vulnerable to extreme natural phenomena.

As far as it regards the climate change adaptation strategies for informal settlements, the need for integrated, streamlined and standardized vulnerability assessment procedures and upgrading methodologies is apparent. Focusing its attention on vulnerability assessment and upgrading strategies for informal settlements subjected to flooding, the present document is aiming to reach out to a wide-range of people by providing guidelines on how to assess and to mitigate the vulnerability of informal settlements to flooding. The objectives of the present document can be summarized as: increasing public awareness to the flooding phenomenon and flood-prone areas; encouraging the commitment of public authorities to flood risk mitigation for informal settlements; providing relatively easy-to-implement strategies for natural disasters adaptation in informal settlements.

After the introduction and a brief description of the terminology, this deliverable offers an ample description of construction material properties, the in-situ and laboratory tests for determining them and the material mechanical properties found in existing literature. The following section provides a perspective of site and structural features that are going to significantly affect the vulnerability of a structure to flooding. The flooding actions, classified into hydro-static and hydro-dynamic are described in the next section. These actions are going to be employed for defining the structural flood loading for the purpose of performing structural analyses. A section is dedicated to describing a step-by-step procedure for probability-based flooding risk assessment, based on structural analysis results, whenever applicable, and taking into account the structural modelling uncertainties. The final section is dedicated to the over-view of a wide spectrum of flood risk mitigation strategies with particular attention to preventive measures. Finally the step-by-step flooding risk assessment procedure described in this document is demonstrated for an urban hot-spot in Dar-Es-Salaam and the final results are presented in terms of the mean annual frequency of exceeding the life-safety limit state for individual structures.

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1 FOREWORD

The present deliverable strives to lay out the base for a pre-code guide-line for the vulnerability assessment and reinforcement measures for informal settlements to natural phenomena with specific focus on flooding. From different points of view, this deliverable should be considered as a "living document". It needs to be further enhanced and refined through different stages of validation and extensive peer/end-user feedback in order to become a general purpose guideline. This deliverable is first and foremost a technical document that is written with the objective of making it consultable by inhabitants of the informal settlements, community leaders, peer engineers and urban policy makers. Therefore, it is worth clarifying that the recommended reinforcement, mitigation and adaptation strategies overviewed in this deliverable do not necessarily coincide with the points of view of urban policy-makers.

While preparing this document, the authors have been keen on maintaining a balance between a purely technical document and one that is aiming to reach out to the inhabitants of informal settlements, community leaders and urban policy-makers. The authors hope to have managed to keep this delicate balance. In this regard, the vulnerability assessment of informal settlements as a system of spatially-distributed unit constructions has been advertently kept out of this document. This has been done with the objective of relaying as much information as possible regarding a single house-hold. The subsequent deliverables are going to delve into the issue of vulnerability assessment of spatially distributed systems.

The portrait drawn in this deliverable of the general slum conditions in selected case-study African cities is mainly based on existing literature results. The authors hope that the actual slum conditions have improved significantly with respect to the information provided in this document. This can be attributed to the enormous effort that is being pursued in this regard under the auspices of numerous slum-improving programs in different African cities.

Although the vulnerability assessment procedures laid out herein focus primarily on flooding, the findings can be also extended to other types of natural phenomena. Moreover, the phenomenon of flooding is closely related to other natural phenomena such as landslides, salinisation, sea-level rise and erosion. Therefore, whenever applicable, possible inter-dependences with other natural phenomena are explored. The authors would like to spend a final word on the title of the deliverable and its actual scope. As it is also reflected through the title, this document is initially born as a guidelines concerning the adobe houses. However, after observing that the African urban informal settlements texture is consisted of various construction types and based on peer feedback within the project, the authors have decided to extend the scope of the document to informal settlements in general.

2 INTRODUCTION

Africa and climate change:

Africa arguably is the continent most vulnerable to climate change and its adverse effects, despite being the continent least responsible for global greenhouse gas emissions. Africa's vulnerability to climate change can be attributed to its dependence on rain-fed agriculture, poverty and insufficient adaptation capacity. The adverse effects of climate change in Africa may include, reduced agricultural production, worsening food security, the increased incidence of flooding and drought, spreading disease and an increased risk of conflict over scarce land and water resources. Therefore, it is clear that immediate action is needed in both reducing the global carbon emissions and adapting to the adverse effects of climate change [1]. Hence, climate change and its associated impacts on the natural, physical and social systems asks for the integration of a forward-looking perspective into decision-making processes to ensure that climate change adaptation strategies are fully addressed.

Climate change and natural disasters:

There is increasing evidence about correlation between the phenomenon of climate change and extreme climate-related events. As evidence of the link between climate change and extreme events, one can cite the increased frequency of heat waves, the increase in temperature maxima, increased likelihood of flash floods and draughts, change in rainfall patterns and intensity, increase in hurricane intensity, sea-level rise [2]. Figure 1 illustrates few examples of extreme climate-related events. The climate-related extreme events are transformed into natural disasters when they hit vulnerable areas. Therefore, assessment and prediction of the adverse effects of climate change and extreme weather-related events and identifying the vulnerable areas are undoubtedly important steps in an integrated climate change adaptation strategy.

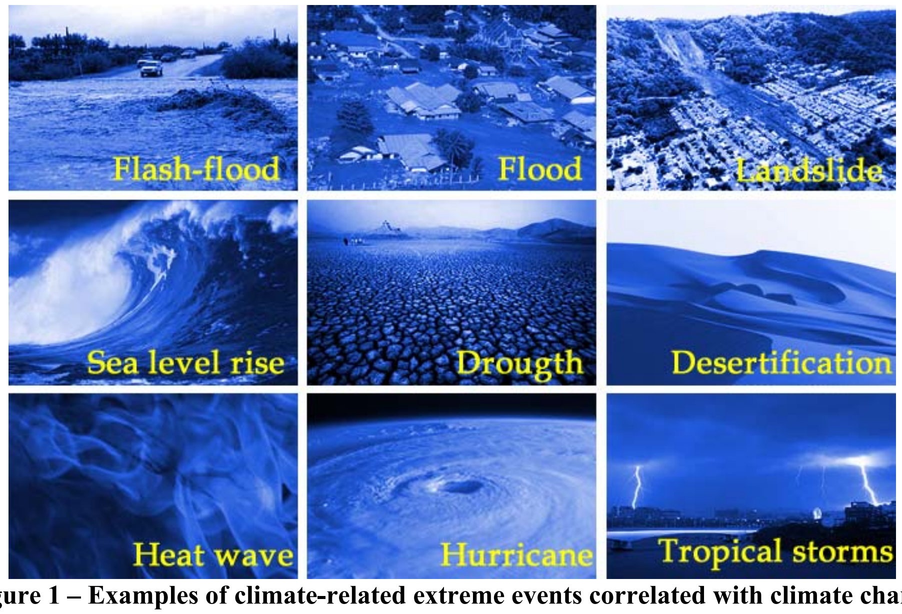


Figure 1 – Examples of climate-related extreme events correlated with climate change

Natural disasters and urban areas

Africa has the highest rate of urbanization around the world (3.5%/year, [3]). Around 40 percent of the African population currently lives in the urban areas [3]. This number by 2050 is going to increase to 61.8 percent of Africa's projected population [3]. Table 1 reported below outlines the break-down of the percentage of urban population in Africa. Figure 2 reported below show the relative increase of the urban population percentage increase in the next 40 years.

AFRICAN REGION	2010	2050
SUB-SAHARAN AFRICA - SSA	37.3%	60.5%
EASTERN AFRICA – EA	23.7%	47.6%
NORTH AFRICA – NA	52.0%	72.0%
SOUTHERN AFRICA – SA	58.8%	77.6%
WESTERN AFRICA – WA	44.6%	68.0%

Table 1 - Percentage of urban population [4]

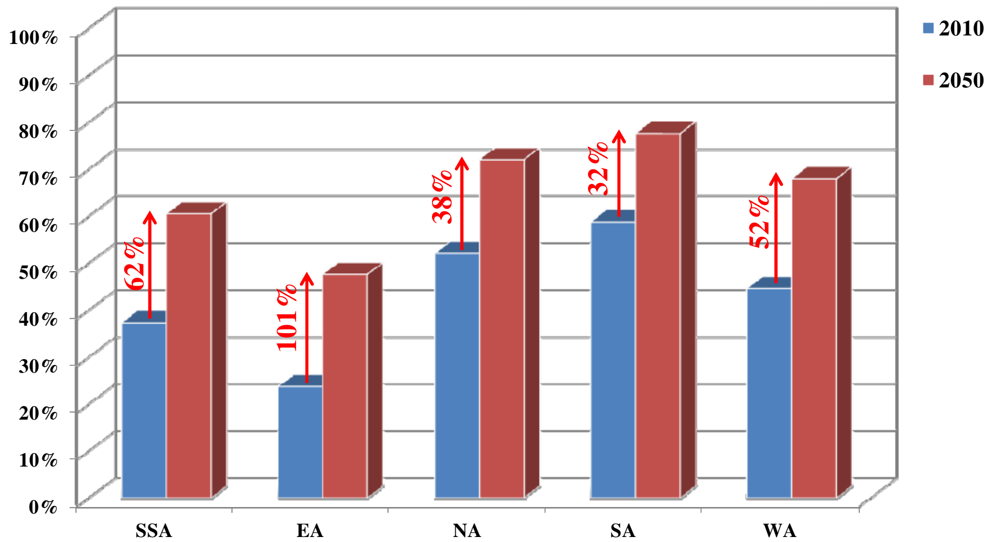


Figure 2 – Increase of the percentage of urban population in the next forty years

However, the infrastructure development and economic growth in urban areas lag behind the rapidly-growing urbanization phenomenon. In simple terms, the cities develop too fast and there is not enough time margin left for being able to properly absorb its new inhabitants. This leads to high levels of unemployment, inadequate standards of housing and services, and impacts on human health and development. These are amongst the reasons why the urbanized areas are potentially vulnerable to climate-related extreme events.

The informal settlements

Due to a large percentage of rural-to-urban and intra-city migration, large birth rates and very little and/or very irregular income, a large percentage of the urban population has very little chances of being formally integrated inside the urban economy as potential buyers, loaners or renters. Unable to pay regular rents or mortgage payments, they end up taking over un-occupied lands in the outskirts of the city and build make-shift dwellings. Therefore, these shanty-towns are continuously in expansion in the extreme margins of the city or the peri-urban areas. In most of the cases, the "choice" of the building site is completely improvised ignorant of the risks; therefore, many instances of constructions in the flood prone areas, close to waste disposals, and close to unstable steep slopes can be observed. Other than being very cheap, self-built housing has many advantages for its occupants/builders; it can be built from almost any material available, it can be occupied and inhabited also during the building period, and it can be improved over time as financial resources permit. As far as it concerns public services, the residents of these make-shift housings have very little access to services and need to rely on water tanks, open sewer systems and un-paved streets for long periods of time.

One of the most significant consequences of the rapid urbanization process is the phenomenon of the squatter settlements also known as the informal settlements, shanty towns, and slums. Although they defer slightly in their definitions, these denominations all refer to generally poor standards of living. General estimates indicate that about 60 percent of the urban population in Africa lives in informal settlements and shanty towns [4]. The Table 2 below reports the proportion of the urban population living in slums in Africa in the last 20 years (source [3]).

YEAR	1990	1995	2000	2005	2007	2010
PERCENTAGE OF URBAN POPULATION LIVING IN SLUMS IN NORTH AFRICA	34.3%	28.3%	20.3%	13.4%	13.4%	13.3%
PERCENTAGE OF URBAN POPULATION LIVING IN SLUMS IN SUB-SAHARAN	70.0%	67.6%	65.0%	63.0%	62.4%	61.7%

Table 2 - Proportion of urban population living in slums

According to UN habitat [3], the slum households are characterized as a group of individuals living under the same roof in an urban area, lacking one or more of the following five amenities: (1) durable housing (a permanent structure providing protection from extreme climatic conditions); (2) sufficient living area (no more than three people sharing a room); (3) access to improved water (water that is sufficient, affordable and can be obtained without extreme effort); (4) access to improved sanitation facilities (a private toilet, or a public one shared with a reasonable number of people); and (5) secure tenure (secure tenure status and protection against forced eviction).

However, only the first four indicators are used to define slum households, and then to estimate the proportion of the urban population living in slums.

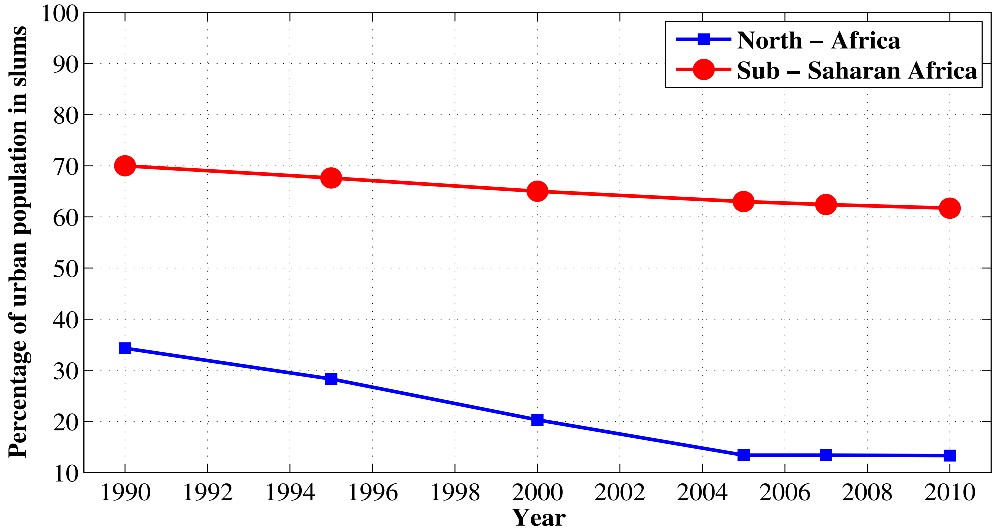


Figure 3 - Proportion of urban population living in slums

The informal settlements are diffused in African cities. They are a direct effect of high rates of urban growth as a result of post-colonial rural/urban migration trends. Summing up the large rate of increase in urban population to new fragile economies results in ever-growing urban areas but not necessary in changes and improvements in the infrastructures, employment and the services. Therefore, most African cities are characterized by a dual face, the old colonial city and the new and often improvised city, highlighting the large gaps between the standard of living for the rich and the poor. Figure 3 illustrates the percentage change in slum proportion in selected countries in Africa between 1990 and 2010. As it can be observed, the percentage of urban population living in slums has been reduced in the past twenty years thanks to policies such as slum-improvement projects, public involvement in decision-making and government low-cost housing incentives. North African countries such as Egypt and Morocco have been particularly successful in reducing the percentage of population living in slums, by removing around 7.5 million people from informal settlements to formal housing standards. In sub-saharan Africa, South Africa has been the most successful country in reducing the slum population. It is estimated that it has removed around 2 million people from slum living conditions [3].

Although the percentage of urban population living in slums has been reduced in Africa over the past twenty years, the total number of people living in slum areas has increased. In other words, the decrease in the number of people living in slums is outnumbered by the slum population growth. It is estimated that the urban slum population has increased from around 102,588 thousands in 1990 to 199,540 in 2010 [5].

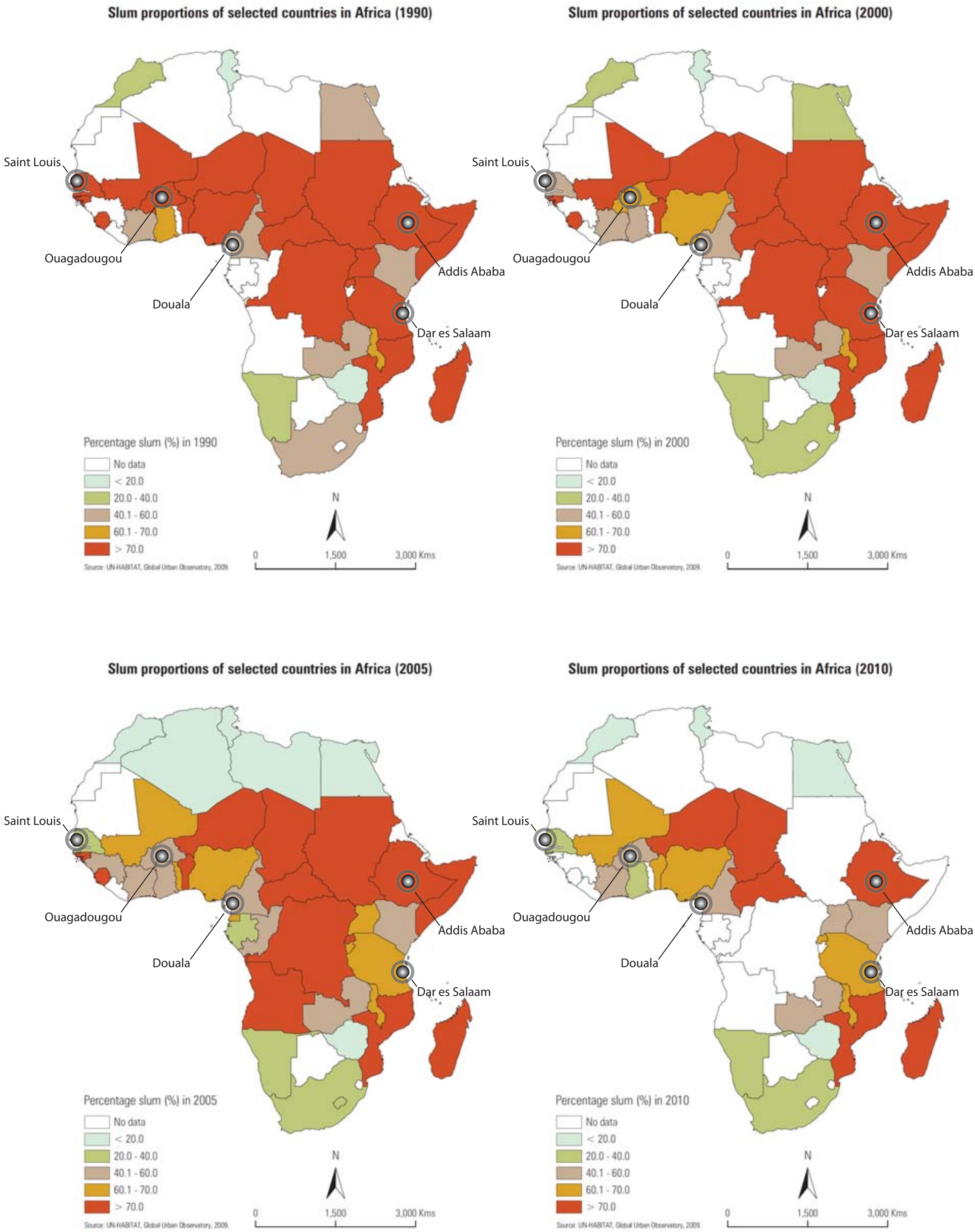


Figure 4 – Percentage change in slum proportion in selected countries in Africa between 1990 and 2010 (estimate) – [3]

Buildings materials employed in informal settlements in Africa*

The material used for the construction of informal settlements is generally easy to produce and abundant. Usually the building materials are characterized based on the material used for the construction of walls. The typical building material used for the construction of walls in the informal settlements is outlined in the following.

Earthen (Adobe) house

A common type of building material used in the construction of informal settlements is the earth "adobe" material. Adobe material is composed of sand, clay and water, pressed in blocks and is sun dried. Use of these sundried blocks dates back to 8000 B.C. This material is very common in low income rural areas due to its low cost and relative simplicity in construction; the popularity of adobe material is partly due to its excellent thermal and acoustic proprieties. In Figure 5 the world-wide distribution of earth architecture is illustrated. It can be observed that these constructions are very popular in Africa

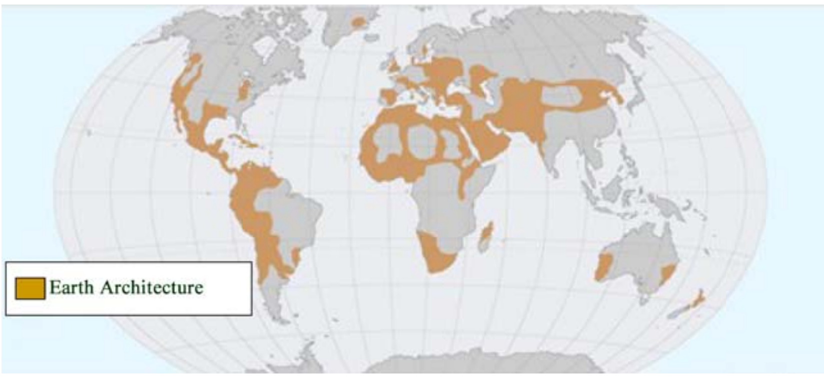


Figure 5 - World distribution of earth architecture [Errore. L'origine riferimento non è stata trovata.**]**

This structural type, in addition to being particularly vulnerable to seismic actions, is also affected by adverse climate change effects; such as, erosion due to cycle of rain/drought and wind action, the prolonged contact with water in case of flood or intense and prolonged rain (often leading to an overall ageing and deterioration of structural resistance), salinisation of material due to sea lever rise at the level of groundwater (resulting in reduction of mechanical properties of base blocks), and direct impacts with water and debris flow during the flood, flush-floods and landslides.

The earthen houses can be classified in to following sub-categories: adobe bricks(un-baked sun-dried earth bricks) and rammed earth.

Masonry blocks

In this type of construction masonry units (burnt brick, stone, cement-stabilized sand blocks) are bound by mortar. Buildings made up of cement blocks are quite common in African cities.

Timber buildings

Houses entirely made of timber houses are not very common in Africa. Timber is mostly used to construct frame structures, such as roof structural frame, posts and framing for mud or corrugated iron sheet walls. Stilted houses, which are somewhat uncommon in urban areas, often have a floor of timber planks. It is important to note that good quality timber is high demand, is generally expensive and needs to be imported from other zones (is not usually found in flood planes). Therefore, low-income villagers can seldom afford it. The use of bamboo instead is more common in the areas in which bamboo grows.

Hybrid buildings – mud and wood (a.k.a., wattle and daub)

The use of wattle and daub material dates back to several thousand years ago. This hybrid construction technique consists of creating a wooden frame/lattice and embedding (daubing) the adobe material (combination of wet soil, clay, sand, animal dung and straw) inside. This construction type is quite common in Africa.

2.1 INFORMAL SETTLEMENTS IN THREE CLUVA CASE-STUDY CITIES

2.1.1 Dar-Es-Salaam

Dar-Es-Salaam is one of the fastest growing cities in Sub-Saharan Africa with an estimated growth of 8 percent per year [5]. Rapid unplanned urbanization in Dar-Es-Salaam has led to flood risk in many informal settlements, with a wide range of health-related consequences for residents. Figure 6 below demonstrates a map of the spread of the informal settlements in Dar-Es-Salaam which is overlaid on the zones of high flooding risk in the city. It can be observed that a significant portion of the informal settlements are facing the flooding risk.

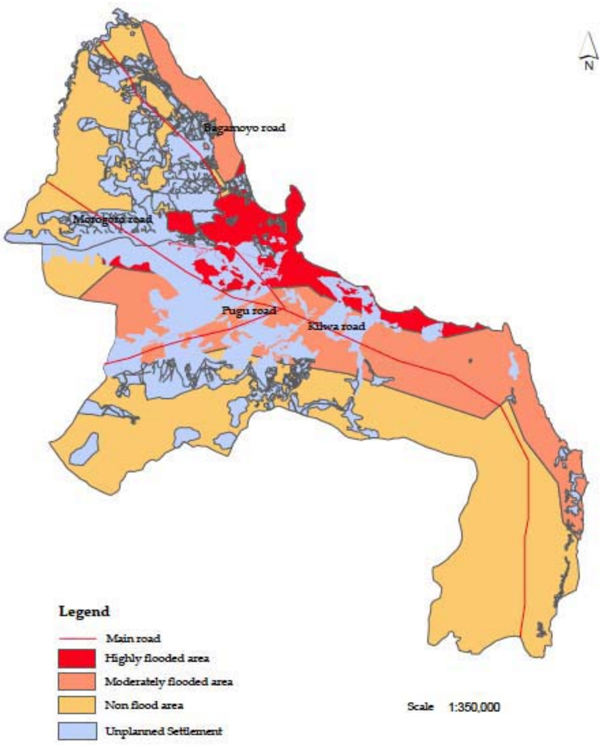


Figure 6 - Flood hazard zone map overlaid on urban informal settlements (source: Ardhi University)

Roof			Wall				Floor	
Iron Sheet	**Grass**	**Grass & mud**	**Cement Bricks**	**Sun-dried bricks**	**Backed bricks**	**Poles & Mud**	**Cement**	**Mud**
90.4 %	3.6 %	0.2 %	87.7 %	2.4 %	0.1 %	7.9 %	86.3 %	12.8 %

Table 3 - Material used for the construction of floors, walls and roof in the informal settlements in Dar-Es-Salaam

Table 3 illustrates the types and percentages of various materials used in the construction of floors, walls and roof in the informal settlements in Dar-Es-Salaam over the past twenty years (up to 2002). As it can be observed, the floor is usually constructed with cement and tiles (around 86%), The walls are usually constructed using concrete, cement and stones (around 88%) and the roof system is consisted predominantly of metal sheets (around 90%). Infact, the modern “Swahili” housing type has the same predominant construction features described above; namely, it has a proper foundation built with stone/cement/concrete, the walls are made up of cement-stabilized sand blocks and the roof is covered with metal sheets (Figure 7). The average number of room per household in Dar is estimated to be around 1.8 units.

Figure 7 - informal settlement in Dar-Es-Salaam (photo by R. De Risi)

Moreover, a trend can be observed as much as it regards a shift from earth constructions towards the use of concrete and cement over the years. An important socio-economic feature of the informal settlements in Dar-Es-Salaam is that the informal settlements have both rich and poor inhabitants. The causes for this phenomenon can be traced in the facility of access to land in the informal market, and the relatively secure land tenure and favourable land policies in the informal settlements of Dar [5]. The Dar municipality is divided in three wards (districts) of Kinondoni, Temeke and Ilala. The following table (Table 4) demonstrates the population living in informal settlement, areal extent of the informal settlements and the percentage of people estimated to be living in the informal settlements. It can be observed that around 70% of the urban population in Dar leaves in informal settlements as of 2002.

Municipality	Total Area (hA)	Informal Area (hA)	Total Population	Population in informal areas	% of total population in informal area
Kinondoni	53100	2560	1089000	768000	70%
Temeke	771500	2000	771500	600000	78%
Ilala	21000	1095	637500	328500	52%
Total	845600	5.655	2498000	1696500	68%

Table 4 - Break-down of the areal extent and the percentage of urban population living in urban informal settlements in Dar-Es-Salaam

2.1.2 Addis Ababa

Addis Ababa, the national capital of Ethiopia is host to some 26 percent of the national urban population (estimated around 77 million, second in sub-Saharan Africa) [6]. Like any other major city of Africa, it is suffering from a range of social and economic problems including widening inequality, deepening poverty, rising unemployment, severe housing shortage, poorly developed physical and social infrastructure and wide-spread slum and squatter settlements. It is estimated that 80 percent of the urban population leaves in informal settlements. This, compared to the average 72 percent UN HABITAT estimate for the whole of urban Africa, highlights the severity of housing conditions in Addis.

The majority of the residential units in Ethiopia are poorly constructed. The 1994 population and housing survey indicates that about 80 percent of all urban housing units in the country are made of wood and mud (wattle and daub), and 73 percent have earthen floors. Roofs are almost invariably made of corrugated iron sheets. It is worth mentioning that a significant category of buildings has no roof whatsoever. Nearly 98 percent of the units are one-storied and 54 percent are attached row houses. The majority of urban housing is consisted of one- and two-room shelters accounting for 41.84 percent and 30.54 percent respectively of all urban housing units. As many as 42.3 percent of urban housing units have no toilet and 39.2 percent are without kitchens. Only 3.23 percent of the units have indoor plumbing, with some 27 percent relying on non-tap water sources. Moreover, The 1994 census showed that the total number of urban households exceeded the total number of housing units by approximately 92,000. Around 36 percent of the urban housing stock had six or more residents per unit. The average number of room per household is estimated to be around 2.8.
Sewerage networks are virtually non-existent in Ethiopian towns and cities, except for a tiny area in Addis Ababa. Similar to Dar, Addis is characterized by neighbourhoods in which the poor and the wealthy live side-by-side and no particular concentration of ghetto areas is observed.

As mentioned above, the majority of housing types in Addis Ababa is consisted of mud and wood constructions (Figure 8). Table 5 lists the distribution of different construction types per city district in Addis Ababa. These data confirm again the prevalence of the mud and wood construction type in Addis Ababa.

Figure 8 - Make-shift mud and wood house in Addis Ababa. (photo by N. Yonas)

Table 8.2 Housing Units of Sub Cities by Construction Material of Wall: 2007

Sub City	All Housing Units	Construction Material of Wall: Wood and Mud	Wood and Thatch/ Wood only	Stone and Mud	Stone and Cement	Plastered Hollow Blocks	Unplastered Hollow Blocks	Bricks	Corrugated Iron	Reed/ Bamboo	Mud Bricks	Others
ADDIS ABABA CITY ADMINISTRATION	628,986	483,636	1,636	5,171	15,585	81,972	8,445	9,730	18,824	439	148	3,400
AKAKI KALITY-SUB CITY	45,749	36,940	191	175	641	5,239	890	143	1,298	42	5	185
NEFAS SILK-LAFTO-SUB CIT	75,079	49,936	150	515	1,373	17,217	1,507	1,131	2,874	38	11	327
KOLFE KERANIYO-SUB CITY	93,335	71,246	156	768	1,863	15,264	1,885	542	1,337	43	11	220
GULELE-SUB CITY	57,840	50,593	115	555	1,330	3,644	283	539	555	16	16	194
LIDETA-SUB CITY	44,351	37,398	122	319	1,187	2,194	330	453	2,018	43	5	282
KIRKOS-SUB CITY	52,581	40,238	126	453	2,116	4,974	558	1,169	2,437	42	5	463
ARADA-SUB CITY	47,367	38,461	239	773	1,982	2,413	332	784	1,889	78	16	400
ADDIS KETEMA-SUB CITY	49,042	43,372	135	303	1,185	1,558	222	379	1,461	43	11	373
YEKA-SUB CITY	87,347	72,220	196	742	1,674	8,366	890	1,298	1,558	48	21	334
BOLE-SUB CITY	76,298	43,232	205	569	2,234	21,103	1,549	3,292	3,398	47	47	622

Table 5 - Distribution of different construction types per city district in Addis

Flooding, caused by torrential rain in the rainy season, occurs regularly in Addis Ababa. During the rainy seasons a large part of the run-off is stored in the low-lying parts. There are several rivers and streams which originate in the mountain range surrounding Addis Ababa. Torrential rain, which is common during the rainy season, causes sudden rise in the flow of these rivers and streams, resulting in flood damage to settlements along their banks. Inadequate drainage and inappropriate waste disposal in the city also cause urban runoff resulting in traffic congestion, damage to road infrastructure and deterioration of surface water [7].

2.1.3 Ouagadougou

Ouagadougou is the capital city of Burkina Faso. The 2007 courvey results for Burkina Faso indicate that around 50% of the dwellings in the central region (the region whose center is Ouagadougou) are constructed with earth material and the remaining 50% are built with cement. The absolute majority of the roof are made up of iron sheets (more than 90%) . In terms of tenure security, around 50% of the dwellings in Ouagadougou is self-owned, a 30% is rented and around 16 is occupied for free [8].

The main feature of informal settlements in Ouagadougou is its relative low population density. In 1994, 80% of residential development had a density of population between 42 and 91 people per hectare compared to 300 and 400 inhabitants / hectare in some other big African cities [9].

a) 

b) 

Figure 9 – a) Queue for drinking water, Ouagadougou [9]; b) Flood in Ouagadougou [Cluva dropbox]

2.2 THE SCOPE AND OBJECTIVES OF THIS GUIDELINES

The scope

As far as it regards the climate change adaptation strategies for informal settlements, the need for integrated, streamlined and standardized vulnerability assessment procedures and upgrading methodologies is apparent. Focusing its attention on vulnerability assessment and upgrading strategies for informal settlements subjected to flooding, the present document is aiming to reach out to a wide-range of people by providing a guideline on how to assess and to mitigate the vulnerability of informal settlements to flooding.
Along these lines, the work is structured in the following order:

- A brief overview of terminology;
- Material properties;
- Site and structural features;
- Flood actions;
- Flood risk assessment;
- Flood risk mitigation strategies;
- Case-study: Flood vulnerability assessment for an urban hot-spot in Dar-Es-Salaam

The objectives

The objectives of the present document can be summarized in the following points:

1. Increasing public awareness to the flooding phenomenon and flood-prone areas;
2. Encouraging the commitment of public authorities to flood risk mitigation for informal settlements;
3. Providing relatively easy-to-implement strategies for natural disasters adaptation in informal settlements

All the above inter-dependent objectives are aligned with ISDR (International Strategy for Disaster Reduction, [10]). For instance, translating the scientific knowledge and research state of the art into accessible information is going to be a major contribution towards increasing the level of public awareness on natural hazards, and encouraging decision-makers to incorporate this information in the policy-making process.

3 TERMINOLOGY

It is worthwhile to provide a brief description of the most recurring terms and concepts throughout this document.

Hazard
The term hazard is used to refer to the frequency of occurrence of natural phenomena. In general, the term hazard is used interchangeably to refer to also the natural phenomena and their intensity. In this report, hazard is referred to as the mean annual frequency of exceeding a variable representative of the natural phenomenon of interest. For flooding phenomenon, by flooding hazard, the mean annual frequency of exceeding a specific flood height is intended.

Vulnerability
Vulnerability can be defined as the degree to which a (natural, physical or social) system is susceptible to, or unable to cope with the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity [11]. Therefore, it is clear that vulnerability can be classified into natural(ecosystem), physical and social vulnerability categories. In this report, the focus is on physical vulnerability of informal settlements. The physical vulnerability can be evaluated both for a single structure and also for a group of spatially-distributed structures.

Fragility
The concept of fragility specifically addresses the physical vulnerability of a system (e.g., structure, group of structures, road, a network of roads, ..., etc). In this report, by fragility, the probability of exceeding a limit state given a specific value for the variable that represents the natural phenomenon is intended. For instance, in the case of flooding, the fragility is the probability of exceeding a limit state given a specific flooding height. Thus, the structural fragility for a certain natural phenomenon represents the vulnerability of the structure to that phenomenon. It is also common to represent the concept of fragility graphically in the form of the fragility curves. The fragility curves for a given limit state are plotted in terms of the probability of exceeding limit state given the representative variable (e.g., flood height in case of flooding) versus different values of the representative variable.

Limit states
The limit states refer to different performance thresholds prescribed for the system. Therefore, the vulnerability of a system is evaluated as function of a designated limit state. Serviceability, severe damage, light damage, life safety are examples of various limit states. Hence, each fragility curve corresponds to a specific limit state.

Risk
The term risk is used herein to quantify the adverse effects of natural phenomena on a system. Therefore, the risk integrates information on both the intensity and the rate of occurrence of natural

phenomena (i.e., hazard) and the degree to which a (natural, physical or social) system is susceptible to the adverse effects of the natural phenomena (i.e., vulnerability).

Urban hot-spots

The urban zones in which high vulnerability to natural phenomena coincide with high hazard levels are referred to as the urban hot-spots. The urban hot spots are characterized by highest levels of risk. Figure 10 below illustrates the hot-spot concept in a schematic manner.

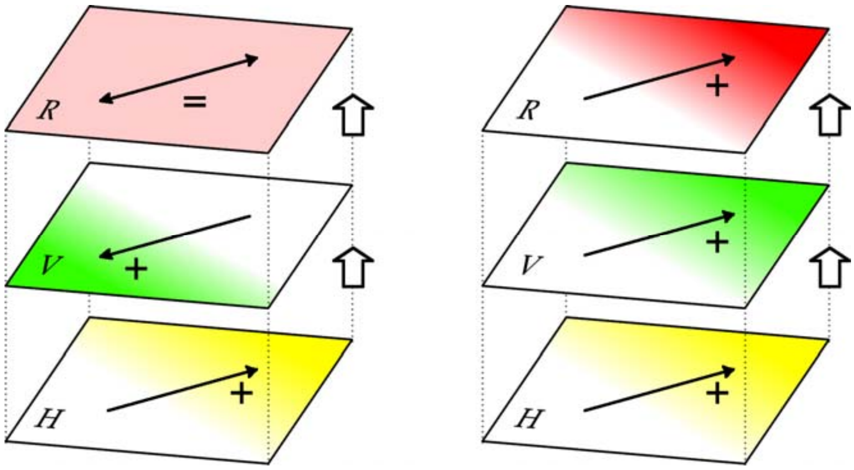


Figure 10 - Hazard, vulnerability and risk, the concept of urban hot-spots

Informal settlements

The definition of informal settlement can be subjected to some variation. Furthermore, the common denominations for this category of buildings are quite varied; for example, they are referred to as informal settlements, slums, shanty towns, ..., etc. However, all denominations imply generally poor conditions of living. According to UN habitat [3], the slum households are characterized as a group of individuals living under the same roof in an urban area, lacking one or more of the following five amenities: (1) durable housing (a permanent structure providing protection from extreme climatic conditions); (2) sufficient living area (no more than three people sharing a room); (3) access to improved water (water that is sufficient, affordable and can be obtained without extreme effort); (4) access to improved sanitation facilities (a private toilet, or a public one shared with a reasonable number of people); and (5) secure tenure (secure tenure status and protection against forced eviction).

4 MATERIAL PROPERTIES

The first step towards an elaborated assessment of structural vulnerability is to evaluate the fundamental mechanical properties of the construction material. On the other hand, the mechanical properties of the construction material used in the informal settlements are going to be directly related to the soil property close to the construction site. Moreover, determining the soil properties is going to be very important for determining the effectiveness of the foundation. In this section various in-situ and laboratory tests results for measuring both the soil and the construction material mechanical properties are described. The (less accurate) field test results can be used as preliminary estimates before performing the (more accurate) laboratory tests.

4.1 PRELIMINARY MATERIAL ANALYSIS: SIMPLE FIELD TESTS FOR SOIL PROPERTY

With regard to the soil property, it is important to have a thorough grasp of the following three fundamental characteristics:

a) The texture or particle size distribution of the soil, i.e. the quantity of stones, gravels, sands, silts and clays present;

b) The plasticity of the soil or the ease with which it can be shaped;

c) The compressibility of the soil, or the extent to which voids, and therefore its porosity, can be reduced to a minimum.

The following tests are not very accurate, and, generally, are realized with makeshift, that can be less precise. However, they are very useful in characterizing the soil properties away from a laboratory. They lead to a qualitative evaluation of the proportion of clay, silt and sand in the soil mixture used as a base for constructing the bricks. In general a good brick building mix needs to have sufficient clay content so that it is deformable.

Preparing a plastic/moist soil specimen

Many tests described in the following involve the preparation of a plastic soil "dough". This means that some water needs to be added to the specimen in order to render it more "plastic". Therefore, it is described herein how a plastic soil dough can be prepared and how much moisture is needed for preparing it.

Moistened earth is formed into a ball of 20-30 mm in diameter. This ball is rolled into a thin thread of 3 mm diameter. If the thread breaks or develops large cracks before it reaches a 3 mm diameter, the mixture is slightly moistened until the thread breaks after reaching a diameter of 3 mm.

Touch test or Nibble test [12]

The touch test consists of taking a little quantity of soil on the palm of one hand and rubbing it with another hand in order to feel the texture. The sensation of abrasion on the skin is indicative of presence of sand, since the finer fractions (clay and silt) are impalpable. The sensation of agglomerates more or less resistant to the pressure between the fingers, is indicative of the presence of adhesives elements like clay. If humidified, the sandy earth becomes slightly plastic and not very cohesive, while the clayey soil becomes plastic and sticky.

Visual test

If is easy to see the aggregates in a soil sample, it indicates the presence of gravel or sand. Otherwise, if the particles are difficult to distinguish visually, it indicates the presence of clay, silt or fine sand (i.e., sand particles with a diameter less than 0.08 mm). On the other hand, the soil colour is a sign of presence of elements such as iron, sulphor, ... etc. that does not necessarily affect the mechanical behaviour of the soil.

Smell test

This test permits to evaluate the presence of organic elements in the soil. If humidified or heated, the soil is going to present a pronounced smell of humus or mildew. Pure loam is odourless.

Wash test [12]

This test identifies the presence clay in the soil. A humidified soil sample is rubbed between the hands. If the particles can be clearly felt, it indicates sandy soil. On the other hand, if the humidified sample is sticky but the hands can be rubbed clean when the sample dries out, it is indicative of silty soil. However, if the sample is sticky, but it is necessary to use water to clean the hands, it is indicative of a clayey soil.

Cutting test [12]

A humidified soil sample is formed into a ball and is cut with a knife. If the cutting edge is shiny, it indicates high clay concentration in the soil mixture. On the other hand, if the cutting edge is opaque, it indicates a high concentration of silt.

Adhesion test

A humidified soil sample is formed into a ball and is cut with a knife or a spatula. while cutting the sample, if the knife or the spatula encounters some resistance and sticks to the soil, it indicates high concentration of clay. If the knife or the spatula cuts the ball encountering no resistance and can be extracted easily from the sample, it indicates low concentration of clay.

Sedimentation test

The soil sample is stirred with a lot of water in a transparent cylindrical glass jar or bottle, of at least 1/2 litre capacity (approx. 1/4 soil and 3/4 water volume-wise). The jar is then sealed, and the content is well shaken and is left to stand for at least 30 minutes. This leads to a stratification of the soil particles based on their weight/size.

Retreat test or Alcock test

A 1-cm deep slot is cut out from a wooden rectangular bar of 60cm x 4cm x 4cm. The slot surface is then greased with Vaseline or other type of lubricant in order to prevent the soil specimen from cracking. The slot is then filled with the soil mix after removing the larger particles and it is left to dry out completely (at least three days in a dry environment). The dried soil sample in the slot is pushed forward. The samples with a higher concentration of clay are going to be more deformable.

Dry strength test
This test, described in more detail in [2], consists of forming the humidified soil into 6 balls of about 2cm of diameter. Once the balls are dried out (after 48 hours), they are pressed between the thumb and forefinger. If the balls deform under pressure without breaking, it indicates a high concentration of clay. On the other hand, if the balls break while being deformed, it indicates a low concentration of clay.

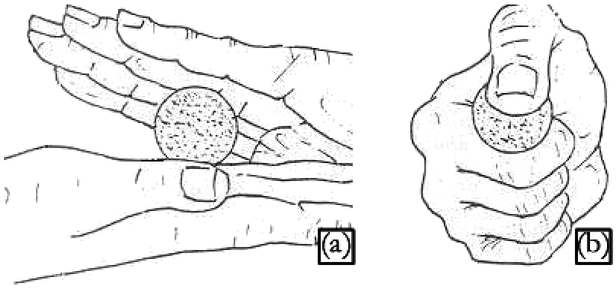


Figure 11 - Dry strength test soil [2], (a) preparation, (b) test

Ball dropping test [12]
The soil mixture specimen needs to have the minimum moisture content that lets it to be formed into a ball of 4cm diameter (a total of 4 bars need to be formed). The balls are then dropped from a height of 1.5m to a flat surface. depending on the proportion of clay in the specimen the following outcomes can happen:

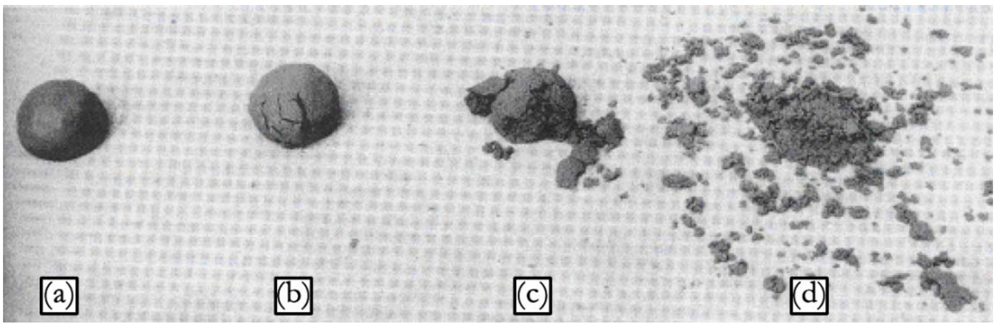


Figure 12 - Balls after the dropping test [12]

If the ball flattens without breaking apart (Figure 12(a) and (b)), it is indicative of a very high clay content. In this case, the mixture should be balanced by adding some sand. On the other hand, if the ball breaks apart in small pieces (Figure 12(d)), it is indicative of a very low clay content. In this case, the mixture should be balanced by adding some clay. It should be mentioned that the situation illustrated in Figure 12(c) is somewhat representative of the material used for making the mud/adobe bricks.

Sweat test
A ball with fine granular gradation (diameter less than 5mm), humid enough to demonstrate plasticity, is flattened against the palm of one hand and is pressed so that it releases the pore water. If the water surfaces easily and the remaining soil crushes after loosing the water content, it is indicative of a significant sand or silty sand content. On the other hand, if the water emerges slowly

(e.g., after 20-30 taps) and the ball flattens without crushing, it indicates a high content of silt or silty clay. Finally, if the water does not emerge after tapping the specimen repeatedly, it indicates high concentration of clay.

Consistency test [12]

Moistened earth is formed into a ball of 20-30 mm in diameter. This ball is rolled into a thin thread of 3 mm diameter. If the thread breaks or develops large cracks before it reaches a 3 mm diameter, the mixture is slightly moistened until the thread breaks after reaching a diameter of 3 mm. This mixture is then formed into a ball. If this is not possible, then the sand content is too high, and the clay content is too low. If a lot force is needed for crushing the ball between the thumb and forefinger, it indicates a high clay content (the mixture should be balanced by adding some sand). If the ball crumbles very easily, it indicates low clay content (the mixture should be balanced by adding some clay). In case the resulting ball demonstrates a soft and porous texture, it indicates the presence of organic material.

Cohesion test or "Cigar" test [12]

This test enables one to observe the degree of cohesion in the soil and above all, estimate the quantity of the clay in the soil mix. A specimen with a fine granular content is chosen. It is moistened and kneaded until a smooth paste is obtained. The resulting paste is left to stand for 30 minutes or more so that it gains a smooth consistency. Consequently, the loam is rolled between the hands into cigars of about 30 mm in diameter. The "cigar" is then placed against the palm of the hand and is pushed gently forward with the other hand, until a piece is detached. The length of the detached piece is measured. This procedure is repeated several times. Finally, an average value of the detached length is obtained. If the average length of the detached piece is less than 50mm, it is indicative of high sandy content. On the other hand, it is more than 150mm, it is indicative of high clay content. Values between 50 and 150 mm indicate that the soil has good cohesion. If is not possible to model any "cigars", the soil has little or no cohesion.

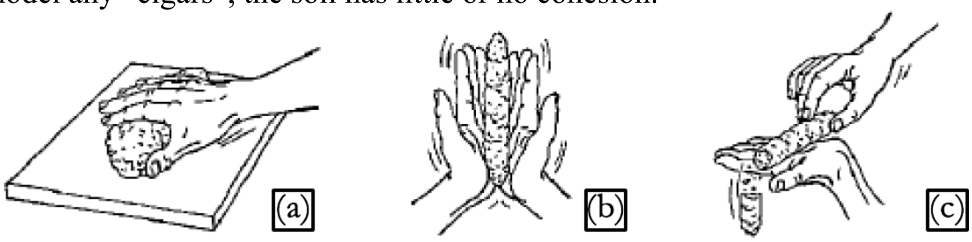


Figure 13 -"Cigar test" [13], (a) Mixture preparation, (b) "cigar" preparation, (c) test execution

"Biscuit" test [13]

The test consist of preparation of three earth biscuits, from the moist soil "dough", of diameter around 8 cm and thickness of about 1 cm). The three biscuits or disks are then laid under the sun so that they dry completely. The dried biscuits are then broken into two halves or compressed between thumb and forefinger. If the tablet is hard to break (i.e. if it breaks with an audible crack) and it crumbles with one snap like a biscuit or if it is possible to crush without reducing it to dust, it indicates a high concentration of clay. If is not too difficult to break the tablet, and it is possible to reduce it to dust by pressing, it indicates a high concentration of sand or silty sand. Finally, if the tablet is broken easily and it is crushed into dust without any difficulty, it indicates a high concentration of sand.

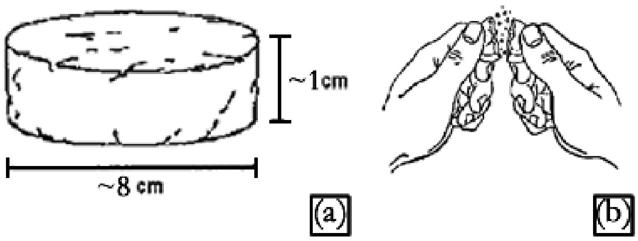


Figure 14 - "Biscuit test" [13], (a) Specimen dimensions, (b) test

4.2 EVALUATION OF BRICK AND MORTAR ADEQUACY

The tests described in the previous section are very useful in obtaining a general idea of the clay and sand content in the soil mix used as base material for constructing bricks. On the other hand, the tests described in this section can be performed on a wall panel that is constructed with the building bricks and mortar.

Microcracking control test [2]
This test consists of making two or more sandwiches (two bricks joined with mortar). After 48 hours drying in the shade, the sandwiches are carefully opened and the mortar is examined. If the mortar does not show visible cracking, then it is adequate for construction.

The same test can be adopted in order to find the optimal proportion of soil/coarse sand to be used as a base for the mortar. For this purpose, at least eight sandwich units are manufactured with mortars made with mixtures having different proportions of soil/coarse sand. Generally, it is recommended that the proportions of soil to coarse sand vary between 1:0 and 1:3 in volume. The sandwich with mortar having the minimum proportion of soil/coarse sand necessary for not showing visible cracks when being opened after 48 hours, is going to be chosen as the optimal mortar mixture.

Mortar joint bond strength test [12]
Two bricks are joined by a 20 mm thick mortar in a cross-wise manner (i.e., the upper brick is rotated 90º with respect to the lower brick. After the mortar is dry, the upper brick is laid on brick supports at both ends, while the lower brick is loaded with a sand-filled container. The weight of the lower brick and the sand-filled container, at the moment the mortar bond fails, divided by the mortar area gives the adhesive strength of the mortar/brick bond. This is true when the rupture occurs at the joint (i.e. at the mortar-brick interface). If the failure occurs within the mortar layer, then the calculated strength represents the mortar’s tensile strength and not that of the mortar/brick bond.

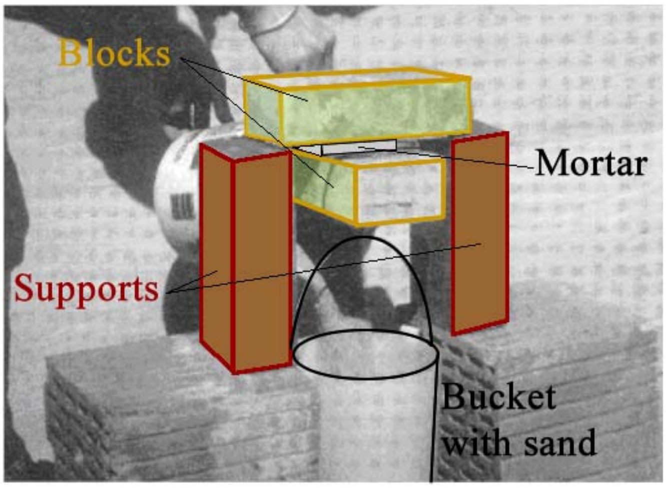


Figure 15 - Mortar joint bond strength test

Qualitative strength test of individual bricks [2]
The strength of a brick can be qualitatively evaluated by the following make-shift strength test. The building bricks should be strong enough to support in bending the weight of a man (around 70-85 kg). If the block breaks, it indicates that the mix used for making the bricks should be improved (e.g., adding more clay, fibrous material and/or stabilizers).

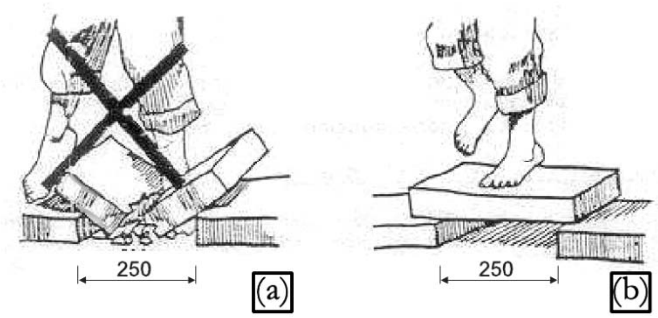


Figure 16 - Adobe brick strength field test, (a) poor-quality brick, (b) good-quality brick

4.3 LABORATORY EXPERIMENTAL TESTS

The most appropriate way to evaluate the mechanical properties of the building material (e.g., adobe, rammed earth, mud and earth, cement blocks) is to perform laboratory tests on a prism or panel (macro-element) constructed using the same material and technology as in the field. This provides an overall picture of the quality of the bricks and the quality of the brick/mortar interface (in the case of mud and earth construction, it provides an overall picture of the wooden frame and the mud infill). Herein, a number of laboratory tests on macro-element are described.

4.3.1 Axial compression test

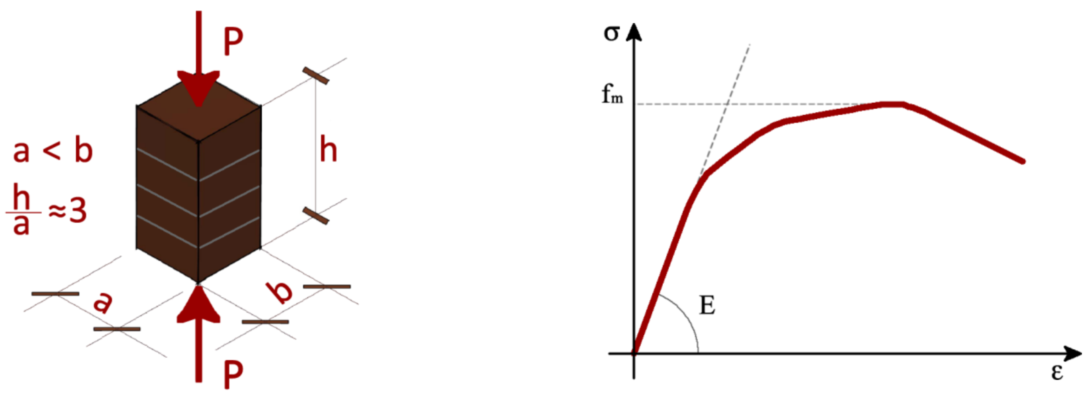
The wall panel compressive strength (f_m) may be determined trough the simple axial compression test. The specimen of this test must be a prism built with the same material and technology used in the field. In general, this test set-up is applicable to constructions with brick and mortar.

The test specimen prisms are composed of the number of full bricks necessary to obtain a height/thickness ratio of three. It is preferable that the prisms are made up of a minimum of 4 bricks and that the mortar thickness is limited to 20 mm. In the case of sun-dried blocks, the prism should be tested after 30 days from the time the prism is built in order to allow for the mortar joint to dry.

The better way to perform this test is trough a displacement control procedure. The setup must be composed of a fixed base at the bottom of the specimen, an actuator in the top part of the specimen, a load cell between the actuator and the upper face of the prism (that allows to read the applied force value) and a couple of LVDTs (Linear Variable Displacement Transducer) or potentiometers on the two opposite vertical face of the specimen. In this way the output is a force-displacement (P-Δl) curve, that can be transformed in stress-strain (σ-ε) curve with standard formulas.

$$\sigma = \frac{P}{a \cdot b} \tag{1}$$

$$\varepsilon = \frac{\Delta l}{h} \tag{2}$$



(a) (b)

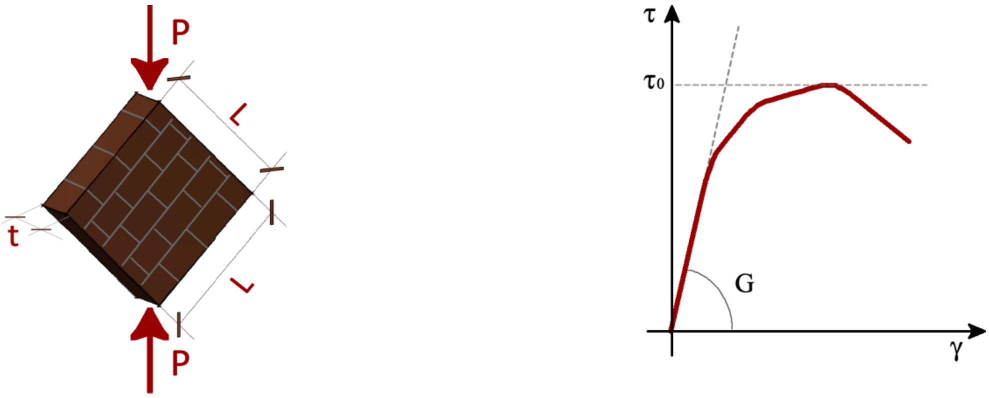
Figure 17 - Axial compression test, (a) test sketch, (b) typical stress-strain curve.

The slope of the first branch of the curve is equal to the modulus of Elasticity, also known as the Young's modulus (E).

4.3.2 Diagonal compression test

This test aims to evaluate the shear strength (τ_0) of a wall panel. The panel specimens are built with the same material and technology used in the field. The prisms will be composed of the number of bricks necessary to build a square panel with height/thickness ratio of about six. At least four bricks need to be used for constructing the panel and the mortar thickness should be less than 20 mm.

Special care should be taken to keep the specimens vertical during the test. The panels should be tested after at least 30 days of construction in order to ensure that the mortar joint has dried completely.



(a) (b)

Figure 18 - Diagonal compression test, (a) test sketch, (b) typical stress-strain curve.

The better way to perform this test is trough a displacement control procedure. The setup must be composed of a fixed base at the bottom of the specimen, an actuator on the top of the specimen, a load cell between the actuator and the upper face of the prism (in order to read the applied force value) and two sets of LVDTs (Linear Variable Displacement Transducer) or potentiometers positioned orthogonally on the two opposite vertical faces of the specimen (one horizontal and other vertical). In this way the output is a stress-strain (τ-γ) curve with standard formulas.

$$\tau = \frac{P}{\sqrt{2} \cdot t \cdot L} \tag{3}$$

$$\gamma = \varepsilon_{LVDT(vertical)} + \varepsilon_{LVDT(horizontal)} \tag{4}$$

The shear modulus G is characterized as the initial slope of the stress-strain curve obtained as mentioned above.

4.3.3 Pure bending test

The pure bending test, or vertical flexure test, is realized to study the property of the wall when the bending occurs about the vertical axis. In the latter case the failure will either occur entirely in the mortar joints going around the bricks or the break will cut across some of the bricks. This test is realized with a simply supported beam (i.e. the wall panel) loaded at the one third points (Figure 19). The value of applied bending moment is equal to P·L/3. The displacements were measured with two LVDT's on opposite sides of the beam at the mid-span. With this test it is possible to obtain the flexural strength of the specimen trough the follow relation:

$$f_t = \frac{P \cdot L}{3} \cdot \frac{12}{L \cdot t^3} \cdot \frac{t}{2} = 2 \cdot \frac{P}{t^2} \tag{5}$$

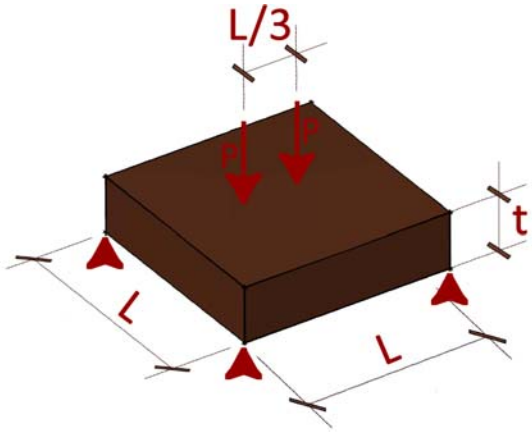


Figure 19 - Four points pure bending test

4.3.4 Degradation

Extreme environmental conditions such as prolonged contact with water, alternating dry/wet or thaw/freeze cycles, heat waves and so on can lead to significant degradation in material mechanical properties. In order to evaluate the adverse effect of extreme environmental conditions, one can emulate these conditions in laboratory. This is done in order to measure the resulting effect on material mechanical properties compared to standard conditions in which the building material is perfectly dry and subjected to moderate ambient temperature.

For instance, one can emulate in laboratory the adverse effects of prolonged contact with water on mechanical material properties. It is possible to perform a series of laboratory tests (e.g., compression test, diagonal test) on specimens that, after the drying and maturation process, are put in contact with water for different time intervals (i.e. 8 hours, 16 hours, ..., 32 hours). This can provide the strength degradation trend as a function of the time of contact with water.

4.4 MATERIAL PROPERTIES BASED ON EXISTING LITERATURE

In this section, material properties per building material are discussed based on existing literature. This can be useful as a knowledge base in lieu of case-specific laboratory tests. The following construction materials are discussed herein: earth architecture (e.g., adobe, rammed earth), stone masonry, brick masonry (baked bricks, and cement-stabilized un-baked bricks), timber structures (e.g., bamboo), hybrid structures such as mud and wood (wattle and daub) and wood and corrugated iron sheet.

4.4.1 Earth Architecture

A detailed literature survey of the mechanical properties of the material used in earth architecture (adobe and rammed earth) is described herein. The material properties cited in literature are highly sensitive to both the geographic location of the building [25] and also to the process followed for the construction of the blocks. As much as it regards the block construction process, the mechanical properties of the adobe material depend on, (a) the relative proportions of water, clay and sand [14], (b) type and quantity of vegetal fibers used and their orientation in the block ([15], [16]), (c) type of aggregated material [17], (d) direction of the excitation (larger strength for load parallel to the direction in which the brick were pressed, [18]), (e) The aspect ratio of the specimen [19] and (f) ageing of the specimens [20]. Table 1 below reports the results of the literature survey. The blank spaces indicate material property types not available from the particular study cited.

References	f_m (MPa)	τ_0 (MPa)	E (MPa)	G (MPa)	γ (kN/m^3)
[20]	0.79		170	70*	
[21]	0.84	0.026		40	
[22]	0.15	0.020			
[23]	0.76	0.033	97		18.2
[24]	0.62	0.030			
[16]	0.94				
[17]	1.00				
[14]	1.50				
[17]		0.150			
[18]	1.35				
[25]	1.17		187		
Median	0.89	0.030	151.33	55	18.2
Standard Deviation (natural logarithm) ≈ C.O.V.	0.65	0.79	0.36	/	/

Table 6- Material mechanical properties available in literature.

4.4.2 Masonry structures with natural stones

The stone masonry structure can be distinguished based on whether they are regular or irregular. A masonry structure is defined regular when the stones are shaped in regular prismatic forms. Conversely, it is defined irregular when the stones are directly used in the walls construction without any further elaboration. Another important feature of stone masonry is the presence or absence of horizontal recursive elements. These elements are usually realized with stronger material with respect to the base material. A schematic description of various types of stone masonry and the corresponding material property values are reported herein.

Masonry with round pebbles

This kind of masonry is realized with smooth and round stones, such as, small or medium river pebbles. The stone elements can be organized in a both organized and irregular patterns. Figure 20 below illustrates different types of masonry with pebbles.

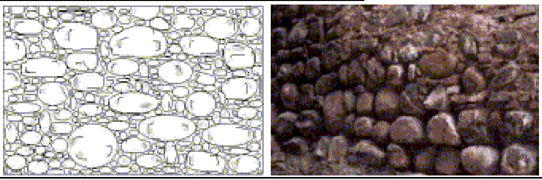
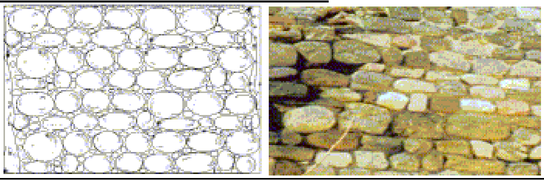
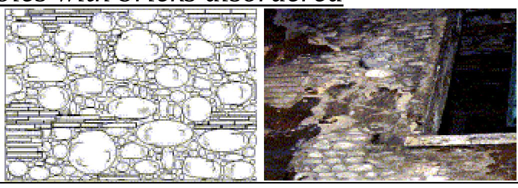
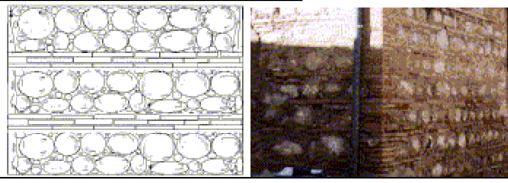
WITHOUT RECURSIVE ELEMENTS	
pebbles with disordered texture 	*pebbles with ordered texture* 
WITH RECURSIVE ELEMENTS	
pebbles with bricks disordered 	*pebbles with bricks ordered* 

Figure 20 - Masonry with round pebbles and without recursive elements

Rough stone masonry

This kind of masonry is realized with rough stones of different shapes with sharp edges. Figure 21 below illustrates different kinds of masonry with rough stones.

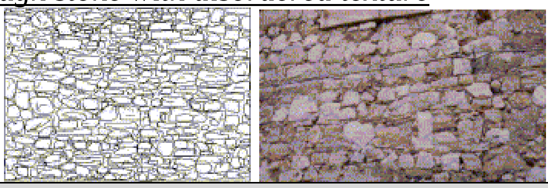
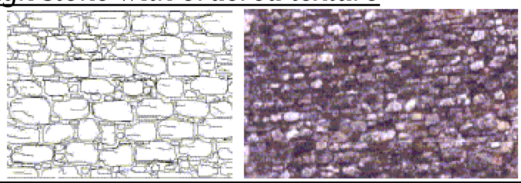
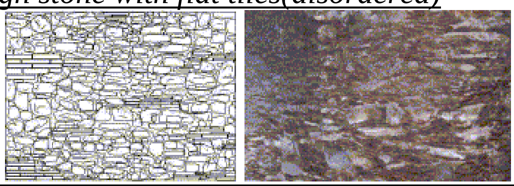
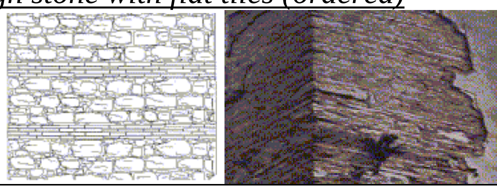
WITHOUT RECURSIVE ELEMENTS	
Rough stone with disordered texture 	*Rough stone with ordered texture* 
WITH RECURSIVE ELEMENTS	
Rough stone with flat tiles(disordered) 	*Rough stone with flat tiles (ordered)* 

Figure 21 - Rough stone masonry with and without recursive elements

Masonry with sheet-like stone

This kind of masonry is generally realized with semi-finished sheet-like obtained from low quality rock that tend to break along horizontal planes. The regular shape of the element excludes the possibility of disordered texture. Figure 22 shows two different types of masonry with sheet-like stone with and without recursive horizontal elements.

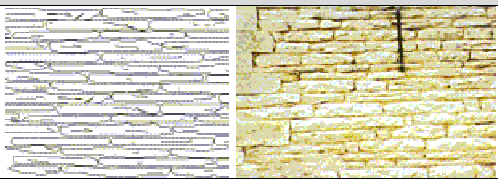
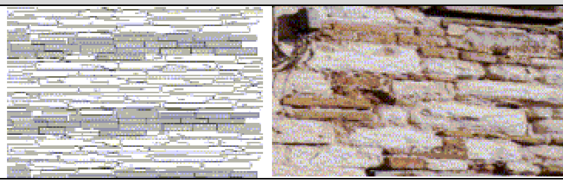
WITHOUT RECURSIVE ELEMENTS	WITH RECURSIVE ELEMENTS
	

Figure 22 - Masonry with sheet-like stone

Rough stone semi-regular masonry
This kind of masonry is realized with semi-finished almost regular stone normally larger in dimension with respect to sheet-like stone. The pseudo-regularity of the element shape exclude the possibility of disordered texture. Figure 23 below illustrates two types of semi-finished stone masonry with and without recursive horizontal elements.

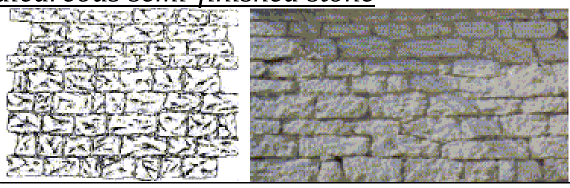
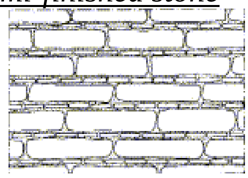
WITHOUT RECURSIVE ELEMENTS	WITH RECURSIVE ELEMENTS
Calcareous semi-finished stone 	*Calcareous semi-finished stone* 

Figure 23 - Rough stone semi-regular masonry

Regular masonry with squared natural stone
This kind of masonry is realized with perfectly squared stones with prismatic shape. Figure 24 below illustrates two types of regular stone masonry with and without recursive horizontal elements.

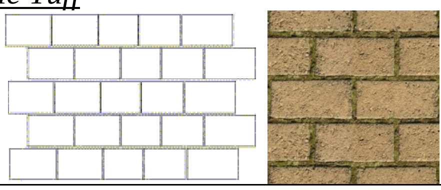
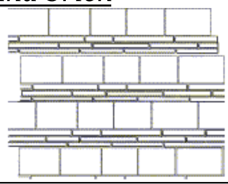
WITHOUT RECURSIVE ELEMENTS	WITH RECURSIVE ELEMENTS
Volcanic Tuff 	*Volcanic Tuff and brick* 

Figure 24 - Regular masonry with squared natural stone

As it might be expected, regular stone masonry is characterized by a better mechanical property with respect to the irregular masonry. Table 7 below reports standard values for regular and irregular stone masonry

Material Type		f_m (MPa) Min - Max		τ_0 (MPa) Min - Max		E (MPa) Min - Max		G (MPa) Min - Max		γ (kN/m^3)
Irregular Masonry		1.0	1.8	0.02	0.032	690	1050	230	350	19
Regular Masonry	Tuff	2.6	3.8	0.056	0.074	1500	1980	500	660	21
	Calcareous	1.4	2.4	0.028	0.042	900	1260	300	420	16

Table 7- Material mechanical properties available in literature.

4.4.3 Masonry structures with cement-stabilised mixture

Cement-stabilised building brick is a generic name covering a wide range of building materials. The cement-stabilized bricks are formed from a loose mixture of soil and/or sand and/or aggregates, cement and water, which is compacted to form a dense block and is left until the cement hydrates. After hydration, the stabilised brick should demonstrate higher compressive strength and improved durability compared to a block realized without the addition of cement. There are a variety of methods available for the construction of cement-stabilised bricks. They can range from hand-tampered soil blocks containing only enough cement to slightly enhance their dry strength (hardly any enhancement with regard to long-term wet strength) to high-tolerance high-density concrete blocks, mechanically mass produced and suitable for multi-storey construction. The cement-stabilised building blocks have been traditionally categorized into, sand-crete and soil-cement. The key differentiating factors between soil-cement and sand-crete are the cohesion/strength of the bricks freshly removed from the mould and the brick-size.

In Figure 25 various forms of cement-stabilized bricks, distinguished by different percentages of their hollow spaces, are illustrated:

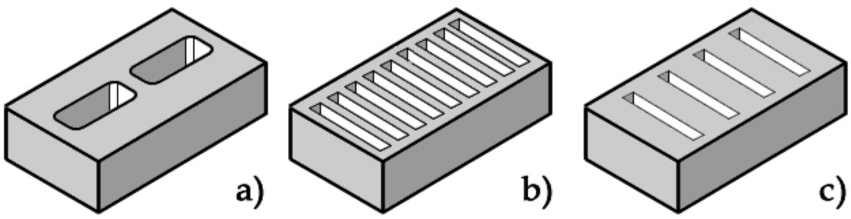


Figure 25 – Different types of hollow bricks: a) and b) hollow space percentage between 45% and 65%; c) hollow space percentage less than 45%.

Material Type	f_m (MPa) Min - Max		τ_0 (MPa) Min - Max		E (MPa) Min - Max		G (MPa) Min - Max		γ (kN/m^3)
Hollow space 45% - 65%	1.5	2.0	0.095	0.12	1200	1600	300	400	12
Hollow space < 45%	3.0	4.4	0.18	0.24	2400	3520	600	880	14

Table 8- Material mechanical properties for cement stabilized bricks available in literature.

As it can be expected, the strength and the stiffness of the material decrease with the increase of the hollow spaces.

4.4.4 Timber structures

The main type of wood employed in the construction is the bamboo. Two main types of bamboo is encountered in the constructions, namely, thick-walled bamboo and thin-walled bamboo. The thick-walled bamboo can be found in the village homesteads and plantations. It is used as supporting elements for walls and roofs, wherever strength is required, such as the wall posts in the mud and wood structures. The thin-walled bamboo usually grows in the forests. It is usually transformed into stiff woven nets used for constructing/reinforcing the wall panels and sometimes for constructing the roof. Bamboo has a very short life-span due to its sensitivity to environmental exposure. For example, the service life of bamboo is reduced significantly due to contact with water or humidity or due to alternating wet/dry periods. In general, the mechanical properties of bamboo depends on its diameter. Table 9 below reports typical mechanical properties for bamboo.

Material Type	$f_{compression}$ (MPa)	$f_{tension}$ (MPa)	E (MPa)	γ (kN/m^3)
Bamboo	150	39	1800	6

Table 9 - Typical mechanical properties in literature.

5 SITE AND STRUCTURAL FEATURES

In this section, various characteristics and features of informal constructions in Africa are discussed. The informal constructions are usually constructed by the owner or the local people in the neighbourhood. Although builders are not trained in specialized schools and learn the job in-situ through experience, they are reasonably skilled. The informal settlements are not covered by design standards or regulations. Hence, engineers or architects are not involved in the design and construction of these constructions[1]. Therefore, the focus of this section is on the site and structural features of informal settlements such as, the site position, soil type, the plan, the division of internal spaces, building material used in floors, walls and roof, the type of foundation, the number and the percentage of openings (i.e., doors and windows) in the walls, the roof structure and the secondary material used for roof, to name a few. One salient feature of the informal settlements in Africa is that they are predominantly one-storey buildings. This is due to obvious limitations in the construction technology and the building materials[2].

5.1 SITE POSITION

In many cases, the informal constructions are exposed to risk, by default and irrespective of their structural robustness, because they are built in the risk-prone areas. Figure 26 provides an overview of the different high-risk site positions.

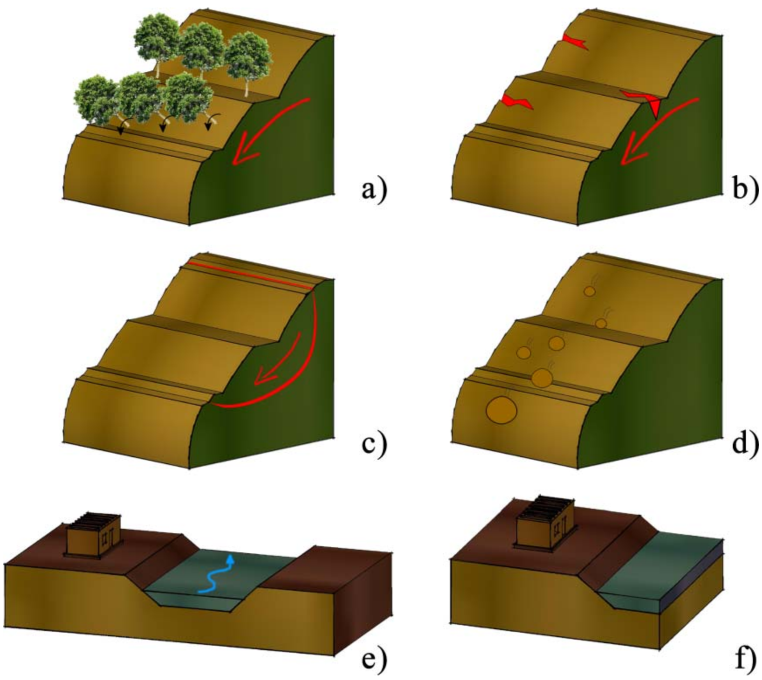


Figure 26 - Schematic illustration of risk-prone building sites

[1] The subject of land tenure in informal settlements is discussed in detail in literature [3].
[2] On hill-side areas it is possible to encounter situations in which the roof of one buildings becomes the floor of another buildings.

One example of risk-prone terrain for constructions is a slope in which the trees are bending forward in an un-natural manner as illustrated in Figure 26 (a) or a slope with visible cracks in the terrain as shown in Figure 26 (b). These are both signs that the ground is moving or is susceptible to movement in case of intense or prolonged rainfalls. Another potentially risky position is at the bottom of steep slopes where there is a high risk of slope instability (Figure 26 (c)) or a high risk of debris or rocks falling (Figure 26 (d)). Needless to say, there are various climate-change related phenomena, such as soil erosion or intense or prolonged rainfall, that can lead to an increase in the risk of soil instability. Last but not least is that case of building sites in the river basin (Figure 26 (e)) or close to the sea (Figure 26 (f)). In the case of buildings built in the river basin, an extreme rain-fall event can lead to a river over-flow and eventually wash away the structures built in the vicinity of the river. In the case of structure built too close to the sea, they may be subject to salinisation (leading to an overall degradation in material properties) due to sea-level rise or they may be subject to slope instability due to coastal erosion.

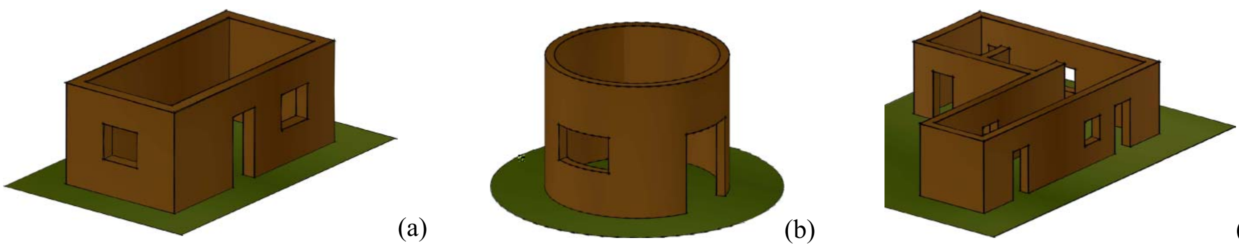
5.2 SOIL TYPE

The soil type in the site of construction is of utmost importance since it needs to be able to resist the loads transmitted to it by the construction. Here are a few situations in which the soil type is going to significantly influence the structural vulnerability to natural phenomena:

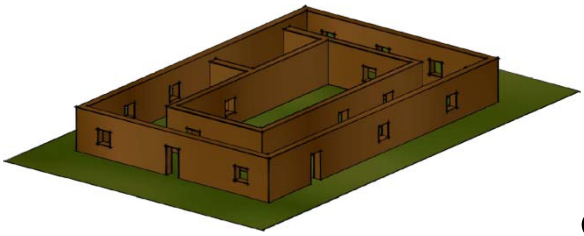
- The building terrain may be used for anchorage of the wooden poles in the case of mud and wood construction.
- The soil's capacity in absorbing water is going to affect the water run-off in the building site. For instance, sand has a larger water absorbing capacity with respect to clay.
- In the absence of a proper foundation, the structure can have a problem with water uplift (explained in more detail later in the next section). In permeable sandy soils, the uplift effect is revealed more quickly compared to less permeable soil types with a high clay content. The soil type can be evaluated by means of the simple tests described in the section 4.1 of this report.

5.3 PLAN CONFIGURATIONS

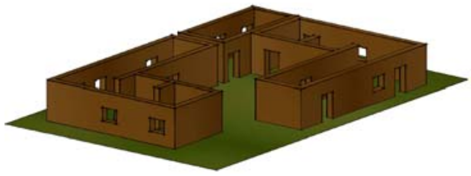
Most recurrent plan configurations in African urban and rural areas can be classified as following: rectangular, circular, L-shape, rectangular with inner courtyard and L- or C-shaped with inner courtyard, as illustrated schematically in Figure 27 below.



(a) (b) (c)



(d)



(e)

Figure 27 - Typical plan configuration, (a) rectangular, (b) circular, (c) L- or C- shaped, (d) rectangular with inner court, (e) L- or C- shaped with inner court

The rectangular form in Figure 27 (a) can consist of many rooms/units, such as the Swahili house category very common in Dar Es Salaam. With the exception of the circular configuration which can be found more frequently in rural areas, the other configurations all have a rectilinear forms that can fit easily in an urban orthogonal grid. As it can be seen in Figure 27 (d) and (e) the informal construction can consist of different individual modules that could be built and "appended" to the house in different periods based on the needs and the resources of the inhabitants.

5.4 WALLS

The walls can be considered the main load resisting elements in informal constructions. In fact, the building typologies are usually distinguished in terms of the material used in the construction of walls, for example, the adobe material, rammed earth, mud and wood, bamboo, etc. Generally speaking, the techniques used for constructing the walls can be divided into those with and without a “frame” or a “skeleton”. The presence of a frame if detailed and anchored properly can significantly improve the robustness and the continuity of the structure. The adobe and rammed earth construction are characterized by the absence of the frame; whereas, the mud and wood construction type has a wooden frame that is filled with adobe material.

5.5 INTER-WALL CONNECTIONS

Construction detailing is a fundamental element in ensuring the continuity in the structure. One of the most important construction details regards the cross-connection between orthogonal walls which ensures interaction between the walls or the so-called "box-action". One way to ensure a good cross-connection in brick constructions is to place the bricks in a staggered manner. In non-brick construction such as rammed-earth, other types of cross-connecting links should be employed. Also wood or bamboo can be employed as horizontal reinforcement for creating cross-connections between walls in various types of constructions such as earth and mud, timber, rammed earth, ..., etc. Among other link elements employed in order to improve the box-like behaviour, one can name also the ring beam, which as its names suggests, connects the perimeter walls in the structure. Also buttresses can be used in order to reinforce the corners and increase the overall stability and strength of the structure. Figure 28 below illustrates some structural detailing techniques used to increase continuity and to improve the overall box-action.

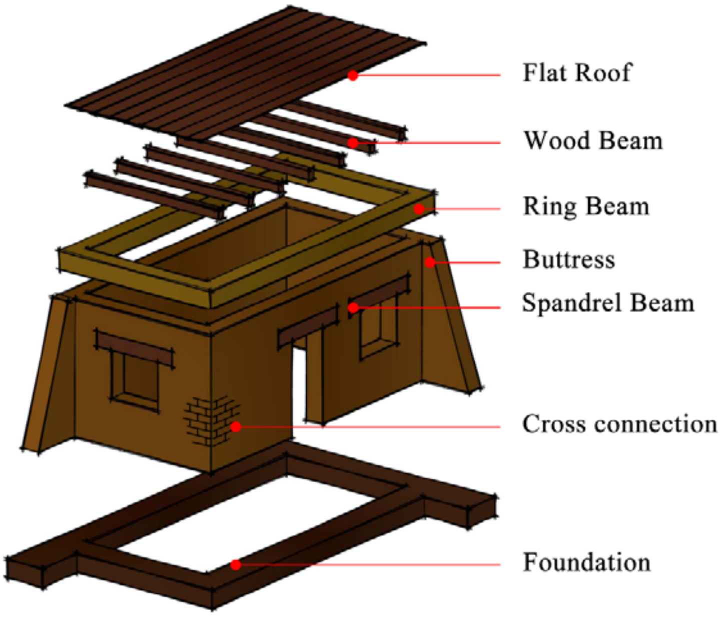


Figure 28 Structural detailing techniques employed for increasing robustness and continuity

5.6 ROOF

Different types of roof structures can be encountered in African informal constructions. They are usually constructed using local available material. The main roof typologies can be identified as the flat roof, the pitch roof and the vaulted roof. In general, the flat roof structure is consisted of the primary roof elements consisting of roof beams (e.g., timber, metal tubes) and the secondary roof elements consisting of the roof cover (e.g., metal sheets, straw , mud, and so on). The pitch roof (one-sided and two-sided) has a similar structure to that of the flat roof; however, the primary roof element is usually a frame (made up of wood, bamboo or metal). One advantage of the pitch roof is that it creates a mezzanine space that can be used as a refuge in case of flooding. The vaulted roof is realized with blocks, of the same material of the wall, arranged to form an arch structure. The most important function of the roof is the removal of storm water rapidly away from the structure. Figure 29 below illustrates various types of roof encountered in informal settlements in both rural and urban areas.

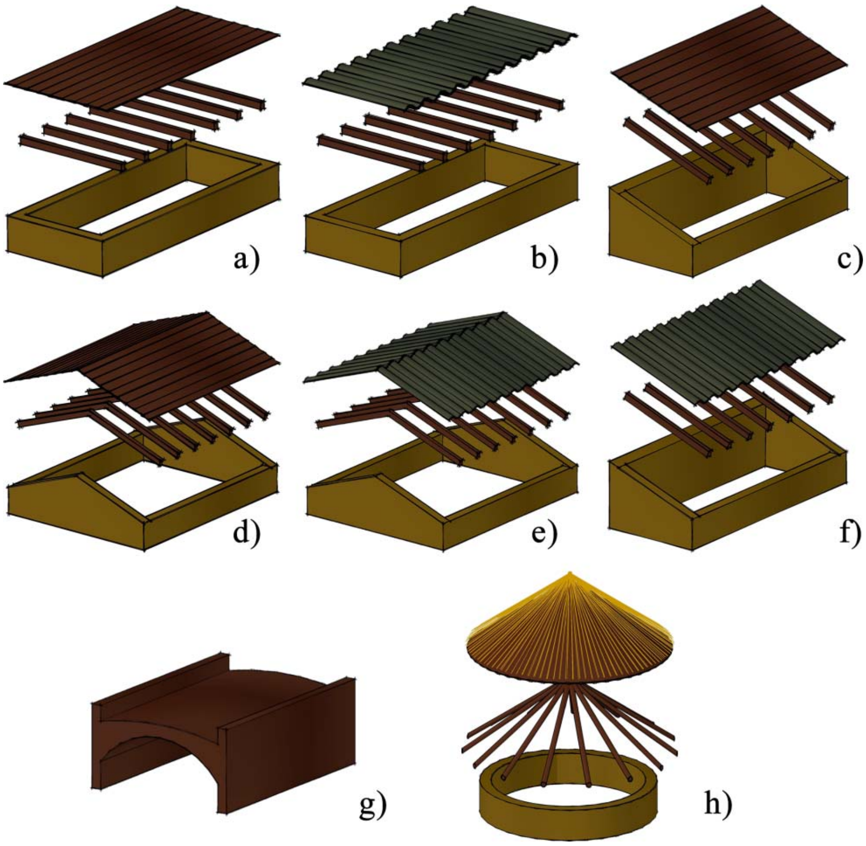


Figure 29 - a) wooden flat roof, b) iron sheet flat roof, c) one-side wooden pitch roof, f) one-side iron sheet pitch roof, d) pitch wooden roof, e) pitch iron sheet roof, g) arched roof, h) roof for circular plan.

It is important to underline that if there is a hipped roof (four slopes), it is better and stronger respect to a pitched roof (only two slopes ore on slope).

5.7 FOUNDATION

The foundation is the structural element that links the structure to the ground. This, in terms of mechanical behaviour, consists of transferring the resisting forces from wall to ground. Given their low weight, the informal structures normally do not have deep foundations. It is common that the informal settlements are raised a bit above ground level in order to protect them from flooding. Thus the floor platform used to raise the structure above the ground level often serves also as the foundation (Figure 31). Figure 30 below illustrates two types of foundations, namely, embedded foundations and foundations above ground level. As it can be observed from the figure, the foundations have generally larger dimensions with respect to the walls in order to facilitate the load transfer to the ground. Apart from load transfer to the ground, the presence of a monolithic foundation serves also for mitigating the problems related to flood uplift. Generally speaking, the foundations are realized with the same material as those used for the construction of the walls (e.g., earthen blocks, cement-stabilized sand, etc.). Later on, in Section 8, several techniques for constructing and reinforcing the foundations are discussed.

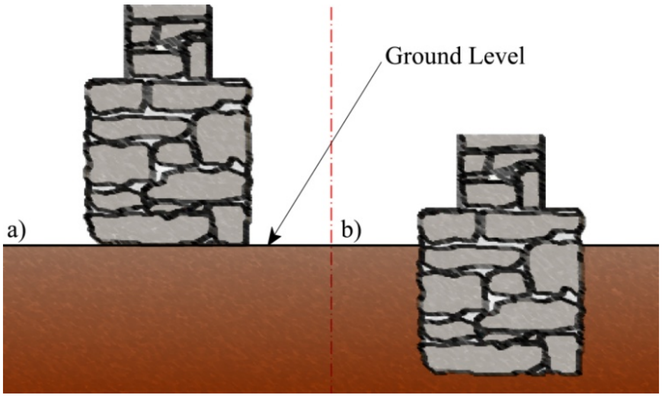


Figure 30 - a) Foundation on the ground level, b) foundation under the ground level (embedded foundations)


Figure 31 - Raised foundation with stone bricks and mortar (photo by R. De Risi)

5.8 OPENINGS

The openings play an important role in determining the structural behavior against flooding. If the construction has perfectly sealed openings (e.g., doors and windows), the flood-induced forces are applied entirely to the structure. Usually, especially in the case of informal constructions, the structure is never perfectly sealed and there are infiltrations inside the structure. In these cases, the flood-induced forces are reduced, at the price of compromising the serviceability of the structure.

Generally speaking, the openings constitute the weakest links in the structure and reduce the overall robustness and continuity of the structure. Therefore, it is important to reduce the percentage of openings in the walls made up of earthen materials as much as possible.

6 FLOOD ACTION

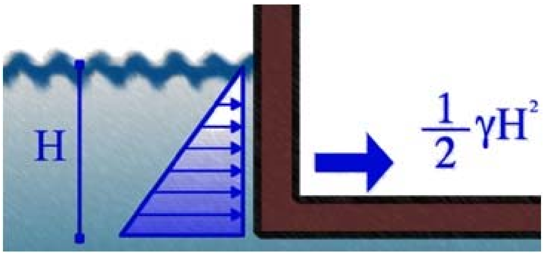
Direct contact of water with the structure due to flooding can produce different kinds of action in the structure such as forces/pressures, chemical reactions, strength degradation, debris impact and so on. The flood-induced actions can be classified into hydro-static and hydro-dynamic main categories. The flood-induced hydro-static actions can be sub-divided into, hydrostatic horizontal load, hydrostatic uplift pressure, elongated immersion, and the capillary rise. The hydrodynamic actions can be sub-divided into, hydrodynamic pressure, debris impact, erosion and undermining.

6.1 HYDROSTATIC ACTIONS

In this section, a brief description of different types of hydrostatic action is reported.

6.1.1 Hydrostatic horizontal load

The hydrostatic horizontal load is the result of the hydrostatic pressure that is governed by the Stevin's law. Figure 32 illustrates a schematic diagram of lateral hydrostatic forces applied to a structure with foundation above the ground level. The hydro-static pressure p(z) can be calculated as:



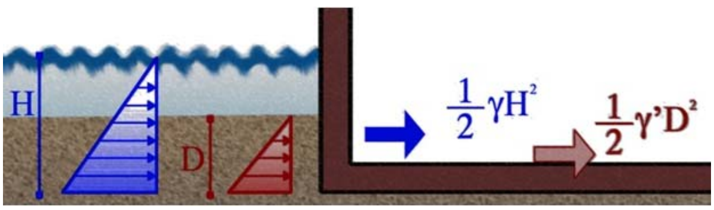
$$p(z) = \gamma_w \cdot (H - z) \qquad (6)$$

$$S = \frac{1}{2}\gamma_w \cdot H^2 \qquad (7)$$

Figure 32 - Hydrostatic horizontal load

where γ_w is the specific weight of water, z is the abscissa measured from the bottom of the structure, H is the flooded height and S is the hydrostatic resultant load that has its centroid at ⅓ of the flooded height measured from the base.

If the foundation is under the ground level, the hydrostatic pressure due to the soil column should also be considered. Figure 33 below illustrates the resulting forces in this case. The hydro-static pressure and the resultant forces can be calculated from the following expressions:



$$p(z) = \gamma_w \cdot (H - z) + \gamma' \cdot (D - z) \qquad (8)$$

$$S = \frac{1}{2}\gamma_w \cdot H^2 + \frac{1}{2} \cdot K_0 \cdot \gamma' \cdot D^2 \qquad (9)$$

Figure 33 - Load contribution due to lateral ground

where γ' is the dry soil specific weight, K_0 is the coefficient of earth pressure at rest (a generally smaller than unity coefficient that can be calculated through the formula 1-tgϕ, where ϕ is the soil friction angle), D is the depth of the structure under the ground level and z is the abscissa measured starting from the base of the structure.

In case water can enter the structure through openings, the level of water is going to increase also inside the structure. Figure 34 below illustrates a schematic diagram of hydrostatic pressure acting on the structure in the presence of openings.

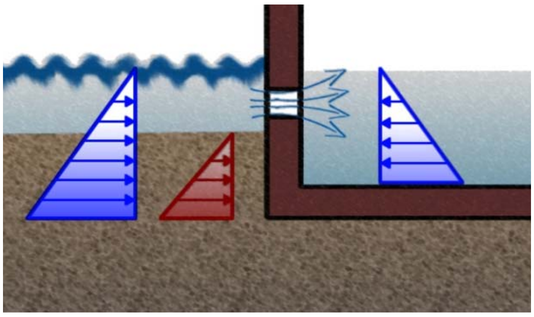


Figure 34 - Effect of the openings near the foundation

It is interesting to note that the equations for calculating the hydro-static pressure and the resulting forces are applicable for calculating the actions applied to both structural elements and non-structural elements such as doors and windows.

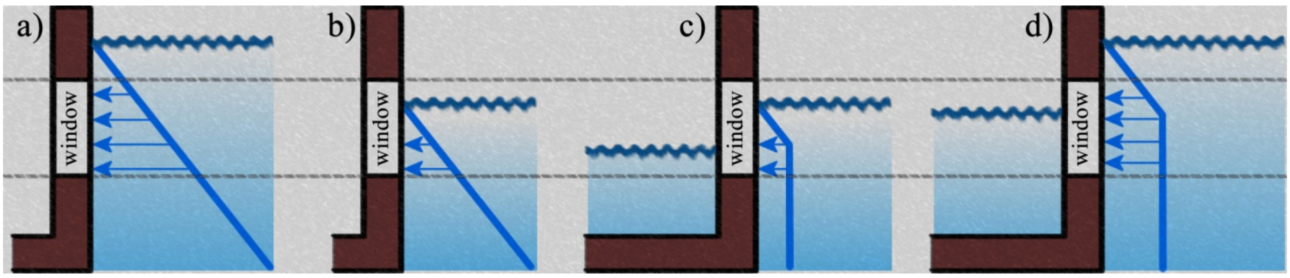


Figure 35 - Water levels and pressure distributions on building component in each situation

Figure 35 above illustrates schematically various possible configurations for calculating the resulting hydro-static forces acting on a window: namely, (a) water covers the entire window on one side yielding a linear pressure; (b) water partly covers the window only on one side; (c) water partly covers the window on both sides; (d) water covers entirely the windows on one side meanwhile it covers only partly the other side. It can be observed that the first two cases are related to a structure that is perfectly water-proof. The last two cases describe situations in which the structure is not perfectly sealed and some water enters the structure. It should be noted that in the case of informal settlements it is reasonable to assume that the structure is not perfectly water-proof and some water manages to infiltrate inside.

6.1.2 Hydrostatic uplift pressure

The problem of uplift pressure is especially critical in permeable soil types having low clay and silt content. In these cases, the excess water accumulated due to flooding is going to infiltrate inside the ground and exert an upward buoyancy pressure to the foundation. Figure 36 below shows the schematic diagram of hydrostatic uplift pressure applied to the structure. It can be observed that, the uplift pressure distribution is constant and its numerical values can be calculated from the following expression:

$$p_u = \gamma_w \cdot H \tag{10}$$

Obviously, if there are openings in the wall, the uplift pressure is reduced by the self weight of the water that has infiltrated inside the structure. Moreover, the uplift pressure is applicable in the case of monolithic foundations made up of resistant and reasonably water-proof material. Otherwise, the water is going to infiltrate through the pavement.

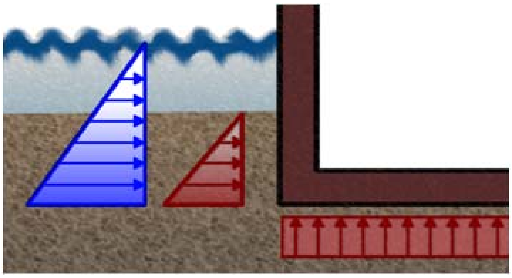


Figure 36 - Uplift pressure

6.1.3 Capillary rise and salinisation

Capillary action refers to the ability of a liquid to flow in narrow spaces in opposite direction with respect to gravity. It occurs because of inter-molecular forces between the liquid and solid surrounding surfaces. The capillary rise inside the building components causes the water/humidity to travel beyond the flood level. In [40] it is demonstrated that the capillary action occurs in material with pore diameter between about 0.1 and 100 μm. In fact, the material normally used in informal constructions normally has porosity characteristics that makes it a suitable medium for capillary rise. The presence of humidity leads to degradation in material properties and variation in self-weight. The degradation due to capillary effects is aggravated by the presence of active agents such as in the case of sea-water (e.g., due to sea-level rise). This latter phenomenon is better known as the salinisation. Capillary rise and salinisation are both frequently encountered in informal constructions constructed in the flood-prone areas or close to the coasts.

6.1.4 Prolonged immersion

Prolonged contact with water can lead to un-desirable consequences for the constructions in general and informal constructions in particular. Direct contact between the construction material and humidity can be looked upon as a sort of contamination since the presence of water may lead to physical or chemical modifications in the material properties. There are many factors that may lead to prolonged contact between construction material and water. For instance, if the terrain at the construction site is not permeable, days may pass before the flooding water is absorbed. The topographic conditions can also play a significant role; for example, flood water may disappear very slowly in low-lying valley areas. Buildings with inner courts or verandas are also susceptible to prolonged contact with water as the excess water may get trapped inside the building. Therefore, it is important to ensure that the construction can be directly exposed to sun-light, so that part of the excess water is going to evaporate.

6.1.5 Static action due to debris

Static debris action is the hydro-static pressure due to sediments accumulating externally or internally against the walls of a construction. This phenomenon can take place during flooding where the flow of debris can get sedimented against the building walls. The accumulated sediments may create a soil back-fill that exerts lateral forces on the wall. The amplitude of these forces depends on the soil characteristics, the degree of soil compactness and saturation, the geometry of the debris accumulated and eventual movements in the wall or the foundation due to the presence of sediments.

6.2 HYDRODYNAMIC ACTIONS

Generally speaking, the hydrodynamic actions can be induced due to both flow velocity and also due to transient water level (i.e., waves). However, in an urban context, the hydrodynamic actions due to velocity of the flow seem to be more critical.

6.2.1 Hydrodynamic pressure

The force induced by a water flux with velocity v and flow volume in time Q can be calculated as:

$$S = \rho_w \cdot Q \cdot v \tag{11}$$

where ρ_w is the water specific weight. Thus, the hydro-dynamic pressure at height z from the ground can be derived as:

$$p(z) = \rho_w \cdot v(z)^2 \tag{12}$$

where v(z) is the flow velocity at height z. Therefore, the hydrodynamic pressure distribution is directly related to the velocity distribution along the height of the flow. In lieu of detailed hydraulic calculations, the distribution of velocity along the height can be obtained based on simplified assumptions. Figure 37 below illustrates a typical representation of the velocity profile along a vertical surface. It can be observed that the maximum velocity is reached somewhat below the water surface.

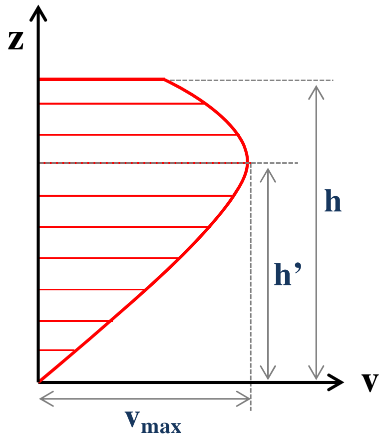


Figure 37 - Velocity profile along the vertical axis

6.2.2 Solid debris impact

The flow of water during flooding can be accompanied by the transport of solid objects (e.g., tree trunks, cars, etc.). The forces applied by the solid objects can be evaluated as impact forces proportional to the velocity of the flow and the weight of the solid objects and inversely proportional to the duration of impact. Figure 38 illustrates the schematic diagram of the debris impact on a structure.

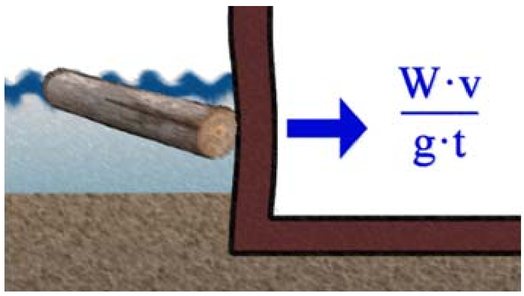


Figure 38 - Load induced by debris impact

For instance, the concentrated forces due to the impact of a tree trunk floating in the flood water with the structure can be evaluated as follows:

$$F = \frac{W \cdot v}{g \cdot t} = \frac{m \cdot v}{t} \tag{13}$$

where *W* and *m* are the debris weight and mass respectively, *v* is the velocity of the flow in which the debris is moving, *g* is the gravity acceleration and *t* is the impact duration, generally around in few seconds (i.e. 1-2 seconds).

The impact of flow debris with the structure can also lead to severe erosion due to separation of building components and/or contents. Therefore, along the course of flood, the flow is going to accumulate solid objects and debris in an increasing manner as it moves down-stream.

6.2.3 Erosion and undermining

The fast-moving flow during flooding can also lead to erosion in the foundation by scouring away soil from the foundation bed as illustrated in Figure 39 below. The erosion mechanism is usually caused by lift and drag forces. Moreover, the turbulence in the flow may lead to instantaneous uplift forces on the foundation.

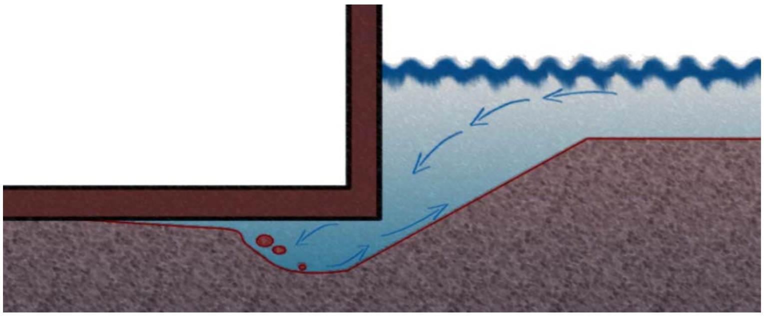


Figure 39 - Effect due to the erosion and undermining

7 FLOOD RISK ASSESSMENT

The structural risk for flooding for a given limit state can be checked based on the following performance criterion:

$$H_{critical}(LS) \leq H_{flood} \tag{14}$$

Where H_{flood} is the inundation height and $H_{critical}(LS)$ is the water height necessary for exceeding the limit state LS. Related to the above performance criterion, one can define the structural risk as the probability that the performance criterion is NOT satisfied for a given limit state:

$$P(LS) = P(H_{critical}(LS) \leq H_{flood}) \tag{15}$$

Many different terms are used in the literature in order to refer to P(LS), namely, the limit state probability, the failure probability, structural reliability for a given limit state, and structural risk. Since there is uncertainty associated with the determination of the quantity H_{flood}, the term P(LS) can be calculated by integrating on all the possible values of H_{flood}:

$$P(LS) = \sum (H_{critical}(LS) \leq H_{flood} | H_{flood}) p(H_{flood}) \tag{16}$$

for all possible H_{flood} values. The term $p(H_{flood})$ denotes the probability of having a certain flood height; it is better known as the flood *hazard*. The flood hazard is more commonly reported as the (mean) annual frequency of exceeding a specific flood height H_{flood} denoted by $\lambda(H_{flood})$. Accordingly, the structural *risk* can be calculated as:

$$\lambda(LS) = \sum P(H_{critical}(LS) \leq H_{flood} | H_{flood}) |\Delta\lambda(H_{flood})| \tag{17}$$

Where the structural risk is expressed by the mean annual frequency of exceeding a limit state LS and denoted by $\lambda(LS)$. The term $P(H_{critical}(LS) \leq H_{flood} | H_{flood})$ denotes the probability of exceeding the limit state LS for a given flooding height. This term is known as the structural *fragility* for the limit state LS or more generically the structural *vulnerability*:

$$F(LS) = P(H_{critical}(LS) \leq H_{flood} | H_{flood}) \tag{18}$$

where F(LS) denotes the structural fragility for limit state LS. In this section, a step-by-step procedure for the evaluation of structural vulnerability of the informal buildings to flooding is laid out. It should be hereby mentioned that the procedure outlined in this section is quite general with respect to the type of natural phenomenon considered and can be implemented in case of wind, earthquakes, landslides and so on.

7.1 THE LIMIT STATES

The definition of the limit states to consider is quite subjective and depends on many factors. In any case, the number of structural fragility curves (as a function of flood height) is going to be exactly equal to the number of structural limit states defined. In this document, three discrete structural limit states are defined. However, one can proceed and define different custom limit states for the specific problem at hand. The limit states defined include, serviceability, severe damage, and life safety. The limit states defined herein are identified based on the corresponding critical water height threshold.

7.1.1 Serviceability

This limit state is marked by the critical water beyond which the normal activities in the household is going to be interrupted, most probably due to water infiltration. For informal buildings built on a raised foundation, one can assume that the critical serviceability water height is in the order of the height of the raised foundation above ground level. For buildings constructed according to flood-resistant criteria, the critical water height related to serviceability can be as large as the critical height needed for exceedance of the life safety limit state.

7.1.2 Severe Damage

This limit state marks an intermediate state of the structure where the life-safety limit state is eminent but still not yet reached. For informal buildings built not according to specific flood-resistance criteria, it may be assumed that the critical severe damage water height is in the order of the window height in the building. Similar to serviceability limit state, for buildings constructed according to flood resistance criteria, the severe damage critical water height can be as high as the life safety threshold.

7.1.3 Life Safety

This limit state marks the ultimate state of the structure in which the lives of the inhabitants is going to be in danger. This can be caused either due to the infiltration of water inside the building or the collapse of the walls, loss of support of the roof, or the loss of load bearing capacity of the building due to elongated contact with water or salinisation.

7.2 FLOOD DAMAGE IN THE INFORMAL BUILDINGS

The flood damage in the informal buildings can be classified into the following categories described in Table 10. Each category is described in more detail in the following.

INFILTRATION - SEEPAGE	Seepage through floor system
	Infiltration through roof cover
	Infiltration through doors/windows
MATERIAL DETERIORATION/EROSION	Material Deterioration/Erosion through elongated contact with water
	Salinisation of the material due to the presence of active agents
STRUCTURAL MEMBER FAILURE	Wall failure/loss of bearing due to static/dynamic pressure
	Roof failure/loss of bearing due to excessive rain
	Loss of vertical load bearing capacity due to deterioration/erosion

Table 10 - Flood damage in the informal buildings

7.2.1 Infiltration-Seepage

The informal buildings due to their generally poor or non-existent structural detailing and the material used for their construction, are particularly vulnerable to water infiltration and seepage during extreme rain-fall and/or flooding. If the material used for the foundation is not water-tight or if the foundation is on or under the ground level, the water can easily reach the building. In this case, if the doors are not properly sealed, the water can enter the building. During intense raining periods, the water can enter the building through non water-tight roof system. Also the existence of non-properly sealed windows can lead to water infiltration. It should however be mentioned that if the water enters the buildings, the total hydrostatic pressure exerted on the walls is going to be reduced and therefore the risk of wall failure will becomes more remote. However, the un-planned presence of water inside the building is going to lead to material deterioration and erosion, non-sanitary living conditions and even risk of drowning in water.

7.2.2 Material deterioration/erosion

The elongated contact with water is going to manifest itself either in the form of the physical loss of material volume (erosion), chemical reaction due to chloride content in the water (salinisation due to sea-level rise), and overall reduction in the material mechanical properties (loss of resistance). The informal settlements made up of earthen material and/or poor quality cement blocks are particularly vulnerable to material deterioration as a result of elongated contact with water. Moreover, these buildings are generally constructed without specific flood-resistant provisions and therefore are particularly exposed to the undesirable effects of direct contact with water.

7.2.3 Structural member failure

The structural wall failure in a mid-section due to flooding pressure is more likely to take place due to a combination of the hydrostatic and hydrodynamic pressure, assuming that the walls are sufficiently anchored by the corners and that the openings are sealed properly in case of rain. In case the walls are not anchored properly, it is more likely to observe wall over-turning due to water pressure. Roof failure due to intense rain-fall is going to take place in cases where the rood cover is not inclined and/or has a high water-absorbing capacity. Similar to the case of the walls, the roof failure can be observed either in the form of the total loss of roof bearing due to weak anchorage in the walls or roof failure in a mid-section. It is also important to note that the material deterioration and erosion can also lead indirectly to structural failure in the form of the loss of vertical load bearing capacity.

7.3 STEP-BY-STEP PROCEDURE FOR DETERMINING THE CRITICAL WATER HEIGHT

In the following a step-by-step procedure is described for determining the critical water height.

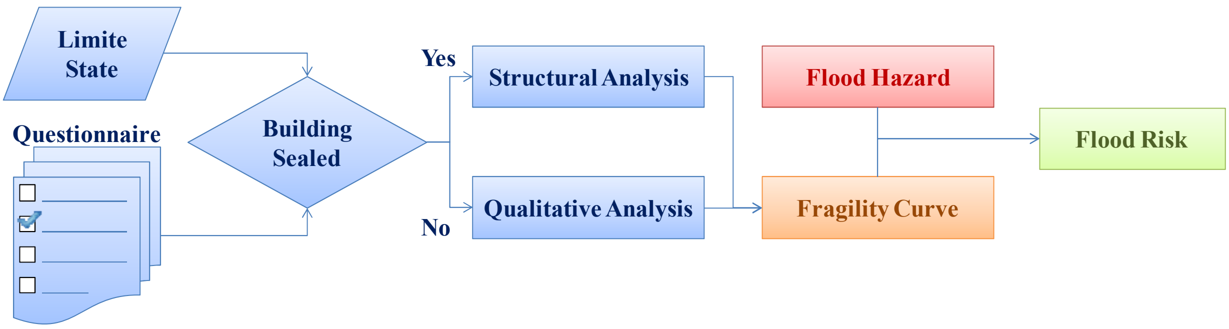


Figure 40 - Flow-chart for flood-risk evaluation

1- Define the limit state for which the structural vulnerability is going to be evaluated (e.g., serviceability, severe damage, life safety).
2- Use the questionnaire attached in the Appendix A to this document in order to perform a thorough visual inspection of the building.
3- Based on the questionnaire results decide whether the building is properly sealed (e.g., quality of doors and windows and their closure)
4- If the building is properly sealed, the critical water height can be determined based on structural analysis (described in the following).
5- If the building is not properly sealed, the water height might be assigned qualitatively. For instance the Following table recommendation[3] could be used in lieu of other criteria for determining the critical height.

Table 11 - Qualitative critical water height thresholds when the building is NOT properly water-proof

Serviceability	Severe Damage	Life Safety
$H_{foundation}$ (above ground)	50 cm* (*with respect to $H_{foundation}$)	1.00 m* (*with respect to $H_{foundation}$)

6- After the critical water height is determined, a simple fragility curve can be constructed as a step function of the flooding height. This is equivalent to assigning a fragility of zero when the flooding height is less than the critical height and a fragility of one when the water height is more than the critical height.

[3] It should be noted that the values reported in Table 11 are qualitative values. They need to be revisited based on expert opinion and past flooding experience.

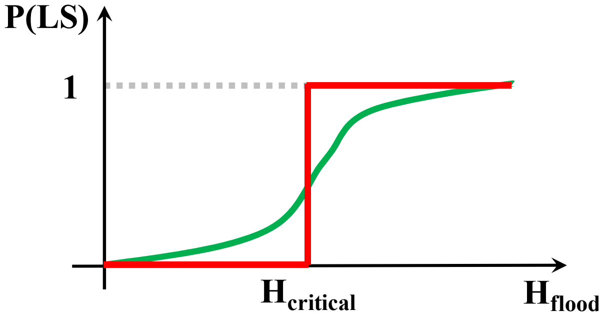


Figure 41 - Fragility function

In case, the uncertainties in the material properties or other structural features (further elaborated in the section on the uncertainties) are taken into account, the fragility curve is not going to be a heaviside function anymore and assumes a curvi-linear shape (as it can be seen in Figure 41).

7- The resulting fragility curve can be integrated with the flood hazard curve in Equation 4 in order to obtain the flood risk.

7.4 THE STRUCTURAL ANALYSES

In case the building is sufficiently sealed against water, the structural analysis can be used as an analytical tool for deciding the critical water height that is going to lead to structural failure.
The structural analysis can be used in order to:

1- Determine the water height that is going to lead to the over-all wall failure due to combination of hydro-static and hydro-dynamic pressure.
Based on the building construction features the following failure modes may be observed:
-failure section in the middle (e.g., sufficient anchorage in the corners, large percentage of openings)
-failure section in the corners (e.g., insufficient anchorage in the corners)
-failure sections in the base (e.g., sufficient anchorage in the corners, small percentage of openings)

2- Determine the rain-fall intensity that is going to lead to roof failure (due to the weight of water).
Based on the roof typology and its anchorage to the structural frame/main body, the following failure modes may be observed:
-loss of bearing of roof cover/beam (insufficient anchorage in the main body of building)
-roof beam/cover failure (sufficient anchorage in the main body of the building)

3- Determine the water height/contact duration that is going to lead to a loss of load bearing capacity in the building due to deterioration and/or erosion.

In this case, the structure is going to be analysed subjected to its own weight plus the excess weight due to water seepage considering the deterioration caused by elongated contact with water and/or reduction in the resisting section due to erosion.

7.4.1 The structural analysis methods

Limit Analysis

A typical method used in the structural analysis is the limit analysis based on virtual work theorem. Usually, the limit analysis is paired up with a rigid-plastic simplified structural model, where the structure is modelled as an ensemble of rigid elements connected by rigid-plastic or elasto-plastic or fragile link elements (a.k.a. the *plastic hinges*[4]). The output of the limits analysis consists of the load factor applied to the service loads acting on the structure in order to bring the structure to the verge of .instability (in the structural engineering jargon it is also called the onset of the formation of a global mechanism). This type of analysis is very efficient if one can a priori identify both the position of the plastic hinges in the structure and the mechanism displacement shape. For instance, for the structure illustrated in Figure 42a different mechanisms can be identified. One can identify an out-of-plane over-turning mechanism where a hinge forms in the base (Figure 42b). In this case the wall can be considered a rigid block prone to overturning around a pivot point (O) in the inner side as demonstrated in the schematic diagram in Figure 42b. The destabilizing force (F^W) is applied at the z^w height, that can be calculated given the shape of pressure and the height of water. The wall and roof self weight (P and P^R respectively) are stabilizing gravity forces aligned with the pivot point. Depending on the roof typology, one may also need to apply a horizontal drag force R. The wall failure takes place if the ratio between stabilizing and destabilizing action is lower than unity. This is demonstrated in the following expression which is written by balancing the stabilizing and de-stabilizing moments around the pivot point:

$$\frac{P \cdot y + P^R \cdot y^R + R \cdot z}{F^w \cdot z^w} \leq 1 \qquad (19)$$

Alternatively, for the wall panel a "three-hinge" out-of-plane mechanism can be identified in which three plastic hinges are formed in a mid-section and the two sides of a wall panel as illustrated in Figure 42c. The stability of the wall panel can be controlled based on the principle of virtual [5]work by calculating the work done by both external forces and the internal resisting moments at the plastic hinge locations.

[4] The terminology "plastic hinge" may lead to some confusion. A more precise term may be a concentrated non-linear link model/element.

[5] It is called the principle of virtual work since the mechanism displacement is virtual and its exact amount is not known.

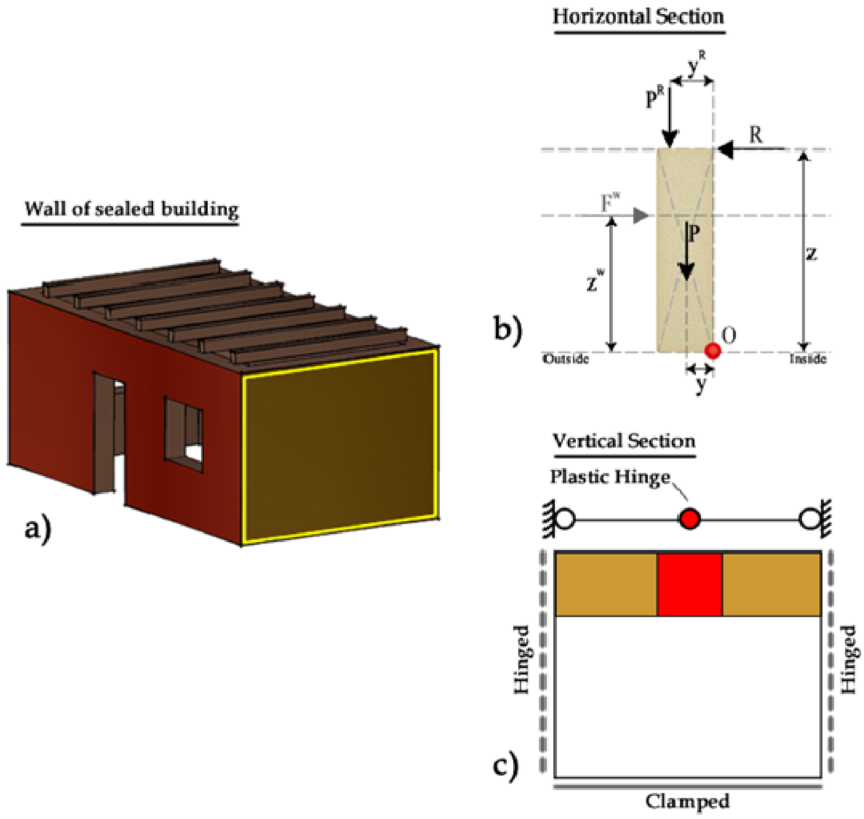


Figure 42 - Modeling of a wall using limit analysis

Finite Element Analysis

A more elaborate and sophisticated method for structural analysis is the finite-element method. The finite element method discretizes the structure into smaller units (one, two or three dimensional elements) such as, shell, membrane or plate elements and ensures the force continuity and deformation compatibility between the units.

7.4.2 The parameter uncertainty

The assessment of structural vulnerability is in general subjected to uncertainties. In Table 12 below, various sources of uncertainties in structural parameters are classified.

A general classification of structural modelling uncertainties
Geometry (e.g., wall thickness, ….)
Material Mechanical Properties (e.g., density, compressive strength, shear strength, …)
Construction details (e.g., anchorage quality into foundation, roof anchorage quality, wall corner anchorage quality)
The effect of degrading phenomena: prolonged contact with water, salinisation, capillary rise, erosion

Table 12 - Various sources of uncertainty in structural parameters

The modeling parameters used in the structural analyses are in general going to be subjected to significant amount of uncertainty. This uncertainty can be attributed to the following sources:

1- Lack of building-specific data: This category of uncertainty is due to the incomplete information available. For example, the lack of laboratory tests on material properties and their deterioration as a function of the duration of contact with water. This type of uncertainty can be reduced by performing laboratory tests on the material used for construction (a sample laboratory test set-up is included in the Appendix B).

2- Spatial Uncertainty: Even if detailed in-situ laboratory testing is performed on material properties, the spatial distribution of the material properties in the structure is not going to be fully understood.

In lieu of building specific information, a study of building-to-building variability in material mechanical properties per building material may be used (although not strictly rigorous) in estimating the statistics (e.g., median and coefficient of variation) of the material properties (a representative study performed on adobe material is reported in Section 4). A sample fragility analysis for a flood-prone zone of Dar Es Salaam considering the structural uncertainties is described in detail in the final setion.

8 FLOOD RISK MITIGATION STRATEGIES

The flooding phenomenon affects the informal settlements on the community level and suitable adaptation and mitigation strategies involve the community as a whole. Hence, the flood mitigation strategies overviewed in this section start from a single house and often involve the whole settlement. In a certain sense, given the scarce resources and the periodicity of flooding, the community needs to adopt suitable techniques for learning how to live with it [26].

The flood mitigation strategies can be classified in the following categories:

- Flood plain zoning
- Flood warning communication
- Construction in Elevation
- Structural plan configuration
- Foundation detailing
- Water-proofing (dry protection)
- Water-proofing (wet protection)
- Flood water management
- Creating safe zones and flood accumulation basins
- Decreasing run-off and soil erosion
- Changing Location

In the following, each of the above categories is discussed in detail.

Flood Plain Zoning

The first and foremost stool for flood risk mitigation is improving the state of knowledge about the flood extremes likely to happen in the zone. Arguably, in many cases the informal settlements are developed in high-risk flood-prone zones with the explicit knowledge of the risks due to a total lack of viable alternatives. However, still in many other cases, ignorance is a major cause of the unsuitable choice of housing location. This can be avoided by the delineation of critical flooding heights. The delineation of flooding height can be not only useful for identifying the high-risk areas but also for getting an idea on how much the structures need to be raised in elevation or on low-lying areas that can be used for water storage (discussed further later on). In the following some techniques for flood plain zoning are described.

River basin flood delineation

One technique for flood zoning is the delineation of the river basin. This can be achieved by marking for example, the 50 year flood water height, the 25 year flood water height and a designated flood line below which the construction of houses should be prohibited and enforced (see Figure 43).

Marking the last flood level
This is a simple technique for flood zoning which consists of simply marking by a coloured paint the maximum level of inundation in the ultimate flooding event. This is an effective way of keeping the memory of danger alive.

Memory of the elderly people
The elderly people in the community are an invaluable resource for finding out about the flooding history in a zone. It is important to learn to know the past in order to be able to be more prepared for future flooding events.

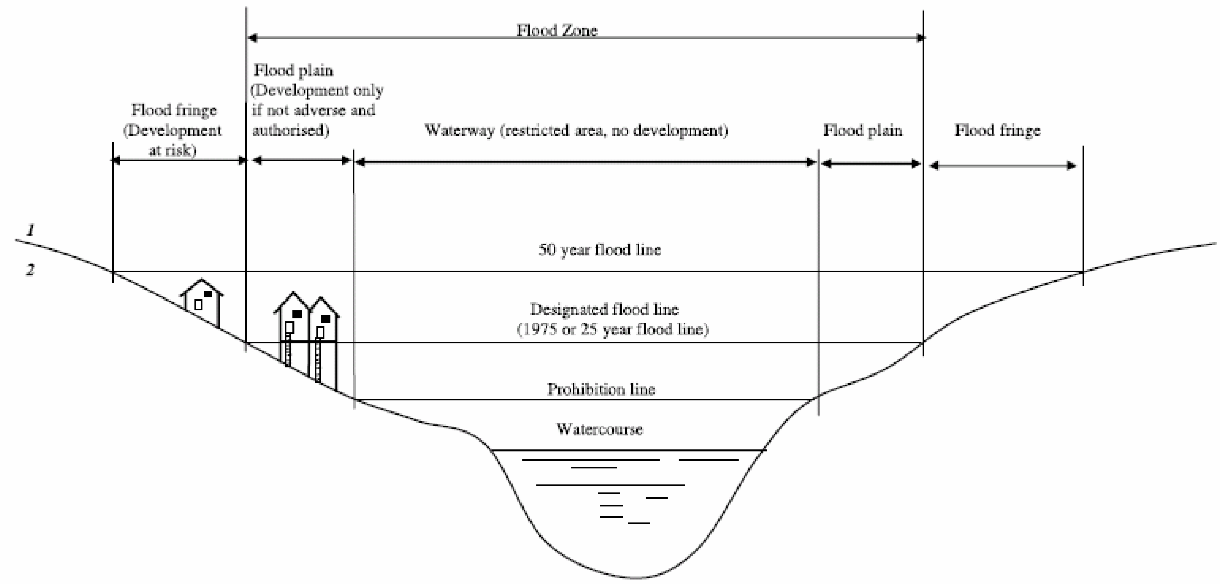


Figure 43 - Delineation of the flooding zone in the flood basin. (Figure courtesy of *Stephenson, D., 2002*)

Flood Warning
Flood zoning activities described before are going to be quite useful for releasing eventual flood warnings to flood-prone communities. For example, delineating the flood line on the river basin and constant monitoring of the water height constitutes an efficient and simple flood warning system (as shown in Figure 44). In case of continuous rainfall and substantial increase in water height, a flood warning should be generated. In such case, the leaders of the communities play a crucial role in communicating the eminent flooding to the people at risk.

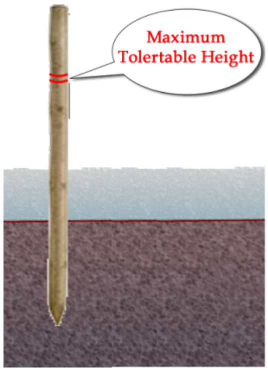


Figure 44 - Monitoring of the flood height in the flood basin.

Construction in Elevation

The knowledge of the past flooding heights can be quite useful in planning to protect the houses, goods and the drinking water. There are numerous flood-proofing techniques that aim on elevating the level of construction. In the following, an overview of the these techniques is reported:

Structural Plan Configuration

The plan configuration affects the mechanical behaviour of the structure subjected to flood action in alternative ways. In general, simple regular forms behave better than irregular forms. Moreover, it is important the building dimensions are proportional (i.e., the building does not have a large aspect ratio). The division of internal spaces can play an important role in deciding the (free) span length of the wall that resists the flood action. In order words, the internal walls can serve as support to the perimeter walls. Therefore, it is generally recommended to keep the overall shape of the structure as simple as possible and if necessary subdivide the building into smaller units. Note that this is in contrast to usual mode of construction in informal settlements where the buildings are created over time by appending smaller units as resources permit. Moreover, it is important that there is an even distribution of inner walls in order to have equal distribution of strength of across the building plan. The plan configuration of a building also affects the duration of direct contact with water in case of flooding. For example, it takes a longer time for the water to get dissipated in buildings with a inner court-yard.

Foundation detailing

Generally speaking, as far as it regards the foundation construction details, it is important to make sure that water and humidity does not get trapped inside the foundation. Therefore the finishing surface of the foundation should be built with an outward slope in order to facilitate drainage of water away from the foundation. In order to prevent the ground humidity to infiltrate in the structure, a buffer layer can be positioned between the foundation base-plate and the bed terrain. This buffer layer can be made up of a stones covered with mortar or with cement-stabilized soil or a mixture of soil and bitumen. Alternatively, this buffer layer can be constructed by placing a layer of wooden pallets covered with a finishing material in order to create a smooth and stable surface for the foundation base-plate.

Raising the foundation

A very efficient technique for protecting the building against flooding is to raise the foundation above the ground level. The raising foundations can be constructed in different ways described in more detail below.

Concrete Flooring

This is a concrete platform that is constructed above the ground level. This option is not particularly cheap but it lasts a long time and offers efficient means of preventing water seepage inside the house. The negative points include, the difficulty in pouring the concrete and possible pooling of water. Moreover, in case of damage it is difficult to repair the concrete flooring system. In case the house needs to be displaced, it is not easy to move a concrete foundation [27].

Cement stabilized earthen plinth

Stabilization of the typical earthen plinth can be carried out with a mixture of earth and cement. The proportion of cement to be added depends on the soil properties. For soil with more than 40% sandy-silty content, 5% cement additive is adequate. For soil with less sandy content, additional sand has to be added to raise the content above 40% and may require a somewhat higher proportion of cement additive [28]. If using cement for stabilizing the entire plinth results too costly, one can use cement only for stabilizing the upper part (as shown in the Figure 45).

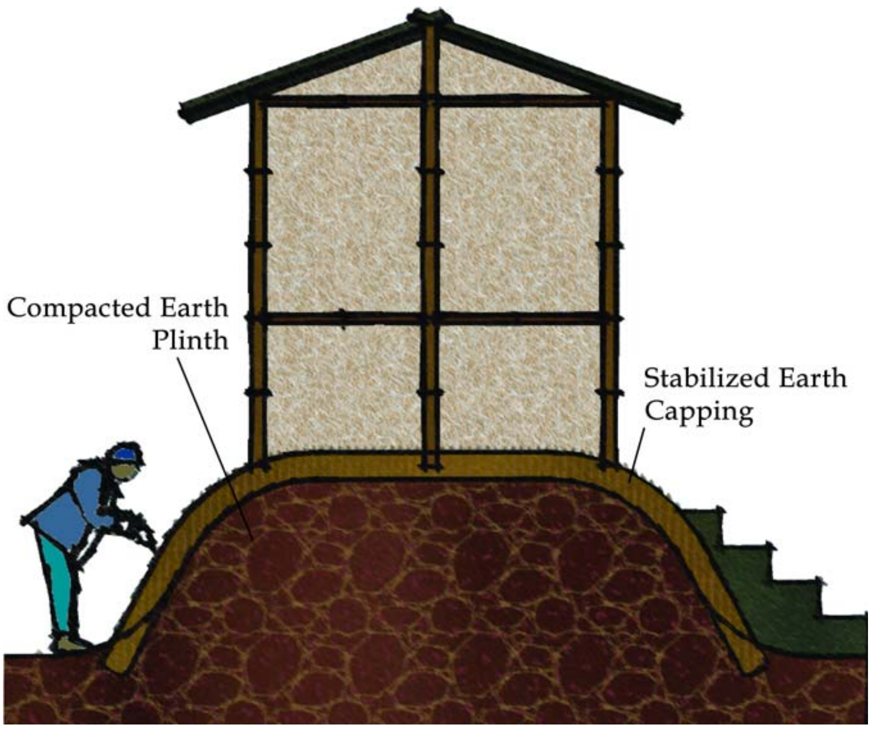


Figure 45 - cement stabilized foundation

Construction of brick perimeter walls

In order to protect the plinth from erosion, a brick perimeter wall can be built around it [28]. However, the following points need to be kept in mind:

- If soil is too weak or loose (can be determined from the field tests), the foundation of the perimeter wall should penetrate to sufficient depth below ground.
- Since small amount of load is imposed on the wall, the footing can be constructed with brick without the need for a concrete footing.
- Soil cover on the foundation should be thoroughly compacted and should preferably have plant or grassy cover to prevent scouring during flood.
- Infill should be of cement-stabilized soil to prevent muddiness and settlement due to saturation and loss of soil from below.

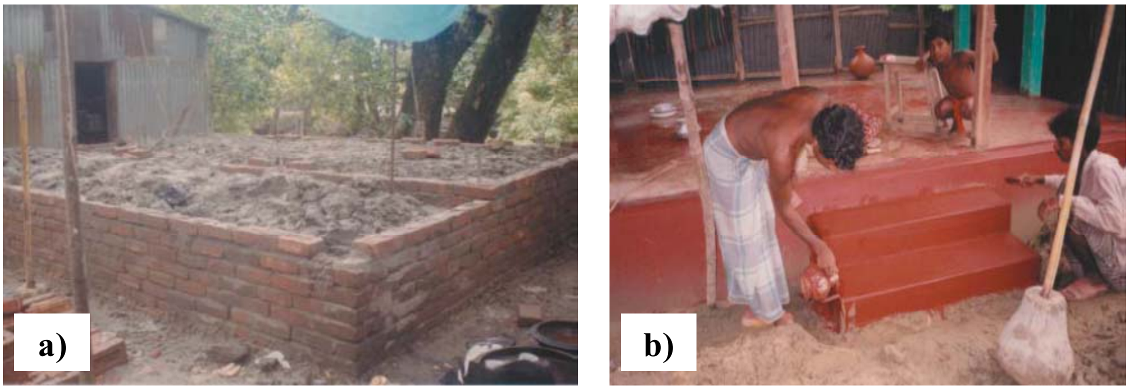


Figure 46 - (a) brick perimeter wall construction (b) painting a glossy cover to protect against scouring

Brick and Concrete Foundation

This is a relatively expensive solution but it is more durable and flood resistant. Listed below are some important points to keep in mind regarding this foundation type:

- Should properly compact sub-base soil to avoid settlement. If necessary, can provide a layer of sand filling.
- If soil is too weak or loose, a layer of brick soling should be provided (as it can be seen in the Figure 46 a).
- Soil cover on the foundation should be thoroughly compacted and should preferably have plant or grassy cover to prevent scouring during flood.
- The cement topping shown in the figure has a fine granular distribution; meanwhile, the cement layer underneath has a coarser granular decomposition.

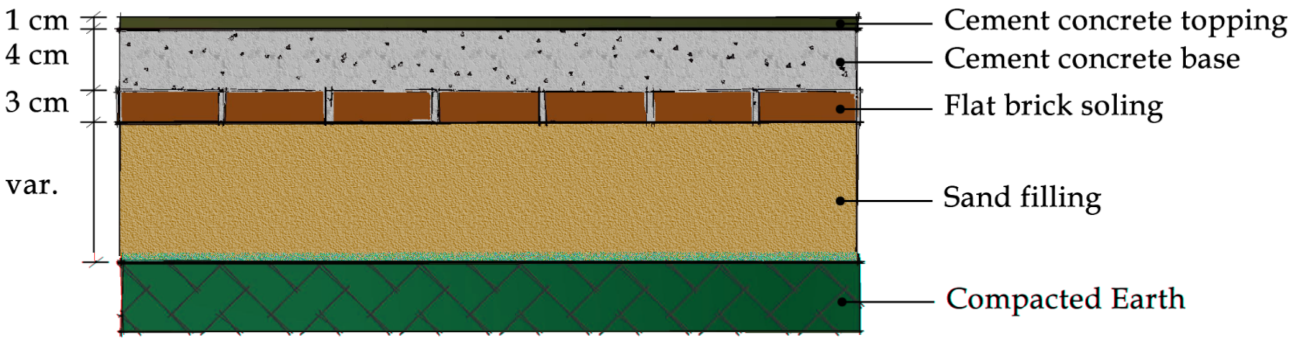


Figure 47 - the layers of the concrete and brick foundation.

Use of pallets
The wooden pallets can also be used in order to raise the level of foundation. This is a very cheap and easy-to-make solution but leaves the floor system somewhat unstable, exposed to water seepage from beneath, and exposed to rotting [27].

Use of stilts
The stilts are another means of raising the floor level above ground. They are effective in raising the house above the flooding height. In the dry periods it can also be used as storage place. However, it is not easy to construct and requires a minimum level of expertise in constructing it. Moreover, it might have stability problems and does not seem to be adequate for earthquake-prone areas. Obviously, the cost-effectiveness of this solution depends on the availability of lumber.


Figure 48 - a raised house by means of stilts [26]

Constructing a mezzanine level (false roofing)
A mezzanine level under the roof is a very effective system for creating a shelter for storing drinking water, food, seeds, documents, and other important goods and thus protecting them from being affected by flood. In this case, it is important to leave some opening in the roof; such opening can be used as an alternative entrance in the case of extreme flooding. The figures shown below illustrate how the mezzanine level can be used in the extreme flooding cases.

Obviously, this false roofing system can be created when the inclined roofing systems are adopted. Moreover, the use of inclined roofing system is highly recommended in the flood-prone areas. This is to make sure that the flooding water can drain more quickly from the roof. The construction of such mezzanine level demands a roofing truss system that can be made from bamboo, wood or metallic material. The final choice depends on the availability of material and its costs. In general, it is desirable to create a light-weight trussing system. The figure below illustrates a sample construction detail for the roof truss.

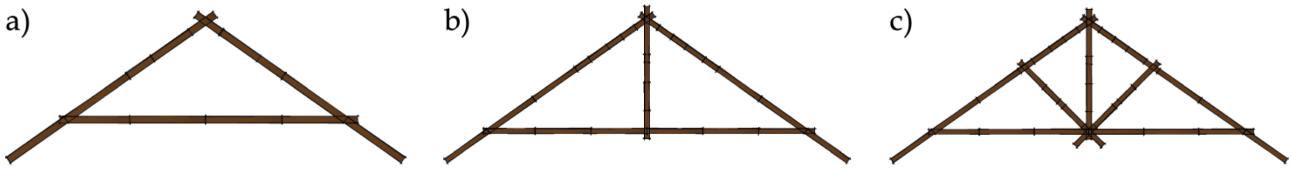


Figure 49 - The construction details of a bamboo truss.

With increasing bay length and loading, it is recommended to pass from solution a) to the solution c) in Figure 49.

Elevating the supply of drinking water

It should be mentioned that it is of utmost importance that the drinking water container is placed in an elevated position (higher than the highest previous flooding levels). The techniques described above for constructing a water-tight platform can be used also in this case. Obviously, if the topography of the informal settlements is in such a way that there are some higher points in the immediate surroundings, it is crucial to exploit them as shelter places. This is of utmost importance since if the drinking water is not placed sufficiently in elevation, it risks contamination by the flooding water. The same logic is true for the food and seeds. It is important that they are secured in a safe place in elevation. It is important to keep in mind that the flooding water may contain heavy objects such as tree trunks and cars are moving with velocity. Therefore, it is not recommended to swim in the flooding water. In places were flooding is very frequent, it is a good idea to have small boats or canoes handy in order to access the water/food supply.

Elevating the latrines

The latrines can be significant source of contamination of flood water. Therefore it is very important to construct the latrines in elevation higher than the previous flooding levels.

Elevating the construction zone

This option regards the planning of homesteads (a group of individual housing units with courtyard). It is important to ensure that the center of the courtyard is the highest point with a small slope towards the sides of the homestead. Ideally, a homestead should be built on raised and compacted soil that is stabilised by plantations on all four sides. The plantations are going to act as slope stabilizer and would also contribute in decreasing the run-off flooding water. However, planting trees it should be kept in mind that the housing area should always receive the sunshine. This would help in drying out more quickly the homestead housings. Moreover, it should be kept in mind that it is preferable to construct a group of separated housing units. This would ensure that the water is not going to be trapped in the courtyard.

Water-proofing (dry protection)
One way of improving the flood-resistance of the housing units is to impede direct contact with water. This can be achieved in many different ways.

Coating the posts
An effective way for waterproofing the structure is to coat the lower ends of the vertical posts (used in mud and wood houses, bamboo construction, wood construction, reinforced concrete, steel, …etc) with water-proof paint. The water-proof paint should at the very least be extended up to the level of maximum previous flood level experienced. The coating material can be made of molten bitumen, mobil or sump oil, or a combination of these for water-proofing the wooden posts (note that the fire safety and possible health-related consequences should be controlled for the coating material adopted).

Water-proofing the walls
A very effective strategy for protecting the walls (especially in case of earth construction) against water is to make sure that the roof protrudes beyond the walls. Moreover, it is essential to make sure that the rain water is drained quickly from the roof and has no direct contact with the walls.

Water-proofing the doors and windows
The door and windows should be preferably made with material with low water-absorption capacity. They should resist the flooding forces and should be connected properly to the structure. Therefore, also the connection needs to resist the reactions due to flooding forces.

Water-proofing the floors
The floor need to be able to resist the uplift forces created due to seepage of water in case of flooding. If the floor system is permeable the seepage water is going to infiltrate from the pavement.

Water-proofing the roof
The roof should be made with light-weight material with low water-absorbing capacity. For instance, the sun-dried earth blocks with a high clay content can absorb a great quantity of water and become very heavy.

It is quite important to make sure that the rain-water is quickly removed from the building since elongated contact with water would lead to several problems such as erosion, structural collapse, deterioration in material properties and scouring. Therefore, it is important the roof has some inclination and is not completely flat. Moreover, the use of a drainage system in the roof is going to ensure that water is not going to get trapped inside the structure.

Making flood barriers
Another strategy for dry water-proofing is the construction of flood barriers around flood-prone areas. The techniques used for making the barrier are going to be similar to those proposed for raising the level of foundation beforehand. In general, they can be classified into water abutments, compacted raised earth, and sandbags. Obviously, constructing the flood barriers is a relatively

costly measure. However, it is quite important to make sure that the constructed barriers have sufficient stability against other types of natural phenomena such as wind, landslides and earthquakes. In this regard, their application is in general not recommended in cases where the flooding height is more than 1.50 meters [29].

Guided Flooding (wet protection)
This category of solution aims at improving and modifying a building in a way that contact with water can be permitted. Substantially, it consists of allowing the water to enter inside the building. In this case, the hydrostatic pressure on the walls are going to be balanced out and the resulting forced acting on the walls is going to be significantly reduced. Obviously, the application of this strategy implies that the parts of the house that are going to be under the flooding level should be able to resist direct contact with water. Furthermore, the house needs to have higher-lying shelter areas and alternative entrances (e.g., the mezzanine solution described beforehand). After each flooding event, it is essential to do an overall maintenance and monitoring of the flooded house.

Flood water management
The shortage of drinking water is a fundamental problem during flooding/drought periods. In particular, during the flooding, the limited supply of drinking water risks being mixed with potentially contaminated flooding water. This can lead to significant sanitary problems. However, the rainfall events should be regarded also as an opportunity for accumulating drinking water. This not only increases the water-supply but also helps in removal of excess water from the roof avoiding roof collapse. In particular, for buildings with flat roofing (e.g., corrugated iron roofing), it is quite important to provide some draining and water accumulation mechanism.

Creating safe zones and flood accumulation basins
An effective strategy for mitigation of flood risk is to take advantage of the natural topology of the area in which the settlements are located. It is important to mark the highest and the lowest parts of the area. The highest parts of the area can be thought of as shelter areas in case of flooding. Therefore, it is good practice to store some drinking water and food in the highest parts of the area. On the other hand, the lowest lying parts of the area can be thought of as a natural pool or basin where the excess water can be accumulated. Obviously, no constructions should be allowed in these low-lying parts. In normal situations, they can be used for sports and recreational activities.

Decreasing run-off and soil erosion
The trees are optimal means for preventing soil erosion and decreasing the water run-off during floods. Their presence not only enhances the ability of the soil to absorb the excess water but also acts as a stabilizer of the terrain. It is clear that in the planned settlements the green areas should be managed and maintained carefully. In un-planned situations, it is important that the inhabitants of the area plant some trees around their houses as an informal means of protecting the terrain. However, it is important to keep in mind that that the trees should not prevent the sun to arrive to the house, since it would delay the evaporation of the excess surface water in case of flooding. In summary, planting can achieve the following multi-purpose objectives:

- Protecting the soil from erosion and flood impact.

- Ensuring some local food supply.
- Producing timber supply for house construction and repair.
- Reinforcing the courtyard layout (if present) and defining territory.

Changing Location

Prevention is probably the most effective mitigation strategy. Thus, in the zones of high risk of flooding the best and the safest practice is to remove the houses exposed to flooding to safer zones. However, this is probably the most expensive and the least realistic strategy. There are a few factors that are going to impede effective reinforcement of such strategy:

- Lack of incentives with regard to viable alternatives
- Complications regarding the land ownership
- Attachment to the local community

9 CASE STUDY: FLOOD VULNERABILITY ANALYSIS INFORMAL SETTLEMENTS IN DAR ES SALAAM

In this section, the vulnerability analysis results obtained for three locations in Suna Sub-ward in Dar Es Salaam are demonstrated. The three locations are marked as P1, P2 and P3 in Figure 50 a) below. This area is located in the Msimbazi river basin as it is indicated from the results of numerical inundation analysis shown in Figure 50 b) below and confirmed by the inhabitants of the area.

a)

b)

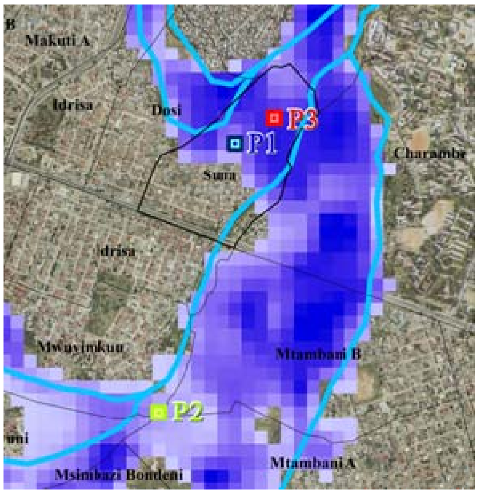
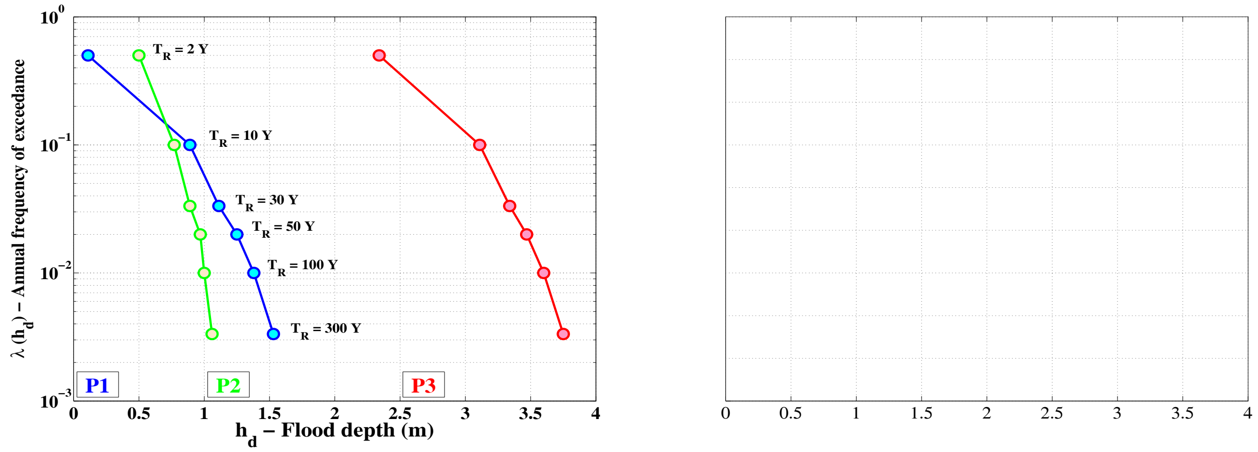


Figure 50 – a) Case studies area and points, b) Preliminary numerical inundation scenario

The three points taken into account are distinguished by color, **P1** blue, **P2** green and **P3** red. These three points serve as an illustration that the different points within the basin may be subjected to different water height/velocity pairs, for a given return period/rate of exceedance. In particular, **P1** is subjected to low values of both flood height and velocity; **P2** is subjected to low values of flood height and high values of flood velocity; **P3** is subjected to high values of flood height and low values of flood velocity. The hazard curves in terms of annual frequency of exceedance of a given value of flood height for the three study points, calculated based on a detailed hydraulic analysis, are plotted in Figure 51 a). In order to be able to relate the flood velocity at each point to the corresponding flood height for a given return period, the flood velocity is plotted in Figure 51 b) versus the flood height for all three locations for different return period (i.e. 2, 10, 30, 50, 100 and 300 years). The presence of a power-law trend of the form $v_d=a\cdot v_d^b$ can be observed from the curves reported in Figure 51 b). Therefore, the a power-law curve is fitted to the three sets of velocity-height data pairs by performing a linear least squares regression in the logarithmic scale and the corresponding regression parameters are reported on the Figure.


$\lambda(h_d)$ – Annual frequency of exceedance
h_d – Flood depth (m)
T_R = 2 Y
T_R = 10 Y
T_R = 30 Y
T_R = 50 Y
T_R = 100 Y
T_R = 300 Y
P1
P2
P3

mechanical properties of the wall panels built with cement-stabilized bricks, the nominal values reported in Table 7 are used assuming that proportion of empty spaces inside the bricks varies between 45% and 65%.

In order to take into account the uncertainties in the structural modeling parameters, a standard Monte Carlo simulation procedure is adopted. In particular the uncertainties in the compressive strength f_m, shear strength τ_0, elastic modulus E, material density γ, the wall thickness t and the length of the wall panel L have been taken into account. Therefore, it is possible to distinguish each structural model realized in the simulation procedure by the vector of uncertain parameters $\boldsymbol{\theta}$:

$$\boldsymbol{\theta} = [f_m, \tau_0, E, \gamma, t, L] \tag{20}$$

It is worth noting that, although it has been possible to detect the building plan dimensions from the orthophotos, the length of the wall panel considered has been randomized in order to reflect a more generic structural type in the zone. Given the scarce information available about the probability distribution of the components of the vector $\boldsymbol{\theta}$, uniform distribution is used to describe the uncertainty in the modeling parameters. For instance, the maximum and minimum values reported in Table 7 for the mechanical material properties are used in order to construct the intervals for the uniform probability distributions. For example, Figure 53 demonstrates the uniform distribution employed for describing the uncertainty in Young modulus *E*.

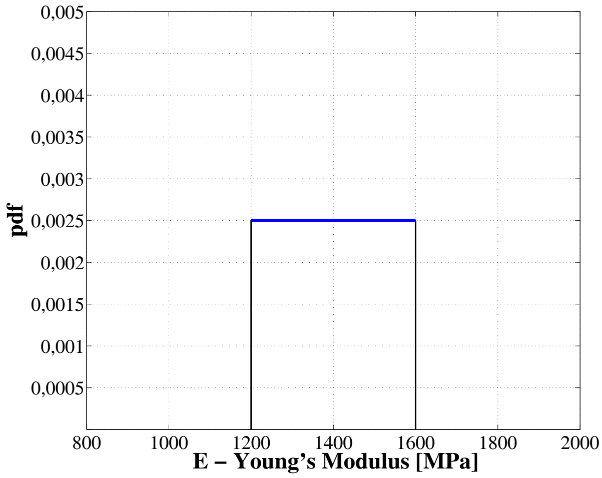


Figure 53 - Uniform distribution for the Young's Modulus

A two-dimensional finite element structural model of the individual wall panels is used for analyzing the effect of flooding. An elastic shell element is used to model the wall panel by using the finite elements. Figure 43 shows a schematic diagram of the finite element model of the wall panel and the mesh used in the discretization of the wall with shell elements. It is assumed that the panel is clamped (fixed) at the base and hinged at the two vertical sides. The clumped restraint in the base is represents a good wall-foundation connection; meanwhile, the hinge restraint on the two sides is represents a fair transversal connection between two orthogonal walls.

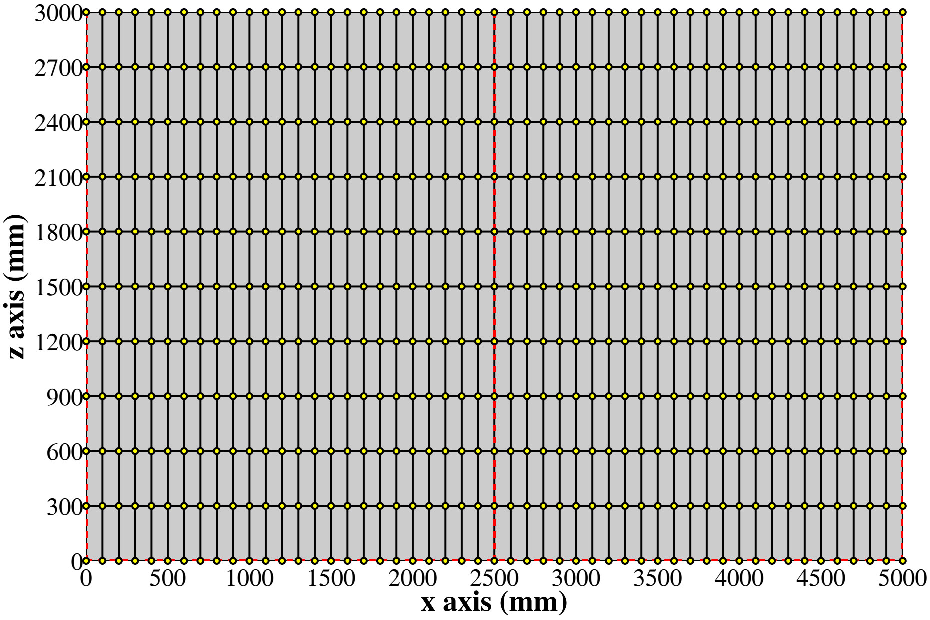


Figure 54 - Schematic modeling of the wall through elastic shell element

The discretization is realized with 500 elastic shell elements (i.e. grey elements in Figure 54). The elements are interlinked at the joints level (i.e. the 561 yellow points in Figure 54). As written before, all the joints at the base (i.e. the joints with z=0 mm) are clumped and all the joint on the external sides (i.e. the joints with x=0 mm and x=5000 mm) are hinged. This model neglects the effect of openings. The dashed red lines mark the two control sections for verifying the resistance.

In order to evaluate the maximum flooding height and velocity for each structural model generated as a realization of the Monte Carlo procedure, the loading characteristics should be first established. Both kinds of hydro-static and hydro-dynamic action are considered as loading applied to the wall panel in case of flooding. The hydrostatic loading depends on the flood height; whereas, the hydro-dynamic loading depends on flood velocity. Equation 20 and 21 below express the profile of the above-mentioned loading patterns along the height of the structure.

$$p(z) = \gamma_w \cdot (H - z) \tag{20}$$

$$p(z) = \rho_w \cdot v(z)^2 \tag{21}$$

The power-law relation derived between the flooding height and velocity at a given point and given a specific return period can be used to calculate the velocity given that the flooding height is known. Figure 55 below demonstrates the hydro-dynamic pressure (velocity) profile (55a) and the simplified form adopted in the analyses (55b). The simplified velocity distribution is expressed by the following relation:

$$\frac{v(z)}{v_{\max}} = -\left(\frac{z}{h}\right)^2 + 2 \cdot \left(\frac{z}{h}\right) \tag{22}$$

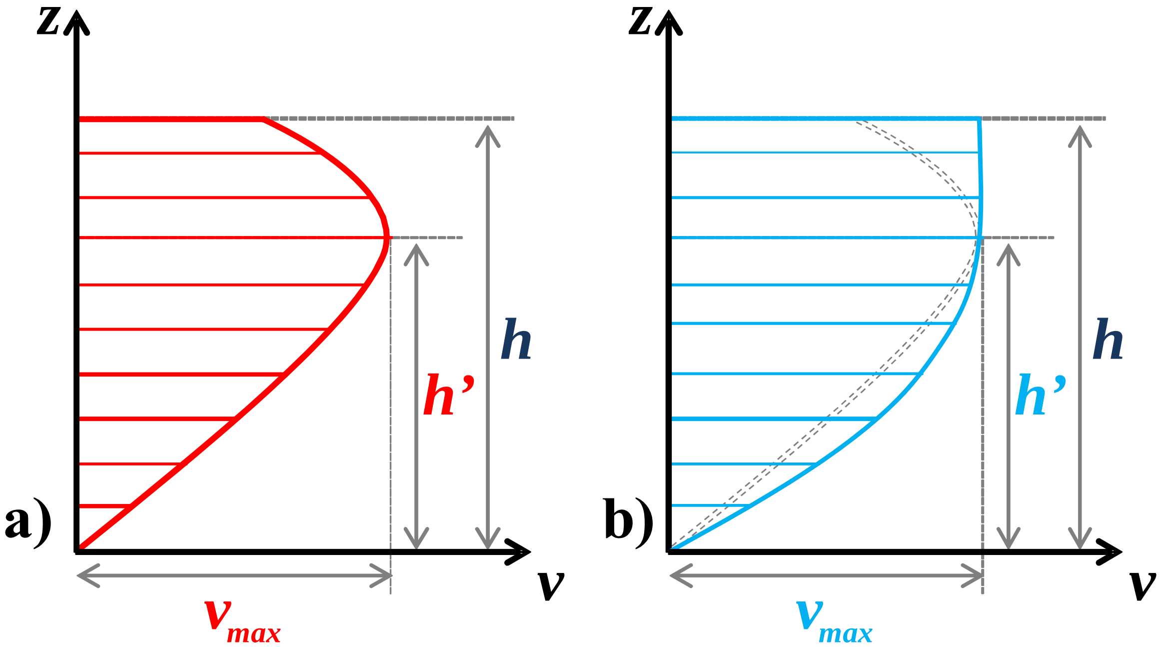


Figure 55 - a) real velocity distribution, b) approximated velocity distribution

It is then possible to define the loading on the structure, for a given flood height, as the sum of the hydrostatic and hydrodynamic pressure functions. In order to calculate the critical flood height that the wall panel can resist, the flooding height is increased in a step by step manner in order to find the maximum flood height that panel can endure. Figure 56, Figure 57 and Figure 58 below illustrate the total pressure acting on the wall panel (the right-hand column) and its break-down into hydro-static and hydro-dynamic components for a set of increasing flooding heights for the points P1, P2 and P3.

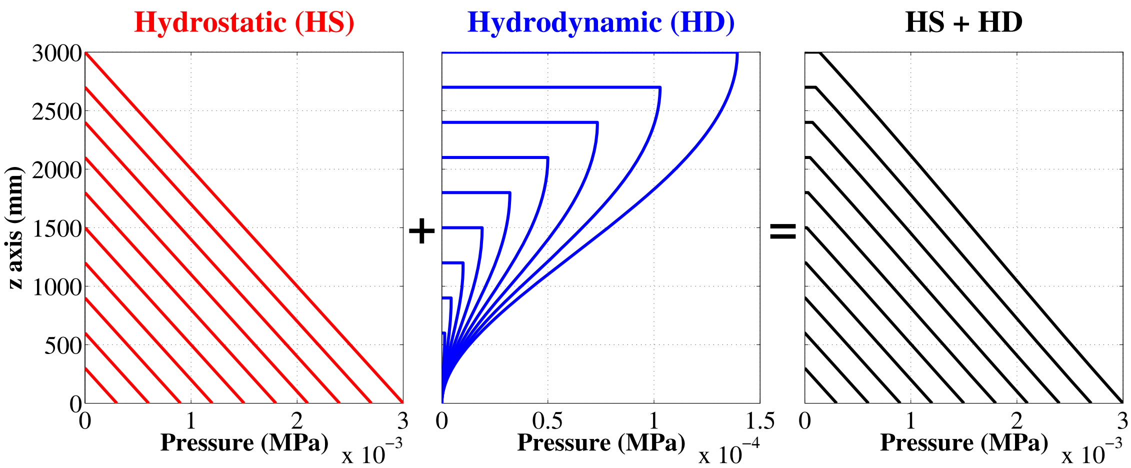


Figure 56 - Increasing of flood height and hydraulic load for point P1 in the study area

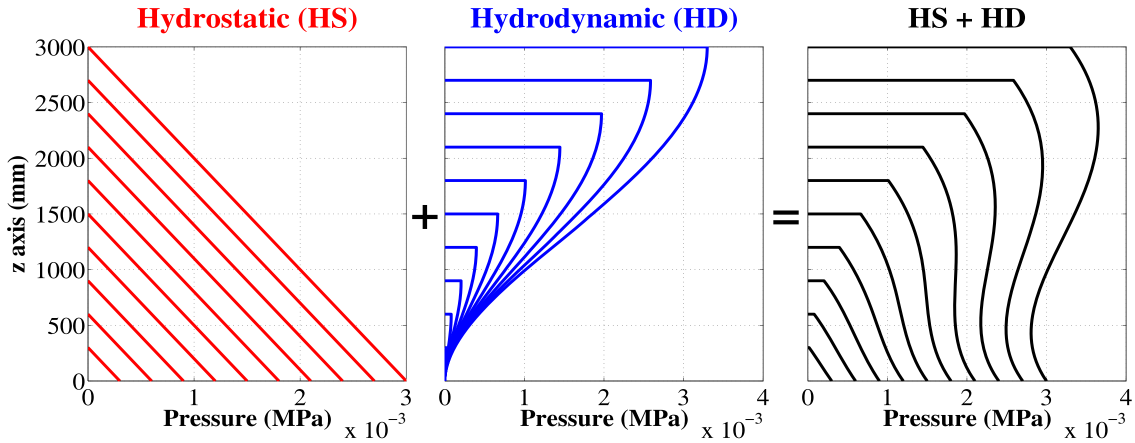


Figure 57 - Increasing of flood height and hydraulic load for point P2 in the study area

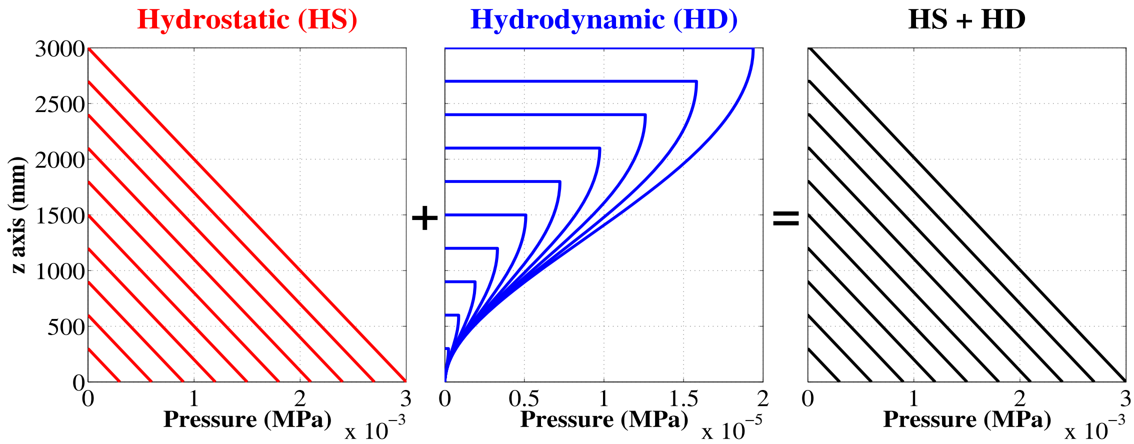


Figure 58 - Increasing of flood height and hydraulic load for point P3 in the study area

It can be observed that the contribution of hydro-dynamic pressure is significant only for point P2 with small flooding height and large flooding velocity. The structural assessments for each (increasing) flooding height considered consists of checking whether the section forces exceed the corresponding section resistance for the critical sections marked on Figure 54. In particular, the shear strength (V_{Rd}) for all the three sections, and bending strength (M_{Rd}) for the base and middle sections are take into account. These quantities are calculated from the following relationships:

$$V_{Rd} = \tau_0 \cdot A_{section} \tag{23}$$

$$M_{Rd,Base} = \frac{N \cdot t}{2} \cdot \left(1 - \frac{N}{0.85 \cdot f_m \cdot A_{section}}\right) \tag{24}$$

$$M_{Rd,Middle} = \frac{f_m \cdot H \cdot t^2}{6} \tag{25}$$

where $A_{section}$ is the value of section area and N is the axial force at the base of the wall. Figure 59 below illustrates the 5 different safety-checking assessment performed for determining the critical water height. The first three safety-checking procedures (referred to as Check 1, Check 2 and

Check3) regard the shear in the base, in the mid-span of the wall panel and along the lateral side of the wall panel. The final two operations regard the bending moment in the base and the bending moment in the mid-section. For each, safety-checking procedure, the critical water height corresponding to the section resistance is obtained as also marked on the figure. The minimum value (h_c) between the 5 safety-checking assessments is representative of the structure capacity. As the histogram reported in Figure 59 indicates the bending moment in the middle section is more critical in this case and determines the critical water height.

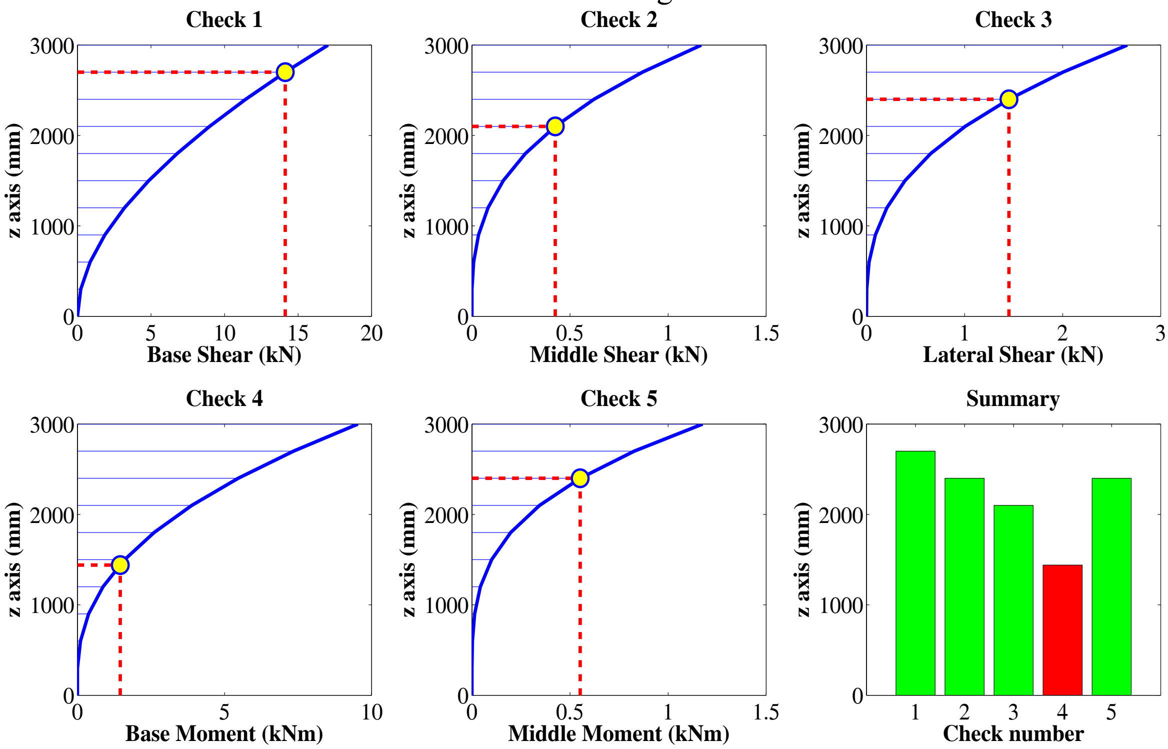


Figure 59 - Structural assessment

Finally, for each Monte Carlo realization of the structural model, a value for the critical water height h_c is obtained. The fragility of the structure/wall panel is then obtained by evaluating the cumulative probability distribution of the flooding height values according to Equation 18 in section 7. This is done by fitting a Lognormal probability distribution to the set of h_c calculated. As a result, a smooth fragility curve can be obtained for each location considered. Figure 60 below illustrates the resulting fragility curves calculated by considering both the hydro-static and hydro-dynamic pressures on the wall panel for locations P1, P2 and P3. It should be noted that if only the hydro-static pressure was considered, the fragility curves would be equal for the three points. Therefore, the difference observed between the curves is due to hydro-dynamic forces that are dependent on the velocity. It can be observed that for the points P1 and P3 the results are similar to the hydrostatic case; whereas, for the point P2, the resulting fragility curve is different. This is also confirmed from Figure 57 where the hydro-dynamic pressure is shown to be significant only for P2 which is subjected to a small water height and high velocity due to flooding. It can be observed that for a given flood height, the structural fragility is larger in P2 compared to P1 and P3. This emphasizes the importance of taking into account the hydro-dynamic forces in the structural assessment procedure.

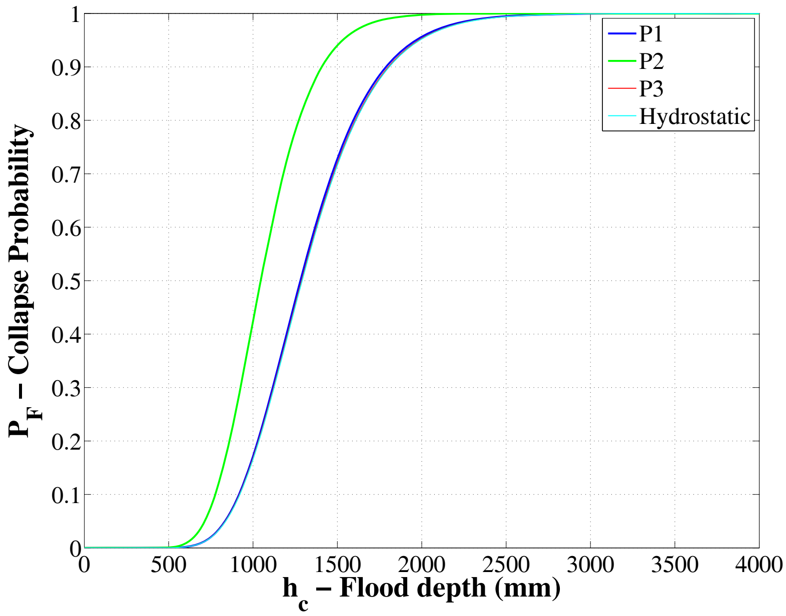
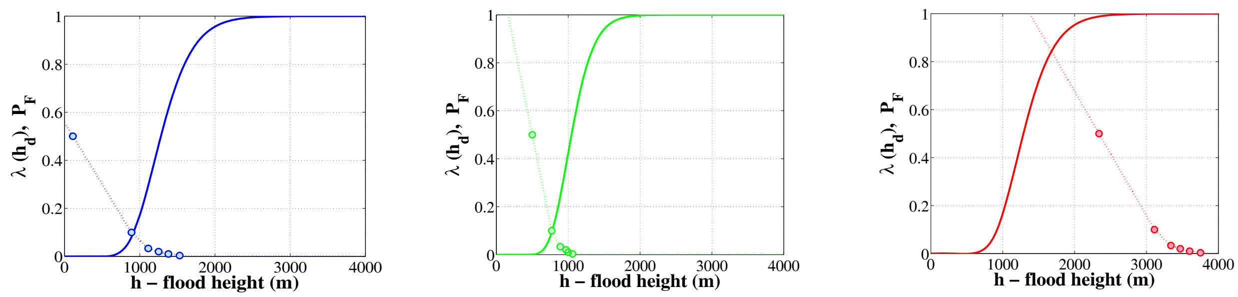


Figure 60 - Fragility curves for the case studies

Finally, the flooding risk at P1, P2 and P3 can be calculated by integrating the fragility and hazard as stated in Equation 17 in Section 7. The superposition of the fragility and hazard curves for the three locations considered is reported in Figure 61 below.



a) b) c)

Figure 61 - Superposition of fragility curves and hazard curves

The risk evaluated in terms of the mean annual rate of exceeding the critical flooding height for the three locations considered is reported in the Table 14 below and illustrated on the map as a bar-plot.

P1: R = 0.0335	**P2:** R = 0.0346	**P3:** R = 1.0235

Table 14 - The flooding risk calculated for the three locations considered

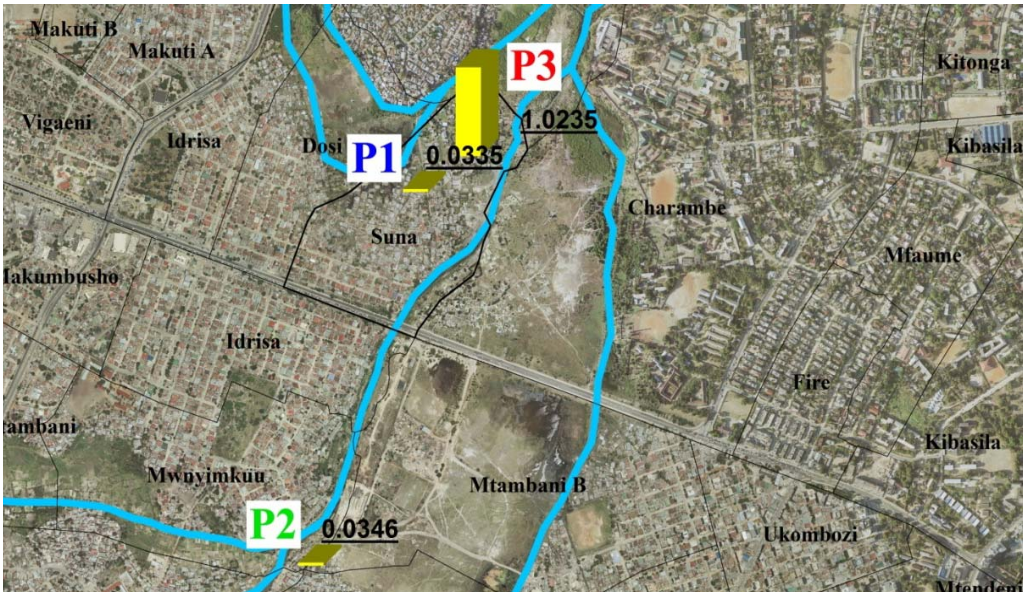


Figure 62 - Risk evaluation for the three points

It can be observed that the point P3 has a annual frequency of exceeding the critical water height equal to 1.02. This indicates that on average assuming that the structure is going to be reconstructed each time after it is collapsed, the structure is going to collapse once a year due to flooding. This is consistent with the high flooding values expected at P3; for example, the flooding height corresponding to a return period of 2 years is around 2.5 meters.

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APPENDIX A

Sample detailed housing survey sheet

The following survey sheet can be used both for collecting the building characteristics essential for creating a structural model and also for characterizing the uncertainties in the structural modeling parameters.

PLAN VIEW WITH EXTERNAL SIZE

PHOTO 1	PHOTO 2

GPS Coordinates	

N° of stories		Height of story	
Presence of Mezzanine (Mansard)		Yes □	No □

Geometrical size			
L (plan Length)		W (plan width)	

Wall Material		
Wall Thickness		
Presence of cross connection in the corners	Yes □	No □

Presence of buttresses	**Yes** □		**No** □	
Presence of plaster	**Yes** □		**No** □	
Presence of water-proof paint	**Yes** □		**No** □	
If the wall material is wood and mud:	**Are the wooden piles anchored in foundation?**		**Yes** □	**No** □
	Are the wooden horizontal piles connected and continuous over the perimeter?		**Yes** □	**No** □

Roof Typology	**Flat** □	**Pitch** □		**One Side** □
				Two Side □
	Structural Material (a)			
	Presence of roof beams	**Yes** □	**If yes, material (b):**	
		No □		
	Presence of drainage or drip	**Yes** □	**No** □	
	Presence of roof coverage	**Yes** □	**If yes, material (c):**	
		No □		
	Use of waterproof Material	**Yes** □	**If yes, material:**	
		No □		

Presence of foundation	**No** □	**Yes** □	**If yes:**	
			Construction material	
			Elevation from ground	

Presence and typology of lintel beam	**Yes** □	**No** □

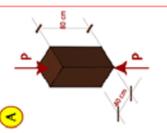
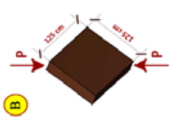
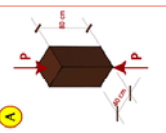
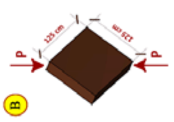
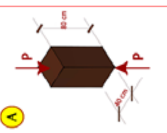
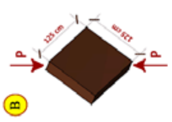
Functionality of doors and windows (in impeding/delaying the water entrance)	**Quality of the doors:**	**Good** □	**Bad** □
	Quality of the windows:	**Good** □	**Bad** □
Minimum height of the windows above the floor			
Window dimensions			
Height of the door above floor			
Door Dimensions			

(a): arched roof, truss roof, other;
(b) wood, bamboo, steel, other;
(c) corrugated iron sheet, straw, tiles, other;

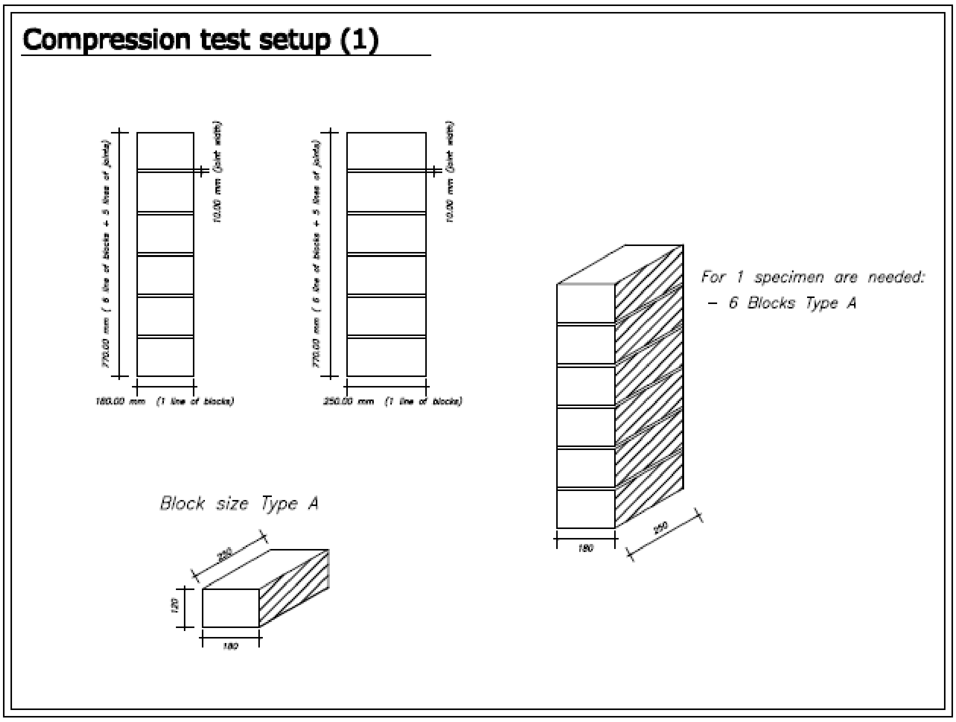
APPENDIX B

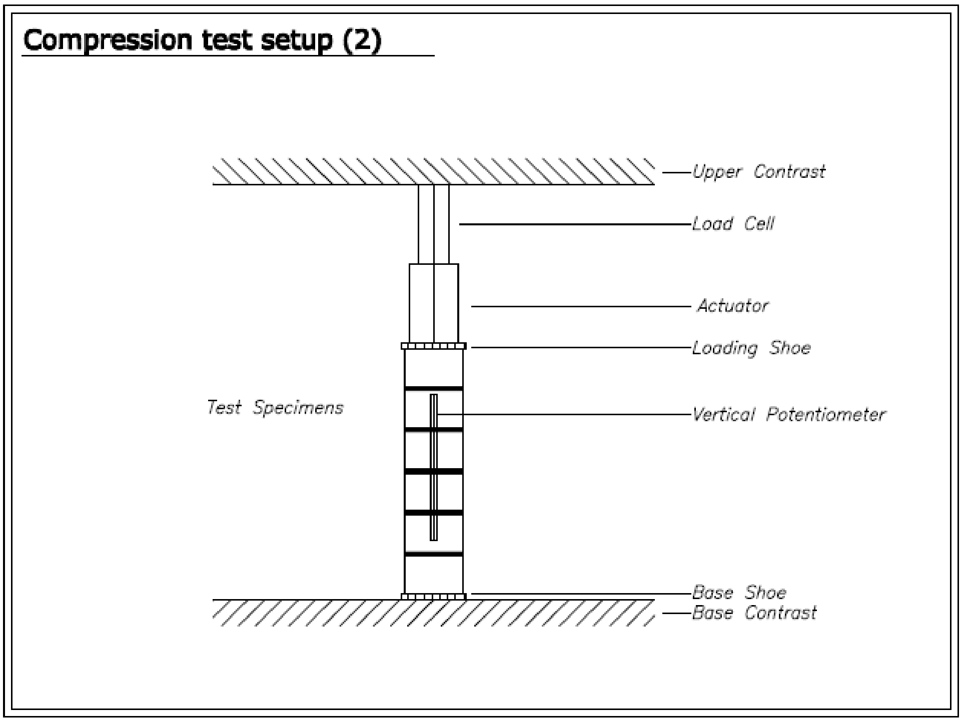
Sample laboratory test program and set-up

In this appendix a sample campaign of laboratory tests on brick material properties is proposed, taking into account the effect of prolonged contact with water.

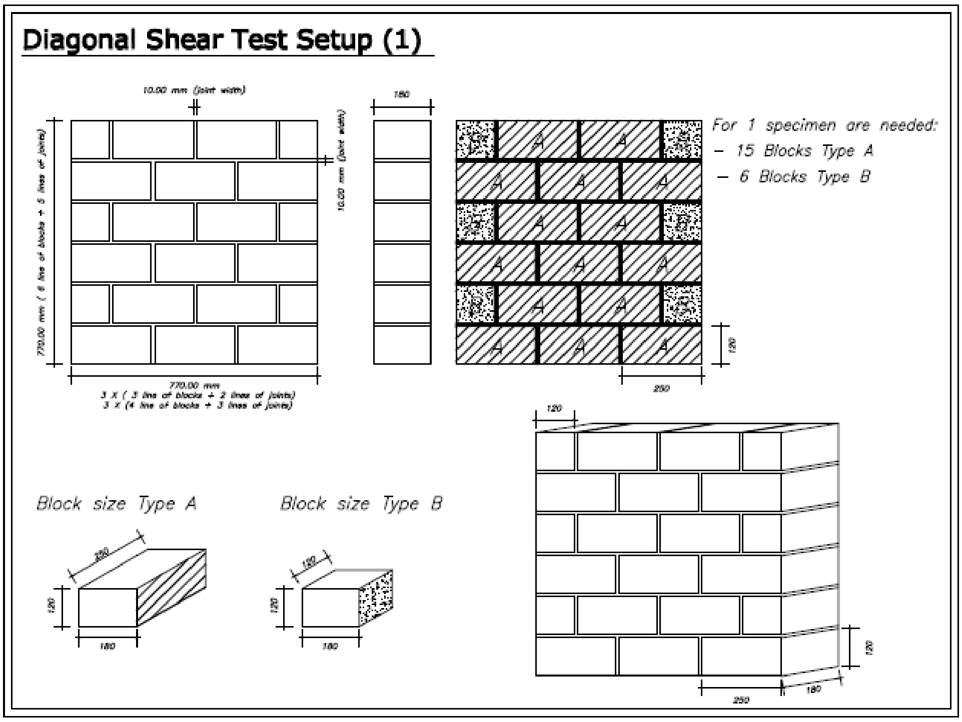
					Note 1	Note 2	tot
1	Time in water 0h (natural humdity content)	3 X	A COMPRESSION TEST 	B DIAGONAL TEST 	At least 3 walls panels are needed in order to carry out test type A, 3 other wall panels are needed in order to carry out test type B. N° = 6	A small wall panel should be dedicated for determining the humidity content. N° = 1	7
2	Time in water 24h	3 X	A COMPRESSION TEST 	B DIAGONAL TEST 	At least 3 walls panels are needed in order to carry out test type A, 3 other wall panels are needed in order to carry out test type B. N° = 6	A small wall panel should be left in water together with rest of the panels, dedicated for determining the humidity content. N° = 1	7
3	Time in water 72h	3 X	A COMPRESSION TEST 	B DIAGONAL TEST 	At least 3 walls panels are needed in order to carry out test type A, 3 other wall panels are needed in order to carry out test type B. N° = 6	A small wall panel should be left in water together with rest of the panels, dedicated for determining the humidity content. N° = 1	7
						TOTAL	21

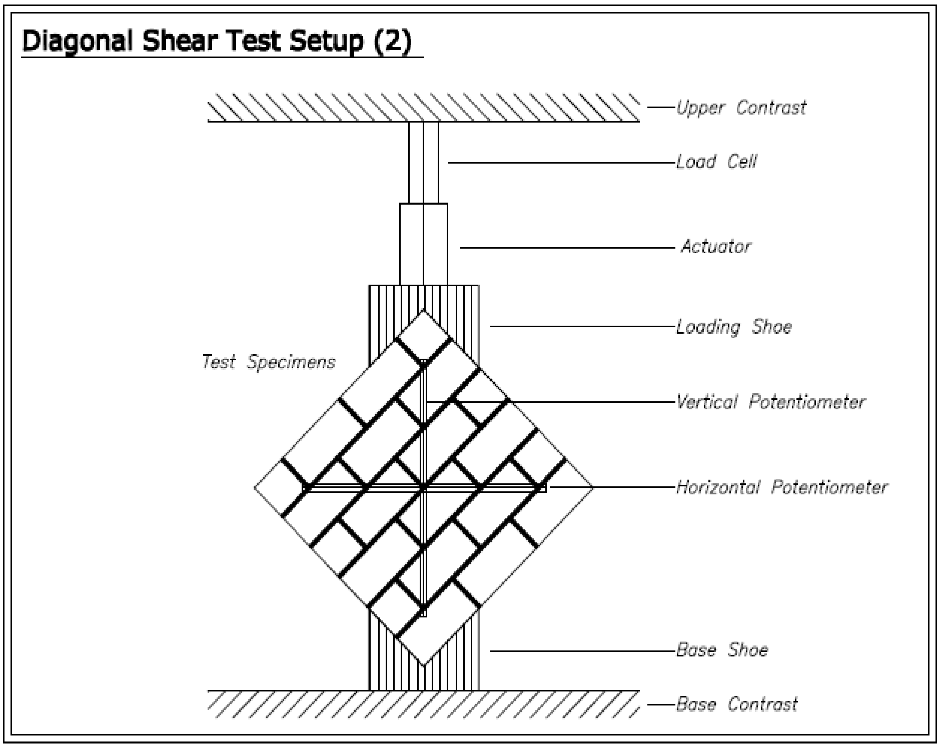
The compression test setup is as follows:





The diagonal shear set-up is:


Diagonal Shear Test Setup (1)
10.00 mm (joint width)
180
770.00 mm
For 1 specimen are needed:
– 15 Blocks Type A
– 6 Blocks Type B
120
250
Block size Type A
Block size Type B
250
120
180
180


Diagonal Shear Test Setup (2)
Upper Contrast
Load Cell
Actuator
Loading Shoe
Test Specimens
Vertical Potentiometer
Horizontal Potentiometer
Base Shoe
Base Contrast