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SEVENTH FRAMEWORK PROGRAMME

CLUVA

SUMMARY

A large percentage of the residential houses in the African urban context can be classified as informal settlements. The informal settlements can be characterized by their generally low quality of construction and poor living conditions. They are often constructed without formal criteria and in the flood-prone areas. 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. In fact, the three case-study cities reflect the above-mentioned construction types: Dar Es Salaam (cement brick houses), Addis Ababa (mud and wood houses), and Ouagadougou (adobe houses). As far as it regards the climate change adaptation strategies for informal settlements, the need for integrated, streamlined and standardized vulnerability reduction methodologies is apparent. The present report focuses its attention on vulnerability reduction strategies for informal settlements subjected to flooding. The objectives of the present document can be summarized as: increasing public awareness to the high vulnerability and critical conditions of informal settlements; providing relatively easy-to-implement strategies for natural disasters adaptation in informal settlements. In the first part of the document, an ample description of general risk mitigation strategies for informal settlements is provided. The second part of the document focuses on city-specific vulnerability assessment for both the as-built condition and after implementation of alternative viable mitigation strategies. Whenever possible, the effect of the mitigation strategies in risk reduction is quantified. The final part of the document provides some specific construction details for mud and wood material. These construction details lead to an increase in the overall strength and continuity of the structure made up of mud and wood. The risk and vulnerability assessment is performed through an analytic and modular approach proposed by the authors in the context of the CLUVA project. This probabilistic approach is particularly suitable for situations in which a large amount of uncertainty is present. The visual risk and vulnerability platform (VISK), which provides a graphic user interface for the above-mentioned methodology, is used for calculating the fragility curves and risk assessment.

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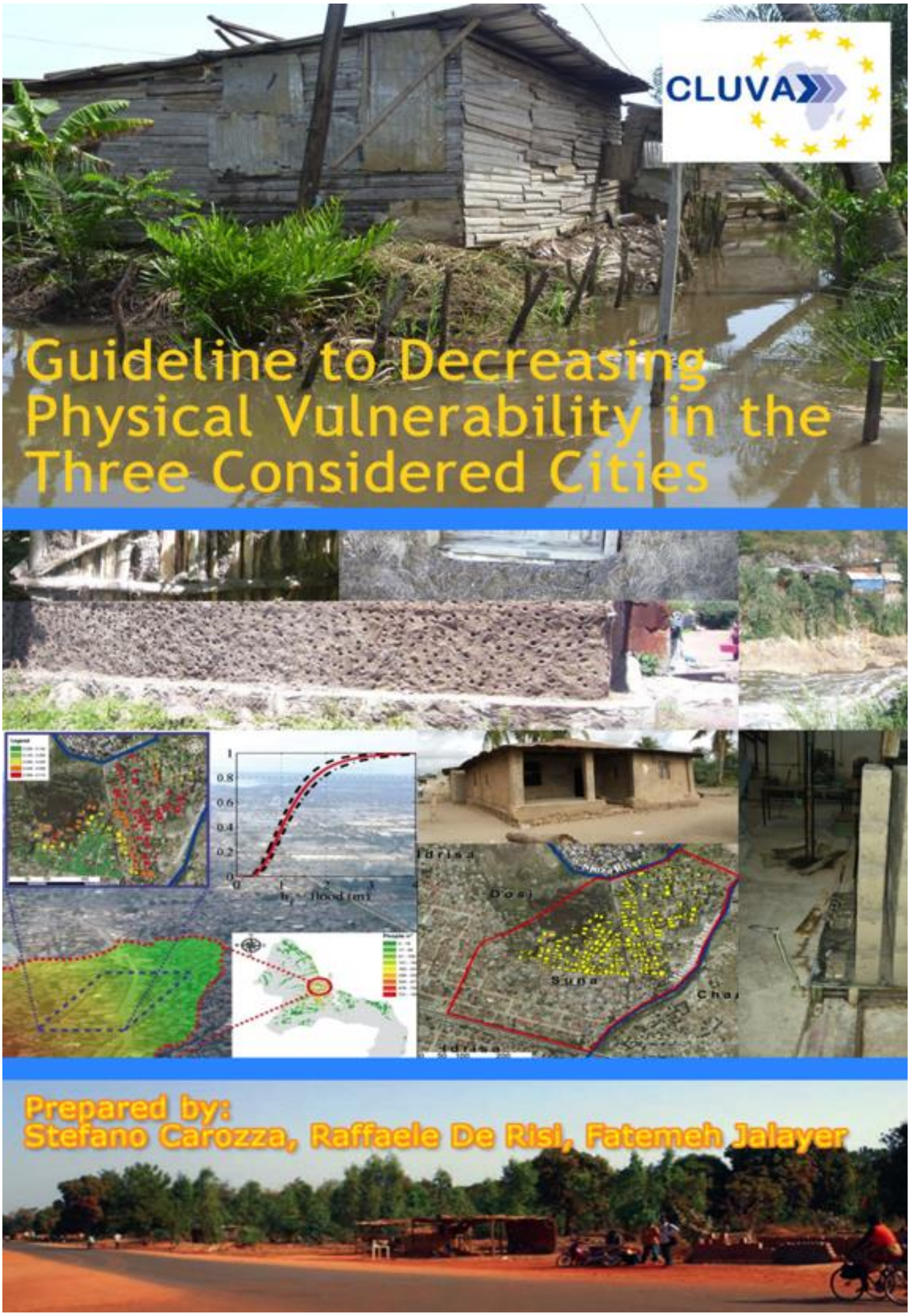
CLUVA
Guideline to Decreasing Physical Vulnerability in the Three Considered Cities
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1 FOREWORD

The vulnerability and risk assessment results presented in this deliverable are based on mechanical properties of materials as reported in the literature. Unfortunately, location-specific laboratory test results for the construction materials investigated in this report were not available. Moreover, no specific information on the durability of the material and its degree of deterioration due to direct contact with water was available. The mitigation and reinforcement strategies studied herein are almost always inspired from local climate adaptation strategies. These strategies are often effective in reducing the vulnerability but not sufficient in rendering the building fully flood-resistant and climate-proof. In general, the recommended strategies do not lead to a radical reduction in vulnerability. We believe that more substantial upgrading operations need to be first verified by experimental tests. Finally, although the mitigation strategies laid out herein focus primarily on flooding, they may be also applicable for other types of natural phenomena such as debris flow, salinisation, sea-level rise and erosion.

2 INTRODUCTION

Around half of the world's population lives in urban areas. By 2050 this ratio is estimated to rise up to around 70% (UN-HABITAT 2010). One of the most significant consequences of the rapid urbanization process is the phenomenon of the squatter settlements also known as informal settlements, shanty towns, and slums. Although slightly different in their definitions, these denominations all refer to generally poor standards of living. A significant proportion (around one third) of the urban growth in the developing regions is un-programmed and in the form of informal urban human settlements (UN-HABITAT 2010). The lack of formal engineering criteria in the construction of informal settlements together with their generally poor construction quality renders them particularly vulnerable to extreme natural phenomena (De Risi et al. 2013a).

It can be argued that, assessment and prediction of the adverse effects of climate-related events, quantification of the vulnerability of the affected areas, and finally risk assessment, are important steps in an integrated climate-related adaptation and strategic decision-making. In particular, rainfall-induced flooding can pose a serious threat to high-density urban areas; this is especially the case for informal settlements built on river banks and in flood plains. 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 rainfall and/or flooding. The flood damage to buildings can be classified into two main-categories: damage due to direct contact with water and structural failure. If the material used for the foundation is not water-tight or if the foundation is on or under the ground level, or if there are no barriers built in front of the door, the water can easily come into contact with the building. In this case, if the building is not sufficiently water-tight, the water can infiltrate inside the building. This is going to lead to material deterioration and erosion, non-sanitary living conditions and risk of drowning. On the other hand, structural failure is more likely to take place due to hydrostatic pressure, hydrodynamic pressure, debris impact and a combination of these actions (Kelman and Spence 2004).

In the recent years, increasing attention is placed on flooding risk assessment. In fact, several publications discuss the consequences of flooding, such as loss of life (Jonkman et al. 2008), economic losses (Pistrika 2009, Pistrika and Jonkman 2009, Pistrika and Tsakiris 2007) and damage to buildings (Smith 1994, Chang et al. 2009, Kang et al. 2005, Schwarz and Maiwald 2012). These research efforts have many aspects in common, such as a direct link between the flooding intensity and the incurred damage, and that they are based on real damage observed in the aftermath of the flooding event. On the other hand, many research efforts are starting to galvanize in the direction of proposing analytical models for flood hazard and vulnerability assessment taking into account the many sources of uncertainties. Nadal et al. (Nadal et al. 2009) propose a stochastic method for the assessment of the direct impact of flood actions on buildings. A general methodological approach to flood risk assessment is embedded in the HAZUS procedures for risk assessment (Scawthorn et al. 2006a, Scawthorn et al. 2006b). Lacasse and Nadim (2011) proposed various case studies on the assessment of hydro-geological risk, presenting a range of methods from simple/qualitative to more complex/quantitative approaches. Apel et al. (Apel et al. 2009) have done a comprehensive study on the various scales of complexity and precision involved in the flood risk assessment. De Risi et al.

(De Risi et al. 2013a) presented an integrated modular probabilistic methodology for predicting flooding risk of spatially-distributed structures in a portfolio at a detailed micro-scale (e.g., a neighborhood) in a Geographical Information System's (GIS) framework. Although the methodology presented is general with respect to any structural type, it is specifically oriented towards application for the case of informal settlements. It is also particularly suitable for problem-solving based on in-complete information. This aspect is particularly evident in the construction of the rain-fall curve and in data acquisition and processing for the vulnerability assessment of informal settlements. De Risi et al. (De Risi et al. 2013b) developed a new software tool for flood risk assessment for individual buildings. VISK, acronym of Visual Vulnerability and (Flooding) Risk, is a GIS-compatible platform that performs micro-scale flood risk assessment for buildings located in homogenous (i.e., characterized as a single class of buildings) urban areas. This report uses the tools developed De Risi et al. (2013a, 2013b) in order to analytically investigate the effect of alternative local adaptation strategies on structural vulnerability in three case-study cities. The objectives of the present document can be summarized as: increasing awareness to the high vulnerability and critical conditions of informal settlements; providing relatively easy-to-implement strategies for natural disasters adaptation in informal settlements.

Adaptation or mitigation?

In the technical language of risk and reliability engineering, risk and vulnerability mitigation strategies refer to actions that lead to reduction of risk and vulnerability, respectively. However, in the context of climate change related studies, mitigation strategies refer to those studies that reduce the adverse effects of climate change by reducing the green house emissions. Instead, the climate adaptation strategies refer to those strategies that aim at reducing the adverse effect of climate change. In this report we have used both terms mitigation and adaptation interchangeably. Clearly, the term mitigation refers to the interpretation common in the engineering and risk analysis community.

In the *Chapter 3* , the general flood risk mitigation strategies are discussed. The mitigation strategies are classified based on whether they lead to a reduction in hazard, vulnerability, or exposure. Given the focus of this report, special attention is placed on those strategies that lead to a reduction in vulnerability in the African context. However, it can be argued that for spatially distributed natural phenomena such as flooding, strategies that lead to a reduction in hazard and exposure, might be much more effective in reducing fatalities, injuries and economic losses.

In the *Chapter 4,* geomorphologic datasets called as urban morphology types (UMT's, for details see CLUVA deliverables D2.7 and D2.8, Cavan et al., 2013, Lindley et al., 2013) are used in order to detect the predominant residential housing types in three case-study cities of Dar Es Salaam, Addis Ababa and Ouagadougou. In *Chapter 5,* the methodology discussed in De Risi et al. (2013a) is employed in order to analytically calculate the structural vulnerability for three representative buildings for the three case-study cities, namely, cement brick type for Dar Es Salaam, mud and wood type for Addis Ababa and adobe type for Ouagadougou. The visual risk and vulnerability platform VISK ((De Risi et al. 2013b), see also the appendix) is used in order to do the structural analysis and extract the fragility curves. The case-study buildings are investigated both in their as-built condition and also after implementation of alternative viable mitigation strategies. These mitigation strategies are almost always inspired from local climate adaptation strategies.

Is the flood risk calculated based on climate change projections?
In this report, the flood hazard calculations are based on historical rainfall data and not on climate change projections. It should be noted that the risk based on historical data proves to be high for the type of buildings considered. For more information on flood risk assessment for Dar Es Salaam also based on climate projections see (Jalayer et al. 2013).

In *Chapter 6*, special recommendations are made regarding the mud and wood building material. This composite material has potential for improvement as far as it regards its resistance to lateral loading. These recommendations in general aim at improving the continuity of the building and its resistance to lateral loading, humidity and active agents. In the *Appendix*, a brief overview of the visual risk and vulnerability platform VISK is provided.

3 GENERAL FLOOD RISK MITIGATION STRATEGIES

The flooding risk can be represented as the convolution of hazard, vulnerability and exposure:

$$R = H \cdot V \cdot E \qquad \text{Eq. (1)}$$

This schematic representation is useful also for classifying various flood risk mitigation strategies. In particular, the risk mitigation strategies can be classified as follows:

1. **Strategies aiming at reducing the exposure to flooding:** This category of mitigation strategies is effective in reducing the exposure to risk without necessarily intervening with regard to hazard and/or vulnerability components. Examples of these strategies include, flood zoning, legislation that prevents construction in areas of high hazard, imposing insurance against natural hazards, ..., etc.

2. **Strategies aiming at reducing the vulnerability to flooding:** This category of mitigation strategies strives to reduce the risk by improving the properties of the physical components exposed to risk (e.g., buildings, bridges, roads, galleries, etc.). Examples of this category of solutions include, using better construction materials, improving the construction techniques, designing the structure so that it withstands the flooding action, ..., etc., just to name a few.

3. **Strategies aiming at reducing the flooding hazard:** This category of strategies strives to reduce the probability of occurrence of flooding or the natural phenomena in question. Examples of this category of solutions include, flood run-off reduction techniques, choice of suitable land-cover type, design of adequate draining systems, and, construction flood-resistance structures.

The focus of this report is on the second category of strategies; that is, those strategies that aim at reducing the vulnerability to flooding. However, in this section, a general overview of all the above three categories for flood risk mitigation is provided. Special care has been taken to identify those strategies that are more adequate for the African cities.

3.1 STRATEGIES AIMING AT REDUCING THE EXPOSURE TO FLOODING

3.1.1 Flood Plain Zonation

The first and foremost step in an integrated flood risk management cycle is improving the state of knowledge about the flood extremes likely to happen in the area. Informal human settlements are often developed in flood-prone areas due to both the lack of sufficient knowledge of imminent risks and also lack of viable alternatives. Delineation of flood-prone areas can be considered as a step towards prevention of new urban development in these areas. In the following, some techniques for flood plain zonation are described.

River basin flood delineation

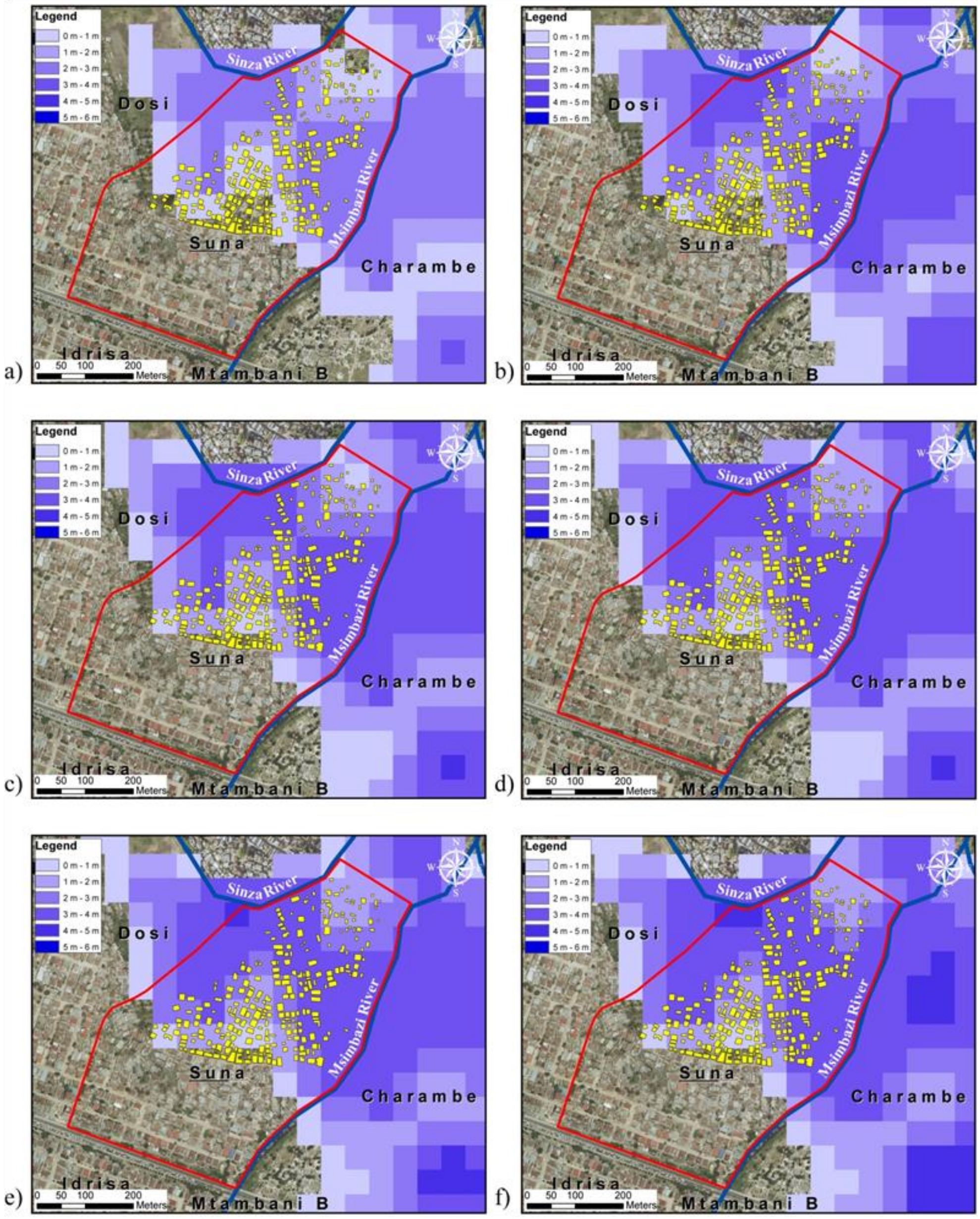


Figure 1 Inundation profiles for different return periods in terms of h_{max}: a) T_R=2 years, b) T_R=10 years, c) T_R=30 years, d) T_R=50 years, e) T_R=100 years, f) T_R=300 years.

One viable technique for flood zoning is the delineation of the potentially inundated areas. This can be achieved by marking, for example, the 25- or the 50-year flood water height, and a designated flood line below which the construction of houses should be prohibited. The delineation of these areas can be realized with different degrees of complexity: with very sophisticated methods and software (FLO-2D 2004, O'Brien et al. 1993), or through more simple methodologies (Brunner

1995). Figure 1 demonstrates the inundation profile for Magomeni Suna (Dar Es Salaam) for various return periods.

Marking the last flood level
This simple technique for flood zonation consists of marking the maximum level of inundation in the ultimate flooding event, by a coloured paint. This is an effective way of keeping the memory of danger alive. If more financial resources are available, the delimitation of the interested area can be implemented in the physical system through the use of fences or similar structures.

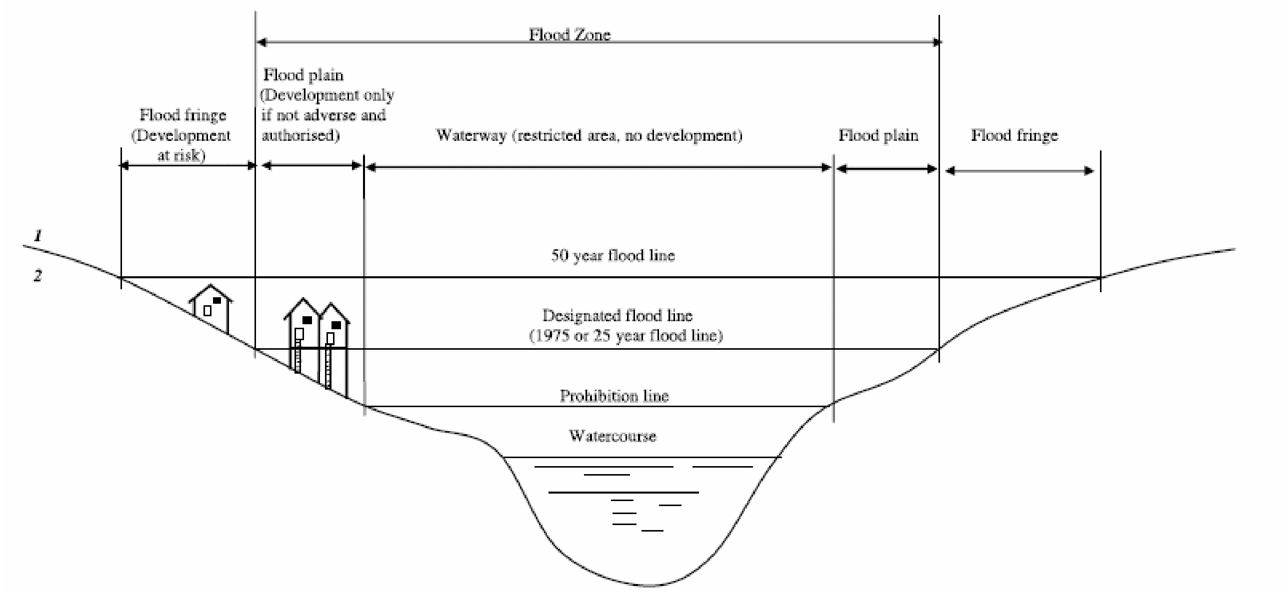
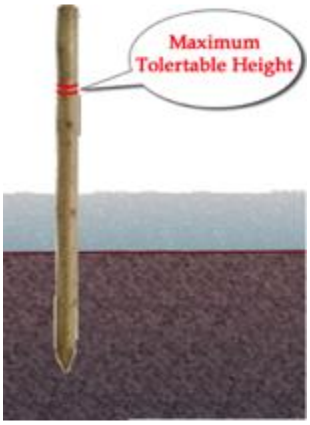


Figure 2 - Delineation of the flooding zone in the flood basin. Figure courtesy of (Stephenson 2002)

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 know the past in order to be able to be more prepared for future flooding events.

3.1.2 Flood Warning Communication

The flood zonation activities described before are very useful for releasing eventual flood warnings to flood-prone communities. In particular, through the results of hydraulic studies (i.e. flooding maps, TWI maps, etc...), it is possible to identify a specific threshold of water depth, beyond which an alert for the life safety of the people is going to be issued. Therefore, the delineation of the flood line on the river basin and constant monitoring of the water height constitutes an efficient and simple flood early warning system (see Figure 3 a). 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 (see Figure 3 b).

a) 

b) 

Figure 3 - (a) Monitoring of the flood height in the flood basin; (b) A simple flood early warning/alert system. Sketch courtesy of (Feuerhake 2010)

3.1.3 Creating safe zones and flood accumulation basins (Flood plain storage)

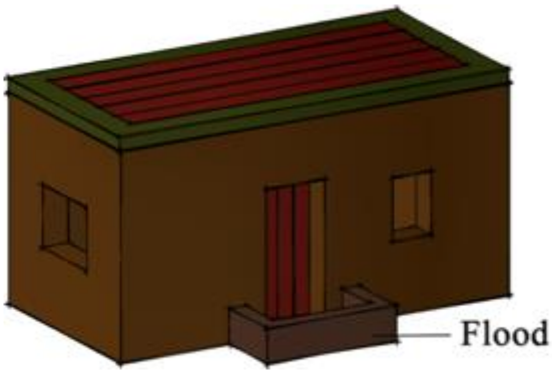
An effective strategy for mitigation of flood risk is to take advantage of the natural topology of the area in which the settlements are located. It is important to mark the highest and the lowest parts of the area. The highest parts of the area can be thought of as shelter areas in case of flooding. 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.

Figure 4 (right) Houses built on an elevation in the little Akaki Area, Addis Ababa. The lower part is inside the flood plane (Photos by F. Jalayer); (left) an overlay of the aerial photo of the zone with the inundation profile calculated for a return period of 300 years.

3.2 STRATEGIES AIMING AT REDUCING THE VULNERABILITY TO FLOODING

3.2.1 Making flood barriers (a dry water-proofing strategy)

One 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. Figure 6 below, demonstrates low-rise flood barriers constructed in front of the entrance to buildings. In general, they can be classified into water abutments, compacted raised earth, and sandbags. 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.



a)

b)

c)

Figure 6 – (a) Low-rise flood barrier in front of the entrance; (b) This adaptation technique is widely encountered in the informal settlements of Dar Es Salaam, Tanzania; (c) Abutments and compacted raised earth (sketch courtesy of (AdbPo 2009))

3.2.2 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 is 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., through the mezzanine floor). After each flooding event, it is essential to do an overall maintenance and monitoring of the flooded house.

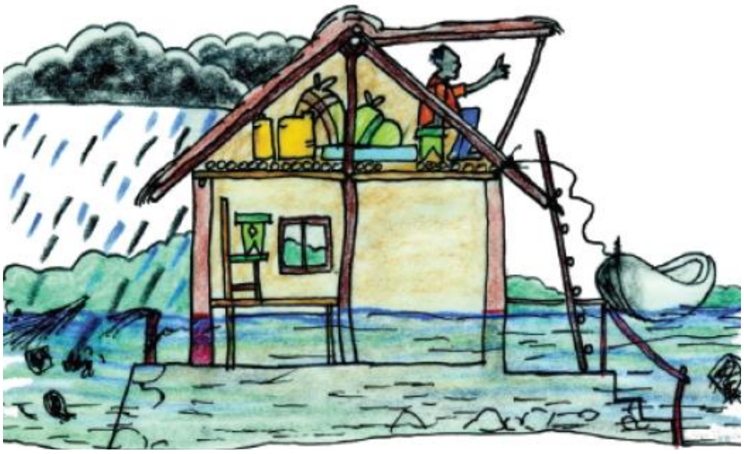


Figure 7 – wet protection (Sketch courtesy of (Feuerhake 2010))

3.2.3 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.

Raised 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 (see Figure 5 below, see (Ahmed 2005) for more information on foundation detailing).

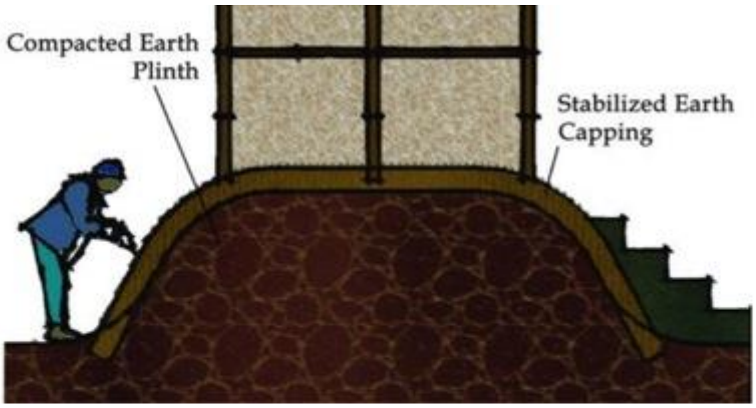


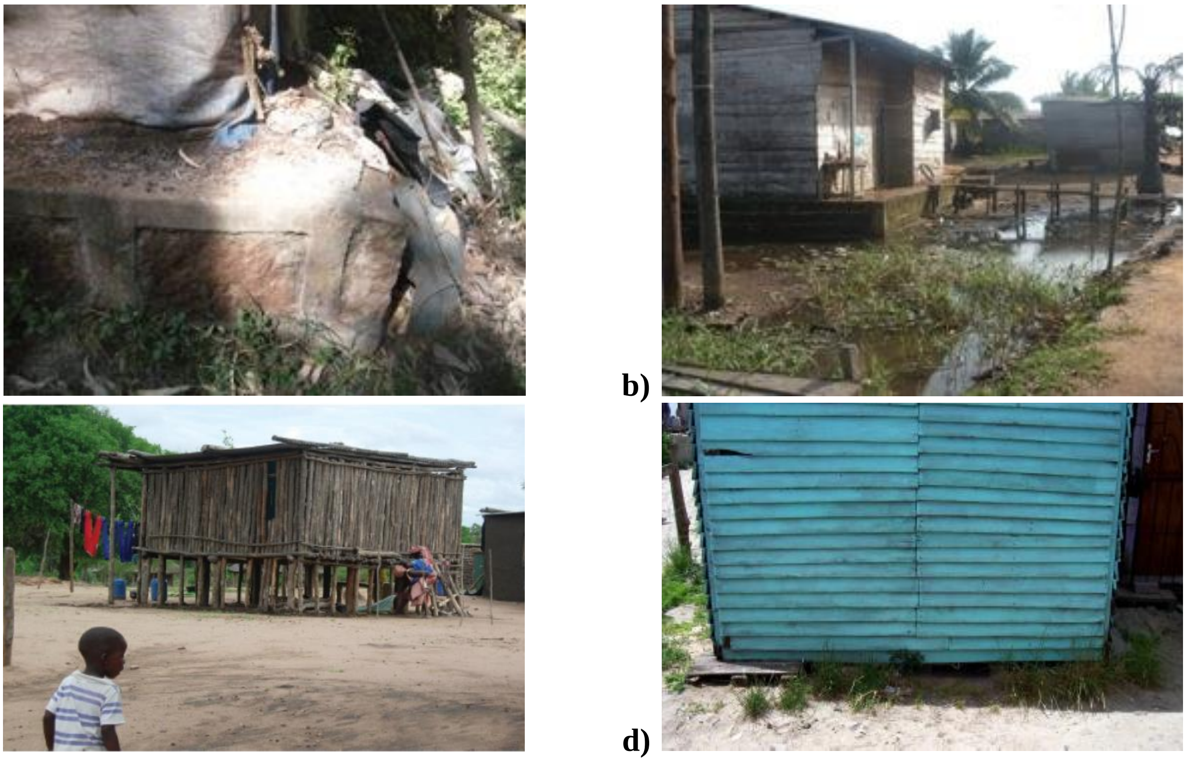
Figure 5 - Raised foundation detailing

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.

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. If using cement for stabilizing the entire plinth results too costly, one can use cement only for stabilizing the upper part (see Figure 8 a).



a) b) c) d)

Figure 8 – Various types of raised foundation: (a) raised foundations made up of cement-stabilized earth and stone (Little Akaki, Addis Ababa, Photo by F. Jalayer); (b) construction of brick perimeter walls (Mbanda, Douala, Figure by R. Fuemba); (c) stilt foundations (Chicualacula, Mouzambique, figure courtesy of (Feuerhake 2010)); (d) use of pallets (Lotus river, South Africa, figure courtesy of (Bouchard 2007));

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 (see (Ahmed 2005) for more information and detailed sketches):

- 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.
- 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 9 below illustrates detailing instructions for a cement and brick raised foundation.

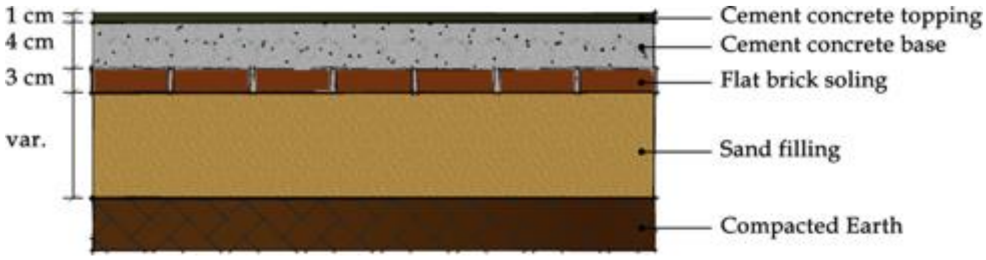


Figure 9 – Recommended detailing for a brick and cement raised foundation.

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. Figure 8 d demonstrates an example of the use of pallets in Lotus River, South Africa.

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 8 c demonstrates the use of a stilt foundation in Chicualacula, Mouzambique.

Construction of brick perimeter walls
Figure 8 b illustrates an example of the construction of a brick perimeter wall around the foundation in Mbanda, Douala. In order to protect the plinth from erosion, a brick perimeter wall can be built around it. 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.

3.2.4 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 that the building dimensions are proportional (i.e., the building does not have a large aspect ratio, see Figure 10 for examples of buildings with regular and irregular plan). 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 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 (see Figure 10 b).

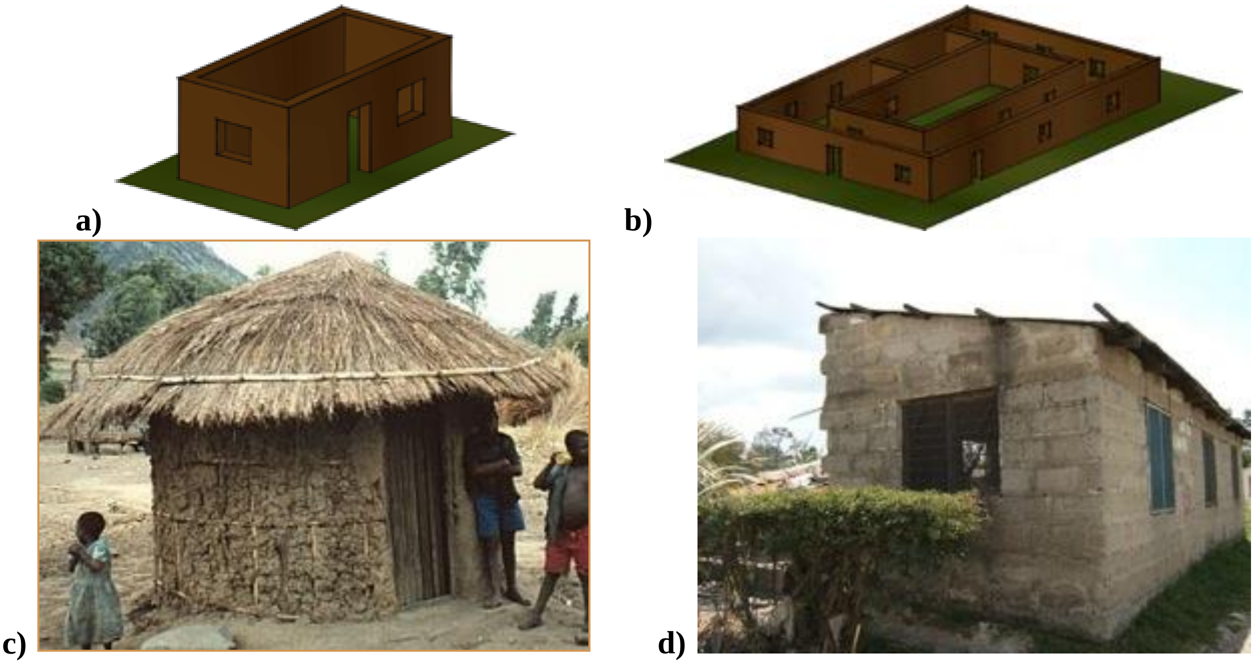


Figure 10 – Various building configurations: (a) sketch of a regular building; (b) sketch of a building with courtyard; (c) a rural-type circular house (photo courtesy of CLUVA dropbox); (d) an irregular building with a large aspect ratio (Suna, Dar es Salaam figure by F. Jalayer)

3.2.5 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. Obviously, the false roofing system can be created when inclined roofing systems are adopted. On the other hand, 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.

3.2.6 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.

3.2.7 Elevating the latrines

The latrines can be a significant source of contamination of flood water. Therefore it is very important to construct the latrines in elevation higher than the previous flooding levels. Figure 11 below illustrates some examples of latrines not elevated properly in the area of Mbanda, Douala.

Figure 11 – Examples of latrines not elevated properly (Mbanda, Douala, photos by R. Fuemba)

3.2.8 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, when 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.

3.2.9 Water-proofing (a dry protection strategy)

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/poles
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, see (Ahmed 2005) for more details).

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. Figure 11 (left) shows an example of non water-proof med and wood wall system in Little Akaki, Addis Ababa, where the adobe material has been eroded. Figure 11(right) demonstrates an adaptation strategy which consists of covering the walls with plastic sheets. Figure 11(bottom) shows an example of plaster coating for cement brick walls.

a)  **b)** 

c) 

Figure 12 – (a) mud and wood wall not protected properly. The erosion of adobe material is evident (Little Akaki, Addis Ababa, photo by F. Jalayer); (b) local adaptation strategy which consists in raising the foundation, plastering the walls and covering them with plastic sheets (Little Akaki, Addis Ababa, photo by F. Jalayer); (c) plastering the walls (Suna, Dar Es Salaam, photo by F. Jalayer)

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.

a)  b) 

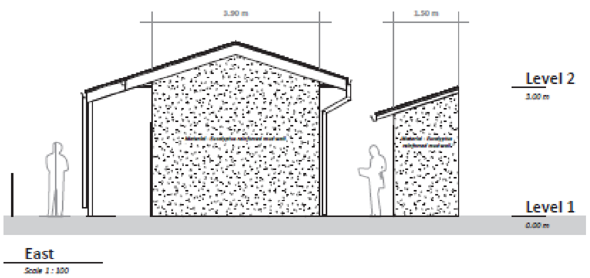
Figure 13 – (a) a sealed window in a mud and wood wall protected by plastic sheets; (b) a non water proof window in an un-protected mud and wood wall (Little Akaki, Addis Ababa, photos by F. Jalayer)

Water-proofing the floors

The floor needs 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 through 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.



a)

b)

Figure 14 – The elevation (a) and 3d (b) view sketches of a mud and wood structure with water-proof roof system. Note the position of drains and the inclination of the roof (drawings courtesy of EiABC)

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 that 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. Figure 14 illustrates the elevation and three-dimensional sketches of a water-proof roof detailing. It can be noted that the detailing respects the following three principles: (a) the distance between the rood and the walls helps in protecting the walls from water; (b) the inclination of the roof helps in draining away water from the roof as quickly as possible; (c) the presence of a drainage in the roof.

3.3 STRATEGIES AIMING AT REDUCING THE FLOODING HAZARD

3.3.1 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 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 (it should be mentioned that the water accumulated through such procedures might not be suitable for drinking, due to direct contact with roof material).

3.3.2 Planning of a Regular Maintenance

The regular maintenance of a river bed (or, generally speaking, of a channel) and of the annexed functional constructions (i.e. stems, banks, etc…) allows a better propagation of the discharges. The planning of a regular maintenance is an essential activity which must be carried out by stakeholders and policy makers and that must be envisioned in the phase of urban planning.

3.3.3 Increasing of the flow capacity or adjustment of the river line

If the financial resources are available, more elaborate measures can be adopted for increasing the flow capacity. One possibility is to increase the flow capacity of the channel or of the river, by digging the river bed or the channel section. Another costly alternative is to deviate the river/channel line in order to avoid zones of high exposure.

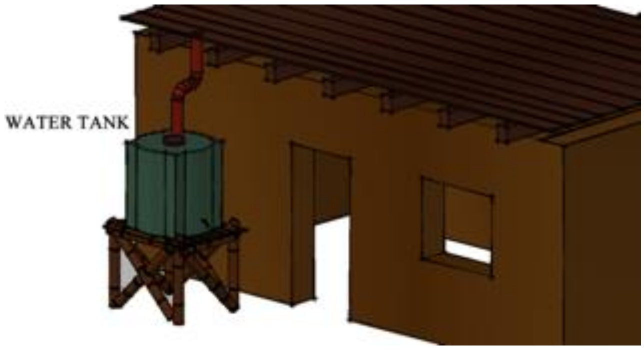
a)  **b)** 

Figure 15– (a) People queuing for drinking water, Ouagadougou (photo courtesy of Cluva dropbox); (b) A container for accumulating the rainfall water. This has also the advantage of draining water away from the roof.

3.3.4 Decreasing run-off and soil erosion

Trees can prevent soil erosion and decrease 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. 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 (see CUVA deliverable D2.9, Pauleit et al., 2013):

- 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.

4 IDENTIFICATION OF THE PREDOMINANT STRUCTURAL TYPES IN THE THREE CASE STUDY CITIES

This chapter provides a brief overview of the dominant structural types in the three case study cities considered. Urban morphology types (see CLUVA deliverable 2.7,(Cavan et al. 2012)) are employed herein in order to provide a spatial overview of the dominant residential buildings types in Dar es Salaam and Addis Ababa. The urban morphological types (Pauleit and Duhme 2000, Gill et al. 2008, Cavan et al. 2012) form the foundation of a classification scheme which brings together facets of urban form and function. Once an appropriate UMT classification scheme is established for a particular study area, individual UMT units can be delineated using aerial photography and other geospatial data sources. UMT units are often mapped at a 'meso'-scale (i.e. between the city level and that of the individual units). This makes them a suitable basis for the spatial analysis of cities.

4.1 DAR ES SALAAM

The urban morphology types for Dar Es Salaam are classified and delineated based on aerial photos acquired in December 2010. Below in Figure 16, the aggregate level UMT map for Dar is shown.

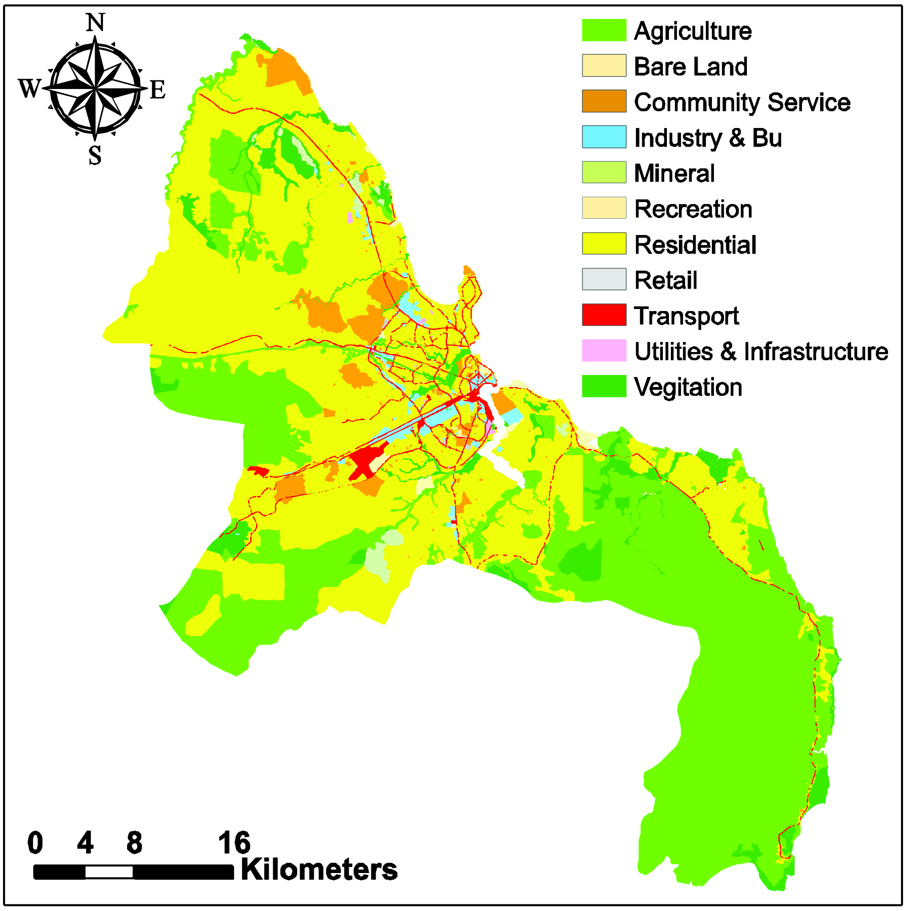


Figure 16 - Aggregate level UMT map for Dar Es Salaam.

The spatial units characterized as residential cover about the 47% of the entire city surface; in which about the 60% of the population is concentrated. This category is further divided in five sub-categories: a) condominium and multi-storey buildings (cover the 0.2% of the city surface and contain the 0.5 % of the population), b) villa and single storey stone/concrete buildings (cover the 7.8% of the city surface and contain the 17% of the population), c) mud and wood construction (cover the 0.4% of the city surface and contain the 2% of the population), d) scattered settlement (cover the 25% of the city surface and contain the 5.3% of the population) and e) mixed residential (cover the 13% of the city and contain the 36% of the population). Figure 17 illustrates the different typologies of urban residential areas.

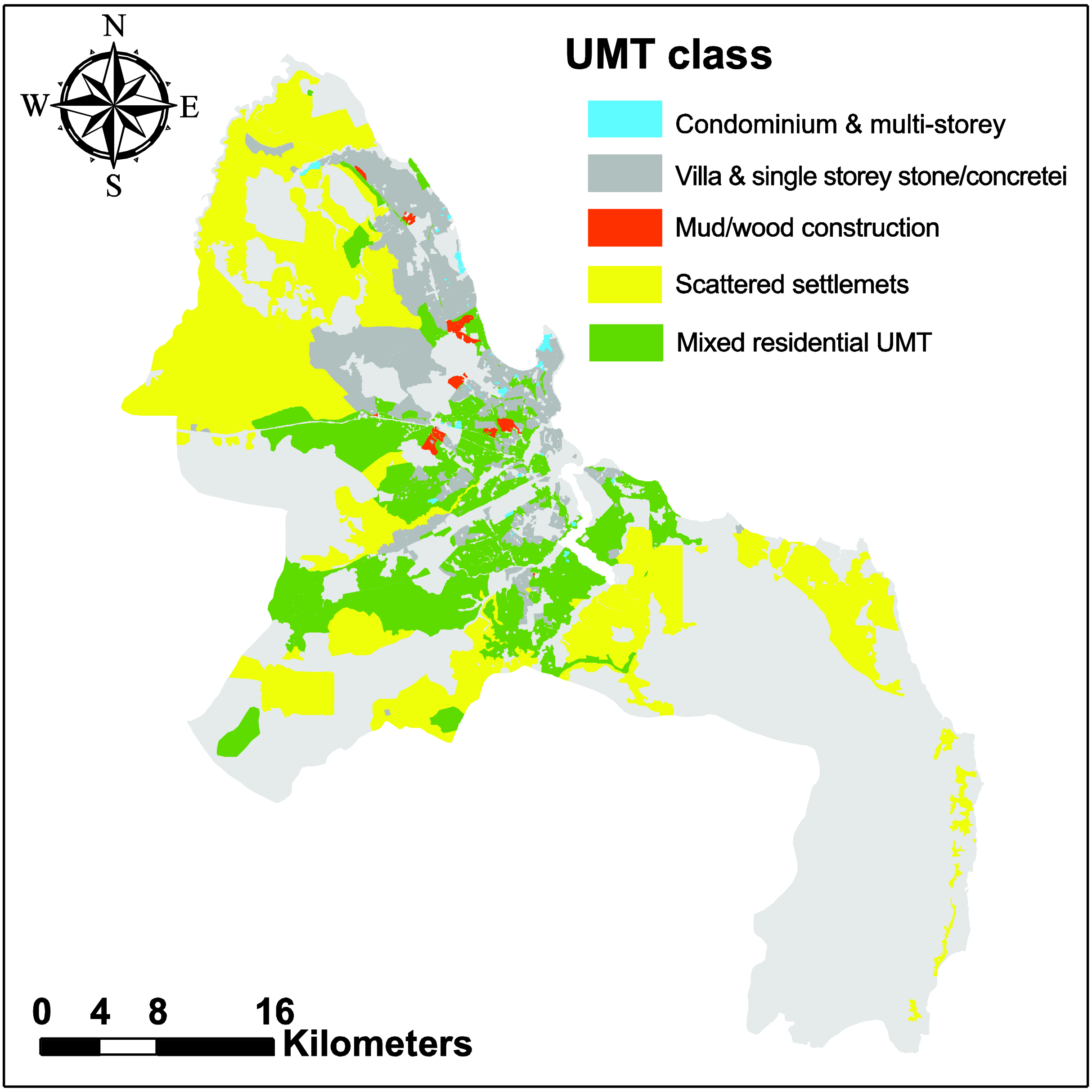


Figure 17 - Residential areas in Dar es Salaam

4.2 ADDISS ABABA

The urban morphology types for Addis Ababa are classified and delineated based on aerial photos of December 2010. Below in Figure 18, the high level UMT map for Addis Ababa is shown.

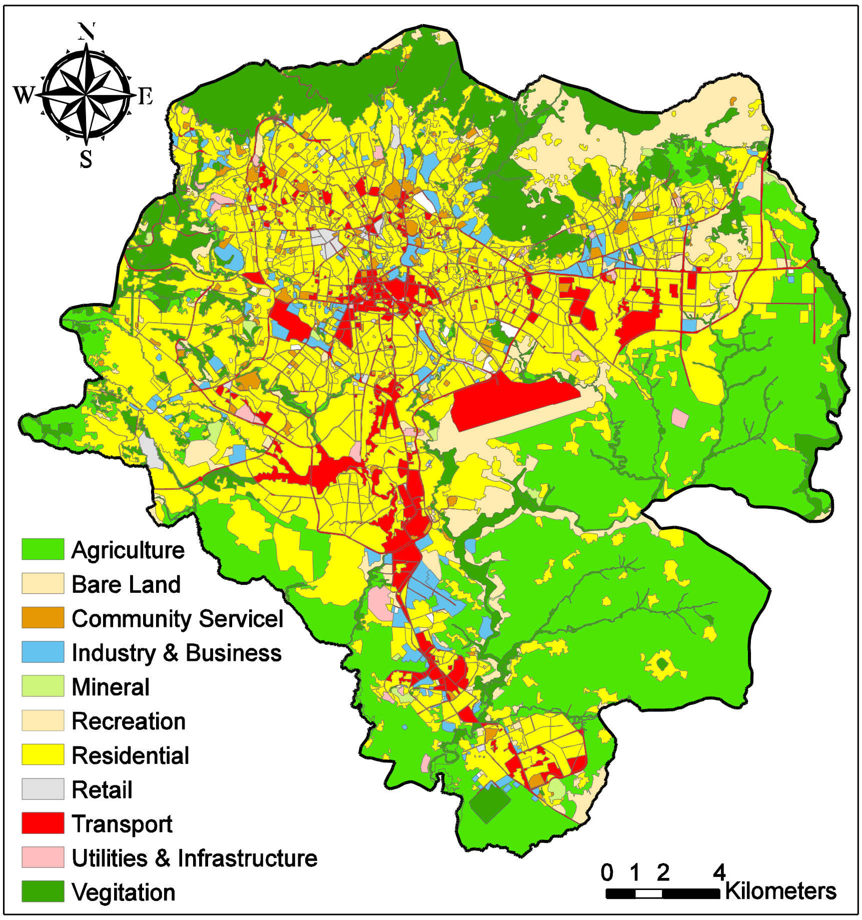


Figure 18- High level UMT map for Addis Ababa.

The spatial units characterized as residential cover about the 35% of the entire city surface; in which about the 46% of the population is concentrated. This category is further divided into three sub-categories: a) condominium and multi-storey buildings (cover the 5.3% of the city surface and contain the 4 % of the population), b) villa and single storey stone/concrete buildings (cover the 13.3% of the city surface and contain the 16% of the population), and c) mud and wood construction (cover the 16.1% of the city surface and contain the 26% of the population). Figure 19 illustrates the delineated urban residential areas in Addis Ababa.

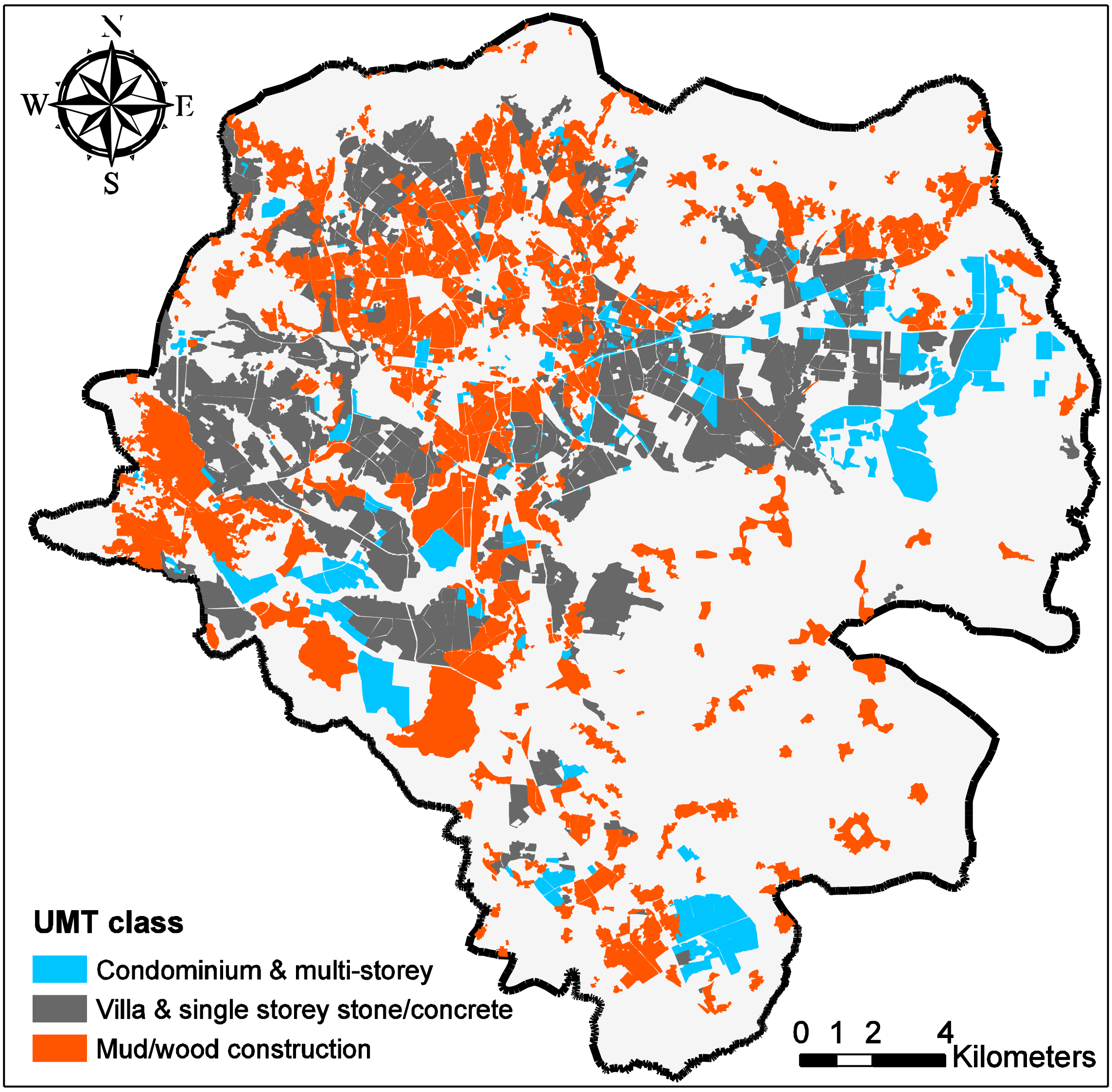


Figure 19- Residential areas in Addis Ababa

4.3 OUAGADOUGOU

Ouagadougou is the capital city of Burkina Faso. The 2007 survey 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%). 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 (United Nations Human Settlements Programme and Technical Cooperation 2007).

5 CITY-SPECIFIC MITIGATION STRATEGIES

In this chapter, various alternative local adaptation strategies identified are investigated in terms of their efficiency in reducing the vulnerability of the structure. It is important to touch on some basic concepts and definitions before discussing the results for each case-study city.

Structural vulnerability

The structural vulnerability in this work is seen from the point of view of the effects of the natural phenomena on the physical integrity of the structure. Therefore, the calculations provide an estimate of the probability that the structure is going to lose a specific functionality due to a decrease in its physical integrity.

Limit states

The limit states mark various significant thresholds from the point of view of structural performance. For the problem of flood vulnerability assessment for informal settlements three limit states are considered (De Risi et al. 2013a, De Risi et al. 2013b); namely, serviceability (SE), life safety (LS), and structural collapse (CO). The limit state thresholds are expressed in terms of the critical flooding height. *Serviceability* 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 example, for an insufficiently water-tight buildings built on a raised foundation, the critical serviceability water height is equal to the height of raised foundation above the ground level. For buildings constructed according to flood-resistant criteria, the critical water height for limit state of serviceability is taken asymptotically equal to the critical height needed for exceeding collapse limit state assuming brittle failure modes. *Collapse* limit state is defined as the critical flooding height in which the most vulnerable section of the most vulnerable wall in the building is going to break. Life safety limit state defines the critical flooding height in which lives of the inhabitants is going to be in danger. This can be caused either due to the infiltration of water inside the building (with the increasing risk of drowning in water), or the structural collapse (defined in the same manner as the critical height for collapse limit state). The critical water height for structural collapse is calculated by employing structural analysis taking into account the various sources of uncertainties in geometry, material properties and construction details (see for example (Jonkman et al. 2008)). In this report, the vulnerability of typical informal building types is studied mostly for the ultimate limit state of collapse.

Flood height as an intermediate variable between hazard and vulnerability:
In this report, the flood height has been used as the intermediate variable (i.e., a flood intensity measure) linking the hydrographic basin analysis and flooding vulnerability assessment of informal settlements. This means that the hazard curves are represented in terms of the annual rate of exceeding different flood height values. On the vulnerability side, the critical flood height is used as a proxy for the flood resistant capacity of the structure. That is, the critical flood height for a given limit state is the threshold flood height value beyond which the structure no longer satisfies that limit state. For example, the critical water height for collapse is the flood height beyond which the structure collapses.

Fragility curves

The fragility curves provide a visual and efficient way of representing the structural vulnerability. One of their characteristics is that they correspond to a specific structural limit state. Formally, the flooding fragility can be defined as the probability of exceeding a specific limit state given a specific value of flood height.

The hazard curve

The flooding hazard curve, as the name implies, represents the frequency and the intensity of the flooding event. Formally, it is defined as the mean annual rate that a certain flood height value is exceeded.

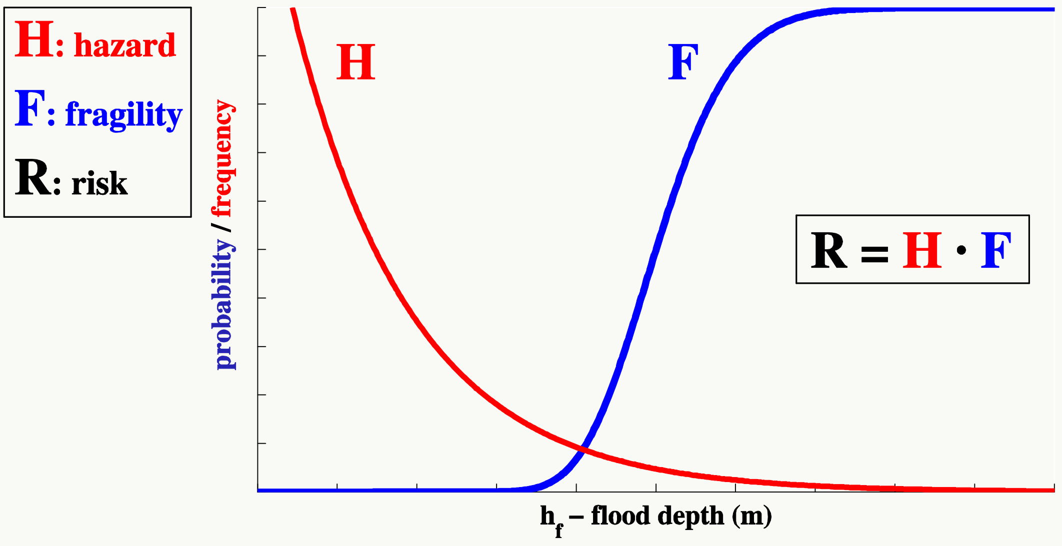
The return period

The return period can be regarded as an alternative way of describing hazard. Formally, the return period is equal to one over the hazard. Thus, it has a dimension of time. It can also be defined as the mean time that passes between the occurrence of two flooding events of a certain intensity. The inhabitants of informal settlements sometimes use this concept to indicate the frequency and the intensity of a flood event. For example, they might say: "this kind of flooding occurs on average every two years".

The risk

There are various definitions and various possible metrics for representing the risk. In this report, we define risk as the mean annual frequency of exceeding a certain limit state. Technically speaking, it can be calculated as the integral of fragility and hazard (see the related information box).

How to calculate risk? Risk (see the definition inside the text) can be calculated as the integral of fragility and hazard.



Capacity
As mentioned in the box on flood height, we express the structural capacity for a given limit state in terms of its the maximum flood height that the structure can endure before exceeding the limit state threshold.

The uncertainties
In the context of this report, the uncertainties in the structural mechanical material properties have been taken into account. This has been done in order to take into account both the lack of laboratory tests and also the lack of knowledge about how the construction material is going to behave when it is in direct and prolonged contact with water. However, it should be noted that even if laboratory tests had been available, the uncertainties would not have been completely "eliminated"; rather, they would have been reduced.

Factored capacity
The factored capacity in this report refers to the effective flooding height that leads to exceeding a limit state (e.g., collapse, life safety). This concept is used in order to take into account the uncertainties that can exist for evaluating the structural water height capacity. Herein, the factored capacity is calculated based on the information provided from the fragility curve as the median critical water height for the limit state of collapse multiplied by a de-amplification factor. please see (Cornell et al. 2002, Jalayer and Cornell 2003) for a complete derivation and discussion of the factored capacity concept.

The capacity in terms of return period
As mentioned above, the return period is a useful concept for communicating the frequency and intensity of flooding. In fact, it can also be used for conveying the structural capacity for a given limit state. The return period capacity for the limit state of collapse can be described as the return period value that corresponds to a flood height equal to factored capacity from the flood hazard curve. This provides a quick way of controlling the frequency and the intensity of the flooding event that the structure can withstand.

5.1 DAR ES SALAAM

In Dar Es Salaam, the typical residential buildings (formal or informal) are made of regular masonry with cement blocks. They may have a different percentage of hollow space and are not always placed with mortar layers. The walls are generally not protected with a waterproof layer. The thickness of wall is almost invariable and is generally equal to the thickness of the cement block (125mm) plus the plaster thickness (between 10-20 mm).

Figure 20– Typical buildings in informal settlements in Dar Es Salaam (photos by R. De Risi)

5.1.1 Field-survey for typical cement block building

A detailed survey conducted by the Institute of Human Settlements Studies (IHSS, Ardhi University) group on an informal building located in Magomeni Suna, Dar Es Salaam has been chosen as a representative case for cement brick informal buildings in Dar Es Salaam (De Risi et al. 2013a). Figure 21 below is shows the compiled survey sheet for this building.

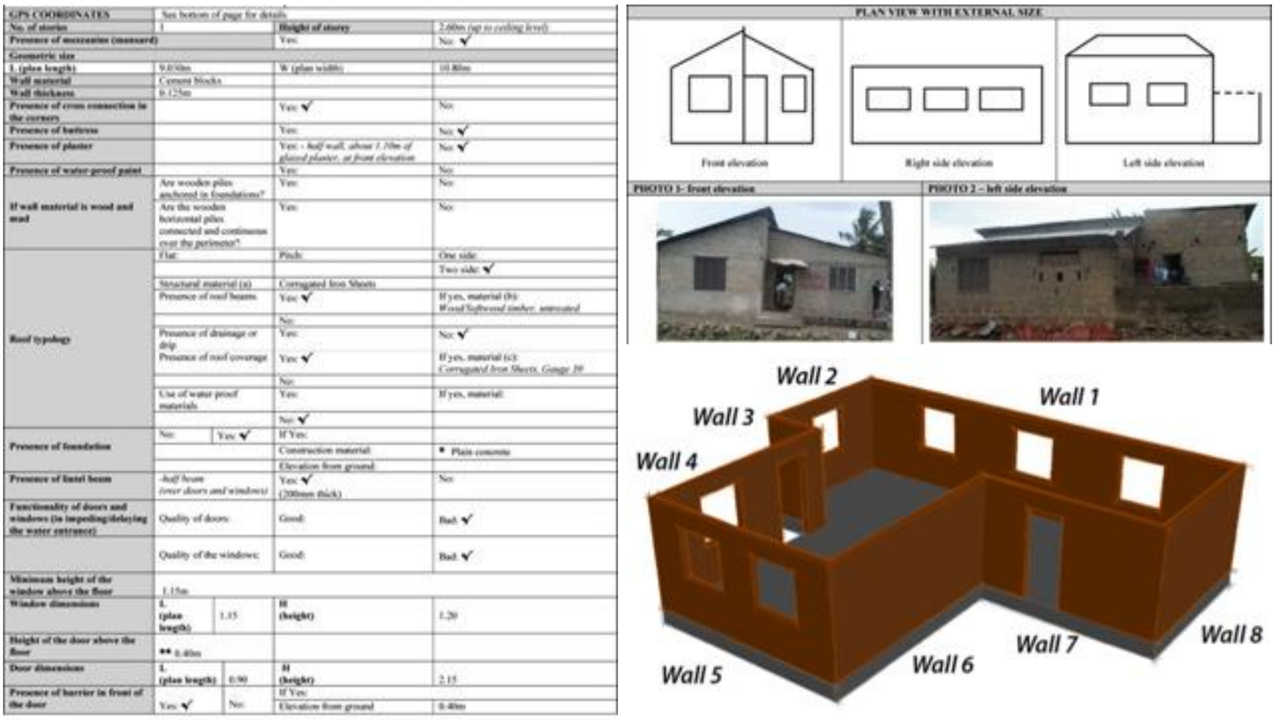


Figure 21– The compiled survey sheet an informal building located in Magomeni Suna, Dar es Salaam.

The mechanical material properties for this building are characterized by a considerable amount of uncertainty. This is due to both the variability of the material strength values in different parts of the same building (e.g., some parts of the structure may suffer degradation due to elongated and direct contact with water) and the lack of laboratory tests. To take into account these uncertainties, the mechanical properties of materials are characterized by probability distributions.

5.1.2 The structural model

Materials. In the following table, the material mechanical properties for the case-study building for Dar Es Salam city are synthesized.

Mechanical properties	Distribution type	Mean Min	Standard Deviation Max
γ (kN/m^3) – specific weight	Uniform	14.0	18.0
f_m (MPa) – compression strength	Uniform	1.0	3.0
τ_0 (MPa) –shear strength	Uniform	0.03	0.1
f_{fl} (MPa) –flexural strength	Uniform	0.2	1.5
E (MPa) –linear elastic modulus	Uniform	1200	1200

Table 1 – Mechanical properties for Dar Es Salaam case-study building

The presence or not of a waterproof paint on the walls may change the strength of the material. That is, in the absence of a water-proof layer, the material reveal reduced mechanical properties due to various factors, such as, direct contact with water, the presence of active agents and humidity. To take into account the degradation of material properties in case the walls are not water-proof (through plastering or water-proof paint), a reduction coefficient of 0.75 has been applied.

Geometry. The case-study building is composed of three completely full walls, three walls with windows, one wall with door and window and one wall with only door. The rigidity of the connection between the walls is not known so that wall models may be considered hinged or fixed -end (clamped) at the vertical side. The constraint at the bottom side of the wall may be modeled as a fixed-end (clamped). The entire building is realized on a raised platform of the height equal to 40 cm. Table 2 below outlines the geometrical properties of the most critical wall panel in the building (wall 7).

Geometrical property	
L (m) - wall length	4.30
H (m) - wall height	2.60
t (m) - wall thickness	0.125
L_w (m) - window length	1.15
H_w (m) - window height	1.20
H_{wfb} (m) - window rise	1.00
L_d (m) - door length	0.90
H_f (m) - foundation rise	0.40
H_b (m) - barrier height	-

Table 2 – Geometrical properties for Dar Es Salaam case-study building (wall 7) (De Risi et al. 2012)

Flood loading. The flood loading takes into account the effect of hydrostatic loading, hydrodynamic loading and the accidental debris impact (please see the appendix for more details on structural analysis procedure). According to the survey sheet illustrated in Figure 21, the doors and windows are not sufficiently water-proof. The effect of insufficient closure system is considered in the analysis in an overall manner. For example, since the doors are not sealed, the hydrostatic loads are not considered for water height values above the height of the raised platform.

As-built condition. Apart from the uncertainties in material mechanical properties, there is also a lack of information about the basic structural modeling assumptions. In particular, the modeling hypothesis can regard the boundary condition (hinged or fixed-end section), sealed or not-sealed openings, and the presence or absence of a water-proof layer and protecting plaster. We have defined the default structural model (denoted as D) as a model with the following characteristics: platform height 40cm, closure system (doors and windows) not sealed, and hinged vertical side. Figure 22 below illustrates the fragility curves calculated for the case-study building for the default condition.

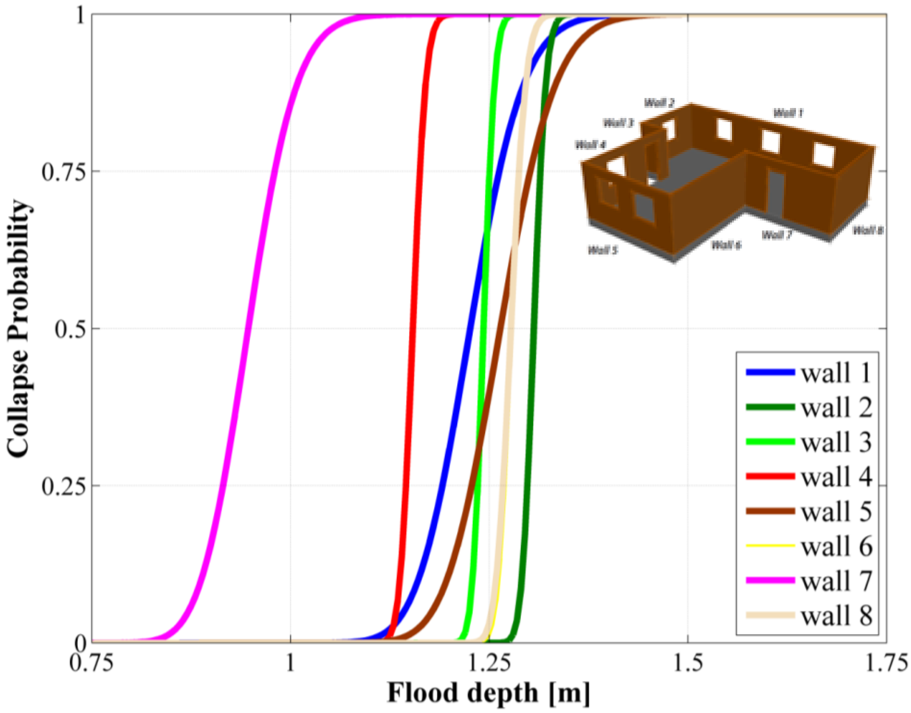


Figure 22–Fragility curves all the walls within the default structure (D)

The details regarding the calculation of the fragility curves are reported in the Appendix (see also (De Risi et al. 2013a, De Risi et al. 2013b) for more details). It can be observed that wall number 7 is the most critical wall in the structure (see the box for how to read a fragility curve for more information). As mentioned before, in this report we have considered a weakest link model, in which the structural collapse is defined as when the weakest wall collapses. Therefore, in the next elaborations we have considered only the results for wall 7. Figure 23 below depicts the fragility for the wall 7.

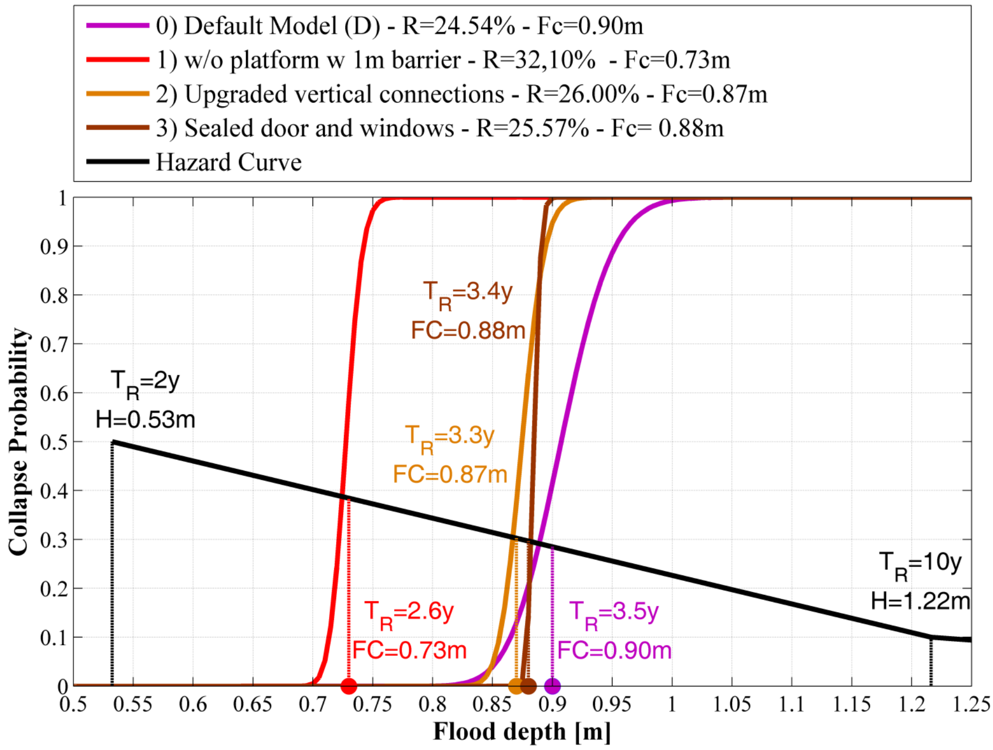


Figure 23–Fragility curves for wall 7 corresponding to alternative as-is conditions for a brick building

Presence of a barrier: It can be observed that the presence of a 1meter barrier in front of the doors (option 1instead of the 40cm raised platform, option 0) results less advantagous for the structure. This result is somehow to be expected since the presence of the barrier neither strengthens the building nor reduces the flood action (loading).

Fixed-end vertical connections: It can be observed that having upgraded vertical connections (i.e., fixed-end connections, option 2) does not change much the overall resistance. This conclusion however might be very much dependent on the building configuration and geometry (e.g., the thickness of the wall, position and number fo the opennings and the aspect ratio of the walls).

Sealed doors and windows: It can be observed that the presence of sealed openings (option 3) leads to a slight decrease in structural resistance (critical flood height capacity). This can be explained by the fact that the presence of sufficiently water-proof opennings prevents the infiltration of water inside the building. Consequently, the hydrostatic forces have been fully considered in the analyses. It should be emphasized that this reasoning holds for the limit state of structural collapse. Clearly, for the limit state of life-safety, having sealed openings is of utmost importance. In fact, one of the strategies for having a flood-proof building is to let the water get inside the house. However, such an option can be only considered when the house has reliabale shelter areas in the upper levels. For example, the construction of a mezzanine level can be a viable solution. In this case, it is important to ensure that the mezzanine level has independent access to outside and that the predicted maximum flood height does not exceed the critical flood height level the structure can withstand before collapse.

How to read the reported fragility results:
The fragility curve for the as-is condition in Figure 23 (wall 7) can be read as: *the building is going to collapse with 50% probability due to a flood height of around 0.92 m and it is going to collapse with 100% probability due to a flood height of around 1m.*
The annual risk of collapse (fragility integrated with hazard) is shown as a percentage next to the legend. The risk can be interpreted as following: *There is around 24.5% probability that the building is going to collapse in a one year time frame.*
The *factored capacity* value (equal to 0.90) is the effective flood height value for which the structure is going to collapse. An alternative way to describe this result is to say that the structure is going to collapse for flooding events with return periods larger than 3.5 years.

What is the difference between a fixed-end (clamped) connection and a hinged one?
In a fixed-end connection, the walls cannot have relative rotations at the connection. On the contrary, for a hinged connection, relative rotations at the connection are possible. In order to ensure the presence of a fixed-end connection, special detailing techniques are employed. For example, the use of reinforcements, or a special placing of bricks. In the cities of Addis Ababa and Dar Es Salaam, we did not come across specific techniques that would ensure a fixed-end connection at the wall joints. However, we have examined the effect of hypothetic fixed-end wall connections.

5.1.3 Climate adaptation/risk mitigation strategies

In this section, we investigate possible risk mitigation and climate adaptation strategies for the case-study building in Dar Es Salaam. These risk mitigation strategies stem from the climate adaptation strategies exercised by the local community. In the following, these mitigation strategies are examined in terms of their effects on structural vulnerability. We have distinguished these alternative methods also in terms of their effectiveness in reducing the vulnerability for specific limit states. Recall that the limit states are distinguished based on the following notation: *(CO) collapse* limit state; *(LS) life safety* limit state; *(SE) serviceability* limit state. Figure 24 below reports the structural fragility curves for the collapse limit state for various possible mitigation strategies.

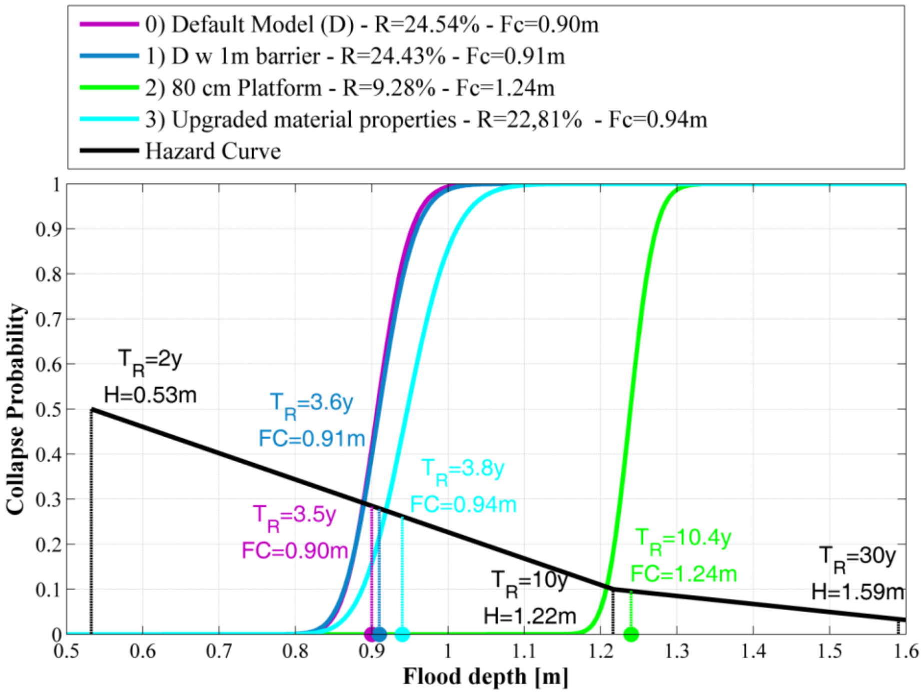


Figure 24 – Fragility curves for the upgraded structure with different mitigation strategies

A protection barrier (in front of the door): The fragility curve for the default model (D) plus a barrier of one meter in height in front of the door is plotted as option 1 in Figure 24. It can be observed that this strategy does not influence significantly the structural resistance to collapse limit state. As mentioned before, the barrier is mostly effective in preventing the water to get inside the building. (SE).

Presence of plaster. The presence of a plaster layer helps in protecting the building construction material from direct contact with water, wind and active agents. As a result, it helps in preventing the material deterioration due to elongate water contact. However, it should be noted that in cases where the construction material is too weak to withstand the flooding actions (the case of informal settlements), the presence of plaster does not make the structure flood-resistant. In fact, the fragility curve for the case when the material properties do not suffer from degradation is plotted in Figure 24 as option 3. It can be observed that the overall effect on structural resistance is positive but insufficient (CO-LS).

Raised platform. This strategy consists in increasing the level of the floor inside the building to reduce the flood water pressure on the walls. It should be emphasized that the raised platform should have sufficient rigidity for resisting the flood uplift pressure and scoring effects (see the section on general mitigation strategies for various techniques for construction of a raised foundation). The fragility curve corresponding to the presence of a 80 cm raised platform is plotted in Figure 24 as option 2. It can be seen that this strategy leads to a significant reduction in risk (from 24% to 9% approximately) and an increase of around 0.35 meters in the critical flood height capacity corresponding the collapse limit state (CO - LS - SE).

It can be concluded that among the climate adaptation strategies commonly used, the raised platform is the most effective one for limit states of serviceability, collapse and life safety. However, this does not mean that the presence of the raised platform is going to render the structure acceptable in terms of flood resistance. It is only going to lead to a reduction in flooding risk and vulnerability.

ADDIS ABABA

The typical informal residential buildings in Addis Ababa are made of mud and wood material. The walls are generally composed of a series of poles placed side by side. The poles have different diameter sizes. The presence of a transversal support for the poles does not seem to be guaranteed. This is because (when present) this transverse support consists of one or two poles horizontally disposed in an irregular manner (moreover, the presence of a sufficient connection to the vertical elements is not guaranteed). In some cases, the wooden posts are covered by a mud layer mixed with straw that confers a good thermal insulation to the building. In this last case, if the walls are not protected with a water-resistant layer/plaster coat, the mud risks being washed out by flooding.

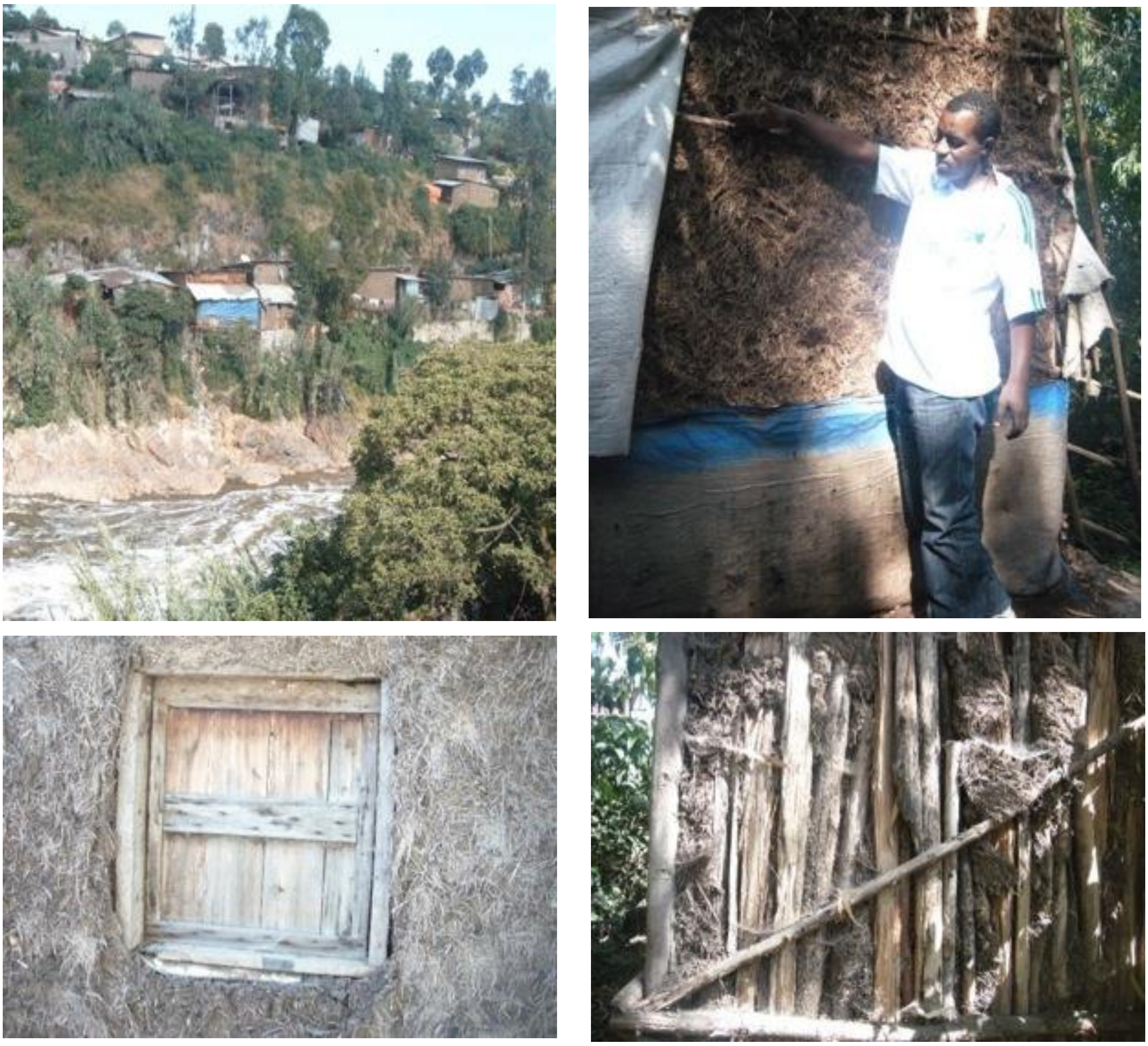


Figure 25 – Typical mud and wood buildings in Addis Ababa; (top left) mud and wood buildings constructed in elevation next to the river; (top right) a partially protected mud and wood building located in the flood-prone area; (bottom right) an un-protected mud and wood building with non-

sealed window; (bottom left) an un-protected mud and wood wall where most of the med layer has been washed out. The presence of horizontal transverse wood poles can be noted.

5.1.4 Field-survey for typical mud and wood building

A mud and wood building located in the flood-prone area is chosen as the case-study building for Addis Ababa. A detailed field survey has been conducted by the EiABC team for this building. This building has also been chosen because of its large aspect ratio (see plan in Figure 26). Note that a large aspect ratio (without the presence of internal partition walls) is generally considered an undesirable condition for the structure (see the chapter on general mitigation strategies).

Figure 26 – Field survey sheet for the case-study building (provided by N. Yonas)

The material mechanical properties of the case-study mud and wood building are subjected to significant amount of uncertainty due to both the variation of material properties in different parts of the same building (also because of frequent replacing of material after flooding events) and the complete lack of laboratory tests for this material.

5.1.5 The structural model

Material properties. In the table below, the mechanical properties of the materials attributed to the case-study building in Addis Ababa are synthesized.

Mechanical properties	Distribution type	Mean Min	Standard Deviation Max
γ (kN/m³) – wood specific weight	Uniform	6.0	8.0
γ (kN/m³) – mud specific weight	Uniform	14.0	18.0
f_m (MPa) – wood compression strength	Uniform	10.0	20.0
τ_0 (MPa) – wood shear strength	Uniform	5.0	10.0
f_{fl} (MPa) – wood flexural strength	Uniform	2.0	3.0
E (MPa) – wood linear elastic modulus	Uniform	12000	15000

Table 3 – Mechanical properties for Addis Ababa building (De Risi et al. 2012)

In order to take into account possible erosion of the mud material, only the weight of the wood is considered in the calculations (note that the structural weight in such cases plays a stabilizing role). However, the weight of the mud above the reach of water is considered as an over-weight in the calculations.

Geometry. The considered building is composed of three walls without openings and one wall with one door and a window. The connection between the walls does not seem to be very rigid so the wall models are considered always hinged at the vertical side. The constraint at the bottom of the wall may be modeled as hinged or fixed end depending on the anchorage length of the wooden poles inside the foundation. In fact, in the next chapter, suggestions for sufficient anchoring of wooden poles are presented. For the analysis purposes, the wall with openings is labeled *W1*, the long full wall is labeled *W2* and the two short walls are labeled *W3*. Table 4 outlines the geometrical properties for walls *W1* and *W2*.

Geometrical property	
L (m) - wall length	9.63
H (m) - wall height	2.50
t (m) - wall thickness	0.10
L_w (m) - window length	0.78
H_w (m) - window height	1.00
H_{wfb} (m) - window rise	0.50
L_d (m) - door length	0.82
H_f (m) - foundation rise	-
H_b (m) - barrier height	-

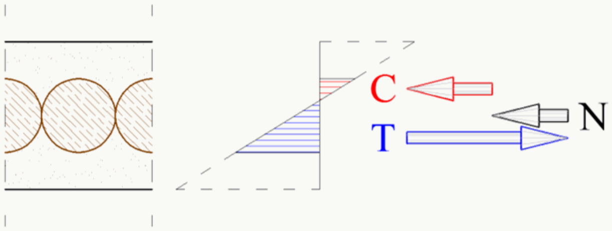
Table 4 – Geometrical properties for Addis Ababa building (W1 and W2, data based on a field survey conducted by N. Yonus and the EiABC group)

Flood loading. The door and window are not sealed and on the wall surface the presence of holes and void spaces between the wood poles can be observed. Therefore, water may easily infiltrate into the building so that only hydrodynamic loads and accidental debris impact might be exerted in the case of flooding. However, in the structural analysis also the presence of hydrostatic forces is taken into account.

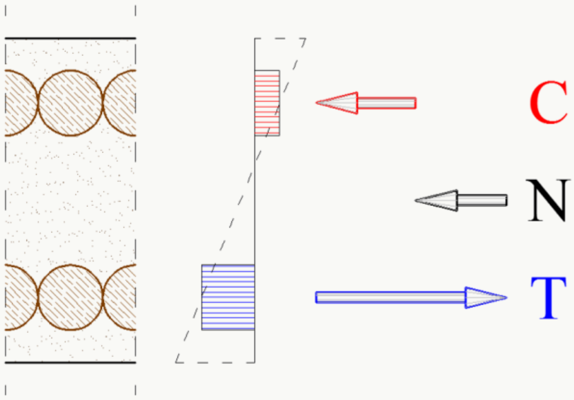
As-built condition. In its as built condition, the structure is assumed to have fixed-end connection at the base (i.e., sufficiently anchored wooden poles). An approximate manual procedure (described in the box below) is employed for structural analysis. It is assumed that the case-study building consists of a row of wooden poles of 40mm diameter and the adobe/wood composite material has an overall thickness of 100mm. It should be noted that the software VISK (see the appendix) in general cannot be used for analysis of this type of buildings, since this software is only suitable for masonry types of material.

Structural analysis for the mud and wood frame through a manual procedure

A manual check of the capacity for the wall is performed in order to evaluate the flexural and shear strength of a single row of poles. In both cases, the adobe/mud matrix is neglected and all the resistance is entrusted to wooden poles. In the figure below, the model used to evaluate the flexural capacity of the wall is depicted.



To evaluate the capacity of a wall made of two rows of wooden poles, the flexural and shear capacity is calculated together with a control on the instability of the "compressed" poles. The wall capacity is evaluated as the capacity of a single couple of poles that are in front one to the other. The contribution of adobe material and the transversal connection between the pole system is only necessary to transfer the tension between the poles in order to ensure that one pole works in compression and the other works in tension. It has been assumed that the stress is uniformly distributed in the transversal section of the pole.



For each flood height value considered, the second order effects caused by displacement of the point of application of the vertical load (due to lateral deformation of the wall) is taken into account. This calculation is done taking into account the equivalent inertia of the full transversal section of the wall. The poles are also verified with respect to the instability. This can be taken into account in two ways: considering a reduced compression strength of the wood (with a safety coefficient that avoids reaching the tension of instability) or verifying that the action on the compressed pole is smaller than the critical compression strength evaluated with Euler's formula. Herein, the first approach is used.

5.1.6 Climate adaptation/risk mitigation strategies

Possible risk mitigation strategies and climate adaptation measures for the case-study building in Addis Ababa are examined in terms of both the potential for implementation? and their effectiveness in reducing the structural vulnerability. Figure 27 below depicts the as-is condition and the different mitigation strategies in terms of the corresponding fragility curves, capacity in terms of the critical flood height, the flooding return period that leads to collapse of the structure and risk expressed in terms of the mean annual rate of exceeding the limit state.

The as-is condition.
As mentioned before, it is assumed that the case-study building in its as-is condition has water-proof openings, plaster-coated walls, and a fixed-end connection at the foundation level. The green curve in the figure depicts the as-is condition, with a critical flood height of 0.78m, risk equal to around 25% and an critical flood return period of 3.5 years.

More anchorage length for the poles. Ensuring a sufficient anchorage length for the wooden poles is going to lead an effectively fixed-end connection at the base. If the anchorage length is larger than 1/3 of the off-ground height of the wall, one can assume a fixed-end connection in the base. Otherwise, the connection needs to be considered hinged. Having a fixed-end base section often leads to a reduction in the stress concentration in the proximity of the openings. (CO).

Protecting the wall with plaster coating.
Adding a plaster coating/water-proof layer is going to help in protecting the mud matrix from dissolving into water. (CO) (LS - SE) only if is accompanied with a good closure system.

Adding a second layer of wooden poles.
This is going to be an effective strategy (see the related box for the configuration of the second wood layer) since it leads to an overall increase both in the flexural capacity of the wall but also its stability (CO). The blue curve in the figure corresponds to the case where a second layer of wooden poles is added, increasing the overall thickness of the wall to 200mm. It can be observed that the critical flood height increased to 1.23m (around 0.5m increase), the risk was reduced to around 19% and the critical flood return period increased to 10 years.

Raised platform. This strategy consists in increasing the level of the floor inside the building to reduce the flood water pressure on the walls. It should be emphasized that the raised platform should have sufficient rigidity for resisting the flood uplift pressure and scoring effects (see the section on general mitigation strategies for various techniques for construction of a raised foundation). The purple curve in the figure corresponds to the case where a second layer of wooden poles is added, increasing the overall thickness of the wall to 200mm and the foundation height is raised to 0.4 meters. It can be observed that the critical flood height in increased to 1.60m (around almost 1m increase with respect to as-is condition), the risk reduces to around 7% and an critical flood return period increases to 20 years.

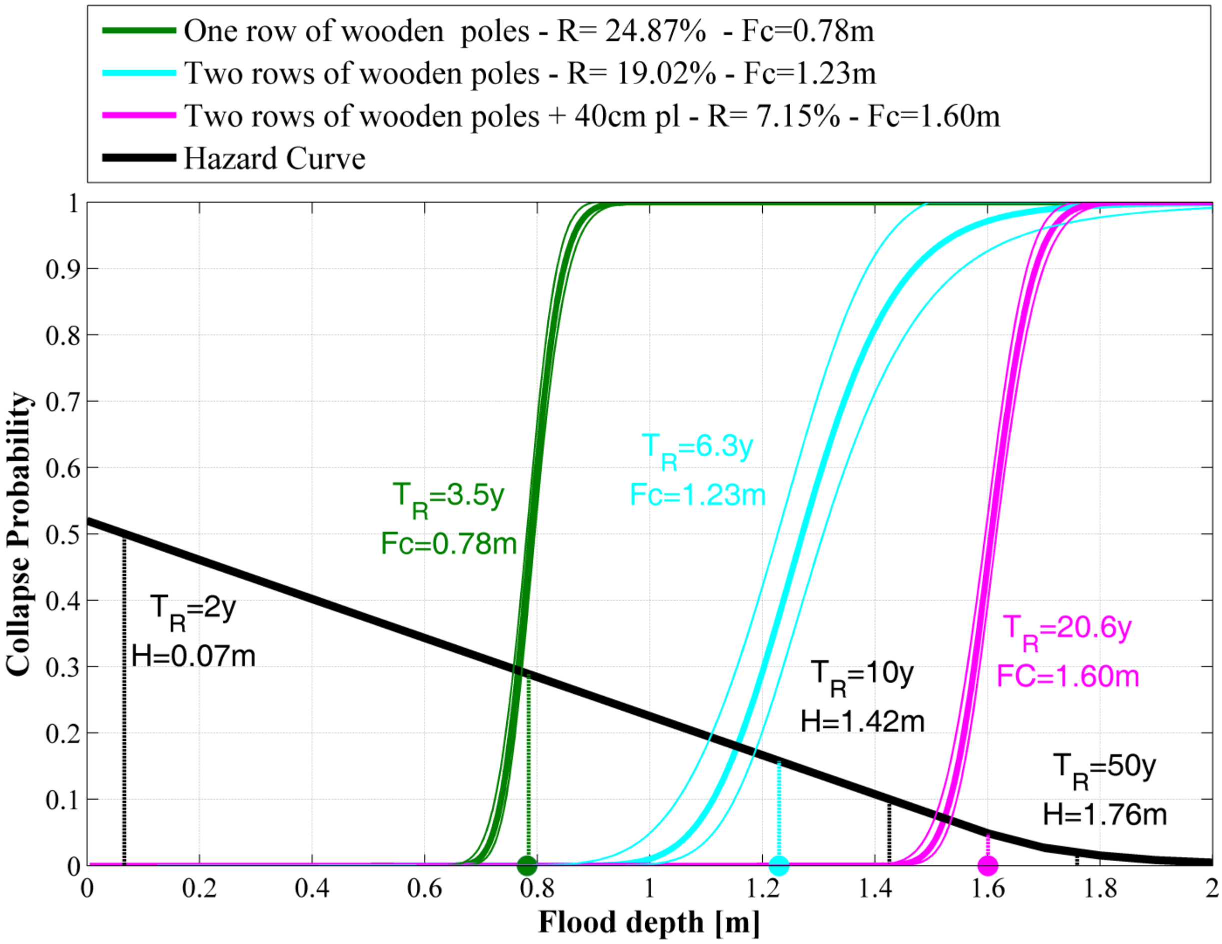


Figure 27– Fragility curves for the upgraded structure with different mitigation strategies

5.2 OUAGADOUGOU

In Ouagadougou, the typical informal buildings are made of adobe material. The walls are generally not protected with a waterproof layer. The primary roof system is made of wood beams of variable dimension.

Figure 28– Typical buildings in Ouagadougou; (top left) a regular adobe building with small openings; (top right) a wooden roof system with irregular spacing of the beams; (bottom left) a circular rural adobe building with bamboo reinforcement and a roof system made up of hay; (bottom right) an insufficiently water-proof roof system. The walls reveal visual signs of degradation (source: Google Images)

5.2.1 Typical adobe building in Ouagadougou

Since building-specific survey results were not available for Ouagadougou, we considered the general class of adobe buildings (attributing both building-to-building variability in geometry, configuration and the uncertainty in material mechanical properties). Again, the VISK platform (see the appendix) is used in order to perform the vulnerability assessment for the limit state of collapse.

5.2.2 The structural model

Materials. In the following table, the mechanical properties of the adobe material are synthesized. The statistics reported in the table are based on a literature survey described in CLUVA deliverable 2.4 by (De Risi et al. 2012).

Mechanical properties	**Distribution type**	**Mean Min**	**Standard Deviation Max**
γ (kN/m^3) – specific weight	deterministic	18.0	18.0
f_m (MPa) – compression strength	Lognormal	0.89	0.65
τ_0 (MPa) –shear strength	Lognormal	0.03	0.79
f_{fl} (MPa) –flexural strength	Uniform	0.2	1.5
E (MPa) –linear elastic modulus	Lognormal	151	0.36

Table 5 – Mechanical properties for Ouagadougou building

As mentioned before, the lack of an effective waterproof layer/plaster coat, may lead to an overall degradation in material mechanical properties. Herein, it is assumed that the lack of the plaster coat is going to lead to an overall decrease of 50% in material properties.

Geometry. It is assumed that 15% of buildings have a raised platform, that 5% of the buildings have a raised platform and a barrier and 5% have only barrier. Door and windows are always considered not sufficiently water-proof. It is considered that the 25% of the walls have only one door; 12% have door and windows and the 62% do not have not openings. The height of walls are supposed variable between 2.5-3.5m and the length is supposed to be variable between 3.0-8.0m. It should be noted that the above-mentioned percentages are loosely based on surveys conducted for other cities (see e.g., De Risi et al. 2013) and may not reflect the real situation in Ouagadougou and they need to be verified by conducting building-specific field surveys. Table 6 below outlines the geometrical properties assigned to the buildings within the portfolio.

Geometrical property	Distribution type	Mean Min	Standard Deviation Max
L (m) - wall length	Uniform	4.00	10.00
H (m) - wall height	Uniform	2.50	3.50
t (m) - wall thickness	Uniform	0.30	0.40
L_w (m) - window length	Uniform	0.80	1.20
H_w (m) - window height	Uniform	0.80	1.00
H_{wfb} (m) - window rise	Uniform	0.80	1.20
L_d (m) - door length	Uniform	0.80	1.20
C_d (m) - corner length	Uniform	0.80	0.90
H_f (m) - foundation rise	Lognormal	0.30	30%
H_b (m) - barrier height	Uniform	0.10	1.00

Table 6 – The geometrical properties for the class of adobe buildings

Flood loading. Hydrostatic pressure, hydrodynamic pressure and the accidental debris impact can be considered (see the appendix and (De Risi et al. 2013b) for more information on the loading). It should be noted that since the hydraulic profiles for Ouagadougou were not available, the maximum flood velocity/maximum flood height relation might not be realistic.

5.2.3 Climate adaptation/vulnerability mitigation strategies

Due to the lack of flood hazard curves for Ouagadougou, the possible climate adaptation strategies are evaluated only in terms of the structural fragility and the critical flood height that the structure can resist. Figure 29 reports the structural fragility curves calculated for the as-built condition and after implementing alternative viable mitigation/adaptation strategies. In this section, we have done the fragility calculations by only considering sealed openings and hydrostatic pressure. Figure 29 below reports the fragility curves calculated under such assumptions.

As-built condition. The fragility curve for the class of adobe buildings is reported in Figure 29 as option (0). It can be observed that the median critical flood height resistance for the collapse limit state is equal to 1.10m.

Adding a plaster coat. Adding an effective plaster coat/water-proof layer is going to protect the adobe material from degrading, due to elongated contact with water (CO-SE-LS). The curve labeled as option (1) corresponds to the case where a water-proof layer has been added. A significant increase in critical flood height for the collapse limit state can be observed with respect to the as-built condition (the critical flood height is around 1.80m).

Raised platform. This strategy consists in increasing the level of the floor inside the building to reduce the flood water pressure on the walls. It should be emphasized that the raised platform should have sufficient rigidity for resisting the flood uplift pressure and scoring effects (see the section on general mitigation strategies for various techniques for construction of a raised foundation) (CO-SE-LS). The fragility curve depicted as option (2) corresponds to the case where a raised platform of height 40cm is being added (to 100% of the buildings within the class). It can be observed that the presence of the raised platform lead to a significant increase (around 0.90m) in the critical flood height capacity for the collapse limit state, with respect to the as-built condition.

Upgrading the vertical connection.
As another mitigation strategy, the detailing of the wall connections can be improved so that these connections can be considered as fixed-end (instead of hinged). The fragility curve corresponding to the implementation of this strategy (to the as-built condition) is plotted in Figure 29 as option (3). It can be observed that this strategy may lead to slight increase in the median critical flood height capacity of the structure for the limit state of collapse (around 1.3m).

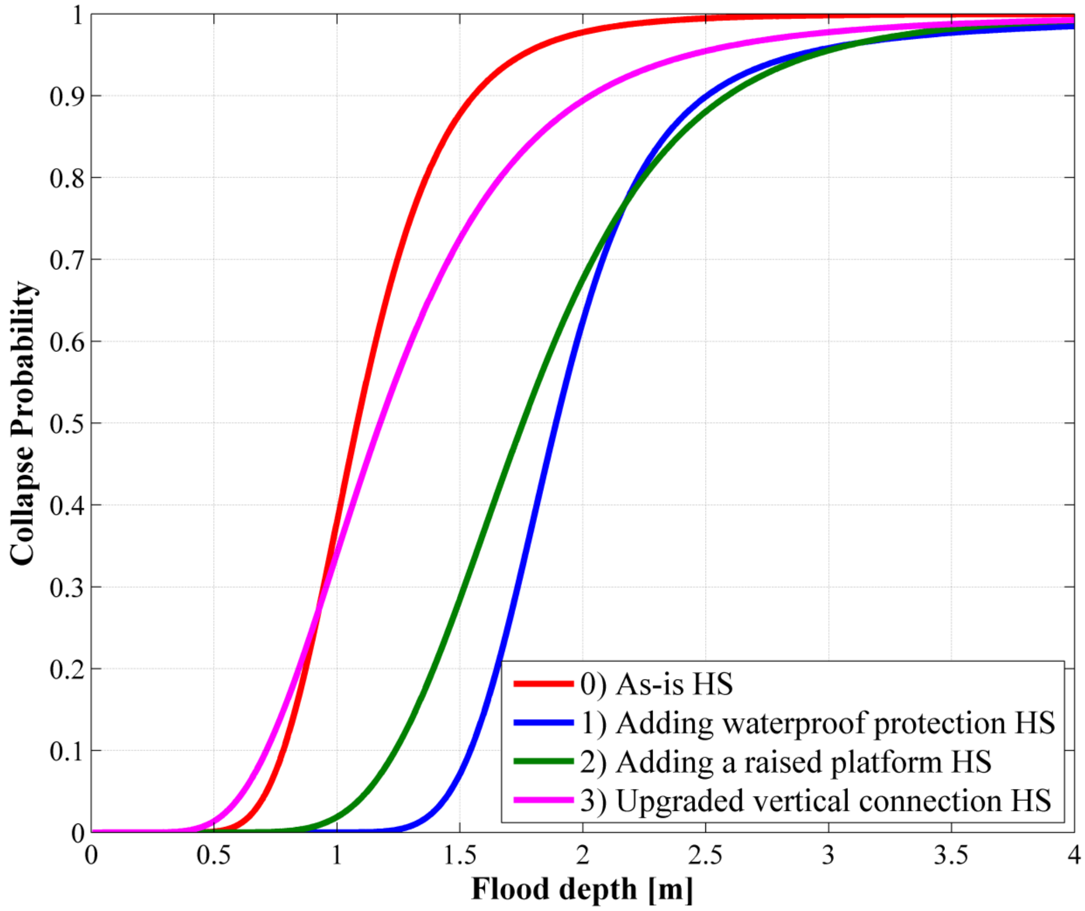


Figure 29 – Fragility curves for adobe buildings with sealed openings and subjected to hydro-static pressure

6 SUGGESTIONS FOR A WATER-RESISTANT MUD AND WOOD BUILDING

In this section, we provide some recommendations for improving the performance of the mud and wood buildings. This composite building material is worth considering from different points of view, it is made up of natural material available in-situ, it can use the excellent structural properties of wood, and last but not least it can exploit the thermal properties of adobe material. However, in order to make sure that this natural composite can behave in a desirable manner, certain principles must be respected during its construction. It should be emphasized that this chapter provides indicative suggestions and improvements. However, formal criteria for a flood-resistant mud and wood housing can only be established after extensive laboratory tests.

Sufficient anchorage length.

In order to model the base connection as a fixed-end, it is important to ensure that the wooden poles are sufficiently anchored in the soil/foundation. To guarantee a sufficient anchorage length, the wooden poles need to be embedded in the soil for a distance at least equal to 1/3-1/4 of the length of the pole off-ground. For example, for wooden poles with an off-ground height of 2.80, the anchorage length must at least equal to 0.75 m. With houses with a raised platform, the embedding length in the soil might be reduced by the height off foundation. Figure 31 illustrates the anchorage details for the two cases (when a raised platform is present or not).

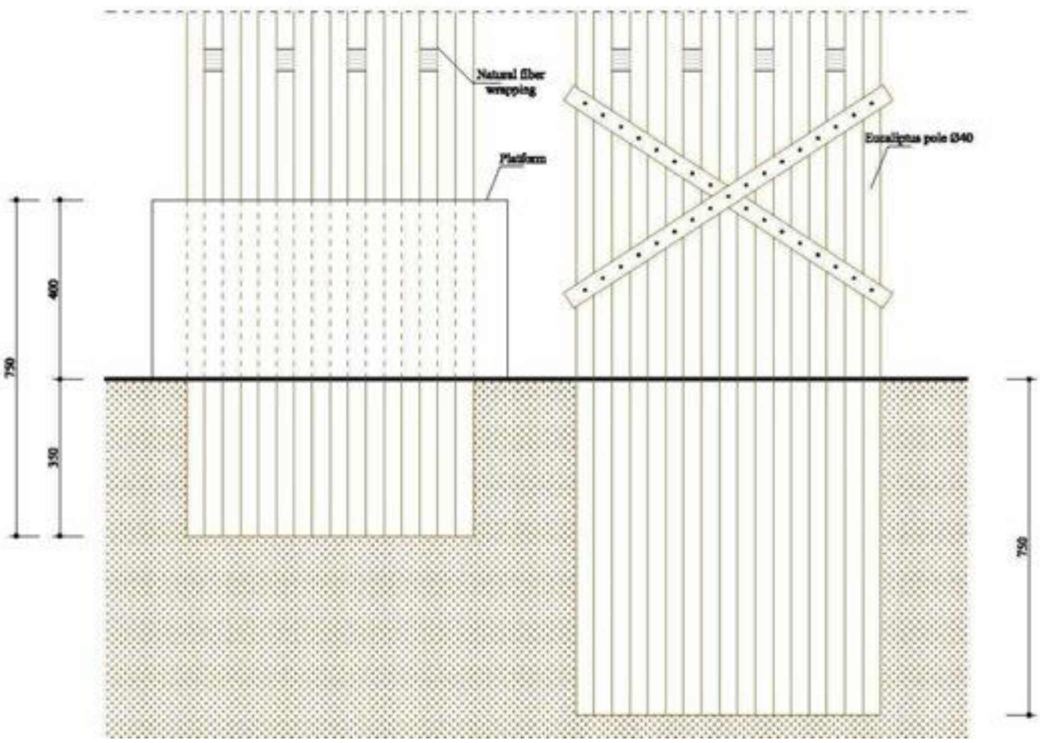


Figure 31– Suggested anchorage length and lateral bracing details for wooden poles

In order to ensure the lateral stability of the wooden poles and the overall connectivity of the building, regular lateral bracing in the form of diagonal and horizontal wooden poles should be provided (see the detail in Figure 31).

Water-proofing the embedded part of the poles.
It is important to make sure that the embedded part of the wooden poles does not suffer from deterioration due to direct contact with water and active agents. Painting the pole with a water-proof paint or wrapping them in water-proof sheets can slow-down the deterioration process. The water-proofing process should be extended at least to the height corresponding to previous flooding events. It should be noted that the wooden poles are also subject to insect and termite attacks. The water-proof paints do not usually protect the wooden poles against such attacks. See (Ahmed 2005) for more details on protecting the lower-end of the wooden poles.

Stabilizing the adobe matrix.
Stabilizing the adobe matrix with cement adds to the durability and the stability of the adobe matrix (see Chapter 3 for some general specifications).

Adding a second row of wooden poles.
Adding a second row of wooden poles can significantly improve the performance of the mud and wood building. This technique consists in arranging two layers of wooden poles connected by a natural fiber wrapping system, embedded in a (preferably cement stabilized) adobe matrix. Arguably, this configuration increases the lateral (out-of-plane) load-resisting capacity, and is going to render the wall less vulnerable to instability and second-order effects (see also the box in the previous chapter).

Ensuring box effect
It is desirable to ensure that the building possesses enough integrity and continuity in order to resist the forces as an ensemble. This is also known as the *box effect*. In order to ensure the box effect, the connectivity of the structure at the connection between the walls should be guaranteed. Therefore, the wall angles need some special detailing. The construction detail illustrated in Figure 32 below shows how a special arrangement of the wooden poles and regular cross connections between the two rows can lead to an increase in the overall connectivity of the structure.

In order to ensure the box effect in the building, it is also necessary to realize a ring beam above the walls. The ring beam can consist of a horizontal beam consisted of several wooden poles Figure 32 shows the cross section of the wooden ring beam.

Roof detailing
It is important that the roof system is not heavy. Therefore, the use of a wooden truss roof system is often recommended. Such a truss system can also lead to the creation of a mezzanine level that is quite useful as a shelter for goods and inhabitants. Alternatively, the roof can be composed of a bi-directional (primary and secondary) beam system with a water-proof layer and a corrugated iron sheet (see Figure 33 below for the details). The main beams must be embedded in the ring beam using special detailing (emending the beam in particular wood saddle) or with a natural fiber connection.

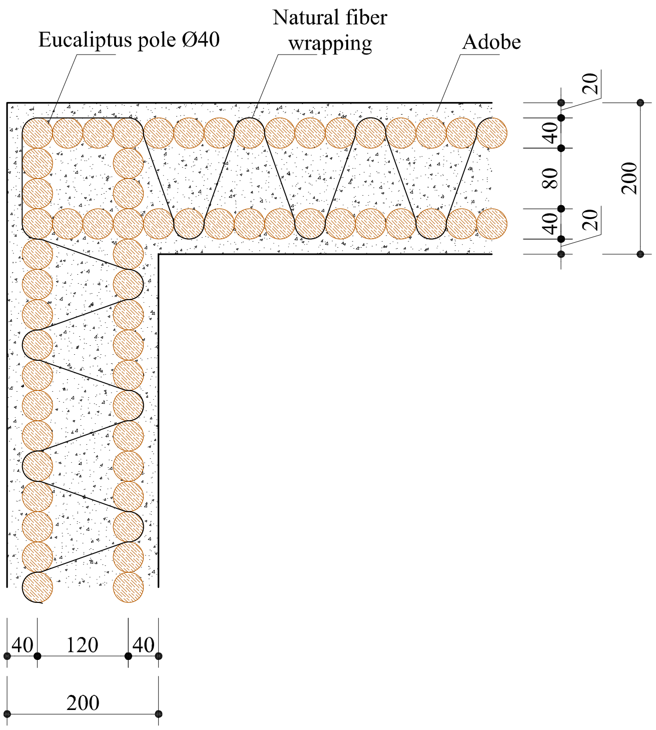


Figure 32– Detail of the wrapping system between the two layers of wood poles in the angles and of the cross connection between two layers.

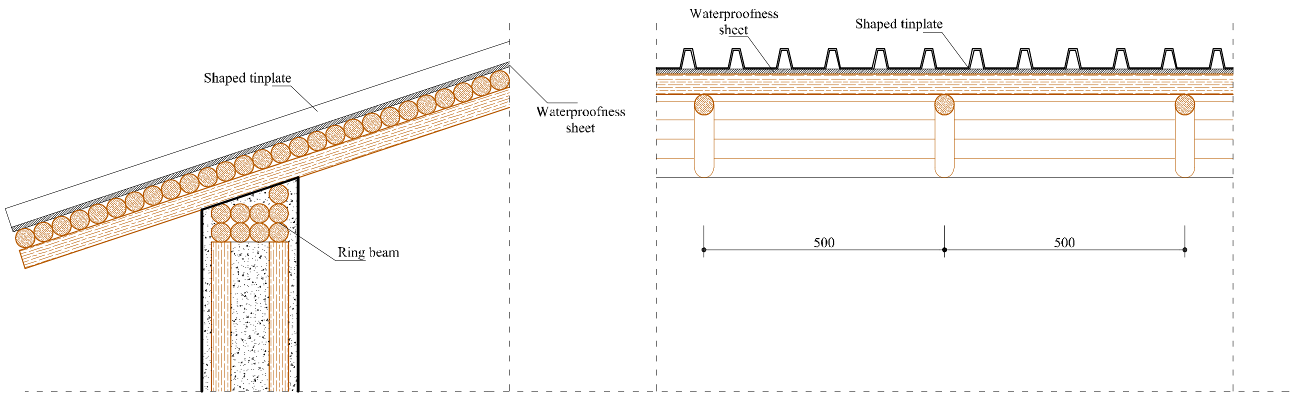


Figure 33– (left) Ring beam cross-section; (right) embedding detail for the primary roof beams within the ring beam

Waterproofing/plastering the walls

As mentioned before, in order to slow- down the erosion and deterioration of the adobe matrix, it is important to protect the walls by a plaster coat or a water-proof paint (see Chapter 3 for general descriptions).

7 CONCLUSIONS

Alternative flood risk mitigation strategies are classified based on whether they lead to a reduction in hazard, in vulnerability or in exposure. This report focuses on the mitigation strategies that lead to reduction in vulnerability. In the city-specific studies, three particularly vulnerable building types are identified for the three cities of Dar Es Salaam, Addis Ababa and Ouagadougou. A risk-based modular methodology is employed for the calculation of flooding hazard, vulnerability and risk. In particular, structural fragility curves for the limit state of collapse are calculated using a visual vulnerability and risk platform (VISK). For the two cities Dar Es Salaam and Addis Ababa, detailed field survey results were available for the representative buildings (add references for the two studies). Therefore, the hazard and vulnerability calculations reflect the specific configuration of the buildings in question and their location. However, detailed field survey results were not available for Ouagadougou. Therefore, the vulnerability calculations represent a class of buildings and not a specific building. For each of the three case study cities, locally adapted climate adaptation strategies were applied to the analytic model and the results on the structural vulnerability to collapse were investigated. Below, some city-specific conclusions are presented.

Dar Es Salaam. The case-study cement brick building has a good connection of the wall at the bottom. The presence of a barrier does not lead to a significant change in the vulnerability of the building in terms of collapse limit state. However, it remains an effective adaptation strategy in reference to life safety or serviceability limit states. From the point of view of the reduction of vulnerability to collapse limit state, increasing the height of the raised platform seems to be the most effective. In particular, for the case-study building, if the platform level is raised from 0.40m to 0.80m, the risk of collapse reduces about 15%. It should be emphasized however, that this type of building material, even after the implementation of the adaptation strategies, does not seem to be sufficiently flood resistant. This building may be further reinforced by the use of horizontal and diagonal wooden braces.

Addis Ababa. The case-study building examined in this city is made of mud and wood material. The protection of the wall against direct contact with water is a crucial aspect. This is because the mud/adobe matrix risks being washed away by flood and wind. The loss of mud leads to a reduction in the structural weight and hence, increases the propensity to instability problems. In addition, the wooden poles need to be embedded sufficiently into the soil in order to guarantee a fixed-end based connection for the mud and wood walls. Another important point is to make sure that the wooden poles are laterally inter-connected by means of horizontal and diagonal braces. A very effective mitigation strategy against collapse is to raise the floor level. The most effective strategy seems to be the addition of a second layer of wooden poles which leads to a reduction of about 24% in risk of collapse. Combing the last two mitigation strategies (i.e., adding the second layer of wood and raising the platform) leads to an overall reduction of 71% in risk.

Ouagadougou. The general class of adobe buildings is studied in order to have an overall understanding of the flooding vulnerability in Ouagadougou. Due to the absence of maximum flood velocity values for Ouagadougou, only hydrostatic pressure was considered as the flood action, assuming that the door and windows are sealed. It can be observed that applying a plaster coat leads to an increase of about 70% in critical flood height collapse capacity. Moreover, adding a raised platform of 0.4m leads to an increase of about 60% in critical flood height collapse capacity. In general this building type can be improved by improving the building connectivity through the achievement of connection details at the angles, addition of horizontal and diagonal wooden braces and envisioning a ring beam in the perimeter of the structure. Due to the lack of city-specific information, the conclusions drawn for this building type need to be verified.

It should be emphasized that this deliverable can be classified as pre-code (i.e., before a building code is established) preliminary document for the vulnerability assessment and reinforcement measures for informal settlements to natural phenomena with specific focus on flooding. The findings of this deliverable should be validated with extensive laboratory tests on specimens, wall panels and full- or reduced-scale structures. Moreover, the presented recommendations need 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.

It should also be mentioned that in the Deliverable 2.17 (Jalayer et al. 2014) some micro- and meso-scale risk maps were generated for the city of Addis Ababa which are also based on the findings presented in this report. These risk maps can be eventually used to achieve a risk zoning (in terms of the mitigation strategies to adopt). For example, for those houses that are located in the areas of highest risk perhaps moving out would be the only viable solution. On the other hand, for those houses that are located in the zones of low to medium risk some suitable mitigation strategies can be adopted with the objective of reducing the risk to an acceptable level (that needs to be established). In fact, increasing the existing knowledge about the constructions through field surveys and laboratory and in-situ tests (see Deliverable 2.4 De Risi et al. 2012) would significantly contribute to check the validity of the conclusions drawn in this report.

As a final word, this effort can be seen as just the beginning of a long road. In order to improve the performance of the buildings to flooding and other climate-related hazards, it is important to pursue a multi-lateral strategy. For example, on the higher levels of decision-making it is important to activate joint ventures with the specific task of preparing guidelines and codes for buildings. Moreover, it is important to disseminate various useful construction technologies at the local level (e.g., increase ing the overall building continuity and robustness, efficient water-proofing techniques, ..., etc.). It is also crucial to plan ahead for early-warning systems/evacuation plans. Last but not least, any effort that can lead to reliable risk maps is commendable in that it improves the level of information and awareness both for the policy makers and the people. Although, out of the scope of this report, special care should be given to the category of mitigation strategies that lead to an overall reduction in the flooding hazard (e.g., adjusting the river line, increasing the flow capacity, regular maintenance of the drains, and decreasing the flow run-off).

APPENDIX A: a GIS-compatible platform for micro-scale assessment of flooding risk and vulnerability in urban areas

Delineation of flood prone areas and the evaluation of the vulnerability of buildings in the urban areas to flooding are fundamental steps in taking adaptive measures for flooding risk. This demands cross-cutting scientific and technical support from different disciplines, such as but not limited to, climate modeling, hydraulic engineering, structural engineering, risk modeling and urban policy making. In recent years, increasing attention is focused on flooding risk assessment. In fact, several publications document and discuss the consequences of flooding, such as loss of life (Jonkman et al. 2008), economic losses (Pistrika and Jonkman 2009, Pistrika and Tsakiris 2007, Pistrika 2009) and damage to buildings (Smith 1994, Kang et al. 2005, Schwarz and Maiwald 2012, Schwarz and Maiwald 2008). These research efforts have many aspects in common, such as a direct link between the flooding intensity and the incurred damage, and that they are based on real damage observed in the aftermath of a flooding event. On the other hand, many research efforts are starting to galvanize in the direction of proposing analytical models for flood hazard and vulnerability assessment taking into account various sources of uncertainties. For instance, in (Nadal et al. 2009) a stochastic method for assessment of the direct impact of flood actions on buildings is proposed. A general methodological approach to flood risk assessment is embedded in the HAZUS procedures for risk assessment (Scawthorn et al. 2006b, Scawthorn et al. 2006a). Moreover, (Apel et al. 2008) provides a classification of flood risk assessment methods based on their degree of complexity and precision. In this context, development of tools that allow for quantifying flooding risk efficiently and with sufficient accuracy is essential. These methods serve as technical support to the stakeholders and policy makers, for flood risk mitigation, emergency preparedness, response and recovery, both in short- and long-term.

In this appendix, a new software tool for flood risk assessment for individual buildings is presented. VISK, acronym of Visual Vulnerability and (*Flooding*) Risk, is a GIS-compatible platform that performs micro-scale flood risk assessment for buildings located in homogenous (i.e., characterized as a single *class* of buildings) urban areas. Figure 34 below demonstrates the graphical user interface for VISK.

The main parts of the graphical user interface for VISK are: (1) the central display panel in which the orthophoto of the case study area is shown. The orthophoto can be overlaid on the spatial polygons representing buildings' foot-prints (i.e., a GIS shape file) and the flooding height/velocity profile for a prescribed return period; (2) the orthophoto input panel where an orthophoto of the case-study area can be up-loaded; (3) the flood profile panel where a lattice of nodes containing maximum flood depth and velocity pairs for each node for a given return period can be up-loaded; (4) building shape panel where the GIS shape file of the buildings' spatial boundary can be up-loaded; (5) a panel for miscellaneous information in which data such as spatial delineation of administrative boundaries can be up-loaded; (6) a panel for the acquisition of data regarding buildings' spatial foot-prints, where in lieu of shape files, for each building, the spatial foot-print can be specified manually and processed by the program; (6) a digital survey sheet where the results of building-specific field survey can be specified. This digital panel is matched with a building-specific survey sheet; (7) a structural analysis panel where a specified number of structural model realizations are generated and analyzed based on the data provided by the digital survey sheet; (8) a fragility assessment panel where the fragility curves for a specified limit state are derived based on the results of the simulations performed in the structural analysis panel. This panel also envisions up-loading of user-defined fragility curves; (9) risk map generation panel where risk maps are plotted for various risk metrics such as the frequency of exceeding a given limit state, expected repair/replacement costs, etc; (10) a progress panel which visualizes the progress of the program. In the following, various functionalities of VISK are discussed in detail.

Figure 34 – The graphical user interface for VISK.

Background: VISK is created inside the European FP7 project CLUVA**:** Climate change and urban vulnerability in Africa. The original idea was to create a tool for vulnerability assessment of informal settlements in Africa. The problem of vulnerability assessment for a portfolio of "informal" and non-engineered buildings is particularly challenging due to many aspects such as lack of complete information and poor construction details. In fact, the core vulnerability assessment methodology created for VISK is organized in a manner so that various sources of uncertainty can be taken into account, with particular attention to structural detailing and water-tightness. Moreover, due to lack of precise survey data, the software uses sample surveys as a basis and constructs probability distributions for the probability of observing/not observing certain structural details in a given building in a Bayesian framework. VISK as a visual interface and platform for vulnerability and risk assessment is applicable not only to the non-engineered structures in an African context but also to other structural typologies in alternative contexts.

7.1 Input data

The input data required by the VISK platform are: orthophoto of the case-study area, spatial foot-print of the buildings, flooding height/velocity profiles for prescribed return periods and the uncertainties in structural modeling parameters related to both material mechanical properties, construction details and geometry (in the form of probability distributions).

7.2 Visual vulnerability assessment platform

Structural vulnerability assessment lies in the core of VISK platform. The vulnerability assessment results are represented as the fragility curves, expressing the probability of exceeding a prescribed limit state given flood height. The software envisions various modes for acquiring the necessary input: (a) calculating the fragility curves based on the input provided to VISK; (b) creating Normal/Lognormal fragility curves based on the first two moments (i.e., mean and standard deviation); (c) creating fragility curves based on data uploaded by the user from a file; (d) creating step-function fragilities, referred to in the program as the Nominal fragilities. In this section the methodology used for calculating the fragility curves based on approach (a) listed above is described.

7.2.1 The limit states

The fragility curves are calculated for three limit states, namely, serviceability (SE), life safety (LS), and structural collapse (CO). In VISK, limit state thresholds are expressed in terms of the critical flooding height. Serviceability 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 example, for an insufficiently water-tight buildings built on a raised foundation, the critical serviceability water height is equal to the height of raised foundation above the ground level. For buildings constructed according to flood-resistant criteria, the critical water height for limit state of serviceability is taken asymptotically equal to the critical height needed for exceeding collapse limit state assuming brittle failure modes. Collapse limit state is defined as the critical flooding height in which the most vulnerable section of the most vulnerable wall in the building is going to break. Life safety limit state defines the critical flooding height in which lives of the inhabitants is going to be in danger. This can be caused either due to the infiltration of water inside the building (with the increasing risk of drowning in water), or the structural collapse (defined in the same manner as the critical height for collapse limit state). The critical water height for structural collapse is calculated in VISK by employing structural analysis taking into account the various sources of uncertainties in geometry, material properties and construction details. As far as it regards life safety considerations, VISK allows the consideration of judgment-based or code-based nominal water height.

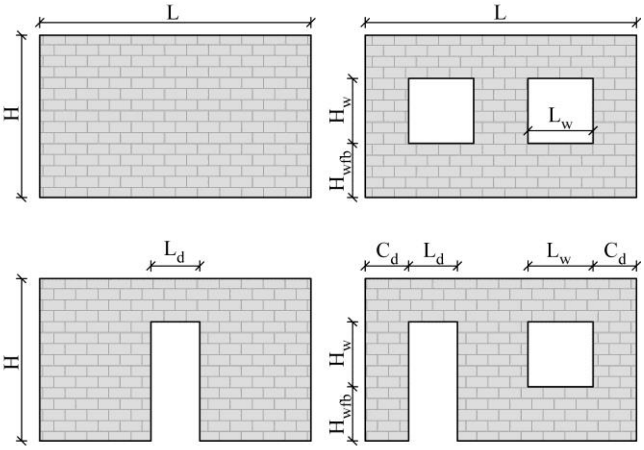
For all the limit states considered within VISK, a simulation-based routine is employed in order to propagate the various sources of uncertainties described in Section 2.2. VISK employs an efficient simulation-based procedure relying on a small number of simulations (e.g., in the order of 50-100).

Assuming that vector $\boldsymbol{\theta}$ consists of all the uncertain parameters considered in the problem, simulation *i* corresponds to the i^{th} realization of vector $\boldsymbol{\theta}$. Each $\boldsymbol{\theta}_i$ is sufficient for defining the structural configuration, flood action, and material strength values for i^{th} simulation realization. Having this information, the critical water height can be calculated for each realization of the structural model/action. With reference to the uncertain parameters considered by VISK, vector $\boldsymbol{\theta}$ is partitioned in two sections: $\boldsymbol{\theta}_1$ lists the discrete binary uncertain parameters considered; and $\boldsymbol{\theta}_2$ is related to continuous uncertain parameters. Each simulation realization is generated according to the probability distributions for vector $\boldsymbol{\theta}$ (at present, correlation structure is considered only for the discrete parameters defined using logic trees).

It is important to emphasize that the sampling procedure is going to involve both the structural model (configuration and material properties) and the flooding action. In particular, the load considered in the structural analysis is going to depend on the degree of water-tightness assigned to the structure based on the quality of doors and windows.

7.2.2 The structural analysis

VISK platform relies on the open-source structural finite element analysis software OpenSees (McKenna et al. 2006) for structural analyses. The structural models developed herein are consisted of two-dimensional elastic shell finite element panels with openings (considered as voids). Three types of transversal boundary condition restraints are considered: (a) fixed end; (b) hinged; (c) free. For example, if a good transversal connection between two orthogonal walls is verified, wall panel with fixed-end restraints can be used. Based on the uncertain parameters related to the geometrical configuration of the buildings, four different types of structural models are generated. These models are distinguished based on the type, number and relative positioning of openings (door and windows). Figure 35 below illustrates various configurations generated in the simulation procedure.



L (m) - wall length
H (m) - wall height
t (m) - wall thickness
L_w (m) - window length
H_w (m) - window height
H_{wfb} (m) - window rise
L_d (m) - door length
C_d (m) - corner length
H_f (m) - foundation rise
H_b (m) - barrier height

Figure 35 – Four structural configurations considered in the analysis.

The current version of VISK considers three kinds of flood action on the structure: (1) hydrostatic; (2) hydrodynamic pressure; (3) waterborne debris impact; (4) material property deterioration (due to elongated contact with water). Detailed description of the above-mentioned flood actions can be found in (Kelman and Spence 2004). As far as it regards the flooding pressure, the flooding profile across structural height is considered and the resulting forces are discretized to the panel joints. The discretized force on the openings (if they are sealed) is applied to the joints located at the opening boundary (neglected if the opening is not sealed).

VISK included also a procedure to evaluate the fragility of a definite model of wall that may be for the analysis of a single structure (as opposed to a class of structures).

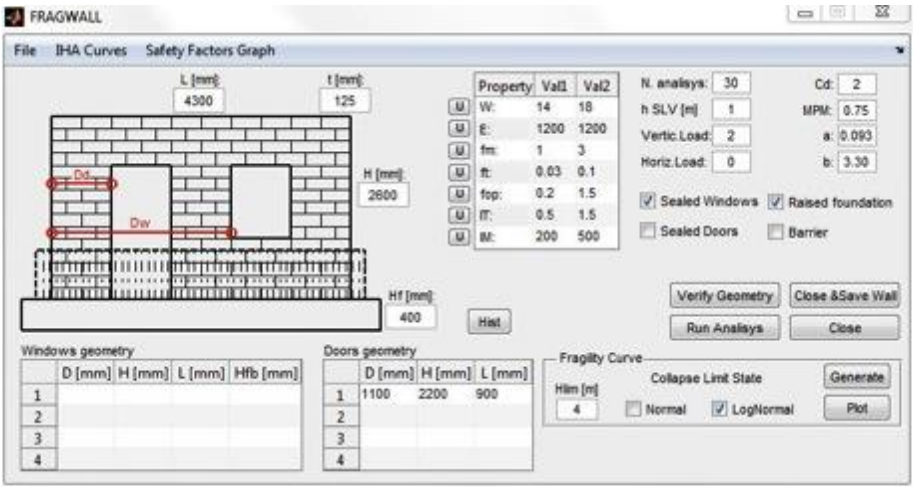


Figure 36 – The interface used for the analysis of a single wall panel

7.2.3 Incremental flood loading analysis

The critical flooding height for the structure is established through a procedure referred to as incremental flood loading analysis. In this procedure, for increasing levels of flooding height, the structural model is analyzed considering the above-mentioned combination of actions (assuming that waterborne debris are going to hit the structure at the flooding water level assumed). The critical water-height for a given limits state is considered as the water-height in which the limit state in consideration is exceeded for the first time. For each flooding height level, this consists in controlling whether the section force, or demand, denoted by *D*, exceeds the corresponding section resistance, or capacity, denoted by *C*, for the specified limit state, for zones of stress concentration.

Safety-checking: For all the identified zones of stress concentration and for each water height level, safety-checking is performed in terms of both shear force and out-of-plane bending moment. It should be noted that safety-checking for bending moment is differentiated with respect to horizontal and vertical sections, due to the presence of axial forces (Figure 38).

Calculating the critical demand-to-capacity ratio: VISK provides an iterative procedure for identification of the zones high stress concentration by searching through prescribed critical sections. Figure 37 below illustrates various critical sections (highlighted) identified in relation to structural configuration and geometry.

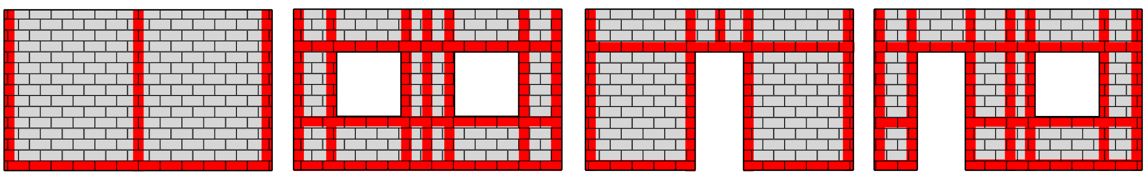


Figure 37 – Zones of panel that are checked for high stress concentration.

Zones of high stress concentration can verify due to, debris impact, asymmetric boundary conditions, and geometrical configurations/presence of openings. Strictly speaking, local stress concentrations do not necessarily translate into global failure mechanisms; however, – in lieu of more accurate information – they can be considered as precursors to failure for a brittle structure. For each critical section *i* considered, the zone(s) of high stress concentration are identified by: (a) discretizing in smaller *sub-sections* (with a discretization step of 25 cm); (b) calculating the demand to capacity ratio (for both flexure and shear), for each sub-section *j* of the critical section considered, denoted by D_{ji}/C_{ji}. This is done in an exhaustive manner considering all the possible sub-sections; (c) defining the zone(s) of high stress concentration as those having the largest demand to capacity ratio $\max_j D_{ji}/C_{ji}$. In this manner, VISK can determine, for each water height level *h*, the critical demand to capacity ratio as the demand to capacity ratio *Y(h)* that takes the structure closer to the onset of specified limit state (Jalayer et al. 2007):

$$Y(h) = \max_i \max_j \frac{Dji}{Cji} \tag{1}$$

VISK platform registers the critical section *i*, the mode of failure (shear/flexure), and the water height h_{cr} that corresponds to $Y(h_{cr})=1$ (Figure 39).

For each Monte Carlo realization of the structural model identified by vector θ, a value for the critical water height $h_{cr}(\theta)$ is obtained, for a given limit state, defined as $Y(h_{cr}(\theta))=1$. The dependence of critical water-height on θ is dropped for convenience hereafter.

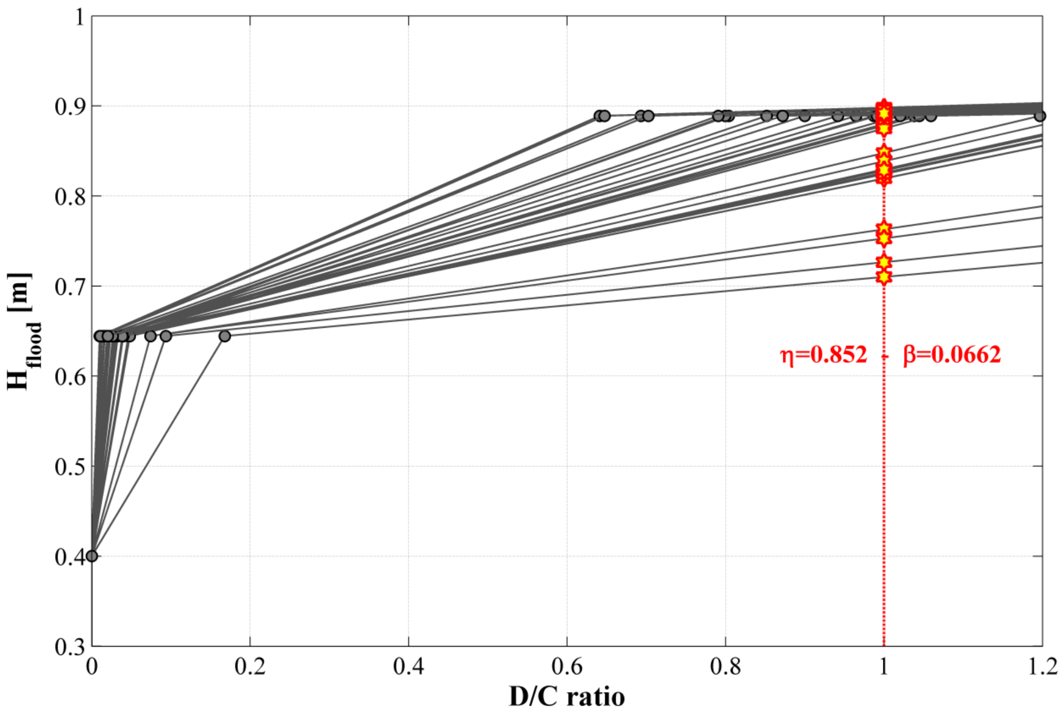


Figure 38 – Incremental hydraulic analysis.

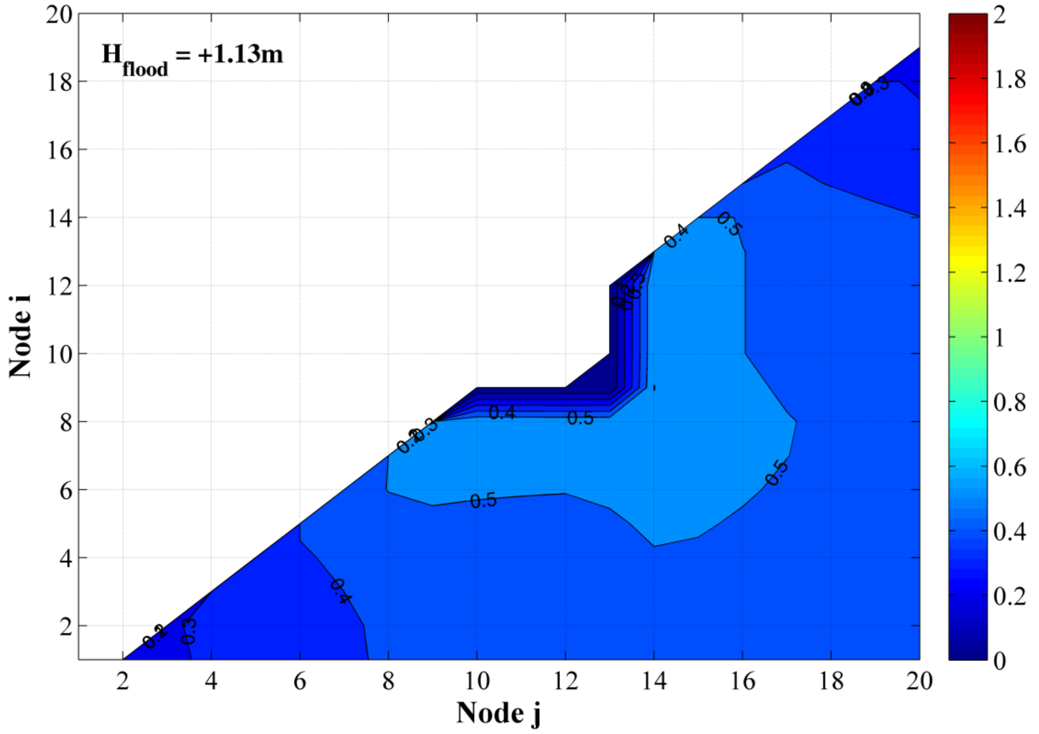


Figure 39 – Safety factors for a given mechanism.

7.2.4 The robust fragility estimation

Denoting the parameters of the analytic fragility function as χ (e.g., $\chi=[\pi,\eta,\beta]$ for LS), the joint probability distribution for the vector of parameters χ can be expressed as $p(\chi)$. Using Bayesian parameter estimation, the probability distribution for the parameters of the fragility function for a given limit state can be updated using formulas described in (Box and Tiao 1992) based on the set of critical height values obtained from simulation. The updated or posterior probability distribution can be denoted as $p(\chi|\mathbf{H_c(LS)})$ [1] where $\mathbf{H_c(LS)}$ is the vector of simulation-based critical height values for limit state LS. This probability distribution represents the uncertainty
in the vector χ due to limited number of simulations.

The robust fragility denoted by $F(h_f|\ \mathbf{H_c})$ is calculated as the expected value of the analytic function $F(h_f|\chi)$ in Eqs. 3, 4 and 5, over the entire domain of vector χ and according to the updated joint probability distribution $p(\chi|\mathbf{H_c})$:

$$F\left(h_f \mid \boldsymbol{H_c}\right)=E\left[F\left(h_f \mid \chi\right)\right]=\int_{\Omega} F\left(h_f \mid \chi\right)\cdot p\left(\chi \mid \boldsymbol{H_c}\right)\cdot d\chi \qquad (2)$$

where $E[.]$ is the expected value operator and Ω is the domain of the vector χ. The variance σ^2 in fragility estimation can be calculated as:

[1] LS is dropped hereafter for brevity.

$$\sigma^2\left[F\left(h_f \mid \chi\right)\right] = E\left[F\left(h_f \mid \chi\right)^2\right] - E\left[F\left(h_f \mid \chi\right)\right]^2 \tag{3}$$

where $E[F(h_f|\chi)]^2$ can be calculated from Eq. 12 replacing $F(h_f|\chi)$ with $F(h_f|\chi)^2$.

Numerical Example: Figure 40 below illustrates the robust fragility curves and their plus/minus one standard deviation interval, corresponding to the three limit states (SE, LS and CO) taken into account into in VISK, based on N=50 Monte Carlo simulations.

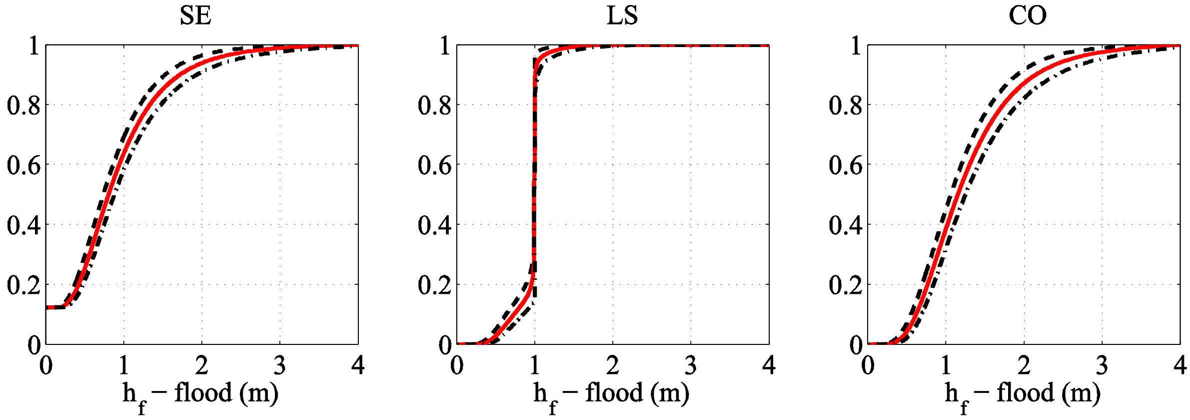


Figure 40 – Robust Fragility curves and their plus/minus one standard deviation interval (SE), (LS) and (CO), respectively.

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