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Flood hazards and masonry constructions: a probabilistic framework for damage, risk and resilience at urban scale

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Abstract. This paper deals with the failure risk of masonry constructions under the effect of floods. It is developed within a probabilistic framework, with loads and resistances considered as random variables. Two complementary approaches have been investigated for this purpose:

- a global approach based on combined effects of several governing parameters with individual weighted contribution (material quality and geometry, presence and distance between columns, beams, openings, resistance of the soil and its slope...),
- and a reliability method using the failure mechanism of masonry walls standing out-plane pressure.

The evolution of the probability of failure of masonry constructions according to the flood water level is analysed.

The analysis of different failure probability scenarios for masonry walls is conducted to calibrate the influence of each "vulnerability governing parameter" in the global approach that is widely used in risk assessment at the urban or regional scale.

The global methodology is implemented in a GIS that provides the spatial distribution of damage risk for different flood scenarios. A real case is considered for the simulations, i.e. Cheffes sur Sarthe (France), for which the observed river discharge, the hydraulic load according to the Digital Terrain Model, and the structural resistance are considered as random variables. The damage probability values provided by both approaches are compared. Discussions are also developed about reduction and mitigation of the flood disaster at various scales (set of structures, city, region) as well as resilience.

1 Introduction

In a great number of cities around the world, popular constructions are masonry. In developing countries, they are very often erected without any respect to modern building regulations and suffer, in consequence, great vulnerability to any hazard. In the case of occurrence of a strong event (strong rainfalls, earthquakes, hurricanes, tsunamis, mud and debris flows, etc), the expected human and socio-economic losses can be very important (Bimal Kanti Paul, 1997; Borga et al., 2011; Fedeski and Gwillian, 2007; Linnekamp et al., 2011; Marchi et al., 2011; Qi and Altinakar, 2011; Ruin et al., 2008; Treby et al., 2006; Versini, 2012; Vinet, 2008).

In fact, structural as well as non-structural responses are needed for integrated approaches devoted to risk assessment and management. Sometimes, the non-structural losses can be exaggeratedly important. Therefore, the hazard prone areas and dwellings require special studies and decisions, preparatory or remedial, since high risk requires high attention, accurate assessment and special protective measures (Barriers such as embankments, dikes, gabion walls, floodwalls, dispersions, delay action dams, bypass structures, and channelization of floodwaters, etc).

The present study aims to develop a methodology for quick evaluation of existing structures regarding their structural risk against natural hazard. It can be therefore useful, mainly for developing countries, as a ranking method for hierarchical classification of the existing masonry constructions. As the global methodologies developed for operational purposes may appear as being empirical and depending on a set of simplified hypotheses, additional theoretical developments (mechanical models and numeric simulations, for instance) are required in order to justify and calibrate these operational methodologies.

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In the case of flood hazards and risks, for instance, depending on the kind of floods (fluvial flooding, river flooding, flash floods, torrential rains and storms, etc), appropriate hydraulic, mechanical, probabilistic and numeric models should be developed in order to provide accurate estimates of the expected values for structural as well as non-structural losses.

Therefore, it is of great importance to develop robust methodologies and calibrate operational frameworks able to:

- predict, by the use of operational methods at large scales (city, region, country, etc), the expected structural damage level that might be caused if a potential event (natural or industrial hazard) occurs in order to reduce and mitigate the potential disaster by taking adequate preventive measures.
- evaluate, at large scale also, the structural damage level and the residual bearing capacity in order to evacuate, demolish or strengthen the damaged structures.
- assess, by sophisticated methods, the theoretical risk of failure for a given structure or typology under a natural event in order to obtain "exact" probability of failure and calibrate operational framework for quick evaluation to be used at the large scale.

This paper develops an integrated probabilistic framework that aims to assess the failure risk for masonry structures under flood hazard. This natural hazard, as well as the structural vulnerability or damage, are considered as random variables involved in the reliability analysis to be performed.

Two different complementary approaches are investigated to assess the risk of failure:

- a global and operational approach that derives this risk on the basis of a selected set of individual parameters (indicators of damage) that govern the capacity of a building such as the quality of materials, number of storeys, geometric regularity, etc;
- and a reliability analysis based on the structural failure modes under the hydrodynamic effect of the flow flood pressure. The present study is restricted to the case of masonry walls standing out-plane pressure caused by a flood. The resistance to in-plane load is supposed more important than an out-plane case.

The risk of failure or the damage probability is expressed in quantitative terms ranging from 0 (no damage) up to 1 (collapse).

For both approaches, a relationship between damage level and flow depth and velocity (i.e. hydraulic pressure) is developed. The damage probability values provided by these two approaches are compared. Obviously, technical and scientific knowledge are required in order to fill the evaluation sheet and derive the risk of the existing structures: the technical offices, in addition to the local or municipal authorities, are able to use the methodology and map the risk that might be helpful and objective for the decision making. The same procedure remains also valid for other kinds of hazards: technological or natural such as earthquakes, for instance.

These calculations may contribute to human lives and material saving and protection. Furthermore, objective and optimal decision making relies on adequate use of hazard and risk mapping by adequate urban planning or protective measures of existing urban or rural sets. Actually, environmental changes and threats are to be adequately managed by authorized institutions (municipal and local authorities, governmental agencies, etc) in order to achieve public safety and prepare mitigative measures.

This methodology is afterwards applied in the case of a real city, Cheffes sur Sarthe (France). The probabilistic distribution of the river discharge is based on collected in situ measures. The Digital Terrain Model of the city is used in order to run hydraulic numerical simulations and obtain the probabilistic distribution of the hydraulic load on each existing structure. The historic flood event that occurred in 1995 is used in order to validate the simplified hydraulic model. A mechanical model is developed to evaluate the probabilistic distribution of the masonry walls resistance to out-plane flood pressure. In the present case, the flow results from river flooding. Differential inside and outside pressures of the building are therefore considered. However, debris, rocks, mudflows, for instance, are not considered in the present hydraulic and mechanical models. Improvements will be required to deal with the general case of debris, impacts, vehicles transported by the stream.

Monte Carlo simulation and a GIS system (Mapinfo) are considered in order to provide the spatial distribution of damage risk for different flood scenarios. The construction failure concerns the building resistance; it consequently impacts the urban resilience. This kind of study may be helpful in order to improve the resilience by proposing mitigation solutions at an individual scale (protect a construction by surrounding barriers or balancing the unfavourable effect of flood pressure) or at a global scale (dike erection, dam, etc). The adequate strengthening and protection of the concerned constructions are a possible option in reducing and mitigating the potential natural disasters (Fedeski and Gwillian, 2007; Kazmierczak and Cavan, 2011; Linnekamp et al., 2011; Mens et al., 2011; Qi and Altinakar, 2011; Schelfaut et al., 2011; Treby et al., 2006; van Herk et al., 2011; van Ree et al., 2011).

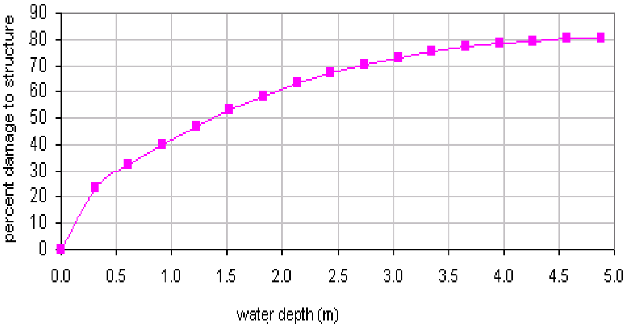


Fig. 1. Example of damage curves as function of the flow depth (US Army Corps of Engineers, 2000).

2 Global and operational approach: vulnerability assessment

2.1 General purpose

An evaluation of the structural vulnerability to flood effect might be requested by the decision makers and stakeholders in order to predict, at a large scale (urban zone, city, region, etc), the socio-economic losses that may be caused by a possible flood event.

This so-called building vulnerability regarding floods is usually measured by damage functions, where damage is related to the water depth (flood level)(see example of this kind of curve found in Penning-Rowsell and Chatterton (1977); US Army Corps of Engineers (1997, 2000); Kelman (2002)). These functions are usually established from observations or modelling based on post-flood surveys. Figure 1 presents an example of water depth-damage function.

In fact, the damage level is very often related to the economic impact rather than to the bearing capacity of building structure under the water loading. As the damage level should be related to the mechanical effect of the flood, we propose a new methodology that might be useful for quick evaluation at a large scale for masonry constructions. Obviously, this global approach has to be calibrated on the basis of either structural damage database collected during post-flood disaster event or mechanical simulation. For this purpose, we present hereafter:

- a global and operational method that assesses the structural damage as a combination of damage due to individual governing structural parameters;
- a simplified mechanical model that is considered for numeric simulations in order to calibrate this global method according to the theoretical ("effective" rather than supposed), structural failure risk, as detailed in Valencia et al. (2011).

Table 1. Parameters and their relative weight in Benedetti-Petrini's method.

	K_i				ω_i
Parameter	D	C	B	A	
State of conservation	45	25	5	0	1.0
Soil slope and foundations	45	25	5	0	0.75
Conventional resistance	45	25	5	0	1.5
Horizontal diaphragm	45	15	5	0	1.0
Roof type	45	25	15	0	1.0
Horizontal regularity	45	25	5	0	0.5
Vertical regularity	45	25	5	0	1.0
No structural elements	45	25	0	0	0.25
Respect to the seismic norm	45	20	5	0	1.0
Quality of materials	45	25	5	0	0.25
Max. distance between walls	45	25	5	0	0.25

2.2 Existing global method for seismic vulnerability: Benedetti-Petrini Method

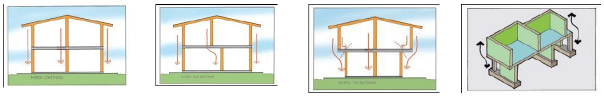
The empirical method developed in the 80s by Benedetti and Petrini (1984) is often used to evaluate the seismic vulnerability of buildings at a large scale. This method considers a set of structural parameters governing the seismic resistance: mechanical parameters, material quality, geometry, presence and distance between columns, beams, openings (windows and doors), resistance of the soil and its slope, state of conservation and execution quality.

Each parameter is considered as ranging within four classes (A, B, C, D): $A =$ very safe, $B =$ safe, $C =$ dangerous and $D =$ very dangerous. To each parameter is allocated a relative weight ω_i and to each class(A up to D) corresponds a weight k_i(see Table 1). The vulnerability index I_v may then be defined as:

$$I_\mathrm{v} = \sum_{i=1}^{N} k_i \times \omega_i \tag{1}$$

where: $k_i =$ influence of parameter i among categories A, B, C or D ; $\omega_i =$ relative weight to each parameter among the total number N of parameters that govern the resistance or vulnerability of the considered structure.

The principal advantage of this method relies on its ability to evaluate the intrinsic vulnerability of a construction. In fact, the vulnerability index indicates whether the structure is safe or dangerous but it does not give any effective and practical value of the structural vulnerability. Moreover, the vulnerability does not evolve with the hazard level. This is the main drawback of similar existing methods based on weighted influences (de Vries, 2011; Fedeski and Gwillian, 2007; Fernandez and Lutz, 2010; Jonkman et al., 2008; Kazmierczak and Cavan, 2011; Kelman and Spence, 2004; Pappenberger et al., 2007).



Category: « A » *Category:* « B » *Category:* « C » *Category:* « D »

Fig. 2. Effect of the vertical regularity of the masonry construction: $A =$ very safe, $B =$ safe, $C =$ dangerous and $D =$ very dangerous.

2.3 New global method: probabilistic development and proposal

Derived from this traditional Benedetti method, a new method has been already developed within a probabilistic framework in the case of seismic vulnerability by Mebarki and Valencia (2003, 2004). In the present paper, it is adequately transformed and adapted to the case of flood by Valencia (2006). For this purpose, the vulnerability is expressed as a structural damage probability denoted P_f. Damage functions are expressed as functions of the flood water level H.

Of course, the calibration of the governing parameters also influences the damage probability P_f functions, used for this global approach, should be performed by developing and running a complete reliability analysis: probabilistic description of the hazard, probabilistic description of the conditional vulnerability and convolution integral providing the risk of failure (Aronica et al., 2011; Schumann et al., 2007).

2.3.1 Governing parameters and vulnerability identity matrix $\mathbf{I}_\mathrm{v}$

In a first step, the structural vulnerability against flood is supposed to rely on the combined effect of the set of N governing parameters. Actually, from post-flood damage reports (US Army Corps of Engineers, 1995; NFPC 1998), we adopt a set of $N = 14$ structural parameters that govern the structural capacity of a masonry building under the effect of hydro-dynamic pressure, as shown in Table 2.

The effect of each parameter i among the N selected is so that the structure is classified into one of the adopted category of sensitivity to damage: A, B, C or D, as indicated in Fig. 2 for the "vertical regularity" parameter effect, for instance.

It is therefore required to establish the structure identity, i.e. vulnerability identity matrix $\mathbf{I}_\mathrm{v}$:

$$I_\mathrm{v} = \begin{pmatrix} I_\mathrm{v}(1,1) & \dots & \dots & I_\mathrm{v}(1,M) \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & I_\mathrm{v}(i,j) & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ I_\mathrm{v}(N,1) & \dots & \dots & I_\mathrm{v}(N,M) \end{pmatrix} \tag{2}$$

where (see Table 2 as example):

- $I_\mathrm{v}(i,j) = 1$ if the parameter i, i from 1 up to N, is so that the structure has to be classified into the category j, j from 1 up to M ($M = 4$: categories A, B, C and D)
- $I_\mathrm{v}(i,k) = 0$ for $k \neq j$ with $k \in \{1..M\}$, i.e. for the 3 other categories.

2.3.2 Vulnerability value matrix $\mathbf{P}_\mathrm{v}$

Furthermore, the individual contributions of the parameters are assumed to represent individual failure probability, called $\mathbf{P}_\mathrm{v}$, instead of using the parameter weighting adopted for Beneditti's method

$$P_\mathrm{v} = \begin{pmatrix} P_\mathrm{v}(1,1) & \dots & \dots & P_\mathrm{v}(1,M) \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & P_\mathrm{v}(i,j) & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ P_\mathrm{v}(N,1) & \dots & \dots & P_\mathrm{v}(N,M) \end{pmatrix} \tag{3}$$

where $P_\mathrm{v}(i,j) =$ structural failure due to the parameter i ($i =$ 1 up to N) when the structure is classified into the category j ($j = 1$ up to M).

By analogy with the seismic vulnerability methodology proposed by Mebarki and Valencia (2004) and Mebarki et al. (2008) and based on damage curves collected from literature (Penning-Rowsell and Chatterton, 1977; US Army Corps of Engineers, 1997, 2000), we assume, in the present study, that the relationship between the single contribution of each governing parameter and the water level H follows an elliptic relationship (see Fig. 3)

$$\left(\frac{P_{\mathrm{v}i}(h) - P_{\mathrm{v}i}(h_0)}{P_{\mathrm{v}i}(h_\mathrm{max}) - P_{\mathrm{v}i}(h_0)}\right)^2 + \left(\frac{h_\mathrm{max} - h}{h_\mathrm{max} - h_0}\right)^2 = 1 \tag{4}$$

where: $h =$ is the corresponding value for water level H; where h_max is the maximal value of H (upper bound of the validity domain) and h_0 is a reference value; $P_{\mathrm{v}i}(h)$ is the corresponding value of the probability $P_\mathrm{v}(i,j)$ that represents the single damage contribution of the governing parameter i, in the structural category j, for the water depth h. Figure 3 shows the evolution of damage risk according to flood level (hydraulic load) and according to each category (A, B, C, D). The accuracy and validity of this methodology can be analysed and calibrated on the basis of a complete reliability analysis (Valencia et al., 2011).

Usually, similar studies consider the vulnerability as a global parameter, regardless of the level of hazard. An innovative aspect of the present methodology relies in the fact that the vulnerability and the individual contributions take, in fact, conditional values as they are expressed according to the level of hazard (assumed elliptic relationship between the hydraulic pressure and the corresponding conditional vulnerability). In general, only sophisticated methods with numeric simulations consider the probabilistic hazard (distribution of

Table 2. Identity matrix for a given masonry construction considered as example.

Parameter ($i=1$ up to N)		Classes ($j=1$ up to M)			
		D	B	C	A
1	Number of storeys	$I_{\mathrm{V}}(1,D)=1$	0	0	0
2	Quality of materials				
3	Wall geometry				
4	Wall thickness				
5	State of conservation	0	$I_{\mathrm{V}}(5,B)=1$	0	0
6	Type of soil and foundations				
7	Structural system: columns and beams	0	0	$I_{\mathrm{V}}(7,C)=1$	0
8	Openings (doors and windows)				
9	Horizontal and vertical regularity				
10	Wall orientation with respect to the flow				
11	Type of slab and roof				
12	Location, environment				
13	Potential debris				
14	Basement and type of flooring				

the flow velocity and hydraulic pressure), the probabilistic vulnerability (distribution of the bearing capacity) and the convolution product that provides the risk of failure. The methodology presented herein considers explicitly the evolution of the conditional vulnerability according to the hazard level. It is then easy to derive the risk of failure as shown hereafter.

2.3.3 Governing parameter contribution to structural damage and vulnerability, P_{f}

Let us denote the global structural failure as a probabilistic combination of the individual failure due to each of the governing parameters:

$$E=\bigcup_{i=1}^{N} E_i \tag{5}$$

where E = "global failure" event of the structure; E_i = failure event caused by the governing parameter i, $i=1$ up to N.

The corresponding damage probability or probability of global structural failure is derived from the elementary contribution E_i due to each governing parameter i (Mebarki and Valencia, 2003, 2004). Obviously, many of these individual contributions can be physically and statistically dependent. To take into account the existing dependency between individual events, one might consider either the covariance matrix or the conditional probabilities of occurrence between events. For instance, eigenvalues and eigenvectors of the correlation matrix could provide adequate governing combination of dependent individual events. Furthermore, numeric simulations can be run in order to analyse the risk sensitivity to each or sets among the whole governing parameters and find the most influent for which special attention needs to be devoted. The correlation and dependency between events can be established according to experimental data and feedback or pure theoretical assumptions and developments. In the present study, such experimental data are not available; it is not easy therefore to consider objective dependency. Therefore, the hypothesis of independency appears as a convenient hypothesis and simplifies the theoretical developments. However, the proposed framework remains valid, as it can easily integrate the correlation matrix and conditional probabilities if available.

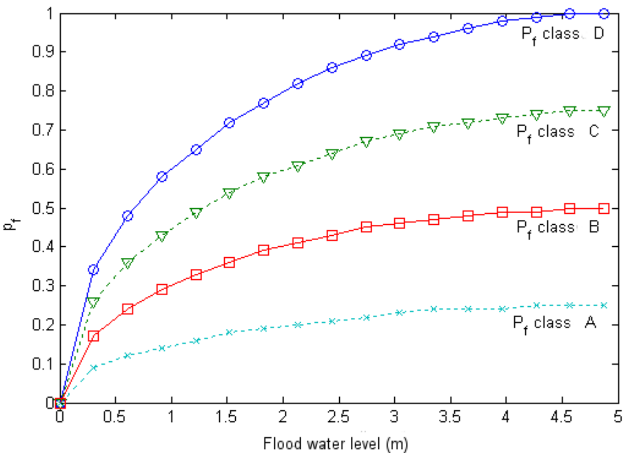


Fig. 3. Evolution of damage risk P_{f} according to the flood level.

Hence, the present methodology assumes that the global vulnerability depends on the combined influence of individual and independent governing parameters. It is therefore restricted to the case of acceptable hypothesis of independence. Actually, as a first approach, the individual events E_i are assumed to be independent. The damage probability of a masonry construction, P_{V}, becomes then:

$$E_\mathrm{s} = \bigcap_{i=1}^{N} E_{\mathrm{s}i} \Rightarrow P_\mathrm{f} = 1 - \prod_{i=1}^{N} (1 - P_{\mathrm{v}i}) = 1 - \overline{P_\mathrm{v}} : I_\mathrm{v} \quad (6)$$

as general term

$$\bar{P}_\mathrm{v}(i,j) = 1 - P_\mathrm{v}(i,j) \quad (7)$$

where E_s = structural capacity event of the structure as being the complementary event to the failure E; $E_{\mathrm{s}i}$ = structural capacity event due to parameter i, i from 1 to N; I_v = identity matrix of the structure; $P_{\mathrm{v}i} = P_\mathrm{v}(i,j)$ = single damage contribution of parameter i for category $j(j = 1$ up to $M)$; P_v = damage probability as a cumulative effect of all governing parameters.

It is necessary to define the single contribution of each governing parameter, $P_{\mathrm{v}i}$ with $i = 1$ à N, regarding structural damage probability, P_f.

2.3.4 Operational value of the failure probability, P_f

Various steps are required in order to evaluate the vulnerability and risk of failure for a given masonry construction:

- *Step 1:* vulnerability identity matrix $\mathbf{I}_\mathrm{v}$

the infield inspection (mainly visual) of a masonry construction allows establishing its vulnerability identity matrix $\mathbf{I}_\mathrm{v}$. An evaluation sheet is developed: for each existing masonry structure, the inspector fills the evaluation form and establishes the vulnerability identity matrix $\mathbf{I}_\mathrm{v}$;

- *Step 2*: flood level hazard parameter in order to estimate the structural damage and vulnerability $\mathbf{P}_\mathrm{f}$

for each value of the flood water level H, the exceedance probability is established by a Monte Carlo simulation (river discharge at the entrance of the channel, described as random variable, is coupled with a hydraulic numerical model in order to provide the velocity and water depth at any point of the considered zone for the whole constructions under study);

- *Step 3:* vulnerability value matrix $\mathbf{P}_\mathrm{v}$ in order to estimate the structural damage and vulnerability $\mathbf{P}_\mathrm{f}$

the individual contribution of the parameters allows estimating the structural damage using Eq. (6);

- *Step 4:* GIS map of failure risk and structural damage due to flood effect

the structural risk of failure as well as the socio-economic expected losses can therefore be adequately summarised in GIS maps. These synthetic maps are useful and objective for decision making and resilience analysis of the zone or the set under study.

3 Application to a real case: Cheffes sur Sarthe (France) and comparison to Sarthe river flood in 1995

For illustration purposes, the village of Cheffes sur Sarthe in France has been selected as an experimental zone for this flood hazard analysis. Actually, the village has suffered many floods; for instance, in 1995, Sarthe river flooded 90 % of the residences and caused serious non-structural as well as structural damages.

Water depths and velocities in the floodplain are computed using HEC-RAS software developed by the US Army Corps of Engineers. This tool allows performing one-dimensional steady flow and unsteady flow based on the solution of continuity and momentum equations for open channels. The data required for the river modelling are the discharge hydrograph upstream, the Digital Terrain Model describing the floodplain and the geometry of the channel, as well as the hydraulic properties of the river channel such as slope, shape, roughness, etc.

The flood hazard parameter is characterised in a probabilistic framework as the exceedance probability of a critical water level H. The water level H can be obtained through an hydrological model and hydraulic numerical study combined with Monte Carlo simulation from the discharge Q, at the entrance of the channel, up to the flow depth y and velocity V arising downstream in the floodplain. This procedure is shown in Fig. 4.

From these two last parameters, the flood water level is derived as:

$$H = y + \frac{V^2}{2g} \quad (8)$$

where y = flow depth, V = velocity, and g = acceleration due to gravity.

Hydrodynamic pressure generated by the flood velocity depends on multiple factors and local conditions that are difficult to evaluate. Actually, scouring, erosion and flood acceleration, for instance, are not taken into account in this study.

Flood frequency and exceedance probability of a critical discharge Q are calculated from a hydrological analysis. Water level frequency and exceedance probability, for a critical water level H, are calculated from a hydraulic numerical model combined with a Monte Carlo simulation, with a procedure developed for this purpose, as shown in Fig. 4.

For the real case considered herein, i.e. the French village Cheffes-sur-Sarthe flooded in 1995, the observed values of the stream height have been compared with acceptable accuracy to those predicted by simulations (Valencia et al., 2011). The structural damages observed during the real floods have not been neither detailed nor reported. Unfortunately, there is therefore no opportunity to compare the damages predicted by the present methodology to those that could have occurred during these historical floods. Due to the fact that the flow height and the out-plane resistance of the masonry walls are

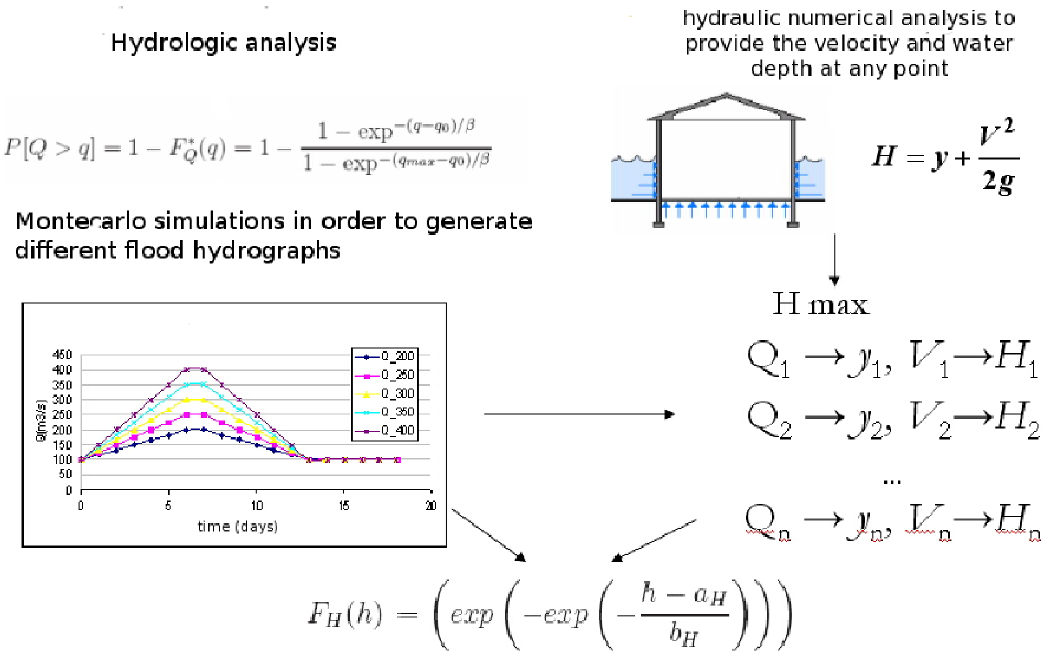


Fig. 4. Example of data required for river modelling.

accurately predicted, the evolution of the conditional vulnerability according to the hazard intensity (hydrodynamic lateral pressures), one may assume that the present methodology will provide correct risk values in absence of particular events, i.e. mudflows, debris and impacts, etc (Valencia et al., 2011). However, the present methodology can be significantly improved by considering additional aspects such as debris flows (debris brought by streams, etc) and impacts as well as mud flows, as they are influent causes of structural damages; i.e. rocks, trees and vehicles for instance.

4 Flood risk and risk maps

The Geographic Information System (GIS) tools are adequate to represent risk at the regional or local scale. These tools allow storing data related to the individual information and the geometry for each building (governing parameters and class from *A* up to *D*). Once the damage curve and the flood hazard are determined, the damage probability of each building can be easily computed and a risk map can be generated in order to help decision-making.

As an example, convivial interfaces have been developed under MapInfo in order to assess the risk at a regional scale. Cheffes sur Sarthe village was chosen as an experimental zone. Figure 5 shows the evolution of damage probability for three different levels of flood hazard (flow water elevation).

Thus, different scenarios can be studied in order to predict the consequences of a flood. The implementation of the methodology within a GIS may produce useful information for decision-making processes.

This paper is, in fact, the first part of a complete study devoted to masonry structures vulnerability regarding natural hazards (Valencia et al., 2011). Actually, the theoretical calibration of the global methodology detailed herein relies on a sophisticated and more detailed approach, i.e. probabilistic description of the hazard (river discharge, stream velocity and flow height), probabilistic description of the masonry wall resistance to out-plane hydrodynamic pressure, numeric simulations and level-2 method in order to calculate the failure risk. Sensitivity analyses were required in order to compare the assumed evolution (adopted in the first part: elliptic evolution of the conditional vulnerability) to the numeric values. The individual influences as well as the relationships adopted for the evolution of the conditional vulnerability (for each governing parameter), according to the hazard level, have been investigated in the case of masonry walls under out-of-plane loads. The results reported in the paper seem to be in good accordance with the evolution that has been adopted (Valencia et al., 2011).

5 Urban resilience under flood hazard

5.1 Aspects related to urban resilience

The risk reduction through masonry structure strengthening is a common practice regarding natural and industrial hazards. Usually for flood events, the mechanical aspects do not require so great attention as the non-structural losses are more important. The global protection is rather, in general, provided by barriers such as dike, dam, etc. However, if these

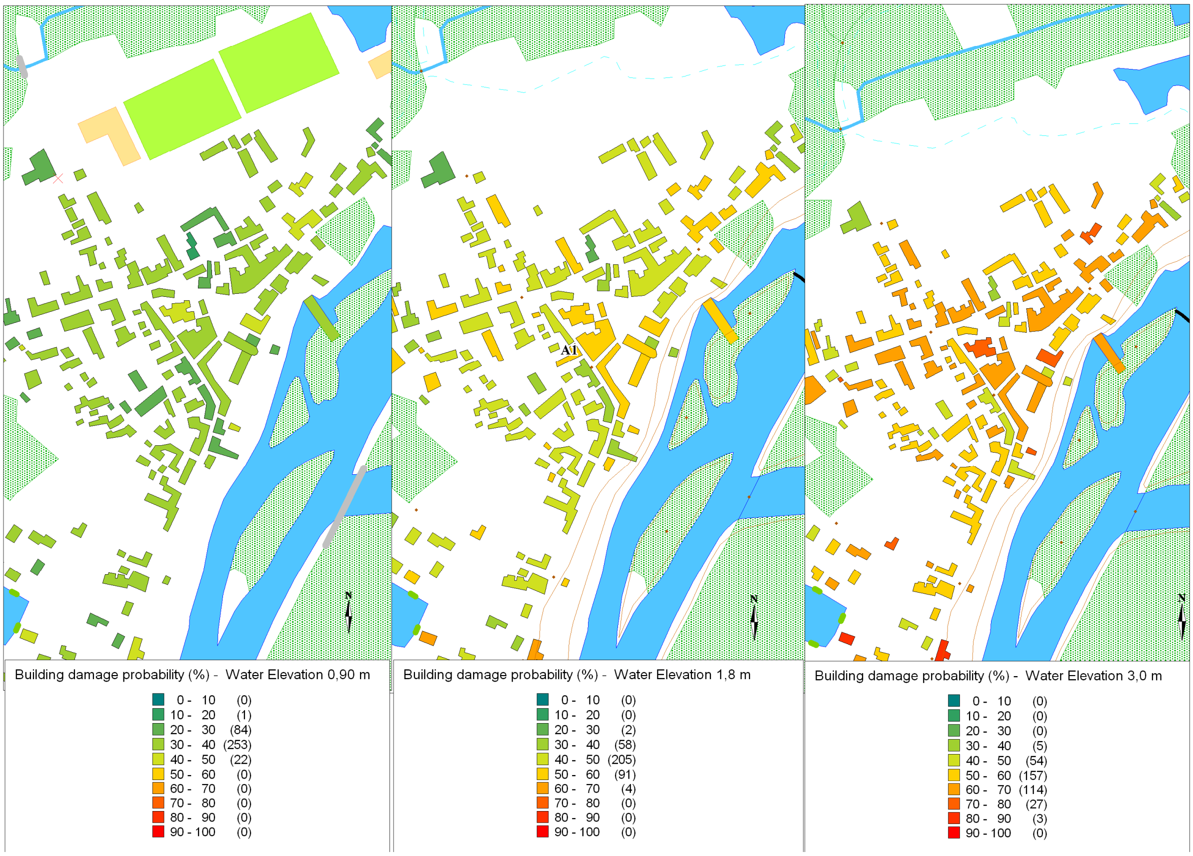


Fig. 5. Risk maps: evolution of damage failure for building at three different levels of flood hazard (hydraulic load level).

mechanical barriers collapse under the natural event, they might generate other kinds of risks and lead to a disastrous situation. For instance, the domino effect may take place and give rise to catastrophic situation. Similar situations and successive sequences of failure happened during the recent tsunami in Japan during the Tohuku quake in March 2011.

However, vulnerability assessment of the existing constructions is helpful in disaster reduction and mitigation since potential options might be prospected and adopted in order to strengthen the weak elements and reduce their vulnerability. Actually, the assessment of masonry vulnerability and damage prediction is a crucial step in order to elaborate adequate strengthening and protection. As these constructions are constitutive components of a wide territory, taking care of these components strengthens partly the territory and makes it more resilient. According to Folke (2011), “Resilience is the long-term capacity of a system to deal with change and continue to develop”. Urban areas are complex and dynamic systems that are exposed to various hazards. Beyond the damages that might be suffered due to its vulnerability, a resilient territory needs adequate and efficient organization. Errors and disturbances generated during past catastrophic events should be detailed and analysed in order to stimulate its memory and build its knowledge database (scientific, economic, social, management, psychological and human behaviour, etc) and to be able to stand any similar event that might occur during its lifetime. Therefore, new/original or existing strategies can be developed or adopted for the reduction of constructions and territory vulnerability. GIS maps and socio-economic models are helpful in balancing the residual risk and the socio-economical aspects (Bimal Kanti Paul, 1997 ; Fedeski and Gwillian, 2007; Kazmierczak and Cavan, 2011; Linnekamp et al., 2011; Mens et al., 2011; Qi and Altinakar, 2011 ; Schelfaut et al., 2011; Treby et al., 2006; van Herk et al., 2011; van Ree et al., 2011).

An urban territory contains a large set of constructions, facilities, lifelines and human beings. Therefore, it is considered as a complex system whose ability to remain in adequate service depends intimately on each constitutive element vulnerability. Interactions and dependency between them have great influence on the system vulnerability and residual risk regarding a natural hazard such as floods, for instance. Actually, the resilience of the territory depends intimately on the residual capacity, survival and recovery functions of the components and their resulting interactions, after an occurrence of a disastrous event. The resilience improvement for a territory (neighbourhood, city, etc) requires also improvement of the structural bearing capacity of its constitutive constructions. Furthermore, based on matrix values describing the buildings fragility and their socio-economic importance, the Flood Vulnerability Assessment tool may be helpful in ranking the buildings and organizing into hierarchy their priority of strengthen (Barroca et al., 2006).

5.2 Theoretical approach and socio-economic aspects for risk reduction at urban scale

The GIS maps of the flood hazard and the resulting structural failure risk are therefore helpful for disaster mitigation and reduction. The natural disasters have, in general, several consequences of great importance.

Actually, optimization of the required expenses in order to reduce the expected risk, for the structural aspects, can be done theoretically by Mebarki et al. (2008):

$$C_{\mathrm{g}}^{*} = \min\left\{C_{\mathrm{g}}\right\} \tag{9}$$

$$C_{\mathrm{g}} = \sum_{k=1}^{N_{\mathrm{s}}} \left(C_0(k) + \Delta C(k) + \left(P_{\mathrm{f}}(k) + \Delta P_{\mathrm{f}}(k)\right) \times C_{\mathrm{f}}(k)\right) \tag{10}$$

where: C_{g} = generalised cost over the whole set of $\mathbf{N}_{\mathrm{s}}$ structures under study; $P_{\mathrm{f}}(k)$ = failure probability of the k-th structure; $C_{\mathrm{f}}(k)$ = socio-economic consequences of k-th structure failure; $\Delta C_{\mathrm{f}}(k)$ = additional expenses due to strengthening or repair of the k-th structure in order to reduce the failure risk by the order $\Delta P_{\mathrm{f}}(k); k = 1$ up to N_{s}.

In fact, this optimal global cost seems easy to be theoretically calculated. However, several aspects such as respect of human life, pollutions and aggressive products release, losses of jobs, transportation breakdown, reactions of public opinion and political decisions make this optimization not so easy to be reached in practice. However, this theoretical formulation may also be helpful in prospecting objective investments and accompanying measures (survey and early warning systems, automatic control and shutdowns, protective barriers, vicinity planning and organization) that result in risk reduction, disaster mitigation, and satisfy resilience and quick recovery requirements.

In practice, various solutions might be considered in order to protect the structure or reduce its vulnerability. For illustrative purposes, at the individual building scale, one may consider various strategies for strengthening and reducing damage risk, as shown in Fig. 6:

- The building partly rests on stilts. Required retention capacity has to be performed within the building plot, while providing access in case of a flood.

- Part of the retention capacity is located within the building perimeters, as the ground floor is temporarily flooded. This requires both temporary installations, which can be disassembled in case of a flood and a corresponding choice of materials. Staircases and other structural elements not to be flooded need to be built to be water-proof.

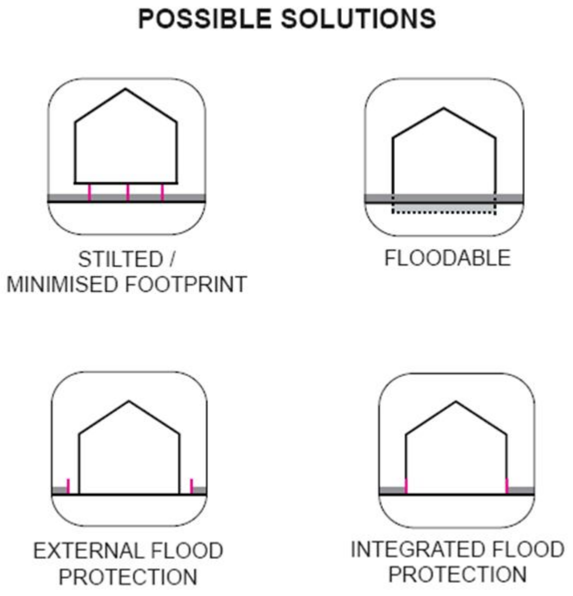


Fig. 6. Various solutions for structural resilience against flood hazard (Redeker, 2010).

- Retention capacity is located outside of the flood defense, creating flood-secure open space. The reduction of the retention area implies a deeper excavation which in turn requires a solution regarding the water return after the flood event.

- Floodable areas directly adjoin the building.

6 Conclusions

This paper contributes to the development of a new integrated probabilistic methodology in order to assess failure risk of masonry constructions against flood hazard at the large scale. This methodology is based on the hypothesis that the global structural damage results from the contribution of several parameters describing the structural capacity.

The approach requires to study and model flood hazard. The distribution of the discharge is derived from the maximum discharge records and different flood scenarios are built from different flood hydrographs. The peak of these hydrographs is generated from a Monte Carlo simulation of the discharge, whereas the adopted shape of the hydrograph is derived from the reference discharge that corresponds to a historic flood. Hydraulic simulations are performed in order to estimate water level for a chosen floodplain cross section. Monte Carlo simulation is used in order to establish the distribution of the critical water level in each location in the floodplain.

To assess the masonry construction vulnerability, the proposed methodology assumes a mechanical inspection of the construction in order to establish its identity matrix.

Actually, according to each parameter describing the structural capacity, several classes can be considered. For each class, a conditional probability of failure risk is associated. Once the evolution of the failure risk according to flood level (hydraulic load) is adopted, the failure risk for a masonry construction can be assessed within a probabilistic framework: values 0 (no damage) up to 1 (collapse).

For illustration purposes, convivial interfaces are developed under MapInfo in order to map the risk at the regional scale. This global approach appears greatly appropriate to evaluate the evolution of failure risk for masonry constructions under flood hazard. GIS maps of this risk are helpful for cost optimisation in order to reduce or mitigate the flood disaster at various scales: set of structures, city, region or even country.

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