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Methodologies to assess vulnerability of structural systems

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1 Executive Summary

The main objective of this deliverable is to review and discuss the existing concepts and methodologies for physical vulnerability assessment related to four natural hazards: earthquakes, floods, landslides and volcanoes, in order to help to understand possible connections between the various practices and to provide elements useful for the physical dimension of vulnerability, which will be part of the global conceptual framework to be built within the ENSURE project. The other vulnerability concepts and definitions (e.g. socio-economic, ecological, institutional, psychological, etc.), are not addressed in this deliverable, but within ENSURE Deliverables 1.1.2 and 1.1.3.

There is no consensus on how to measure and to combine the various intrinsic components of risk, but whatever the model used to represent it, evaluation of the risk to an exposed element (or set of elements) from a hazardous event within the affected area, requires a consideration of the element's vulnerability, which expresses its propensity to suffer damage. In the technical/engineering literature for natural hazards (disaster risk reduction community), this vulnerability is generally defined on a scale ranging from 0 (no loss/damage) to 1 (total loss/damage), representing the degree of loss/potential damage/fragility of the element at risk. This concept allows to translate the assessed level of hazard to an estimated level of risk. However, in contrast with the steps concerned with the evaluation of hazard and of the elements at risk, which are generally similar for different natural phenomena, the stages related to the evaluation of vulnerability and the combination of the hazard and the vulnerability to obtain the risk (usually entitled as 'Scenario') differs significantly between hazards.

In this deliverable, we summarize the main hazard parameters, as well as methodologies used to assess vulnerability of structural systems against the four reviewed natural phenomena, giving some indication on key parameters relevant at each stage of analysis and discriminating whenever possible, between local and regional scales.

First remark drawn from this review concerns methodologies where fragility curves are used for physical vulnerability assessment. In these methodologies, the hazard aggression is generally represented by very few parameters (generally one), leading to strong uncertainties and to inadequacy of vulnerability curves.

Another important remark is that the incorporation of vulnerability within risk assessment is not developed at the same level for all reviewed hazards. Within earthquake risk assessment, the methodology consists in deriving and combining fragility curves for different types of elements at risk, in order to estimate the expected level of damage given a level of hazard, leading to an estimate of the level of risk. On the contrary, quantitative estimations are not often made for mass movements and volcanoes, where fragility curves are rarely used. For these hazards indeed, physical vulnerability is poorly modelled for a number of reasons that are essentially related to the nature of the peril itself. Their goal of assessments is different to that of earthquakes, as they usually seek to locate areas at danger for evacuation purposes or to prevent the occurrence of the possible event by using an engineering approach, rather than to estimate the possible impact of events. Therefore, there is less incentive to assess the impact of an event, by using fragility curves for example, because it may be possible to prevent its occurrence and the benefits of considering an element's physical vulnerability may be considered as limited.

2 Introduction

2.1 Schools of thought in risk assessment

When trying to define the meaning of vulnerability and risk terms, one is faced to the large variety of possible definitions, depending for instance on the "object" focus for assessment (e.g. one single building or groups of buildings? lifelines? people? etc.). There is no consensus on how to measure and to combine the various intrinsic components of risk, but whatever the model used to represent it, the result should be the same in the end. However, risk can be considered as a dynamical process with respect to time, and it can be derived basically from the convolution of two main components:

- The hazard is the probability of occurrence of a particular event (e.g. natural, technical) within a given time-period/geographic space.
- The vulnerability term represents the pre-disposition of elements at risk (buildings, infrastructures, people, services, processes, organisations, etc.) to be affected, damaged or destroyed by the event.

Recent publications also incorporate other components such as the coping capacity, the exposure -global value of elements at risk in a given territorial system-, the deficiencies in preparedness, the lack of resilience, etc. Hereafter are some of the existing definitions for risk:

- ISDR 2004:

  Risk = Hazard × Vulnerability

- UNDRO, 1979; Dilley *et al.*, 2005:

  Risk = Hazard × Vulnerability × Exposure

For instance, this definition has been used by the Technical Chamber of Greece in a project (1999-2005) aiming at proposing a national strategy for seismic retrofitting of existing buildings, with an additional coefficient **k** expressing the population density and the socio-economic significance of the function of the buildings (TCG, 2001; see section 3.6 for details):

Risk = Hazard × Vulnerability × Exposure x k

Another formulation has been also used by the Technical Chamber of Greece in the 2nd phase of the same project (see section 3.6 for details) :

Risk = (Hazard - Design Seismic Action) × Vulnerability × Exposure x (factor to adjust damage to costs)

- For Alexander (2002), the risk is the probability that some given elements may sustain a particular level of loss due to a given level of hazard, whereas "Total Risk" means the sum of predictable casualties, damages and losses:

  Total Risk = Hazard × Vulnerability × (Σelements at risk)

- Villagrán De León, 2001:

  Risk = Hazard x Vulnerability x Deficiencies in Preparedness

- Hahn, 2003:

  Risk = Hazard + Vulnerability + Exposure – Coping Capacity

- Definition used by many agencies (see Villagrán De León, 2006):

  Risk = (Hazard x Vulnerability) / Coping Capacity

In this context, the coping capacity refers to the means by which people or organisations use available resources and capacities to face adverse consequences related to a disaster.

Whatever the definition of risk, it should include the potential effects of correlative impacts (socio-economic impacts on employment, production, etc.) or induced effects (hazardous industries impacts, dams collapses, fires and explosions, etc.) and the human or social dimension through the analysis of vulnerability factors (demographic, social organisational, political, educational and cultural aspects). Hence, risk assessment requires a multi-disciplinary approach that accounts not only for physical impacts, but also for less quantifiable factors, such as social, environmental, organisational and institutional factors.

In the technical/engineering literature for natural hazards (disaster risk reduction community), vulnerability is defined on a scale ranging from 0 (no loss/damage) to 1 (total loss/damage). It represents the degree of loss/potential damage/fragility of a particular element or set of elements at risk, within the area affected by a hazardous event characterized by a given intensity or level (e.g. see ISSMGE-TC32, 2004). This approach to vulnerability estimation is referred to as *physical* or *technical*, because it is related to the physical interactions between the potentially damaging agent and the vulnerable elements of the physical environment (e.g. roads, industries, public equipments and building stock vulnerability or urban tissues, infrastructures, building aggregates and individual buildings). Moreover, the methodologies to assess physical vulnerability are strongly dependent on the observation and resolution scale:

- At the *regional-territorial scale*, the analysis includes strategic elements such as roads, industries, public equipments; building stock vulnerability is carried out on "indirect" data such as building age, site occupancy indexes, social conditions of population, illegal building concentration, and so on.
- At the *urban-local scale*, the analysis includes urban tissues, building aggregates and individual buildings as well as in-depth analyses of strategic equipments.

In this vision, the human system is the passive agent in the vulnerability estimation and the conceptual affinity between *vulnerability*, *fragility* and *loss* is pertinent, as part of the consequence estimation. Accordingly, quantification of vulnerability is made through the use of a function -called indifferently vulnerability or fragility function-, which relates the probability of reaching or exceeding a given damage state with the type and intensity of the hazard, and for different classes (characteristics) of elements at risk. This vision dominates the engineering literature on the topic, where the emphasis is on the assessment of hazards and their impacts, while the role of human systems in mediating the outcomes is downplayed.

However, the vulnerability concept has also a broad coverage in social sciences, where the human system is put on the central stage. Such a concept is related to the management of various risks that the society faces, such as poverty, loss of life and/or health, food insecurity, effects of natural and anthropic disasters, climate and ecosystem changes, etc. Therefore, research on vulnerability in social sciences is always concerned with the question: "vulnerability to what?". Although vulnerability assessment depends on the answer to this question and although there is no unique definition of vulnerability in social sciences, some general principles can be listed (Alwang *et al.*, 2001):

> *"Vulnerability is probability of loss of welfare relative to a benchmark."*
>
> *"A household is vulnerable to loss of welfare due to uncertain events."*
>
> *"Degree of vulnerability is dependent on the nature of risk and household's response capacity to risk."*
>
> *"Vulnerability is a time-dependent parameter as the risk and the household characteristics change over time."*
>
> *"The poor are more vulnerable due to their limited access to resources and limited response capacities to risk."*

Social/societal vulnerability concentrates on determining the coping capacity of the society or of the individuals in the society when a natural hazard hits. Hence, contrary to the hard sciences vision, it directs attention to the underlying structural factors that reduce the capacity of the human system to cope with a range of hazards, rather than the negative impacts following one specific hazard. Therefore, when assessing social vulnerability, the focus is on determining the indicators of society's coping capacity to any natural hazard and searching for the vulnerable groups/individuals in the whole society based on these indicators.

When considering physical vulnerability, there must be an attempt to further develop assessment tools for different types of structures (e.g. ordinary buildings, "special buildings", such as churches, theatres, public facilities, etc.) and different hazards. There are nowadays elements to build on, for instance the parameters to assess physical vulnerability are available in literature and in case studies for most hazards. However, there are still areas (e.g. landslides), where parameters useful for risk assessment are not available or not yet completely defined, or for which no consensus really exists. Unless for specific structures, physical vulnerability models can be derived and defined either on the basis of statistical processing of damage observations (with or without including the expert judgments), expert opinion, analytical/simplified-mechanical models or score assignment. All these methods are in general defined with reference to a typological classification, grouping set of exposed elements according to the peculiar features affecting their behaviour. Anyhow, there is still a need for further developments regarding the methodology, and the identified parameters have also to be corroborated through laboratory and computer simulations. A path has to be proposed in order to attain such a level of codification.

2.2 Generalities on vulnerability

Vulnerability relates to the consequences of the impact of a natural force, and not to the natural process or force itself. In practice, vulnerability and consequences are linked. There are basically two different approaches for examining vulnerability: one that is based on natural or hard sciences and another that is based on the social science methods and assumptions.

The natural science perspective of vulnerability dominates the engineering literature on the topic, where the emphasis in on the assessment of hazards and their impacts, putting aside the role of human systems in mediating the outcomes. Vulnerability in this case is defined as the physical vulnerability of the elements at risk, and it is an important component of consequence evaluation.

The social science perspective of vulnerability puts the human system on the central stage. It directs attention to the underlying structural factors that reduce the capacity of the human system to cope with a range of hazards, rather than the negative impacts following one specific hazard. There is no unique definition of vulnerability in social sciences, where different views and various definitions differentiate between natural, physical, ecological, technical, economical, social, political, institutional, ideological, cultural and educational vulnerability.

A possible link between both perspectives is the urban vulnerability concept, which is developed mainly in the geographical literature, and which tries to model vulnerability of the urban environment by considering the society's interaction with its physical environment based on a given magnitude of hazard. Here, the urban environment is considered as a system and the main focus is to determine the spatial distribution of urban vulnerability and determine the vulnerability hotspots for decision makers. Urban vulnerability combines social and physical vulnerability indicators into an overall vulnerability of the urban place (Cutter *et al.*, 2000). Since the assessment is carried out on a spatial basis, use of GIS and spatial analytical models is widespread. However, urban vulnerability assessments are essentially used for earthquake and flood hazards (e.g. FEMA-NIBS 1999; Cutter *et al.*, 2000; Rashed and Weeks, 2003; Haki *et al.*, 2004). For instance, a Urban System Exposure methodology was developed in the framework of earthquake hazard (see GEMITIS, 2003; RISK-UE 2004), in order to implement a global and integrated Risk Reduction Strategy for improving the risk-assessment effectiveness in urban areas, including the generation of crisis scenarios and mid- to long-term seismic-impact assessment.

Regarding methodologies for assessment, existent techniques to supply data about vulnerability can be variously divided. This subdivision may apply or not depending on the nature of exposed elements (i.e. single building, tunnel or bridge to town, country, region) and the spatial scale or resolution for analysis (i.e. urban/local scale 1:500 – 1: 5000 for a bloc of buildings, network junction or regional/ territorial scale 1:5.000 – 1:50.000 for a whole network system or a territory).

Some techniques may be qualified as direct, i.e. supplying an effective prevision of damages caused by the threat or indirect, i.e. establishing a vulnerability index related to the external aggression through correlations.

It is worth noting that some approaches use either quantitative techniques - such as the damage probability or equivalent deterministic relations - or qualitative techniques - describing the vulnerability in terms of "low", "middle" and "high"-.

The method used for evaluation of vulnerability may vary for different hazards and depends on the quality and quantity of available data. For large scale vulnerability evaluation, it is common to establish typologies of exposed elements and evaluate the vulnerability of a representative element exposed to the external aggression in the first step. The second step consists in attributing a vulnerability indicator (such as vulnerability index or fragility function) to the whole group of elements either uniformly or randomly in order to derive information about urban areas on the whole.

However, it is common to assess vulnerability by building fragility functions, relating the probability to reach or exceed a certain degree of damage to the force exerted by the relevant indicator(s) of aggression. The definition of this (these) indicator(s) or vector(s) and the evaluation of how relevant it is (they are) are very challenging. Whatever the methodology for the vulnerability may be, the definition of the fragility functions remains debatable, not only due to the possible complex response of exposed elements to the aggression but also due to the identification of aggression vectors themselves. For instance, the fragility curves for buildings subjected to tsunami-induced waves or flash floods ask for a pertinent choice of aggression factor(s) (water height, duration, impact-wave speed or kinetic energy?). Hence, a key step in assessing physical vulnerability is to acknowledge the type of physical stresses that will be sustained by affected structures (e.g. the stress provoked by ground shaking is different from that of pyroclastic falls, soil settlement or flooding, etc.). Furthermore, the various hazards present a variety of potential threats, according to varying levels of intensity, location and time of occurrence.

A second level at which hazard and vulnerability are interlinked relates to the possibility that given exposed objects or systems may be vulnerable, but may be considered as a threat for the community as well, in case a natural event strikes: vulnerability may well turn into more severe, increased or new natural as well as technological hazards in this case, leading to the so-called Na-Tech disasters.

Finally, another issue which is generally not envisaged in current vulnerability assessment methodologies is how to account for the combination of various natural hazards with different return periods. This is different from analyzing the impact of cascaded hazardous phenomena, as two or more hazards having a low level of intensity when considered separately, may lead however to an increased risk when occurring simultaneously. Hence, it is important to understand how vulnerability changes in the face of estimated/perceived extremes' return periods/likelihood vs. their estimated/perceived magnitude, and whether it will. Asking this question is relevant in the search for integration between the "disaster" and climate change communities. While the first has traditionally started any assessment from the characterization of the hazard (mainly in terms of probabilities), the latter has been focusing since the earliest stage of research on the adaptive capacity of communities likely to suffer the heaviest changes in the environment brought by climate change. How much those two different perspectives may learn from each other is relevant to ask, especially when uncertainties in modelling hazards (particularly enchained ones) and insurmountable difficulties in balancing between probabilities and extremes severity are taken into account.

2.3 Main objective of this deliverable

The main objective of Deliverable 1.1.1 is to highlight common grounds and main differences existing between the various practices, by reviewing the existing methodologies for physical vulnerability assessment related to natural hazards within a given territory. By pointing out the similarities and differences existing between the various hazard-specific practices, we will try to provide elements useful for the physical dimension of vulnerability, which will be part of the global conceptual framework to be built within the ENSURE project. Whenever possible, we will give some indication on key parameters that may be relevant at each stage of analysis (e.g. input parameters representing the aggression level or related to the built environment, etc.), considering four natural hazards addressed in the ENSURE project (earthquakes, floods, landslides, volcanoes). This will help to understand possible connections between the various practices. Furthermore, this review will try to highlight the possible gaps to be filled in each field (e.g. poorly developed methodologies).

3 Vulnerability in Seismic Risk Assessment

3.1 Issues about seismic hazard parameters

Earthquakes cannot be predicted or prevented. Besides, people cannot be evacuated from the areas at risk since the damages that are provoked often occur on very short time-scales, generally during the few seconds of strong shaking. Although it is feasible to alter the exposure to some extent (e.g. through land-use planning), it is then necessary to reduce the vulnerability of exposed elements, since earthquakes themselves rarely kill: it is rather the damage to a building that causes deaths and injuries. In order to accomplish this task in a cost-effective manner, quantitative risk assessments in some target regions need to be conducted (Douglas, 2007). This is all the more needed to provide estimates of loss.

Trying to characterise accurately the physical stress due to ground shaking is not an easy task, as it represents a complex loading to structures. In current practice and depending on the scale of analysis, simple methods are usually preferred to assess physical vulnerability, due essentially to computational constraints. Therefore, ground motion is generally expressed in terms of macroseismic intensity (e.g. European Macroseismic Scale (EMS98); see EMS, 1998) or Peak Ground Acceleration (PGA), which may be a more objective measure of the earthquake's severity and which is obtained by using known correlations with the macroseismic intensity. However, PGA shows almost no correlation with the damage potential of the ground motion. Another shortcoming of PGA is that it ignores the relationship between the frequency content of the ground motion and the fundamental period of vibration of the buildings. Alternative parameters have then been proposed, such as spectral acceleration or spectral displacement at the natural period of the structure (e.g. Scawthorn *et al.*, 1981; Shinozuka *et al.*, 1997; Rossetto and Elnashai, 2003), which may be in some cases, modified by a factor to account for earthquake duration. Nonetheless, when considering special buildings or critical infrastructures, the physical vulnerability assessment is generally performed by using seismic time-histories for the input motion (acceleration or displacement), together with detailed structural models. Fragility curves are then developed by using the chosen single parameter to relate the level of shaking to the expected structural damage.

However, it appears that representing the seismic aggression by only one parameter leads to strong uncertainties and hence, to an overestimation of damages when compared to observations, to a poor definition of the actual seismic aggression (e.g. amplitude, frequency content, duration, energy) and an inadequacy of capacity and vulnerability curves. The standard method which is used to develop fragility curves, neglects the scatter in the estimated damage, which means that this uncertainty cannot be propagated to the following components of the risk assessment analysis nor can its importance be estimated. For example, the same structure would be more damaged by shaking with a long duration earthquake than shaking which lasted only a few seconds even if the amplitude of expected ground shaking, characterised for example by a PGA value, is the same.

Some on-going research projects (e.g. French projects partly funded by the National Research Agency; see VEDA, 2008 and EVSIM, 2008) try to circumvent this issue and aim at decreasing the uncertainties related to the vulnerability assessment procedures, by proposing a new methodology, in which a minimum number of orthogonal ground motion parameters (at least two) are chosen to represent the strong motion, but also to account for the structural response and soil-structure interactions. Candidate parameters proposed by the VEDA project are Spectral displacements (Sd) for the first two fundamental vibration modes of the target building (Figure 1). They show also that considering **fragility surfaces**, instead of fragility curves leads to a significant reduction in the scatter for the estimated damage (Chalmers, 2008; Seyedi *et al.*, 2008). However, a balance needs to be sought between introducing some more parameters to reduce the scattering, and the uncertainty due to the estimation of these new parameters within a given earthquake scenario.

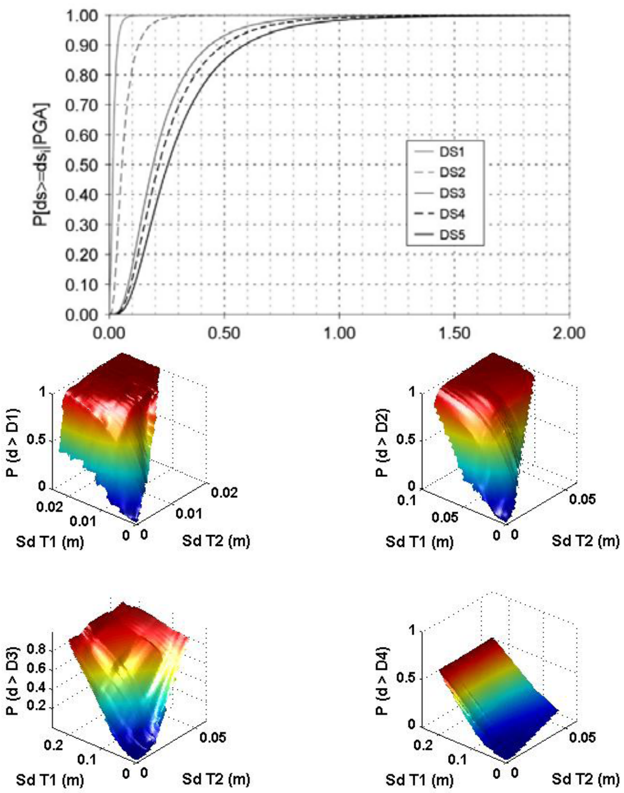


Figure 1: Vulnerability functions relating the probability of exceeding some given Damage State levels to the chosen ground motion parameters, such as: (upper) PGA (Kappos et al., 2008); (bottom) Spectral displacement (Sd) for first two fundamental vibration modes (T1, T2) of the building (Seyedi et al., 2008; Chalmers, 2008)

3.2 State-of-the-art and discussions on physical vulnerability assessment

Unlike most other types of natural hazards, the risk to earthquakes is often assessed quantitatively using vulnerability or fragility curves, which relate the probability of reaching or exceeding a specific damage (or performance) state to a given ground motion level, which should be a continuous variable. Accurate construction of fragility curves for building damage is compulsory, as human losses and injuries are generally caused by the physical damage to buildings and infrastructures.

Several classifications have been proposed in the literature to describe the numerous methods that have been used so far to assess seismic vulnerability (e.g. Lang, 2002; Calvi *et al.*, 2006). These methods can be roughly divided into two categories, which are more or less related to the space scale considered for analysis (e.g. urban level or building level, etc.). At large scale, approaches based on empirical methodologies consisting in assessing vulnerability from observations of statistical damage distributions due to past earthquakes or expert judgement are generally preferred. On the contrary, at local scale, vulnerability assessment is performed on a mechanical basis by considering individual structural features, as well as local soil characteristics, and using some detailed numerical analyses. A schematic representation of this classification, as well as the advantages and drawbacks of these two main approaches, is shown in Figure 2.

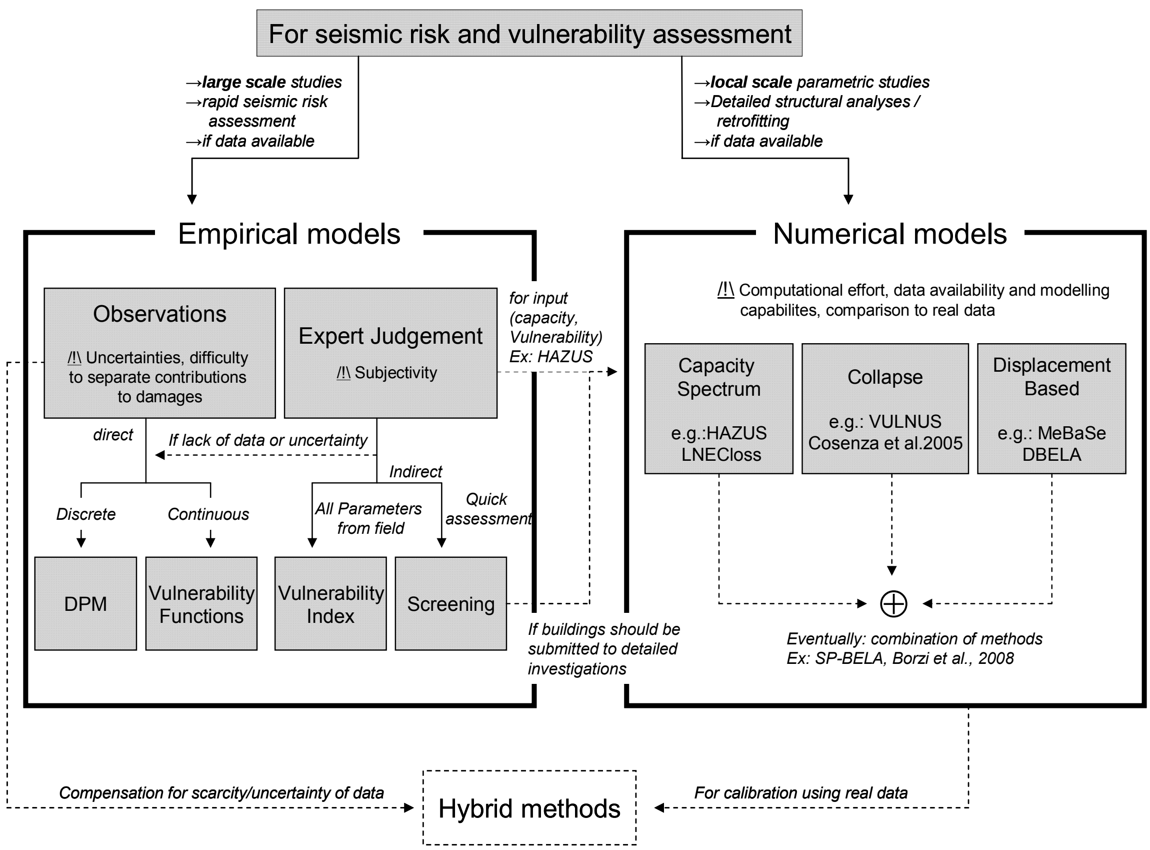


Figure 2: Schematic representation of the classical models for seismic vulnerability and risk assessment.

In the United States, the HAZUS-MH (*Hazards U.S. Multi-Hazard*; e.g. see FEMA, 2003, 2004), a multi-hazard methodology (with applications related to floods, earthquakes and hurricanes) being developed by the NIBS (National Institute of Building Science), under agreements with the FEMA (Federal Emergency Management Agency), is used to assess the earthquake loss for a built environment and population in urban areas. The last version (HAZUS-MH MR3 Patch 2) has been released very recently (September 2008). The HAZUS methodology is also used all over the world with some regional adaptations, as the fragility and capacity curves have been originally designed for US buildings and infrastructures only. Examples of these adaptations can be found in the RISK-UE project (2004), where the methodology has been successfully applied to assess seismic vulnerability for seven European cities.

In Europe, a total of 18 non commercial tools, developed over the past decade for Earthquake Loss Estimation (ELE) purposes, are currently available. These packages are being assessed in terms of their suitability to rapid post-earthquake response applications in European urban centers. In their paper, Strasser and co-workers (Strasser *et al.*, 2008) present a comparative study of the results in terms of damage and social loss estimates provided by different European ELE methodologies:

- The KOERILOSS methodology (e.g. Erdik *et al.*, 2003) is currently being developed by the Kandilli Observatory and Earthquake Research Institute (KOERI) in Istanbul. It has been used to estimate the potential losses from earthquakes in the Istanbul area. The vulnerability calculations can be based on empirical results (EMS98 intensity-based) or on a response-spectrum-based method similar to HAZUS (see section 3.2.2), considering either classical fragility functions and replacement cost ratios for loss estimation, or building fragilities and replacement cost ratios derived from a Monte Carlo simulation approach. The outputs include direct economic and social losses due to building damage.
- The SELENA tool (SEismic Loss EstimatioN using a logic tree Approach; see Molina *et al.*, 2007) developed at NORSAR, Spain, together with the International Centre for Geohazards in Norway, is dedicated to near-real-time damage assessment derived from the earthquake source parameters (location and magnitude at least). It uses the HAZUS capacity and vulnerability curves, or alternative user-defined curves, and allows for calculation of epistemic (i.e. knowledge deficit) uncertainties thanks to a logic-tree approach (Molina and Lindholm, 2005 and 2007). The ground motion model uses the standard response spectral shape constructed based on PGA and Spectral Acceleration (SA) at 0.3s and 1.0s. Guidelines are provided to infer spectral shape when only PGA values are available. This methodology has been applied to the city of Oslo, Norway (Molina and Lindholm, 2005) and the Arenella district of Naples, Italy (Lang *et al.*, 2008).
- The ESCENARIS package (e.g. RSE, 2003), which has been developed for application in Barcelona and the surrounding Catalonia region by the Geological Institute of Catalunya (IGC), proposes levels 0 and 1 analyses (see Table 2). Losses are expressed in terms of social impact (number of fatalities, injured, and homeless), as well as the number of dwellings in each damage state. The tool used by the Spanish Civil Protection for the assessment of potential earthquake losses in Spanish municipalities (SES, 2002), is based on the Level 0 ESCENARIS software.
- Finally, the LNECLOSS methodology (e.g. Campos-Costa *et al.*, 2002), is an automatic GIS-based seismic scenario loss estimate methodology, which includes

local soil effects, vulnerability analysis, as well as human and economic losses. One of the main differences between this approach and the one proposed by HAZUS is that the performance point is evaluated through an iterative equivalent non-linear stochastic methodology. It has been used in the framework of the European LESSLOSS project (2007) to evaluate losses due to earthquakes in the metropolitan area of Lisbon, Portugal (Campos-Costa *et al.*, 2006).

Hereafter, a review of the main methodologies used for seismic vulnerability assessment of buildings, is made, including statistical/empirical as well as mechanical-based approaches.

3.2.1 Statistical/empirical assessment

Statistical/empirical methodologies are widely used world over to quickly assess the seismic risk on a large scale or to decipher which buildings should be submitted to more detailed studies thanks to *screening methods*. They can also be used for calibrating numerical studies. **The main drawbacks** of these approaches **lie in the lack of data** (especially for high magnitude earthquakes) **and heterogeneity** (both in time and space), as well as their inability to assess the physical implications of the various characteristics of exposed elements (buildings, etc.) in an accurate and straightforward manner. This is a severe limitation, in particular, when evaluating retrofit options.

Hereafter, we recall the main methodologies used in practice, based on statistical/empirical approaches.

- **Screening and vulnerability index methods**

The *vulnerability index* and *screening* methods consist in gathering quantitative information on a building or stock of buildings, by using vulnerability-assessment forms including predetermined set of parameters, such as quality of materials, type of foundations, number of storeys, state of conservation, or stiffness of the structure. Depending on the parameters value, a score is attributed to each building to quantify the level of damage likely to be sustained according to the severity of ground motion. The main objective of these procedures is to determine whether a particular building should or should not be subjected to a more detailed investigation, using the next screening level or some numerical analyses (mechanical approaches). It has an important role to play for prioritising buildings for seismic retrofit. Moreover, they are qualified as *indirect* methods, as no direct relationship between the seismic action and the observed damage is provided: the damage index or score is determined on the basis of building observations only (data collected from surveys, expert judgment).

The GNDT (*Gruppo Nazionale per la Difesa dai Terremoti*, http://emidius.mi.ingv.it/GNDT) vulnerability index method (Augusti and Ciampoli, 2000; Gent Franch *et al.*, 2008) has been extensively used in Italy in the past few decades. In this approach, the index (or score) of each building is evaluated by calculating a weighted sum of the various parameters. The vulnerability model is calibrated on the observed data from past earthquakes to get a good correlation between vulnerability index, damage and macroseismic intensity or PGA.

This method is well suited in the case of urban environments having no detailed micro seismicity data, but good estimates on the seismic intensity, has been successfully applied to seven European cities in the RISK-UE European project (e.g. see Lantada *et al.*, 2008, Kappos *et al.*, 2008).

Moreover, the vulnerability index approach is easily implemented within a GIS-based multirisk evaluation framework, which are generally used to draw up seismic scenarios for urban areas and consist in simulating a single earthquake, usually the reoccurrence of the main historical event in the area, and in giving a realistic distribution of the consequences due to this seismic event (e.g. Sedan and Mirgon, 2003).

Rapid screening versions of these approaches can be adopted to quickly assess the seismic performance of buildings (e.g. Sucuoglu *et al.*, 2007). A common example is the LSU-vulnerability survey of Catania in Sicily (Faccioli *et al.*, 1999). Following the ATC-21's procedure (ATC-21, 1988), only some of the eleven parameters needed to calculate the index have been directly determined from the field survey (e.g. present state of the building or type of structural resisting system). The remaining parameters were based on a range of values deduced from historical considerations or recent construction practices in the studied region. This led to lower and upper bounds of the vulnerability index.

In Canada, the primary methodology for seismic screening is given in the 1993 manual developed by the National Research Council of Canada (see NRCC, 1993). It has been modified to be in conformity with the current (2005) edition of the National Building Code of Canada (NBCC, 2005).

In Japan, the JBDPA (*Japanese Seismic Index Method*, JBDPA, 1990) describes three seismic screening procedures to estimate the seismic performance of a building, which is represented by a *seismic performance index*, function of parameters such as strength, ductility, stiffness, number of storeys, or time-dependent deterioration of the building. This index is compared to a *seismic judgement index*, to determine whether the structure is safe for a given ground motion.

This method has been adapted for Turkish buildings (Seismic Safety Screening Method SSSM, Ozdemir *et al.*, 2005). Other procedures include the definition of a *Priority Index*, function of area of walls, infill panels, columns and floor (Hassan and Sozen, 1997) or a *capacity index* (Yakut, 2004) considering the orientation, size and material properties of the components comprising the lateral load resisting structural system.

The FEMA-154 method (see FEMA, 1988) has also been widely used to rapidly compile a building database from field observations, especially in the U.S. (e.g. McCormack and Rad, 1997, for the city of Portland, Oregon).

- **DPM (Damage Probability Matrices) and vulnerability functions**

Damage Probability Matrices give in a discrete form the probability Pij of reaching a level of damage i for a given earthquake intensity j and class of buildings (e.g. Whiteman *et al.*, 1973; Di Pasquale *et al.*, 2005). This assumes that buildings with a given structural typology should statically display the same level of damage when submitted to earthquakes with similar intensities. It is considered as a *direct* method because a direct relationship between observed damage and building typology is obtained.

The first DPM were based on damage data from past earthquakes (e.g. Whiteman *et al.*, 1973). However, the derivation of seismic vulnerability functions requires the availability of a large amount of statistical information. This is often not the case in practice: large magnitude earthquakes are not so frequent; buildings features are different from one country to another, and evolution of these characteristics with time is difficult to be accounted for. Expert judgement has been introduced afterwards (ATC-13, 1985) to deal with the case of scarce observational data or too high uncertainties in building damage classification. However, this method is subjective, and its reliability can be questioned from a statistical point of view since experts might influence each other.

Damage Probability Matrices can be represented graphically by continuous vulnerability (or fragility) functions (generally curves). As already mentioned, these curves relate the probability of reaching or exceeding a specific damage state to a given ground motion level, which is generally expressed in terms of macroseismic intensity (e.g. EMS98, see Table 1) or Peak Ground Acceleration (PGA). As already mentioned in section 3.1, such a methodology, which is based on a single-parameter representation for the seismic aggression may lead to strong uncertainties in the estimation of damages when compared to observations, due to a poor definition of the actual seismic aggression.

Table 1: DPM for the Irpinia earthquake (Giovinazzi and Lagomarsino, 2001): probability of reaching a specific damage state for a given macroseismic intensity and depending on the building class.

EMS Intensity	V	VI	VII	VIII	IX	X
Class A	0.020	0.284	0.423	0.726	0.860	0.923
Class B	0.010	0.185	0.284	0.501	0.700	0.850
Class C	0.005	0.065	0.167	0.334	0.500	0.700

Finally, a main drawback of the DPM is that they are *vague*: qualitative terms, such as *few*, *many*, or *most* rather than numerical quantities are given to describe the expected damage. They are also *incomplete*: no information is given within a given class and level of intensity, for some damage grades (only the most common and easily observable situations are considered by the scale). Giovinazzi and Lagomarsino (2004) have proposed to improve the methodology, by translating the qualitative terms (*few*, *many*, *most*) into a quantitative manner, applying the Fuzzy Set Theory and assuming a beta damage distribution (Figure 3). Details of this methodology are given in section 3.2.2.

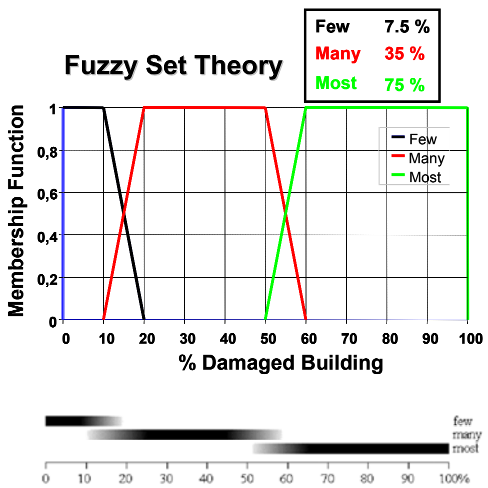


Figure 3: Application of the Fuzzy Set Theory to translate the qualitative terms used for damage description into a quantitative graphical manner (Giovinazzi and Lagomarsino, 2004)

3.2.2 Numerical/mechanical-based assessment

Mechanical approaches are able to provide a more accurate and straightforward assessment of the buildings behaviour under seismic ground motions, as they use vulnerability curves generally derived from numerical analyses performed on either detailed or simplified structural models (see schematic methodology in Figure 4). They are preferably used at local scale, due the substantial computational effort involved in the case of large study areas. However, they can be used in parametric studies for urban planning or retrofitting matters.

The reliability of simple mechanical models is currently being questioned, as arising of significant discrepancies have been observed, depending on the choices of the analysis method and assumptions. For instance, soil-structure interactions including soil non linearity, are still not currently used in practice, whereas a number of known effects (e.g. Pitilakis *et al.*, 2005a; Lopez-Caballero and Modaressi Farahmand-Razavi, 2008) may change the outcome of analysis (Saez *et al.* 2006), such as a possible increase of the demand. For these reasons, more sophisticated analyses are preferred when accurate vulnerability assessment of a single building (e.g. churches, schools, hospitals, bridges) is required. In this case, a detailed 3D numerical analysis of the structure is envisaged (Figure 5).

Whatever the complexity of the models, a comparison with damage observations is important for validation. This comparison may not be easy in practice, in particular because of the uncertainties relative to ground motions (e.g. Crowley *et al.*, 2008b) and due to a lack of data or subjectivity in expert judgments. *Hybrid* models can be found, where simplified methods are combined with observations (e.g. Nagato and Kawase, 2004; Kappos *et al.*, 2006) and specific calibration procedures may be used for the structural models, while avoiding excessive computational effort.

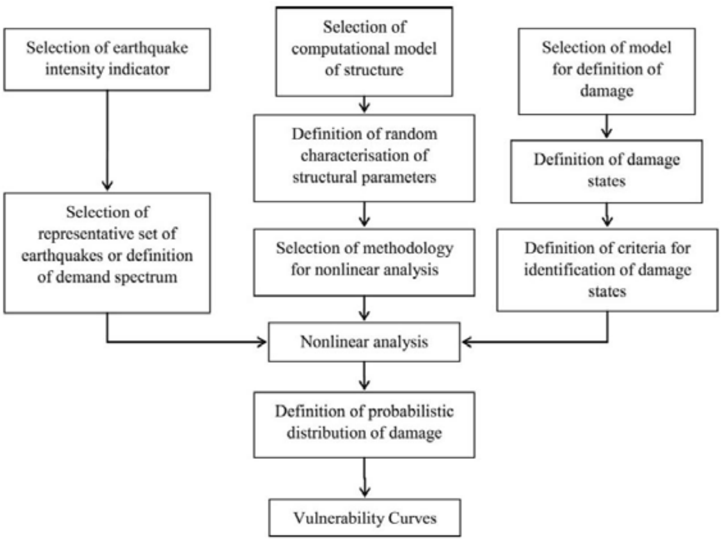


Figure 4: Schematic representation of the methodology adopted in mechanical approaches (adapted from Dumova-Jovanoska, 2004)

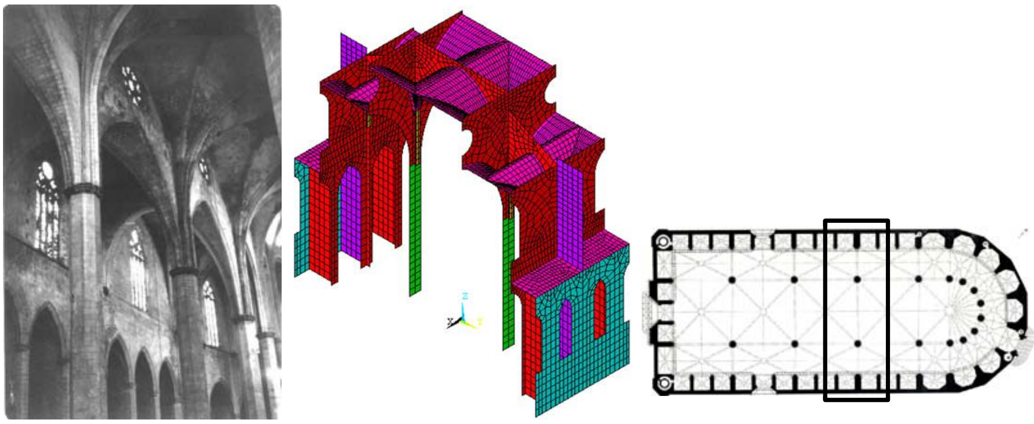


Figure 5: Detailed 3D analysis of the Santa Maria del Mar church in Barcelona, during the RISK-UE project (source: Lagomarsino, 2006a).

Hereafter, we recall the main methodologies used in practice, based on numerical/mechanical approaches.

- **Capacity Spectrum-Based methods**

The Capacity Spectrum Method (CSM) is a performance-based analysis technique, in which displacements constitute the demand parameter. In this approach, a nonlinear static analysis (so called *pushover* method) is performed to determine the building capacity to sustain a given ground motion (or demand), based on a simplified mechanical approach in which an equivalent single-degree-of-freedom model is used to represent the target structure and is subjected to an increasing lateral static load (Freeman *et al.*, 1975; Freeman, 1978). The performance point of a single building or a building typology is estimated by the intersection of the capacity curve, relating the total lateral shear force to the lateral roof displacement or inter-storey drift, with the seismic demand curve in a spectral acceleration-spectral displacement form (Figure 6). The demand curve is generally reduced to account for the inelastic behaviour of the system (damping) and the degradation with time. The spectral displacement values obtained for the performance point of a specific building class, is used as input into fragility curves for the different damage states. These curves are often assumed log-normal, with a standard deviation including the variability for structural damage state, capacity curve and demand spectrum. This method has been used and developed originally in HAZUS methodology (e.g. see FEMA-NIBS, 1999; FEMA 2001, 2003; Olshansky *et al.*, 2004).

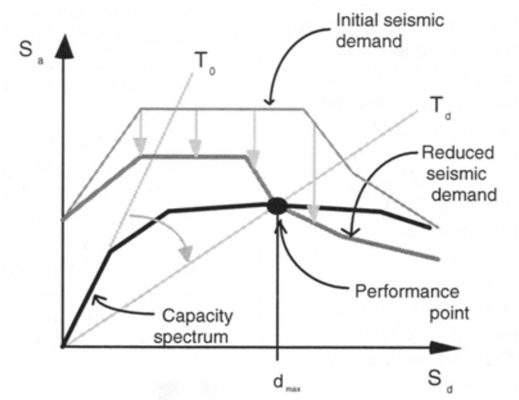


Figure 6: Determination of a building performance point for a given seismic demand

- **Collapse Mechanism-Based methods**

These methods can be used to determine the most probable collapse mechanism by calculating indexes or *collapse multipliers* (see Bernardini *et al.*, 1990), which describe the geometrical and mechanical characteristics of a building or groups of buildings.

In the VULNUS procedure (Bernardini, 1999), the probability of exceeding the collapse limit state for a group of buildings is a function of four parameters: the collapse multipliers for in-plan and out-of-plan behaviour, the mean absolute acceleration response of the building (maximum base shear divided by total weight), as well as an uncertainty factor expressed using fuzzy-set theory as a combination of seven weighted vulnerability factors, such as walls system quality or interactions between soil and foundations. An advantage of this method is that it allows classifying the surveyed buildings thanks to the computation of an absolute vulnerability measure. One of the drawbacks is that uncertainties in the geometrical and mechanical properties are not accounted for.

The FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) method (D'Ayala and Speranza, 2002) has been developed to assess the seismic vulnerability of masonry historic buildings. The principle is to determine the most probable failure mechanism by calculating the associated load factor or collapse multiplier. The analysis is performed by means of an equivalent static method. The procedure includes gathering of data on the field via an electronic form, computation of the equivalent shear capacity for each façade wall, and classification of the collapse mechanisms according to its value. While this method has some advantages (like inclusion of a friction coefficient), it suffers several drawbacks. The uncertainties in the geometrical and mechanical properties of buildings are not taken into account, and no clear indication is given on how to assess the probability of exceeding given limit states.

A more satisfactory framework for the treatment of uncertainties has been developed by Cosenza *et al.* (2005) for the capacity assessment of reinforced concrete buildings. In this approach, the evaluated capacity of a building class (determined in terms of base shear coefficient and global drift) is represented by a number of responses due to the different geometrical and mechanical properties, which are studied through the Monte Carlo simulation technique to calculate the probability of having a capacity lower than an assigned threshold value. However, like in the FaMIVE procedure, no straightforward explanation is given on how to calculate the probability of exceeding a given level of damage.

- **Fully Displacement-Based methods**

In these methods, displacements are considered as the fundamental indicator of damage. The non-linear behaviour of buildings is not derived from pushover curves but from displacement capacity and period of vibration of a single-degree-of-freedom (SDOF) structure equivalent to a multi-degree-of-freedom (MDOF) system.

The DBELA (Displacement-Based Earthquake Loss Assessment) is an advanced probabilistic loss estimation tool currently being developed at the ROSE School/EUCENTRE in Pavia (Crowley *et al.*, 2004, 2006, 2008a). The procedure, which is a refined version of the approach proposed by Calvi (1999) for reinforced concrete buildings, is based on a mechanical approach derived from the Direct Displacement-Based Design method (e.g., Priestley, 2003). It uses vulnerability functions considering displacement response spectrum as demand parameter specified by user at various periods and different limit states. The demand spectrum is derived for classes of buildings grouped by structural types (materials/geometries) and failure mechanism (see Bal *et al.*, 2008 for details). The capacity functions for building classes are expressed in terms of period through a relationship between period and height of the buildings. Maxima and minima are applied to the period and displacement to account for epistemic uncertainties. The subsequent *capacity area* is plotted against period along with the demand spectrum to determine the proportion of buildings exceeding the limit state (Figure 7). Future developments of DBELA should include, among others, the ability to attain a collapse failure mechanism at any storey within the building (Crowley *et al.*, 2008a).

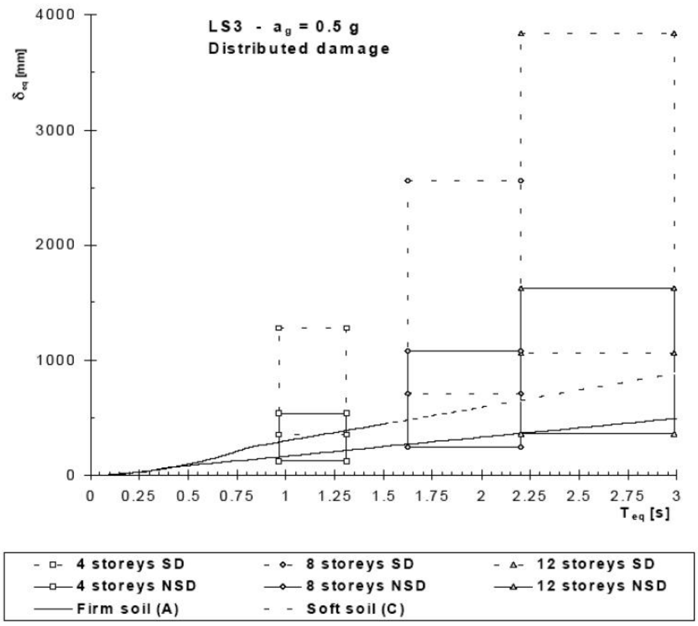


Figure 7: Example of the intersection of capacity areas and demand spectrum (Calvi, 1999)

The MeBaSe procedure (Mechanical-Based procedure for the Seismic risk Estimation of unreinforced masonry buildings), a procedure carried out in parallel by different authors (Restrepo-Vélez, 2005; Modena *et al.*, 2005), includes also out-of-plan mechanisms and displacement-period dependency, which were not considered by Calvi (1999).

Finally, the Simplified Pushover-Based Earthquake Loss Assessment method (SP-BELA), proposed by Borzi *et al.* (2008) and Crowley *et al.* (2008a), combines a displacement-based approach closely related to DBELA with a simplified collapse mechanism-based method similar to the one proposed by Cosenza *et al.* (2005), in order to assess the vulnerability of buildings classes at different limit states. According to Borzi and co-workers (Borzi *et al.*, 2008), this method has the advantage of allowing dynamic analysis for a large number of structures within a reasonable time span. Moreover, comparison with finite elements-based analyses seems to show that SP-BELA gives better predictions of a building behaviour than DBELA (Crowley *et al.*, 2008a). However, the authors concede that further improvements (such as the inclusion of the effect of infill panels, have to be done before using this method in large scale loss assessment studies (Borzi *et al.*, 2008).

3.3 Methodologies for buildings

The methodology used for assessment (e.g. statistical/empirical, numerical) essentially depends on the scale of investigation. At large scale for instance, vulnerability assessment requires the use of methodologies based mainly on statistical data together with empirical models derived from *facts* and/or *experience*, deduced from data collected during surveys (e.g. field, space, etc.) or from expert judgements. Detailed or simplified mechanical models are preferred when sufficient observations data is available, and rather for local scale analyses.

First, the methodology consists in establishing an exhaustive inventory of exposed elements, which will be categorized by classes (typology):

- Strategic (rescue/emergency) or public structures: schools, hospitals, fire department, civil protection;
- Ordinary buildings: number and volume of dwellings, inhabitants, commercial activities, functions, presence of people in the different hours of the day, etc.;
- Other special buildings: industrial plants;
- Historical buildings (Cultural Heritage).

The classification uses the Building Typology Matrix (BTM) of the European Macroseismic Scale (EMS98, Figure 8), adding information on: types of floors in masonry buildings, particular typologies of R.C. buildings, number of stories, earthquake resistance design, etc. Basically, six vulnerability classes (from A to F) of decreasing vulnerability are defined: A, B and C classes for ordinary buildings designed without explicit control of seismic resistance; D, E and F classes for buildings with levels of progressively increasing protection.

Then, exposure data is geo-located using a GIS-based map, considering various reference units for representation:

- each single building
- a group of buildings (a block, a census tract)
- larger geographic areas (a district, postal code, a municipality, ...).

For larger geographic areas (e.g. a town), homogeneous units are defined allowing to criteria related to urban planning, building age or function (e.g. residential or commercial areas, historical centers, etc.).

	Building typology
	Unreinforced Masonry
M1	Rubble stone
M2	Adobe (earth bricks)
M3	Simple stone
M4	Massive stone
M5	U Masonry (old bricks)
M6	U Masonry - r.c. floors
	Reinforced /confined masonry
M7	Reinforced /confined masonry
	Reinforced Concrete
RC1	Concrete Moment Frame
RC2	Concrete Shear Walls
RC3	Dual System
S	**Steel Typologies**
W	**Timber Typologies**

Earthquake Resistant Design			
Ductility Class		**Strength**	
WDC	Without ductility class	-I	Zone I
MDC	Medium ductility class	-II	Zone II
HDC	High ductility class	-III	Zone III

	Horizontal structures typology
M_.w	Wooden slabs
M_.v	Masonry vaults
M_.sm	Composite steel and masonry slabs
M_.ca	Reinforced concrete slabs

	Sub -typologies
RC1.i	Infill wall
RC_.p	pilotis

Figure 8: Extracts from the Building Typology Matrix of the European Macroseismic Scale (adapted from RISK-UE, 2004)

The objective of vulnerability assessment is to give the probability distribution of each expected damage state. The approach to be considered for analysis depends on the information level (Table 2) for available exposure data (e.g. see the RISK-UE project, 2004):

- Level 0: when only the number of buildings in a geographic area is available, together with a statistical knowledge of the main characteristics (construction material, number of floors, built volume, inhabitants);
- Level 1: availability of a database with poor information on each single building, eventually aggregated in small areas (census tract) (typology, age of construction, etc.);
- Level 2: information from a vulnerability survey by proper forms (floor's typology, regularity in plan and in elevation, pilotis, details - short columns, etc.).

Level 2 is generally preferred for the assessment at smaller space scales, when numerical structural analyses can be performed in a more accurate manner and for fewer target buildings.

Table 2: Holistic approach used for vulnerability assessment at large scale (adapted from RISK-UE 2004 and Lagomarsino, 2006a).

Analysis Level	Current Buildings	Monuments	Macroseimic approach	Mechanical approach
Level 0	Building's number and statistical knowledge of the main features	Typology (church, palace, tower, castle, etc.) and expert judgment	Distribution of the vulnerability classes and vulnerability index	Capacity curve representative of the group of buildings
Level 1	Existing database with poor information on each building, aggregated in small areas	Few data related to the seismic behaviour, obtained by a quick vulnerability survey	Vulnerability index for each single building or group, refined by taking into consideration behaviour modifiers	Capacity curve obtained from the vulnerability index, considering the known structural parameters
Level 2	Vulnerability survey with information on the typology and the geometrical, structural and technological features	More detailed information related both to the building geometry and the vulnerability elements in each macroelement	Vulnerability index for each single building, by an accurate assessment (survey of macroelements)	Capacity curve derived from mechanical methods (e.g. equilibrium limit and/or numerical FEM analyses)

Building damage and loss assessment requires building fragility models that identifies different building damage states. Commonly used damage state labels describe qualitatively the state of the structural systems following an earthquake action. They are formulated based on in-city building inspection and identification of grades of inflicted damage/destruction. Actual building damage varies as a continuous function of earthquake demands. For practical purposes it is usually described by five to six damage states (Table 3).

Table 3 – Earthquake damage grading for buildings (source: RISK-UE, 2004)

Damage Grade	Damage Grade Label			Description
	LM1	LM2	FEMA-NIBS (HAZUS)	
0 (D0)	None	None	None	No damage
1 (D1)	Slight	Minor	Slight	Negligible to slight damage
2 (D2)	Moderate	Moderate	Moderate	Slight structural, moderate nonstructural
3 (D3)	Substantial to heavy	Severe	Extensive	Moderate structural, heavy nonstructural
4 (D4)	Very heavy	Collapse	Complete	Heavy structural, very heavy nonstructural
5 (D5)	Destruction			Very heavy structural, total or near total collapse

3.3.1 The macroseismic approach

The macroseismic approach is based on the observed vulnerability through damage assessment data collected after earthquakes of different intensities related to a macroseismic scale (e.g. EMS98). It corresponds to the RISK-UE LM1 method (RISK-UE, 2004).

The membership of a building to a specific vulnerability class of the BTM may be defined by a vulnerability index V_I represented by a membership function. Its values are arbitrary, as it represents only a score that quantifies the seismic behaviour of the building class. The membership functions of the six vulnerability classes have a plausible (χ=1) and linear possible ranges, defining the transition between two adjacent classes (Figure 9).

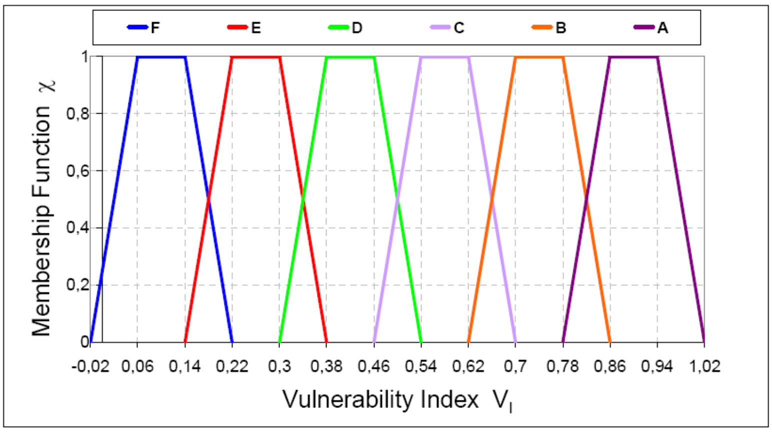


Figure 9: Membership functions of the vulnerability index for six classes of buildings (source: RISK-UE, 2004)

In fact, for each building type is associated a series of vulnerability indices obtained by proper survey (Table 4):

- V_I*: the most probable value for the vulnerability index V_I;
- [V_I^-, V_I^+]: bounds of the plausible range of the vulnerability index V_I (usually obtained as 0.5-cut of the membership function);
- [V_I^{min}, V_I^{max}]: upper and lower bounds of the possible values of the vulnerability index V_I.

Table 4 – Vulnerability indices for BTM buildings (source: RISK-UE, 2004)

Typology	Description	V_I representative values				
		$V^{min}_{I,BTM}$	$V^{-}_{I,BTM}$	$V^{*}_{I,BTM}$	$V^{+}_{I,BTM}$	$V^{max}_{I,BTM}$
M1.1	Rubble stone, fieldstone	0.62	0.81	0.873	0.98	1.02
M1.2	Simple stone	0.46	0.65	0.74	0.83	1.02
M1.3	Massive stone	0.3	0.49	0.616	0.793	0.86
M2	Adobe	0.62	0.687	0.84	0.98	1.02
M3.1	Wooden slabs	0.46	0.65	0.74	0.83	1.02
M3.2	Masonry vaults	0.46	0.65	0.776	0.953	1.02
M3.3	Composite steel and masonry slabs	0.46	0.527	0.704	0.83	1.02
M3.4	Reinforced concrete slabs	0.3	0.49	0.616	0.793	0.86
M4	Reinforced or confined masonry walls	0.14	0.33	0.451	0.633	0.7
M5	Overall strengthened	0.3	0.49	0.694	0.953	1.02
RC1	Concrete Moment Frames	-0.02	0.047	0.442	0.8	1.02
RC2	Concrete shear walls	-0.02	0.047	0.386	0.67	0.86
RC3.1	Regularly infilled walls	-0.02	0.007	0.402	0.76	0.98
RC3.2	Irregular frames	0.06	0.127	0.522	0.88	1.02
RC4	RC Dual systems (RC frame and wall)	-0.02	0.047	0.386	0.67	0.86
RC5	Precast Concrete Tilt-Up Walls	0.14	0.207	0.384	0.51	0.7
RC6	Precast C. Frames, C. shear walls	0.3	0.367	0.544	0.67	0.86
S1	Steel Moment Frames	-0.02	0.467	0.363	0.64	0.86
S2	Steel braced Frames	-0.02	0.467	0.287	0.48	0.7
S3	Steel frame+unreinf. mas. infill walls	0.14	0.33	0.484	0.64	0.86
S4	Steel frame+cast-in-place shear walls	-0.02	0.047	0.224	0.35	0.54
S5	Steel and RC composite system	-0.02	0.257	0.402	0.72	1.02
W	Wood structures	0.14	0.207	0.447	0.64	0.86

When a building typology is directly identified within the BTM as given in Table 4, the vulnerability index values (V_I, V_I^-, V_I^+ V_I^{min}, V_I^{max}) are univocally attributed. If the available data are not sufficient to perform a direct typological identification, more general categories are defined based on experience and knowledge of the construction tradition. The typological distribution inside the defined categories is supposed to be known.

For each category the vulnerability index values are evaluated knowing the percentage of the different building types recognized inside the category:

$$V^*_{I,C^J} = \sum_t p_t V^*_{I,BTM^J}$$

where p_t is the ratio of buildings inside the category C^J supposing to belong to the building type BTM^J.

A Regional Vulnerability Factor ΔV_R is introduced to take into account the particular quality of some building types at a regional level. It modifies the vulnerability index V_I* based on expert judgment or accounting for observed vulnerability. The factor ΔV_R can be introduced both referring to a typology or to a general category.

Finally, some behaviour modifiers V_m can be introduced as well and the overall score ΔV_m is evaluated by summing all the modifier scores, with additional weighing if a set of buildings is considered (Table 5).

Table 6 summarizes the overall procedure to obtain the final vulnerability index $\overline{V}_I$.

Table 5 – Examples of vulnerability modifying scores (V_m), in the case of masonry buildings (source: RISK-UE, 2004)

Vulnerability Factors	*Parameters*	
State of preservation	Good maintenance Bad maintenance	-0,04 +0.04
Number of floors	Low (1 or 2) Medium (3, 4 or 5) High (6 or more)	-0.02 +0.02 +0.06
Structural system	Wall thickness Distance between walls Connection between walls (tie-rods, angle bracket) Connection horizontal structures-walls	-0,04 ÷ +0,04
Soft-story	Demolition/ Transparency	+0.04
Plan Irregularity	…	+0.04
Vertical Irregularity	…	+0.02
Superimposed floors		+0.04
Roof	Roof weight + Roof Thrust Roof Connections	+0.04
Retrofitting interventions		-0,08 ÷ +0,08
Aseismic Devices	Barbican, Foil arches, Buttresses	
Aggregate building: position	Middle Corner Header	-0.04 +0.04 +0.06
Aggregate building: elevation	Staggered floors Buildings of different height	+0.02 -0,04 ÷ +0,04
Foundation	Different level foundation	+0.04
Soil Morphology	Slope Cliff	+0.02 +0.04

Table 6 – Procedure to estimate the final vulnerability $\overline{V}_I$ (source: RISK-UE, 2004)

		Single Building	Set of buildings
V_I^*	Typology $V^*_{I\,BTM}$	Values from Table 2.2	$V^*_{I_{BTM}}[Set] = \sum_t q_t \cdot V^*_{I_{BTM}}[S.b.]$ q_t is the ratio of buildings inside the set supposing to belong to a certain building type
	Category $V^*_{I\,C}$	$V^*_{I_{cat}\,i} = \sum_t p_t \cdot V^*_{I_{BTM}\,t}$ p_t is the ratio of buildings inside the category C_i supposing to belong to a certain building type	$V^*_{I_{cat}}[Set] = \sum_c q_c \cdot V^*_{I_{cat}}[S.b.]$ q_c is the ratio of buildings inside the set supposing to belong to a certain building category
ΔV_m	Typology/Category	$\Delta V_m = \sum V_m$	$\Delta V_m = \sum_k r_k V_{m,k}$ r_k is the ratio of buildings characterized by the modifying factor k, with score $V_{m,k}$
ΔV_R	Typology/Category	ΔV_R Established on base of an expert judgment or available observed vulnerability data	$\Delta V_R = \sum_t r_t \Delta V_{R\,t}$ Where r_t is the ratio of buildings recognized as belonging to a specific typology t affected by the recognized $\Delta V_{R\,t}$
$\overline{V}_I = V_I^* + \Delta V_R + \Delta V_m$			

For each intensity, a mean damage grade μ_D (a continuous parameter, 0< μ_D <5) is calculated, which correlates the seismic input (e.g. macroseismic intensity I or PGA properly converted into I) to observed damage grades, D_k (k = 0,…, 5). A mean semi-empirical vulnerability curve (e.g. Figure 10), which is expressed in terms of μ_D, is derived for each building class, considering the final vulnerability index $\overline{V}_I$ and the ductility index β, which determines the rate of damage with intensity (e.g. β=2.3):

$$\mu_D = \left[1 + \tanh\left(\frac{I + 6.25\overline{V}_I - 13.1}{\beta}\right)\right]$$

Finally, a beta distribution is used to compute the damage distribution (DPM and fragility curves) for each vulnerability class.

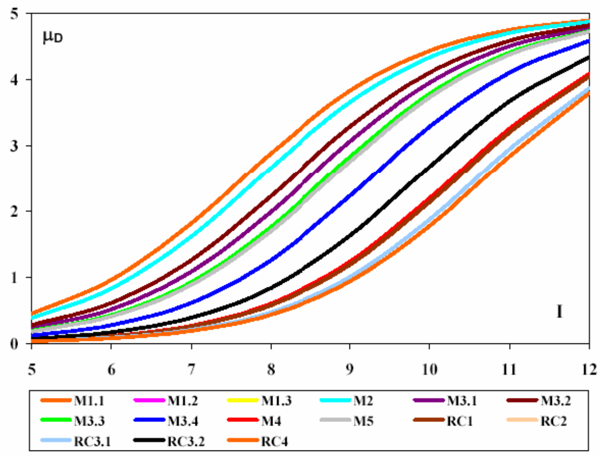


Figure 10: Mean semi-empirical vulnerability functions for common building typologies of the BTM (from RISK-UE, 2004)

3.3.2 The mechanical approach

The mechanical approach is a performance-based damage estimation process (CSM) and corresponds to the RISK-UE Level 2 (LM2) method (see details in RISK-UE, 2004). The procedure is the following (Figure 11):

1. Selection of the building model from the BTM allowing to structural characteristics (construction material, structural system, height class, expected/identified design and performance level, etc.);
2. For the selected model, definition of the capacity model and conversion into a capacity spectrum;
3. Determination/modelling of building's site-specific demand spectrum;
4. Calculation or modelling of the expected buildings' response (performance) by intersecting capacity and demand spectra, and determination of the intersection (performance) point;
5. From the corresponding fragility model, estimation of conditional probabilities that for a determined performance point the building or building group will exhibit certain damage states.

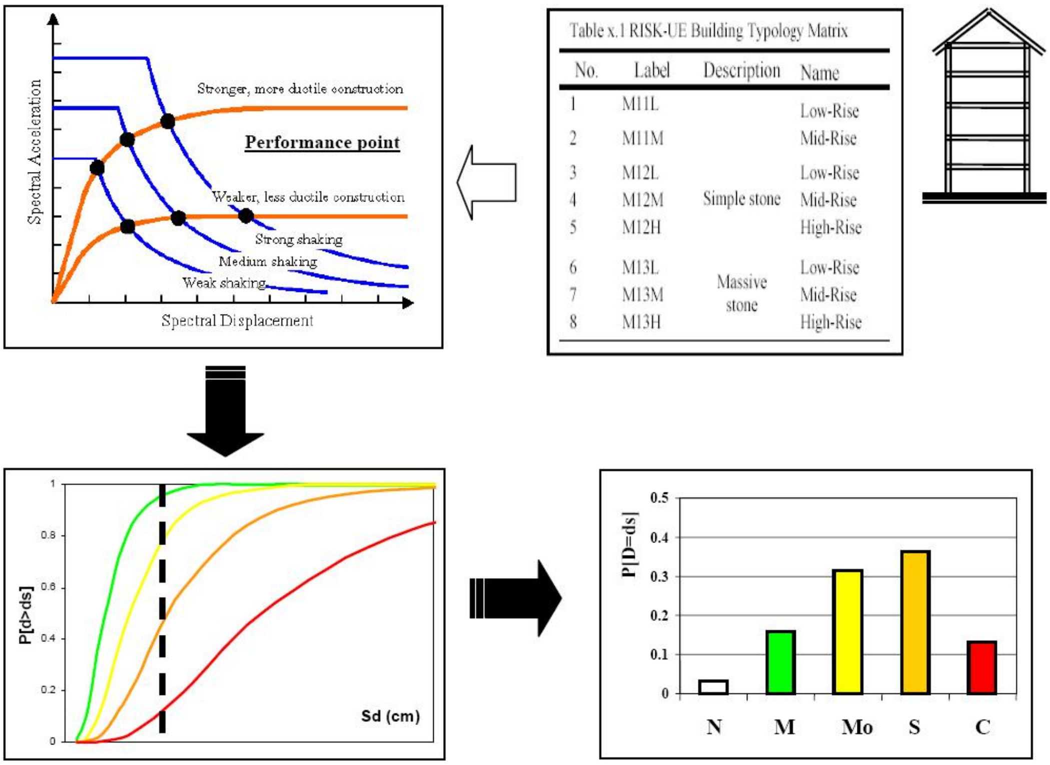


Figure 11: The damage estimation process as adopted by RISK-UE (2004)

3.4 Methodologies for lifeline elements and infrastructures

When considering a lifeline component crossing a slope or unstable area, the damage caused by seismic ground motion and associated displacements, is mainly estimated through the use of empirical (based on reported damage during past earthquakes and engineering judgment) vulnerability curves, together with the definition of different levels to categorize damage. However, such curves are still missing at the European level, due essentially to the limited damage data and the lack of homogenized inventory.

Depending on the lifeline element at risk, different methodologies are adopted for vulnerability estimation. In the following sections, we present a short review drawn mainly from LESSLOSS Deliverable 16 (2006) and 93 (2007), regarding the available empirical vulnerability models for lifeline elements, namely pipelines, roads and tunnels, due to ground failure, e.g. caused by earthquakes and/or landslides.

3.4.1 Pipelines

Damage to pipelines is quantified through the Repair Ratio (RR/km), which represents the number of repairs per kilometer of pipeline. Five damage states are considered for analysis (Table 7) and two types of analyses can be performed, depending on the intensity of the demand: for relatively small seismic motions, ground shaking parameters are used (acceleration, velocity, strain), while for larger input levels, where Permanent Ground Displacements (PGD) occur, these latter are used as input parameters.

Table 7: Damage states for pipelines, according to the Repair Ratio, i.e. the repair rate per km (adapted from LESSLOSS Deliverable 93, 2007).

Description of damage state	Repair Ratio
No Damage	0 ≤ RR ≤ 0.001
Low	0.001 ≤ RR ≤ 0.01
Low-Moderate	0.01 ≤ RR ≤ 0.1
Moderate	0.1 ≤ RR ≤ 0.7
Moderate-High	0.7 ≤ RR ≤ 1.4
High	1.4 < RR

For the first type of analysis, different empirical relationships can be used to estimate the Repair Ratio, using maximum values of ground velocity (PGV) or acceleration (PGA), as well as the soil axial strain, calculated along the studied cross section (e.g. see Table 8).

- When using the PGV, which is the parameter conventionally used in current practice (Pitilakis *et al.*, 2005b), the estimated damage level tends to be lower and fairly evenly distributed along the cross-section;
- When using the PGA (earlier fashion), damages may prove uneven and enter into higher levels near the toe of the slope;
- Using axial ground strains, which is probably the most recent approach and is still being developed (Paolucci and Pitilakis, 2007), calculated repair ratios

may vary much more along the section and are much higher, particularly at the toe. So this method tends to be more conservative and also appears to be more capable of discriminating between different damage levels along the 2D section. Overall, it appears to provide a satisfactory way of estimating damage, at least in the absence of more relevant data.

Table 8: Empirical vulnerability equations used for the estimation of pipeline Repair Ratio in case of ground shaking (adapted from LESSLOSS Deliverable 93, 2007).

Empirical Relationship for Repair Ratio RR	Ground motion parameter	Reference
	PGA (g)	
$RR = 1.698*10^{-16}*PGA^{6.06}$	Cast-iron	Isoyama & Katayama (1982)
$RR = 2.88*10^{-6}*(PGA-100)^{1.97}$	Diameter =100-150mm, non-liquefiable alluvia (cast-iron)	Isoyama *et al*. (2000)
	PGV (cm/sec)	
$RR = k1*0.0035*PGV^{0.92}$	S waves	O'Rourke & Deyoe (2004)
$RR = K1*24.1*PGV$	Asbestos cement, cast-iron, welded steel	ALA (2001a,b)
$RR = 0.0012*PGV^{0.7677}$		Eidinger *et al*. (1995), Eidinger (1998)
$RR = 0.0006*PGV^{1.5542}$		
$RR = 6*10^{-5}*PGV^{2.2949}$		
$RR = k1*513*\varepsilon^{0.89}$	**Strain ε**	O'Rourke & Deyoe (2004)

k1, K1: factors related to pipe materials and joint types (e.g. =1.0 for non flexible or brittle pipes)

As regards to permanent ground displacements induced by earthquakes and/or landslides, it is interesting to categorize the ground failure type with respect to the different impacts on pipelines. For instance, Meyersohn (1991) established three types of landslides: Type I includes rock fall and topple, which can cause damage to pipelines built above ground by direct impact of falling rocks; Type II refers to earth and debris flow (viscous fluid behaviour for transported materials), in which large movements are often expected; Type III includes earth slump and slides, which can be considered as earth blocks. The last two types are associated with most of pipeline damages.

The HAZUS methodology (FEMA-NIBS, 2004), where no distinction is made between spatially distributed and localized abrupt PGD, proposes empirical equations to estimate the Repair Ratio as a function of the calculated PGD values (e.g. see Table 9). The resulting RR is to be multiplied by a factor denoting the percentage of map area with landslides susceptible deposits, considering both dry and wet conditions.

Alternatively, in order to compute PGD related to ground shaking (e.g. lateral spread, ground settlements), the critical acceleration (kc) of the slope is first calculated, based on the Newmark's sliding block model at the average depth of the slide's shear zone. Earthquakes with PGA higher than the critical acceleration, will incur permanent displacements on the shear surface. Then, a Newmark rigorous rigid block analysis may be performed to calculate displacements, preferably using several recordings as input motions and averaging the results.

Alternatively, for PGD related to landsliding, can be estimated using other empirical or analytical relations (e.g. see LESSLOSS Deliverable 16, 2006).

Table 9: Empirical vulnerability equations used for the estimation of pipeline Repair Ratio due to permanent ground displacements (i.e. PGD in m) (adapted from LESSLOSS Deliverable 93, 2007).

Empirical Relationship for Repair Ratio RR	Reference
$RR = K*7.821*PGD^{0.56}$	Honegger & Eguchi (1992)
$RR = K2*23.674*PGD^{0.53}$	Eidinger & Avila (1999)
$RR = K2*11.223*PGD^{0.319}$	ALA (2001a, b)

K, K2 : factors related to pipe materials and joint types (K2=1.0-0.5 and K=1.0-0.3, resp. for non flexible or brittle pipes to flexible or ductile pipes)

3.4.2 Roads

Fragility curves are given by HAZUS for major (4 lanes) and urban (2 lanes) roads, as a function of PGD, which is useful to describe both liquefaction and landslide hazards. Log-normal functions are used to give the probability of reaching or exceeding different levels of damages for a given level of ground failure (Table 10). Each curve is characterized by a median value of PGD (ground failure) and an associated dispersion factor (log-normal standard deviation β), which are generally based on engineering judgment (Table 11). However, the resulting curves (Figure 12) seem to give a reasonable estimation of roadways' response to ground failure.

Table 10: Damage states for roads (adapted from LESSLOSS Deliverable 93, 2007).

Damage State	Description	Serviceability level
No Damage	-	Fully open
Minor	Slight settlement (< 30cm) or offset of the ground	Open to traffic. Reduced speed during repairs.
Moderate	Moderate settlement or offset of the ground (30 to 60cm)	Fully closed due to temporary repairs for few days. Partially closed to traffic due to permanent repairs for few weeks. The duration of closure depends on the length and width of damaged roadway.
Extensive/Complete	Major settlement or offset of the ground (> 60cm)	Fully closed due to temporary repairs for few days to few weeks. Partially closed to traffic due to permanent repairs for few weeks to few months. The duration of closure depends on the length and width of damaged roadway.

Table 11: Fragility curves parameters for roads (adapted from LESSLOSS Deliverable 93, 2007).

Classification	Damage State	PGD	
		Median value (m)	β
Urban roads	Minor	0.15	0.7
	Moderate	0.30	0.7
	Extensive/Complete	0.60	0.7
Major roads	Minor	0.30	0.7
	Moderate	0.60	0.7
	Extensive/Complete	1.50	0.7

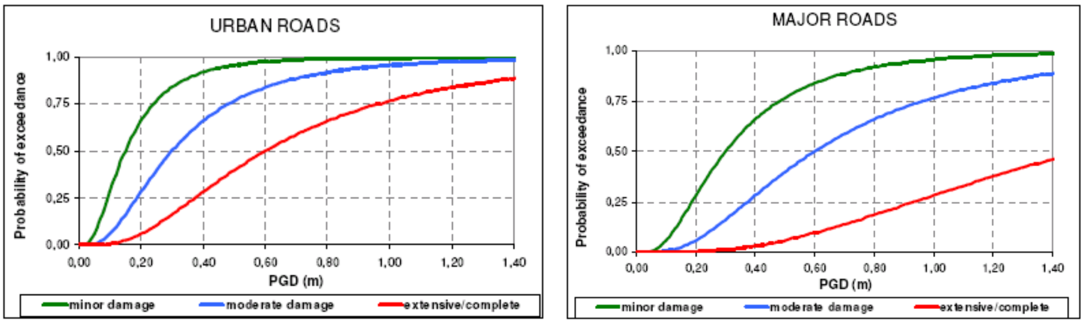


Figure 12: Fragility curves for roads (FEMA-NIBS, 2004)

3.4.3 Shallow tunnels

In general, tunnels perform well during earthquakes, as the shaking intensity decreases under the ground surface and also, as a fully embedded structure, it tends to move with the ground without experiencing the inertial motions sustained otherwise above ground. However, they may suffer damages, especially in highly seismic regions or when crossing unstable areas.

The same way as for pipelines, two classes of earthquake effects can be distinguished for vulnerability analysis: ground shaking and ground failure (Hashash *et al.*, 2001). Most of the damage records are linked to PGD due to ground failure, i.e. fault rupture through a tunnel, landsliding (e.g. at tunnel portal) and soil liquefaction.

So far, the vulnerability assessment for tunnels has been mainly based on empirical models, which can not account for soil effects on the structural response (i.e. soil-structure interactions). In the LESSLOSS project, a methodology was proposed to improve the fragility curves, by using a two-dimensional quasi-static plane strain analysis, which includes both the soil and tunnel. Therefore, this methodology permits to account for the tunnel features (geometry and strength capacity), the local soil conditions and the input ground motion characteristics (see LESSLOSS Deliverable 93, 2007).

The analytical fragility curves obtained by the proposed methodology were compared to the empirical curves, for a typical circular shallow tunnel cross-section embedded in three soil classes (namely soils B, C and D of EuroCode 8 classification). The analysis was performed for both ground shaking and ground failure and the respective curves were developed in terms of PGA and PGD. The curves are based on a log-normal distribution giving the probability of reaching or exceeding different levels of damages for a given level of ground shaking or failure. Each fragility curve is characterized by a median value of PGA or PGD at which the tunnel section reaches the threshold of the considered damage state, and by the related log-normal standard deviation β, describing the total variability associated to the curve. Allowing to FEMA-NIBS (2004), three factors participates to the total dispersion for a given damage state: the discrete threshold definition, the capacity of each structural type and the ground shaking itself. In the performed analysis, the uncertainty linked to the damage state definition was assumed to be equal to 0.4 (same as HAZUS for buildings), and the variability associated with the capacity, to be equal to 0.3 (same as in BART system for bored tunnels; see Salmon *et al.*, 2003). The uncertainty associated with the seismic demand was estimated by computing the variability in the results of inelastic dynamic analyses carried out for a great number of input motions for different levels of PGA in bedrock.

In order to define damage states, a damage index DI is introduced, which corresponds to the ratio of the developing moment to the moment resistance of the tunnel lining. In this way, the DI is derived from the PGA or PGD at the surface of the model (Figure 13). Based on engineering judgment and past observations, three damage states for tunnels were defined by indicating the corresponding DI ranges (Table 12).

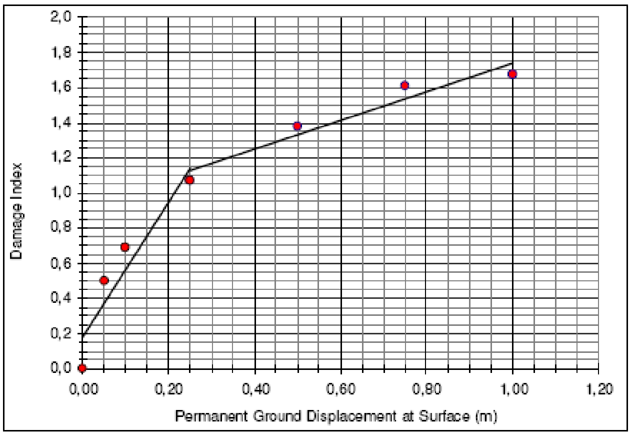


Figure 13: Example of damage index- surface PGD relationship in soil type C (source: LESSLOSS Deliverable 93, 2007)

Table 12: Proposed damage states for tunnels (source: LESSLOSS Deliverable 93, 2007).

Damage State	Damage Index	Average value
No Damage	DI ≤ 0.7	-
Minor	0.7 < DI ≤ 1.0	0.85
Moderate	1.0 < DI ≤ 1.3	1.15
Extensive	1.3 < DI ≤ 1.6	1.45

Comparisons between the proposed analytical fragility curves and the empirical curves derived from past observations (ALA, 2001a,b) and expert judgment (HAZUS from FEMA-NIBS, 2004), without integrating soil conditions and for bored tunnels, are shown on Figure 14 and Figure 15. From these curves, it seems that analytical curves tend to "envelop" the empirical ones, indicating that the empirical curves express an average performance of the tunnels. However, the authors point out that empirical curves refer to all possible damage types, including the ones in the longitudinal direction (the analytical curves are valid only in the transversal direction).

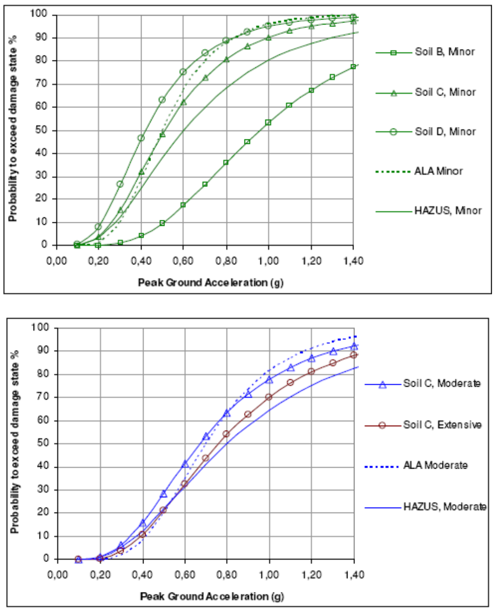


Figure 14: Comparisons between analytical and empirical fragility curves due to PGA, for circular shallow tunnels for three EC8 soil types (source: LESSLOSS Deliverable 93, 2007)

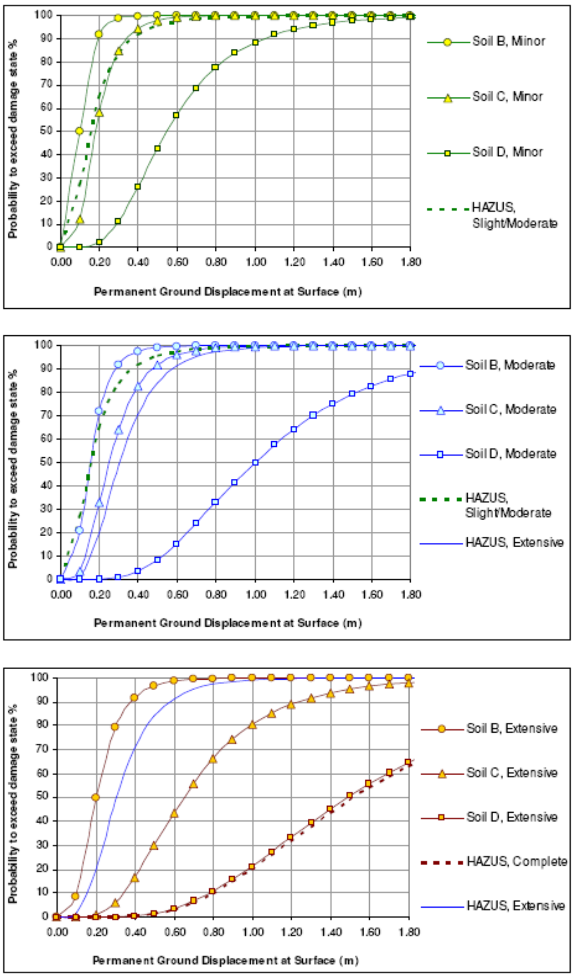


Figure 15: Comparisons between analytical and empirical fragility curves due to PGD, for circular shallow tunnels for three EC8 soil types (source: LESSLOSS Deliverable 93, 2007)

3.5 Methodology for Cultural Heritage

One of the main specificities regarding the protection of Cultural Heritage assets is to consider both safety and conservation that guarantees their capacity of lasting over time against decay, natural hazards and extreme events, without loosing their authenticity and usability. Thus, in the case of historic buildings, the safety of the assets and of the people using them and the conservation of the Cultural Heritage should be considered in an integrated approach.

The damage assessment to Cultural Heritage assets after recent earthquakes, in particular in Italy (Reggio Emilia, 1996; Umbria and Marche, 1997; Molise Region, 2002; Garda Lake, 2004), showed the high vulnerability of some types of historical structures (churches, towers), as their damage was considerably higher than that observed on ordinary buildings in the same region. Such vulnerability is likely to be expected for other structures, such as mosques or minarets. These earthquakes also proved that strengthening interventions adopted in the last decades (e.g. replacement of original timber floors and roofs with heavy and stiff reinforced concrete slabs, etc.) are not effective and even increase the vulnerability. Thus there is a need for a really effective strategy regarding risk mitigation of cultural heritage.

The evaluation of the seismic hazard plays a fundamental role in the seismic risk assessment of Cultural Heritage assets, which are sensitive to particular characteristics of the seismic input (earthquake duration, frequency content in the long period range, vertical component of the motion, fling and directivity effects,…). Moreover, soil amplification effects and soil-structure interactions are to be evaluated properly, especially in the case of massive and stiff masonry structures, where soil-foundation problems are very important, even in static conditions.

In the next sections, we summarize the holistic methodology which has been applied within the RISK-UE project for the vulnerability analysis of historical buildings (RISK-UE, 2004; Lagomarsino, 2006a,b).

3.5.1 Evaluation of exposed elements

As for non Cultural Heritage assets, the analysis of Cultural Heritage has to be based on a typological classification, in order to account for various needs:

- investigation and analysis of a large sample of historical buildings, on a widespread territorial scale;
- estimation of the historical-architectonic values, which generally implies a more detailed approach, in comparison with those used in the vulnerability analyses of ordinary buildings;
- validation of the analysis, by comparing with seismic damages actually observed after past earthquake events.

Hence, from data collection and surveys, the analysis should establish correlations between the constructive, typological and technological aspects, and the seismic damage observations, as surveys may highlight which features are determinant in the vulnerability evaluation.

The classification used for monumental buildings considers a great variety for types: palace, monastery, castle, church, oratory/chapel, mosque, theatre, tower/bell tower, bridge, urban walls, triumphal arch, obelisk, statue/monumental fountain.

3.5.2 Vulnerability analysis

In many technical rules and guidelines for the rehabilitation of existing buildings (e.g. FEMA documents, Eurocode 8), the performance-based design concept is recommended, as it allows the design or upgrade of buildings with a realistic risk estimation (safety of life, occupancy, economic loss) that can occur due to future earthquakes. This concept is also used in the case of cultural heritage, and depending on the quality and quantity of available structural data, level 1 (poor data) and level 2 (more detailed data) analyses can be used (see Table 2 for details).

3.5.2.1 Level 1 methodology

In this approach, vulnerability is mainly connected to the monument typology (palace, church, tower, castle, etc) and is based on the attribution of a vulnerability index to each single building, established from survey forms. The vulnerability index is defined in function of the monument type and corrected through modifier scores, that are correlated to some easily noticeable parameters (state of maintenance, material quality, structural regularity, etc). This methodology is similar to the macroseismic approach presented previously for non historical buildings (see section 3.2.2). The characterization of the typology behaviour is defined on a statistic basis (buildings and churches), as well as on an analogical basis. It allows to define damage levels, which represent a quantitative interpretation of the consequences caused by the earthquake on the structural and non-structural elements (cracks, deformations).

Apart from the general information (Table 13), common to all typologies, but not explicitly contributing to the estimation of the global vulnerability index of each element, some **common vulnerability parameters** are defined for all typologies and refer essentially to the state of maintenance and undergone transformations. There exist also vulnerability parameters which are typology-specific (e.g. plan or section regularity, position, etc.) and require appropriate additional form per element at risk. Specific forms have be prepared, which contain pre-defined answers for each parameter, allowing a mapping with a score value (V_m), which will modify the vulnerability index (V_I^*) of the element (Table 14 to Table 16). Figure 16 shows the corresponding semi-empirical vulnerability curves expressing the mean damage grade μ_D obtained for each cultural heritage typology, using the formula given in section 3.2.2.

Table 13: General information on the monument (adapted from RISK-UE 2004).

Building Name	-
Address	-
Period of construction	-
Prevalent period	period in which the building has taken its present shape, as a result of transformations and restoring.
Ownership	public, private, church-owned, other
Type of use	residential, offices, library, ruin, etc.
Frequency of use	daily / weekly / occasionally
Crowding of immediate surroundings	yes / no
Emergency accessibility	difficult / good / excellent

Table 14: Vulnerability indices for cultural heritage typologies (source: RISK-UE 2004).

TYPOLOGY	Vi-	Vi*	Vi+	β
Palaces/Buildings	0.496	0.616	0.956	2.3
Monasteries	0.616	0.736	1.076	2.3
Castles	0.356	0.456	0.766	2.3
Churches	0.77	0.89	1.26	3
Chapels/Oratories	0.65	0.77	1.14	3
Mosques	0.67	0.73	0.94	2.65
Theatres	0.616	0.736	1.086	2.65
Towers	0.636	0.776	1.136	2.3
Bridges	0.216	0.296	0.566	2.3
Walls	0.396	0.496	0.746	2.3
Triumphal Arches	0.376	0.456	0.706	2.3
Obelisks	0.396	0.456	0.746	1.95
Statues/Fountains	0.236	0.296	0.606	1.95

Table 15: General vulnerability parameters and corresponding modifying score values for monuments (adapted from RISK-UE 2004).

Description	Value	V_m
State of preservation	worst medium good	0.04 0 -0.04
Damage level	severe light nihil	0.04 0.02 0
Architectural transformations	yes no	0.02 0
Recent interventions	yes no	-0.02 0.02
Masonry quality	yes no	0 0.05
Site morphology	ridge sloping flat ground	0.04 0.02 0

Table 16: Specific vulnerability parameters and corresponding modifying vulnerability scores for castles, churches and monasteries (adapted from RISK-UE 2004).

Typology	Description	Value	V_m
CASTLES	**Plan regularity**	yes no	-0.02 0.02
	Section regularity: raised/slender elements	yes no	0.04 0
	Position	not meaningful	0
	Height	high medium low	0.04 0 -0.02
CHURCHES	**Plan regularity:** nave typology	central nave one nave three naves	-0.02 0 0.02
	Section regularity: sailing façade/raised elements	yes no	0.04 0
	Position	included additions isolated	-0.02 0.02 0
	Domes / Vaults	yes no	0.04 0
	Lateral Walls Height	low (< 6m) medium (6 <x< 12m) high (> 12m)	-0.02 0 0.04
MONASTERIES	**Plan regularity**	yes no	-0.02 0.02
	Section regularity	yes no	0 0.02
	Position	included corner/end isolated	-0.02 0.04 0
	Number of floors	low (1-2 floors) medium (3-5 floors) high (> 5 floors)	-0.02 0 0.04
	Cloisters/loggias	yes no	0.01 0

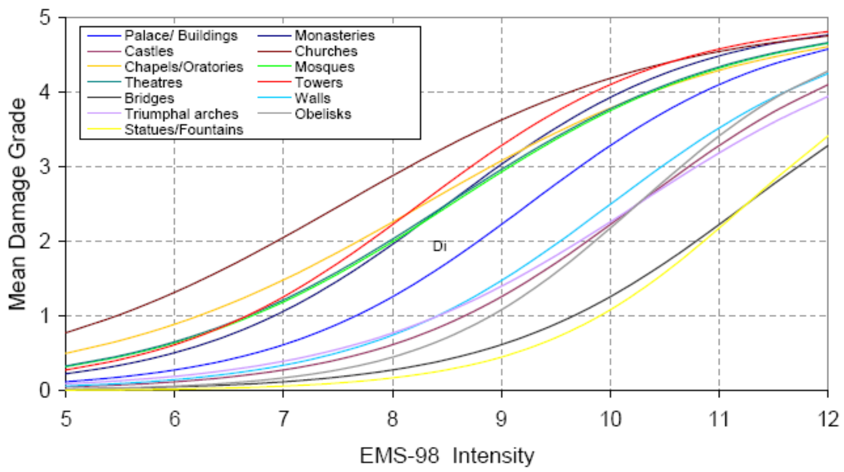


Figure 16: Semi-empirical vulnerability curves for monument typologies (source: RISK-UE 2004)

3.5.2.2 Level 2 methodology

One limit of level 1 analysis is due to the fact that vulnerability is considered in a global way, whereas damage observations have highlighted how, according to the architectonic complexity of monuments, the constructive characteristics (constructive phases, transformations, etc.) and the poor tensile strength of the masonry (material usually employed for fabric), the damage and collapse often take place locally. Hence, only in the case of some specific monumental typologies (tower, obelisk, etc.) is the definition of a vulnerability (capacity) curve describing the global behaviour of the monument conceptually correct.

Thus, the first step of a vulnerability assessment based on a mechanical approach, should be to single out the weakest parts (macroelements) of the building and the corresponding collapse mechanisms, macroelements being characterised by a substantially independent seismic response and simply associable to an architectonic element. Therefore, the modifying vulnerability scores are peculiar to the single construction, and the capacity curve determined in that way becomes significant for this monument and does not represent the whole typology.

This is the methodology, which is applied in level 2 analysis, where a simplified evaluation of the capacity curve is performed for each macroelement identified in the fabric. This approach allows us to estimate, with few geometrical and typological parameters, a macroelement capacity curve, estimating the effectiveness of some aseismic devices (tie-rods, buttresses, etc).

The definition of the capacity curve can be obtained through both detailed or simplified mechanical methods, considering either nonlinear or equilibrium-limit analyses. When collapse mechanisms have to be considered in analysis, the equilibrium-limit analysis is preferred. Details for the analysis of seismic performance of historical buildings can be found in literature (e.g. RISK-UE 2004; Lagormarsino 2006a,b).

However, whatever the procedure, it must remain quite simple, in order to be automatically applicable to a meaningful number of buildings, as it is generally the case when assessing vulnerability of cultural heritages in the European context (urban centers, etc.).

3.6 Studies for the development of a strategy for seismic retrofitting of buildings in Greece

Background

Around 32% of the building stock in Greece is constructed before the Seismic Design Code of 1959 was passed and about 46% while the 1959 Seismic Design Code was in place (2002-2003 data from Kappos 2004). Seismic retrofitting of buildings is therefore a major issue for earthquake protection in Greece.

The Technical Chamber of Greece having in mind to propose a national strategy for seismic retrofitting of existing buildings launched a project in 1995 aiming at better understanding the manifold aspects of the issue. A core matter was the assessment of expected seismic losses in Greece as a basis for justification of preventive interventions.

The project comprises two phases. In the first phase (1999-2001), a multi-disciplinary approach was followed aiming at exploring many dimensions of the problem (engineering, urban planning, policy, legal, professional rights, statistics and GIS). An attempt was made to approach vulnerability and risk assessment for the whole country. The study was conducted for the total building stock in Greece (about 4 million buildings). Data came from the 1991 National Building Census and the 1990 National Population Census.

In a second phase (2002-2005), the study was focused mainly on engineering aspects. A more precise approach was attempted, based on more advanced vulnerability matrices and on more appropriate data from the National Building Census of 2000 and the National Population Census of 2001. In addition studies are performed at a city level for 16 Greek cities (Aftodioikisi Journal, 2008). The application is GIS based (using ArcInfo software) and is available by the Technical Chamber of Greece free of charge.

Phase 1

Definitions and concepts

Vulnerability is understood as the predisposition of a building to suffer damage when subjected to seismic action "H" expressed as macroseismic intensity or ground acceleration (TCG, 2001).

Seismic risk "R" is understood as the total loss that would suffer a small or bigger social group that lives and operates in buildings and infrastructures of mean vulnerability "V' due to seismic activity "H", taking into account:

- The damage of buildings and infrastructures, both structural and non structural, as well as of supporting installations and networks
- The volume of buildings and infrastructures
- The productive and social functions that will be partially or totally slowed down
- Human losses (deaths and injuries)

For a given level of hazard "H" in a small or big area ("H" is always understood as an expressed probability to be exceeded), the buildings in the area have a certain risk "R", which means that they are at risk to suffer various losses, usually expressed in terms of cost:

- Building repair or replacement (concerning all structural and non structural system and installations)
- Value of lost economic activities of tenants and of those who can be affected by the damage of the building
- Monetary value of human losses

Methodology and outcome

At this phase of the study risk is seen as a product of hazard and vulnerability.

More specifically:

R = k.H.V.A

where "A" is a coefficient representing the value of buildings (exposure) in the area (for instance the total area of stories), k a coefficient that expresses the population density and the socio-economic significance of the function of the buildings, V is an indicator of seismic vulnerability of buildings in the area or more simply, the tendency of these buildings to suffer seismic damage.

Building categorisation is based on building features (structure and number of stories) and on the construction year that is considered to correlate mostly with the building codes that had to be followed for design and construction.

Taking into account these criteria, buildings are categorised into 32 categories.

Vulnerability assessment is based on already existing vulnerability matrices that are drafted for the city of Volos. For these matrices to be used it was necessary to convert the hazard factor from intensity to ground acceleration. The hazard factor is expected ground acceleration normalised to the ground acceleration foreseen by the Seismic design Code (ao/ag).

A major issue is the change of design earthquake over the years. For this a coefficient was estimated converting the acceleration that was set by the Seismic Design Code in every area each period to ground acceleration set by the Hellenic Seismic Code of 2000 for the same area.

The above steps led to a set of vulnerability curves one for each building category (Figure 17). Based on the vulnerability curves and available data on building stock, a vulnerability indicator was estimated for each municipality this allowing a rough demonstration of the geography of vulnerability in Greece (Figure 18).

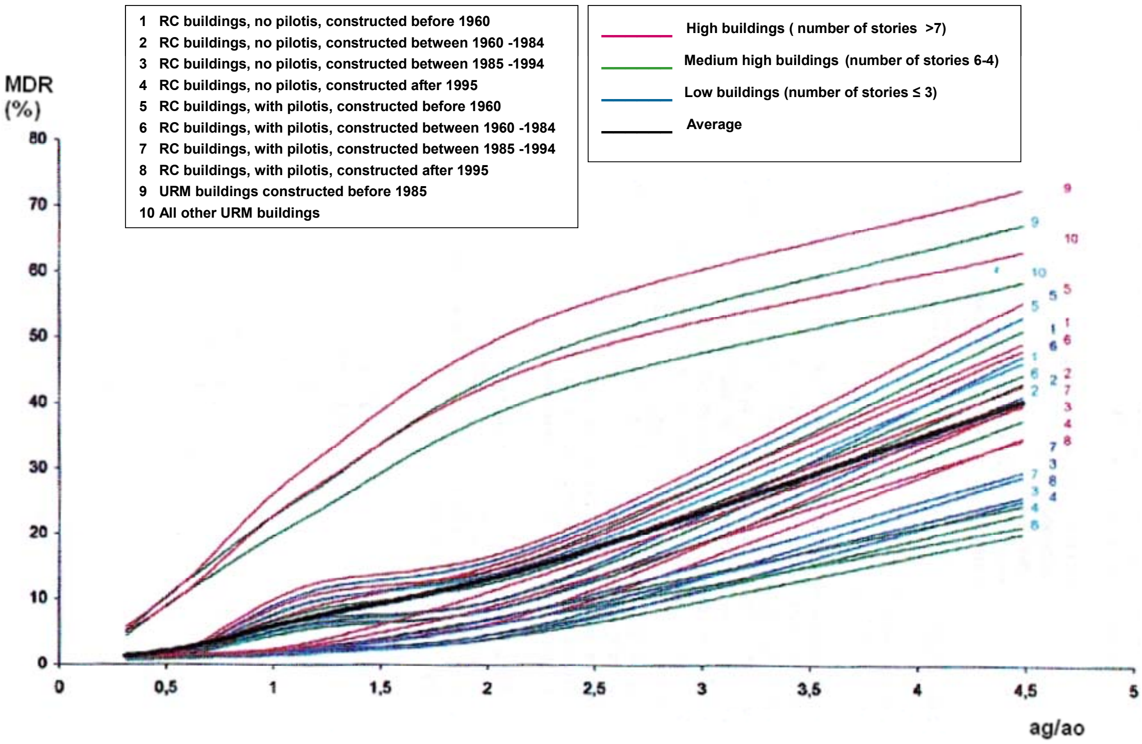


Figure 17: Vulnerability curves for the building stock in Greece (Source: TCG, 2001)

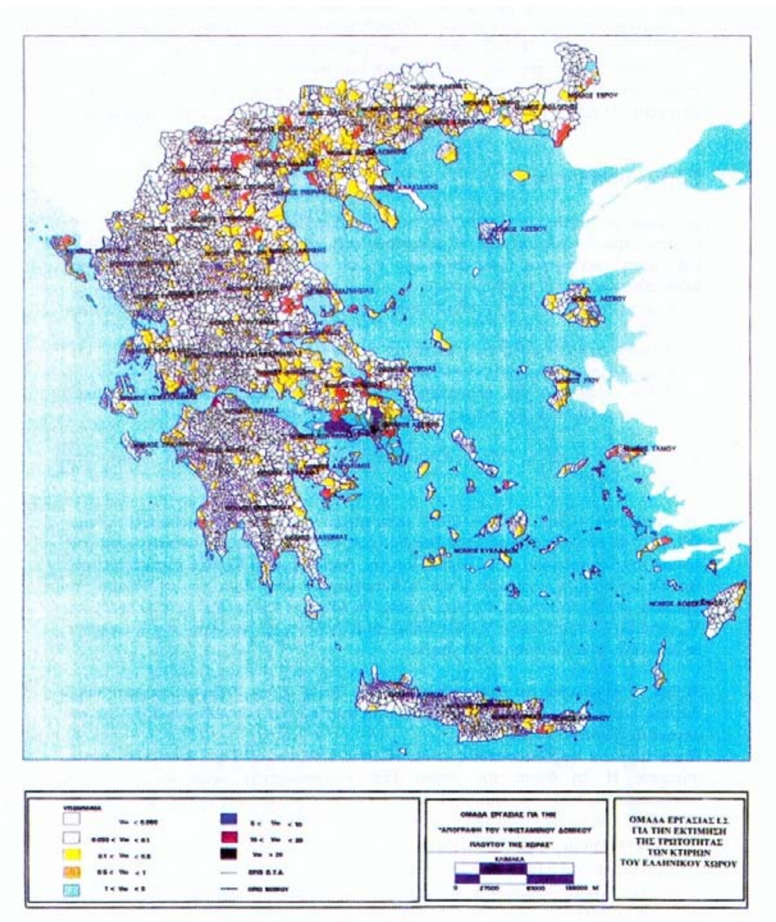


Figure 18: The geography of EQ vulnerability of buildings in Greece

Appropriateness of the method

The overall study gave a significant outcome in exploring many of the dimensions of the problem. Especially as regards to vulnerability, this was a first exploratory phase. The vulnerability curves that were drafted have significant uncertainties and can be used only for rough estimations at large scale (i.e. municipality level). Significant compromises had to be done as regards to both components of vulnerability, that is hazard and building stock. For one, the available data from the 1991 National Building Census and the 1990 National Population Census had significant gaps, e.g. there were no records on the building structure. Experts' opinion and engineering judgment had to be used to counterweight the lack of data.

Nonetheless the study contributed to raising the awareness of policy makers and the public. Even more it paved the way towards the next phase in several ways. First it triggered the change in the survey questionnaire for the next National Building Census; therefore essential information such as the building structure, the infill material, the existence or not of pilotis and basement, the possibility or not of interaction of adjusting building, is now available for all building stock in Greece. It also identified weak points in the approach of vulnerability assessment and even more of risk assessment. It therefore made possible a more appropriate approach for vulnerability and risk assessment in Greece. Last but not least it made apparent the need for more accuracy as regards to data on hazard and especially geotechnical data.

Applications

The method was applied for the city of Xanthi (Karabinis *et al.*, 2006). It was also the base for a rough estimation of risk and vulnerability in the city of Rhodes (Dandoulaki *et al.*, 2006) with the aim to demonstrate the significance of geography and space in earthquake planning (Figure 19).

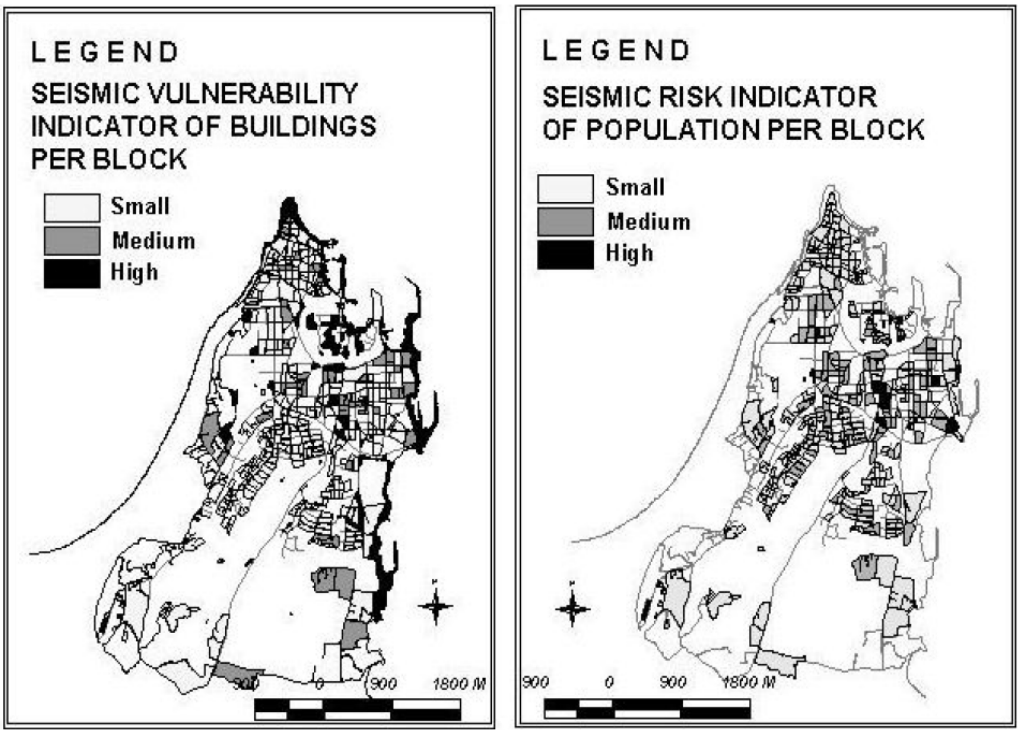


Figure 19: The geography of EQ vulnerability and risk indicators in the city of Rhodes

Phase 2

Definitions and concepts

In the second phase of the study, vulnerability is approached as the quotient of the degree of damage to the change of hazard that caused it.

Risk is understood as the overall loss because of a possible earthquake including loss of life and health, injuries, loss of building content, relocation costs, building repair or replacement costs. Risk is estimated on the basis of expected damage for each building, and it depends on the use of the buildings and the population density.

In the study, risk is calculated as:

$$\mathbf{R = A * V * (H - H_o) * k}$$

where A is the elements at risk, V is the mean vulnerability of buildings under examination, H is the probably seismic action and Ho is the design seismic action for the building, and K is a constant for the adjustment of damage to costs.

Methodology and outcome

In the second phase of the study, vulnerability assessment was based on already existing vulnerability matrices from three research projects:

1. Vulnerability assessment for the city of Volos (Study D1 by AUTH in 2000; see Kappos *et al*., 2001);
2. The 1999 Athens Earthquake: Vulnerability assessment in the disaster area and comparison with the real damage distribution (Study D2 by ITSAK and AUTH; see EPPO, 2004);
3. Damage data were used also from the data base of the research project ARISTION (Study D3; see ARISTION, 2006).

Since vulnerability matrices in these studies were based on macroseismic intensity, intensity was converted to ground acceleration for each city using appropriate empirical relations. As a next step, the mean damage ratio (D_i) deriving from each study was calculated.

7 main building categories were considered (Table 17). It's worth noticing that the height of the building was not taken as an essential parameter.

Table 17: Categorization of buildings for vulnerability assessment in Greece.

RC buildings	Constructed till 1985 (before the revision of the 1959 Seismic Design Code	With pilotis	1
		Without pilotis	2
	Constructed between 1985 and 1995 (after the revision of the 1959 Seismic Design Code and before the 1995 Hellenic Seismic Design Code)	With pilotis	3
		Without pilotis	4
	Constructed after 1995 (after the 1995 Hellenic Seismic Design Code)	With pilotis	5
		Without pilotis	6
Masonry buildings			7

Table 18 presents the vulnerability curves (mean damage factor versus expected ground acceleration normalized by the ground acceleration according to the seismic design code) as calculated based on the three principal studies for four different building categories.

As a next step, the vulnerability indicator V_m was calculated for every Municipality:

$$\mathbf{V_m = [\Sigma Ak_i * Ao_i * D_i * S_i] / [\Sigma Ak_i * Ao_i]}$$

with ΣAk_i the number of buildings of each category, Ao_i the number of stories of each category, D_i the mean damage factor as calculated based on each study, S_i the indicator of seismic action that represents the changes in the design earthquake in the area over the years.

Essentially V_m represents the percentage of loss in a thousand, for the total building stock of Greece per municipality.

Figure 20 presents the geography of vulnerability in Greece. It should be stated that it is at a prefecture scale therefore vulnerability estimations do not take into account changes in the design earthquake over the years.

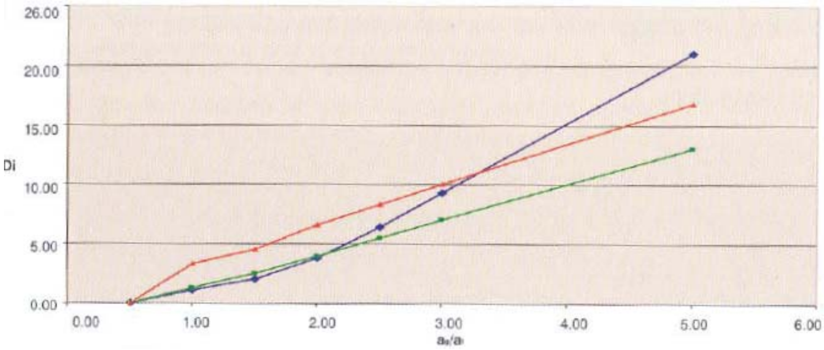
At a second stage, a risk indicator representing the additional economic and social burden on the area due to earthquakes was calculated based on population data from the 2001 National Population Survey.

Moreover, studies are conducted in 16 Greek cities. The aim is to estimate risk and vulnerability at a building block scale. Field surveys at a sample of 5% are done in order to collect appropriate data. The more advanced study is this of Tripolis (Centre Peloponnese) (Figure 21).

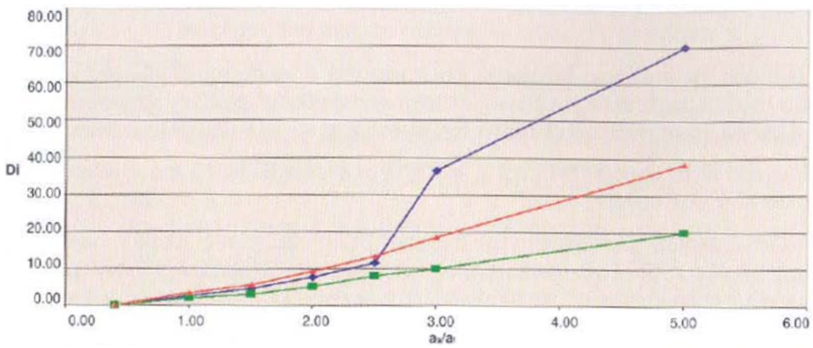
Applications

The study already had promoted seismic retrofitting efforts in the country. Already 5 municipalities (Tripoli, Corfu, Rhodes, Volos and Kalamata) have proceeded to pre-studies for the seismic retrofitting of selected municipal buildings while three more Municipalities are on the way. Seismic retrofitting for school buildings and hospitals has already started although at a slow pace. Moreover, a third phase of the study is impending, targeting the development of a data base of soil information, as well as the further elaboration and use of the pilot studies at a city level.

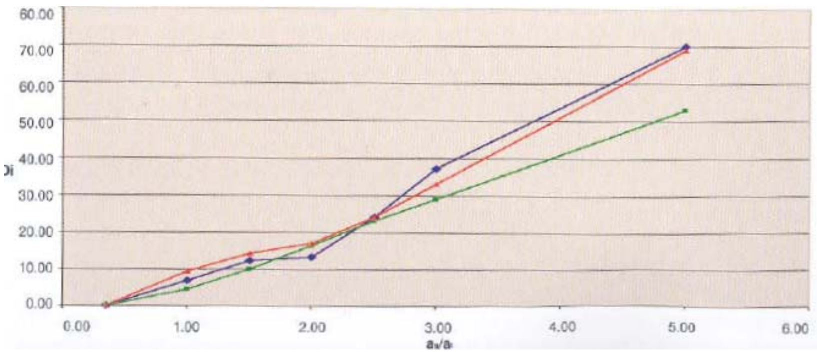
Table 18: Vulnerability curves (Mean Damage Factor "Di" versus expected ground acceleration normalized to the design earthquake "ag/ao" for different building types from the three research projects: -- D1, -- D2, -- D3 respectively.



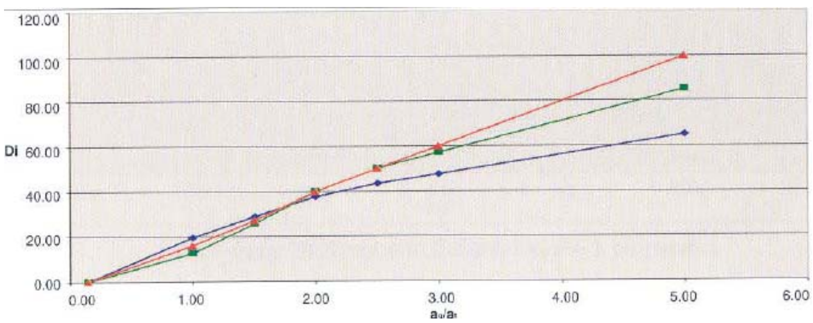
RC buildings after 1995 without pilotis



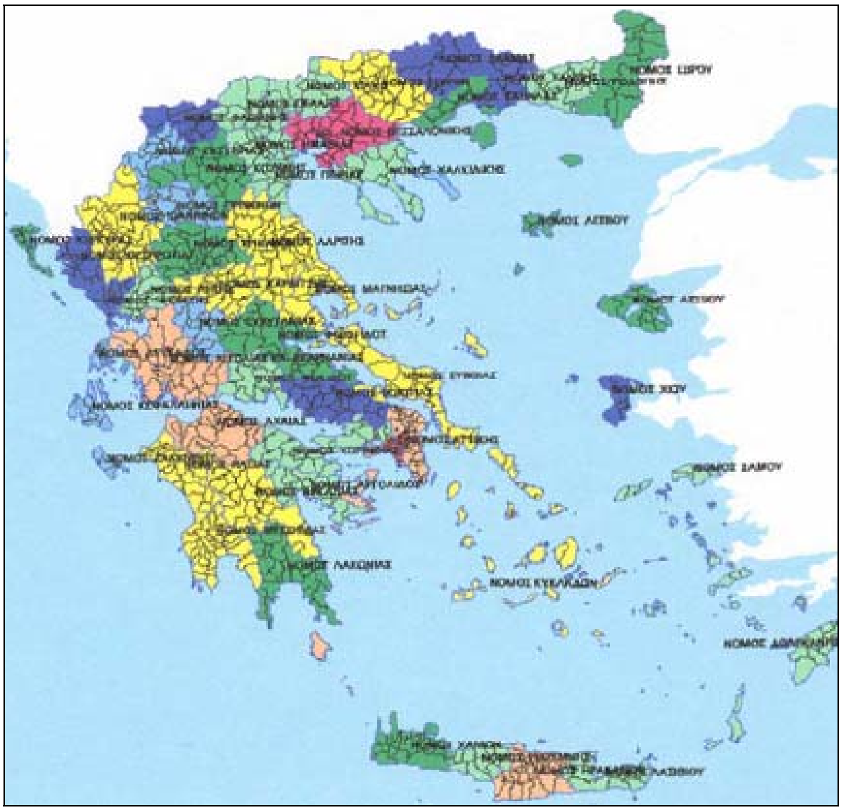
RC buildings between 1985-1995 without pilotis



RC buildings between 1985-1995 with pilotis



Masonry buildings



Legend	(red)	13.00 ≤	(green)	$2.50 < V_m \leq 2.99$
	(magenta)	$8.00 < V_m \leq 12.99$	(light green)	$1.50 < V_m \leq 2.49$
	(light orange)	$5.00 < V_m \leq 7.99$	(blue)	$1.00 < V_m \leq 1.49$
	(yellow)	$3.00 < V_m \leq 4.99$	(light cyan)	$< V_m \leq 1.00$

Figure 20: Risk indicator per municipality in Greece

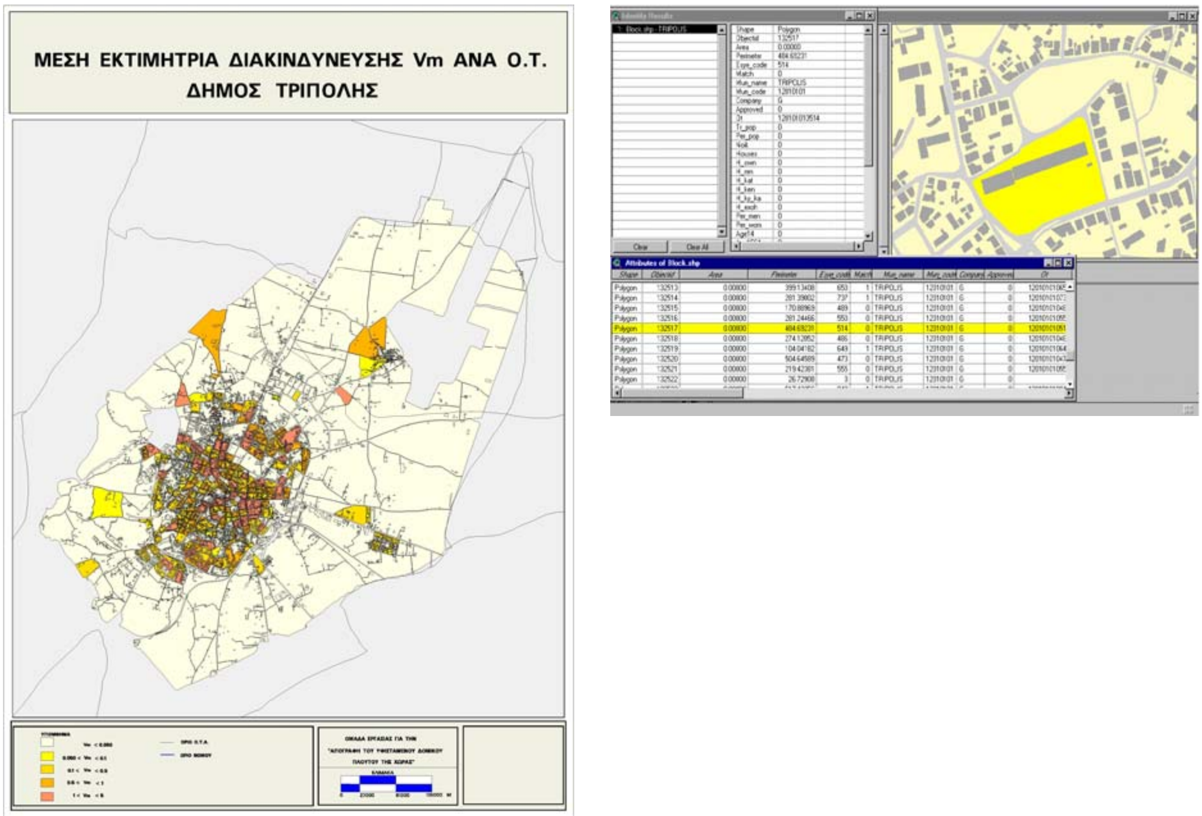


Figure 21: The geography of the risk indicator in the city of Tripolis (left) and screen view of the GIS set up for risk assessment in the city of Tripolis (right)

4 Vulnerability in Flood Risk Assessment

4.1 Introduction

Studies of the physical vulnerability of structures from flooding have emerged for a variety of reasons. One priority has been the identification of existing structures that might suffer damage from flooding, primarily aiming to establish where damages will occur or suggest where the public is most vulnerable during flooding. In addition, in recent years focus has moved towards development control, flood-proofing and policies advocating the development of properties in flood risk areas that are more resilient and resistant to the effects of flooding.

Two main approaches have been established to assess the physical vulnerability of structures to flooding; economic damage assessment and a quantification of the structural integrity of buildings. The first of these is arguably the more widely used approach and is essentially a quantification of the expected, or actual, damages to a property or area either through the estimation of a monetary value or through an evaluation of the percentage of the expected loss. Although some of the spatial approaches described below do include a damage assessment component, this method is mainly considered in more detail in Deliverable Del1.1.3, where other economic vulnerability approaches are described.

This chapter primarily considers the second of these approaches and focuses on assessing the physical vulnerability of individual structure (or group of structures), and on the estimation of the likelihood of occurrence of physical damages or collapse of a single building. This information is incorporated within damage estimation (e.g. through assessing how many properties are likely to be completely destroyed and the associated losses) or within a more general estimation of vulnerability whereby the likelihood of structural collapse is combined with other information (e.g. social vulnerability) to provide a comprehensive assessment of flood vulnerability (e.g. Jonkman *et al.*, 2008; Priest *et al.*, 2007, Zhai *et al.*, 2006). Approaches assessing the risks to human life (including estimations of fatalities and injuries) are considered in more detail when considering the social vulnerability to flooding (see Del 1.1.3).

4.2 Structural integrity of buildings and materials

Much of the research concerned with physical vulnerability to flooding concentrates on the integrity of individual structures or types of structure to the physical characteristics of the flood hazard; notably the depth of the flood water and the velocity. In particular, studies focus on the failure of structures and the hazard conditions that are likely to cause the collapse or partial collapse of structures. This research has traditionally emerged from assessments of the structural vulnerability of properties that might experience dam-break flooding due to the higher flood depths and velocities experienced and fast speed of onset. In recent years flood-proofing and the need to have more information and data about flood resilient materials and types of construction has revived interest in this area. In particular, research no longer focuses solely on the damages directly caused by the flood waters during the event, but also whether, and the ease at which, they are restorable after the flood event. Some studies (e.g. Sangrey *et al.*, 1975; Clausen and Clark, 1990; Lorenzen *et al.*, 1975) have been based on post-event analyses of the actual damage experienced by structures following flood events; whereas others are based on laboratory-based experiments (including Black, 1975; Karvonen, 2000; USACE, 1988) or through theoretical analyses and reinterpretation of previous studies (including Smith, 1991; Karvonen, 2000).

The key parameters that have been used to estimate and quantify the physical vulnerability of structures understandably relate to the forces that flooding is likely to exert on a building or a wall. Black (1975, cited from Karvonen, 2000) highlights that a "house in a water media is subjected to three major forces: buoyancy, hydrostatic pressure and dynamic pressure". Kelman and Spence (2003) developed a flowchart which illustrates the key actions on properties which lead to damage from flooding and have gone on to review the specific forces on buildings from flooding and those studies that have investigated and quantified these properties (Kelman and Spence, 2004) (Figure 22). Based on this review they propose a typology (Table 19) to describe flood actions on building and add to those parameters described above by Black (1975).

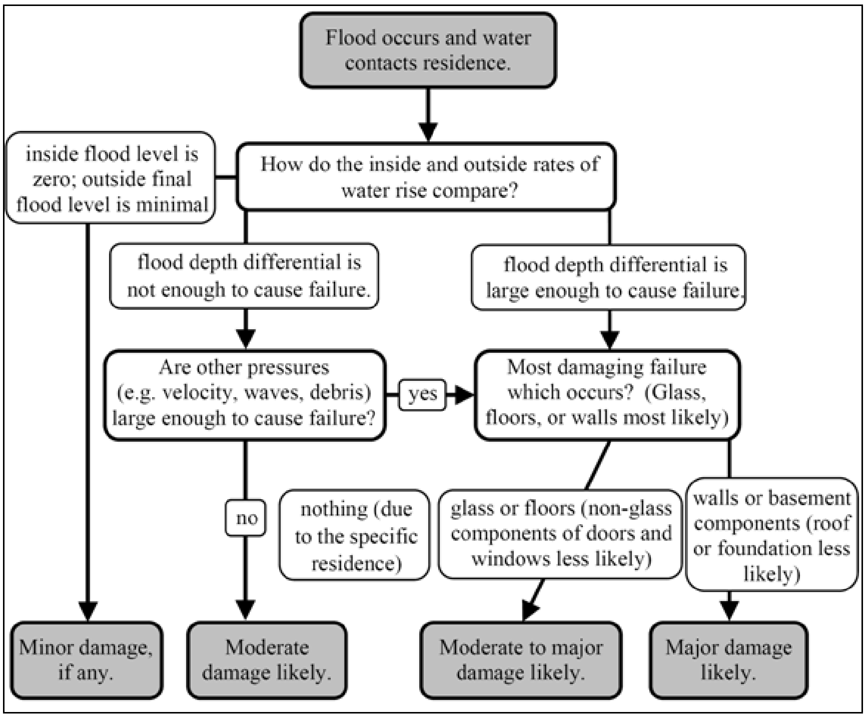


Figure 22: Flowchart highlighting failure from flooding (Kelman and Spence, 2004)

Table 19: Typology for flood actions on building (taken from Kelman & Spence, 2004)

1. Hydrostatic actions: actions resulting from the water's presence • Lateral pressure from flood depth differential between the inside and outside of a building; • Capillary rise.
2. Hydrodynamic actions: actions resulting from the water's motion • Velocity: moving water flowing around a building imparting a hydrodynamic pressure • Velocity's localised effects, such as at corners; • Velocity: turbulence; • Waves changing hydrostatic pressure; • Waves breaking
3. Erosion actions: water moving soil, the water's boundary becomes dynamic and moves into adjacent solids
4. Buoyancy action: the buoyancy force
5. Debris actions: Actions from solids in the water • Static actions; • Dynamic actions; • Erosion actions;
6. Non-physical actions: • Chemical actions; • Nuclear actions; • Biological actions.

Quantifying some, or all, of these forces and actions on buildings has been the major way in which physical vulnerability to flooding has been researched. Studies have attempted to research these forces and provide data about the physical vulnerability of specific materials and construction types; however only a few will be considered in detail. Kelman (2002, p143-144) presents a more comprehensive survey of the empirical research into the structural integrity of properties including a summary of those pressures and depth and velocities that cause the failure of walls (under uniform loading). This research (including CERAM, 2001; Duarte, 1998; Gairns and Scrivener; 1988; Southcombe *et al.*, 1995) was mainly undertaken in the laboratory or through simulating flooding conditions on existing derelict buildings.

The US Army Corps of Engineers has been one of the pioneers in this area of research. Their work has primarily focused on the potential for reducing the structural vulnerability of properties by increasing their resilience and resistance; particularly through flood-proofing. This is especially important in the US with the requirement that those residents, whose properties fall within the National Flood Insurance Program, take effective action to mitigate their risk from flooding. The US Army Corps of Engineers have produced a series of publications which have established regulations and guidance for the flood-proofing of buildings (USACE, 1995; 1997; 1998). Kelman (2002) argues that laboratory-based testing undertaken in the 1980s is likely to have formed a basis for many of the future recommendations of the USACE. Specifically, USACE (1988) focused on better understanding the hydrostatic pressures that lead to wall failure. Both brick-veneer solid walls and concrete-block solid walls were subjected to lateral water loads when the point at which failure occurred was noted. These experiments suggested that the walls of a structure (i.e. when the wall is part of a whole property) were safely able to withstand flood depths of up to 0.9m.

Escarameia *et al.* (2007) have also undertaken a recent laboratory study to investigate the resilience of different materials to floodwaters. The aim of this study was to inform UK building regulations about those materials which are most resistant and resilient to flood waters and therefore should be used to construct properties in areas at risk from flooding. Both masonry and timber framed walls (of various types including walls with and without and with different types of insulation and with different types of internal facing materials) are included. In all, fourteen different combinations of walls were tested, and for each three different measurements over time were recorded: the rate of leakage through the walls (measured in l/hr), the accumulation of water in the cavity (for empty cavity walls) and the drying of the surface of the external and internal faces (time taken to recover to original moisture levels) (Escarameia *et al.*, 2007). On the basis of these investigations a general classification of the resilience characteristics of walls was presented (Table 20).

The Oak Ridge Laboratories (ORNL) adopted a more holistic approach to estimating physical vulnerability of timber buildings by testing complete (albeit prototype) structures to simulated flood conditions (Figure 23) (Aglan *et al.*, 2004). Wingfield *et al.* (2005, p29-30) argue that the advantage of this technique is "that it assesses the flood resilience of typical building element junctions as well as the resilience of the building elements and construction materials, and is most likely to represent the behaviour of a real building short of testing a full-size dwelling." The main focus of these experiments was not whether the structure suffered a collapse, but more about the integrity of the structure after flooding, how water entered properties and the longer-term impacts of flooding on different materials (Figure 24). Different methods of flood-proofing the properties were also tested using this experimental approach.

Table 20: Flood resilience characteristics of walls

Material	Resilience characteristics*		
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity
External face			
Engineering bricks (Classes A and B)	Good	Good	Good
Facing bricks (pressed spike or sand textured)	Medium	Medium	Good
Internal face			
Concrete blocks	Poor	Medium	Good
Aircrete	Medium	Poor	Good
Cavity insulation			
Mineral fibre batts	Poor	Poor	Poor
Blown-in expanded mica	Poor	Poor	Poor
Rigid PU foam	Medium	Medium	Good
Renders/Plaster			
Cement render – external	Good	Good	Good
Cement/lime render – external	Good	Good	Good
Gypsum Plasterboard	Poor	Not assessed	Poor
Lime plaster	Poor	Not assessed	Poor

*Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth; ratings are for new build only.

Figure 23: An example of the testing conditions (Aglan et al., 2004, p2)

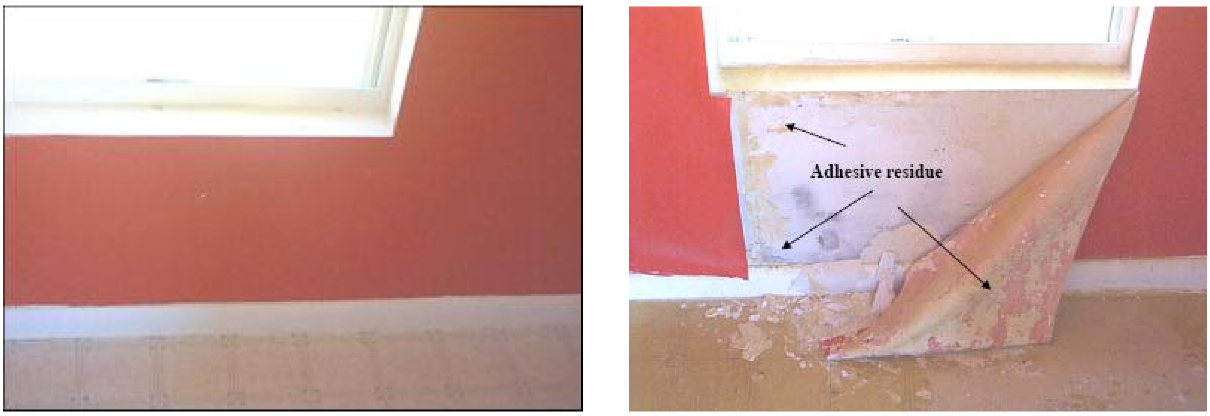


Figure 24: Example of preflood and post flood conditions of one element tested (Aglan et al., 2004, p18).

Kelman (2002) focused on the physical vulnerability to flooding of coastal residences within the UK, specifically focusing on the coastline of eastern England. This work adopted a field-based survey approach in order to identify the types of properties located in two case study areas; Kingston-upon-Hull and Canvey Island, both areas that have experienced extensive flooding in the past. Using surveys and previous empirical and theoretical studies Kelman identified that the failure modes of most concern were caused by: the rate of rise of flood water inside a residence (establishing pressure differentials that could damage the residence), analysis of glass failure (focusing on large, low units in doors) and analysis of wall failure (focusing on cavity walls of unreinforced masonry) (Kelman, 2002, piii). As part of the work, two-dimensional vulnerability matrices were developed in order to profile the vulnerability of properties, with "flood depth differential along one axis, flood velocity along the other axis, and the matrix cells displaying a damage outcome". These have then been applied to different simulated storm surge scenarios for the Canvey Island case study.

One of the other main approaches in which the physical vulnerability to flooding is portrayed and quantified is through graphical representations of critical depth and velocity thresholds which suggest when building failure is likely to occur. Figure 25 is one such graph which is presented within a review of urban flooding in Queensland, Australia (Smith, 1998). This information is intended for use within spatial development strategies as well as for the identification of those areas which are more vulnerable during flooding. In this case it is clear that single-storey properties constructed from weatherboard are the most vulnerable to flooding and therefore emergency planning and evacuation plans should therefore target areas with large numbers of these types of structures.

Similar vulnerability functions have been produced for Naga City in the Philippines by Sagala *et al.* (2006) although alternatively through a survey approach, whereby an inventory of 245 buildings were examined, as well as interviews with 68 households about the impact of previous flooding to their homes. The study identified six different types of construction materials and established that the impact of flooding is directly related to the construction material. A vulnerability function has been produced each of the six construction types which is "based on the percentage of damage to the construction material after the construction was exposed to a flood" (Sagala *et al.*, 2006) (Figure 26) and these highlight that one metre of water is a critical depth. Results also indicate that those properties with plywood walls and wooden floors are most vulnerable to flooding; whilst those properties that are constructed from concrete are the least vulnerable.

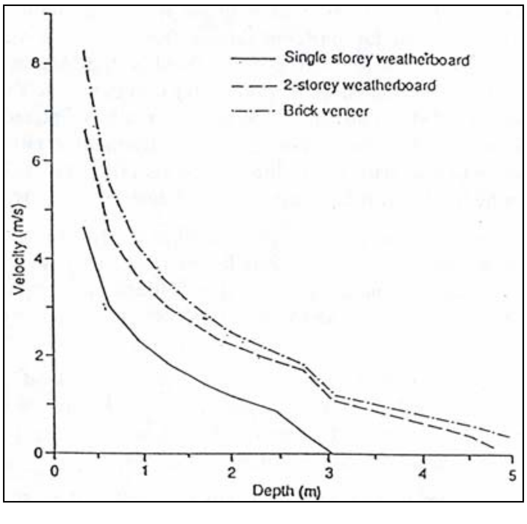


Figure 25: Combinations of flood depth and velocity that lead to building failure for a range of Australian building styles. (Data based on work undertaken by Black (1975) and Smith (1991) but are reproduced in Smith (1998, p5).

Sagala *et al*. (2006) states that research in poorer communities should focus primarily on the structural damage that is expected from flooding as this is the main component of the damage; rather than also considering the contents of the properties. When the vulnerability to building contents was investigated in this case (through interviews) the key variable affecting vulnerability is the number of floors of the property; that is those properties with more than one floor have a lower vulnerability than properties with only one level (Figure 27). This therefore indicates that the type of flooding experienced and the availability of a higher level, where contents might be stored during flooding, reduces the overall vulnerability of the property to flooding.

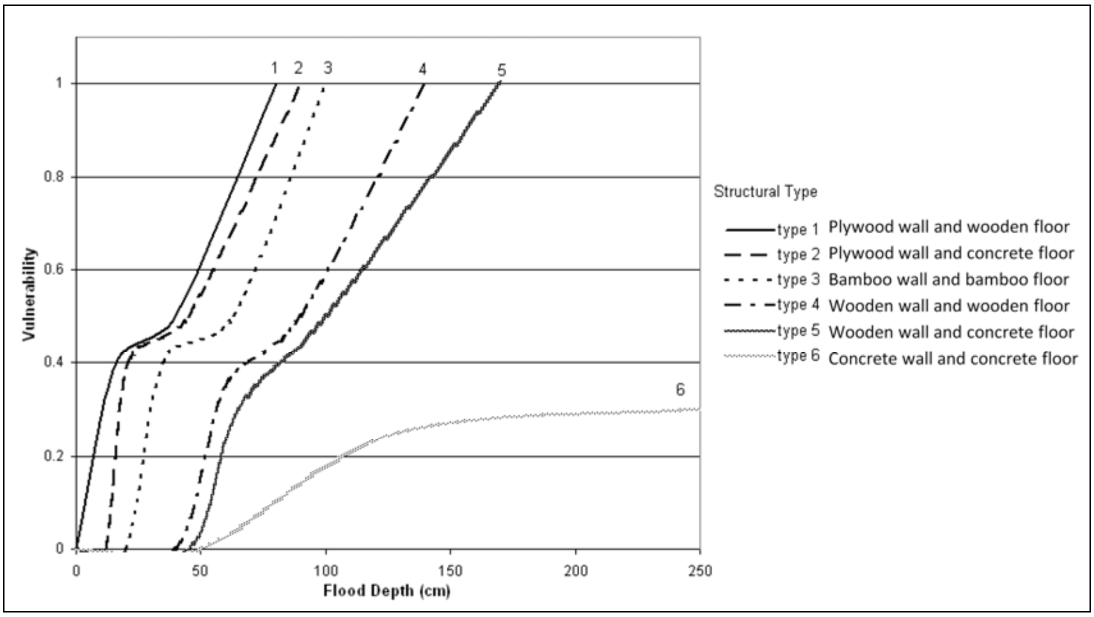


Figure 26: Vulnerability function for each of the structural types in Naga City (Sagala et al., 2006).

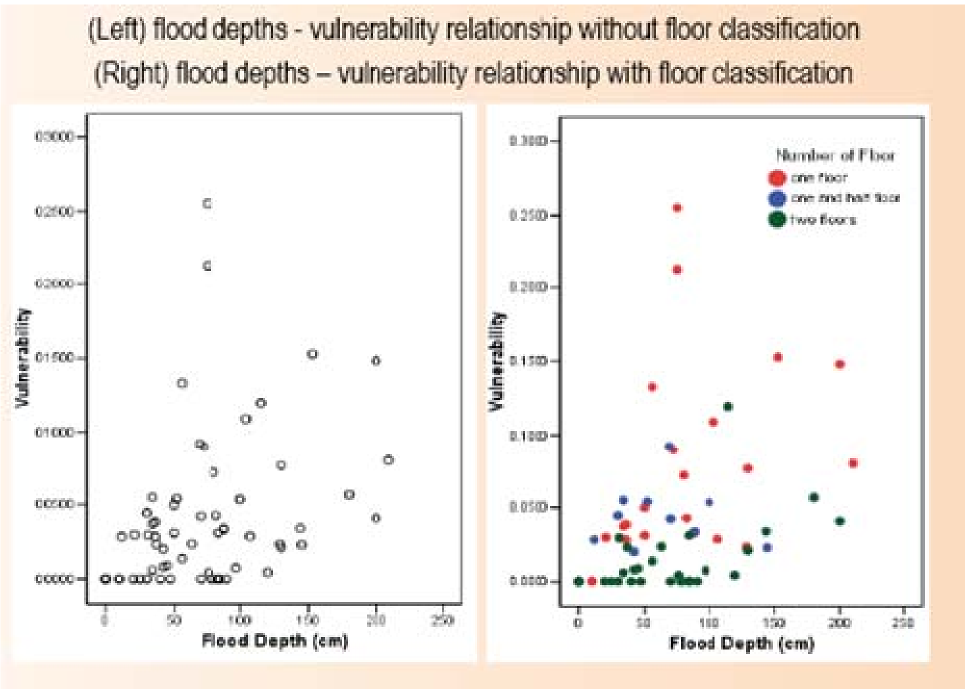


Figure 27: Scatter plot of flood depth and vulnerability of building contents (Sagala, 2007).

Karvonen (2000) is an example of a recent study that has combined the work of many of the previous studies (notably Black, 1975; Clausen and Clark, 1990; Lardieri, 1975; Lorenzen *et al.*, 1975; Sangrey *et al.*, 1975 and Smith, 1989; 1991 and 1994) to provide an assessment of flood vulnerability for the types of buildings common in Finland. Table 21 provides the results of this assessment and estimations of those depths and velocities of flooding where damages would be expected. The RESCDAM work also used physical models to investigate Manning's roughness and the direction and impacts of the flow between structures.

Table 21: Estimated depths and velocities when properties are damaged (Maijala, 2001)

House type	Partial damage	Total damage
Wood-framed		
Unanchored	$vd \geq 2$ m²/s	$vd \geq 3$ m²/s
Anchored	$vd \geq 3$ m²/s	$vd \geq 7$ m²/s
Masonry, concrete and brick	$v \geq 2$ m/s and $vd \geq 3$ m²/s	$v \geq 2$ m/s and $vd \geq 7$ m²/s

Damage parameter vd (m^2/s) = flow velocity (v) multiplied by water depth (d)

Although the majority of these studies are based on the relationships between depths, velocities and measures of the forces present and the damage experienced, when assessing the physical vulnerability of a particular location it is important to employ damage curves or thresholds that are as close to the existing property-types as possible, as materials and construction method have been observed to have a significant impact on vulnerability. In addition, if a pre-flood assessment is required, it is necessary to have reliable estimates of both the depth and velocity of the flood waters; data that can often be missing unless hydrological or hydraulic modelling of the floodplain has been undertaken.

4.3 Vulnerability of roads and road users

An additional strand of work has concentrated on the vulnerability of those travelling during flood events, specifically concentrating on vehicles, roads and road users. This research is important as not only are victims likely to be caught in vehicles during fast onset flooding, but also because of the reliance on motorised vehicles for both official and unofficial rescue and evacuation. Many of those who die from flooding, particularly in the developed world, are in cars, either through being caught out or from underestimating the strength of the flood waters or those depths and velocities a vehicle will withstand.

Reiter (2000) as part of the RESCDAM work presented estimated depths (Table 22) at which personal motor cars will become unstable in flood waters. These estimates are again based on a depth/velocity product and have been estimated based on observations during laboratory-based experiments, empirical evidence and theoretical estimations.

Table 22: Critical parameters for damage to motor vehicles applied to dam break flooding (Reiter, 2000, p11).

Risk of damage	Damage parameter (depth x velocity) m²/s		
	Small damages, small danger	Medium damages, Medium danger	Total damages, very high danger
Personal cars	< 0.3	0.50 - 0.60	> 0.6

Work in Australia and New Zealand (Floodplain Management Working Group, 2000) has combined elements of human vulnerability to flooding and vehicular vulnerability (based on Keller and Mistch, 1993) to present estimates of those thresholds where different aspects become vulnerable to identify the critical points for evacuation of both pedestrians and vehicles (Figure 28).

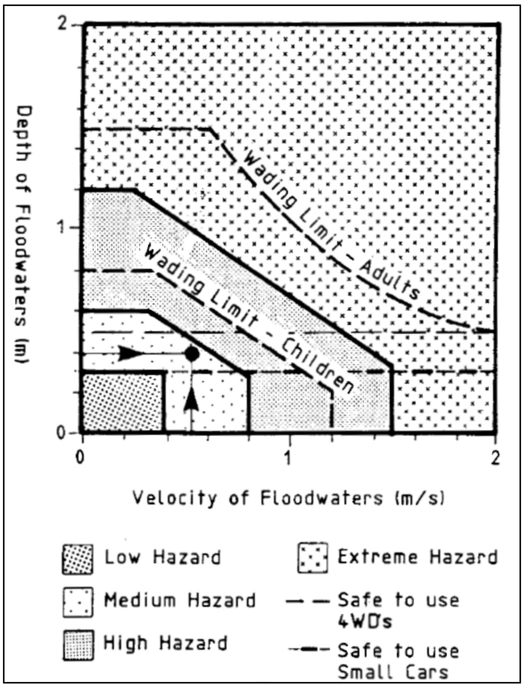


Figure 28: Estimation of hazard along evacuation routes (Floodplain Management Working Group, 2000, p72).

A similar approach was adopted by the U.S. Bureau of Reclamation (1988), (Figure 29), who provided a hazard graph of the flood danger for cars, which are used in conjunction of other information about the likely depths and velocities experienced downstream of a dam to classify the hazard that would be caused by a dam break. These curves were derived theoretically and it is argued that they bear some relationship to similar theoretical interpretations, as well as empirical evidence (U.S. Bureau of Reclamation, 1988).

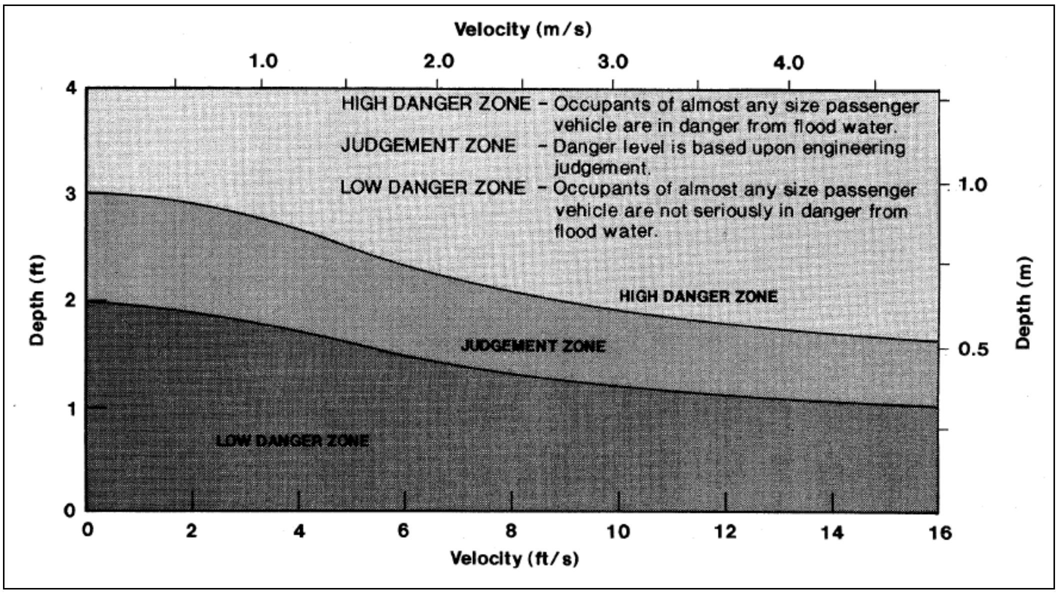


Figure 29: Depth-velocity flood danger level relationship for passenger vehicles (US Bureau of Reclamation, 1988).

Concern about the number of deaths occurring within, or escaping from motor vehicles has led to research (including Gruntfest, 1977, 2000; Staes *et al.*, 1994; Gruntfest and Ripps, 2000) aiming to explore why individuals drive into flooded waters. This research might be coupled with the information about the stability of vehicles in flood water in order to provide an overall vulnerability of vehicles to flooding. Drobot *et al.*, (2007) employed a survey-based approach within the US to identify some of the major risk factors associated with driving into flooded water; the results showing that those who do not take flood warnings seriously and younger drivers more likely to drive on flooded roads. Ruin *et al.* (2007) in their research in the Gard region of Southern France, employed an cognitive mapping approach, combined with GIS data processing, to identify those stretches of road that were perceived by the public to be dangerous to drive on when there was heavy rainfall or when flooding was forecast. This area suffers from very fast onset flash flooding and viewing how the public perceives different routes at times of flooding would provide emergency managers with an insight into where to target resources to best protect road users.

4.4 Vulnerability to historical buildings, monuments and cultural heritage

Assessments of physical vulnerability to flooding have focused primarily on providing either an assessment of the physical damage of structures or an economic assessment of the value of property threatened by flooding. Assessing the vulnerability of flooding to historical properties, monuments or settlements is more challenging. Not only might historical buildings be more susceptible to the effects of flooding, and in particular salt water flooding; their value cannot only be measured in monetary terms. Despite the large numbers of areas with cultural value at risk from flooding; this is a largely under-researched area of flood studies.

Traditionally, Italy has hosted a large number of historic monuments and artwork, much of which is located in flood risk areas (for instance Genoa, Venice and Florence). The Florence flood of 1966 saw significant damage to artworks and documents. However despite this, with few exceptions, little has been done in Italy in terms of effective and extensive defensive measures to protect cultural heritage against the risk of flooding. Lanza (2003) assessed evidence of the vulnerability to flood risk of the cultural heritage of the urban environment in Genoa, Italy. This city has eight urban watercourses that flow and intersect the city centre and the city is highly susceptible to drainage flooding problems. This study began by completing an extensive survey of historic documents reporting past flood events over the last 100 years to identify and map those areas at risk from flooding. Although not a perfect approach as it only included areas that have actually flooded, rather than all areas that might flood, it did provide a basis for investigation in the absence of more sophisticated hydraulic and hydrological information. However, future modelling should lead to refinement of the maps. This mapped information on past floods was integrated with the distribution of heritage sites and assets to derive a vulnerability map in order to define priorities for the design of low cost technical interventions at the urban scale.

The city of Prague is listed on UNESCO World Heritage List and the city has kept precise flood records since the 18th century. Štulc (2008) has considered the impacts of the 2002 flood event in the Czech Republic on building heritage. Vernacular housing in the Czech Republic is very vulnerable to damage from flood waters as it is often built with adobe (unfired brick). The collapse of these types of properties during the 2002 flood was considered itself to be a cultural loss, in addition to the terrible losses suffered by collections in museums and art galleries, libraries and archives. The 2002 flood event was devastating (it was estimated at a 500-year event), the city was not prepared and there was not a sufficiently early flood warning to avert losses. In addition to the damage directly caused by the flood waters, unsuitable repair and rehabilitation techniques on old properties and building fabric was undertaken in the recovery phase. Many buildings were demolished when they could have been rehabilitated, often as it was more profitable to construct new buildings in areas of high value. Adaptive practices from the past, such as using basements for storage only are also now being abandoned leading to the increase in the vulnerable assets. Štulc (2008) argues that in order to reduce the vulnerability of the cultural heritage of Prague and ensure that where future flooding does occur, a better preparedness programme is required.

Within England, English Heritage (2004) advises the public on all matters affecting the welfare of the built heritage. They have prepared a report aimed at owners of historic properties covering preventative measures on how to minimise damage. This advises property owners and managers about how to assess flood risk before deciding what protection is needed based on an assessment of the local topography, the history of flooding in the area, and existing flood defences. It also provides advice about maintaining adequate insurance and adopting a flood-kit and emergency plan, as well as good conservation practice. However, the report does not advise about methods of assessing the specific vulnerability from flooding of different properties or contents, it only assumes that by their presence within an area at flood risk, that they are vulnerable.

Ribera Masgrau *et al.* (2003) have recognised the need to go beyond traditional approaches to physical vulnerability and only mapping aspects and locations of cultural importance at risk from flooding. It has been recognised that assets within a region at high risk of flooding might not necessarily be seriously vulnerable to flooding; alternatively other assets which are not as highly exposed may be more vulnerable due to their characteristics. The authors introduce a more comprehensive approach, to try to recognise the multiple dimensions of vulnerability and have added a variable named intrinsic vulnerability. They define this as the "characteristics of the element itself that may make this element more subject to degradation, independently of its exposure to flooding" (Ribera Masgrau *et al.*, 2003, p348). In order to assess the intrinsic vulnerability of the element they have considered four different aspects.

1) State of conservation of the element – the physical state of the element and assumes that vulnerability is inversely proportional to the state of conservation.
2) Physical protection – the presence of actions addressed to the conservation of the element (e.g. restoration) again assuming that vulnerability will be inversely proportional to protection.
3) Ownership status. The ownership of the heritage asset is a crucial factor when planning for protection. The hypothesis is that the element will benefit from a more effective protection if it is under public rather than private ownership since more resources are likely to be available. Therefore, vulnerability will be directly related with private ownership and inversely related with public ownership.
4) Legal Protection. An element protected under law has in principle better conservation. Vulnerability is gain will be inversely related to legal protection of the element.

Adapted from Ribera Masgrau *et al.* (2003, p349).

For each cultural asset, the first three of these characteristics are quantified on a scale of 0, 1 or 2 (the fourth being represented on a scale of 0 or 1 indicating whether or not legal protection is present) with the scores of the elements being added to provide a total reflecting the intrinsic vulnerability. These scores are then used to define intrinsic vulnerability as low, medium or high. This information is further combined with the physical vulnerability into a matrix to produce an element that the authors describe as final vulnerability (Figure 30). Ribera Masgrau *et al.* (2003) have applied this approach to the Fluvià River basin and some of its tributaries in Girona (Spain) and have mapped the results. As well as locating the most vulnerable assets, the research also indicates that for 20% of the elements the final vulnerability does not coincide with physical vulnerability to flooding. They argue that this indicates the importance of intrinsic vulnerability and that vulnerability cannot, and should not, be defined according to physical exposure alone.

		Intrinsic vulnerability		
		HIGH	MEDIUM	LOW
Physical vulnerability	HIGH	Very high	High	Medium
	MEDIUM	High	Medium	Low
	LOW	Medium	Low	Very low

Figure 30: Final vulnerability matrix (Ribera Masgrau et al. , 2003, p247).

4.5 Spatial approaches to assessing structural vulnerability to flooding

The depth velocity relationship has a wider influence on flood management as well as being used to assess structural damages and predict the integrity of a particular building from flooding. In some management contexts the thresholds that are derived from this relationship (and from the consequences of a flood with a particular velocity depth product) have been used to develop hazard categories (often low, medium or high) used for spatial planning. An example of this is within the development control guidelines produced for New South Wales, Australia (Figure 31). The Floodplain Management Manual (New South Wales Government, 2001) define three hydraulic categories of flood prone land: floodways, flood storage and flood fringe each of which are used as "tools to assist the preparation of an appropriate floodplain risk management plan" (New South Wales Government, 2001, pG-1). The hydraulic categorisation (based upon the depth and velocity of flooding) provide the initial starting point for the categorisation of flood prone land and provide only a provisional hazard category to which other factors (such as local flood management plans and emergency response measures) can be added.

In addition, this parameterisation of the flood hazard has also been used in different circumstances (and alongside other components) to try to estimate and predict the risk to human life and safety from flood events (HR Wallingford, 2005; Priest *et al.*, 2007; Jonkman and Vrijling, 2008).

Many of the methodologies adopted to assess the physical vulnerability of flooding over a wider area and for a specific location, now typically use a geographical information system to integrate different data, to calculate potential damages and economic losses and also to present the data output. Within the US, the Federal Emergency Management Agency (FEMA) has developed an approach that allows development and emergency planners to combine flood hazard analyses (including information about expected flood discharges, flood depth and velocity) with information about the types of properties affected, to calculate the expected economic and physical damages from floods (FEMA, 2004). One of the benefits of the approach is that it permits a range of different impacts to be assessed including the physical damages to residential and commercial buildings, schools, critical facilities and infrastructure, as well as economic losses (through damage, lost employment, business interruption, repair and the costs of reconstruction).

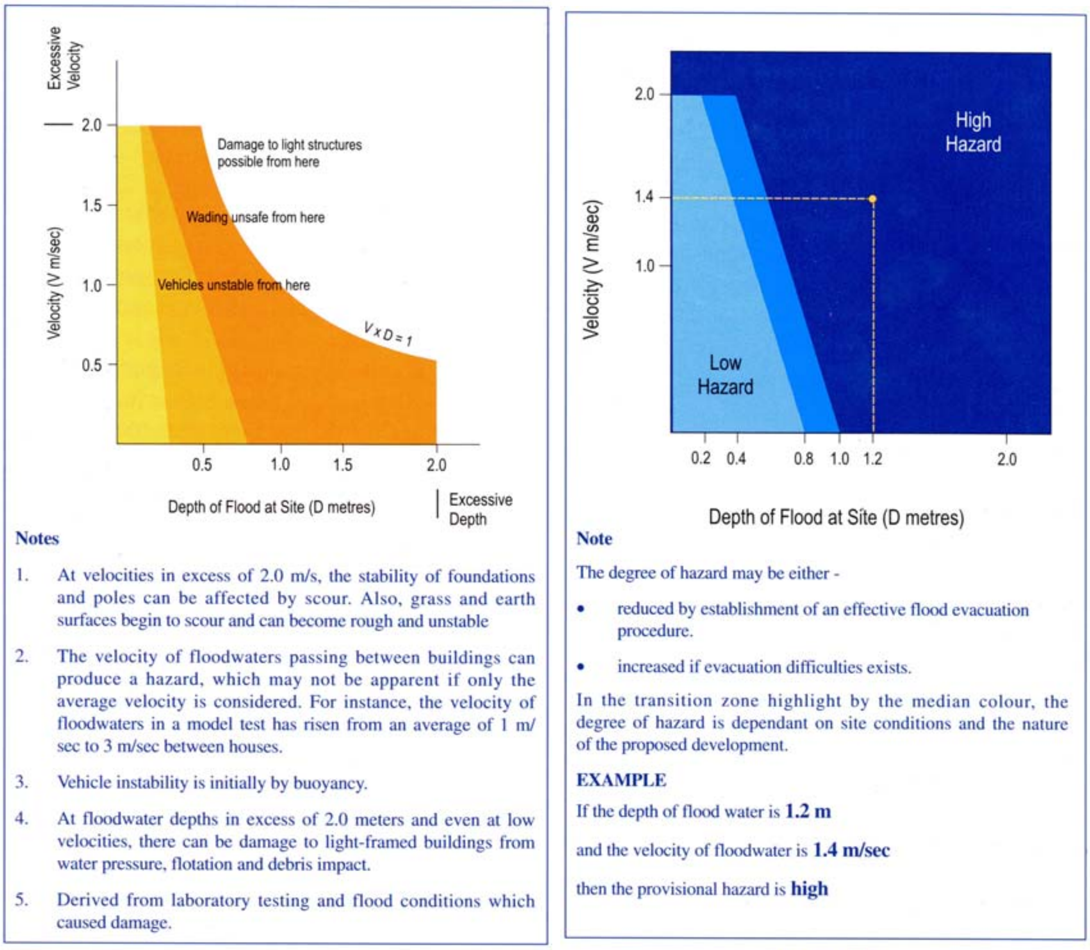


Figure G1
Velocity & Depth Relationships

Figure G2
Provisional Hydraulic Hazard Categories

Figure 31: Velocity-depth relationships and hydraulic hazard categories (New South Wales Government, 2001).

The HAZUS-MH methodology has been widely applied by State and local officials for investigating the likely consequences of flooding and for planning purposes (see FEMA website, http://www.fema.gov/plan/prevent/hazus/hz_flood.shtm#2). An example where this approach has been adopted is within Joyce and Scott (2005): they have produced an assessment of the vulnerability of the State of Maryland to flooding (100 year event) and provide recommendations about how best to mitigate against the impacts. This study uses the approach developed by FEMA to integrate data on the flood characteristics (both from coastal and fluvial events) with building inventory data about the specific types of properties affected. Data on vulnerability to damages are calculated for each individual county in Maryland and are presented in five different ways namely; "a count of damaged buildings by type, count of damaged buildings by occupancy, amount of building damage (in square feet) by type, amount of building data by occupancy, and the amount of direct economic losses from damage to buildings (in dollars)" (Joyce and Scott, 2005; p27). Examples of the output type are shown in Figure 32. These data have then been used to identify the most vulnerable areas and suggest appropriate mitigation activities.

A similar approach has been adopted by the Pennsylvania Emergency Management Agency for the State of Pennsylvania, however damages have been estimated for different flood event scenarios (10, 50, 100, 200 and 500 year floods). Data are presented as GIS files indicating economic losses (in total damages, building damages and contents damages) as well as information about the physical damage to homes. This latter information includes;

"total homes at risk, the total number damaged, substantially damaged homes, and homes by percent of damage for each of the affected census blocks" (PEMA, 2007).

Forte *et al.* (2006) have applied an integrated methodology using GIS, aerial photography and remote sensing to estimate flood losses and the vulnerability for flooding in an agricultural area in Southern Italy. The method has been applied to an area located in the central area of the Salento Peninsula where the "geological and morpho-structural characteristics make the agricultural areas susceptible to floods during the rainy season" (Forte *et al.*, 2006, p582) to investigate the physical vulnerability of three different types of unit; agriculture, houses and greenhouses. Remotely-sensed imagery and aerial photography to have been used to identify and classify different types of land cover, previously flooded areas and identify those areas of terrain which are particularly susceptible to flooding. The HAZUS methodology described above, and in particular the associated CACFDAS (Computerized crops flood damage assessment system) model, has been used and adapted to generate damages and loss estimations, using vulnerability functions described by Meijerink *et al.* (2003) for agriculture, houses and greenhouses (Table 23).

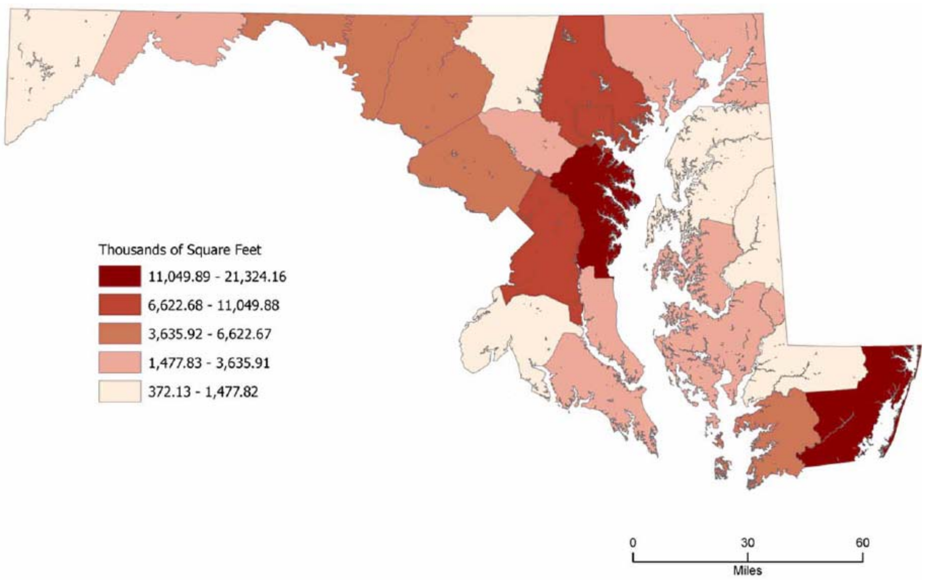
The results are considered by the authors to be satisfactory which they attribute to the good quality and detailed inventory maps that were developed. However, more research is needed for those areas not previously flooded and therefore where no information is available about expected flood characteristics. In addition, more detailed information in some areas would allow for vulnerability assessment to be undertaken at a larger scale.

Roos (2003) presents a model developed for the Netherlands which aims to investigate the impact of flooding on buildings. The work is focused primarily on dam break events and the author argues that this work advances that of previous studies as it not only focuses on the structural vulnerability through the collapse of walls, but also integrates the scouring of a building's foundation and identifies four different types of loads which are present on buildings during flooding: hydrostatic pressure due to the differences in water level inside and outside of the building; velocity of the incoming water; wave action and pounding debris.

In order to apply the model, buildings were categorised into the type of property (e.g. single family dwelling of e floors, maisonettes), construction material (e.g. timber frame, solid walls, cavity walls) and the date of construction. These data, gathered from a database which provides information about the whole building stock of the Netherlands, were combined with location-based information to produce a profile of the housing stock within the study location. This information was further combined with flood-related data (velocity, depth and wave height) and used identify the likelihood of the full or partial collapse of buildings (Figure 33). The results indicate that higher velocities (greater than 2m/s) and floods with a depth greater than 0.5m lead to partial damage to all types of structure; therefore understandably those properties which are closer to the breach are more vulnerable to collapse. Figure 34 shows the depth velocity curves that are expected to cause the total collapse of properties of different types. A significant result that this study proposes is that there is not a linear relationship between depth and the velocity of the flood waters in causing damage (Roos, 2003).

County	Degree of Damage							Total Damaged
	None	1-10%	11-20%	21-30%	31-40%	41-50%	Substantial	
Allegany	276.30	1,509.51	613.82	112.42	69.63	31.15	15.88	2,352.41
Anne Arundel	2,522.95	9,110.29	2,795.45	1,311.88	692.55	561.13	1,061.04	15,532.34
Baltimore City	435.07	3,873.79	1,667.82	1,137.21	220.49	58.20	699.38	7,656.89
Baltimore	2,418.92	5,707.85	1,175.96	531.32	594.19	180.78	615.12	8,805.22
Calvert	430.17	1,088.86	375.49	212.12	131.67	152.09	366.44	2,326.66
Caroline	75.91	245.27	59.88	37.37	14.14	11.54	23.48	391.69
Carroll	985.20	335.92	22.33	7.28	1.20	2.51	2.89	372.13
Cecil	447.58	1,010.32	376.13	237.80	41.02	16.17	10.45	1,691.90
Charles	554.00	955.74	138.88	24.46	1.83	0.00	32.20	1,153.11
Dorchester	83.03	899.12	486.03	266.41	131.23	151.14	774.14	2,708.08
Frederick	1,739.66	2,799.65	797.63	311.92	69.75	98.31	218.61	4,295.87
Garrett	236.80	477.45	149.78	79.21	33.41	4.97	127.00	871.83
Harford	1,440.27	2,258.78	756.15	202.48	230.90	117.76	69.83	3,635.91
Howard	3,995.27	2,589.41	59.70	28.16	0.95	0.00	0.00	2,678.21
Kent	175.98	290.21	69.96	42.11	35.64	12.46	26.86	477.23
Montgomery	3,943.62	3,144.28	708.48	377.96	94.36	40.91	70.82	4,436.80
Prince George's	2,200.68	8,462.98	1,531.75	424.68	151.58	114.50	364.39	11,049.88
Queen Anne's	349.63	1,101.53	230.67	89.94	24.61	0.72	30.35	1,477.82
Somerset	113.97	883.18	319.30	202.72	217.39	203.76	3,854.91	5,681.27
St. Mary's	407.85	906.39	297.78	192.37	114.07	103.44	319.05	1,933.10
Talbot	283.50	1,284.42	416.14	166.84	93.14	52.60	154.56	2,167.70
Washington	1,227.36	2,787.68	658.33	226.75	353.78	436.54	1,009.08	5,472.15
Wicomico	120.43	807.96	174.35	69.28	11.71	27.95	75.41	1,166.66
Worcester	304.45	8,220.97	5,316.36	2,693.36	1,258.75	1,463.71	2,371.01	21,324.16
TOTAL	24,767.48	60,754.23	19,199.15	8,987.30	4,587.98	3,843.18	12,293.70	109,665.55

Building damages by percent in thousands of square feet.



Potential building damage resulting from riverine and coastal flooding in thousands of square feet.

Figure 32: Damage assessment from the assessment of Maryland's vulnerability to flood damage (Joyce and Scott, 2005, pp30-31).

Table 23: Functions to calculate the vulnerability of agriculture, greenhouses and houses to flooding (Meijerink et al., 2003, taken from Forte et al., 2006, p589).

Vulnerability functions	
Vulnerability for agriculture	iff(fldm < 3.5,min(fldm,0.24×fldm +0.4,0.07×fldm+0.75),1)
Vulnerability for houses	iff(fldm < =2,0.005×fldm×fldm+0.045×fldm, iff(fldm < =4,0.045×fldm×fldm+0.015×fldm-0.1, iff(fldm < =5,-0.32×fldm×fldm+3.2×fldm-7, 1)))
Vulnerability for greenhouses	iff(fldm < =0.25,0.16, iff(fldm < =0.75,0.33,iff(fldm < =1.50,0.66,1)))

fldm flood depth in meters

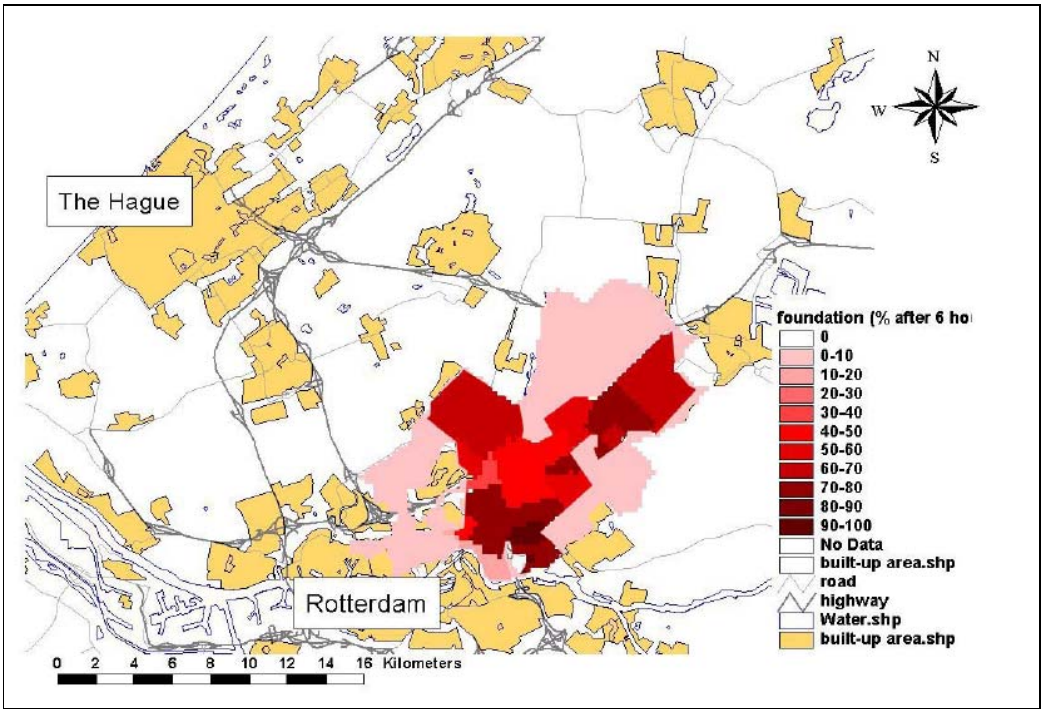


Figure 33: Percentage of partial collapse when the mechanisms of the failure of walls and the scouring of the foundation are combined (Roos, 2003, p42).

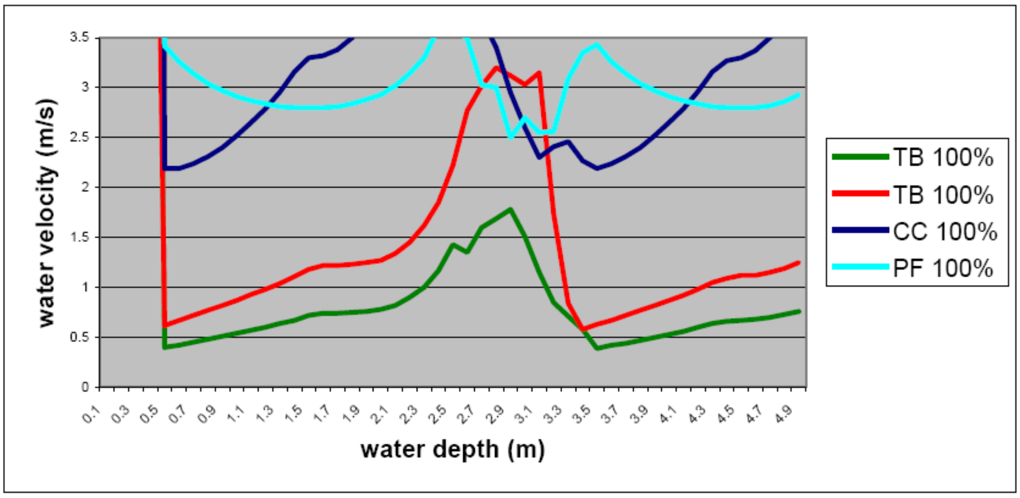


Figure 34: Damage curves for each of the structures when there is total collapse of walls (Roos, 2003, p39).
(CC- cast concrete structures, PF – prefabricated concrete, TB (green) – Traditional way of building (with solid walls), TB (red) Traditional way of building (with cavity walls))

The majority of research concerning physical vulnerability to flooding has focused on providing critical thresholds (mainly in terms of depth and velocity) that structures, parts of structures or materials are able to resist. The wealth of engineering-based research that has been completed to date, has provided a strong foundation for the estimation of physical vulnerability of individual structures (although there is still work to do in this field). What is not as well developed is the integration and testing of this data within more comprehensive and holistic methodologies. For instance, few studies focus on the physical vulnerability of groups of properties and how the presence (or absence) a particular property may impact upon adjacent properties. Damages to different types of infrastructure are also often considered post-event or within economic damage assessment. They are less well considered within other measures of physical vulnerability.

There are also fewer studies that focus on the physical vulnerability of properties in less developed countries. However, in many cases despite there being few formal assessments of physical vulnerability, awareness of floods and their physical impacts can said to be well-developed within the consciousness of the local population. Experience of previous flood events and knowledge about when flooding occurs has led many communities (over many years) to adapt both the design of buildings, the materials used for construction or the way in which communities are structured. This may increases either their physical resilience to flooding (i.e. the properties are less susceptible to flood damages) or their social resilience (i.e. the community is better able to respond and recover from flooding). Other aspects of cultural vulnerability and responses to flooding are considered in Deliverable 1.1.3.

5 Vulnerability in Landslide Risk Assessment

5.1 Generalities on Landslide Risk Assessment

Landslides cause frequent and widespread damage to the population and built-up environment in many areas of the world. Still, the hazard, vulnerability and risk analyses are extremely difficult to establish (e.g. Cardinali *et al.*, 2002; Glade, 2003; Lee and Jones, 2004; Alexander 2005; Cascini *et al.*, 2005; Glade and Crozier 2005; Roberds, 2005).

Landslides may be defined as a mass of soil, debris and/or rock which moves downslope or laterally because of gravitational or inertial forces (e.g. see Crozier, 1999). This definition includes a large variety of ground motions such as debris flows, deep failure of slopes, rock falls, etc. The various kinds of landslides can be classified by the type of movement and the nature of material involved. A commonly-used classification based on these parameters is shown in Table 24.

Table 24: Types of landslides (Cruden and Varnes, 1996)

TYPES OF MOVEMENT		TYPE OF MATERIAL		
		Bedrock	Soils	
			Coarse	Fine
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
Complex				

Landslide risk analysis can be practised at various levels of detail, ranging from qualitative evaluations to detailed quantitative risk analyses. The risk assessment requires the addressing of a large number of questions, such as:

- What is the slope geometry, geology, groundwater, potential movement mechanism?
- Will a landslide initiate on the slope, what are the probabilities of the initiation of sliding, and what are the causes (e.g. precipitation, seismicity, human activity)?
- What is the landslide volume, velocity, run out?
- Will there be warning signs, such as tension cracks or movement, that will allow mitigation of the probability of sliding or of the consequences, by for example, evacuating persons?
- What are the typologies of the exposed elements (i.e. property, persons) and their temporal probability?
- What is the vulnerability of the exposed elements?
- What is the risk to property and persons?

We see that contrary to other natural threats such as flooding and earthquakes, the complexity and the wide range of variety of processes (Leone *et al.*, 1996) make the assessment and quantification very difficult for landslides. Glade (2003) listed various effects that have to be considered:

- *The vulnerability of different elements at risk for similar processes*. For example a house may have the same vulnerability to a slow- and a fast-moving landslide, but the persons living in the house may have a low vulnerability to the slow-moving landslide (they can move out of the way) but a high vulnerability to the fast-moving landslide (no time to escape).

- *The temporal probability* for a person/moving object (e.g. a car) being present during the landslide event, affects the vulnerability.
- *Different groups of humans have different coping potentials*. For example, in contrast to many adults, children might not be able to react adequately to endangering processes.
- *Early warning systems* affect the vulnerability of people.
- *Spatial probability of landslides* varies.

And so on.

A general definition can be entrusted such as **Expected loss in terms of human lives, damage to properties and economic activities due to a specific natural event. Risk can be expressed as annual cost or number/amount of lost units x year.**

In terms of conditional probabilities landslide risk can be assessed as follows (AGS 2000; Morgan *et al.*, 1992):

Loss of life

R(DI) = P(H) x P(S l H) x P(T l S) x V(L l T)

where:

R(DI) is the risk (annual probability of loss of life to an individual)

P(H) is the annual probability of the landslide event

P(S l H) is the probability of spatial impact (i.e. landslide impacting a building) of the landslide given the event

P(T l S) is the temporal impact (i.e. building being occupied) given the spatial impact

V(L l T) is the vulnerability of the individual (probability of loss of life of the individual given impact)

Properties

R(PD) = P(H) x P(S l H) x V(P l S) x E

where:

R(PD) is the risk (annual loss of property value)

P(H) is the annual probability of the landslide event

P(S l H) is the probability of spatial impact (i.e. landslide impacting a building)

V(P l S) is the vulnerability of the property (proportion of property value lost)

E is the element at risk (i.e. value of the property)

A theoretical flowchart for risk assessment is given in Figure 35. In practice, although a large number of studies relative to landslide hazard assessment can be found in the literature (e.g. Aleotti and Chowdhury, 1999; Morgan *et al.* 1992; Gorsevski *et al.*, 2003; Guzzetti *et al.*, 2005; Van Westen *et al.*, 2006), only a few published works have been carried out on vulnerability and damage assessment (e.g., Fell, 1994; Cardinali *et al.*, 2002; Liu *et al.*, 2002; Glade, 2003; Lee and Jones, 2004; Alexander, 2005; Cascini *et al.*, 2005; Copons *et al.*, 2005; Düzgün and Lacasse, 2005; Fell *et al.*, 2005; Glade and Crozier, 2005; Roberds, 2005;

Wong, 2005; LESSLOSS Deliverable 93, 2007). The risk associated to landslides is then rarely quantitatively calculated, especially for large areas.

In Italy for instance, risk is generally expressed as a qualitative degree (i.e. low, medium, high) based on expertise. A typical risk susceptibility analysis is represented by risk maps (at municipality scale) produced by Law 267/98 starting from:

- landslide inventory;
- overlapping of element at risk with landslide areas;
- definition of 4 risk classes (R1-R4), defined following potential damage over socio-economic setting.

In these risk maps, the element of vulnerability is almost underestimated or even disregarded, assessing risk directly from the relationship between hazard and exposed elements. This is on the implicit assumption that an exposed elements has two vulnerabilities only: 0 (no vulnerability) if not involved in hazard areas; 1 (vulnerable) if involved.

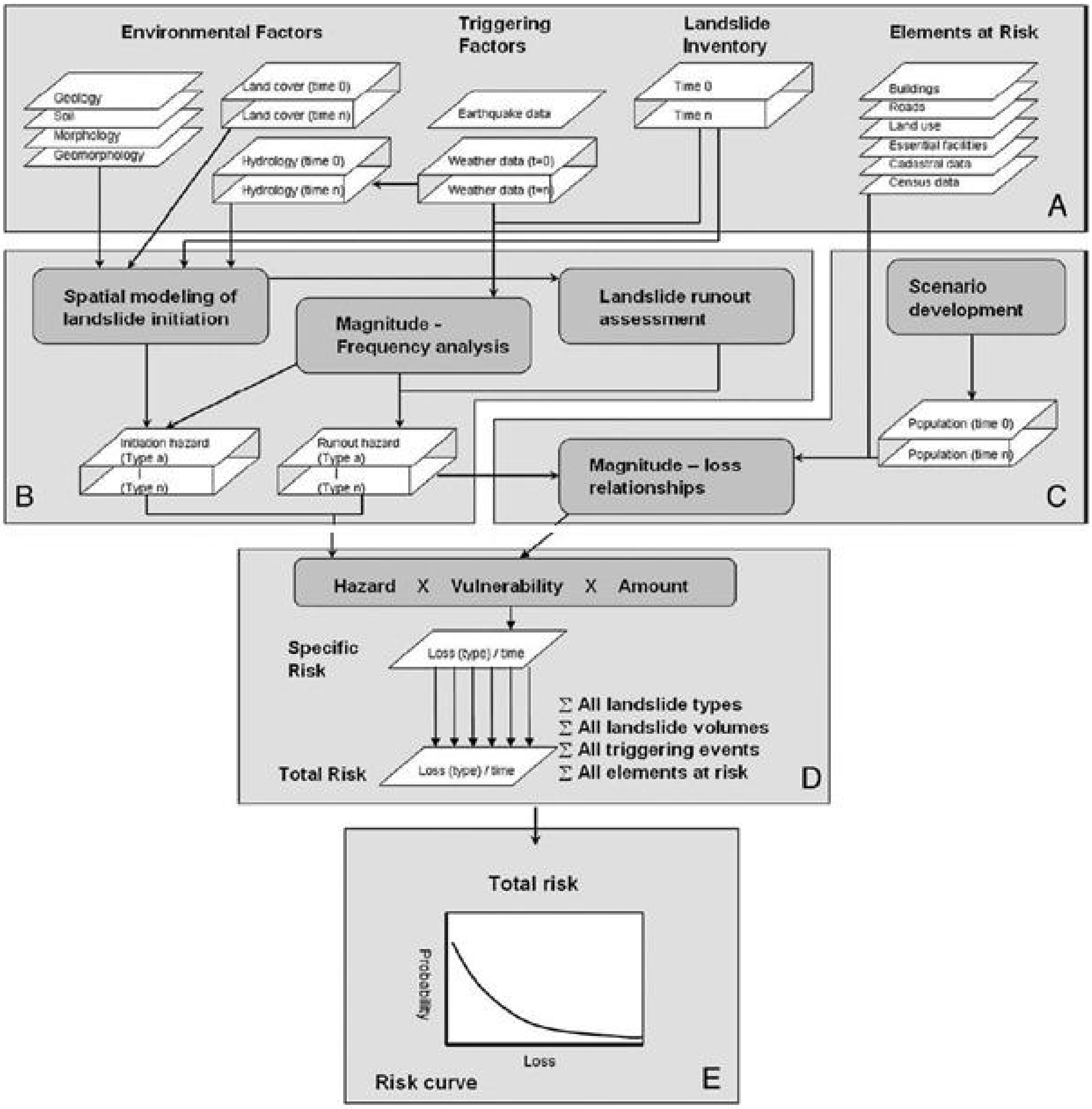


Figure 35: Schematic representation of the landslide risk assessment procedure. A: Basic data sets required, both of static, as well as dynamic (indicated with "time…") nature, B: Susceptibility and hazard modelling component, C: Vulnerability assessment component, D: Risk assessment component, E: Total risk calculation in the form of a risk curve (adapted from Van Westen et al., 2008).

5.2 State-of-the art and discussions on physical vulnerability assessment

There is no widely accepted and validated method at present to assess landslide vulnerability. For instance, according to the definition of vulnerability to property as given in section 5.1, we derive the monetised consequence of failure. However, in the framework of decision theory, it is not always easy to translate a given damage state or possible consequences into monetary values (e.g. environmental or aesthetical damages). Moreover, following the context prevailing, a given damage level will not have necessarily the same level of consequences. For instance, non repairable cracks on a house may be tolerable when the house is not to be sold, whereas it may reduce the house monetary value and induce sale difficulties when it will be put up for sale. Such a damage is function of the house market state at the time of the decision-making. When considering a probabilistic perspective, this variability of consequences due to the decision-making context, may be represented by a *utility function* (also called *cost or loss or weight or function*), which constitutes an indicator of the interest associated to a specific situation, without necessarily implying monetary consequences. This function denotes the utility to take this measure or another applying to a possible damage level (Canceill, 1983). Hence, one difficulty for landslide vulnerability assessment comes from the estimation of these damage levels.

Another main reason for the difficulty to assess and quantify vulnerability in case of landslides, is the lack of accurate data: only events that caused substantial damages have been recorded and precise information on the type, characteristics and damages due to the failure are often missing. Other difficulties include the temporal variations of the environment factors (especially just after a landslide), site-specificity of the parameters (such as the triggering factors), quantitative heterogeneity of vulnerability of different elements at risk for qualitatively similar landslide mechanism, the wide range of processes and characteristics possible (e.g. size, shape, velocity, momentum), as well as the numerous categories of damages (Figure 36). Another concern is that there is no common database in many countries since there is no overseeing agency. Available databases are then often incomplete and biased. Figure 37 shows the stage of development of landslide risk assessment methodologies according to RAMSOIL (Risk Assessment Methodologies for SOIL threats), a joint European project that aims at providing an inventory of the different risk assessment methodologies for soil threats regarding agricultural soils that are currently used in the European Union.

The proposed approaches for physical vulnerability assessment to landslides vary significantly in detail of analysis and resulting numerical values (Table 25). Besides, a comparison of different studies is difficult due to the differing types of construction and materials used. Studies conducted in Australia (e.g. Fell and Hartford, 1997) are hardly comparable to studies carried out in Switzerland (e.g. Romang *et al.*, 2003) due to differing resilience of the values at risk. Moreover, most of these analyses are subjective, as they are largely based on expert knowledge or historical data. A trend in harmonizing procedures and proposing standards should nevertheless gain ground due to the execution of future EU-funded projects.

Hereafter, we present a selective, but non-exhaustive review of studies that have been done to assess vulnerability to landslides, considering vulnerability from the natural science point of view, i.e. as the expected degree of loss or potential damage of an element or set of elements at risk exposed to a clearly defined type of event (e.g. earth slide) with a given intensity (e.g. permanent displacements).

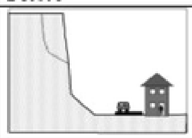
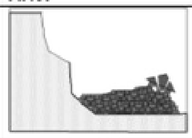
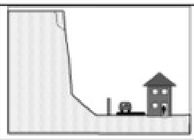
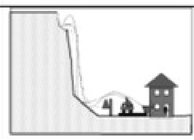
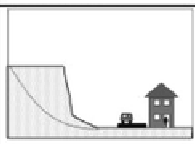
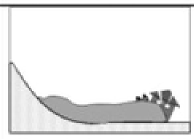
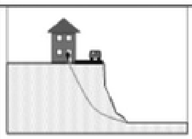
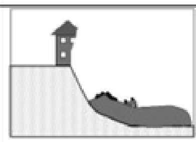
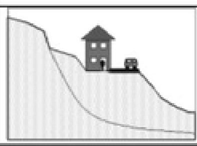
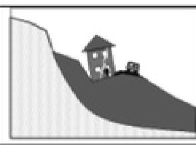
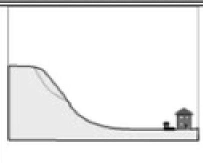
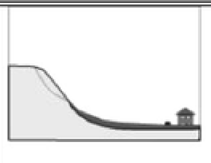
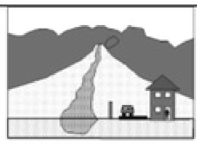
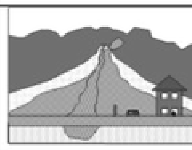
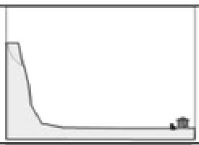
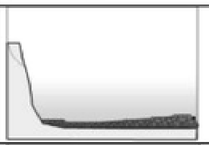
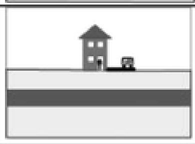
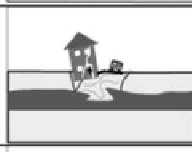
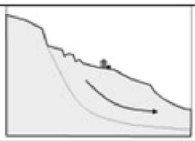
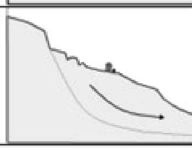
Type	Before	After	Likely damage to elements at risk	Factors determining risk
Impact by large rockmass			**Buildings:** Total collapse likely **Persons in buildings:** Loss of life/ major injury likely **Infrastructure:** Coverage and obstruction / destruction of surface **Persons in traffic:** Loss of life/ major injury possible	• Volume of rockfall mass • Location of source zone • Distance to Elements at risk • Triggering factors • Local topography along track • Intermediate obstacles • Precursory events
Impact by single blocks			**Buildings:** Total collapse not likely. Localized damage **Persons in buildings:** Minor to major injury likely **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** Loss of life/ major injury possible	• Volume of rockfall blocks • Number of rockfall blocks • Location of source zone • Distance to Elements at risk • Triggering factors • Local topography along track • Intermediate obstacles
Impact by landslide mass			**Buildings:** Collapse / major damage depending on volume **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** None, persons are normally able to escape	• Volume of landslide mass • Water content • Landslide material type • Triggering factors • Distance to Elements at risk • Local topography along track • Speed of landslide movement
Loss of support due to undercutting			**Buildings:** Collapse / major damage likely **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Complete destruction of road surface. **Persons in traffic:** None, persons are normally able to escape	• Volume of landslide mass • Water content • Landslide material type • Triggering factors • Retrogressive landslide • Cliff erosion • Speed of landslide movement
Differential settlement /tilting due to slow movement			**Buildings:** Tilted buildings with cracks. Normally no collapse **Persons in buildings:** None, slow movement. People not in danger **Infrastructure:** Tilting and cracks, traffic slowed down **Persons in traffic:** None, slow movement	• Volume of landslide mass • Water content • Landslide material type • Triggering factors • Speed of landslide movement • Amount of displacement
Impact by debris flow on slope			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** Minor-major injuries. Depends on speed. **Infrastructure:** Coverage of road surface. Obstruction of traffic. **Persons in traffic:** Minor-major injuries. Depends on speed.	• Volume of landslide mass • Water content • Slope steepness • Local topography • Landslide material type • Triggering factors • Speed of movement • Size of blocks transported
Flooding by debris flow on alluvial fan			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage **Persons in traffic:** None, persons are normally able to escape	• Volume of debris flow • Water & sediment content • Local topography of fan • Triggering factors • Distance from source • Distance from lahar channel • Speed
Impact by Sturzstrom			**Buildings:** Total collapse **Persons in buildings:** Loss of life **Infrastructure:** Total destruction **Persons in traffic:** Loss of life	• Volume of rockfall mass • Location of source zone • Distance to Elements at risk • Triggering factors • Local topography along track • Distance from source zone • Precursory events
Liquefaction			**Buildings:** Differential settlement, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks **Persons in traffic:** no-injuries	• Soil types • Soil strength • Grainsize distribution • Foundation types • Earthquake intensity • Water table
Deep seated creep movement			**Buildings:** Differential settlement, tilting, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks, broken pipes **Persons in traffic:** no-injuries	• Speed of movement • Local geological situation • Age of landslide • Seasonality of movement

Figure 36: Schematic overview of landslide damage types, in relation with landslide typology, types of elements at risk and their location with respect to the landslide occurrence (Van Westen et al., 2006)

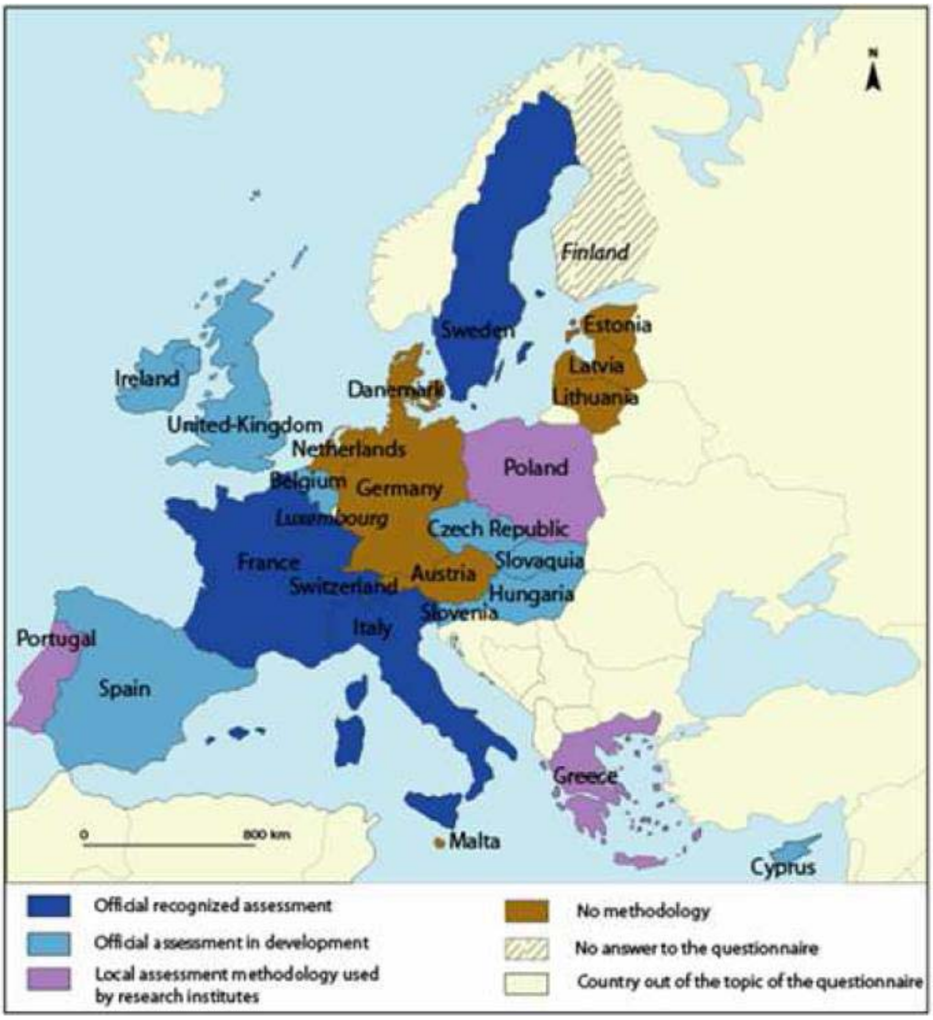


Figure 37: Stage of development of landslide Risk Assessment Methods (RAMs) in the European Union (Malet and Maquaire, RAMSOIL, 2008)

Table 25: Vulnerability assessment of structural elements to debris flows (Fuchs et al., 2007)

			Intensity							
			qualitative				(semi-)quantitative			
			low	medium	high	very high	low	medium	high	very high
			not specified	not specified	not specified	not specified	not specified	h < 1 m or v < 1 m/s	h > 1 m and v > 1 m/s	not specified
Vulnerability	qualitative	(1) Leone et al. (1995/1996); Finlay (1996)	not linked to process intensity							
		(2) Cardinali et al. (2002)	superficial	functional	structural	structural				
	quantitative	(3) Fell and Hartford (1997)	0.1	0.4	0.7	1.0				
		(4) Michael-Leiba et al. (2003)	0.1 (distal)		1.0 (proximal)					
		(5) Bell and Glade (2004)	0.1	0.2	0.5	not specified				
		(6) Romang (2004)	not specified	0.1 - 0.2	0.5	not specified				
		(7) Borter (1999) [for channel debris flows]					not specified	0.1	0.5	not specified

5.2.1 Qualitative assessment

An example is the vulnerability matrix (e.g. Figure 38) method proposed by Leone *et al.* (1996), in which the type of damage is described qualitatively. Vulnerability values are given for a wide range of situations, depending on the characteristics of the landslide (e.g. scale, velocity, run-out distance) and the resistance of elements at risk. However, the origin of these values is not clearly stated. This option requires the use of a large amount of data to be relevant.

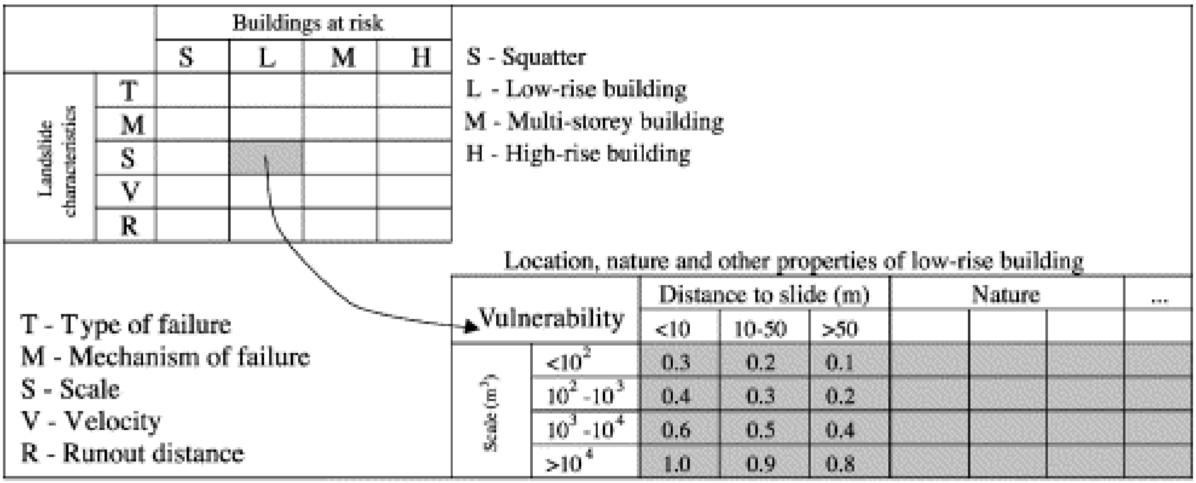


Figure 38: Example of a structural vulnerability matrix used in vulnerability assessment to landslides (Dai et al., 2002)

Cardinali *et al.* (2002) proposed an empirical GIS-based geomorphological approach to evaluate landslide hazard and risk. Using stereoscopic aerial photographs and field mapping, they tried to represent the changes of distribution and shape of landslides to assess their expected frequency occurrence and intensity. Damages to structures (classified as *superficial*, *functional*, or *structural*) are estimated using a qualitative relationship between landslide intensity/type and consequences (Table 26). This idea of multi-temporal analysis has been stressed by Romeo *et al.* (2006), to compute average recurrence time for individual landslides and to forecast their behaviour within reference time periods.

Table 26: Qualitative relationship used for damage estimation to structures (A = superficial or aesthetical/minor damage; F = functional or medium damage; S = structural or total damage) (Cardinali et al., 2002)

Landslide Intensity		Elements at Risk													
		Structures and infrastructures											Population		
		Buildings						Roads				Others			
		HD	LD	IN	FA	SP	C	MR	SR	FR	RW	Q	Direct	Indirect	Homeless
Light	Rock fall	A	A	A	A	A	A	A	A	A	A	A	No	No	No
	Debris flow	A	A	A	A	A	A	A	F	F	A	A	No	No	No
	Slide	A	A	A	A	A	A	A	F	S	A	A	No	No	No
Medium	Rock fall	F	F	F	F	F	F	F	F	F	F	F	Yes	Yes	Yes
	Debris flow	F	F	F	F	F	F	F	F	F	F	F	Yes	Yes	Yes
	Slide	F	F	F	F	F	F	F	S	S	F	F	No	Yes	No
High	Rock fall	S	S	S	S	S	S	S	S	S	S	S	Yes	Yes	Yes
	Debris flow	S	S	S	S	S	S	S	S	S	S	S	Yes	Yes	Yes
	Slide	S	S	S	S	S	S	S	S	S	S	S	No	Yes	Yes
Very high	Rock fall	S	S	S	S	S	S	S	S	S	S	S	Yes	Yes	Yes
	Debris flow	S	S	S	S	S	S	S	S	S	S	S	Yes	Yes	Yes
	Slide	S	S	S	S	S	S	S	S	S	S	S	No	Yes	Yes

5.2.2 Quantitative assessment

Historical records of landslides in Hong Kong constitute one of the best databases available. Finlay and Fell (1997) and Finlay *et al.* (1999) used these data to assign values of landslides vulnerability to buildings in this area. These records have also been used to assess the probability of landsliding for individual slopes.

Liu *et al.* (2002) established empirical relationships to assess the physical, economical, environmental and social vulnerability for debris flows. The latter is expressed for example as a function of age, education and wealth. Their model is applied to compute the hazard, vulnerability and risk for each prefecture of the Yunnan province (South-Western China).

Michael-Leiba *et al.* (2003) carried out a GIS-based assessment of the landslide vulnerability of people, buildings and roads for the Cairns community (Australia), useful for planning and emergency management purposes (Table 27). Data were derived from information provided by the *Australian Landslide database* (people and buildings on hill slopes) or the Cairns City Council (roads on hill slopes). Vulnerability values were assumed for large debris flows.

Table 27: Example of landslide vulnerability assessment for people, buildings and roads (uncertainties unknown) (Michael-Leiba et al., 2003)

Unit	Vulnerability of resident people	Vulnerability of buildings	Vulnerability of roads
Hill slopes	0.05	0.25	0.3
Units susceptible to proximal debris flow	0.9	1.0	1.0
Units susceptible to distal debris flow	0.05	0.1	0.3

Bell and Glade (2004) developed a raster-based quantitative method to assess risk to individual life for debris flows and rock falls for Iceland, and tested it in Bildudalur (N-W Iceland). Vulnerability levels of people and buildings where derived from general information found in the literature, based on the buildings material and the existence of large windows on the mountain side (Glade, 2003; Jonasson and Sigurdsson, 1999) and adapted for Icelandic conditions.

Borter (1999) proposed a quantitative methodology based on a "three-stage procedure", depending on the scale of the risk analysis. In this approach, vulnerability values are deduced empirically. It is a standard procedure for the mitigation of natural hazards in Switzerland.

Msilimba and Holmes (2005) analysed the hazard and potential risk of landslides in the Vunguvungu/Banga Catchment, Northern Malawi, area. Indexes of vulnerabilities were calculated based on eight empirical, readily determinable variables, such as slope or type of vegetation. Many approximations had to be made to this aim. No attempt has been made for example to weight the variables in terms of their relative significance in promoting instability.

In Spain, hazard and risk assessment methods are essentially based on the analyse of landslides and subsequent damages after 1954, using statistical techniques (Remondo *et al.*, 2005, 2008). A large variety of data are used, such as location, slope type and hydrologic condition, bedrock, regolith type, geometry of rupture zone and deposit, type of movement, area, approximate date, probable trigger, degree of activity or damages. A detailed inventory of exposed elements (infrastructures, buildings, land resources) is carried out to assess vulnerability. Numerical values are given by comparison of past damages experienced by each type of elements at risk with their own actual value.

Using data from a well-documented debris flow event that occurred recently in the Austrian Alps, Fuchs *et al.* (2007) derived a quantitative vulnerability function to fit best the observed damage pattern of the buildings studied in the test site. Although these authors concede that a wider application of this method to additional test sites would be necessary for further improvements, they claim that the presented intensity-vulnerability relationship is applicable to the brick-masonry and concrete constructions within European mountains.

Using historical data of landslides in Umbria, central Italy, Galli and Guzzetti (2007) established empirical vulnerability threshold curves and mapped the geographical distribution of vulnerability for buildings and roads in the hills surrounding the town of Collazzone. They claim that the established vulnerability thresholds (Table 28) can be used to assess vulnerability to landslides of the slide and slide-earth flow types on the entire Umbria region, provided that a sufficiently detailed landslide inventory map is available (Galli *et al.* 2007). However, they concede that further work has to be done to determine if their results can be used for other areas in Italy or elsewhere.

Table 28: Minimum and maximum landslide vulnerability threshold curves established in Umbria for three different types of elements at risk. V_L is the vulnerability to landslide and A_L, the landslide area (Galli and Guzzetti, 2007)

	Minimum vulnerability	Maximum vulnerability	Range of landslide area
Buildings	$V_L = 0.0006A_L^{0.62}$	$V_L = 0.0045A_L^{0.70}$	$2.5 \times 10^2\ m^2 \leq A_L \leq 2.0 \times 10^4\ m^2$
Major roads	$V_L = 0.0013A_L^{0.62}$	$V_L = 0.0050A_L^{0.85}$	$5.0 \times 10^1\ m^2 \leq A_L \leq 4.0 \times 10^4\ m^2$
Secondary roads	$V_L = 0.0010A_L^{0.62}$	$V_L = 0.0048A_L^{0.80}$	$2.7 \times 10^2\ m^2 \leq A_L \leq 1.7 \times 10^5\ m^2$

Zêzere *et al.* (2008) analysed the landslide risk for roads and buildings in a small area (20km²) north of Lisbon (Portugal). Vulnerability was classified for the three landslide groups studied, based on average geometrical features of landslide types and damage levels produced by past events.

In the LESSLOSS project, a number of methodologies have been explored for landslide vulnerability assessment at urban and element levels.

Regarding the urban level, a new methodology based on expert judgement and on the *First-Order Second-Moment* (FOSM) approach, has been proposed, which allows for quantification of uncertainties from the input parameters up to the vulnerability estimates. This methodology has been applied to the village of Lichtenstein, Baden-Württemberg, Germany (Kaynia *et al.*, 2008).

At the building level, we have already mentioned that one common approach for vulnerability assessment is to use empirical methods, which are based on data collected from field surveys and aim to establish criteria of serviceability (allowable settlements) by relating the observed deformation to the damage. One possible damage criterion for buildings and that is wildly used in technical literature, is the *angular distortion* defined as the ratio of the differential settlements and the distance between two points after eliminating the influence of the tilt of the building. For instance, a limit value of the angular distortion can be given, which corresponds to a threshold for crack initiation in walls and finishes. Greater values then would cause structural damage. Other criteria can be defined, which depend on the *slope* (difference of settlement of two adjacent supports relative to the distance between them), the *relative deflection* (ratio of deflection to the deflected part length) and the average settlement under the building.

However, another methodology has been explored within the LESSLOSS project, based on structural engineering principles (e.g. definition of criteria for initial cracking and building damage based on the calculation of critical tensile strains in a simple structure considered as a isotropic, weightless, elastic beam, considering two possible extreme modes of deformation, namely bending/shearing).

The proposed methodology has consisted in analyzing the structural response of a simple structure (e.g. a single bay-single storey encasing RC frame building), representing a continuous superficial foundation or building with a basement, subjected to differential settlements (see LESSLOSS Deliverable 93, 2007). The choice of such a structure was governed by the following observations:

- the building height is not critical in assessing building response due to ground failure;
- the displacement demand is concentrated in the ground floor column (if the imposed displacement concerns a marginal column);
- the vertical deformation in level ground beneath a single-bayed frame, places the same deformational demand on the members as in a multi-bayed frame.

For the encasing foundation type, the main characteristics of the structure model that could influence the structural behaviour (cross-section geometry, section reinforcement degree, displacement magnitudes and inclination angles) were modified, in order to: i) evaluate the importance of these parameters in the structural response, and ii) provide some classification criteria for them. A number of parametric studies (encasing case) were performed using the finite element method, by imposing displacements directly at the bottom of one frame column, without considering any interaction between the soil and the structure. The results have revealed that the key parameters affecting the behaviour of the frame elements are the displacement magnitude and inclination angle.

For differential settlements, the foundation type is critical and it is reasonable to assume that buildings on deep foundation are less affected by the settlements than building on shallow foundation. Hence, the methodology should also distinguish damage based on the building type.

Attempts to define post-yielding or damage limit states have been made within the LESSLOSS project, by specifying allowable values of concrete and steel strains for the considered structure type (Figure 39). A set of preliminary fragility curves has been obtained from numerical analyses (Figure 39), each curve giving the conditional probability of exceeding the proposed kth limit state (LSk), over a range of ground motion intensity (differential settlements in this case). The probabilistic framework of the damage estimation was done by counting the number of cases for which the structure reaches one of the four limit states, for a given differential displacement, considering a maximum magnitude value of 45cm (value in agreement with field observations for differential settlements).

Post-yielding (damage) limit state	$\varepsilon_{concrete}$	ε_{steel}
LS2	0.004	0.015
LS3	> 0.006	0.04
LS4	> 0.006	0.06

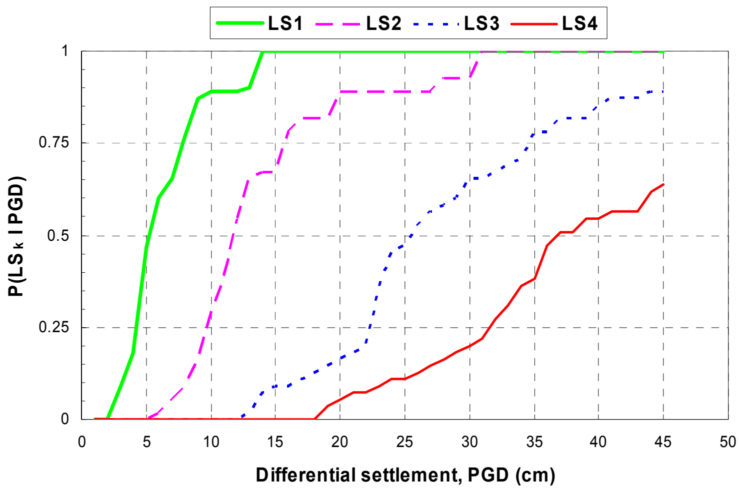


Figure 39: Fragility curves obtained for a one bay-one storey encasing RC frame building, considering 4 damage levels (LS1 to LS4, LS1 is for yielding strain limit) (LESSLOSS Deliverable 93, 2007)

This approach was particularly suitable for damage estimation analysis, since in addition to the direct damage building evaluation, it allowed extensive and repetitive parametric studies to be carried out in a cost-effective manner.

5.3 General methodology

5.3.1 Exposed elements

A correct and exhaustive exposure map should exhibit the inventory of all exposed elements:

- Urban areas, commercial, industrial and agriculture activities, expressed as density, building typologies and function;
- Transport infrastructure facilities;
- Services infrastructures such as, lifelines and pipelines;
- Public structures (i.e. schools), rescue and emergency structures (i.e. hospitals, fire department, civil protection);
- Technological and industrial plants (induced pollution);
- Cultural and environmental heritage.

For each single typology of element at risk, the economic value ***W*** or number of units of each element at risk located in a given location should be defined:

$$\mathbf{W = W(E)}$$

The value of element at risk should be expressed in terms of number *N* or quantity of exposed unity (i.e. number of persons, buildings) or in terms of exposed area *S* (i.e. hectares of terrain) or, if possible, as money.

The worth is a specific function of each single element at risk:

$$\mathbf{W = N} \qquad \textbf{otherwise} \qquad \mathbf{W = S}$$

For the comparison between different elements at risk sometimes it is useful to express the value in monetary terms, by multiplying the number ***N*** of elements or the surface ***S*** by a unitary cost ***w***

$$\mathbf{W = N \times w} \qquad \textbf{otherwise} \qquad \mathbf{W = S \times w}$$

The expression of the worth in monetary terms is particularly indicated for the risk analysis of elements with difficult parameterisation.

In same cases it should be useful to express value as total worth, taking into account all the elements at risk in a landslide prone area.

In monetary terms, total worth is the sum of the values of each element at risk (Del Prete *et al.*, 1992):

$$\mathbf{W = [R_m\,(M_m - E_m)]\,N_{ab} + N_{ed}\,C_{ed} + C_{str} + C_{morf}}$$

where:

R_m : average income of the inhabitants;

M_m : average life hope of inhabitants;

E_m : average age of inhabitants;

N_{ab} : number of inhabitants;

N_{ed} : number of buildings;

C_{ed} : average cost of buildings;

C_{str} : cost of structures and infrastructures;

C_{morf} : cost of morphological modifications.

5.3.2 Vulnerability concept and definitions

In general terms, the vulnerability is the degree of loss to a given element or set of elements at risk within the area affected by a landslide.

Vulnerability is generally expressed on a scale of 0 (no damage) to 1 (total loss). It is a function of the landslide intensity and typology of element at risk:

V=V(I;E)

The concept of vulnerability defines the correlation between the intensity of a landslide with his possible consequences (i.e. the risk).

Formally the vulnerability concept should be expressed in terms of conditional probability, namely, the probability that the element at risk is subjected to a specific damage after the occurrence of a landslide with a given intensity (Einstein, 1988):

V = P (damage|event)

The concept of vulnerability is strictly related to the measurement of severity of damage.

Following Morgan *et al.* (1992), the complete assessment of vulnerability in landslide analysis may be expressed by the following equation (each component is expressed by a relative scale from 0 to 1):

V = VS x VT x VL

where:

- *VS* is the probability of spatial impact: probability that a certain element at risk is affected by a landslide, (e.g. the probability that a rapid debris flow involve a specific building).
- *VT* is the probability of temporal impact: variability of characteristics of the element at risk with the time (e.g. the probability that a specific building is occupied during the landslide occurrence).
- *VL* is the probability of death of each occupant of the element, or the worth of damaged structures.

Vulnerability, is lower where prevention policies and emergency plan are active.

The evaluation of vulnerability should be based on statistical methods, in case of frequent and repeatable landslides. For example, considering a rock fall, a statistical assessment of the probability that a rock detachment may produce a specific damage on a specific building can be carried out.

According to the French experience (DRM, 1990), three main groups of exposed elements susceptible to damage are defined:

1. property or land, including structures, but also whole areas or land use means;
2. people;
3. various activities and functions.

Each group has its specific type of damage function:

- a structural damage function for material assets;
- a corporal damage function for people;
- an operational damage function for the various activities and functions.

When the element at risk is mainly represented by human life, vulnerability should be expressed by the probability of dead, injured or homeless after the occurrence of a specific landslide of a given intensity (Table 29). In this case, vulnerability depends on the population density in the exposed area (Fell, 1994).

Table 29: Example of probability in terms of effects on human life for different scale of intensity. (DRM, 1990)

Damage	H_0	H_1	H_2	H_3
dead	0	10^{-5}	10^{-3}	10^{-2}
injured	0	10^{-4}	10^{-2}	10^{-1}
homeless	0	10^{-4}	10^{-1}	10^{-1}

For goods and/or activities, vulnerability can be expressed as the percentage of the economic value that could be lost after the landslide (Table 30), considering:

1. aesthetical damage;
2. functional damage;
3. structural damage.

Table 30: Vulnerability scale of goods and activities (Fell, 1994)

Vulnerability of goods and activities	Vulnerability
Extremely high	$V \geq 0.9$
High	$0.5 \leq V < 0.9$
medium	$0.1 \leq V < 0.5$
Low	$0.05 \leq V < 0.1$
Very low	$V < 0.05$

Since vulnerability is related to damageability, some attempts has been done to relate the damageability to the depth of foundation, such as in Table 31 (after Ragozin & Tikhvinsky, 2000).

Table 31: Vulnerability vs. depth of foundations and failure (Ragozin & Tikhvinsky, 2000)

Depth of foundations (m)	Depth of slip surface (m)	Vulnerability
≤ 2	< 2	1.0
> 2	< 2	0
Minor than slip surface	2 – 10	1.0
10 –13	2 – 10	0.5 – 1.0
> 13	2 – 10	0 – 0.5*
Every depth	> 10	1.0**

A more detailed description of vulnerability to landslides is given in DRM 1990 (Table 32, Table 33).

Table 32: Conventional scale of damage severity, inspired from Mercalli scale (DRM, 1990)

Degree of damage	% of building value	Type of damage
1	some %	Light damage and non structural. The stability is uncompromised.
2	10 – 30	Crack on the walls.
3	50 – 60	Important deformations. Crack open. Evacuation is necessary.
4	70 – 90	Partial floor subsidence and walls disarticulations. Immediate evacuation.
5	100	Total disruption: restoration is impossible.

Table 33: Relative damage evaluation due to different landslide typology and intensity, correlated to building structural typology (DRM, 1990)

Intensity	typology	A	B	C_1	C_2
E_1	sliding	5	3 – 4	2	1 – 2
	flow	2 – 5	1 – 3	1 – 2	1
	fall	4 – 5	3 – 5	3 – 5	2 – 3
E_2	sliding	5	5	3 – 5	3 – 5
	flow	3 – 5	1 – 4	1 – 3	1
	fall	5	5	5	4 – 5
E_3	sliding	5	5	4 – 5	4 – 5
	flow	5	3 – 5	1 – 5	1 – 5
	fall	5	5	5	5
E_4	sliding	5	5	5	5
	flow	5	5	5	5
	fall	5	5	5	5

A = Old buildings, mediocre quality, without foundations. B typology included when affected by structural decay.
B = Normal and traditional buildings in masonry or light structure without concrete (i.e. small cottages).
C = Concrete or CAP buildings. Category divided into two sub-classes:
C1 = single buildings of small dimensions
C2 = buildings > 3 floors

At municipality scale, the vulnerability for each single building is very difficult to assess. It should be more reasonable to define the percentage of damage in homogeneous areas (land use map) as a function of landslide intensity (Table 34).

Table 34: Damage degree divided in percentage of homogeneous area with respect to land use and landslide intensity (DRM, 1990)

Land use area	E_1	E_2	E_3
Agricultural area	70	90	100
Isolated buildings	60	90	100
Group of buildings	36	80	100
Village	10	60	90
Commercial and industrial areas	40	80	100
Urban areas	50	80	90 - 100

5.4 Methodology for Cultural heritage

Despite of the great importance of vulnerability analysis in Landslide Risk Assessment procedures, there are still few studies on this fundamental issue due to its complexity and multi-disciplinarity.

Theoretically, in Landslide Risk Assessment, Vulnerability is defined as the potential degree of loss of an exposed element at risk (or a group of elements at risk) caused by a landslide with a given intensity and probability of occurrence affecting the site $V=V(I;E)$

When dealing with cultural heritage the following peculiarities arise:

- *Element at Risk* – peculiarity of Cultural Heritage
- *Worth of Cultural Heritage* – economic value/units
- *Landslide Intensity* – necessity to better define mobilised volumes, velocity, depth of failure, energy, etc.

In fact, the concept of worth, used for other typologies, is not appropriate and somewhat misleading for Cultural Heritage due to their singularity, peculiarity and un-repeatability of goods. Also parameterisation (not economical) of historical, cultural, religious, artistic characteristics, although very controversial and/or difficult to assess.

A new approach on Cultural Heritage vulnerability has been recently developed in Italy within a special project funded by the Minister of Scientific Research and dealing with the definition of a rigorous procedure for natural hazard risk assessment of Cultural Heritage. The project, coordinated by C. Margottini, involved experts both of natural hazards and of restoration, conservation and management of Cultural Heritage. The experience described in this section is mainly referred to the identification of physical vulnerability of cultural heritage to landslides.

The general process is reported in Figure 40 and examples presenting details of each individual element of the chain are given later in this section. The process is quite traditional but any individual item has been investigated and fitted to allow a better knowledge, and then a better protection of exposed cultural heritages.

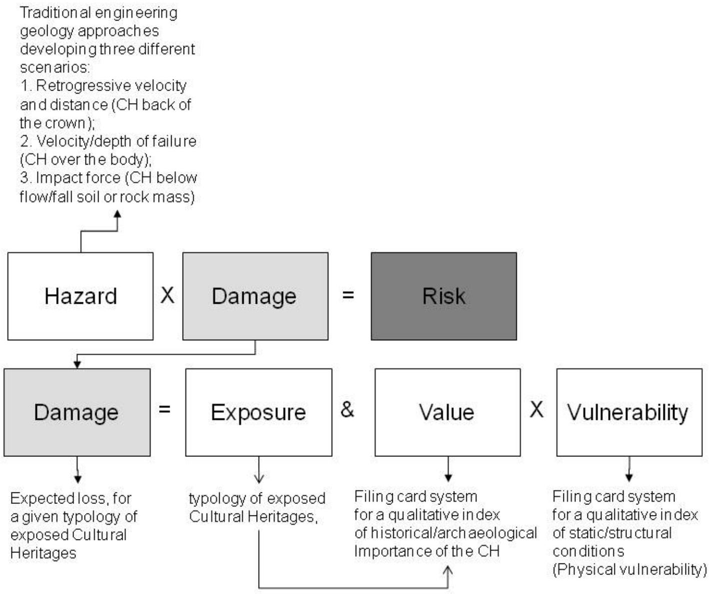


Figure 40: Proposed flow chart and detail of individual assessment in risk analysis for cultural heritage.

5.4.1 Evaluation of exposed elements

An innovative database for vulnerability analysis of Cultural Heritage to landslides has been developed, by adapting the Cultural Heritage code proposed for field survey by the Italian Ministry for Cultural Heritage (ICR). The following main categories are recognised:

- Archaeological heritage,
- Architectural heritage,
- Cultural Heritage depository (e.g. museums, etc.).

Within the above main categories, a very detailed list of cultural heritage typology is provided to characterize the individual exposed element (element at risk) as well as its "value". As an example, Figure 41 shows the map of exposed elements in the town of Civita di Bagnoregio. From such a map, it is possible to highlight the different typologies of involved Cultural Heritage.

Figure 41: Typology of Cultural Heritage exposed elements in the town of Civita di Bagnoregio (Central Italy)

For each typology of element at risk, an **Index of Importance/Exposure** ***(I_E)*** has been assessed, fundamentally based on historical and cultural characteristics of the element. The methodology is based on the elaboration of all the information derived from the stage of inventory and filing. The database can be resumed through the sum/product of the different values that constitute the Index of Exposure.

The proposed indicators and definition are reported as follows:

- **Importance** is related to the total of elements of the same typology; it represents the capability of each element to represent the historical/cultural identity of a given typology in the study area.
- **Typological frequency** is the frequency of the typology of a given element related to the sum of the exposed elements in the study area.
- **Presence of decorative elements and goods** produce an additional "value" of the single element characterised by the presence of other significant elements.
- **Preservation degree** is related to the entire Cultural Heritage, considering any kind of restoration works and modifications after the original realisation.
- **Present exploitation** is useful to define the importance of the Cultural Heritage as a function of the present destination.
- **Accessibility**, is related the possibility to access and visit an archaeological site.
- **Planimetric Index** is referred to the dimension of the single element in order to normalise the scale effects.

For each element at risk, the final index I_E can be expressed either in quantitative or qualitative form, by combining two main indicators, which are representative of the various aforementioned indicators:

$$I_E = (I_A + I_B) * SI$$

with:

- ***Indicator I_A (historical/cultural)***, including the importance, typological frequency, preservation degree and presence of other decorative elements and goods;
- ***Indicator I_B (economical/tourist)***, related to the present use and accessibility of the element at risk.

In case of archaeological heritage, Table 35 shows the detail of the database for typologies of goods and, in the lower part, the indicators to assign the importance from an historical and cultural point of view.

For archaeological heritages, the following categories have been defined: religious, funerary, defensive, civil, infrastructure, urban complex.

Nevertheless, for the purpose of landslide risk analysis, it was preferred to join the "value" and typology of Cultural Heritage in a single elaboration and map, obtaining a single indicator Index of Importance) not differentiating the various typologies.

Figure 42 to Figure 46 show examples of the adopted assessment methodology of the Index of Importance, undifferentiated for various typologies of Cultural Heritage.

Table 35: An example of the adopted system for archaeological elements

ARCHAEOLOGICAL ELEMENT AT RISK CLASSIFICATION								
MUNICIPALITY	LOCALISATION			N.FOLDER		OPERATOR	DATE	
TYPOLOGY								
RELIGIOUS			CIVIL			INFRASTRUCTURES		
Altar	TR1		Arch	TC1		Aqueduct	TI1	
Sacred fence	TR2		Amphitheatre	TC2		Cistern/w ell	TI2	
Dolmen	TR3		Basilica	TC3		Hydraulic w ork	TI3	
Menir	TR4		Library	TC4		Fountain	TI4	
Mitreus	TR5		Shed	TC5		Fish-pond	TI5	
Chapel	TR6		House	TC6		Bridge	TI6	
Sanctuary	TR7		Circus/arena/stadium	TC7		Arbour	TI7	
Temple	TR8		Column/obelisk	TC8		Decuman	TI8	
Environmental site	TR9		Cave	TC9		Road	TI9	
Paleo-Christian Church	TR10		Tabernacle	TC10		Paving	TI10	
Crypt	TR11		Store	TC11		Square	TI11	
FUNERARIUS			Market	TC12		Garden/hortus	TI12	
Catacomb	TF1		Nimpheus	TC13		Latomie	TI13	
Burial site	TF2		Gymnasium	TC14		Scale	TI14	
Mausoleum	TF3		Fish-pond/poll/bath	TC15		Statue	TI15	
Monument	TF4		Peristyle	TC16		Furnace	TI16	
Sepulchre	TF5		Shop	TC17		URBAN COMPLEX		
Tumulus	TF6		Theatre	TC18		Acropolis	TU1	
DEFENSIVE			Thermal baths	TC19		Park	TU2	
Walled tow n	TD1		Gallery	TC20		Historical green	TU3	
Fortress	TD2		Rustic villa	TC21		Historical aquatic park	TU4	
Moat	TD3		Residential villa	TC22		Fountains	TU5	
Enclosure	TD4		Palace	TC23		Village	TU6	
Arsenal	TD5		Triclinic/atrium/hall	TC23		Forum	TU7	
Tow n w alls	TD6		Base	TC24		Settlement	TU8	
Nuraghe	TD7		Exedra/pavilion	TC25		Insulae	TU9	
Portal	TD8		Area	TC26		Necropolis	TU10	
Tow er	TD9		Edifice	TC27		Quarter/district	TU11	
PRESENCE OF OTHER DECORATIVE ELEMENT								
ARCHEOLOGICAL								
Mosaic	PD1		Wall painting	PD3		External decorative element	PD5	
Internal decorative element	PD2		Frieze/stone material	PD4		Sepulchre	PD6	
HISTORICAL								
Wall painting	PD7		Stone material	PD9		Mosaic	PD11	
Internal decorative element	PD8		External decorative element	PD10		Frieze	PD12	
ENVIRONMENTAL								
Historical garden	PM1		Park	PM3		Historical aquatic park	PM5	
Botanical garden	PM2		Historical green	PM4		Play of w ater	PM6	
PRESENCE OF GOODS								
Metallic element	PB1		Furniture	PB3		Various painting	PB5	
Independent sculpture	PB2		Table painting	PB4		Various report	PB6	
RAPPRESENTATIVITY								
LOW	R1		MEDIUM	R2		HIGH	R3	
ACTUAL USE								
Tourist /archaeological	F1		Other use (cultural, representative, cult, civil inhabited, etc.)				F2	
ACCESSIBILITY								
Unexcavated	A1		Closed to people	A3				
Partially excavated	A2		Open to people	A4				
CRONOLOGY								
Prehistory	C1		Classic (V-IV sec B.C.)	C4		Ancient (476 - 600 A.D.)	C7	
Proto-history	C2		Hellenistic (V-I sec B.C.)	C5		Mediaeval (601 - 1400 A.D.)	C8	
Archaic (VII-V sec. B.C.)	C3		Romanic (I - IV A.D.)	C6				
FLOOR					VERTICAL ELEMENT			
Typology				m^2	Typology			m^2
Original floor (%)			Mosaic		Original w alls (%)			
			Broken Crockery					
			Plaster					
Other (%)			Other		Reconstructed w alls (%)			

Figure 42: Index of Importance for the Villa Arianna roman complex (Naples - Italy).

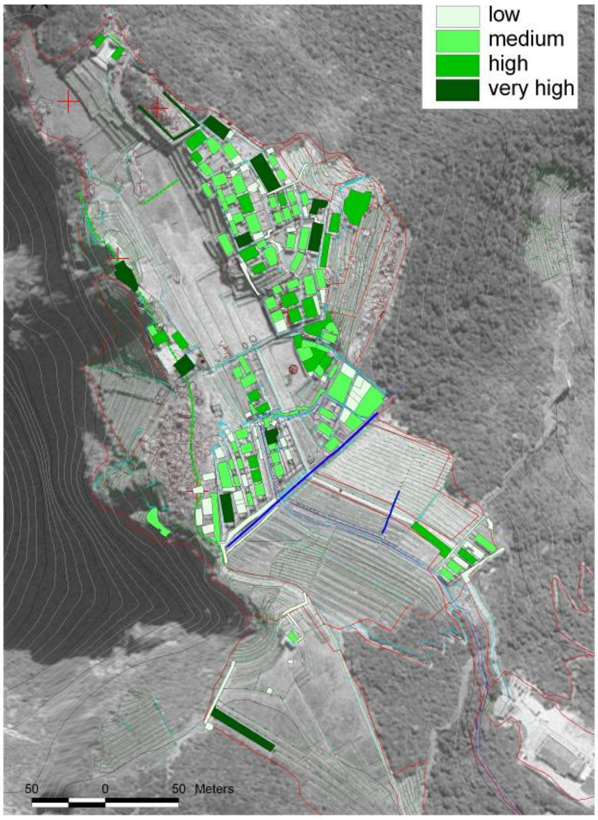


Figure 43: Index of Importance for the Inca citadel of Machu Picchu (Peru).

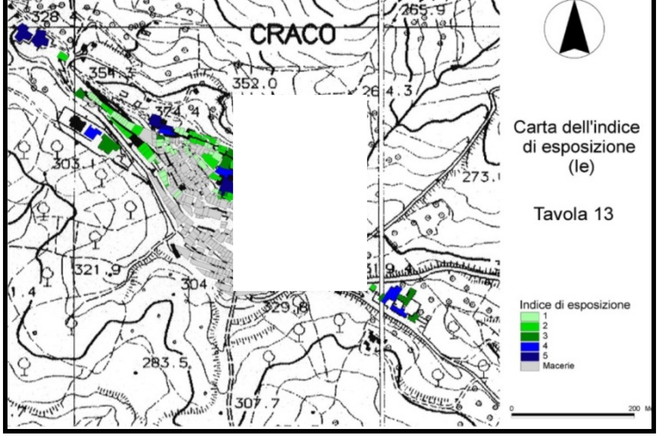


Figure 44: Index of Importance for the abandoned town of Craco (Southern Italy); from 1 (very low) to 5 (very high).

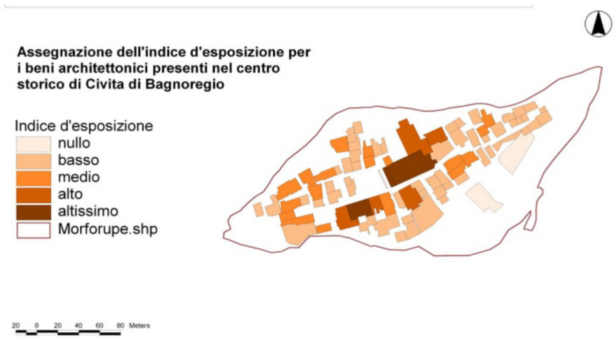


Figure 45: Index of Importance for the town of Civita di Bagnoregio (Central Italy); from 1 (very low) to 5 (very high).

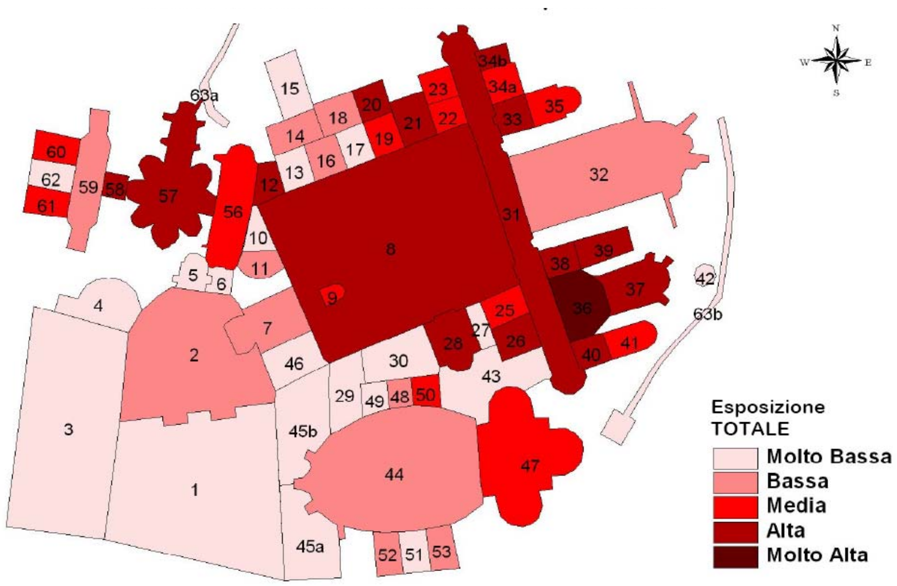


Figure 46: Index of Importance for the archaeological site of Piazza Armerina (Sicily); from 1 (very low) to 5 (very high).

5.4.2 Vulnerability assessment

The vulnerability analysis, i.e. the understanding of potential damage to be suffered by a given exposed Cultural Heritage affected by an intensity of hazard, is the real fundamental step in risk assessment. Nevertheless, the state of the art on the matter is still very poor and almost missing when the exposed element is a Cultural Heritage. The proposed approach has been developed in some previous project but not a final model, for a more general use, can be presented. In the case studies, the analysis has been carried out with the purpose to assess the risk of loss for some cultural heritages affected by landslide hazard. For this reason, the vulnerability has been identified in the static-structural condition of the Cultural Heritage, that coupled with intensity of hazard may allow the potential risk of loss. This approach is conceptually similar to the "fragility" curves developed for seismic risk but, without a large data base of information, cannot be applied in a general way. In fact, the elaboration hereby developed are related to the physical vulnerability and then to preserve the integrity of the structure. The different response to landslide hazard of diverse Cultural

Heritage has been recognized not so large and, in any case, treated individually in each case study. This is not correct in theory but it helps to manage the different Cultural Heritages when affected by landslide hazard.

After the definition of the conceptual model, case studies have been implemented, to verify the correctness of the proposed approach and the robustness of selected indicators (i.e. Index of importance). With respect to hazard, three different scenarios have been considered to merge with static structural conditions (Figure 47):

- retrogressive morphological processes affecting the Cultural Heritage, as in the case of sliding and fall;
- a Cultural Heritage over the body of mass movement having a given velocity and depth of failure;
- a Cultural Heritage sustaining the impact force of a rock/earth mass.

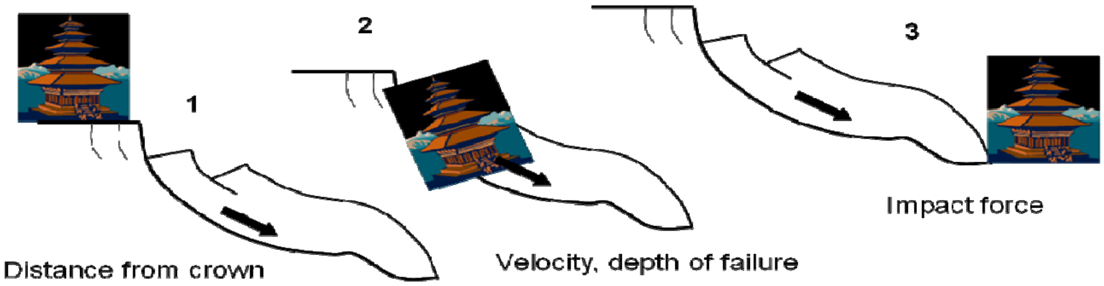


Figure 47: The three different scenarios to combine landslide hazard and static-structural index.

The methodological process should consider the following steps:

- definition of the **localisation** of the element at risk (up-hill, landslide body, down-hill);
- intensity/damage analysis of classes of elements at risk characterised by the same building/structural typology;
- implementation of a vulnerability function depending on each class of exposed elements with respect to minimum/maximum expected landslide intensity

Figure 48 to Figure 50 describe such functions qualitatively. These functions, expressing potential damage, which are not yet developed in detail, are presently only implemented in selected case studies.

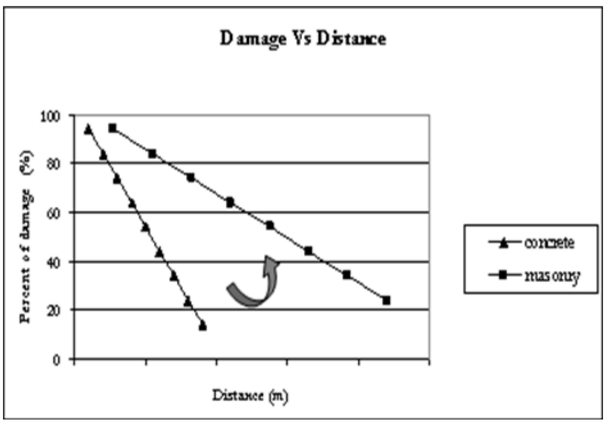


Figure 48: Potential physical vulnerability function describing damageability of different structural typology of Cultural Heritage with respect to distance from crown.

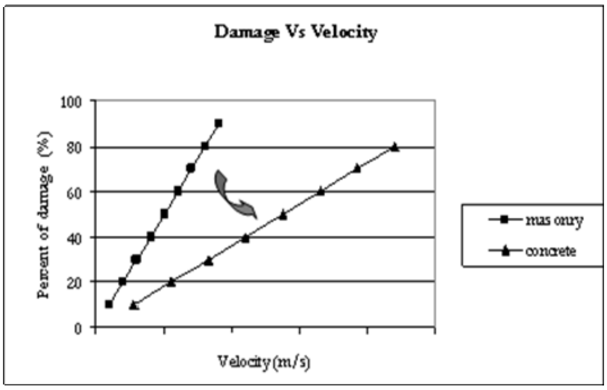


Figure 49: Potential physical vulnerability function describing damageability of different structural typology of Cultural Heritage with respect to velocity and depth of failure.

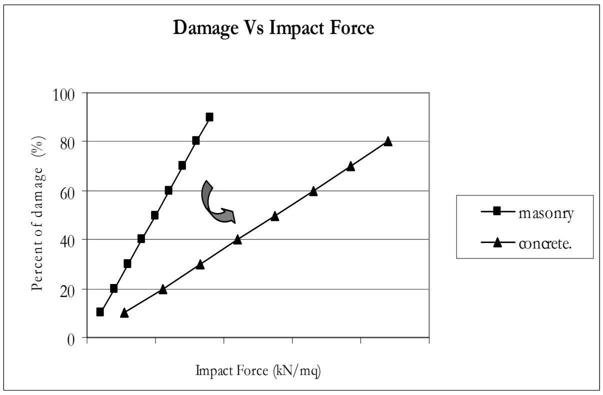


Figure 50: Potential physical vulnerability function describing damageability of different structural typology of Cultural Heritage with respect to impact force.

Considering the need of understanding the possibility of physical destruction for a given Cultural Heritage exposed to landslide risk, a database for the field survey of the static-structural conditions has been developed and applied in some case studies.

The following categories of indicators are related to Cultural Heritage typologies and landslide characteristics (see the proposed filing form in Table 36):

- **geometric properties** of the Cultural Heritage in terms of height and wall thickness, in order to correlate these data with e.g. the impact force of fast slope movements;
- **presence of restoration works**, useful to understand past damage and, as well, the present capability to resist to a landslide with a given intensity;
- **presence or absence of coverage** is a fundamental parameter to understand the impact of weathering on structures;
- **presence of cracks** in order to reconstruct damage derived from the interaction between structure and soil;

- **analysis of active strain processes** (i.e. sinking, swelling, tilting) and degradation (i.e. humidity, decreasing of resisting sections) sub-divided into vertical and horizontal elements;
- **classification following** the main building typologies and their structural characteristics.

Figure 51 and Figure 52 describe the adopted methodologies.

Table 36: Filing form for evaluating static-structural condition of Cultural Heritages at risk

STATIC-STRUCTURAL-CONDITION EXSTIMATION FOR THE ARCHEOLOGICAL GOODS								
MUNICIPALITY	LOCALISATION			N.FOLDER		OPERATOR		DATE
GEOMETRIC PROPERTIES								
HEIGHT						**RESTORATION WORKS**		
Above the ground			*Underground*			Chains	I1	
Number of floor	AP1		Number of floor	AP2		Buttress	I2	
Total height (m)	AM2		Total height (m)	AM2		Abutment	I3	
Coverage								
Present	C1		Absent	C2		Partially covered	C3	
Wall thickness								
x < 50 cm	SM1		50 cm < x < 80 cm	SM2		x > 80 cm	SM3	
Humidity								
Absent	U1		Capillarity	U2		Infiltration	U3	
VERTICAL ELEMENT						**HORIZONTAL ELEMENT**		
FRACTURE						**FRACTURE**		
Closed	LV1		**classes**			Closed	LO1	
Opened	LV2		<0,5 cm.	LV31		Opened	LO2	
Consolidated	LV3		0,5cm.<x<3 cm.	LV32		Consolidated	LO3	
Value in cm.	LV4		>3 cm.	LV33		Value in cm.	LO4	
SLOPE/GRADIENT						**SINKING**		
Straight	INV1		**classes**			Absent	CE1	
Tilted	INV2		< 5°	INV31		Present	CE2	
Bulged	INV3		5°<x<10°	INV32		**CONSTRUCTION TYPOLOGY**		
Value in degree (°)	INV4		>10°	INV33		Vault w ithout chain	TCV1	
SWELLING						Vault w ith chain	TCV2	
Absent	RG1		Localised	RG21		Original coverage	TCV3	
Present	RG2		Diffused	RG22		Other	TCV4	
CONSTRUCTION TYPOLOGY								
Cyclopic w alls	TCO1		*opus squadratum*	TCO4		*opus reticulatum*	TCO7	
Polygonal blocks	TCO2		*opus cementicium*	TCO5		Isolated pillar	TCO8	
Brickw ork in squared blocks	TCO3		*opus latericium*	TCO6		other	TCO9	
DAMAGE								
KIND OF DAMAGE								
Absent	TD1		non-structural damage	TD2		Crack on the w all	TD3	
Remarkable deformation	TD4		Floor sinking	TD5		Remarkable damage to vertical and horizontal element	TD6	
PERCENTAGE OF DAMAGE								
0	PD1		1 - 10 %	PD2		10 - 40 %	PD3	
40 - 60 %	PD4		60 - 90 %	PD5		90 - 100 %	PD6	

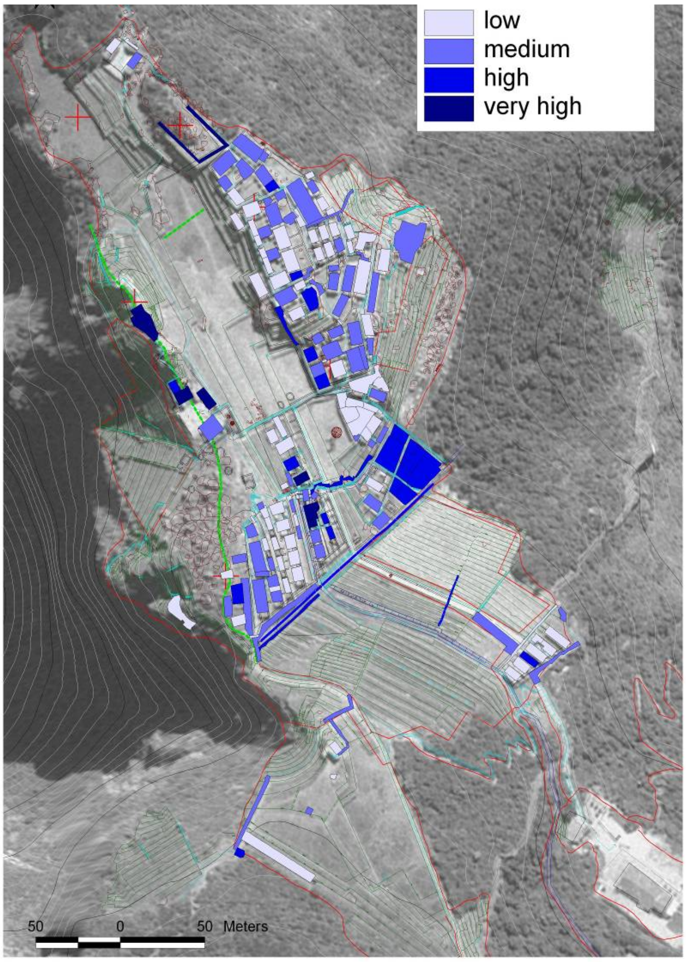


Figure 51: Static structural condition (Physical vulnerability) of Machu Picchu INCA citadel (Peru).

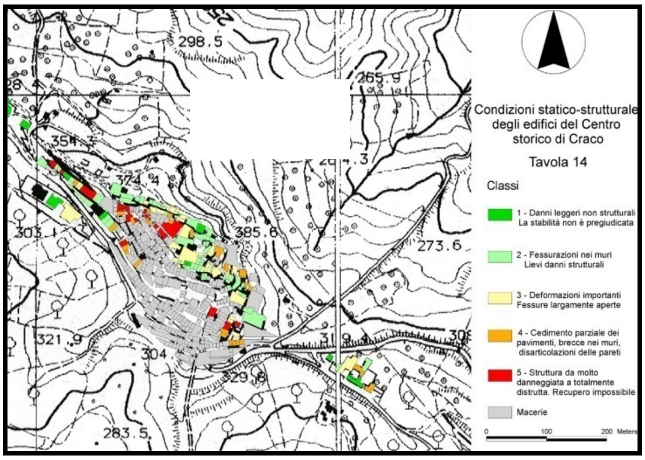


Figure 52: Static structural condition (physical vulnerability) of the Craco town in Southern Italy.

In order to make the process more simple, as previously mentioned, the different typologies of cultural heritages have been grouped together, in the index of importance. The product of this indicator and the synthetic representation of the static-structural conditions provides a first view of the state of Cultural Heritage, hereby considered all of the same importance and differentiated only by their respective value. Figure 53 to Figure 56 represent this intermediate passage, before the comparison with the hazard (risk assessment).

Figure 53: Index of Importance multiplied by static-structural condition for Villa Arianna roman complex (Naples, Italy).

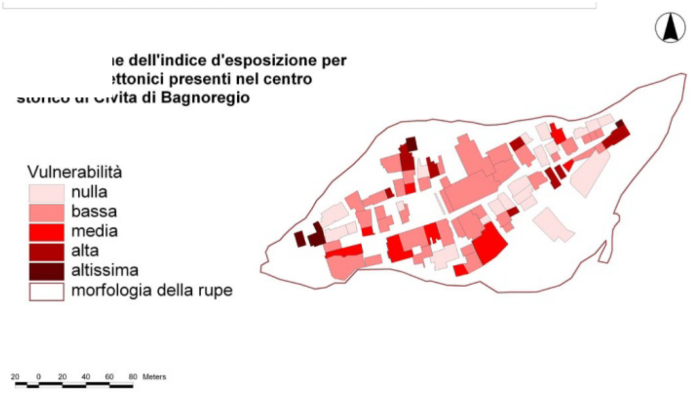


Figure 54: Index of Importance multiplied by static-structural condition for Civita di Bagnoregio village (Central Italy).

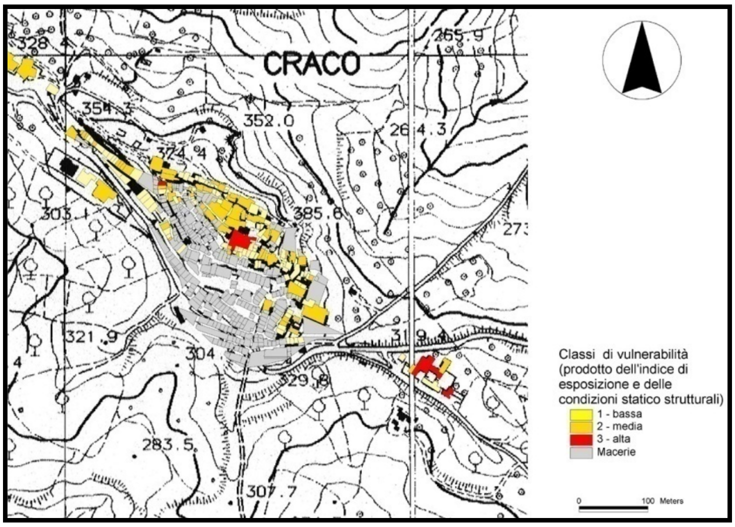


Figure 55: Index of Importance multiplied by static-structural condition for Craco Village (Southern Italy).

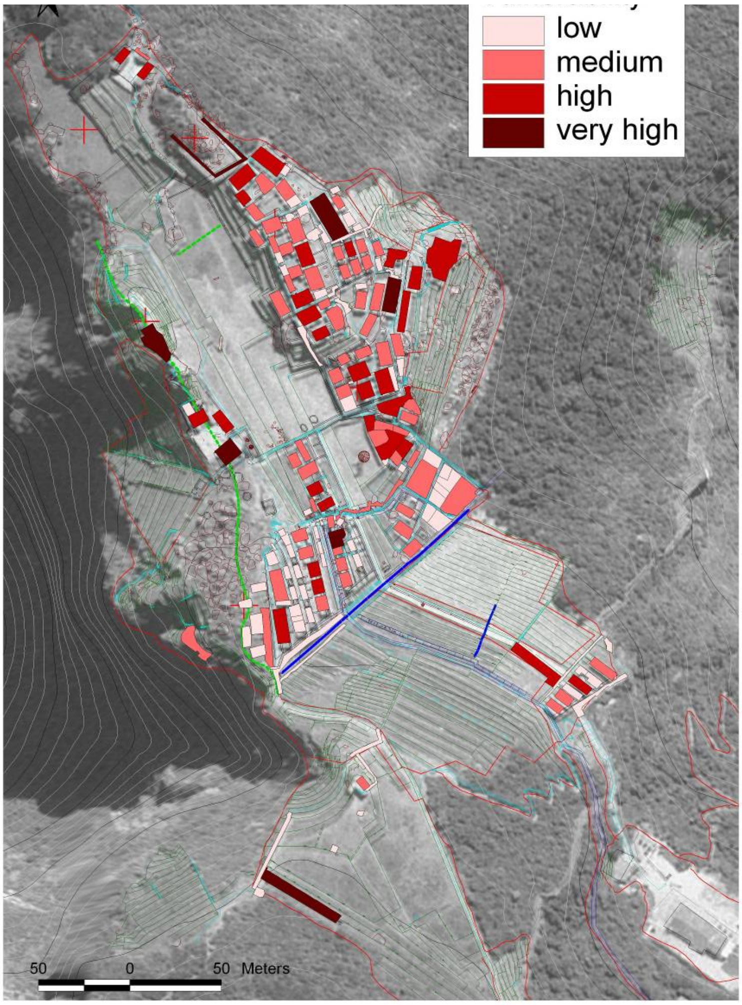


Figure 56: Index of Importance multiplied by static-structural condition for Machu Picchu INCA citadel (Peru).

5.4.3 Risk assessment

The previous information on the index of importance and the vulnerability analysis (in this approach the static-structural condition) may provide a basic tool for assessing the risk that is affecting a given cultural heritage affected by landslide hazard. The methodology is still under development, as clearly demonstrated by Figure 57 and Figure 58, showing examples where the procedure has been fully implemented.

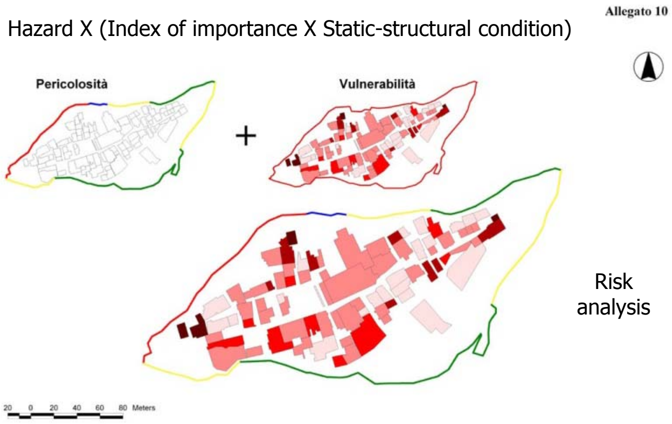


Figure 57: Risk map for the village of Civita di Bagnoregio, also reporting the hazard (retrogressive of the cliff from rock fall and the product Index of importance X Static-structural condition.

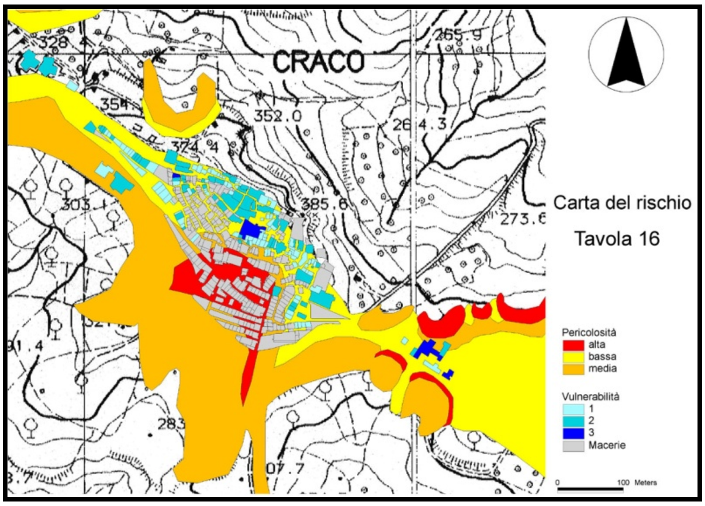


Figure 58: Risk map for the village of Craco (Souther Italy).

In other sites, like in the case of the cliff of Bamiyan (Central Afghanistan), the methodology cannot be fully implemented and a direct comparison with the exposed caves has been done from a geomorphological map (Hazard), providing simply the information that a Cultural Heritage can be involved in a rock fall or affected by soil erosion (Figure 59 and Figure 60).

Figure 59: Historical caves in the Bamiyan cliff potentially in danger from rock fall.

Figure 60: Historical caves in the Bamiyan cliff potentially in danger from soil erosion.

Finally, the present methodology can also be applied to evaluate more properly the risk factor, since it is possible to introduce the “time” issue into the process, i.e. in the evaluation of different scenarios according to present day cliff evolution (proper landslide hazard assessment). Figure 61 shows an attempt to derive such combination for the archaeological site of Villa Arianna, Naples (Italy).

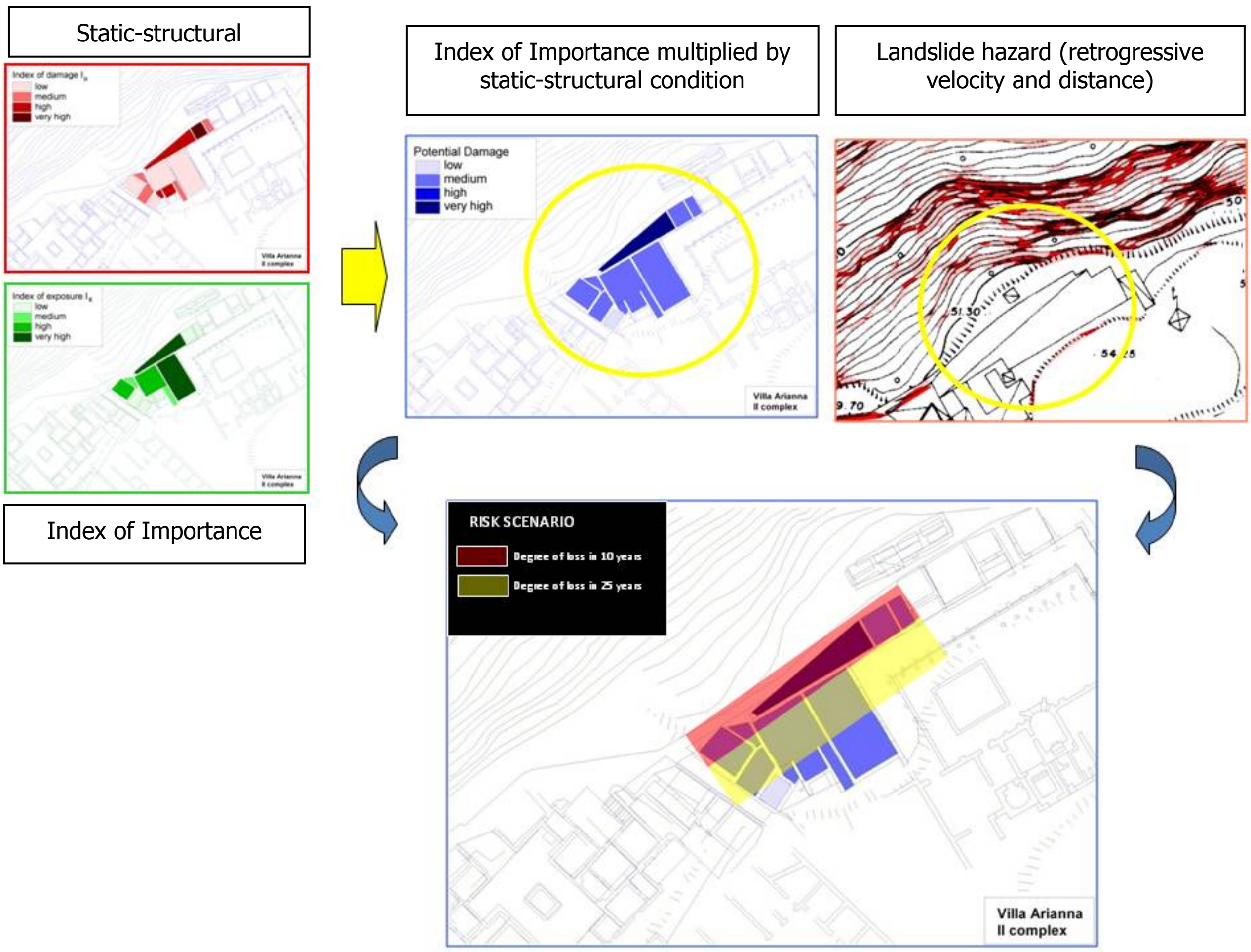


Figure 61: Different risk scenarios based on cliff evolution at 10 and 20 years from now, for the archaeological site of Villa Arianna, Naples (Italy).

6 Vulnerability in Volcanic Risk Assessment

6.1 Physical stresses and relevant parameters

Although volcano hazard maps are quite common nowadays, vulnerability assessment studies and risk maps remain relatively unusual. Vulnerability assessment methodologies are clearly not as developed for volcanoes as they are actually for other types of hazards, especially earthquakes and fragility curves are not systematically developed. The explanation mostly lies in the multiplicity of causes that might induce damages, as there are many types of volcanic activities and eruptions, ranging from mild emissions of lava flows to violent explosions. In addition, volcanic eruptions are also typically characterized by several volcanic phenomena (e.g. earthquakes, pyroclastic density currents, lava flows, tephra fall, lahars, gas release, and tsunamis) associated with different types of hazards that can affect different sectors of society in a variety of way, over different time scales and with different degrees of intensity. Things get even more complicated if one considers risks to human life (not treated here) since other factors such as noxious gases have to be taken into account (e.g. Baxter *et al.*, 1998).

In Table 37, we summarize the main hazard types and related mechanisms that might induce damages to structures. Not all volcanic phenomena listed here will be discussed in terms of structural vulnerability assessment, as dedicated methodologies are not always available.

Table 37: Volcanic hazard characteristics pertinent to vulnerability and risk assessment (adapted from Blong, 2000).

Lava flows	- Temperature above ignition points of many materials - Velocities from a few tens of m/hour to 60 km/hour - Bury or crush objects in their path - Follow topographic depressions; can be tens of kilometers long - Noxious haze from sustained eruptions
Ballistic ejecta	- 10+ km radius of vent - High impact energies - Densities < $3t/m^3$ - Fresh bombs above ignition temperatures of many materials
Tephra Falls	- Downwind transport velocity < 10 to < 100 km/hour - Power-law decrease in thickness downwind - Can extend 1000+ km downwind - Material <64 mm diameter at thermal equilibrium - Can produce impenetrable darkness - Compacts to half initial thickness in a few days - Surface crusting encourages runoff - Abrasive, conductive, and magnetic
Concentrated pyroclastic density currents (Pyroclastic flows)	- Concentrated gas-solid dispersion - Flow velocities up to 160 m/s - Emplacement temperatures < 100 to > 900 C - Small flows travel 5-10 km down topographic lows - Large flows travel 50-100 km - Large flows climb topographic obstructions
Dilute pyroclastic density currents (Pyroclastic surges)	- Low concentration but high kinetic energy - Radius of deposition 10-15 km - Climb topographic obstructions - Emplacement velocities > tens of m/s
Lahars	- Generated with rainfall < 10 mm/hour - Bulk fluid densities 2-2.4 t/m^3, sediment content 75-90 wt% - Peak flow rates > 10,000 m^3/s; velocities > 10 m/s not uncommon - Increase turbidity and chemical contamination in water bodies - Rapid aggradation, incision, or lateral migration - Travel distances up to tens of kilometers - Hazard may continue for months or years after eruption
Jokulhaups	- Can occur with little or no warning - Discharges may be > 100,000 m^3/s
Rock/debris avalanches	- Sector collapse, minimum volume 10-20 million m^3 - Travel distances 20-30+ km - Deposit cover 100+ km^2 - Emplacement velocities up to 100 m/s - Create topography, pond lakes - Can produce tsunamis in coastal areas
Earthquakes	- Maximum modified Mercalli intensity of 8 or less - Damage limited to small areas - Damage dependent on subgrade conditions
Ground deformation	- Damage limited to 15-20 km radius - Subsidence may affect hundreds of km^2
Tsunamis	- Open ocean travel rate > 800 km/hour - Exceptionally, waves to 30+ m - Inundation velocities 1-8 m/s
Air shocks	- Up to 15-fold amplification of atmospheric pressure
Lightning	- Cloud-to-ground lightning from ash cloud - Strikes related to quantity of tephra
Gases and aerosols	- Water vapor a major component - SO2 next most important - SO2, H2S, HF, HCL (corrosive/reactive) - CO2 in areas of low ground or poor drainage - pH of associated rainwater may be 4.0-4.5

6.2 State-of-the art and discussions

Given the variety of hazards occurring both at different volcanoes and during a same eruption, dedicated vulnerability models and methodologies need to be developed for different volcanic phenomena. Other factors might also explain the lack of models in comparison with other natural hazards: contrary to earthquakes for instance, where sudden ground motions induced by tectonic movements cannot be predicted, short- and mid-term forecasting is sometimes possible for volcanoes through careful monitoring (Marzocchi *et al.*, 2004; Douglas, 2007). Moreover, it seems rather unlikely that people in the open or buildings near the volcano might survive to hazards such as pyroclastic or lava flows (e.g. Blong, 1984, Lirer and Vitelli, 1998). Hence, in some cases reducing vulnerability by land-use planning is the most obvious and effective risk reduction methodology (e.g. lava flows, lahars). Therefore, much of the research relative to volcanoes essentially concentrates on forecasting considerations or hazard assessment studies, more than on vulnerability appraisal.

Still, recent efforts have lead to significant improvements, in the framework of European projects notably (e.g. EXPLORIS, 2005). The methodology that has been the most widely used so far has consisted in carrying out structural surveys and in estimating vulnerability through observations from past events on structures with similar characteristics. A more recent trend however is to replace such empirical (often subjective) analyses by more quantitative approaches based on analytical/numerical or on experimental procedures.

In this section, we first present a brief overview of the main methodologies adopted for structural vulnerability assessment in the literature, which can be grossly classified into three categories, namely empirical, analytical/numerical and experimental. Finally, we indicate some characteristics and issues to be considered in the assessment of structural vulnerability to volcanoes, focusing on three particular volcanic hazards, namely tephra falls, pyroclastic density currents and volcanic earthquakes.

6.2.1 Empirical assessment

As far as volcanoes are concerned, vulnerability and loss assessment studies must be preceded by a very careful inventory of all the types of threats and characteristics of hazards and buildings that have to be taken into account for carrying a realistic evaluation of damages. There are indeed, as mentioned before, a large variety of processes liable to threaten the integrity of structures in the case of volcanic hazards. In Table 37 (adapted from Blong, 2000), we have indicated a range of volcanic hazards, itemizing those physical characteristics that might be relevant in a prospective of vulnerability assessment.

Observations from past events seem to indicate that a wide variety of damage states exist, which are not *binary* (0 for no damage, 1 for total loss). Hence, establishing a risk map necessitates a careful assessment of vulnerability in this case. Therefore, the analysis generally requires the combination of observations from past volcanic eruptions and/or judgement of experts.

For instance, based on experience, Booth *et al.* (1983) assumed for example, that some houses in Sao Miguel (Azores) will fail under dry tephra deposits of 25 cm thickness, and that practically all houses would fail under a wet compacted tephra deposit of 50 cm, unless their roofs have a pitch steeper than 35 degrees, or if an effort is made to clear the roofs of their tephra loads, manually.

Pomonis *et al.* (1999) stated that houses typical in the Azores are unlikely to resist a pressure of more than 5kN/m^2. A simple calculation indicates however that pressure associated with pyroclastic flows and surges should amounts to several tens of kN/m^2. They conclude, therefore, that if a house is located in the direct path of a pyroclastic flow or surge, the pressure will be sufficient to cause severe damage leading to collapse in most cases. Based on empirical data presented by Blong (1984), they also concluded that pyroclastic bomb weight in excess of 100 g and impact energy above 300 Joules are necessary to penetrate a typical roof in the Azores, while fibre cement roofs might be penetrated by bombs of less than 100 g or with impact energy below 300J. Penetration of window glass should occur at much smaller values.

More recently, in a study conducted within the framework of the GRINP project (Gestion des Risques Naturels et Protection Civile – *Natural Risk Management and Civil Protection*), Thierry *et al*. (2008) have proposed damage coefficients as a function of discrete physical intensity scale for several hazards (such as ash accumulation), basing their analysis on earlier studies (e.g. Blong, 1984; Leone, 1995; Stieltjes, 1998; Pomonis *et al*., 1999) and on results from analytical and laboratory experiments conducted at Mount Cameroon. The damage coefficients are then used to establish risk maps for structures and infrastructures, as well as for population, vegetation and atmosphere.

Hereafter, we indicate some physical processes and issues relevant for structural vulnerability assessment to volcanoes, focusing on three particular volcanic hazards, namely tephra falls, pyroclastic density currents and volcanic earthquakes.

Tephra falls (mostly lapilli and ash; <64mm)

When considering plinian and subplinian volcanic eruptions, some tephra falls may occur (including ash, lapilli, blocks, and bombs), which may last hours or days, and can affect wide areas. They can accumulate up to tens of kilometres from the source (e.g. Macedonio *et al*., 1990) in a sufficient amount to cause roof collapse, eventually leading to a large number of deaths and injuries. Because of the widespread effects of tephra, vulnerability assessment studies are of importance for easing post-event reoccupation and recovery, but most of all for evacuation debates and mitigation measures before the eruptive event, by providing buildings capabilities to resist the vertical load that they induce.

Pyroclastic blocks and bombs (>64mm) (Pomonis et al. 1999)

Explosive eruptions can produce a large amount of blocks and bombs (>64mm) that follow ballistic trajectories from the eruptive vent. Bombs and blocks can sometimes exceed a diameter of 50 cm and weigh more than 100 kg with densities around 0.6-3.6 g/cm3 (Blong 1981).

Bombs lighter than 1000g are known to have penetrated thatched roofs and galvanized iron roofs (Pomonis *et al*. 1999). Blong (1981) reported that 9.5 mm hardboard is penetrated when the impact energy is in the 60-90 J range, while 20 mm red clay tile is damaged at 20J, fibre cement cladding of 4.5-9.5 thickness is damaged at impact energy of 10-20 J and penetrated at 20-85 J. On the stronger spectrum, plywood sheets of 4.5-12mm required 90-500 J at penetration, while 0.42-0.7 mm sheets of steel classing are impenetrable by projectiles of up to 1000g, penetration occurring when mass is more than 2 kg in case of very dense bombs. Bombs can also significantly damage building walls causing partial or complete collapse.

Bomb's temperature is also important. Blong (1981) reports that initial temperatures are likely to range up to about 1100°C, but the temperature at impact is lower, depending on the size, distance, and height of the eruptive column (Thomas and Sparks, 1992). The ignition temperature of dry timber is around 200°C, plastic 170°C and other materials like clothing and fabric ignite at even lower temperatures.

Pyroclastic density currents

Explosive volcanic eruptions can produce pyroclastic density currents (PDCs), i.e. clouds of erupted particles and gases capable of flowing down volcano slopes at high speeds, which present a serious threat to life for the inhabitants of settlements on the slopes of volcanoes, because of their temperature and lateral dynamic pressure loading due to their high density and velocity. It is assumed in general that if a building collapses, every occupant is killed. However, a similar ending might also occur in case of a window glass failure due to combined effects of pressure and flying debris. An accurate vulnerability assessment of openings along with the whole building is then required for loss estimation. An overview of factors that govern building and occupants' vulnerability to pyroclastic density currents is given as an example in Figure 62. In

Table 38 (adapted from Pomonis *et al.*, 1999), we summarize the main building damages associated with volcanic hazards in a large explosive eruption.

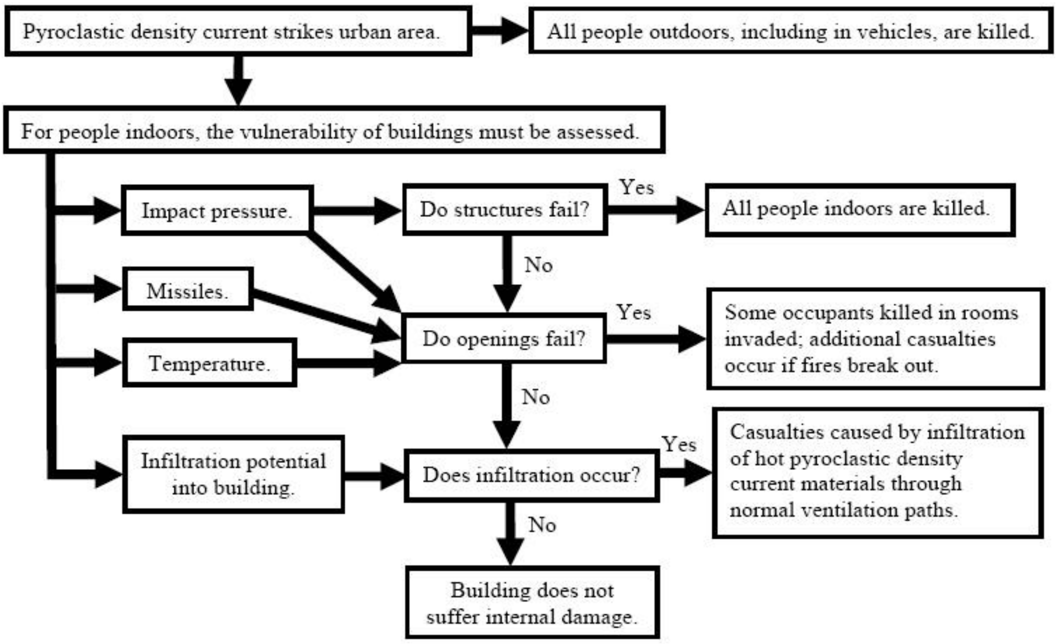


Figure 62: Overview of factors that govern building and occupants' vulnerability to pyroclastic density currents (from Spence et al. 2007).

Table 38: Building damages associated with volcanic hazards in a large explosive eruption (adapted from Pomonis et al. 1999).

Volcanic hazard	Main damage agent	Principal damage consequences	Likelihood of occurrence
Pyroclastic density current	Dynamic pressure	Wall damage Fire; burial; collapse; displacement; flooding Foundation damage Corrosion; undermining	Very high High Moderate Low
Tephra fall	Bomb or block impact; excessive tephra loads	Roof damage; blocked drains Wall damage Burial; corrosion Fire	Very high High Moderate Low
Lahar	Water; dynamic pressure	Flooding; foundation and wall damage; Collapse; displacement; corrosion Burial; scouring Fire	Very high High Moderate Low
Seismic activity	Groundshaking	Damage to contents; minor cracking Wide wall cracking Foundation failure; fire Collapse; burial; flooding	Very high High Moderate Low
Ground deformation	Ground swell (dome); subsidence; cracks dome or crater collapse	Foundation and (or) wall damage Building separation	Very high High
Atmospheric effects	Winds; rainfall; lightning	Roof damage due to wind Fire due to lightning Displacement; flooding	High Moderate Low
Acid rain and gases	Chemical attack	Corrosion; discoloration Fire	Moderate Low

Volcanic earthquakes (from Pomonis et al. 1999)

Volcanic earthquakes are warning precursors of eruptions, but they can cause damage to buildings and infrastructures, trigger landslides, and even cause loss of life (Pomonis *et al.*, 1999). Most volcanic earthquakes do not have the shock characteristics of tectonic earthquakes, but they represent a series of harmonic tremors with less damage potential (Tiedeman, 1992). Due to their shallow focus, they can shake the ground strongly at the vicinity of the vent, but their strength attenuates quickly with increasing distance.

As an example, Pomonis *et al.* (1999) compiled a map of possible isoseismals associated with a potential eruption of the Furnas Volcano in the Azores together with structural information on the existing buildings (i.e. unreinforced rubble masonry, concrete block masonry, non-seismic reinforced concrete). In addition, a proportion of buildings of each structural type that is expected to suffer total or partial collapse is also given on the basis of observations of the effects of volcanic earthquakes around the world (from Spence *et al.*, 1992).

6.2.2 Analytical/numerical assessment

Recent studies give a detailed representation of scenario events, and give values of the physical parameters associated with hazards both in time and space. Like for other hazards, numerical models are generally used to derive more quantitative information relative to the potential destructiveness of volcanic events. Analytical methodologies are preferred when possible since they do not *a priori* rely on subjective considerations.

For instance, Baxter *et al.* (1998) show some numerical simulations of pyroclastic flow propagation at Vesuvius, based on the modelling of the magma ascent along the volcanic conduit and of the subsequent dispersion of the eruptive mixture in the atmosphere. Vent conditions (velocity, pressure and density) were established by applying a one dimensional, steady-state, two-phase flow model based on the volcanological knowledge of the volcanic system as a function of the eruption magnitude. The development and collapse of the eruptive column and associated propagation of pyroclastic flows were then simulated by a transient, axisymmetric, two-phase flow model. These authors conclude in particular that there exist some large areas where total destruction may not be inevitable in small to medium scale events: vulnerability assessment studies are of importance in this case.

Todesco *et al.* (2002) also presented simulations with a more complete description of the eruptive mixture, in which both coarse and fine particles with different dimensions and properties are present. A more appropriate boundary condition along the ground was also implemented to account for the effects of terrain roughness. This model can be used to evaluate the dynamic pressure of the flow and the isotropic pressure variation with respect to the undisturbed atmospheric pressure for damage assessment studies (e.g. see Esposti Ongaro *et al.*, 2002; Spence *et al.*, 2004a).

Another illustration can be found in Spence *et al.* (2004b) for the resistance assessment of glazed openings or reinforced concrete frames to pyroclastic flows. Vulnerability of glazed openings is estimated for example by calculating the maximum bending moment caused by pressure on an opening and the tensile stress in the glass from the standard elastic bending stress formula. Assuming that a log-normal distribution of window resistance corresponds reasonably well to data, the authors derive fragility curves for several types of windows (Figure 63). This work has been recently complemented to account for the effects of temperature and for the presence of missiles entrained in the flow (Spence *et al.*, 2007).

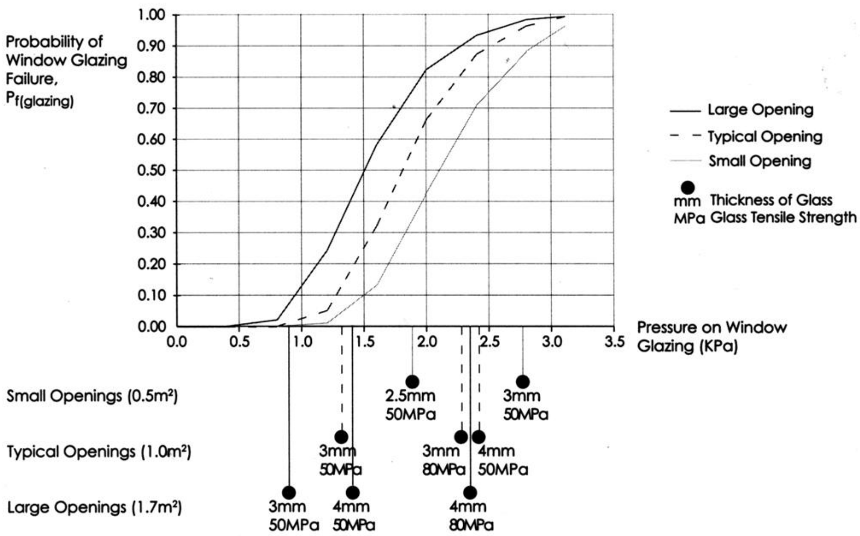


Figure 63: Window glazing distribution (Spence et al., 2004b)

The resistance of reinforced concrete buildings can be estimated through limit (elasto-plastic) analysis, by calculating the uniformly distributed lateral load needed to cause a strong-beam-weak-column or strong-column-weak-beam failure mechanism. The process is described in detail in Petrazzuoli and Zuccaro (2004). The resulting range of resistances for several numbers of floors is shown in Figure 64 for the case of buildings of irregular plan.

Baratta *et al.* (2004) investigated the vulnerability of masonry vault roofs of buildings under ash loads thanks to analytical/numerical models.

More recently, full three-dimensional flow models have been used by several authors (e.g. Zuccaro and Ianniello, 2004; Esposti Ongaro *et al.*, 2007, 2008; Zuccaro *et al.*, 2008), in order to further improve the dynamics of the complex volcanic processes. For instance Zuccaro *et al.* (2008) performed numerical stochastic and deterministic analyses to assess the resistance of buildings under the combined action of pyroclastic flows, ash fall and earthquakes. The results show that up to a certain limit of ash fall deposit, the increment of structure weight increases the resistance of a building to pyroclastic flow action while it reduces its seismic resistance.

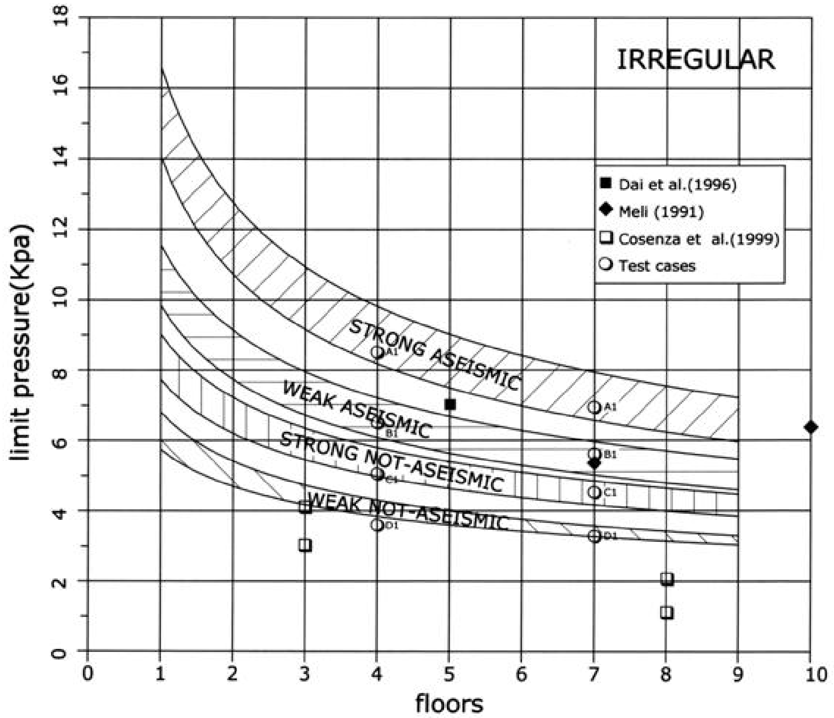


Figure 64: Lateral failure (limit) pressures for reinforced concrete frame buildings of irregular plan (Spence et al., 2004b)

6.2.3 Experimental assessment

Experimental methodologies, based on laboratory or field experiments, may constitute a useful complement to other approaches (e.g. when analytical methods cannot be used or are not reliable).

For example, some experiments were conducted in Cambridge University -Department of Engineering, Structures Laboratory-, in order to investigate the strength of purlins (Pomonis *et al.*, 1999), as it has been observed that this was the most likely source of failure for roofs, when submitted to a vertical load during tephra falls. Using simple considerations on variance, the authors plotted a relationship between the probability of failure and depths of wet tephra fall deposits (Figure 65). Their results, consistent with the empirical estimates made by Booth *et al.* (1983), have been used to assess the risk of residential buildings for an eruption of Furnas Volcano, Sao Miguel, Azores.

Along with analytical/numerical studies, Spence *et al.* (2004b) conducted experimental analyses to assess the vulnerability of masonry panels, as well as shuttered openings and door catches to pyroclastic flows. Resistance of catches has been studied through a series of in-situ tests on representative buildings. The tests investigated the resistance of a standard door or window frames assuming that the frame fails rather than the glazing. The resistance of the catch mechanisms, hinges and frames of windows and doors in good or bad condition were tested, and some limit values of resistance were derived. Resistance of masonry panels was estimated using a hydraulic jack acting through a system of chains, pulling on three types of panels (in-fill panel of hollow terracotta brick with or without openings and tuff brick in-fill panel) in an unoccupied building built in 1990. A summary of the results for the Vesuvian area is presented in Table 39.

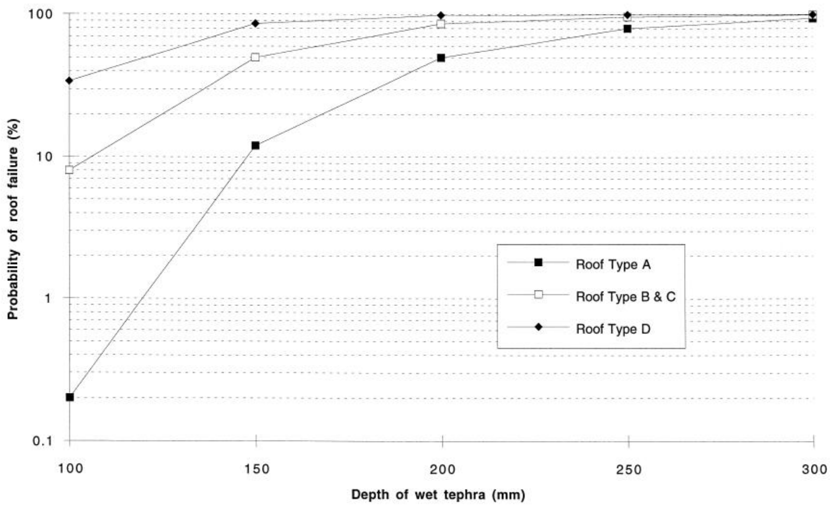


Figure 65: Probability of roof collapse by roof-type, for various depths of wet tephra fall deposits (Pomonis et al*., 1999).*

Table 39: A hierarchy of resistances (given in kPa) of buildings and elements for the Vesuvian area (Spence et al., 2004b).

Weak

Building Elements	This study	Valentine ('98)	Glasstone Dolan ('80))
Window glass of ordinary buildings	1.0-2.5	1-4	3.4-6.9
aluminium window in bad condition	1.5		
aluminium window in good condition	3.0	7-17	
old wooden door	3.5	4-9	2.8-9
Yellow tuff masonry wall	4.2-7.4	15-28	10.3-38
old wooden window	5.0	7-17	6.9-13.8
Weak non aseismic r.c. blds. (1 to 3 storeys)	4.5-8		
Terra cotta tile in-fill panel without window	5.5	10-40	
Strong non aseismic r.c. blds. (4 to 7 storeys)	5-9		
Tuff masonry wall (400mm thick)	6.8-9	15-28	10.3-38
Terra cotta tile in-fill panel with window	7.6-8.9	15-60	
Weak aseismic r.c. building (multi-storey)	5-10		
Tuff masonry wall (600mm)	10-13	15-28	10.3-38
Strong aseismic r.c. building (multi-storey)	6-14		
Volcanic masonry wall (600mm)	20-26		10.3-38

Strong

6.3 Examples of structural characteristics and issues to be considered for assessment

Generally, once the different types of hazard mechanisms and related parameters that might induce damages have been identified, and whatever the methodology chosen for the evaluation of vulnerability, more or less detailed structural surveys are to be conducted in the target area, to produce the typology useful for assessment.

An example is the survey of almost 2000 buildings in several cities in Sao Miguel Island, Azorethe (Pomonis *et al.*, 1999), where a large variety of building's characteristics have been investigated (e.g. structural type, age, condition, number of storeys, roof type, wall condition or structural type, availability of window shutters). Another example in Icod de los Vinos, Tenerife (Canary Islands), is found in Marti *et al.* (2008), where the data collected include vertical structural typology, height, age, roof and openings characteristics, as well as presence of air conditioning or distance between buildings. This survey permitted to estimate the impact of tephra fallout, pyroclastic flows and volcanogenic earthquakes.

Hereafter, we indicate some important characteristics and issues to be considered in the assessment of structural vulnerability to volcanoes, focusing on three particular volcanic hazards, namely tephra falls and pyroclastic density currents.

6.3.1 Tephra falls (mostly lapilli and ash; <64mm)

Blong (1981) produced a largely theoretical paper relating damage to buildings caused by volcanic projectiles and tephra fall, and summarized much of the general literature in a book (Blong 1984). Tiedemann (1992) summarized some additional data. Spence *et al.* (1996) examined damage to a sample of buildings in Castillejos with experiences 150-200 mm tephra fall during the Pinatubo eruption ad developed a Damage Index similar to those used to characterize earthquake building damage. Pomonis *et al.* (1999) and Pomonis (1997) also thought through many of the structural engineering issues relating to building failure in the Azores and Montserrat. Pareshi *et al.* (2000) estimated the proportions of roofs which would collapse under various roof loads in the area around Vesuvius. Porter and Williams (2000) produced an interesting experimental (laboratory) study of the failure of sheet metals under tephra loads. Blong (2003) summarizes building damage produced by the 1994 eruption at Rabaul in Papua New Guinea and draws some conclusions, particularly with reference to timber-frames, metal-decked buildings. As an example, Table 40 shows the effects of various ash loads on buildings in Rabaul 1994 eruption. Finally, Spence *et al.* (2005) estimate the structural vulnerability of buildings to tephra loads based on both analytical studies and observed damage. In addition, they present a new assessment of roof strength around the Vesuvius area and propose a new European tephra fall roof vulnerability curves in areas potentially threatened by explosive volcanic eruptions (Figure 66).

Table 40: Effects of various ash loads on buildings in Rabaul 1994 (Blong and McKee 1995), where L=dρg/1000 (with L=ash load; d=ash thickness; ρ=particle density; g=acceleration du to gravity).

Ash thickness (mm)	Estimated load (kPa)	Observed damage to roofs
<100	1.5-2.0	Roofs and guttering generally remained intact.
<200	3.0-4.0	80-90% of roofs remained intact with little apparent damage. Sagging or partial collapse occurred in some buildings.
<300	4.5-6.0	More than 50% of roofs did not collapse.
500-600	7.5-12.0	More than 50% of roofs collapsed.
>600	9.0-12.0	It is doubtful that buildings survived without significant damage even when the roof remained relatively intact.

Roof Class	Description	Typical design load range	Mean collapse load
WE (weak)	Sheet roofs, old or in poor condition. Tiled roof, old or in poor condition. Masonry vaulted roof.	Pre-design code, or no design code.	2.0 kPa
MW (medium weak)	Sheet roof on timber; average quality; average or good quality tiled roof on timber rafters or trusses. Steel or precast reinforced concrete joists and flat terrace roof.	1–2 kPa	3.0 kPa
MS (medium strong)	Flat reinforced concrete roof not all above characteristics; sloping reinforced concrete roof. Sheet roof on timber rafters or trusses, good quality and condition, designed for cyclone areas.	2–3 kPa	4.5 kPa
ST (strong)	Flat reinforced concrete roof designed for access; recent, good quality construction, younger than 20 years.	>3 kPa	7.0 kPa

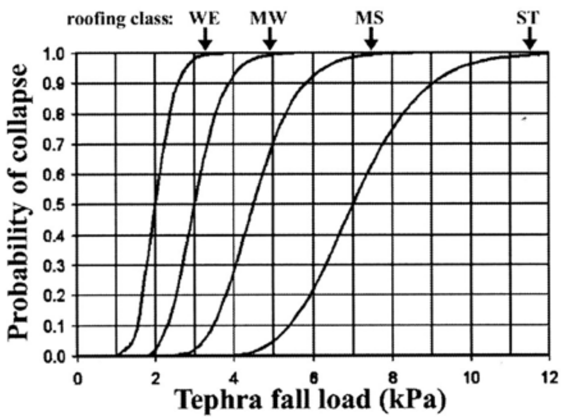


Figure 66: Proposed classification of European roof types for tephra fall resistance and associated tephra fall roof vulnerability curves. From left to right, classes WE, MW, MS and ST (Spence et al. 2005).

The **important characteristics and issues** that need to be considered in the assessment of structural vulnerability for **tephra falls** are:

Roof pitch

Spence *et al*. (1996) show that steeper pitched roofs suffered more severe damage than those with shallower pitches. However, Perret (1950) and Jagger (1956) indicated that flat roofs collapsed preferentially during the 1906 eruption of Vesuvius and the 1914 eruption of Sajukarjima respectively. These differences suggest that differences in local building codes and construction practices may be important in determining the role of pitch in sustaining tephra loads.

Roof span

Spence *et al*. (1996) and Blong (2003) commented that short-span roofs survived better, by a factor of about 5, than long span roofs in Castillejos and Rabaul respectively.

Penetration of airfall ash

Corrosion

Blong (2003) shows that most of the steel roofs and walls that were not destroyed by ash fall were affected by corrosion during the 1994 eruption of Rabaul. It appears that acid solutions quickly dissolve zinc/aluminum (zincalume) coatings exposing the raw steel. Technical data indicates that colorbond coatings provide more protection than unpainted zincalume.

6.3.2 Pyroclastic density currents

Pyroclastic flows are amongst the most dangerous of volcanic hazards because of their rapid onset and potential destructiveness. For any particular type of building, there is a degree of correlation between the near-ground characteristics of the flow and the type and degree of damage, which can be used as a proxy for more direct measures of the flow variables, as with intensity scales for recording earthquake destructiveness (Spence *et al*., 2004a). Baxter *et al.* (2005) have proposed a descriptive classification of building damage levels as a step towards such a scale for pyroclastic flows (Table 41).

Various approaches to structural vulnerability from pyroclastic density currents can be found in the volcanic literature. The European Project ENV4-CT98-0699 (Baxter, 2000; Neri *et al*., 2000; Zuccaro, 2000) has traced a first methodological approach to the vulnerability of buildings in volcanic areas. Spence *et al*. (2004a) combine together numerical modeling of pyroclastic flows, building vulnerability and human casualty estimation for their application to the Vesuvius area.

Detailed work on building structures include the pioneering study of Valentine (1998) on the effects of nuclear explosions that indicated that about 7kPa is the value of pressure at which damage at reinforced concrete building begins, and that 35 kPa is the upper limit of any kind of structures. The lateral loading or dynamic pressure increases in proportion to the square of the velocity using the standard formula:

Dynamic pressure = 0.5 x density x velocity^2.

However, Petrazzuoli and Zuccaro (2004) discuss how these pressure values are too high and derive more credible values for the limit resistance of reinforce concrete buildings in the Vesuvius area. In addition, Zuccaro and Ianniello (2004) present fluid-dynamic simulation impact model to simulate pyroclastic-flow-urban settlements interactions. The results show a partial shielding effect of structures closer to the volcano on structures behind them as well as a total pressure waning pattern along the mean direction of the pyroclastic flow. Finally, Nunziante *et al*. (2003) propose a numerical forecast for the dynamic pressure of pyroclastic density currents (inverse method), based on quantitative experimental data and on structural modeling of buildings.

Table 41: Building damage scale for dynamic pressure impact of pyroclastic density currents (Baxter et al. 2005).

The **important characteristics and issues** that need to be considered in the assessment of structural vulnerability to **pyroclastic density currents** are (Baxter *et al*. 2005):

Resistance of building to lateral loading

The building damage from PDCs in Montserrat was, in general, compatible with a strongly directional lateral loading without having an obvious diffraction or peak pressure component, as in an explosive blast wave, which would have given a more crushed appearance to the buildings, as happens in a conventional chemical or nuclear explosion. A further consideration is the effect of the isostatic pressure operating in all directions around the buildings, due to the force from the height of the surge cloud and other pressure oscillations in the PDC. In fact, all ground observations from the Montserrat eruption were compatible with lateral loading and suction effects from the flow around the buildings, although the thin layers of ash in the few intact buildings we came across may have been partly due to isostatic pressure operating as well. In this typical tropical housing with louver windows, we surmised that the isostatic pressure changes would most likely have rapidly equilibrated across the building envelope without causing significant damage. Missiles and other entrained material could also have accounted for the very anomalous evidence for dynamic pressure that was found, e.g., in the bent steel fence posts and reinforced bars (re-bars), indicating that they had been struck repeatedly by missiles rather than being bent by the dynamic pressure of the surge cloud alone.

Building openings

The most vulnerable aspects of the building envelope to these hazards were the openings, in particular the windows. The louver, or lightly shuttered, windows in tropical countries are designed to allow the free movement of air, but this increased the buildings' vulnerability by permitting the hot ash to enter the closed-up houses even at the limit of the current and ignite the furnishings and fittings. We found some houses had been protected by the simple expedient of covering the windows with plywood boards, a device used to guard against hurricanes when the area was evacuated.

Presence of flammable materials

The heat of the ash ignited all flammable materials and caused widespread destruction even when the dynamic pressure of the flow is too low to inflict mechanical damage.

7 Conclusions

In this deliverable, an attempt has been made to review and discuss the existing concepts and methodologies for physical vulnerability assessment related to different natural hazards (earthquakes, floods, landslides and volcanoes) within a given territory. The aim was to highlight common grounds and main differences existing between the various practices, as well as possible gaps to be filled in each field (e.g. poorly developed methodologies), in order to serve the general objective of the ENSURE project, that is the construction of an integral operational framework aiming at localizing and spatializing vulnerability to different natural/environmental hazards and at integrating/controlling the root causes and underlying mechanisms which set in motion the production and transference of vulnerability.

From the structural or engineering point of view and for the reviewed hazard-specific practices, risk is essentially defined as the product of (UNDRO, 1979; Dilley *et al.*, 2005): (i) hazard, which is the probability of occurrence of a particular natural event; (ii) exposure, which represents the global "value" of elements at risk in a given territorial system (buildings, infrastructures, people, …); (iii) vulnerability, which represents the degree of loss/potential damage/fragility of a particular element or set of elements at risk, within the area affected by the hazardous event characterized by a given intensity or level.

In this case, vulnerability is related to the physical interactions between the potentially damaging event and the vulnerable elements of the physical environment. It is defined on a scale ranging from 0 (no loss/damage) to 1 (total loss/damage) and is also strongly dependent on resolution scale for analysis.

In this deliverable, we have shown that although being hazard-specific, practices for structural vulnerability assessment generally follow the same procedure for analysis:

1. Hazard evaluation

First, this step aims at quantifying the probability of occurrence of the hazardous event (e.g. return periods). Then it aims at estimating the intensity and the typology of physical stresses/actions that will be sustained by affected structures within the territory, in case of event occurrence (e.g. hydrodynamic actions in case of flooding, actions resulting from ground shaking or settlements).

2. Evaluation of the exposed elements

All methods are in general defined with reference to a typological classification, grouping set of exposed elements according to the peculiar features affecting their structural behaviour and response to the possible physical impacts and stresses. The exposure component may also enclose indicators representative of the worth (monetary value) for the elements at risk. In the case of cultural heritage, the notion of importance is also used, which represents the capability of each element to represent the historical/cultural identity of a given typology in the study area.

3. Evaluation of physical vulnerability

Depending on the quality of data for exposed elements, models to assess physical vulnerability can be defined either on the basis of statistical processing of damage observations (with or without including the expert judgments) and expert opinion, or on the basis of analytical/numerical models. Depending on the spatial scale or resolution for analysis, the methodology consists in attributing a vulnerability indicator (e.g. vulnerability index, fragility function, qualitative term) to a single element (building, etc.) or to the whole group of elements either uniformly or randomly in this case.

Tables 42 and 43 summarize the main hazard parameters, as well as methodologies used to assess vulnerability of structural systems against earthquakes, floods, landslides and volcanoes, discriminating whenever possible, between local and regional scales for analysis.

First, we see that, as the various hazards present a variety of potential threats, according to varying levels of intensity, location and time of occurrence, the main challenging issue when assessing vulnerability through fragility functions, will be the definition of the relevant indicator(s) of physical aggression. Whatever the methodology for the vulnerability may be, the definition of these fragility functions remains debatable, not only due to the possible complex response of exposed elements to the aggression but also due to the identification of aggression vectors themselves. From the tables, we see that most of the methodologies for vulnerability assessment represent the hazard aggression by very few parameters (generally one), leading to strong uncertainties and to inadequacy of vulnerability curves. Observations and experiments have shown that parameters such as duration of the event, energy, etc., play an important role in the damage process, but are seldom accounted for. This poor definition of the actual aggression used to develop fragility curves, neglects the scatter in the estimated damage, which means that this uncertainty cannot be propagated to the following components of the risk assessment analysis nor can its importance be estimated.

Second, the incorporation of vulnerability within risk assessment is not developed at the same level for all the reviewed hazards. The methodology developed in earthquake risk assessment, consists in deriving and combining fragility curves for different types of elements at risk, in order to estimate the expected level of damage given a level of hazard, leading to an estimate of the level of risk. On the contrary, quantitative estimations are not often made in practice for a number of natural perils (e.g. mass movements, volcanoes), where fragility curves are rarely used. For these hazards indeed, physical vulnerability is poorly modelled for a number of reasons that are essentially related to the nature of the peril itself and the benefits of considering an element's physical vulnerability may be considered as limited. Hereafter, we list the main reasons that may explain such a less developed practice:

- The cause of human casualties comes from the event itself rather than from building damages;
- There is a lack of observational data on the hazard, the elements at risk and the induced damages.
- The quantitative assessment is difficult to perform due to the variety of possible processes involved in one hazardous event and to the complexity of related structural damage mechanisms: there are numerous event characteristics that are valuable in predicting the damage that occurs to an element at risk and one has to develop separate fragility curves for different types of effects as well as different types of structures.
- For a number of events, such as pyroclastic flows or mass movements, there is little chance that buildings exposed to the full force of the event will be able to be repaired: in this case, the fragility curve would be a constant equal to unity for all non-zero values of the hazard parameter.
- Finally, contrary to earthquakes, which can affect a large region, the level of exposure for some types of hazardous events (e.g. rock falls), can be altered due to their small geographical scale (e.g. efficient land-use planning, engineering works, evacuation). Moreover, building damage may happen over a much longer time scale (e.g. ground creep), than for earthquakes for which strong ground shaking generally lasts for a few seconds or minutes only. Therefore, people are not in physical danger from the event and also, since they are slower events and are often smaller, there is time to plan the evacuation of people. Forecasting is sometimes possible through careful monitoring (e.g. for volcanoes). This means that there is less incentive to assess the impact of an event,

by using fragility curves for example, because it may be possible to prevent its occurrence.

Finally, another important issue which is still not envisaged in current practice is the way to account for the combination of various natural hazards with different return periods. This is different from analyzing the impact of cascaded hazardous phenomena, as two or more hazards having a low level of intensity when considered separately, may lead however to an increased risk when occurring simultaneously.

Table 42: Hazard parameters used as input for vulnerability assessment of structural systems against earthquakes, floods, landslides and volcanoes, considering two scales of analysis (local/regional).

Exposed elements	**Earthquakes**		**Floods**		**Landslides**		**Volcanoes**		
	local	**regional**	**local**	**regional**	**local**	**regional**	**Lava flow**	**Tephra falls**	**Pyroclastic flows**
Buildings	Ground displacement/ acceleration $SD(T_0)$ or $SA(T_0)$	PGA (g) EMS98	FD (m) FV (m/s)	FD (m) FD x FV (m^2/s)	Sliding: PGD (cm), distance from crown Settlements: PGD (cm) Earth Flow: velocity and depth of failure Rock Fall: Impact force	Intensity (function of mobilized volumes, velocity, depth of failure, energy)	Lateral dynamic pressure	Ash thickness (mm) or load (kPa) Particle size (mm), weight and temperature	Lateral dynamic pressure/loading Flow heat
Roads	PGD (cm)		FD x FV (m^2/s)		PGD (cm)				
Pipelines	PGD (cm) Axial ground strains	PGD (cm) PGV (cm/s)			PGD (cm) Axial ground strains Impact of rock falls for pipelines built above ground	PGD (cm)			
Shallow tunnels	PGD (cm) at surface PGA (g)	-			-				

PGD: Permanent Ground Displacement; PGV/PGA: Peak Ground Velocity/Acceleration; EMS98: European Macroseismic Scale for intensity; SD/SA: Spectral Displacement or Acceleration at natural period T_0 of vibration for the structure; FD / FV: Flood Depth or Velocity

Table 43:Methodologies to assess vulnerability of structural systems against earthquakes, floods, landslides and volcanoes.

Exposed elements	Earthquakes		Floods		Landslides		Volcanoes	
	Exposure	**Vulnerability**	**Exposure**	**Vulnerability**	**Exposure**	**Vulnerability**	**Exposure**	**Vulnerability**
Buildings	Number of buildings (special, strategic public, ordinary, historical)	**Local scale:** Vulnerability index Fragility curves (mechanical approach) **Regional scale:** Vulnerability index DPM Fragility curves (statistical/ empirical approaches)	Number of buildings (residential / non residential) Elevation	Fragility curves	Number of buildings (special, strategic public, ordinary, historical) Foundations	Fragility curves (rarely used in practice) Vulnerability index	**Tephra falls:** % Roofs classified allowing to geometry (pitch, span) and materials **Pyroclastic flows:** Number of buildings walls facing crater % Building openings classified allowing to geometry (size) and materials (glazed openings, window frames) % Flammable materials	Fragility curves (rarely used in practice)
Roads	Number of urban (2 lanes)/ major (4 lanes) roads	Fragility curves (serviceability level)	Essentially related to road users (pedestrians, occupants and stability of vehicles)		Number of urban (2 lanes)/ major (4 lanes) roads	Fragility curves (serviceability level)		
Pipelines	Kilometers of pipelines	Fragility curves (RR)			Kilometers of pipelines	Fragility curves (RR)		
Shallow tunnels	-	Fragility curves (Damage Index)			-			

DPM: Damage Probability Matrix; RR: Repair Ratio (number of repairs per kilometer)

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