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A framework and guidelines for volcanic risk assessment

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ABSTRACT: The risk management of natural hazards is a complex issue often due to very significant potential consequences and substantial uncertainties. A framework for risk based decision making in the field of engineering is first described in this paper. This framework is then applied for the risk assessment of volcanic hazards. Towards this end, aspects related to the modeling of the hazard process due to volcanoes are described. A system of classification of structures and identification of different building characteristics that could be used for volcanic vulnerability and risk assessment is then proposed. This is followed by a discussion on the fragility and vulnerability modeling of structures. Finally, general issues concerning the evaluation of risks and their treatment and communication are discussed.

1 BACKGROUND

Natural hazards such as earthquakes, floods, volcanoes and tsunamis constitute a significant source of risk in several regions of the world and are often associated with widespread loss of human lives, damage to the qualities of the environment as well as to property and infrastructure. It is hence a great challenge for the engineering profession to provide methods and tools enhancing decision making for the purpose of efficient management of natural hazards.

Since our understanding of the aspects involved in such decision problems is often less than perfect and that we are only able to model the involved physical processes as well as human interactions in rather uncertain terms, the decision problems in engineering are subject to significant uncertainty. Due to this, it is not possible to assess the result of decisions and consequences in certain terms. However, what can be assessed is the risk associated with the different decision alternatives. If the concept of risk as the simple product between probability of occurrence of an event with consequences and the consequence of the event is widened to include also the aspects of the benefit achieved from the decisions, risk may be related directly to the concept of utility (von Neumann and Morgenstern 1944, Raiffa and Schlaifer 1961) from the economic decision theory. A whole methodological framework is thus made available for the consistent identification of optimal decisions. This framework is considered to comprise the theoretical basis for risk based decision making.

Based on these principles, a document (JCSS 2008) describing the framework and principles for risk based engineering decision making has been recently developed by the Joint Committee on Structural Safety (JCSS). In this paper, the main features of this framework are first briefly described. Then, aspects related to the modeling of the hazard process due to volcanoes are discussed. A system of classification of structures and identification of different building characteristics that could be used for volcanic vulnerability and risk assessment is then proposed. This is followed by a discussion on the fragility and vulnerability modeling of structures relevant for seismic analysis. Finally, general issues dealing with the quantification of risk and their treatment and communication are covered.

2 SYSTEM MODELING IN RISK ASSESSMENT

2.1 *System identification and representation*

In a societal context, risk based decision making needs to be understood from an intergenerational perspective. Within each generation decisions have to be made which will not only affect the concerned generation but all subsequent generations. At an intra-generational level, the characteristics of the system consist of the knowledge about the considered engineered facility and the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives. A very significant part of risk based decision making in practice is concerned about the identification of the characteristics of the facility and the interrelations with the surrounding world as well as the identification of acceptance criteria, possible consequences and their probabilities of occurrence. Managing risks is done by "buying" physical changes of the considered facility or "buying" knowledge about the facility and the surrounding world such that the objectives of the decision making are optimized.

A system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may be physical components, procedural processes and human activities. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times.

2.2 *Knowledge and uncertainty*

Knowledge about the considered decision context is a main success factor for optimal decision making. In real world decision making lack of knowledge (or uncertainty) characterizes the normal situation and it is thus necessary to be able to represent and deal with this uncertainty in a consistent manner. The Bayesian statistics provides a basis for the consistent representation of uncertainty independent of their source and readily facilitates for the joint consideration of purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations.

There exist a large number of propositions for the characterization of different types of uncertainties. It has become standard to differentiate between uncertainties due to inherent natural variability, model uncertainties and statistical uncertainties. Whereas the first mentioned type of uncertainty is often denoted aleatory (or Type 1) uncertainty, the two latter are referred to as epistemic (or Type 2) uncertainties. However, this differentiation is introduced for the purpose of setting focus on how uncertainty may be reduced, rather than calling for a differentiated treatment in the decision analysis.

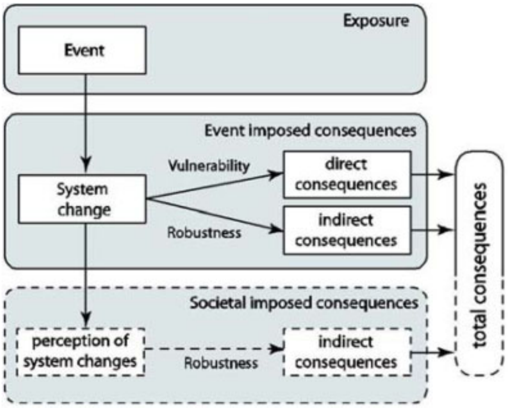


Figure 1. Generic representation used for the risk assessment of a system.

2.3 *System representation*

The risk assessment of a given system is facilitated by considering the generic representation illustrated in Figure 1. The exposure to the system is represented as different exposure events acting on the constituents of the system. The constituents of the system can be considered as the system's first defense in regard to the exposures. The damages of the system caused by failures of the constituents are considered to be associated with direct consequences. Direct consequences may comprise different attributes of the system such as monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents. Based on the combination of events of constituent failures and the corresponding consequences follow-up consequences may occur. Follow-up consequences could be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the system as a whole caused by the combined effect of constituent failures. The follow-up consequences in systems risk assessment play a major role, and the modeling of these should be given great emphasis. It should be noted that any constituent in a system can be modeled as a system itself. In the context of volcanic risk assessment, a system could be an urban area exposed to the effects of a volcano with its constituents being buildings, structures and lifelines. The buildings and structures, in turn, could also be systems with structural members as their constituents. Depending on the level of detail in the risk assessment, the system definition, the exposure, constituents and consequences would be different.

2.4 *Exposures and hazards*

The exposure to a system is defined as all possible endogenous and exogenous effects with potential consequences for the considered system. A probabilistic characterization of the exposure to a system requires a joint probabilistic model for all relevant effects relative to time and space.

2.5 *Consequences*

2.5.1 *Vulnerability*

The vulnerability of a system is related to the direct consequences caused by the damages of the constituents of a system for a given exposure event. The damage of the constituents of a system represents the damage state of the system. In risk terms, the vulnerability of a system is defined through the risk associated with all possible direct consequences integrated (or summed up) over all possible exposure events.

2.5.2 *Robustness*

The robustness of a system is related to the ability of a considered system to sustain a given damage state subject to the prevailing exposure conditions and thereby limit the consequences of exposure events to the direct consequences. It is of importance to note that the indirect consequences for a system not only depend on the damage state, but also the exposure of the damaged system. When the robustness of a system is assessed, it is thus necessary to assess the probability of indirect consequences as an expected value over all possible damage states and exposure events. A conditional robustness may be defined through the robustness conditional on a given exposure and or a given damage state.

2.6 *Large scale indicator based risk modeling*

The risk management of large scale natural hazards requires a systematic and consistent representation and management of information for a typically complex system with a large number of constituents or subsystems. Such representation must enable a rational treatment and quantification of the various uncertainties associated with the constituents as well as the system. The consistent handling of new knowledge about the system and its constituents as and when it becomes available and its use in the risk assessment and decision making process is also essential. Further, the numerous dependencies and linkages that exist between different constituents of the system need to be systematically considered. The above requirements and considerations necessitate the use of generic indicator based risk models for the assessment and management of risks due to natural hazards.

Risk indicators can be understood as any observable or measurable characteristic of the system or its constituents containing information about the risk. If the system representation has been performed appropriately, risk indicators will in general be available for what concerns the exposure to the system, the vulnerability of the system and the robustness of the system. In a Bayesian framework for risk based decision making such indicators play an important role.

In the context of volcanic hazards, the exposure can be related to the triggering factors for the volcanic eruption, the vulnerability represents the physical process of the volcanic eruption and flow, damages to infrastructure and loss of lives and the robustness is associated with the follow-up consequences and the socio-economic or political impact.

The use of Bayesian Probabilistic Networks (BPNs) has proven to be efficient for such large scale risk assessment applications (Faber et al. 2007, Bayraktarli et al. 2005, Straub 2005). Generally, the exposures relating to natural hazards as well as the possible ensuing consequences can be considered to depend strongly on the specific geographical location of the occurrence of the event. For this reason, the use of Geographical Information Systems (GIS) is also important in the context of natural hazards risk management.

3 MODELING OF THE HAZARD PROCESS

Sections 3, 4 and 5 of this paper discuss the application of the framework described in the previous section for the risk assessment of volcanic hazards. First, in this section, the modeling of the hazard process for volcanoes is discussed for two phases – the *Plinian* phase (where typically material is ejected in a tall column, spreads in the atmosphere and falls to earth like rain) and the *Peléan* phase (where material flows down the sides of the volcano as fast-moving avalanches of gas and dust). Then, the modeling of two other scenarios – the occurrence of earthquakes and tsunamis, each together with a volcanic eruption are considered.

3.1 *The Plinian phase*

3.1.1 *Tephra intensity modeling*

Physical phenomenon – The deposits of pyroclastics (or materials that have been blown into the atmosphere by volcanic activity) are generically called tephra and divided in three basic types: air fall, pyroclastic flows and surges. The air fall deposits are formed by the accretion of clasts which fall by gravity from the eruptive column or which are thrown directly in area from crater, according to ballistic trajectories. The deposits of pyroclastic flows and surges are those released by gas-solid dispersions with high or low concentration of particles respectively, which move along the surface under action of gravity. The fall of pyroclasts, from the eruptive column, can have different speeds depending on the pyroclasts size, density and launch height, and the deposit on the ground, happen at various distances mainly depending on the stratospheric wind pressure. The pyroclasts are supported in the column until the upward thrust exceeds the gravity force; after they fall down accelerating until the force of gravity is not counterbalanced by the air friction, when the particles fall with a constant speed.

Actions on the constructions – The tephra deposits produce on the constructions a gravitational load q_V on the roofs, even if the pyroclastic flows and the surges, before transforming into deposits, act through a horizontal pressure q_H on the affected structure. The static load q_V can be considered a gravitational distributed load and can be estimated as follows:

$$q_V = \rho g h \tag{1}$$

where g is the acceleration due to gravity (9.81 ms $^{-2}$), h is the deposit thickness (m), ρ is the deposit density (kgm^{-3}). The deposit density depends on the composition of pyroclasts, their compactness, the deposit moisture and the subsequent rains.

3.1.2 *Bombs, missiles and impact modeling*

Physical phenomenon – The explosive eruptions can also produce flying fragments of pyroclasts called bombs and missiles. The largest clasts are exploded directly from the crater according to pure ballistic trajectories. On the contrary, the smaller clasts can be sustained by convection in the eruptive column. They are then thrown in the atmosphere from the main flow to fall or be transported along the mountainside in gravitational currents. The word missile can relate to flying debris, not involved in the eruption, set in motion by pyroclastic flows. The movement of a volcanic fragment in vacuum with a ballistic trajectory has been studied and reported in Dobran (2006).

During a Plinian eruption, large clasts follow a pure ballistic trajectory. The smaller ones are transported not by the wind, but by another dynamic mechanism such as the lateral and vertical expansions of the eruption column, which reduces the drag force on the particulates; such kind of clasts one called sustained ballistics.

Actions on the constructions – The damage caused by bombs and missiles depends on the kinetic energy and the vulnerability of the affected object. A flying fragment can impact the roofing or the walls of a building, but, in particular, it can hit the most vulnerable parts of the building like the openings. A key factor which governs the vulnerability of buildings is the resistance of openings, especially the glass panes or the shutters which can prevent the hot ash from entering. On the contrary, possible consequent fires and/or breathing difficulties for people inside can arise.

Several studies have looked at the evaluation of the speed of bombs and missiles, produced by explosive volcanic eruption, but the analysis of the effects of these flying objects buildings is not very much developed. Spence et al. (2005) have examined the window failure produced by missiles generated by pyroclastic flows. The probability of impact of flying debris on windows depends on the flow velocity, the flow density, the density of potential missiles in the area surrounding the volcano, as well as the surface and the orientation of windows. Missile impact causes failure when a fragment has a sufficient kinetic energy to break the window.

3.1.3 *Lava flow, temperature and thickness/height modeling*

Physical phenomenon – A volcano is defined as effusive if the magma is emitted in the form of a lava flow characterized by gas bubbles dispersed in a continuous liquid: the Etna volcano in Sicily (Italy), for example, belongs to this category. The lava flows are made of totally or partially fused magma emerging on the surface. Lava can form broad flows or immediately get cold above the volcanic conduit giving rise to domed structures called lava domes.

Actions on the constructions – The lava flow produces a lateral horizontal pressure which can cause the collapse of the affected buildings. The damage is also caused by the degradation of the materials produced by high temperatures of the magma. For example, during the Etna eruption of 2001, the temperature of lava flow, measured with the infrared radiometer, was 1075°C. Generally, the advancing speed of the lava flows is sufficiently low to allow the evacuation and the safeguarding of human lives.

3.2 *The Pelèan phase*

3.2.1 *Pyroclastic flow and impact modeling*

Physical phenomenon – Pyroclastic flows can be generated by the collapse of the eruptive column (as during the eruption of the Soufrière volcano, St. Vincent, Caribbeans, 7 May 1902), by a directional explosion for the slipping of a part of the volcano (as during the eruption of the St. Helens volcano, United States of America, 18 May 1989) or by a lateral explosion at the base of a lava dome (as during the eruption of the Pelée volcano, Martinique, 8 May 1902). They are the most dangerous events of an explosive eruption. Therefore, the estimate of the main physical parameters that characterize the dynamics of transportation and deposition is extremely important. A pyroclastic flow is made of a mixture of gases, within which solid particles of various sizes are dispersed. A multi-phase physical model for the evolution of pyroclastic flows can be found in Todesco et al. (2002).

Actions on the constructions – In the structural analyses, it is possible to schematize the action of the pyroclastic flows as a uniformly distributed static pressure (Petrazzuoli and Zuccaro 2004), with temperature ranges between 200 and 350°C (Giurioli et al. 2008). In general, the first elements to reach the collapse are the glass windows and the shutters. However, they can be easily protected by more resistant panels. Nevertheless, the lateral resistance of a building to pyroclastic flow strongly depends on the design criteria applied to resist ordinary load conditions: of course, an earthquake resistant building presents relatively larger strength and stiffness capabilities.

3.2.2 *Lahar flow and impact modeling*

Physical phenomenon – After explosive eruptive events, the thermal change in the proximity of the volcano often produces rain. Combined with the pyroclasts of poor coherence, with the volcanic high slope of (20–30°) and the distinctive seismicity of the eruptive phase, the rain can cause the mobilization of the volcanic deposits and the consequent formation of mudslide and lahar. The term lahar indicates any type of muddy flow containing volcanic material. Lahar and mudslide are extremely dangerous because of their high kinetic energy, they being generally characterized by speed of the order of some tens kilometers per hour up to above 100 km/h (Carlino 2001). The lahar flows are influenced by the same mechanisms of transportation and sedimentation of the non volcanic material landslides. Indeed, the lahar flows move under gravity with the influence of the shear stress, concentration of the flow and slope gradient.

Actions on the constructions – The effects of lahar flows on the constructions are comparable to those ones produced by the debris flows. However, the lahar flows present the additional variable in the form of the temperature, which causes substantial degradation of mechanical properties of construction materials. The temperature of lahars is widely variable. It depends on the typology and the quantity of the erupted materials and on the time between the deposit and the mobilization.

3.3 *Description and modeling of other possible scenarios*

3.3.1 *Eruption related earthquake*

Physical phenomenon – All volcanic eruptions are accompanied by local seismic activity. While tectonic earthquakes are generally related to a shear-faulting mechanism, volcanic earthquakes may involve tensile, isotropic, and/or shear rock fractures, driven by the percolation of high-temperature fluids/gases or directly by the magma-ascent mechanism. Earthquakes caused by volcanic activity are generally classified into four categories:

- volcano-tectonic (VT) earthquakes,
- long-period (LP) earthquakes,
- harmonic tremor (T),
- surface events (SEs).

From the point of view of seismic-hazard analysis in the pre-eruptive phase, only the VT earthquakes need to be considered. Both SEs and T generally appear during an eruption, and they have very low amplitudes beforehand. Although LP earthquakes could be present in the pre-eruptive phase, high-magnitude events of such a class are rarely observed before an eruption. Moreover, LP earthquakes involve only low-frequency signals, and they are not associated with a well-understood source mechanism.

Actions on the constructions – The intensity of a volcanic earthquake is a function of the entity of the eruptive event. During the evolution of a volcanic system from a quiescent state to an eruptive state, a large number of small- to moderate-sized earthquakes occur. Thus, the cumulative effects of these numerous and small magnitude earthquakes can also cause structural damage from the low-cycle fatigue phenomena. Therefore, very stiff structures such as masonry buildings or low rise reinforced-concrete-frame structures are expected to be affected during the pre-eruptive earthquake occurrence.

3.3.2 *Tsunami*

Physical phenomenon – Tsunami refers to the phenomena of the rogue waves which produce devastating effects on the coast. It is characterized with an initial and temporary withdrawal of the waters, or with a flood which can show like a tide which rapidly comes in, like a waves trains or like a water wall. A tsunami can be produced by any cause able to vertically perturb a sufficiently big column, moving them to its equilibrium position. So, its origin is not only connected with a seismic phenomenon, but could also be volcanic eruptions, explosions, landslides, submarine tectonic displacements and impact with cosmic objects. The normal waves are caused by the wind, which produces the movement of the sea surface only while the tsunami waves move the whole water column from seabed to surface. In the context of a volcanic eruption, the anomalous waves leading to a tsunami can be produced by massive pyroclastic flows which reach the sea. This happened during the explosive eruption of the Krakatua volcano in 1883 in the Sunda Straits between Sumatra and Java that produced a large tsunami killing more than 30,000 people in the coastal villages of the Straits.

Actions on the constructions – According to Palermo et al. (2007), the actions produced by a tsunami on a construction can be grouped into two loading combinations: initial impact and post-impact flow. The initial impact includes surges and debris impact force components. The surge force is produced by the impact of the flood waves on the structures. The debris force is related to impact structures due to significant debris (such as vehicles, components of buildings and drift wood) which the waves can transport. After the initial impact, a proposed second loading combination results, namely the post-impact flow. During this phase, hydrodynamic (drag) forces are exerted on structures due to continuous flow of water around the structure. In addition, the inundation gives rise to hydrostatic forces. The hydrostatic forces can occur on both the exterior and interior of the structure. The latter depends on the degree of damage sustained during the initial impact. Further, the structure is subject to debris from floating objects being transported by the moving body of water. Therefore, the second phase of loading includes hydrodynamic and hydrostatic forces, debris impact forces, and buoyancy forces that result from the structure being submerged after the initial impact.

4 CLASSIFICATION OF STRUCTURES & STRUCTURAL VULNERABILITY

4.1 *Volcanic vulnerability of structures*

As discussed in the previous section, a volcanic eruption is characterized by a series of subsequent physical phenomena, including volcanic earthquakes, ash-fall, pyroclastic flows, lahars, landslides, volcanic missiles and tsunami. As a consequence, the damage impact due to a volcanic eruption depends upon several disastrous events, different from each other, but tightly connected to each other. Each event contributes in different ways to the final scenario. The evaluation of the possible effects due to a volcanic eruption in an urban area is therefore very complex. The damage impact scenario in fact can vary, depending on the type of eruption, and also depends on the development over time of the different phenomena characterizing it. It is also related to the location considered and the typological-structural characteristics of buildings and infrastructures in the area. Therefore, the classification of structures and the identification of the different building characteristics is an important step in the assessment of the vulnerability of structures to volcanic events.

4.2 *The Vesuvius area structural vulnerability assessment*

The assessment of volcanic vulnerability of structures was considered in the Vesuvius area. The assessment referred to the volcanic vulnerability assessment methodology proposed within the EXPLORIS European project (EXPLORIS 2006) and developed by the PLINIVS Centre. It refers to a dynamic model which simulates the whole eruptive process and refers to the potential eruption scenarios for the volcanic activity of Vesuvius and the possible associated hazards which may develop (Neri et al. 2008). The EXPLORIS project considers three volcanic phenomena; earthquakes (EQ), ash-falls (AF) and pyroclastic flows (PF).

The assessment included a data collection exercise, based also on an extensive field investigation activity conducted during the period 2009–2010 (COST C26 2009b). The surveys were necessary to collect information based on various parameters influencing the volcanic vulnerability for each construction. The methodology was applied with respect to the Torre del Greco historic urban centre, the Residential Area, and the School Buildings. (COST C26 2009b). In addition, a detailed survey was carried out for various historic 19th century villas in the Vesuvius area, namely the Vesuvian Villas along the Golden Mile. In this case, additional parameters relating to monuments and historic cultural heritage were considered.

4.3 *Classification of structures and parameters for vulnerability assessment*

In the assessment of the vulnerability of buildings to a volcanic eruption, various relevant parameters need to be evaluated. The methodology, adopted for the volcanic vulnerability assessment of the structures, includes the collection of data, which also requires field surveys and site investigations. The data collection surveys are necessary in order to build up a database of information based on the relevant parameters influencing the volcanic vulnerability. The data collected for an area or region based on these parameters is organized and the building vulnerability can be analyzed. The parameters considered in the Vesuvius field investigations conducted through COST C26 activity, include the following (COST C26, 2009a):

- the Identification section is intended to locate the building with reference to the geographical parameters of the region;
- the General Information Section refers to the building type (ordinary building, warehouse, electrical station, etc.), destination (residence, hospital, school, etc.), use (fully used, partially used, not used and abandoned) and exposure (ordinary, strategic, exposed to special risk) of the construction;
- the Condition Section refers to age and state of conservation of the structure (poor, mediocre, good and excellent) and typology of the finishes (economic, ordinary, luxury);
- the Descriptive Characteristics Section refers to the number of total storeys starting from the lowest ground level, the number of floors above the ground, including the penthouse, the number of residential apartments, the presence of occupied or not basement, the height of the first storey, minimum and maximum heights up to the roof, the presence of barriers with height >2 m, the orientation (angle between the longest or the main façade and the North) and the position of the unit in the block;
- the Structural Characteristics Section refers to the principal typology (reinforced concrete, masonry, wood, steel and mixed), primary vertical structures (sack masonry with or without reinforcements, hewn stones masonry, masonry or tuff blocks, RC frames with weak or resistant cladding, etc.), primary horizontal structures (timber floor, floor with steel beams, concrete-tile structures, vaults, etc.), geometry of the roofing (plane, single pitched, multi pitched and vaults), thickness of the walls and the curtain walls and typology of the curtain walls (tuff blocks or squared stones, concrete blocks, etc);
- the Openings Section refers to the percentage of openings on the façade, the number of small, typical and large windows, their material (timber, PVC, aluminium or timber-aluminium, light steel and steel of security anti-intrusion type), their protection and their conditions (perfect, efficient, poor, bad or lack of windows);
- the Interventions Section refers to the age and type of repairs (extraordinary maintenance, upgrading and retrofitting);
- the Regularity Section refers to the regularity and distribution of curtain walls in plan and along the height, the type of the structure (single or two-directional frames, single or two-directional walls

and walls with frames), soft floor (pilotis on a part of the ground floor, totally open ground floor and intermediate soft storey) and possible presence of stocky beams or columns.

These parameters define each building in terms of geometry, typology and importance and mainly measure the volcanic vulnerability of the construction itself. In particular, these parameters can be divided into main sections. The first section provides information on the main vertical and horizontal structures, the regularity in plan and in elevation, the age and conservation of the construction, the number of storeys. These aspects are associated with the evaluation of the seismic vulnerability of buildings. The second section is specific to the building behaviour under the effect of an explosive eruption, referring to the roof structure typology, and the openings. The information on the type of the roof structure is associated with the collapse due to ash-fall deposits during an eruption. The information on openings, including opening shape, the size and the protection of the openings, is associated with the pyroclastic flows. The structural classification is carried out, with reference to the structural vulnerability and the phenomenon/phenomena considered.

5 FRAGLITY AND VULNERABILITY MODELING OF STRUCTURES

5.1 *Seismic vulnerability assessment methodologies for building aggregates*

5.1.1 *General principles*

The seismic vulnerability analysis has the purpose to evaluate the consistency of a structure in a certain area in order to estimate its propensity to undergo a certain level of damage against an earthquake of a given intensity. In order to perform such an analysis, there are several methods having a level of detail which generally changes with the scale of application. However, for building belonging to urban aggregates, only few provisions are found in literature for their vulnerability assessment. One possible methodology for the structural analysis of a building aggregate can be carried out according to the following steps (Avorio and Borri 2001):

- to perform a structural survey appropriate to the peculiarities of the group of buildings investigated;
- to evaluate the influence of the masonry quality on the safety check;
- to build a series of charts in order to identify the foreseeable disruptions.

In the first step, it is important to realize that the study of the whole building complex is not due to the simple sum of the vulnerability of single constitutive buildings. The difficulty to have information about the buildings adjacent to the examined one suggested to adopt a quick survey method oriented to highlight the constructive typologies and their mechanical characterization. The result is the implementation of a structural survey guide composed of both a base legend and thematic forms on the different structural types. In general terms, within such a phase the following information can be achieved:

- Geometrical survey of urban aggregates, which serves as basis for the structural analysis;
- Structural reading, which allows obtaining information on the different structural elements and the connections among them;
- Analysis of disruptions, which individuate and examine the crack pattern visible on the building.

As a second step, the detection of the masonry quality, even if in a quick manner, is investigated. This is justified from the fact that many of the observed partial collapses of buildings were due to the not satisfactory condition of the masonry apparatus. The following reference parameters, which are easily achieved, can influence the behavior of masonry buildings and therefore have been detected:

- Horizontality of blocks;
- Offset of vertical mortar joints;
- Shape and dimensions of elements;
- Elements located orthogonally to the masonry wall plane;
- Quality of mortar.

The proposed procedure is based on the comparison between the characteristics of the study masonry walls and a series of categories reported into appropriate charts. This comparison provides a given score (s) for each parameter of the study masonry. If the wall apparatus respect the "rules of art", a score of 2 is assigned. Instead, the partial presence of each of the reference parameters listed above gives rise to a score in the range of 0.5 to 1.5. Finally, the absence of these parameters provides a score of zero. The sum of different scores, which qualitatively defines the degree of respect for the "rules of art" for the masonry wall, is defined as the masonry quality. The range of the possible achievable scores is comprised between 0 (very poor quality) and 10 (very high quality). Further, three different categories about the masonry quality have been identified, namely category A (8 to 10), category B (3 to 8) and category C (0 to 3).

Later on, the study of the static behavior of either an isolated building or a group of buildings within a historical centre is conducted by the analysis of a series of standard buildings. In this way, the analysis of large scale portion of buildings is performed quickly, considering the prerequisites of the study masonry walls.

Finally, once the masonry quality is attributed, the static analysis by means of comparison charts is performed following two different directions depending on the masonry type. For category C masonry, the examination of the static disruptions is not carried out, since the poor quality of masonry does not allow for the creation of a valid resistant mechanism. Therefore, the structure is not eligible from the structural point of view. For the other two masonry categories

(A and B), the evaluation of the structural integrity is made with reference to appropriate comparison charts by considering different parameters, namely the type of floors, the vertical and horizontal slenderness of walls, the presence of pushing roof, the presence of pushing arches and vaults and the mechanisms involving either one story or more than one storey masonry walls. All these cases can be considered both for not damaged buildings and damaged ones. In the first case, from the detected boundary conditions and geometry, the structural safety of walls can be assessed by the comparison with the conditions reported in the chart. Instead, for damaged buildings, the chart represents a guide to detect disruptions only. From the Italian normative point of view (M. C. 09), no detailed rules on the global check of urban aggregates are given, but only some indications about simplified methods to be performed for this check are provided.

In the case of sufficiently rigid floors, formal verification at both the Life Safety Limit State and the Serviceability Limit State of a structural unit belonging to an aggregate is carried out, even for buildings with more than two levels, through static nonlinear analysis by both checking separately each building storey and neglecting the variation of axial force in the masonry piers due to the effect of seismic actions.

With the exclusion of structural units placed either at the corner or at the end of an aggregate, as well as parts of buildings not restrained along any side from other structural units (e.g. upper floors of a building having height greater than the one of all adjacent structural units), the analysis can also be done neglecting torsional effects, assuming that the floors can only translate in the direction of the seismic action considered.

If the building floors are flexible, the analysis of either single walls or systems of coplanar walls of the building is done; each of them analyzed as independent structure subjected to both the vertical loads and the seismic action along the direction parallel to the wall. In this case the analysis and check of each wall are made following the references given by the new technical Italian code (M. D. 08) for new ordinary masonry buildings.

The lack of study on the behavior of structural units into urban aggregates, as well as the code deficiencies on this topic, have suggested to develop a new simplified methodology, reported in the next Section, to assess the vulnerability of such building complexes in a global manner.

5.1.2 *The proposed seismic assessment form*

The proposed procedure is applied on a regional scale and therefore a speedy procedure for the estimation of vulnerability based on the compilation of special forms is indicated as appropriate. The seismic vulnerability evaluation of historical aggregates arises essentially from a critical review of the detection form originally introduced by Benedetti and Petrini (1984), which proposed the estimation of the seismic vulnerability of isolated buildings. In particular, through this type of analysis, it is possible to classify the building stock of a given area on a scale of vulnerability. The procedure consists in assigning one of four vulnerability classes (A, B, C or D), as defined in order of increasing danger, to ten parameters representing the geometrical and mechanical characteristics of the building. A score is assigned to each class, whereas a weight is correlated to each parameter of the form, which represents the influence that the same parameter has on the global vulnerability of the structure. Finally, the vulnerability index is obtained as the sum of all scores related to the attribution to classes multiplied by the respective weights.

The original methodology proposed by Benedetti and Petrini (1984) is, however, inappropriate for buildings placed in aggregate, because the procedure does not take into account the structural interaction between adjacent buildings. To overcome this limit, Formisano et al. (2009) have proposed a new form, achieved from the original one with the insertion of new five parameters indicative of the aggregate condition of buildings, which may increase or decrease, depending on the case, the vulnerability of a structural unit inserted within a block of buildings. These factors, in part derived from previous studies found in literature are:

- Interaction in height with adjacent buildings;
- Position of the building in the aggregate;
- The presence and number of staggered floors between the building under investigation and those adjacent;
- The presence of typological and structural heterogeneity among adjacent buildings;
- The difference between the percentage of openings in the facades of adjacent buildings.

Four vulnerability classes have been assigned to each of the above parameters. According to the layout of the original survey form, scores and weights have been assigned to the introduced classes and parameters respectively. In the following, the meaning of the four vulnerability classes defined for each additional parameter of the form, as well as the scores and weights attributed to classes and parameters, respectively, and obtained from the above study, are presented and discussed into detail.

1) Interaction in height with adjacent buildings (Figure 2):

- Class A: −20 points. The building is located between two buildings of equal height.
- Class B: 0 points. The building is located either between higher buildings or between a building with major height and a building with the same height.
- Class C: 15 points. The building is located either between a building with minor height and a building with the same height or between a higher building and a lower one.
- Class D: 45 points. The building is adjacent to lower buildings.

The weight assigned to this parameter is equal to 1.

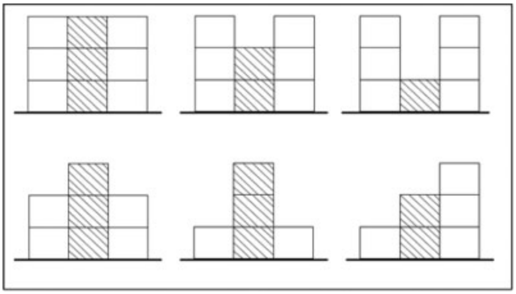


Figure 2. Possible in elevation configurations of a structural unit inserted into a building aggregate.

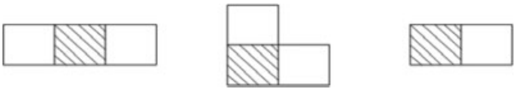


Figure 3. Possible plan configurations of a structural unit inserted into a building aggregate.

2) Position of the building in the aggregate (Figure 3):

- Class A: −45 points. The building is restrained on three sides from adjacent buildings. In this case the nearby buildings operate a confinement function on the building under question, limiting its possible displacements and deformations.
- Class B: −25 points. The building is restrained on two sides from adjacent buildings. Therefore, the adjacent buildings operate a confinement function less significant than the previous one.
- Class C: −15 points. The building occupies a corner position in the aggregate. In this case the containment action is not exercised on two walls of the building and is less effective than before.
- Class D: 0 points. The building occupies a leading position in the aggregate. No containment action is detected and, therefore, the building is more prone to suffer displacements and deformations.

To this parameter a weight of 1.5 is assigned.

3) Presence of staggered floors between adjacent buildings (Figure 4):

- Class A: 0 points. Total absence of staggered floors.
- Class B: 15 points. Presence of a pair of staggered floors.
- Class C: 25 points. Presence of two pairs of staggered floors.
- Class D: 45 points. Presence of more than two pairs of staggered floors.

The weight is less than that given to the two previous parameters, it being equal to 0.5.

4) Typological and structural heterogeneity among adjacent buildings:

- Class A: −15 points. The building is homogeneous with the adjacent buildings from both the typological and the structural point of view.

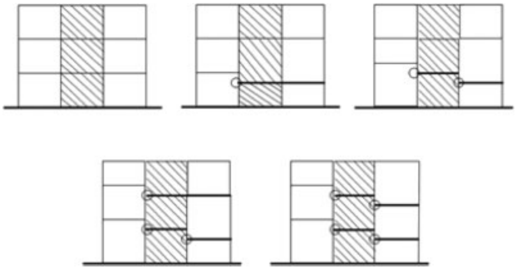
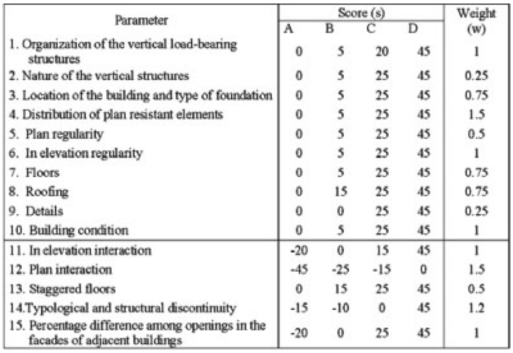


Figure 4. Possible positions of staggered floors.



Parameter	Score (s)				Weight (w)
	A	B	C	D	
1. Organization of the vertical load-bearing structures	0	5	20	45	1
2. Nature of the vertical structures	0	5	25	45	0.25
3. Location of the building and type of foundation	0	5	25	45	0.75
4. Distribution of plan resistant elements	0	5	25	45	1.5
5. Plan regularity	0	5	25	45	0.5
6. In elevation regularity	0	5	25	45	1
7. Floors	0	5	25	45	0.75
8. Roofing	0	15	25	45	0.75
9. Details	0	0	25	45	0.25
10. Building condition	0	5	25	45	1
11. In elevation interaction	-20	0	15	45	1
12. Plan interaction	-45	-25	-15	0	1.5
13. Staggered floors	0	15	25	45	0.5
14.Typological and structural discontinuity	-15	-10	0	45	1.2
15. Percentage difference among openings in the facades of adjacent buildings	-20	0	25	45	1

Figure 5. The new vulnerability assessment form proposed for buildings in aggregate.

- Class B: −10 points. The building is adjacent to buildings made of the same material but erected with a different construction technique (e.g. a sack tuff blocks building close to a squared tuff blocks building).
- Class C: 0 points. The adjacent buildings are made of different materials which have the same structural heterogeneity (e.g. a tuff masonry building next to a brick masonry building).
- Class D: 45 points. The building has structural heterogeneity with respect to adjacent buildings (e.g. a brick building adjacent to a reinforced concrete building).

The assigned weight is equal to 1.2.

5) Difference between the percentage of openings in the facades of adjacent buildings:

- Class A: −20 points. Difference less than 5%.
- Class B: 0 points. Difference between 5% and 10%.
- Class C: 25 points. Difference between 10% and 20%.
- Class D: 45 points. Difference greater than 20%.

The weight assigned to this parameter is 1.

Based on the above considerations, a new type of form based on fifteen parameters giving rise to a maximum vulnerability score equal to 515.25 has been therefore developed as shown in Figure 5.

6 EVALUATION OF RISKS AND THEIR TREATMENT AND COMMUNICATION

6.1 *Quantification of direct and indirect risks*

Following the assessment and evaluation of the exposures/hazards, vulnerability and consequences associated with the system considered for risk assessment, the ensuing risks then need to be quantified and evaluated. For this purpose, the system considered for the risk assessment is assumed to be exposed to hazardous events (EX) with probabilistic characterization $p(EX_k), k = 1, n_{EXP}$, where n_{EXP} denotes the number of exposures. It is assumed that there are n_{CON} individual constituents of the system, each with a discrete set (can easily be generalized to the continuous case) of damage states $C_{ij}, i = 1, 2..n_{CON}, j = 1, 2..n_{C_i}$. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the lth of n_{CSTA} possible different state of damage of all constituents of the facility $\mathbf{C}_l$, conditional on the exposure event EX_k is described by $p(\mathbf{C}_l|EX_k)$ and the associated conditional risk is $p(\mathbf{C}_l|EX_k)c_D(\mathbf{C}_l)$. The vulnerability of the system is defined as the risk due to all direct consequences (for all n_{CON} constituents) and may be assessed through the expected value of the conditional risk due to direct consequences over all n_{EXP} possible exposure events and all constituent damage states n_{CSTA}:

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l | EX_k) c_D(\mathbf{C}_l) p(EX_k) \tag{2}$$

The state of the facility as a system depends on the state of the constituents. It is assumed that there is n_{SSTA} possible different system states S_m associated with indirect consequences $c_{ID}(S_m, c_D(\mathbf{C}_l))$. The probability of indirect consequences conditional on a given state of the constituents $\mathbf{C}_l$, the direct consequences $c_d(\mathbf{C}_l)$ and the exposure EX_k, is described by $p(S_m|\mathbf{C}_l, EX_k)$. The corresponding conditional risk is $p(S_m|\mathbf{C}_l, EX_k)c_{ID}(S_m, c_D(\mathbf{C}_l))$. The risk due to indirect consequences is assessed through the expected value of the indirect consequences in regard to all possible exposures and constituent states, as:

$$\begin{aligned} R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} & c_{ID}(S_m, c_D(\mathbf{C}_l)) \times \\ & p(S_m | \mathbf{C}_l, EX_k) p(\mathbf{C}_l | EX_k) p(EX_k) \end{aligned} \tag{3}$$

The robustness of a system is defined as the ability of a system to limit total consequences to direct consequences. This characteristic may readily be quantified though the index of robustness I_R (Baker et al. 2008):

$$I_R = \frac{R_D}{R_{ID} + R_D} \tag{4}$$

which allows for a ranking of decisions in regard to their effect on robustness.

6.2 *Risk treatment*

The various possibilities for collecting additional information in regard to the uncertainties associated with the understanding of the system performance as well as for changes the characteristics of the system can be considered to comprise the total set of options for risk treatment. The risk treatment options may, in the context of risk based decision making, be considered as the available decision alternatives. Risk treatment is decided upon for the purpose of optimize the expected utility to be achieved by the decision making. Risk treatment can be implemented at different levels in the system representation, namely in regard to the exposure, the vulnerability and the robustness, as shown in Figure 1.

Considering the risk assessment of a load carrying structure, risk treatment by means of knowledge improvement may be performed by collecting information about the statistical characteristics of the loading (exposure), the strength characteristics of the individual components of the structures (vulnerability) and by systems reliability of the structural system (robustness).

Risk treatment through changes of the system characteristics may be achieved by restricting the use of the structure (exposure), by strengthening the components of the structure (vulnerability) and by increasing the redundancy of the structural system (robustness).

6.3 *Risk acceptance and life quality index*

In addition to risks due to economic losses, the decision maker has to take into account also the risks to individuals as well as potential damages to qualities of the environment. It is hence useful to differentiate between tangible and intangible risks, i.e. risks which may easily be expressed in monetary terms and risks which are not. Intangible values especially concern loss of lives and injuries and also qualities of the environment.

The Life Quality Index (LQI) is a measure that facilitates the development of risk acceptance criteria for intangible risks (Nathwani et al. 1997). It is based on demographical indicators that include the incremental increase in life expectancy through risk reduction, the corresponding loss of economic resources, measured through the Gross National Product (GNP) together with the time used for work, all assessed for a statistical life in a given society. The underlying idea of the LQI is to model the preferences of a society quantitatively as a scalar valued social indicator, comprised by a relationship between the GDP per capita, the expected life at birth and the proportion of life spend for earning at living.

6.4 *Risk perception and communication*

Different individuals in society perceive risks differently, depending on their own situation in terms of to what degree they may be affected by the exposures, to what degree they are able to influence the risks and to what degree the risks are voluntary. Generally risks are perceived more negatively when stake holders feel more exposed, when they feel they have no influence and they feel they are exposed to risks involuntary.

Another aspect is related to how adverse events are perceived by individuals and groups of individuals in society when and after such events take place. Again, this depends on the perspective of the affected individuals and groups of individuals. Furthermore, the occurrence of adverse events and the way the information about such events is made available will affect the perception of risks in general but also in many cases trigger actions which have no rational basis and only adds to the societal consequences of such event.

Due to the effects of the perception of risk, it is generally observed that different individuals and groups of individuals have different attitudes in regard to what risks can be accepted. Risk averse and risk prone attitudes are observed, which simply refers to the effect that risks are assigned different tastes depending on these characteristics. Whereas such behavior is a private matter for individuals of society, it leads to an uneven distribution of risks, if exercised in the context of societal decision making and this is clearly unethical and not rational.

The perception of risks may be significantly influenced by information about the risks themselves. Information can and should be used as a targeted means of reducing potential losses caused by reactions to events beyond what is rational, seen in the perspective of normative decision making. Being provided with transparent information in regard to the nature of exposures, possible precautionary actions, information on how risks are being managed and the societal consequences of irrational behavior reduces uncertainties associated with the understanding of risks of individuals. This, in turn, adds to rational behavior and thereby reduces follow-up consequences.

7 CONCLUSIONS

A framework for risk based decision making in the field of engineering is first described. This framework is general enough to accommodate for the special needs of different application areas but at the same time specific enough to ensure a sufficient degree of consistency in modeling and theoretical basis. Towards application of this framework for the risk assessment of volcanic hazards, aspects related to the modeling of the hazard process due to volcanoes are then discussed. A system of classification of structures and identification of different building characteristics that could be used for volcanic vulnerability and risk assessment is then proposed. This is followed by a discussion on the fragility and vulnerability modeling of structures relevant for seismic analysis.

This paper can be hence seen as a preliminary version of a guideline document for the assessment and management of risks due to volcanic hazards. Further work is required, especially in the assessment and evaluation of consequences and risk treatment measures for volcanic hazards.

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