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1.5 Actions due to volcanic eruptions

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1.5.1 INTRODUCTION

Today, about 500 million people are at risk from volcanic hazards. In the past 500 years, over 200,000 people have lost their lives due to volcanic eruptions. An average of 845 people died each year between 1900 and 1986 from volcanic hazards and for the next years, these numbers are predicted rising (Tilling, 1991 & 2005). The reason is not due to increased volcanism, but to an increase in the amount of people populating the area surrounding the active volcanoes. In Europe, this is the case of the Neapolitan area (Italy), where Vesuvius and Phlegrean Fields volcanic complexes threaten the safety of about one million of people. Instead, in the rest of the World, metropolitan areas, like Tokyo (Mt. Fuji), Mexico City (Popocatépetl) and Auckland (Auckland Field) are affected by eruptive risk.

The peculiar importance of this aspect has induced the COST Action C26 “Urban habitat constructions under catastrophic events” (2006–2010) to introduce the analysis of the volcanic risk in the urban areas in its research activities. The objectives are substantially two: to provide a methodology to evaluate the volcanic vulnerability of the urban environment towards an eruption and to propose simple and economical mitigation interventions. The first developed activity is relating to the definition of the actions produced by an eruption on the constructions (Mazzolani et al., 2008 and 2009a), with reference to physical phenomenon and the consequences on the structures. In particular, they are hereafter presented distinguishing between the effects due to the specific products of an effusive (lava flows) and an explosive (air fall deposits, pyroclastic flows and surges and flying fragments) eruption and that one produced by the secondary effects of an eruption, like lahar, tsunami and volcanic earthquake. The main goal of this paper is to describe the main actions due to volcanic eruptions and their consequences on the local environment and particularly on constructions.

1.5.2 ANALYSIS OF VOLCANIC HAZARD

1.5.2.1 Definition

A volcanic hazard (Dumaisnil et al., 2008) is defined as an event that can occur in a given area or location, such as a lava flow or a volcanic earthquake, along with the probability of the event's

Table 1. Indirect volcanic hazards with their physical characteristics (after Blong, 2000).

Indirect hazards	Characteristics pertinent to risk	Example
Earthquakes and ground deformation	Limited damage; subsidence may affect hundreds of km ² .	Sakurajima, 1914, Usu, 2000
Tsunami	Can travel great distances; exceptionally, waves to 30+ m.	Krakatoa, 1883
Secondary debris flows	Can continue for years.	Santa Maria, 1902–1920
Post-eruption erosion and sedimentation	Can affect extensive areas for years after eruption.	Irazu, 1963–64, Pinatubo, 1991–2000
Atmospheric effects	Limited effects.	Mayon, 1814,
Air shocks, lightning		Agung, 1960
Post-eruption famine and disease	Limited effects at present.	Lakagigar (Laki), 1783

occurrence. It is important to understand the hazard, but it is difficult to reduce the hazard itself because most effects of the eruptions are beyond our control.

Hazard refers to the annualized probability of the specific volcanic event (tephra fall, pyroclastic flows, lahars, etc.) occurring in the area under consideration. Various types of volcanic activity can affect people and property (death, injury, destruction, etc.) both in close proximity to and far from a volcano. Some hazards are more severe than others depending on the size and extent of the event taking place and whether people or property is within the path of the volcanic hazardous event. Although most volcanic hazards are triggered directly by an eruption, some occur when a volcano is in a state of quiescence.

The range of volcanic hazards that an area is exposed to needs to be recognized and understood (see Tables 1–2, Figure 1).

1.5.2.2 Process to identify volcanic hazards

Identifying and assessing the range of volcanic hazards that might be relevant at any given volcano, or site near a volcano, is a complex process that encompasses at least six tasks:

- 1) identifying a threatening volcano by using a set of physical, geological, and socio-economic criteria;
- 2) foreseeing an eruption at a given time and site by installing an adequate network of equipment for surveillance;
- 3) defining and ranking possible eruption scenarios based on the past and recent behaviour of the edifice;
- 4) delineating areas likely to be affected by the effects of the eruptive phenomena based on the recognized scenarios;
- 5) identifying and weighing people and communities at risk, vulnerable elements, social, economic, and cultural elements at stake;
- 6) undertaking a land-use policy and emergency procedures, including: civil defence, relief organisation, mitigation, preparedness and consciousness, and risk management aiming at sustainable development.

1.5.3 WHY TO STUDY VOLCANIC HAZARDS?

1.5.3.1 Main reasons to study volcanic hazards

In 2000, an estimated 500 million people were living within a distance of 100 km from an active volcano. Twice during the twentieth century two large towns were destroyed by eruptions: St Pierre, Martinique, in 1902 and Armero, Colombia, in 1985. Major population centres lie within ten to twenty kilometres from several large volcanoes with a likelihood of eruption during this century, e.g., Naples near Vesuvius and Arequipa near El Misti (see Figure 2).

Table 2. Direct volcanic hazards with their physical characteristics (after Blong, 2000).

Direct hazards	Characteristics pertinent to risk	Example
<i>Fall processes:</i> Tephra falls	Downwind transport velocity <10 to <100 km/h, can extend 1000+ km downwind, and can produce impenetrable darkness; surface crusting from tephra fall encourages runoff.	Vesuvius, 1631, 1906 Rabaul, 1994
Ballistic projectiles	Can affect a 10+ km radius from the vent; projectiles have high-impact energies; fresh bombs above ignition temperatures of many materials.	Soufrière St Vincent, 1812
<i>Lava flow:</i> Lava flows Domes	Bury or crush objects in their path; follow topographic depressions; can be tens of kilometres long; and produce a noxious haze from sustained eruptions.	Kilauea, 1960, 1983-present Merapi, Soufrière Hills Montserrat, 1995-present
<i>Pyroclastic flow:</i> Pyroclastic flows Pyroclastic surges	Concentrated gas-solid dispersion; small flows can travel to a distance of 5–10 km within topographic lows, whereas large flows can travel a distance of 50–100 km; large flows can mount topographic obstructions.	Pinatubo, 1991, Unzen, 1991–93, Mount Pelée, 1902, Taal, 1960
Laterally directed blast	Destroy all constructions.	Bezymianny, 1956, Mount St Helens, 1980
<i>Debris flow:</i> Primary (eruption-triggered) debris flows (lahars)	Velocities may exceed 10 m/s; rapid aggradations, incision or lateral migration may occur; the hazard may continue for months or years after eruption.	Nevado del Ruiz, 1985, Kelud, 1919
Jökulhlaups	These high discharge flows are triggered by ice-dammed lake breakouts; can flood extensive pieces of land and can occur with little or no warning.	Katla, 1918 Grimsvötn, 1996
<i>Sector collapse and flank failure:</i> Debris avalanche Magmatic origin Phreatic origin No eruption, seismogenic	Emplacement velocities of up to 100 m/s; can create topography, pond lakes; and produce tsunamis in coastal areas.	Mount St Helens, 1980 Bezmianny, 1956 Bandai-san, 1883, Ontake, 1984 Shimabara, 1792
<i>Other eruptive processes:</i> Phreatic explosions Volcanic gases and acid rains	Damage limited to proximal areas but can be lethal; corrosive, reactive; low pH in water; CO ₂ in areas of low ground.	Soufrière de Guadeloupe, 1976 Dieng plateau, 1979

It is therefore needed:

- 1) to minimize the risk of loss of life from structure collapse or damage in the event of an eruption;
- 2) to facilitate appropriate warning and evacuation systems;
- 3) to protect food-producing areas and other areas of significant economic activity;
- 4) to improve the expected performance of structures and lifelines;
- 5) to improve the functional capability of structures and lifelines that are essential to post-eruption recovery during and after an eruption, and to minimize the risk of damage to hazardous facilities.

1.5.3.2 Field of action

We wish to apply this hazard, vulnerability, and risk assessment to urban environments or to densely populated areas of the volcanic islands of the West Indies (such as Basse Terre, Guadeloupe or

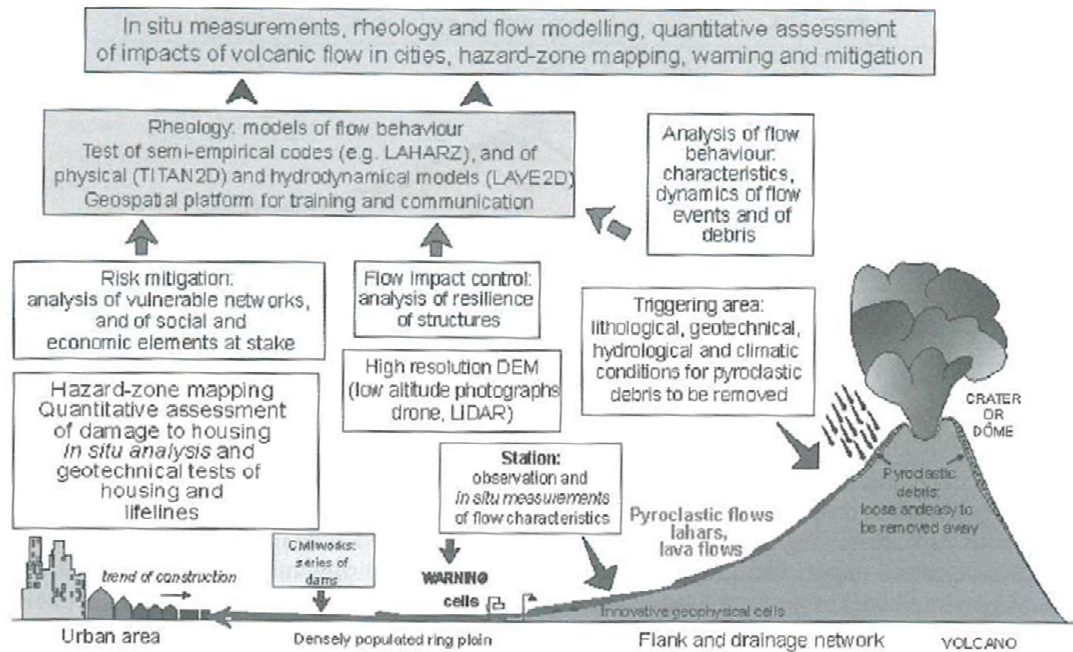


Figure 3. Flow chart (Thouret, 2010).

1.5.4 EFFUSIVE ERUPTION

1.5.4.1 Lava flows

During an effusive eruption, the *lavas*, constituted by totally or partially fused magma, emerge on the surface, flowing in a viscous mass from the crater itself, or from fissures or fractures. Their speeds are generally of few kilometers per hour and they, as well as the temperature, decreases with the distance from the vent. Lava can also be blown away in fragments to create kinds of avalanches moving down slopes at speeds as high as 150 km/h.

The most abundant chemical component of lava is the silica. Depending on the SiO_2 weight content, they are classifiable in: acid, intermediate, basic and ultrabasic. In general, more basic magmas present higher eruptive temperatures (1000–1200°C), than more acid magmas (700–900°C). Lava and magma can be considered as not Newtonian Bingham type fluids and so, the viscosity is their central peculiarity which influences eruptive behavior, mobility and shape.

A construction invested by a lava front is subject to an unavoidable destiny of destruction. Potentially, the risk interests the settlements in areas around the volcano and it grows near the eruptive vents and parasitical cones. The lava flow produces a lateral horizontal pressure which can cause the collapse of the invested buildings. The crisis 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. However fortunately, the advancing speed of the lava flows is sufficiently low to allow the evacuation and the safeguard of human lives. So, the mitigation of lava risk can not require the reduction of structural vulnerability, but it must be pursued by means of two types of interventions: passive and active protection.

The passive protection consists on a proper planning of the territory and of the emergencies management: the buildings must not be built near the areas with probable opening of eruptive vents and fractures or morphologically depressed areas exposed to potential invasion of lava flows. The active protection consists on the containment and/or the deviation of lava flows through barriers, able to withstand lateral thrust of flow and high temperatures. Today, the barriers of earth (generally of unconnected material) have proved their reliability (Colombrita, 1984). However useful contribution will be certainly the study of innovative barriers which are more efficient and more easily erectable than those made of earth (Marsella et al., 2008).

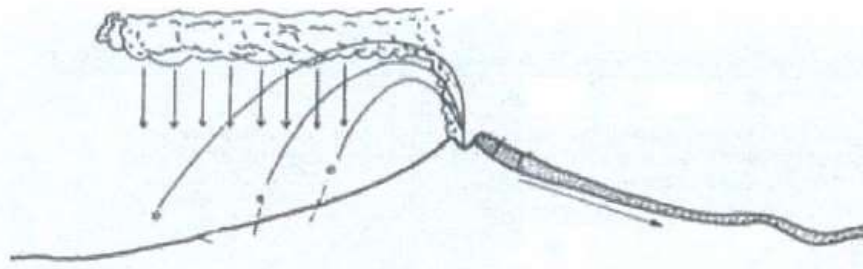


Figure 4. Representation of the air fall phenomenon.

1.5.5 EXPLOSIVE ERUPTION

1.5.5.1 Air fall deposits

During an explosive eruption, 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 (Figure 4). They fall down to a distance which depends on their speed and the initial ejection angle. The largest pyroclastic fall in the environs of the emission point, the most fragmented ones at greater distance and the smallest ones can be transported by stratospheric winds. Generally, air fall deposits cover the topography with uniform thickness, but, because of their poor consistency, they are removed from the most steep slopes ($>20-30^\circ$) and accumulated in the valleys. During violent explosive eruptions (Plinian and sub-Plinian), large deposits of pumice cover an area of elliptical shape around the crater, which is elongated in the direction of wind. The ashes deposit after very long time reaching large distances, above it deposits of pyroclastic flows often follow. Contrary, moderately explosive eruptions, on the contrary, produce deposit of clasts fall, whose distribution is symmetrical around the crater, because the launches are not sufficiently high to be influenced by the wind. Generally, the thickness of air fall deposits decreases with the distance from the eruptive centre.

The air fall deposits action on the ground level can be considered as a gravitational distributed load, which can be estimated as $q_G = \rho gh$, where g is the gravity acceleration (9.81 ms^{-2}), h is the deposit thickness (m), ρ is the deposit density (kg.m^{-3}). The last one depends on the following factors: the composition of pyroclasts, their compactness, the deposit moisture and the subsequent rains. So, the deposit density is weather dependent: in dry conditions it ranges from 400 kg.m^{-3} to 1600 kg.m^{-3} , according to its compactness; in damp conditions it ranges from 800 kg.m^{-3} to 2000 kg.m^{-3} (Spence et al., 2005). The air fall deposits action on the roofs is similar to the snow load, so, with reference to the Italian technical code (M.D. 2008) the air fall deposits action on the roofs can be determine through the following relation:

$$q_R = \mu \cdot q_G \cdot C_E \quad (1)$$

where μ is the shape coefficient, function of the angle pitch (α), q_G is the air fall load on the ground level and C_E is the exposition coefficient which take into account the effect of the topography of the construction site (De Gregorio et al., 2010).

In addition, to the relationship (1), for completing the model of the air fall deposits action, it is necessary to consider the high temperatures ($200-400^\circ\text{C}$) of the clasts, which are able to produce important thermal degradation of the mechanical properties of the materials (Mazzolani et al., 2008 and 2009a).

Some eruptions may send ashes into the stratosphere to heights of 10–30 km above the earth's surface. Combined with the wind, they can spread more or less heavy materials relatively far from the volcano itself. Most of building damages due to ash falls occur when the ash load exceeds the strength of either the roof-supporting structures or material used to cover the structure (sheet metal, plywood, etc.). According to an American study of the U.S. Department of the Interior, dry ash presents a weight ranking from 4 to 7 kN/m^3 , and rainwater can amplify it by 50 to 100%. If the ash becomes saturated by rain, it can reach more than 20 kN/m^3 . So, ash loading may be considered as similar to a specific snow load but with some major differences:

- being heavier, it is a much more severe loading case (Table 3);

Table 3. Density & load comparison, 10 cm of snow and 10 cm volcanic ash.

Load type	Unit weight (kg/m ³)	Load (kPa)
New snow	50–70	0.05–0.07
Damp new snow	100–200	0.1–0.2
Settled snow	200–300	0.2–0.3
Dry uncompacted ash	500–1,300	0.5–1.3
Wet compacted ash	1 000–2 000	1.0–2.0

- ash doesn't melt;
- ash can fill gutters and draining pipes leading to collapse, especially after rainfalls.

For a dry layer of ash about 10 cm thick, the extra load on a building can range from 0.4 to 0.7 kN/m²; a wet layer might reach 1.0 to 1.25 kN/m². In areas where snow load cases exist, a relative protection against ash falls may be expected but it depends highly on the location of the considered structure because snow loads vary with altitude and geographical position.

Ash is dense, abrasive and chemically corrosive. Volcanic ash is a frequent volcanic hazard which can have wide reaching affects on populations due to its distribution in the atmosphere. Most impacts are disruptive rather than destructive; however it is the hazard which most frequently affects the most people. The size of the eruption and the wind speed and direction affect the extent of the distribution. As a result, populations are vulnerable to the impacts caused by volcanic ash. Several recent eruptions have illustrated the vulnerability of urban areas which receive only a few millimetres or centimetres of volcanic ash. This has been sufficient to cause disruption of transportation, electricity, water, sewage and storm water systems.

Ash fall is one of the eruptive phenomena with greater risk for existing buildings and infrastructure, as the expected impact involves (with different levels of intensity) a very large area, which definition is strictly linked to the direction and intensity of the wind, as well as to the type of eruption.

In the case of Vesuvius and Campi Flegrei, the scenarios show an increase of roof loads due to ash fall between 1000–3000 kg/sqm inside the red zone and between to 300–400 kg/sqm for distances up to 30 km from the vent. Different types of damage may also occur in distal areas (more than 100 km from the vent), where the ash deposits are not likely to cause structural problems to buildings, but still could affect transportation networks and HVAC systems (ashes infiltration in filters and ducts). In case of eruption of Campi Flegrei, the direction with higher risk is the whole urban center of Naples, where the population is more than twice the area of the villages around Vesuvius. Ash deposit on roads and transport networks can cause considerable damages especially in proximal areas, causing localized or extended interruptions with direct effects on emergency management.

In accordance with the holistic approach to impact studies, this review encompasses the main sectors where studies have been undertaken concerning the impacts from volcanic ash fall and hence their vulnerability (Sword-Daniels, 2010). The work has been brought together and summarised with the intention to inform future studies on ash fall impacts research, and to provide an insight into some of the collective knowledge in this field. Although the review of studies is not exhaustive, the purpose is to review the main sectors that have been investigated and to use a whole-systems perspective to unearth the gaps in our knowledge and understanding of ash fall impacts and vulnerability.

The engineering and volcanological literature has been searched for references to volcanic ash and its effects, impacts and management. Studies are multi multiple, and vary in quality and depth. The most informative studies have been summarised in brief, in the following sector-by-sector impacts.

It can be seen that despite multiple impact-related studies, only a handful of sectors have thus-far been considered. Sectors are broad and include many subtopics within them; however there are many potential areas of research that remain little-explored.

The following sectors have been studied for ash fall impacts and the main findings are summarised below from the following references: Baxter, 2006; Blong, 1981, 1984 & 2003; Casadevall, 1996; Cook et al., 1981; Dobran, 2006 & 2007; Frameworks Architects et al., 1996; Gordon et al., 2005; Horwell & Cowie et al., 2003; Inbar et al., 1995; Johnston, 1997a, b; Johnston et al., 2000 & 2004; Newnham et al., 2010; Shriever & Hansen, 1964; Spence et al., 1996; Spence et al., 2005; Stewart et al. 2006 & 2009; Wilson et al., 2008; Wilson et al., 2009a, b.

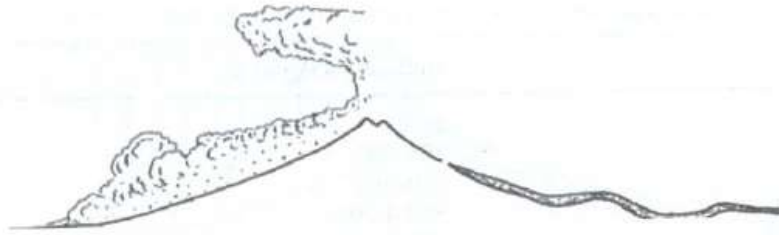


Figure 5. Representation of the pyroclastic flows and surges phenomena.

1.5.5.2 Pyroclastic flows

The *pyroclastic flows* and *surges* are the most dangerous phenomena produced during an explosive eruption. They are constituted by gas-solid dispersions with high or low concentration of particles respectively, which move along the surface under action of gravity. They are characterized by high temperatures and can be partly fluidized. In general, they are controlled by topography; channelled along the valleys, they fill the depressions (Figure 5).

Pyroclastic flows can be generated either by the collapse of the eruptive column, or by a directional explosion for the slipping of a part of the volcano, or by a lateral explosion at the base of a lava dome. Pyroclastic flows are made of a mixture of gases with dispersed solid particles of various sizes. The modelling of the phenomenon is very complex, because it depends on a number of factors difficult to catch among them the mass eruption rate, the volcano topographic profile, the magma properties, such as the water content and the temperature at the crater exit.

Aiming at examining the evolution of a pyroclastic flow, Todesco et al. (2002) adopted a model based on the solution of the Navier-Stokes generalized equations for a multiphase mixture, the latter being represented as a two-phase mixture composed of a homogeneous melt phase, made up of magma and crystals, and a gas phase, made up of water vapor. The mechanical and thermal non-equilibrium effects between gas and various particulates phases are considered.

Pyroclastic flows can produce high damages to the built environment in areas near to the vent. Although they would have a limited action range, the effects can be critical because of the combination of mechanical impact and thermal stress on the vertical surfaces of buildings (Zuccaro, 2010a-d). The main damages come from the impact on openings, particularly vulnerable. In these cases, although not resulting a static failure of the building, a fire risk is associated with the flow passage inside the building following the crash of the openings.

In the case of Vesuvius and Campi Flegrei, pyroclastic flows can cause lateral pressure impact within a range of 0.5 and 10 kPa, and thermal stresses ranging between 150 and 450°C. In Campi Flegrei, due to the probable location of the vent near to densely populated areas (including the west area of Naples), the impact of pyroclastic flows would be particularly serious, while in the case of Vesuvius is expected a decay of the initial power due to the distance of the built areas from the vent.

In the structural analyses, it is possible to schematize the action of the pyroclastic flows as a uniformly distributed static pressure (Petrazzuoli & Zuccaro, 2004), with temperature ranges between 200 and 350°C (Giurioli et al., 2008). In particular, with reference to a sub-Plinian Vesuvian eruption, the dynamic pressures produced by Vesuvian sub-Plinian event are determined (Esposti Ongaro et al., 2002). The pressure was calculated as a function of the angle of flows propagation α at growing distance from the vent, in undisturbed atmosphere above the aerodynamic ground plane at 5 and 15 m, as it is shown in Table 1. Esposti Ongaro et al. (2002) also determined the pressure corresponding to an angle α equal to 30–45°, at 5 and 10 m above the ground and at 4–5 km from the vent (Table 4).

The obtained results are related to 2D models such as to the volcano transversal section. In the *Exploris Project* (Neri et al., 2007) a 4D model was developed, where Vesuvius is schematized with its real geometric dimensions, besides, in the flows modelling the variable time is included. In this case, for a sub-Plinian eruption, a pressure equal to 1–3 kPa at 7.5 km from the vent, with a temperature equal to 250°C was calculated. In addition, with reference to a sector of the town of Torre del Greco (6 km from Vesuvius), Zuccaro & Ianniello (2004) have analyzed the interaction of pyroclastic flows with buildings in an urban settlement. The generated turbulences produce an increment factor of pressure varying over the range $[-3; +2]$. In particular, with an angle $\alpha = 90^\circ$, the pressure equals 3–5 kPa.

Table 4. Dynamic pressure (kPa) in function of the angle of flow propagation α at growing distance from the vent.

α [°]	Distance from the vent		
	2 km	4 km	6 km
30	–	5.0	–
45	–	3.0	–
90	11.0	1.0	1.0
180	4.0	1.0	0.5
360	1.80	0.1	0.0



The experience from the 1997 Montserrat eruption (Canary Islands) has indicated that a building can survive under moderate pyroclastic flows pressure (1–5 kPa) if it remains intact, while if one or more openings fail, allowing hot gas and ash to enter, the entire building is likely to be destroyed (Baxter et al., 2005). In this case the contents of the construction and any timber structure are likely to catch fire; at the same time the principal structural walls and roofing will suffer a combination of internal and external pressures, which will cause partial or total failure (Spence et al., 2004).

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-proof building presents larger strength and stiffness capabilities than a not earthquake-proof building.

1.5.5.3 Flying fragments

The explosive eruptions also are able to produce flying fragments of pyroclasts defined *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. Then they are thrown in the atmosphere from the main flow to fall or be transported along the mountainside in gravitational currents. The word *missile* can also relate to flying debris, not involved in the eruption, set in motion by pyroclastic flows.

The law which regulates the movement in a vacuum of a volcanic fragment with ballistic trajectory is (Dobran, 2006 & 2007) $R = (u_0^2 \cdot \sin 2\theta)/g$, where R is the block ejection distance, u_0 is the ejection velocity, θ is the initial ejection angle of the fragment from the horizontal and g is the acceleration of free fall. This formula is applicable for very large blocks for which the air drag has a negligible effect on the clasts trajectory. In this case, the most efficient ejection angle is 45° . On the contrary, the presence of a stratified atmosphere ensures that the optimum elevation angle is less than 45° . In addition, the θ optimum take-off angle from the eruptive column, and not from the vent, ranges between 47° and 50° for the larger blocks and in the range between 38° and 40° for the smaller ones.

A separate examination is given for missiles (particulates, debris, stones, loose flower pots, dustbins, etc) generated by pyroclastic flows. In fact they are incorporated into the main current and added to the destructive impact. These missiles can be related to the aerodynamics of flying debris with respect to cyclone and wind storm (Wills et al., 1998; Spence et al., 2005).

Bombs and missiles cause damage which depends on the kinetic energy and the vulnerability of the struck object. A flying fragment can impact the roofing or the walls of a building, but, in particular, it can hit the most vulnerable parts, like the openings.

If a building collapses, it is assumed that all occupants are killed. If buildings do not collapse, the main factor which governs vulnerability is the resistance of openings, especially the glass panes or the shutters which can prevent the hot ash to enter. Contrary, possible consequent fires and/or breathing difficulties for people inside can arise (Spence et al., 2005). Several studies aim 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. It is assumed that the energy required to break a glass panel equals the energy absorbed by the panel in its elastic deformation up to the point of failure.

For a Young's Modulus of 65,000 MPa for glass, the energy required to break the window ranges from 8 to 20 J for typical and large window panes of 3–4 mm thickness. Therefore, it can be assumed that, at any given flow velocity, missiles with a kinetic energy less than 8 J will break few windows, missiles with a kinetic energy between 8 and 20 J will break some windows, and missiles with a kinetic energy above 20 J will break many windows.

1.5.6 SECONDARY EVENTS

1.5.6.1 Lahars

The lahars are a relevant risk factor for buildings and structures in volcanic areas. The same phenomenon may have specific characteristics depending on some variables (Zuccaro, 2010a-d). After an eruptive event, especially if explosive, the thermic change in the proximity of the volcano often produces rain. Combined with the pyroclast 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 has an Indonesian origin and 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).

Lahars with a high water content can be assimilated to the Newtonian fluids, whereas the lahar with a high concentration (high solid/water ratio) are assimilated to Bingham fluids. The Newtonian fluids freely move under the gravity until the critical stability condition arises, while the Bingham fluids, because of the greater viscosity, offer some resistance to the motion and so they need an additional strain to mobilize. At the same conditions in terms of gradient, granulometry, etc, the motion capacity of a lahar depends on the water content and the ability of the flow to lose or to absorb water during the way. The effects of lahars on the constructions are comparable to those ones produced by the debris flows.

Damage to buildings caused by lahars can be connected to different factors. Hydrostatic and dynamic strength determine the amount of lateral forces that can bring to failure and collapse of technical elements such as openings and cladding. The density and velocity of the flow determines the magnitude of dynamic forces, while hydrostatic forces depend on the height and composition of the flow. Minor mudslides can cause abrasions of the external finishing of buildings and damage to surfaces and furnishings in case of penetration of the flow in the interior. Local effects may be caused by the transport of medium and large debris, rocks, but also uprooted trees, motorbikes and cars that can act as missiles on buildings exposed. Depending on the magnitude of the phenomenon and orographic conditions of the site, buildings of medium-low height can be buried by lahar. Further damage can be caused to structural parts of both masonry and reinforced concrete buildings, causing even serious cracks and damages, with structural failure involving foundations, due to erosion and soil liquefaction. Structural and non-structural metal elements can also be seriously damaged by the acidity of the flow.

The response of structures and buildings technical elements to the action of lateral forces produced by lahars depends mainly on construction type and materials employed, as well as specific characteristics such as size in plan and elevation, number, size and position of openings, spatial distribution and presence of protective elements around the building able to divert the flow, etc.

Faella and Nigro (2002) have analysed the structural and non-structural damage in the buildings impacted by the debris flows, during the hydrogeological disaster of May 1998 in Campania (Italy). The damage is significantly different in relation with: the position of the construction, the impact direction, the level of kinetic energy of the flow and the structural typology. This study, for masonry and reinforced concrete buildings, has identified the main collapse mechanisms and the debris hydrodynamic horizontal pressures, which assume the values of 150, 73.5 and 37.5 kNm⁻², for speeds of 10, 7 and 5 ms⁻¹, respectively.

With particular reference to Vesuvius case, these pressures can be adopted as lahars actions on the constructions. This because the debris velocities furnished by Faella and Nigro result comparable to those ones calculated by Vallario (1994), with reference to of the possible lahar produced by a

Vesuvian eruption on the Cavallo riverbed (Torre del Greco city, south slope of the Vesuvius). In fact, they range between 3.94 and 10.14 ms^{-1} .

However the lahars, as respect to the debris flows, present the additional variable of the temperature, which causes substantial degradation of mechanical properties of construction materials. Actually, 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. Obviously, at the same conditions, as far as the time passes, temperatures will be reduced.

1.5.6.2 Tsunami

Tsunami is a Japanese word which means “wave (name) in the port (tsu)” and, since antiquity, it describes the phenomena of the rogue waves which produce devastating effects on the coast. It can present 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.

Among the cause of a tsunami, the volcanic eruptions are present. In particular, the anomalous waves can be produced by massive pyroclastic flows which reach the sea. That is the case of the explosive eruption of the Krakatua volcano (1883), in the Sunda Straits, between Sumatra and Java, that produced a large tsunami that killed more than 30,000 people living in the coastal villages of the Straits.

Tsunami hazard in the Gulf of Naples is mostly related to the activity of the main volcanic structures found in the area (Vesuvius, Phlegrean Fields, Ischia) and also far to the south (Stromboli). With reference to Vesuvius, Historical information as well as numerical scenarios indicates that the tsunami hazard for the Gulf of Naples is not frequent, but not at all negligible. Combining this with the high vulnerability related to the huge population density and the very complex urbanization, it turns out that the tsunami risk assessment for the area is a problem whose treatment cannot be delayed any further. According to historical documents, anomalous sea oscillations and waves in the Gulf of Naples were observed not only concomitantly of the largest eruptions (79AD and 1631), but also to some the smaller events, such as the cases of 14 May 1698, 17 May 1813 and 4 April 1906 (Italian Tsunami Catalogue, Tinti et al., 2007; Tinti et al., 2010).

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* F_s is produced by the impact of the flood waves on the structures, while the *debris force* F_i is relating 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 F_D are exerted on structures due to continuous flow of water around the structure. In addition, the inundation gives raise to hydrostatic forces F_{HS} . 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.

1.5.6.3 Volcanic earthquakes

All volcanic eruptions are accompanied by local seismic activity, as it is testified by the swarms registered in occurrence of large eruptions (Benoit and Mc Nutt, 1996). The seismic events that characterize an eruptive phenomenon can be generally considered of low to medium intensity. Nevertheless, the cumulative damage caused by the sequence of earthquakes in various stages of the eruption produces a progressive increase in the level of expected damage (Zuccaro, 2010a-d). According to the sequence of phenomena characterizing the eruptive event, more conditions can occur and raise the damage caused by the earthquake. In particular, the ash fall creates a progressive overload on the roofs, and even when it doesn't result in a partial collapse of the floor; it brings to an increase of reactive mass of the building, thus modifying the response to seismic action. The building types with high vulnerability, with particular reference to masonry structures, would then suffer more damage than for a single event comparable to the maximum intensity expected in case of a Sub-Plinian eruption.

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 (Festa et al., 2004).

In particular, seisms related to volcanic activity are of two general categories: volcano-tectonic earthquakes and long period earthquakes (Chouet, 1996).

The first category, *volcano-tectonic earthquakes*, is produced, on one side, by stress changes in solid rock due to the injection or withdrawal of *magma* through the fractures and, on one other side, by tectonic displacements. They can cause land to subside and can produce large ground cracks. Volcano-tectonic earthquakes do not indicate that the volcano will be erupting but can occur at anytime.

The second category, *long period earthquakes*, is only produced by the injection of magma through surrounding rock. Therefore they are a result of pressure changes during the unsteady transport of the magma. When pressure of the magma injection is high a lot of earthquakes are produced. This type of activity indicates that a volcano is about to erupt. Scientists use seismographs to record the signal from these earthquakes. This signal is known as *volcanic tremor*.

The intensity of a volcanic earthquake is a function of the entity of the eruptive event. For example, in the case of Vesuvius, during several days before the 79AD Plinian event, big earth tremors. Afterwards, the seismic crisis preceding the 1631 Sub-Plinian Vesuvius eruption has been characterized by earthquake intensity equal to 4.0 degree on the Richter scale, temporally limited to some hours before the eruption (Cubellis and Marturano, 2006). After this eruption up to recent times the earthquakes were generally of low-moderate energy and related to eruptive activity. The most dangerous occurred on 15 June 1794 during the lateral eruption which destroyed the town of Torre del Greco. The shocks caused damage to buildings in the Vesuvian area and shattered window panes in Naples.

With reference to the Vesuvius case, a comparison between tectonic and volcanic earthquakes has been conducted, through two real seismograms recorded in the Vesuvian area: the tectonic one of Irpinia (Avellino, Campania, Italy) on the 23 November 1980 and the volcanic Vesuvian one occurred in October 1999 (Mazzolani et al., 2009b and 2010). The first one with a magnitude of 6.9 and an epicentre about 30 km distant from the sea surface. The latter one with 3.6 magnitude and an epicentre 3.8 km distant from the sea surface.

The substantial difference between these earthquakes is related to the peak maximum acceleration frequencies: the peaks of the tectonic and volcanic response spectra, equal to 0.37 g and 0.05 g respectively, occurs next to periods T equal to 0.40 s and 0.14 s respectively.

According to the new technical Italian code (MD, 2008), the building fundamental period T_1 can be calculated through the formula $T_1 = C_1 \cdot H^{3/4}$, where: C_1 is equal to 0.05 and 0.075 for masonry and RC buildings, respectively, and H is the construction total height. So for masonry buildings the period T_1 almost ranges from 0.11 to 0.28 s for heights between 3 and 10 m, while for RC buildings it almost ranges from 0.29 to 0.6 s for height between 6 and 16 m. This would implicate that masonry buildings suffered much more the volcanic earthquake, since its frequency is close to that of the building, while RC buildings are sensible to tectonic earthquakes.

1.5.7 MITIGATION STRATEGIES

1.5.7.1 Ash fall

Mitigation strategies, beside the need to develop an operational plan for the removal of ash on roofs and transport networks, mainly concern the repairing and reinforcement of roofing systems in order to increase the load carrying capacity (see Table 5).

Pitched roofs with wooden or steel structure, reducing the deposits of ashes, would be at risk only in proximal areas where the surface of the cover present disconnections or missing parts. In this case, given the adequate inherent fire resistance of commonly used coating materials (typically clay tiles or panels of steel sheet) is enough to replace the missing elements in order to prevent the passage of hot ashes under the roof covering.

In case of flat roofs it is possible to identify two main types of intervention: the reinforcement of the roof slab in order to increase the resistance according to the expected overload, or the realization of a sloped roof over the existing one.

Table 5. Vulnerability of common roofing typologies.

Vulnerability classes	Roofing type	Load (kPa)	Collapse probability
A_rf	Weak pitched wooden roof	2,0	50%
B_rf	Standard wooden flat roof	3,0	50%
	Flat floor with steel beams and brick vaults		
	Sap floors		
C1_rf	Flat floor with steel beams and hollow bricks	5,0	60%
	R.C flat slab (more than 20 year old)		
C2_rf	R.C flat slab (less than 20 year old)	7,0	51%
	Last generation R.C. flat slab		
D_rf	Last generation R.R. pitched slab	12,0	50%
	Last generation steel pitched roof		

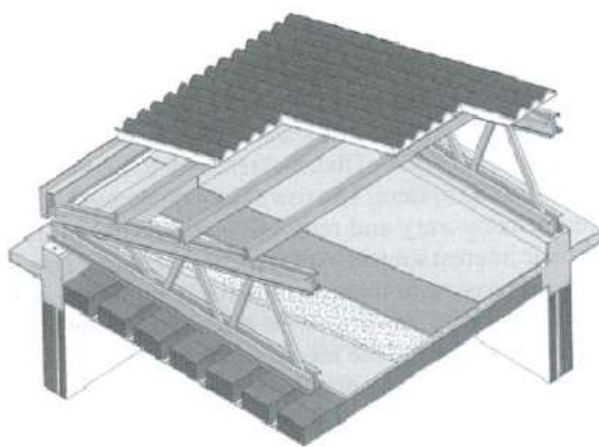


Figure 6. Technical solution for the mitigation of ash fall impact on roofs through the employ of CFS structures (Alborelli, 2009).

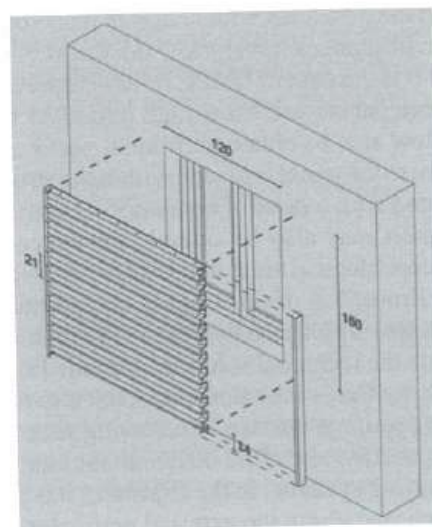


Figure 7. Technical solution for the protection of openings.

In the first case, it is necessary to define the characteristic flexural strength of different types of existing roofs in areas at risk (concrete and bricks, steel or wooden beams and hollow bricks or brick vaults, “Sap” floors, etc.), thus determining the capacity to withstand to overloads produced by ash. It is then possible to apply conventional technologies, such as integration of reinforced concrete slabs placed on the existing floors and connected to existing beams, or innovative solutions, including for instance the use of FRP (Fiber Reinforced Polymers) and FRCM (Fiber Reinforced Cementitious Matrix) systems for reinforcement of beams and joists. The main advantages of such interventions include the possibility of not modifying the existing roofing system.

In the second case a very effective solution is to build truss or lattice structure in CFS (Cold Formed Steel) on top of the existing roof, in order to create a sloped surface. The mechanical properties and lightness of CFS structures allow the realization of a strong roofing system without a high overload on the underlying structure (Figure 6). The coating can be made of steel sheet, with the possibility of providing additional layers in order to offer additional benefits to the intervention of structural retrofit, such as the insertion of insulation or micro-ventilation system for energy conservation, or the integration of photovoltaic thin film for the production of electricity. Such actions may be also connected with housing refurbishment programs, allowing for instance the increase of building volume for intervention of volcanic and seismic mitigation. The realization of lightweight structures for protection from ash fall may be an appropriate solution not only for buildings but also for the several areas of historic and artistic interest (such as Pompeii, Herculaneum, Oplonti, Stabiae, etc.), which might be seriously compromised after an eruption of Vesuvius. In these areas,

however, the mitigation may be invasive in terms of visual impact, and it is possible to develop provisional removable shingles.

An alternative to steel roofing is the realization of UHPC (Ultra High Performance Concrete) shells, characterized by very high mechanical properties, durability, resistance to high temperatures and fire, with very low thickness required (up to 2 cm for spans of 5 m), offering effective and innovative technical solutions in terms of aesthetics and design.

1.5.7.2 *Pyroclastic flow*

Mitigation strategies mainly concern the reinforcement of infill panels in R.C. buildings and measures for the protection of openings (Figure 7).

When reinforcing infill panels, the goal is to increase the impact resistance while withstanding the high temperatures produced by the flow. Currently used techniques for the seismic reinforcement of infill panels are generally effective to prevent them from breaking due to pyroclastic flow, however, as noticed above, the employ of currently used technologies that are particularly sensitive to temperature should be avoided. In the absence of specific constraints to envelope system modification, the goal of increasing infill panel impact resistance may be achieved by overlaying existing facades with coatings made of advanced materials offering high thermal and mechanical performances in very low thickness.

It is the case of UHPC (Ultra High Performance Concrete) components, which can be cast in very large panels and show high durability and resistance to aggressive environment. These operations allow also to obtain additional performances, such as the increase of shear strength in the plane, where the panel is placed within the structural grid, or the increase of thermal resistance, where combined with a layer of insulation or with a ventilated facade system. The use of low thickness UHPC panels may also be suitable for the construction of temporary and removable systems to protect archaeological areas and sites of historical and artistic interest subject to the risk of pyroclastic flows.

Protection of openings is an essential mitigation measure in relation to pyroclastic flows, as it allows minimizing the risk of fire related to penetration of the flow inside the buildings. At the same time the technical solutions provided should be able to withstand the mechanical stresses related to the pressure of the flow itself, but also to the potential presence of debris that can impact as "bullets" on openings surface. Borrowing technologies used in tropical areas for hurricanes protection it is possible to define different solutions, made with removable components or integrated into the shutting systems. In the first case, it is possible to overlay steel or Kevlar sheet to existing openings, anchored along the external perimeter.

Protection systems integrated into the shutting systems, unlike the removable panels, are not always able to assure an effective response to the impact of the flow, but are suitable for medium ranges of temperature and pressure or for short exposition time. It is also possible to apply special protective films on glass surfaces that can provide protection from fire and explosion. Fire safety shutters, steel or aluminum associate the heat resistance with adequate mechanical strength. In some cases, a combination of protective films and special shutters should be provided, in order to reach the required levels of temperature resistance and mechanical strength.

1.5.7.3 *Lahar*

Generally speaking, structures, infill panels and ground floor openings are the technical elements most at risk in case of lahars. The reinforcement of these elements yet does not guarantee the survival of the building in case of direct impact with mudslide and debris, especially in the case of compact urban areas, where a "tunnel effect" can increase speed and height of the flow after the passage inside particularly narrow roads. For this reason the most effective mitigation strategies are related to environmental engineering interventions, to be made in risk prone areas and designed to contain or divert lahars. Measures such as retention basins, alternative artificial canals, high-strength reinforced concrete containing structures, may be appropriate solutions to mitigate risk from lahars, reducing the entity of the phenomenon in residential areas and increasing the probability of survival of the buildings.

1.5.7.4 *Earthquake*

Generally speaking, considering the high seismic vulnerability levels and the construction density in Vesuvius area, cost-effective mitigation measures should be provided. It is possible to choose

cheap and reliable technical solutions (such as iron chains in masonry buildings, the insertion of infill panels or resistant elements in soft floors of reinforced concrete buildings), but also to adopt, in case of seismic reinforcement, specific solutions able to respond effectively also to other volcanic phenomena, such as pyroclastic flows or ash fall. In this context, one solution is the construction of pitched roofs by overlapping light structures in CFS (Cold Formed Steel). This allows to chain vertical structures by increasing the resistance to seismic actions (box behaviour) and simultaneously prevent the deposit of ashes and the structural risks related to overloading of the roof, also in consideration of a possible earthquake following the ash fall phase. At the same time, should be avoided the employ of widely used reinforcement systems not satisfying the conditions of volcanic risk, such as FRP (Fiber Reinforced Polymers) in proximal areas, whose effectiveness is seriously reduced by the possible impact of pyroclastic flows. In fact, the high temperatures produced could affect the polymer matrix, whose physical and mechanical properties degrade in range above 60–80° C, with the consequent failure of the system caused by the loss of adhesion of the reinforcement to the walls. In this cases alternative technologies should be adopted, compatible with the environmental conditions related to a volcanic event, such as FRCM (Fiber Reinforced Cementitious Matrix) systems, able to withstand high temperatures while preserving the mechanical properties.

Global mitigation strategies related to seismic risk in case of a volcanic event may include planning for widespread interventions, defining the areas that require priority actions, such as the building curtains facing the main transport routes and escape routes identified by the Civil Protection Emergency Plan, in order to ensure safe evacuation routes during unrest phase, characterized by increased seismic intensity.

1.5.8 IMPACTS OF ASH FALL

1.5.8.1 *Health*

The health effects of volcanic ash depend on the grain size, mineralogical composition and chemical coatings on the surface of the ash particles.

The reporting of asthma-type symptoms following eruptions is variable and may depend on the ash characteristics and duration of exposure, as well as the social context and willingness to report such personal information. It is thought that pre-existing asthma or bronchitis sufferers are at greater risk of suffering from respiratory impairment than those without a history of respiratory problems, however the health impacts of volcanic ash are inconclusive.

1.5.8.2 *Structures*

Wet tephra is known to have a greater load than dry tephra, and various observations from historical volcanic eruptions in the 20th Century have shown variable critical thicknesses of tephra under which roofs have collapsed; observations vary from 75–300 mm thickness. Building styles, materials and general condition are important factors in the live load bearing capacity. Increasing the cross-sectional area of trusses and reducing the truss span, increases the threshold value that can be withstood by a building. The observations of roof pitch have ambiguous results. Accelerated corrosion of metal roofing is known to occur following ash fall events.

1.5.8.3 *Agriculture & Environment*

Ash reduces water infiltration in the ground and increases surface albedo. When ash falls on leaves it reduces photosynthesis and can cause collapse and crushing of plants and crop. Ingesting ash may be harmful to livestock; causing abrasion of the teeth and in cases of high fluorine content, fluorine poisoning. Acid rain, a result of ash and rain, is capable of burning crops and leaves.

1.5.8.4 *Water & Contamination*

Numerous studies have been undertaken on the composition of volcanic ash leachates and many soluble components have been detected. Aluminium, Iron and Manganese, Fluorine and Sulphate are amongst them. Ash also causes a lowering of the pH level. These contaminants are not thought to pose health risks, but rather cause impacts on potable water supplies, and associated issues of corrosion, scale deposition and staining may affect distribution networks.

Ash fall is known to increase the turbidity of water, which at heightened levels can prevent disinfection treatments from working effectively. Studies have also focused on recording the turbidity of water supplies following eruptions; which increases with the amount of ash entrained into water systems.

Ash also clogs water networks; blocking irrigation systems and clogging the intakes at water processing plants. This build-up of ash in water infrastructure systems can cause extensive corrosion, abrasion and damage or failure.

Ash clean-up commonly involves the hosing down of surfaces, and can therefore cause strain on water supplies.

1.5.8.5 *Electrical distribution networks & computers*

Ash in combination with rain is known to cause power outages on electrical distribution systems. This is a result of electrical flashover which occurs due to the conductive properties of ash. Ash falling on overhead power lines can also cause breakages due to the weight of the ash. Computers have been tested for failure under ash fall conditions. Abrasion was evident and failures occurred, more prevalently if the conditions were also humid.

1.5.8.6 *Aircraft*

Ash is abrasive and causes abrasion damage to several parts of the aircraft, it also blocks intakes and re-melts and accumulates in engines that are running at temperatures of hundreds of degrees Celsius. This can cause a loss engine power and can require entire engine replacement following an encounter with an ash cloud. Some mitigation and prevention measures have been developed including: avoidance of flying near ash clouds and development of ash warning systems to aviation industries, setting engines to low power during an encounter with ash, and covering grounded planes with protective sheeting across windows and openings. Costs of damage, rerouting, delays, cancellations and clean-up are extensive.

1.5.8.7 *Land transport infrastructure*

Ash is known to reduce traction on roads and reduce visibility, making driving on roads more dangerous and disrupting traffic networks. This also restricts access for emergency services which is of critical concern during a crisis. However few studies have focused on the impact of volcanic ash on land transport infrastructure.

1.5.8.8 *Emergency management*

Some effective techniques for the management of ash have been developed in preparedness and planning for ash fall events, public education and training, cleaning methods and apparatus and also preventative measures to ensure damage limitation.

1.5.8.9 *Cost impact assessment*

The costs of ash fall disruption have been estimated where possible in a few studies. The cost implications depend on the industry affected, distribution of the ash and the duration of the event. However ash fall is known to cause extensive losses in business interruption, exemplified in the eruption of Eyjafjallajökull in Iceland in April 2010, with reported airline losses of €1.5–2.5 billion (The Daily Telegraph, 2010). Following the Ruapehu eruption in 1994/95 the Rangipo hydroelectric power station was damaged by ash carried in the river and cost an estimated \$12 million NZD in loss of power generation and \$6 million NZD in replacing damaged blades (Johnston et al., 2000). Cook et al. (1981) estimated crop losses from Mount St Helens ash fall at \$100 million in 1980. Ash is also known to have caused damage to aircraft engines; mechanical parts; agricultural industries from crop or livestock losses; losses in the tourism industry; costs of emergency response and clean-up, and many more. Many losses are unquantifiable.

1.5.9 IMPACT OF PYROCLASTIC FLOWS

The collapse of the sustained column and the consequent pyroclastic flow (PF) are very frequent phenomena in explosive eruptions. In this case the magmatic material erupted is composed by a

mixture of molten and solid pyroclasts in a continuous gas phase. This mixture is the product of gas exsolution and magma fragmentation processes that occur during the magma ascent from the deep magma reservoir to the ground surfaces.

When this mixture of gas and pyroclasts penetrates into the cooler atmosphere it mixes up with the surrounding air forming a volcanic jet.

Crater geometry, outlet pressure and velocity, temperature and gas content control the effectiveness of the mixing and, therefore, the global evolution of the explosive event.

If the mixture at the top of the jet is reduced below the atmospheric density, then the eruption forms a convective buoyant plume called "Plinian" column. Otherwise the eruptive mixture collapses forming a ground PF that can propagate to great distance from the vent.

The action on the vertical surfaces of buildings affected by the flow is a combination of impact and thermal stress, proportional to its mass and velocity.

Pressure and temperature values vary depending on the characteristics of the eruption column and on the morphology of the invaded areas. In case of a Sub-Plinian I eruption the pressure can reach 10 kPa and the temperature can reach up to 400°C. However, considering the way of propagation of the flow within the territory, velocity and temperature values are not uniform, but weaker in lateral areas of the cloud, generally decreasing depending on distance from the vent. This means that not all buildings struck by the flow are destroyed, but it is possible to identify levels of damage as a function of impact characteristics and building vulnerability.

1.5.9.1 *Building behaviour shouted by pyroclastic flow*

1.5.9.1.1 *Background*

Damage resulting from the impact of pyroclastic flows on buildings depends on the combination of several factors: the duration of the phenomenon, the temperature of the flow and pressure produced by the impact (Zuccaro, 2010a-d).

In general, the impact of pyroclastic flows can be classified into three main categories:

- a) The values of pressure and temperature are likely to damage the structure, until partial or total collapse
- b) The values of pressure and temperature are not likely to damage the structure, but there is a breakthrough of non-structural parts (window frames or infill panels) that allows the penetration of the flow into the building
- c) For lower values of pressure and temperature none of the building technical elements is expected to collapse, but the difference between the external and internal pressure causes the infiltration of the flow inside the building.

While it is clear that in the first case the damage is very serious, it should be noted that in the other two cases, the flow infiltration can lead to the destruction of the building, mainly in case of breakage, as the strong internal pressure caused by flow infiltration can "inflate" the building causing the break of the roof or windows to the outside. It has to be considered, finally, the possibility that the high temperature of the flow entering the building could trigger fires, which could destroy the building even in the absence of mechanical damage.

For these reasons we must distinguish three different typologies of vulnerability against three different types of expected damage.

- a) the vulnerability of the major elements (masonry walls, frame)
- b) the vulnerability of non-bearing (coverage, cladding)
- c) understanding vulnerability as "permeability" to infiltration, and expressed as ACH (Air Change for Hour)

1.5.9.1.2 *Vulnerability of bearing elements*

The most significant parameter in this case is the dynamic pressure, whereas the temperature is less decisive. The evaluation of the building structure vulnerability to pyroclastic flow actions requires the estimation of the limit horizontal pressure at the collapse state of the standard buildings. A vulnerability analysis has been carried out by means of fundamental theorems of limit state analysis applied to R.C. frames and to the masonry walls, ((Zuccaro, 2010a-d, Spence et al 2004).

It should be considered that the lateral pressure caused by the flow is quite different from seismic action. Pyroclastic flow action is not cyclical; therefore the ductility as energy dissipation capacity is

Table 6. Pyroclastic Flows – Structural Classification.

Type	Description
Ap	Weak Masonry Buildings of 3–4 storeys with deformable floor.
Bp	Weak or strong Masonry Buildings with more than 4 storeys. Medium Masonry Buildings of 1–2 storeys with deformable floor. Strong Masonry Buildings of 3 or more storeys with rigid floor.
Cp	Strong Masonry Buildings of 1–2 storeys with rigid floor.
Dp	Non aseismic r. c. buildings of more than 6 storeys (High).
Ep	Non aseismic r. c. buildings of 4–6 storeys (Medium).
Fp	Non aseismic r.c. buildings of 1–3 storeys (Low)

less important. Also, unlike the case of earthquake, mass is not directly proportional to lateral action, but plays a stabilizing function. The slenderness of the building is a factor strongly conditioning the level of vulnerability. It has been investigated the behavior of several sample buildings loaded by lateral increasing pressure, exchanging the typological and geometrical characteristics of the buildings, and computing the collapse values.

The results of numerical analysis show a significantly different behavior between masonry and reinforced concrete structures, thus suggesting the definition of two separate vulnerability scales). Were therefore identified three classes of vulnerability (A, B, C) for masonry structures and three for R.C. structures (D, E, F), defining the buildings assignment criteria and the collapse probability as a function of lateral pressure by flow (Table 6).

1.5.10 VULNERABILITY, RISK, AND DAMAGE ASSESSMENT

Identifying and assessing hazards and risks consist of three steps and questions:

- a) where and how does the hazardous volcanic process occur?
This requires the study of thematic maps (geology, topography, population, city plans), archives on past catastrophic events, aerial photographs and satellite images, geodetic surveys and DEMs, and mapping the past extent and path of the volcanic flows and tephra-fall deposits on and around the active volcano.
- b) How large and how often does any given volcanic hazardous phenomenon occur? What is its magnitude and frequency?
Mapping the extent of volcanic deposits, estimating the volume of the deposits, and assessing the path of the volcanic flow are essential tasks for computing magnitude and frequency. This implies detailed hazard-zone mapping for each hazardous process (lava flow, tephra fall, pyroclastic flow, lahars, etc.) and for each of the eruption scenarios, which is based on the past and present behaviour of the volcano. Mapping is best carried out by using statistical approach and modelling. Geomorphic surveys with the aid of satellite imagery form a logical starting point for natural hazard zoning. Geomorphic hazard zonation recognizes old deposits, maps flow paths and delineates hazard zones, which are primary inputs in elaborating eruption scenarios. The second step requires modelling based on semi-empirical codes and on numerical codes, which enable us to delineate the areas likely to be affected in the case of an eruption or a non volcanic crisis (e.g. debris avalanche, rain-triggered lahars, flash floods in cities, etc;). An alternative estimate of hazard zones can be obtained with the aid of mathematical models that simulate the evolution of volcanic phenomena and compute the effects at ground level, allowing the estimation of the area affected by an event according to a certain scenario. Geomorphic and hydrologic parameters are critical input requirements for the use of DEMs and GIS in long-term planning. The use of DEMs and of simulation models such as LAHARZ and FLOW3D have enabled Iverson et al. (1998), Pareschi et al. (2000) and Sheridan et al. (2001) to gauge volcanic flow hazards in densely populated areas around Mt Rainier, Vesuvius and Popocatepetl volcanoes, respectively.
- c) The third step of risk assessment requires the development of a series of scenarios in which eruption magnitudes, hazard types, composite risk zonation and the vulnerability of people

and infrastructure are adequately considered. Eruption scenarios are useful for preparation of emergency plans and long-term land-use planning.

How can we protect people, communities, and elements at stakes?
The volcanic risk should be (see Table 7):

- 1) analysed in terms of frequency and magnitude in order to determine expected damages on housing and infrastructure or lifelines;
- 2) evaluated in terms of a cost and benefit analysis (the value of any given element at risk with and without protection);
- 3) counteracted by land use regulations and careful city planning;
- 4) dealt with civil works for protection (e.g. dams), mitigation procedures and contingency planning (surveillance network, shelters, roads, radio links, etc.) in case of emergency.

1.5.11 STRUCTURAL ASPECTS

1.5.11.1 *Passive and active actions*

Passive protection consists in educating people how to behave in the case of eruption or earthquake, in preparing people to evacuate in advance of a threatening eruption, and in increasing the knowledge of volcanic activity (education programme at school and through workshops) and the awareness of danger.

Active protection consists in designing civil works against the effects of volcanic flows: diverting lava flows (e.g. Etna in 1983), sabo dams filtering lahars, shelters or bunkers against pyroclastic flows, long-lasting, reinforced (steel roof) shelters for protecting people away from the harmful effects of tephra fallout, etc.

1.5.11.2 *Strategies for reducing the effects of volcanic phenomena or damages*

Blong (2000) provides a few strategies and strengthening designs in response to the principal volcanic hazard types (see Table 8).

1.5.12 RESEARCH ACTIVITY AND/OR GUIDELINES

1.5.12.1 *With respect to the state-of-the-art in volcanology*

A better understanding of the eruptive behaviour has been gained through well equipped volcanoes, which have been used as laboratories where surveillance techniques are combined with detailed petrological studies of eruptive products and process modelling (e.g., case study of Montserrat). New petrological and geochemical tools have enabled researchers to better decipher the ascent of magmas within the plumbing system of the volcano and to combine this data with experimental petrology. Statistical (deterministic and stochastic) approach of hazard and risk assessment: quantifying long and short-term volcanic hazard and building up a common strategy (e.g. the probabilistic volcanic hazard assessment PVHA, Marzocchi et al., 2007).

Analogue and numerical modelling: Iverson et al. (1998) automated hazard zone delineation by embedding the predictive equations in a GIS computer program that uses a DEM of topography. The simulation model LAHARZ provides a rapid, automated means of applying predictive equations to regions around edifices and comparing the results with the hazard-zone boundaries established in the field by mapping flow deposits.

Pareschi et al. (2000) used a computer simulation approach to deal with ongoing volcanic hazards controlled by topography, such as lava flows. A maximum slope-statistical approach allows the authors to assign the lava vent and to estimate the zonation of hazards using a map superimposed on a geo-referenced image of Mt Etna and other GIS layers.

Sheridan et al. (2001) have used DEM- and GIS-based computer models for simulating lahars and pyroclastic flows to gauge volcanic hazards at Popocatepetl in Mexico, in addition to a detailed survey of the past eruptive history and a close monitoring of the present activity.

The assessment of physical vulnerability has been undertaken at the scale of a city and city block by using either models of flow impacts on housing and lifelines (e.g. Vesuvius) or in situ geotechnical tests of construction material within and near buildings (Delaite et al., 2005).

Table 7. Elements to be accounted for in vulnerability, risk, and damage assessment (housing, infrastructure, lifelines, people and civil authorities) in case of eruptive crisis.

Vulnerable elements	Description	Meaning
<p>Housing/Land use Residential; educational (primary, secondary, university); commercial (supermarkets, shops); institutional (city hall, district, region); religious sites, cultural and sporting facilities, etc.</p>	<p>Type Construction material; construction quality, number of floors, roof type, wall (principal), doors, windows; number of dwellers; cost of construction.</p>	<p>Role Value with respect to local and regional development; role in district or in city block; role of authorities, as perceived, as exerted; communication network and decision taking process.</p>
<p>Infrastructure Roads (sealed and unsealed), bridges, railway, airport, control points.</p>	<p>Types and tests Material type to be identified (size), mechanical tests: impact strain (uniaxial, punctual, dynamic pressure), yield strength.</p>	<p>Role Value with respect to local material and to mitigation procedures in case of expected or measured damage.</p>
<p>Networks Fluids (gas, electricity, phone, oil), Internet, network of decision making process and chain of command (council, authorities, city hall and region council)</p>	<p>Dysfunctions In case of eruptive or non-eruptive crisis: failure of networks, missing or ill-given orders for evacuation</p>	<p>Factors Physical (e.g. effects of lahars or pyroclastic flows) Technical (dilapidated, defects) Political: failing authorities or failing chain of command</p>
<p>“Natural” areas Gardens and parks Sporting areas (golf, tennis court, fields and running tracks)</p>	<p>Public use Distinct effects according to season, weekdays, day and/or night time</p>	<p>Factors and consequences Temporary or almost permanent occupation, physical abilities of dwellers in case of alert: consequences on injuries and deaths.</p>
<p>People Men, women, children, elderly, social and professional categories.</p>	<p>Characteristics Pattern of spatial distribution, social and economic pattern, age, level of education and culture</p>	<p>Assessment method Survey and interviews for assessing knowledge and perception of risk and level of preparedness and consciousness</p>
<p>Civil authorities National institutions, decentralized state services (actions for mitigation or emergency procedures), territorial and city councils, civil defence bodies</p>	<p>Characteristics Existing tools for management and education: procedures, policies, relief planning, warning dissemination to exposed people, information for mitigation procedures</p>	<p>Assessment methods Social survey and interviews among the decision makers and civil religious authorities, and local leaders.</p>

Table 8. Principal volcanic hazard types.

Volcanic hazard	Risk reduction strategy
Tephra fall	Use steeper roof pitches (>45°), short spans in roof structure, simple roof designs, and roof-sheeting profiles with fluorocarbon polymer coatings noted for corrosion resistance and low frictional resistance; Clean roofs to prevent excessive tephra loads on buildings; Utilize underground electrical supply.
Lava flows	Spray water on advancing lava fronts; Divert lava flows using bombing with guidance systems; Built earth barriers and artificial channels.
Lahars	Drainage of crater lakes; Revegetate unconsolidated tephra; Reconsider bridge clearances; Install crossing gates on roads across lahar channels; Use lahar flow warning systems, retention basins, engineered channels, and land-use planning
Pyroclastic flows	Create refuges in air-tight below-ground cellars; Divert distal flows using earth barriers; Increase awareness on lethal effects of decoupled pyroclastic surges from flows.

Meanwhile the assessment of social and economic factors that make people vulnerable has been undertaken by surveys and interviews in communities living around active volcanoes such as Merapi and Pinatubo or Mayon.

1.5.12.2 *Suggestions for the implementation of design codes and guidelines*

- In situ geotechnical tests for assessing the resilience of housing and bridges to volcanic flows;
- contingency planning and mitigation procedures to be implemented in large cities in the developing world (Indonesia, Andes, Philippines. . .);
- education programs for increasing awareness and improving consciousness among civil authorities of large cities and regional councils in the developing world (e.g. SE Asia, Andean countries).

1.5.13 EXAMPLE OF APPLICATION

1.5.13.1 *A case study: The eruptive crisis of Ubinas volcano, Peru, 2006–2007*

The most recent explosive activity of Ubinas volcano (Rivera et al., 2008) started on 27 March 2006. In response to the volcanic crisis, members of three national Institutions (INGEMMET, IGP, UNSA) as well as the regional Civil Defence offices in Moquegua (RCCDM) and Arequipa formed a joint scientific committee. With foreign help, a preliminary hazard-zone map and a contingency map were produced in early April 2006. The hazard-zone map is based on two eruption scenarios:

- 1) a small eruption similar to the 1990–1998 vulcanian episode of Sabancaya,
- 2) a moderate event such as the AD 1677 scoria-and-ash fall and flow-producing eruption at Ubinas.

Monitoring, consisting of a network of seismometers, EDM, and geochemical survey of thermal springs, has been undertaken by a pool of Institutions on a temporary basis until May 2006 and on a permanent basis ever since.

The scientific committee successfully offered a three-stepped response to the increase in eruptive activity:

- 1) The appearance of an incandescent lava plug in the vent on 20 April prompted the scientific committee to ask RCCDM to evacuate 150 people from the nearest hamlet of Querapi (situated at the foot of the unstable south flank) to the first shelter (village of Anascapa) 8 km away.

- 2) A substantial increase in eruptive activity between 27 April and 2 June led the scientific committee to increase the alert level from yellow to orange and implemented the evacuation plan based on the contingency map. RCCDM further issued the order to evacuate five villages within 12 km of Ubinas. Between 9–11 June 2007, 1000 people were relocated to the second shelter (Chacchagen) 20 km away from the volcano.
- 3) After ~9 months in Chacchagen, the refugees returned to their villages in March 2007, as the population could not cope with less economic resources and a tense situation. The population was also disappointed by the fact that the planned relocation on the remote coast near Moquegua has not been implemented in 2007 (the political decision has not been taken by the government yet). Despite economic and social drawbacks, the challenging crisis of the most active volcano in Peru was the first opportunity for Peruvian institutions to successfully cooperate in, and gain lessons from managing volcanic crises.

1.5.13.2 *Second case study: Physical vulnerability in the city of Arequipa, Peru*

Arequipa (Martelli et al., 2008) is the second largest city in Peru with a population exceeding 860,000. Rapid population growth since the 1940s has resulted in urban growth onto the southwest flank of the volcano, Rio Chili River terraces and adjacent to tributaries within 9 km of El Misti summit. With an expanding city into more hazardous prone areas it is necessary to assess the vulnerability of buildings and infrastructure in response to the threat posed from volcanic mass flows.

Previous studies using Titan2D and LaharZ have attempted the delineation of debris flow inundation zones from El Misti (Delaite et al., 2005). Characteristics such as pending and short run out distances were unrealistic in earlier Titan2D simulations. Four main terraces of the Rio Chili River from Chilina to the Puerte Bolognesi Bridge (approximately 5 km²) were surveyed to obtain detailed topographical data. A DEM was then computed using a DGPS data, aerial photographs and stereophotogrammetry. Lahar volumes ranging from 0.01.10⁶ m³ to 11.10⁶ m³ with solid fractions of 0.3–0.5 were computed. Modelled results are enhanced with a new DEM; however further analysis will need to be undertaken as to whether the simulations are more realistic.

Quantitative descriptions of buildings at building level identified nineteen land-use patterns and ten construction types. Most new construction comprised unreinforced masonry panels (perforated red brick and mortar) with cast-in-situ reinforced concrete frames (horizontal and vertical), and flat or pitched reinforced concrete slab roofs. Large glass windows are throughout with aluminium or wood framing and often secured with steel bars. Doors are solid and wooden with steel security screen/bars. Conversely, Type I construction comprised old stone/ignimbrite base with unreinforced masonry panels (ignimbrite, brick or adobe, with poor quality mortar). The walls are not confined by either reinforced horizontal or vertical cast-in-situ concrete, and in most cases appear unstable. Wooden rafters support corrugated iron roofs, secured with heavy objects such as rocks. Less than 50% of the population surveyed resides in dwellings less than Type C, however, the majority of those are situated in areas that are more hazardous (e.g. Rio Chili lower terraces) areas.

1.5.14 FURTHER DEVELOPMENTS

Identification of further needs for the research and suggestions for possible developments: a geospatial platform for research and training that helps in the decision- and policy-making process (©SUNY at Buffalo, New York: M.F. Sheridan and C. Renschler).

The impact and consequences of extreme geophysical events, like mudflows, on landscape properties and processes can be continuously assessed by a well-coordinated interdisciplinary research and outreach using the Geospatial Project Management Tool (GeoProMT[©]) applied to risk assessment and resilience. Communication between various involved disciplines and stakeholders is a key to the successful implementation of an integrated risk management plan. As the amount of spatiotemporal data representing environmental properties at various scales increases, there is a lag in effective communication among participating disciplines that use this detailed information to predict landscape processes. These issues become apparent at the level of decision support tools for extreme events/disaster management in natural and managed environments. GeoProMT[©] is a collaborative platform for research and training to document and communicate the fundamental steps in transforming information for extreme events at various scales for analysis and management.

GeoProMT[®] is an internet-based interface for the management of shared geo-spatial and multi-temporal information such as measurements, remotely sensed images, and other GIS data. This tool enhances collaborative research activities and the ability to assimilate data from diverse sources by integrating information management. This facilitates a better understanding of natural processes and enhances the integrated assessment of resilience against both the slow and fast onset of hazards and risks. Fundamental to understanding and communicating complex natural processes are:

- a) representation of spatio-temporal variability, extremes, and uncertainty of environmental properties and processes in the digital domain,
- b) transformation of their spatiotemporal representation across scales (e.g., interpolation, aggregation, disaggregation.) during data processing and modelling in the digital domain, and designing and developing tools for:
- c) geo-spatial data management
- d) geo-spatial process modelling and effective implementation, and
- e) supporting decision- and policy-making in natural resources and hazard management at various spatial and temporal scales of interest.

GeoProMT[®] is useful for researchers, practitioners and decision-makers because it provides an integrated environmental system assessment and data management approach that considers the spatial and temporal scales and variability in natural processes. Particularly in the occurrence or onset of extreme events it can utilize the latest data sources that are available at variable scales, combine them with existing information, and update assessment products such as risk and vulnerability assessment maps. Because integrated geo-spatial assessment requires careful consideration of all the steps in utilizing data, modelling and decision-making formats, each step in the sequence must be assessed in terms of how information is being scaled. At the process scale various geophysical models (e.g. TITAN2D, LAHARZ, or many other examples) are appropriate for incorporation in the tool.

Examples that illustrate the application of GeoProMT include:

- 1) Working with geoscientists, public officials, and civil protection authorities to understand and improve the new volcanic hazard map of El Misti Volcano as it presents a threat to Arequipa, Peru;
- 2) Improving and evaluating a new hazard map and mitigation plan for potential mudflows associated with potential future events around La Soufrière of Guadeloupe;
- 3) Developing a plan for monitoring mudflows around Semeru, Java, to calibrate computational models, like TITAN2D and others, for more accurate simulation outcomes. In all three cases, GeoProMT will be used for education, training, and scientific evaluation of data. It will provide an improved new technique for remote transmission of accurate geospatial information between scientists, officials, and responsible authorities in a real-time learning environment.

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