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GIS-aided analysis of the seismic-volcanic risk in the Vesuvius coastal area

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ABSTRACT: In this paper, a study on the damage scenarios due to seismic and volcanic risk in the Vesuvius coastal area is described. It is developed through a multidisciplinary approach based on urban, geological/geotechnical and structural analysis, leading to the definition of an efficient Emergency Plan. The Risk components, i.e. Hazard, Vulnerability and Exposure are evaluated through GIS support, while building clusters defined by Census Tracts were provided by the Italian Institute of Statistics (ISTAT) Census. The processing of the collected data permitted to identify strategies for the reduction of damage and life losses. The study area includes five municipalities located downhill the Somma-Vesuvius volcano, i.e. San Giorgio a Cremano, Portici, Ercolano, Torre del Greco and Torre Annunziata. They are close to each other, identifying a large urban settlement with dense population, which requires a unique strictly interconnected emergency plan.

1 INTRODUCTION

Nowadays in the perspective of urban sustainable development, natural hazards cannot be neglected in the common practice of urban and territorial planning analysis. According to a well-established definition (UNESCO, 1972), Risk (R) encompasses loss of life, injuries, damage to property, disruption of economic activities, due to the occurrence of a harmful event. It is quantified as the product of three factors (1):

$$R = H \times E \times V \tag{1}$$

The Hazard (H) is the probability of observing a phenomenon in time and space; the Exposure (E) identifies the quantity and quality of the elements hit by a damaging event; the Vulnerability (V) is the expression of the resilience of an element or a system of elements. If Hazard is the stressing agent, the Exposure-Vulnerability product represents the environmental man-made effects. The hypothetical zero of the product is obtained when it is possible to cancel at least one of the factors. The step is critical, because it recognizes the relationship between natural and man-made environment. Natural hazards and the associated risks are generated by natural events, such as meteorological or geologic phenomena. This paper deals with the latter and in particular with earthquakes and volcanic eruptions.

2 SEISMIC RISK

In the determination of the Seismic Risk, Hazard (H) defines the maximum magnitude of earthquakes conceivable for a given area in a given time interval. This factor is independent of the presence of artifacts or people, it cannot be modified in any way by human intervention, being exclusively related to the distribution of the seismic sources in a certain area. It can be locally modified due to site conditions based on stratigraphic, topographical and morphological features of the most superficial layers of the soil. The Seismic Vulnerability (V) is the damage sensitivity due to a seismic event of an urbanized system and can be assessed considering a single element (e.g. a building), a series of elements (e.g. an urban aggregate), or a territorial system. This is the factor on which it is possible to intervene for increasing the resilience of the urban system. The Seismic Exposure (E) is a quantity and quality factor of the elements invested by the earthquake, such as people, economic resources, cultural heritage, in the most wide sense of immovable and movable goods and assets that have artistic, historical, archaeological, ethno-anthropological, archival and bibliographic allure and any others having value of civilization (DL 22/01/2004). However it also accounts for social aspects such as dwelling, social development, urban planning, governance, resilience, demography (Jaramillo et al., 2016).

3 VOLCANIC RISK

As regards the Volcanic risk (Narasimhan et al., 2010), vulnerability and exposure can be defined in analogy with the seismic risk. The most difficult element to estimate is the Volcanic Hazard (H), due to uncertainties related to the evaluation of the probability of eruption and to the complexity of the combined phenomena, which characterize the eruption. The most critical event is the explosive eruption, which generates pyroclastic flows, ashfalls, lahars, earthquakes, bombs and missiles ejections (Mazzolani et al., 2009). It is of outmost importance to identify all the areas that would be affected by the eruption and its side-effects also on the basis of the past history of the volcano (Fournier d'Albe, 1979, Neri et al., 2008). The longer the dormant period of a volcano and the fewer eruptions in historical times are recorded, hence it could return active after a period of prolonged rest, finding a territory which is not anymore prepared to deal with a hazard that could suddenly occur (Chester et al., 2001).

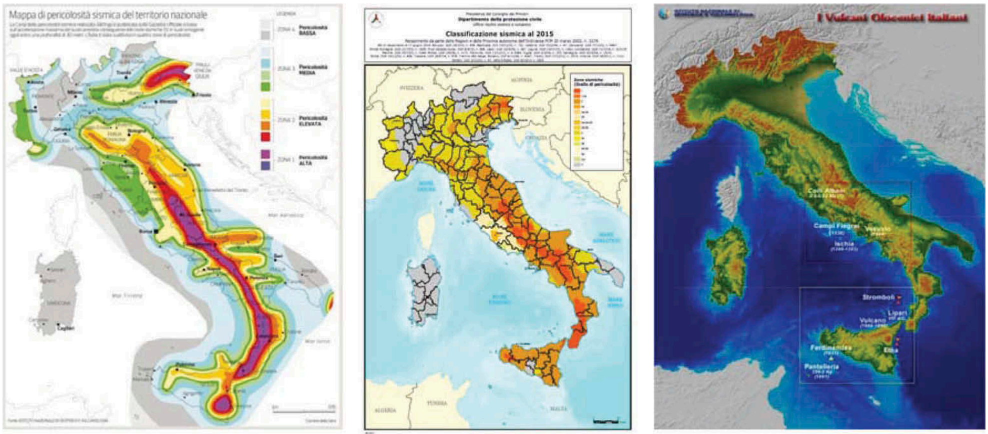
4 THE CASE STUDY OF THE SOMMA-VESUVIUS SYSTEM IN ITALY

Seismic activity in Italy is due to the position it occupies in the Central Mediterranean, which can be simplified as the result of the Africa-Europe plate convergence (Meletti et al., 2000).

If compared to other natural phenomena, earthquakes produce a high incidence of casualties. Only in the last century, earthquakes caused serious economic and social losses with a death toll standing at more than 155.000 and huge sum of money used for the reconstruction. Moreover, 44% of Italian population lives in earthquake-prone areas, where about 60% of buildings is not built in compliance with earthquake standards (Reggio, 2019).

The definition and evolution of the seismic building code in Italy followed the most destructive earthquakes, starting from the first seismic provisions for constructions, namely Casa Baraccata after Campania 1627 earthquake. Afterwards, the first seismic law was issued in 1784, following the destructive Calabria earthquake in 1783 and it was continuously updated after the events of 1908 Reggio Calabria and Messina, 1915 Marsica, 1968 Belice, 1976 Friuli Venezia Giulia, 1980 Irpinia, 1997 Umbria-Marche, 2002 Molise, 2009 L'Aquila, 2012 Emilia Romagna, 2016-2017 Central Italy. As far as the earthquakes occurred, the affected regions were identified as seismic prone zones. As a consequence, the Italian territory was at first subdivided in macro seismic zones according to the seismic hazard (OPCM 3274, 2003), while nowadays a performance-based approach is adopted for the hazard assessment (NTC 2018; Figures 1a, b).

Italy is also characterized by a high volcanic hazard and risk, as the territory around volcanos experienced an intense urban development. Several of those volcanos are inactive (last eruption before 10000 years ago; DPC, 2010), or dormant. In Figure 1c the Italian volcanic map is shown. It highlights that Etna and Stromboli are the only active volcanoes that have erupted in recent years. As pertaining the volcanic area in the neighboring of Naples, three active volcanos are present: i.e. Phlaegrean Fields, Ischia Island and Somma-Vesuvius (more details in Scandone et al., 1991). The Phlaegrean Fields last eruption was in 1538 after a rest of 3000 years, giving rise to Monte Nuovo. Meanwhile, the last eruption of Ischia island was in 1302. For both volcanoes, fumarole and hydrothermal phenomena are still active, which testifies the active state and the possibility of a future explosive eruption.



a) b) c)

Figure 1. Italy Seismic hazard (a, INGV) and classification maps (b, DPC), Holocene volcanos (c, INGV).

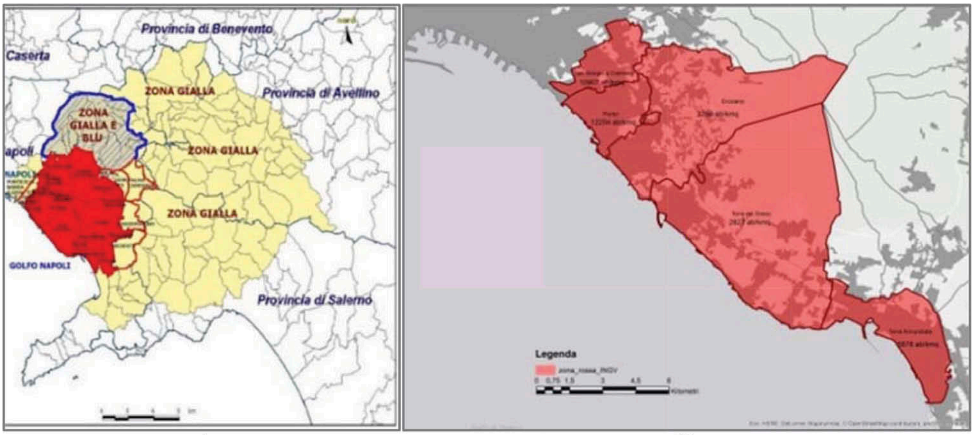
The Somma-Vesuvius is a strato volcano, with a maximum height of 1281m: Somma Mt. is the oldest volcano, Vesuvius is in a rest phase since 1944, after a long period of intense and frequent eruptive activity starting with the eruption of 1631. Eruptions are generally explosive or in few cases mixed explosive-effusive. It is known worldwide mainly for the eruption dated 79 A.D., which interrupted a rest of 7 centuries, destroying the roman towns of Pompeii, Ercolano, Oplontis and Stabiae. Modest fumarole and earthquakes with 6 km ipocentre are observed. At the present state of knowledge, it is not possible to establish, even roughly, the probable duration of the current rest.

Considering that the vent is obstructed, the probability that the next eruption may have the characteristics of one of the typical open-conduct activity, generally dominated by lava flows, is very low. It has to be considered that the danger of lava flows is much lower than the explosive eruptions. Due to the increase in viscosity produced by cooling during the flowing, the lava has, in fact, a slow-moving speed. Even though it can cause considerable economic damage, it hardly ever represents a danger for people. For these reasons, the analysis of eruptive scenarios to be used for the update of the Emergency Plan drafted by Campania Region is only focused on the explosive eruptions of Vesuvius (DPC, 2010). The reference eruption is a sub-plinian event, having a fairly high probability of occurrence and characterized by a Volcanic Explosivity Index, VEI = 4. It is represented by a volume of 10^8 m^3 of extruded materials (tephra), with an eruptive column between 500m to 2km height.

The above considerations highlight the Campania Region, (South Italy), as one of the most critical territory for natural hazards, which might cause large economic and life losses (Zuccaro et al., 2013; Frigerio and De Amicis, 2016). The overall area is inhabited by about three million people with a high population density. In this context, Emergency planning has an important role for preparing the community to respond and recover from disaster (Spence et al., 2004, Ohgai et al., 2014).

The Vesuvius Emergency Plan classifies the neighboring territory into three areas, which partially overlap (DPC, 2010): Red Zone - area exposed to pyroclastic flows, Yellow Zone - pyroclastic depletion area, Blue Zone - area exposed to flood and mud flows. The Red Zone is the area where preventive evacuation is the only measure to safeguard population. It is split in two subzones: the Red Zone 1, already identified in the Emergency Plan drafted in 2001, mainly exposed to pyroclastic flows, and the Red Zone 2, introduced in 2013, that is subjected to high risk of roof collapse for the deposition of pyroclastic falls (yellow area enclosed in the red line in Figure 2a). The Yellow Zone is the area exposed to the significant fall of volcanic ash and pyroclastic materials. The Blue Zone, falling within the Yellow Zone, is additionally subjected to lahars and floods.

This study focuses on the definition of seismic and volcanic impact scenarios in the Vesuvius coastal area with the purpose to draft earthquakes and volcanic risk maps, develop damage



a) b)

Figure 2. a) Volcanic hazard zones (DPC); b) Study Area.

scenarios and understand where planning meets the gap between the ideal pattern and the real one. In particular, five municipalities within the Red Zone (Figure 2b) were examined, i.e. San Giorgio a Cremano, Portici, Ercolano, Torre del Greco and Torre Annunziata. They are highly homogeneous since they are all placed in the area between Vesuvius and the coastline, being seamlessly contiguous. Thus they realize altogether a unique urban settlement, characterized by high population and building density.

5 METHODOLOGY

The adopted approach is carried out in GIS (Geographic Information System) environment, being the software designed to store, retrieve, manage, display and analyze all types of geographic and spatial data. In particular, the examined elements characterizing Hazard, Vulnerability and Exposure are associated to each unit of analysis, corresponding to a Census Tract, using the data collected by Italian Institute of Statistics (ISTAT) during Population Census in 2011 (Frigerio et al., 2016). For each Census section, the related Hazard, Vulnerability and Exposure are assessed, as well as finally the Seismic and Volcanic risks. The study was carried out on 814 Census sections.

Based on the guidelines provided by the Italian Civil Protection Department (DCP, 2010), the adopted methodology was developed according to the following issues:

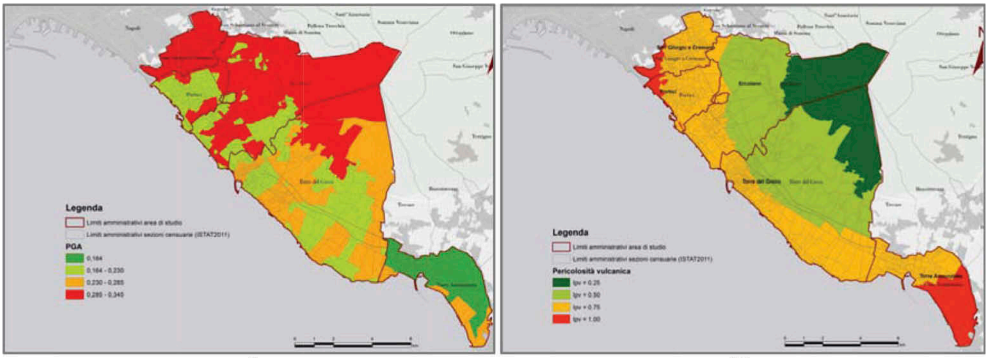
a. definition of Hazard Maps;
b. definition of the Exposure Map;
c. definition of the Vulnerability Map;
d. drafting of the Risk Maps;

Exposure and Vulnerability are represented by single map respectively, while two Hazard and Risk maps are prepared for both seismic and volcanic events.

6 SEISMIC AND VOLCANIC HAZARD EVALUATION

The seismic hazard was assessed on the basis of the Peak Ground Acceleration (PGA), defined by the following product (2):

$$PGA = a_g \times S_s \times S_t \tag{2}$$



a) b)

Figure 3. a) Seismic and b) Volcanic Hazard Maps.

where a_g is the seismic acceleration on bedrock, S_s is the stratigraphic amplification factor, S_t is the topographic amplification factor.

The a_g is defined as the peak acceleration on rock ground with a probability of exceedance equal to 10% in 50 years. With reference to the regional seismic zoning, the study area is classified in second-class hazard ($0{,}15 < a_g < 0{,}25$), according to the first level Microzonation (Silvestri et al., 2016). The area is characterized by three different geologic formations: 1) clay, sands and gravels; 2) lava and pyroclastic deposits; 3) pyroclastic deposits, ignimbrite and tuff. To each of them, the value of a_g with 475 years return period (T_r) was assigned together with the soil class and the Amplification factor (S_s), following the Italian Building Code (NTC, 2018). Through a GIS spatial query the above mentioned data were attributed to each Census Tract. The topographic amplification factor (S_t) is related to the ground slope according to NTC2018. The mean slope value, expressed in degree, of each Census Tract, was derived by processing the Digital Terrain Model (DTM) provided by Campania Region. S_t values are in the range 0.164 to 0.345, which is divided in 4 equal intervals, which weights from 1 to 4 are assigned to. They cover the hazard classes P1, P2, P3, P4 respectively (Figure 3a). Landslides do not affect the seismic hazard, in fact they involve just the crater surface, according to the Inventory of Italian Landslides (IFFI Project, Trigila et al., 2018).

The assessment of Volcanic Hazard is more complex, considering that the eruption is a combination of several phenomena. It was assumed homogeneous as all the five municipalities fall in the Red Zone. The following volcanic vulnerability criteria are accounted for: local volcanic seismic hazard, distribution of ash falls according to the isopachs and distance from the crater for lava and pyroclastic flows. In particular regarding the seismic hazard associated with the volcanic phenomenon, the maximum magnitude expected is 5.5 (DPC, 2010). Considering the very superficial hypocenter and the proximity of the study area to the volcanic-seismic source, the seismic volcanic hazard can be considered homogeneous. Therefore a volcanic seismic hazard Index equal to 1 is assigned to all the Census sections. As regards the Ash Fall, for the Census sections included within the isopachs, the Ash Fall Hazard Index is assigned as equal to 1, while for the Census sections excluded from the isopaches no value is assigned. For the evaluation of the distance from the crater, in GIS support, the distance between the Census section and the crater centers is measured in the range of 885 to 10700 m. In order to consider the exponential growth of lava hazards and pyroclastic flows with the reduction of the Census section distance from the crater, the distance range is divided in 4 equal intervals, which weights from 0.25 to 1 are assigned to. Definitely the volcanic hazard is defined for every census section by the product of the three hazard indexes defined above.

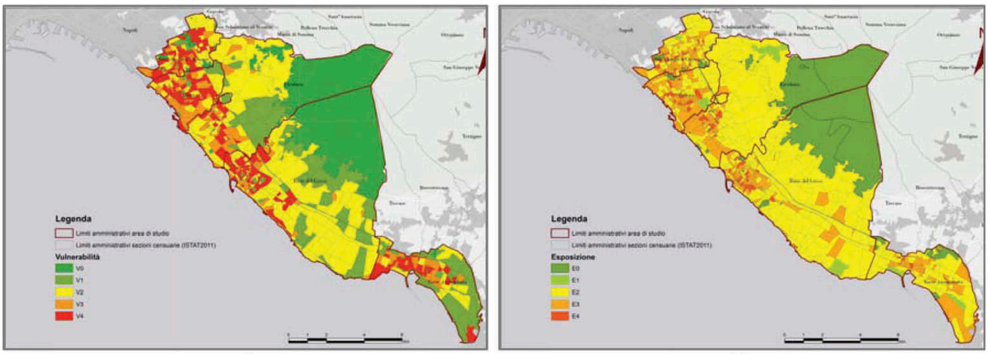
In Figure 3, the results of the final seismic (Figure 3a) and volcanic hazard (Figure 3b) maps is shown.

7 VULNERABILITY EVALUATION

The evaluation of the Vulnerability of constructions at territorial scale requires a comprehensive building register, including all the vulnerability elements of constructions for both the seismic and the volcanic cases, which is not available. Nevertheless, the ISTAT 2011 Census provides few features, which have been used in the current GIS aided evaluation procedure. In particular, the following data for each Census Tract have been processed: type of construction (reinforced concrete, masonry), number of floors (1 to 4 or more) and age of construction by time intervals (before 1919 up to after 2005). With regards to the age, by referring to the evolution of the standard rules for constructions, the following periods are considered: before 1945, [1946-1960], [1961-1980], after1980 (Zuccaro et al., 2012; Faggiano et al., 2015). Each census section has been characterized with reference to the prevalent category for every three previous vulnerability criteria. Where different categories have the same percentage of distribution in the section, the most unfavorable category has been assigned, such as the higher floor number and the oldest age. The combination of the vulnerability criteria for each Census section is obtained through a multi-criteria decision method, already applied for the seismic-volcanic vulnerability assessment of buildings (Mazzolani et al., 2008, 2009a; Faggiano et al., 2011, 2014; Anbazhagan et al., 2012). Therefore each criteria has been identified by an index from 1 to 4; a matrix of binary comparison between the criteria is defined through the Topsis method, where dominance intensity is evaluated from 1 to 9 assuming a vulnerability criteria rank, such as age, typology, number of floors; then the weights of each criteria have been determined. Definitely for each census section the criteria index is multiplied for the corresponding weight, obtaining in all a range of values from 0 to 3.8. This has been subdivided in four intervals that, including the 0, are associated to 5 vulnerability indexes (V0 to V4). The resulting Vulnerability Map obtained is shown in Figure 4a.

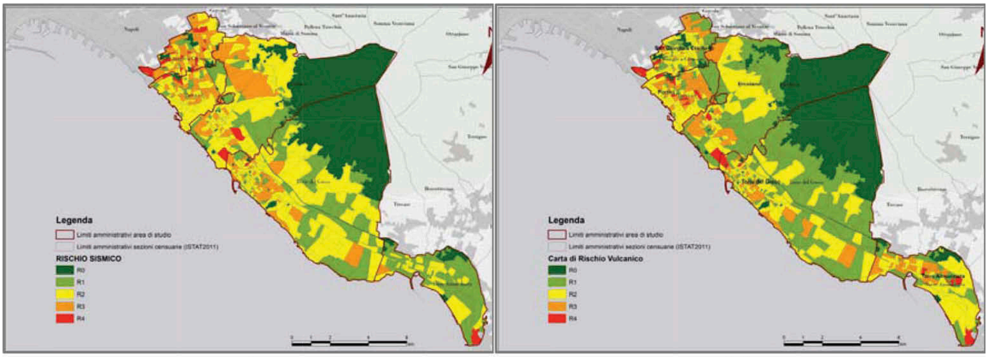
8 EXPOSURE EVALUATION

Exposure depends on the quality and quantity of the goods that undergo the harmful event. In this work, three Exposure Criteria have been identified: population density, area of cultural buildings and area of economic resources. Each criterion was evaluated for each Census Tract. For each criterion five indexes, from 0 to 1, are defined related to the 5 ranges of Population density (from 0 to 157.300), as well as of the percentage of surface occupied by cultural buildings and economic resources within the Census Tract (from 0 to 1). Exposure cannot be the arithmetic mean among the various factors, as living population safety is much more important than economic resources and cultural buildings one. Since, during an emergency phase, population has to be immediately rescued, while cultural and economic resources should be secured later



a) b)

Figure 4. Vulnerability a) and Exposure b) Maps.



a) b)

Figure 5. Seismic a) and Volcanic b) Risk Maps

on, different weights were assigned to Exposure criteria: w_1=0.7 to population, identical weights, w_2= w_3=0.15, to cultural buildings and economic resources (Jaramillo et al., 2016). Multiplying index per weights for the respective criteria, an estimation of exposure is achieved and shown in the Exposure Map, discretized in five classes (Figure 4b).

9 THE SEISMIC AND VOLCANIC RISK MAPS

According to the definition of risk reported in Eq. (1), for each census section by multiplying hazard, vulnerability and exposure indexes with reference to both seismic and volcanic eruption events, the seismic and volcanic risk maps are obtained. They are shown in Figure 5.

10 CONCLUSIVE REMARKS AND FURTHER DEVELOPMENT

Risk depends on multiple causes ranging from the geology and morphology of the territory, to the functions it hosts, to goods, cultural heritages and real estates value and state of conservation, to the degree of urbanization and population density. Given the complex multidisciplinarity of this topic, risk analysis cannot be solved adopting a sectorial approach belonging to a specific technical-scientific field, but it requires the integration of combined knowledge and skills to achieve a more resilient territory.

Based on these observations, the paper showed the seismic volcanic risks on a territorial scale, with regards to the Vesuvius coastal area, in an integrated approach, taking into account geological/geotechnical, structural and urban aspects. The combination of the seismic and volcanic hazards in the same area give rise to an even more challenging case study. The analysis is carried out through the GIS and it was based on ISTAT Census 2011. This is a very efficient tool for carrying out a screening of the investigated area, considering that the territory is divided in census sections characterized according to any type of features. The study has allowed to develop for the selected Vesuvius coastal area eithr hazard, vulnerability or exposure maps, which permitted to obtain risk maps for both seismic and volcanic events. The subsequent step has been the definition of the damage scenarios in the same area ensuing the seismic and the volcanic events, developed through GIS tool, mapping the extent of collapsing buildings, damaged buildings, probable number of people involved in the collapse and homeless. Final purpose has been the integrated urban planning for the appropriate management of the risk, based on the urban territorial diagnosis. This has led to the design of blue green infrastructures, aiming at reducing the risk, valorizing the territory (emergency-off) and optimizing the emergency-on procedures.

The methodology implemented is tremendously powerful. It requires to be improved primarily for data quality, since the ISTAT census data are not dissociable and therefore do not allow an analysis of all phenomenologies and features. To achieve this goal, it is necessary to carry out a capillary in situ campaign for the characterization of the census tracts in the seismic and volcanic hazard zones, in order to obtain holistic outputs. The methodology should be adopted for the entire Red Zone.

REFERENCES

Anbazhagan P., Thingbaijam K. K. S., Nath S. K., Narendana Kumar J. N., Sitharam T. G. 2010. Multi-Criteria seismic hazard evaluation for Bangalore city, India. *Asian Earth Sciences* 38: 186–198.

Chester D.K., Degg M., Duncan A.M., Guest J.E. 2001. The increasing exposure of cities to the effects of volcanic eruptions: a global survey. *Environmental Hazards* 2: 89–103.

DL 22/01/2004. Codice dei beni culturali e del paesaggio. Legislative Decree n.42. Law 6/07/2002 n.137, art. 10.

DPC 2010. Scenari eruttivi e livelli di allerta per il Vesuvio. Department of Civil Protection.

Faggiano B., Formisano A., Mazzolani F. M. 2015. Robustness of the Vesuvian roofs under the combined overload and high temperatures due to air fall. *Structural Fire Engineering* 6: 213–221.

Faggiano B., Formisano A., De Gregorio D., De Lucia T., Mazzolani F. M. 2011. A quick level methodology for the volcanic vulnerability assessment of buildings. *Applied Mechanics and Materials* 82: 639–644.

Faggiano B., Formisano A., De Gregorio D., De Lucia T., Mazzolani F. M. 2012. The structural behaviour assessment of Golden Miles Vesuvian villas through a seismic-volcanic quick procedure. *Wiadomości Konserwatorskie*, 807–815.

Fournier d'Albe, E. M. 1979. Objectives of volcanic monitoring and prediction, *Geological Society of London* 136: 321–326.

Frigerio I., De Amicis M. 2016. Mapping social vulnerability to natural hazard in Italy: A suitable tool for risk mitigation strategies. *Environmental Science & Policy* 63: 187–196.

Frigerio I., Ventura S., Strigario D., Mattavelli M., De Amicis M., Mugnano S., Boffi M. 2016. A GIS-based approach to identify the spatial variability of social vulnerability to seismic hazard in Italy. *Applied Geography* 74: 12–22.

Jaramillo N., Carreno M., Lantada N. 2016. Evaluation of social context integrated into the study of seismic risk for urban areas. *International Journal of Disaster Risk Reduction* 17: 185–198.

Mazzolani F.M., Faggiano B., De Gregorio D. 2009. The catastrophic scenario in explosive volcanic eruptions in urban areas. In: F.M. Mazzolani (ed), *Protection of Historical Buildings* 2: 1529–1534, Roma, 21-24 Giugno 2009, London: CRC Press.

Meletti C., Patacca E., Scandone P. 2000. Construction of a Seismotectonic Model: The Case of Italy. *Pure and Applied Geophysics* 157: 11–35.

Narasimhan H., Borg R.P., Cacace F., Zuccaro G., Faber M.H., De Gregorio D., Faggiano B., Formisano A., Mazzolani F.M., Indirli M. 2010. A framework and guidelines for volcanic risk assessment. In: F.M. Mazzolani (ed), *Urban habitat construction under catastrophic events. COST C26 Final Conference, Napoli, 16-18 September 2010*, 699–710, London: CRC Press.

Neri A., W.P. Aspinall, R. Cioni, A. Bertagnini, P.J. Baxter, G. Zuccaro, D. Andronico, S. Barsotti, P.D. Cole, T. Esposti Ongaro, T.K. Hincks, G. Macedonio, P. Papale, M. Rosi, R. Santacroce, G. Woo, 2008. Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. Volcanology and Geothermal Research 178 (3): 397–415.

NTC 2018. Aggiornamento delle Norme Tecniche per le Costruzioni. Italian Ministerial Decree 17/01/2018.

Ohgai A., Yamamoto T. 2014. Evaluating emergency response activities during Earthquakes in local cities of Japan. *International review for spatial planning and sustainable development* 2 (1): 4–22.

OPCM 3274 2003 and following versions. Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica. Ordinanza del Presidente del Consiglio dei Ministri Italiano.

Reggio P. 2019. La dimensione del rischio sismico in Italia. CRESME.

Scandone R., Bellucci F., Lirer L., Rolandi G. 1991. The structure of the Campanian Plain and the activity of the Neapolitan volcanoes (Italy). *Volcanology and Geothermal Research* 48: 1–2, 1-31.

Silvestri F., Forte G., Calvello M. 2016. Multi-level approach for zonation of seismic slope stability: Experiences and perspectives in Italy. Landslides and Engineered Slopes. Experience, Theory and Practice. Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-1-138-02988-0.

Spence, R., Zuccaro, G., Petrazzouli, S., Baxter, P. 2004. The resistance of buildings to pyroclastic flows: analytical and experimental studies and their application to Vesuvius. *Natural Hazards Review*, 5 (1): 48–59, ASCE.

Trigila A., Iadanza C., Bussettini M., Lastoria B. 2018. Dissesto Idrogeologico in Italia: pericolosità e indicatori di rischio. Rapporti 287/2018. ISPRA – Istituto Superiore per la protezione e la ricerca ambientale.

UNESCO 1972. Report of consultative meeting of experts on statistical study of natural hazards and their consequences, Doc. SC/WS/500, Paris.

Zuccaro G., Cacace F., De Gregorio D. 2012. Buildings inventory for seismic vulnerability assessment on the basis of Census data at national and regional scale. *The 15th World Conference on Earthquake Engineering WCEE, Lisboa (Portugal)*.

Zuccaro G., Federico Leone M., Del Cogliano D., Sgroi A. 2013. Economic impact of explosive volcanic eruptions: A simulation-based assessment model applied to Campania region volcanoes. *Volcanology and geothermal research* 266: 1–15.