Urban seismic risk assessment using the Disruption Index: the case of the volcanic region of Mt. Etna (Italy)

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SUMMARY
This paper presents the ongoing activities for the assessment of the urban seismic risk at Mt. Etna volcano using the “Disruption Index” approach. We use updated information on the historic main seismicity, seismogenic faults and intensity attenuation that in a recent research project produced probabilistic seismic hazard maps and scenarios expressed in terms of macroseismic intensity. To apply the Disruption Index at Etna, we consider a probabilistic approach for seismic hazard evaluation based jointly on macroseismic fields and fault parameters. For information on the urban scale vulnerability, we use a GIS to organise data relating to buildings and network systems (e.g. typologies, schools, strategic structures, lifelines) related to the municipalities more exposed to seismic risk. The convolution of ground motion and vulnerability/ impact is based on a Monte Carlo simulation. We present here some preliminary results on the identification of nodes that are responsible for major disruption in urban systems.

Keywords: Probabilistic hazard and damage scenarios, Disruption Index, urban system, Mt. Etna, Italy

1. INTRODUCTION

Natural disasters, such as earthquakes and volcanoes, have strong effects on the socio-economic well-being of countries and their people. The consequences of these events can lead to complex cascades of related incidents; when these expand across sectors and borders, and in more serious contexts, they can threaten our basic survivability. These events have clearly demonstrated that preparedness and disaster management is a dynamic process that requires a holistic analysis of critical interdependencies among core infrastructures.

In this context of complexity, uncertainty and doubt, the proposed Disruption Index (DI) aims to improve our understanding of earthquake and volcano hazards and their impacts. Several guiding principles and methods have been developed to serve as the basis to measure the different earthquake impacts, with analysis and discussion of the data that provide clearer pictures of how the systems and the disruption of their functionality affect an urban area. The main concepts that explain the DI can be found in Oliveira et al. (2012), with application to the Azores Islands. Further details are given in an accompany paper “DI: The concept of the Disruption Index in urban systems” (Mota de Sá et al. (2012).

2. THE CASE OF THE VOLCANIC REGION OF MT. ETNA

2.1 The Seismic Input on the Studied Area

Mt. Etna is situated in a highly seismic region that has experienced many large earthquakes in the past. In addition to regional events ($6.6 \le M_W \le 7.4$) that have occurred in the Messina Straits and Hyblean foreland (Meletti et al., 2008), the volcanic district of Mt. Etna is affected by very frequent and less energetic local seismicity that is located mainly on its eastern flank (Azzaro, 2004) (Fig. 1).

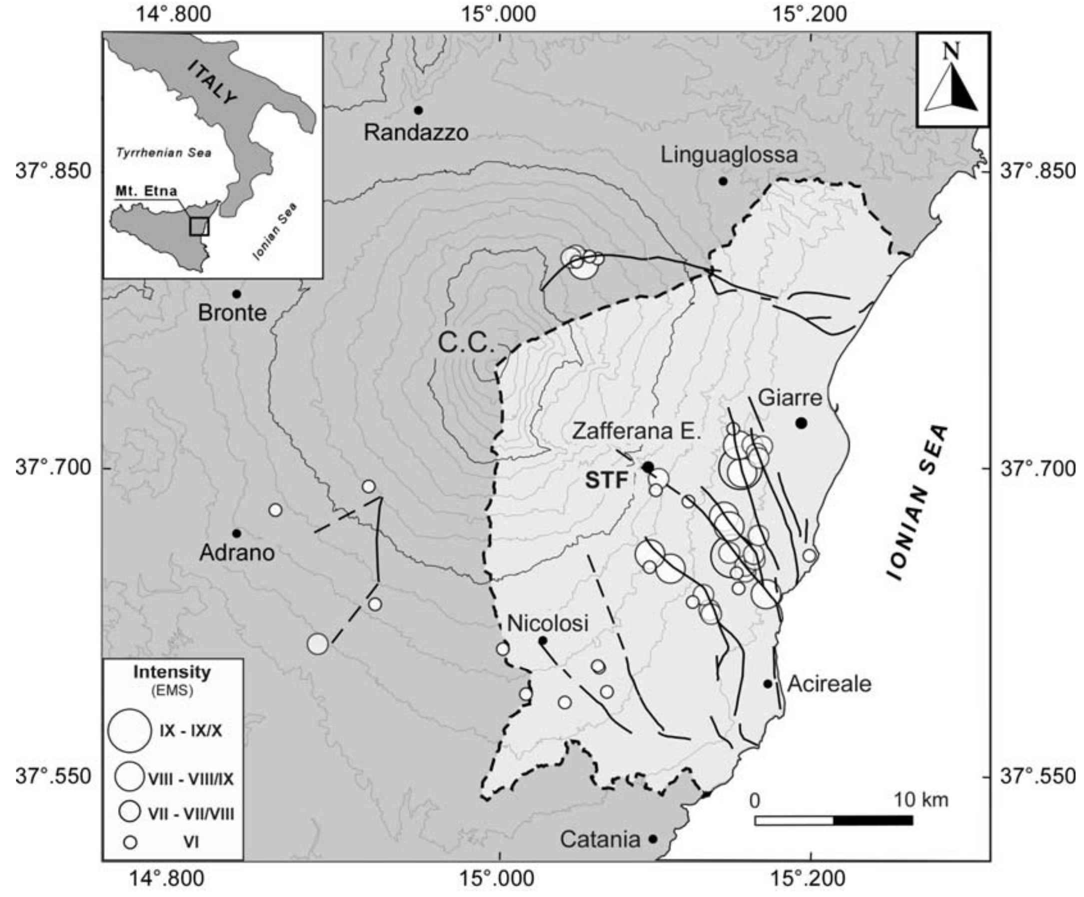


Figure 1. Distribution of the main seismicity (epicentral intensity $I_0 \geq$ VI EMS) in the Mt. Etna region from 1832 to 2010 (data from CMTE Working Group, 2008); the pattern of the active faults is also shown; the light grey area indicates the region investigated with the Disruption Index; STF: the Santa Tecla Fault.

Like other volcanic zones worldwide, for Mt. Etna the earthquakes are characterised by moderate magnitudes ($M_L \leq 5.1$; according to Azzaro et al. 2011a) and shallowness of foci (0.5-2.0 km; Patanè and Giampiccolo, 2004). This implies that these shocks can cause severe damage or even destruction - maximum epicentral intensities have been estimated at up to I_0 IX-X EMS (Azzaro et al., 2000; CMTE Working Group, 2008) - although in small areas that are typically narrow zones up to 5 km long and 1 km wide and are positioned astride the seismogenic source. Most of these events are also associated with coseismic surface faulting, which produces further damage to the cultural features located on the dislocation lines (Azzaro, 1999).

The Timpe tectonic system on the eastern flank of Mt. Etna volcano is the source area that is responsible for most of the largest earthquakes known to have occurred at Mt. Etna over the last few centuries. In the last 180 years, on average, earthquakes that have produced severe damage or partial collapse (VIII $\leq I_0 \leq$ IX-X EMS; Grünthal, 1998) have occurred every 20 years, while minor events that have caused slight damage (I_0 = VI EMS) have hit the volcano once each year. The highest values, up to degree IX EMS, have been concentrated in the very populated areas between Acireale, Zafferana and Giarre - the main towns on the eastern flank - while the Piedmont parts of the volcano and the metropolitan area of Catania have not been affected by significant macroseismic effects.

Another feature of this volcano seismicity is that the attenuation of the macroseismic intensity with distance is much higher than in tectonic zones. Azzaro et al. (2006) derived specific regression relationships for the intensity attenuation in the Italian volcanic districts, which demonstrated for Etna an intensity decay ΔI (the difference between epicentral intensity I_0 and intensity I_s documented at the site S) of 4 degrees in 20 km of distance from the epicentre. Moreover, Azzaro et al. (2006) also indicated the role of a linear source in the attenuation pattern, which determines a preferential propagation of the intensity along the fault strike and a rapid decrease in the effects in the perpendicular direction. Modelling of the attenuation at Mt. Etna has also been tackled through a Bayesian probabilistic approach, which aims to obtain seismic scenarios that are expressed in terms of the macroseismic intensity (Azzaro et al., 2011b). The entire calculation procedure is implemented in the software PROSCEN, and given the location and the epicentral intensity (and eventually the fault parameters) of the earthquake to be simulated, this generates the expected seismic scenario according to a point seismic source or a linear source (finite fault). The results can be plotted on grid maps that represent: (i) the probability of exceeding a fixed intensity (Fig. 2, top line); and (ii) the intensity that can be exceeded with a fixed probability (Fig. 2, bottom line).

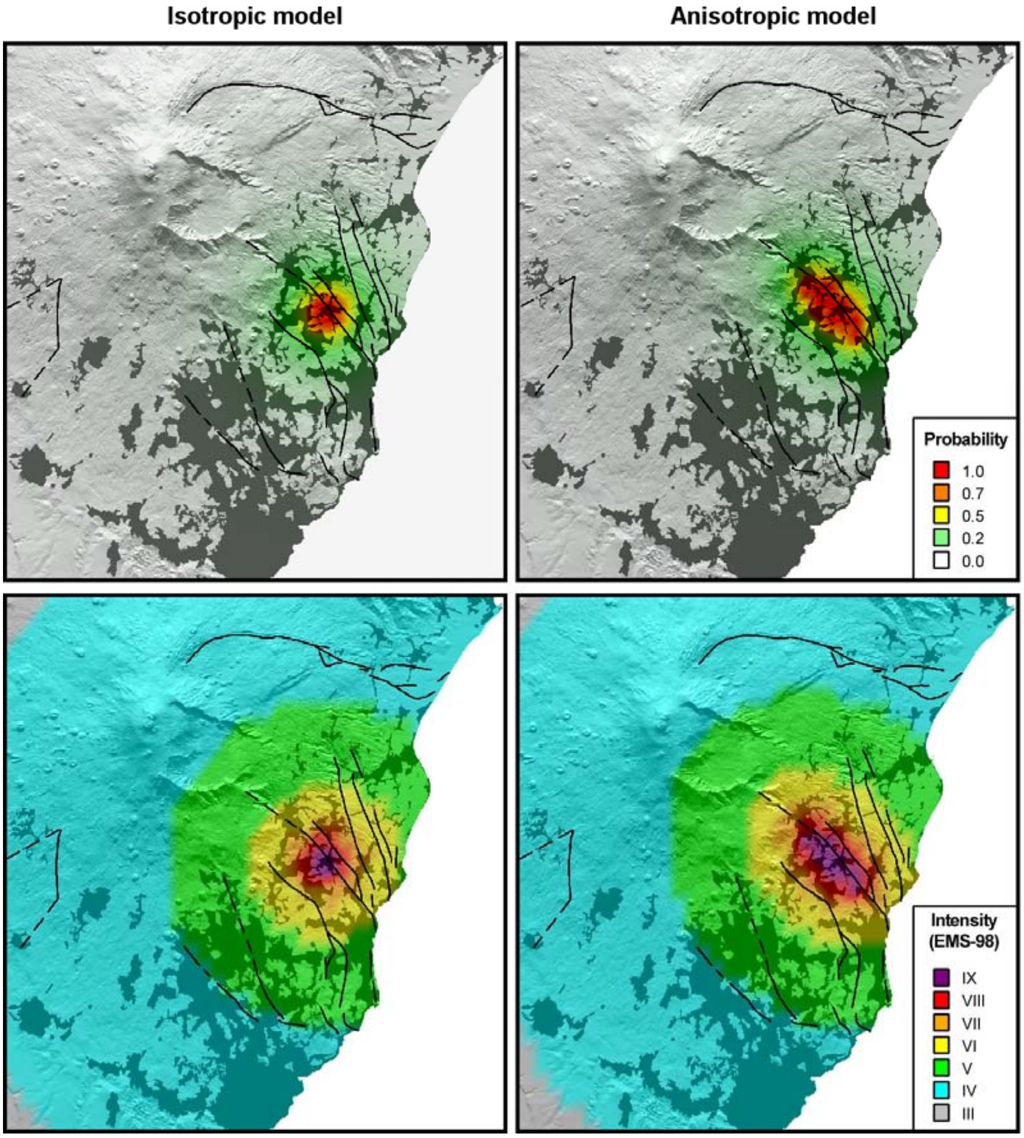
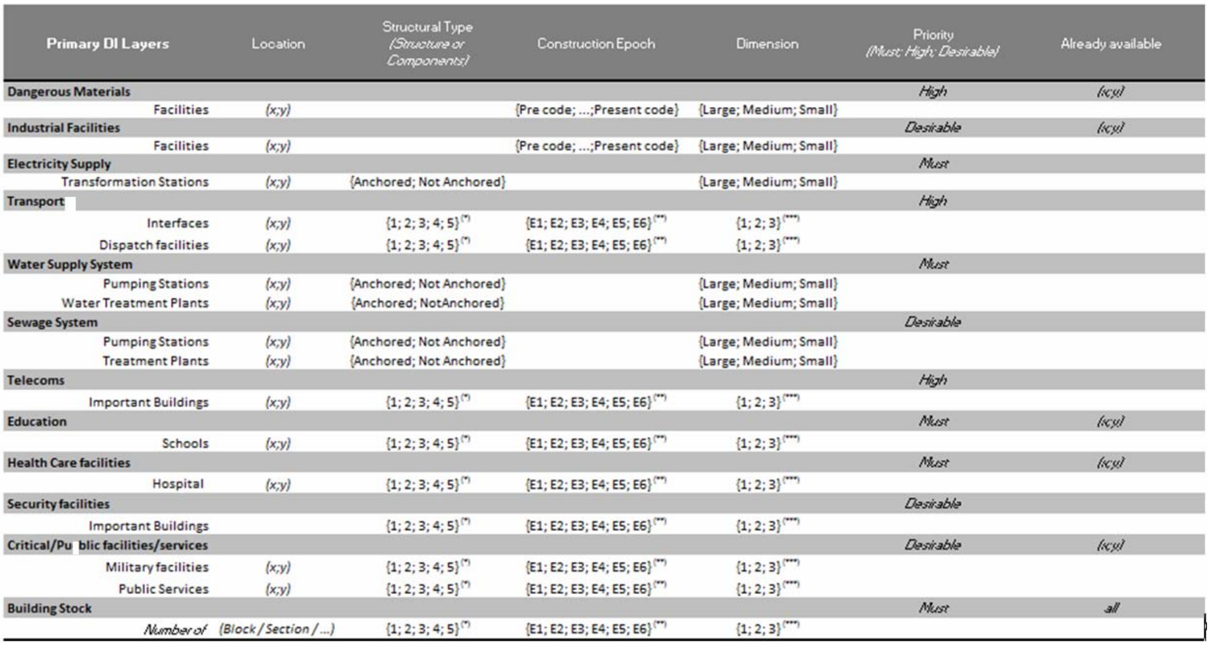


Figure 2. Seismic scenario for an earthquake with epicentral intensity I_0 = IX EMS located on the eastern flank of Mt. Etna, along the S. Tecla fault, simulated according to a point-source model (isotropic, left column) versus a linear finite fault (anisotropic model, right column). The maps show scenarios as (i) the probability for the site intensity VII EMS; and (ii) the expected intensity taken from the mode of the distribution of the probability.

2.2 Territorial Data and Data Collection

Constructing the DI requires good quality information about the physical, spatial and vulnerability conditions of the study area; this means the information that reflects the full knowledge of the true situation. The data that are required to perform a complete application of the DI are given in Table 2.1.

Table 2.1 Theoretical data needed to perform a complete application of the Disruption Index.



Primary DI Layers	Location	Structural Type *(Structure or Components)*	Construction Epoch	Dimension	Priority *(Must; High; Desirable)*	Already available
Dangerous Materials					*High*	*(x;y)*
Facilities	*(x;y)*		{Pre code; ...;Present code}	{Large; Medium; Small}		
Industrial Facilities					*Desirable*	*(x;y)*
Facilities	*(x;y)*		{Pre code; ...;Present code}	{Large; Medium; Small}		
Electricity Supply					*Must*	
Transformation Stations	*(x;y)*	{Anchored; Not Anchored}		{Large; Medium; Small}		
Transport					*High*	
Interfaces	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Dispatch facilities	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Water Supply System					*Must*	
Pumping Stations	*(x;y)*	{Anchored; Not Anchored}		{Large; Medium; Small}		
Water Treatment Plants	*(x;y)*	{Anchored; NotAnchored}		{Large; Medium; Small}		
Sewage System					*Desirable*	
Pumping Stations	*(x;y)*	{Anchored; Not Anchored}		{Large; Medium; Small}		
Treatment Plants	*(x;y)*	{Anchored; Not Anchored}		{Large; Medium; Small}		
Telecoms					*High*	
Important Buildings	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Education					*Must*	*(x;y)*
Schools	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Health Care facilities					*Must*	*(x;y)*
Hospital	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Security facilities					*Desirable*	
Important Buildings		{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Critical/Public facilities/services					*Desirable*	*(x;y)*
Military facilities	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Public Services	*(x;y)*	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		
Building Stock					*Must*	*all*
Number of	(Block / Section / ...)	{1; 2; 3; 4; 5}(*)	{E1; E2; E3; E4; E5; E6}(**)	{1; 2; 3}(***)		

Mt. Etna volcano is a high urbanised area, where many villages are located all around the volcano at different altitudes up to 700 m a.s.l. In particular, the southern and eastern flanks are the most populated areas, where villages are very close to each other. Moreover, there is a dense network of roads, power lines and methane pipelines that connects the villages, roads and railways along the coast.

Using a Geographic Information System (GIS), we have stored a huge quantity of data (Table 2.2) that was collected by the local Civil Defence Protection as part of socially useful work (*Lavori Socialmente Utili*; LSU), to compute the risk maps for Mt. Etna in recent years.

Table 2.2 Available data that is useful for the analysis of the Disruption Index for the Mt Etna area.

Available DI layers	**Structural typology**	**Epoch of construction**	**Dimension**
Dangerous materials		< 1919; 1919-1945; 1946 -1960; 1961-1971; 1972-1981; > 1981	Large, medium, small
Industrial facilities		< 1919; 1919- 1945; 1946 -1960; 1961-1971; 1972-1981; > 1981	Large, medium, small
Telecoms (buildings)	1, 2, 3, 4	< 1919; 1919-1945; 1946 - 1960; 1961-1971; 1972-1981; > 1981	
Education (schools)	1, 2, 3, 4	< 1919; 1919-1945; 1946 - 1960; 1961-1971; 1972-1981; > 1981	
Health care facilities (hospitals)	1, 2, 3, 4	< 1919; 1919-1945; 1946 - 1960; 1961-1971; 1972-1981; > 1981	
Security facilities (buildings)	1, 2, 3, 4	< 1919; 1919- 1945; 1946 - 1960; 1961-1971; 1972-1981; > 1981	
Housing (building stock)	1, 2, 3, 4	< 1919; 1919- 1945; 1946 - 1960; 1961-1971; 1972-1981; > 1981	

A part of the data that includes the electricity systems (e.g. transformation stations), transport (e.g. bridges, roads, tunnels), the water supply systems (e.g. pumping stations, water treatment plants) and the sewage systems (e.g. pumping stations, treatment plants) are not included in Table 2.2 because the relevant information is still missing at this stage. Many other variables could be included if we considered a more complex model. For the sites where the information about the seismic vulnerability is not available, we have estimated here the vulnerability from other information, such as the age, material and size of the object.

2.2.1 Buildings and population

Data about buildings (Fig. 3) were extracted from the 1991 and 2001 ISTAT Italian census. The data are grouped according to the census sections, and the vulnerability indices are evaluated using the approach proposed by Giovinazzi (2001). The ISTAT data on residential buildings allows the definition of the frequencies of groups of homogenous structures with respect to a number of typological parameters: vertical structures, age of construction, number of storeys, state of maintenance, and state of aggregation with adjacent buildings. We have applied this information only to the urbanised area of the whole of the Municipality territory. Moreover, using the LSU database (Cherubini, 1999) for the vulnerability survey of public buildings of southern Italian regions, further data were extracted for the main health facilities (hospitals), schools, municipal offices, and military stations. For the schools, we also obtained individual positions and vulnerability data from forms collected during the 1996-2001 LSU project of the Civil Defence Protection.

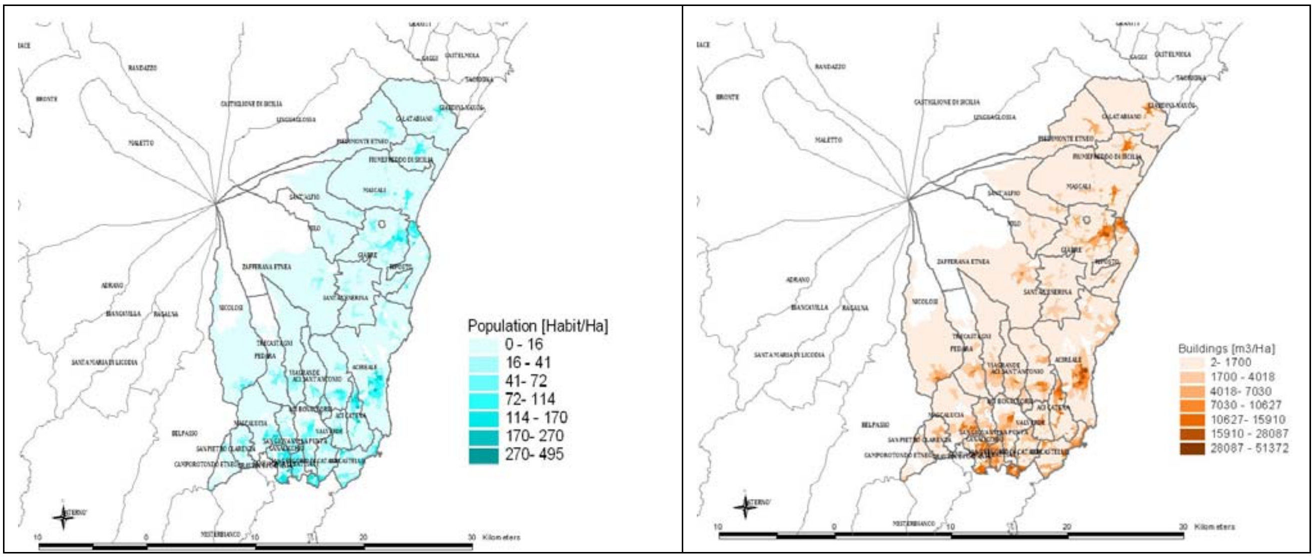


Figure 3. Overview of the population and building stock

2.2.2 Lifelines

We have taken into account the main electricity lines. High voltage power lines and their related pylons were mapped into the GIS together with the positions of high and low voltage substations. Similarly, the main methane pipelines and aqueducts were also mapped. No data were available for the seismic vulnerability, but we estimated a classification according to the age and diameter of the pipeline.

2.2.3 Roads and railways

A dense network of roads connects the villages, and the Messina-Catania main road runs along the coast on the eastern flank of the volcano. Although it is not easy to evaluate effects of earthquakes on roads, we have considered the positions and the seismic vulnerabilities of the bridges, which are the most sensitive elements.

3. THE CONCEPT OF THE DISRUPTION INDEX

Casualties that result from building damage due to ground shaking, or from direct economic damage to buildings and their contents, as well as from debris generated by building damage, are normal outputs from seismic scenarios. Few models have yet been built to estimate or to truly represent the urban disruption that is derived from a collapse, or from some level of damage; in other words, to understand the relationships between buildings, facilities, utilities, networks and their interdependencies. The destruction or degradation of these, or their unavailability for a long period of time, will have consequences on the dimensions of human needs, like “environment, housing, health, education, employment and food”. This paper presents a framework for the classification and evaluation of urban functionality on large scales, using the criteria of comprehensiveness, overall structure, data requirements, calibration and validation, as well as the potential applications.

The idea that traditional seismic simulator models and their results can answer all of our needs tends not to be true nowadays. We have the desire to integrate and link all of the “mechanisms” of urban and human developments and needs, and by virtue of this understanding, to forecast and try to reduce the disaster risk in cities.

The concept of the DI is used to evaluate the effects of changes in relation to certain activities, dealing particularly with housing, the provision of services and/or employment, the transport network, and aspects related to spatial and non-spatial consequences. This general model considers a number of subsystems that deal with the allocation of the activities and components, and their interactions and interdependencies. Crucial to the modelling process of the DI is the capture and analysis of the system dependencies and the chain of influence and effects that cross-multiple the systems (Ferreira, 2012).

For example, we consider that the environmental dependencies are the following: water, sanitation and the critical infrastructure. Water depends on the operation of the water system equipment and of the electricity supply, which depends, in turn, on the electricity system equipment; so we have a chain of dependencies and interdependencies.

An urban area consists of complexity, and highly connected and highly inter-connected systems. A significant loss of housing, education, power or other components will have substantial negative impact. How might constraints in residential areas affect the residential distribution of the region? How might a general change in accessibility due to severe damage affect the population or the economy (e.g. employment changes)?

There are many similar questions that can be posed, either at this aggregated level or at a more disaggregated level.

3.1 Calibrating an Urban Disruption Index

Calibration is not just a mechanical procedure to obtain the best fit of the model output to the actual values; it also allows the model builder to gain an understanding of the way a region functions, as well as indicating the strengths and weaknesses of the model itself. There are several difficulties that occur during the calibration related to, for example, the form and type of the data, the availability of the information, and the way in which damage can be calculated, among other aspects.

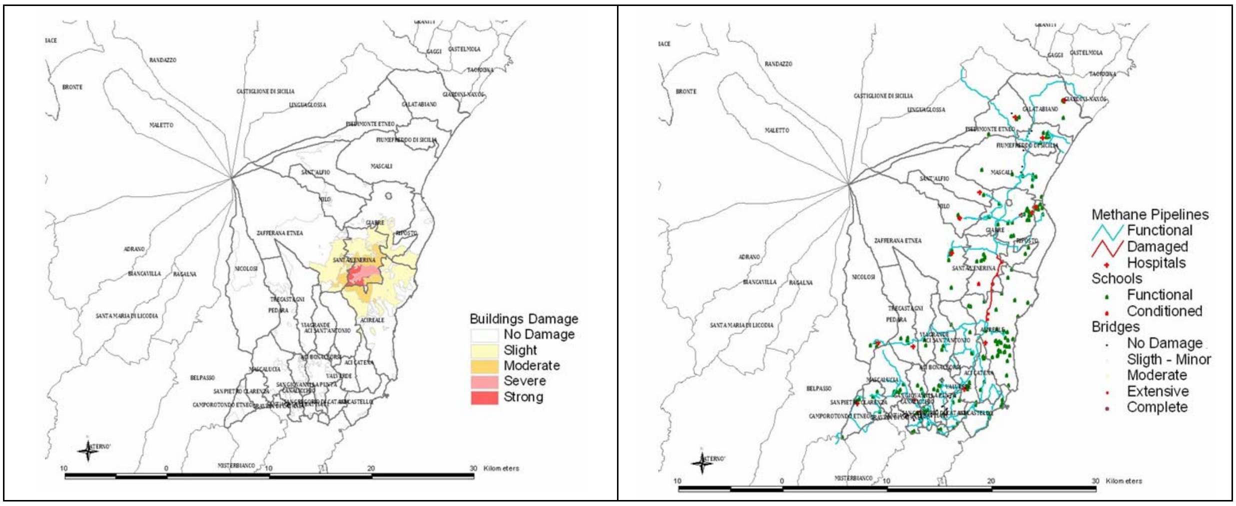


Figure 4. Total expected damage to the building stock and to some of the infrastructure from a postulated earthquake

The calibration, which involves finding the best “parameter values” that reproduce the seismic impact in urban areas with all of the relationships and interdependencies, is carried out using information and experience gained in several earthquake field missions in different regions of the world, including the Azores (Oliveira et al. 1992), China (Costa et al. 2010), Italy (Proença and Ferreira, 2009), Haiti (Oliveira and Ferreira, 2010) and Spain (Ferreira, 2011). This analysis is based on contact and discussion with the affected populations, as well as various entities and agencies, to identify the most important effects on a society, its economy and other sectors. Existing reports and studies related to other earthquakes were also analysed and included. It is highly informative to know which functions, activities and components do conform to the general pattern, and to investigate why this is happening and to find answers for the questions posed at the beginning of the study.

3.2 Using the Disruption Index in Simulators

Part of the overall aim of the Urban Prevention Strategies using Macroseismic and Fault Sources (UPStrat-MAFA) is to include in damage scenarios developed by simulators the concept of the DI and to obtain the levels of disruption for a certain area. For any given point on the map in Figure 4, the expected damage to the building stock and to some of the infrastructure that might be caused by a postulated earthquake is shown, relating to the analysis area of the southern and eastern flanks of Mt. Etna (Figs. 1, 2). The modelling and analysis in a GIS environment is being prepared and will be the topic of future studies; this is relatively new, and time is needed for the modelling of the dynamics of the systems, and for their analysis.

An important note at present is that these systems require consideration of their non-linear and time-dependent behaviours based on certain knowledge of empirical facts and on uncertain knowledge based on hypothetical data.

4. FINAL CONSIDERATIONS

The DI provides a global measure of the effects of an earthquake through the joining of the size of the event (epicentral intensity in this case) and its impact on the local network of systems, taking into account as far as possible their interconnections. At this stage of the project, we have realised that the available data are not sufficient to give an evaluation of the DI in this area of Mt. Etna.

On the other hand, these preliminary results have shown that by adopting the probabilistic approach in the attenuation evaluation, some difficulties can be solved regarding the assessment of the expected damage of an analysed component (e.g. a building, a bridge). At this stage of the project, the data collection is not complete, and thus it is not possible to apply the DI method in the area of Mt. Etna. However, we have been able to determine where and what the missing data are, and we have clear indications how to complete the dataset for the vulnerability of the facilities and the lifelines that are in area. Through these, we will be able to obtain a more realistic risk evaluation.

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