A GIS TOOL FOR THE MANAGEMENT OF SEISMIC EMERGENCIES IN HISTORICAL CENTERS: HOW TO CHOOSE THE OPTIMAL ROUTES FOR CIVIL PROTECTION INTERVENTIONS

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ABSTRACT:

Italy hosts a considerable part of the world's great art treasures. This great heritage must be protected from risks deriving from a territory characterized by hydrogeological problems and high seismicity. For these reasons, despite the preventive measures that can be foreseen, the need to face emergencies is recurrent. The main instrument to address the hydrogeological and seismic emergencies is the Municipal Civil Protection Emergency Plan. In this plan, both strategic viability and strategic buildings (whose collapse could cause significant damage to the historical, artistic and cultural heritage) must be identified.
The paper proposes a methodology, using a GIS platform, useful for achieving two objectives: (1) planning of safe routes in case of critical conditions and (2) identification and planning of safety interventions, thus assigning appropriate priorities to the buildings to be restored, based not only on their relevance to road use, but also on cost considerations.

1. INTRODUCTION

The management of emergencies involves a series of problems to be faced with an interdisciplinary approach (Alexander, 2016). In the italian territory several risk scenarios can be present; to face them, an important role is played by monitoring activities (Artese et al., 2013, 2015, Zinno et al., 2019). In any case, the forecast of the possible risk scenarios and the way to manage them must be addressed both through the general rules (European Commission, 2010) and the local ones.
The peculiarities of each territory require the adoption of guidelines for emergency planning (e.g. Regional Government of Calabria, 2007), to be adapted by the municipalities to the local reality. To this end, city models and GIS can provide considerable support to planners (Artese, 2014, Pollino et al., 2012, Reza et al., 2013).
Among the several risk scenarios, the earthquakes are very difficult to deal with, since the issues involved vary from the structural components of buildings and infrastructure, to the management of individual behavior in mass emergencies. A very important item concerns the setting of adequate planning tools that allow the definition of the safest road infrastructures to be used in the case of a seismic event (Ruan et al., 2013, Zhang et al., 2018).
In the following, a method is proposed for assessing the vulnerability of the routes in the event of an earthquake, with a peculiar attention to the behaviour of the buildings facing the roads involved.
The structure of the paper is the following: in chapter 2 the determination of damage scenarios and vulnerability of buildings is treated; chapter 3 describes the proposed methodology and a GIS tool that allows, for each building, the determination of the level of damage expected and the problems created on the underlying road in terms of vehicle traffic obstruction, as well as the costs to be faced for the adjustment; chapter 4 presents a case study related to a neighborhood characterized by the presence of different types of structures, including buildings dating back to the early 1900s.

2. SEISMIC VULNERABILITY OF BUILDINGS AND DAMAGE SCENARIOS

To perform analyses of seismic vulnerability in urbanized areas, the detailed structural and maintenance data of each building should be available. This is, in general, impossible, also due to the large number of structural typologies present in Italy and in Europe.
To classify the seismic risk of constructions, the recent italian rules (M.D. n. 58 February 28, 2017) state 8 classes of risk (from A+ to G) based on two parameters: the expected average annual economic loss (PAM) and the Structure Security Index (IS-V). To calculate these parameters, information about structural details and peak ground accelerations is mandatory.
Unfortunately, for most of the buildings the *as built* is not available, so this procedure is not applicable currently for an entire city.
A simplified method can be used for the masonry structures, which characterize most of the buildings in the historical centers. It uses the European Macroseismic Scale 1998 (EMS-98), a qualitative scale used to describe the effects of an earthquake (Grunthal, 1998).
The EMS-98 adopts twelve degrees of seismic intensity (from I *not felt* to XII *completely devastating*), six classes of vulnerability (Figure 1) and five degrees of damage. Figure 2 shows the damages to masonry buildings.
The EMS-98 assigns a mean vulnerability class to each type of structure, and a range of possible belonging.

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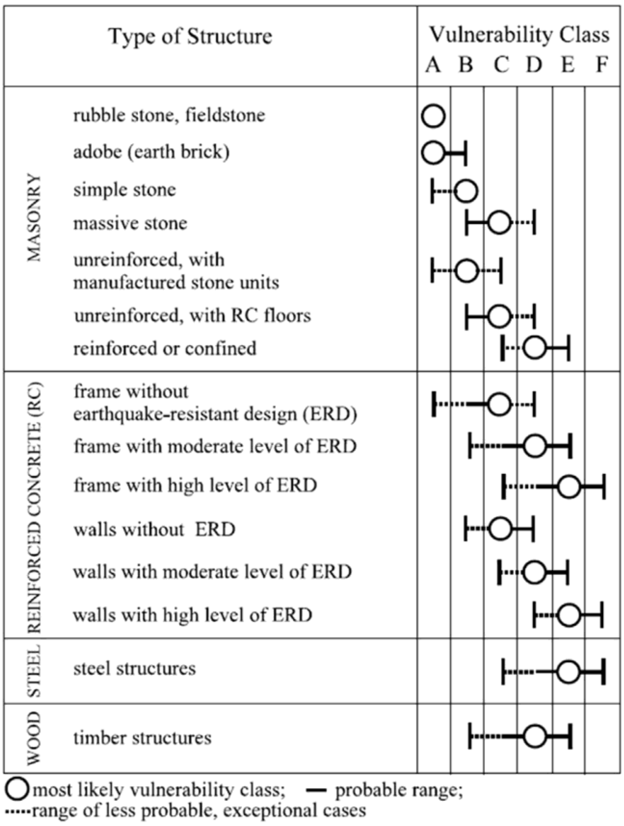


Figure 1. Vulnerability classes of EMS-98.

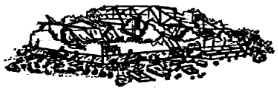
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Figure 2. Classification of damage to masonry buildings of EMS-98.

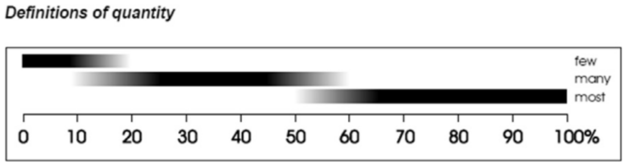


Figure 3. Definitions of quantity of EMS-98.

Furthermore, for each degree of seismic intensity, the number of damaged buildings and the degree of damage suffered is foreseen for each class. The quantity of the number of damaged buildings is provided qualitatively (few, many and most) in Figure 3. A range of values is associated with each quantity so, e.g., a range centred on 10%, and ranging from 0% to 20% (unlikely), is associated with the value few.
In order to perform scenario analyses, a qualitative scale like EMS-98 must be transformed into a quantitative one. In short, descriptions must be changed to numbers.
Starting from EMS-98, a quantitative method that uses a probability beta distribution has been designed (Giovinazzi and Lagomarsino, 2004). This way, Probable Damage Matrices (DPM) are built using linear-type functions. The limit of this choice is that a symmetric distribution is used, while the values of the vulnerability indices show an asymmetric trend.
In order to match the asymmetry of the frequencies, a log-normal distribution is used in the present work.

3. THE METHODOLOGY

The steps of the procedure proposed in this paper are the following: (a) a vulnerability index is defined and assigned to each building; (b) DPM, derived from EMS-98, are built; (c) for each vulnerability class, the quantities of Figure 3 are transformed in numerical values using a log-normal distribution; (d) for each degree of intensity, a threshold vulnerability index is obtained to determine what grade of damage the buildings will suffer; (e) the cost of the adjustment or reconstruction is obtained for each building; (f) the adjustment cost for each route is obtained.

3.1 Vulnerability Index

The behaviour of a building in the event of an earthquake is quantified by a numeric value called Vulnerability Index (Iv). Conventionally, low values are assigned to buildings built according to the most recent anti-seismic rules, while the highest values correspond to the weakest buildings. Usually it ranges between zero and one. The vulnerability index Iv is given by the sum of some corrective indices. For the buildings with masonry structure, the following formula was chosen:

$$Iv = Ivi + Ip + Ii + Im \quad (1)$$

where: I_v is the vulnerability index, I_{vi} is the initial vulnerability index, I_p is the planimetric configuration index, I_i is the index of the works performed and I_m is the maintenance index.
For the buildings with reinforced concrete structures, the following formula was chosen:

$$Iv = Ivi + Irs + Ic + Ip + Iss + Isc + Ii + Im \quad (2)$$

where: I_v is the vulnerability index, I_{vi} is the initial vulnerability index, I_{rs} is the resistive system index, I_c is the cladding index, I_p is the planimetric configuration index, I_{ss} is the soft storey

index, I_{sc} is the index due to squat columns, I_i is the index of the works performed and I_m is the maintenance index.
The initial vulnerability index of a building (I_{vi}) is assigned taking into account the typology of structure, selected from those listed in Fig. 1 and, consequently, the relative most probable vulnerability class. For each vulnerability class, the Initial Vulnerability Index, ranging from 0.9, for class A, and 0.1, for class F - (Table 1) was assigned in accordance with that established by Giovinazzi and Lagomarsino.

Vulnerabily Class	A	B	C	D	E	F
I_{vi}	0.90	0.74	0.58	0.42	0.26	0.10

Table 1. Initial vulnerability indices I_{vi}.

With regard to the structural typology, the indices reported in (Francini et al., 2018) were used. These values were obtained, for reinforced concrete structures, with reference to the second level chart developed by the National Group for the Protection from Earthquakes (G.N.D.T.). The indices I_{rs}, I_c, I_p, I_{ss} and I_{sc}, previously described, have been obtained. For masonry structures, only the index I_p were obtained.
For each index, values between a minimum of -0.04 (improvement) and a maximum of 0.08 were chosen. The sum of these indices can vary between -0.04 and 0.30.
As regards the index of executed works I_i (Table 2) three types of reinforcement works have been considered: strengthening, improvement and local works.
I_i varies between −0.16 and −0.06. The strengthening determines the increase of a vulnerability class, while the minor reinforcement works have more modest effects.

Executed Work	Strengthening	Improvement	Local works
I_i	-0.16	-0.10	-0.06

Table 2. Indices of executed works I_i.

Also for the maintenance index I_m , three levels were considered (Table 3): good, average and poor; the index I_m ranges between 0 and 0.04.

State of maintenance	Good	Average	Poor
I_m	0.00	0.01	0.06

Table 3. Indices of Maintenance I_m.

In the end, the global vulnerability index could have variations between -0.20 (for the best case) and +0.36 (in the worst case), in full agreement with EMS-98.
As for the sediment soil influence, given that the amplification index attainable from the seismic microzonation could be transformed into a component of the vulnerability index only through a thorough knowledge of the single building, currently unavailable, in the present paper, the effect of the local actions is considered incorporated in the degree of intensity taken into account for the tests performed.

3.2 The damage scenarios

The EMS-98 macroseismic scale is a vulnerability model that provides a damage distribution in various types of buildings for each degree of seismic intensity.
For the tests reported in this paper, among the 12 degrees of seismic intensity of EMS-98, only the seismic intensities 7 and above have been considered. As for the damages, among the 5 degrees of EMS-98, the highest damage degrees 4 and 5 (partial or total collapse) have been taken into consideration.

Damage level 4		Vulnerability class					
		A	B	C	D	E	F
Intensity	V						
	VI						
	VII	Few					
	VIII	Many	Few				
	IX		Many	Few			
	X			Many	Few		
	XI			Most	Many	Few	
	XII						
Damage level 5		**Vulnerability class**					
		A	B	C	D	E	F
Intensity	V						
	VI						
	VII						
	VIII	Few					
	IX	Many	Few				
	X	Most	Many	Few			
	XI		Most	Many	Few		
	XII			Most	Most	Most	Most

Table 4. Damage matrices for levels 4 and 5.

The relationships between degrees of intensity, degrees of damage and vulnerability classes are represented by the damage matrices, built for each level of damage. A damage matrix provides, for a given degree of intensity, a qualitative assessment of the number of buildings belonging to a given vulnerability class, to be subjected to the damage level of the matrix itself.
Table 4 reports the matrices for damage levels 4 and 5, of interest for our work.
As regards the valorisation of the expressions used in table 4, the central values used in the EMS-98 have been adopted. Therefore, we get the following quantity/percentage matches: (a) Few = 10%; (b) Many = 35%; (c) Most = 75%.

3.3 The threshold indices of I_v

To perform the analyses of a damage scenario, the above percentages are not exhaustive. It is useful to know how many buildings will suffer a certain damage, but it is not enough: we must identify which buildings they will be. So, for example, it is necessary to transform the expression "*10% of class D buildings will suffer level 5 damage*" in "*buildings with a vulnerability index greater than that corresponding to 90% of the accumulated probability in class D will suffer from type 5 damage*".

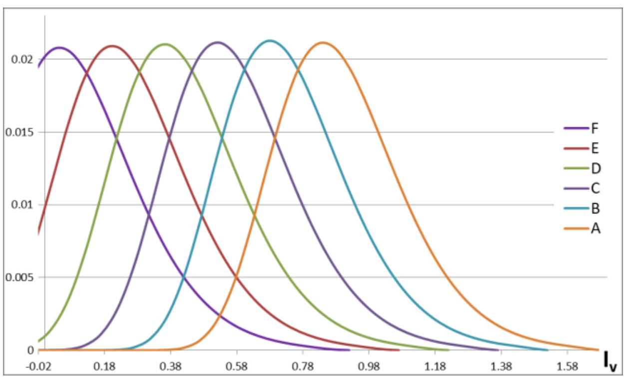


Figure 4. Distribution of probability of belonging of a building in classes A to F as a function of the vulnerability index.

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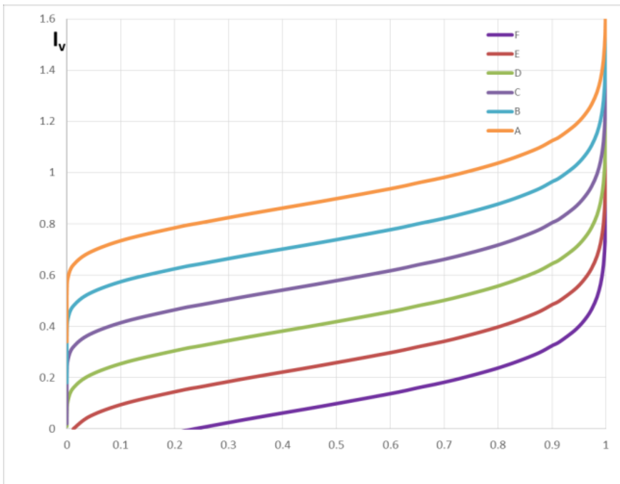

Figure 5. Cumulated probability of belonging of a building in classes A to F as a function of the vulnerability index.

For this aim, one should find a damage probability distribution (for each vulnerability class), as a function of the vulnerability index.
In the present work, we use a probability distribution that takes into account possible values for the index ranging between the initial value Ivi decreased by 0.20 and the same increased by 0.36. These extremes correspond to an increase in a vulnerability class, and to a decrease of two classes. The distribution that fits best is a lognormal distribution.
Figure 4 reports the distribution of belonging of a building in classes A to F as a function of the vulnerability index.
Figure 5 shows the cumulated probability, used in the successive elaborations as threshold index (Fig. 5).
To the quantities few, many and most, correspond, respectively, cumulated probabilities of 90%, 65% and 25%. To each cumulated probability, correspond, in turn, different vulnerability indices, depending on the vulnerability class, as shown in Table 5. By combining these values with those given by Table 4, we can obtain the threshold indices of buildings that collapse, or suffer severe damages, according to the severity of the event (Table 6).
Depending on the level of damage, it is possible to determine the size of the debris or of the expelled material and, consequently, the area encumbered by the material expelled on the road adjacent to a building, in accordance with EMS-98 and the seismic rules NTC2008.

	Vulnerability Class					
	A	B	C	D	E	F
$I_{vthreshold}$ for **Few** (Probability Index = 0.90)	1.12	0.96	0.80	0.64	0.48	0.32
$I_{vthreshold}$ for **Many** (Probability Index = 0.65)	0.96	0.80	0.64	0.48	0.32	0.16
$I_{vthreshold}$ for **Most** (Probability Index = 0.25)	0.80	0.64	0.48	0.32	0.16	0.005

Table 5. Threshold indices for few, many, most quantities.

We can observe how the threshold indices have the same trend, proceeding to the right and downwards. $I_{vthreshold}$ for class D and for the values “Few”, “Many” and “Most” (0.64 – 0.48 – 0.32) is equal to $I_{vthreshold}$ for classes D, E and F and for the value of “Few”.

Intensity degree	Threshold damage 4	Threshold damage 5
VII	1.12	-
VIII	0.96	1.12
IX	0.80	0.96
X	0.64	0.80
XI	0.48	0.64
XII	0.05	0.10

Table 6. Threshold indices by degree of intensity and level of damage.

3.4 The costs of reconstruction or adjustment

The costs of seismic adaptation depend on several factors, related to the types of structure, as well as on the location, the sediment soil, the roads that the yard’s vehicles must travel. For the present work, we refer to the costs incurred to repair buildings damaged by recent earthquakes (Di Ludovico, 2017). We therefore assume a linearly increasing cost in relation to the Iv. Considering a zero cost for buildings with a lv index equal to 0.1 and a maximum cost of 800 €/m2, we get the following equation:

$$Cu = 800 \times (Iv - 0.1) \quad (3)$$

where C_u is the unitary cost in €/m2, and I_v is the vulnerability index.

3.5 The GIS platform

To effectively use the data obtained by applying the methodology described above, we make use of a GIS platform.
Specifically, the basis of the GIS is the 3D municipal cartography, which provides the metric information of the buildings (surface, location, height). The classification is performed through direct surveys, which allow assigning a Vulnerability Index to each building.
In consequence, we can build the scenario of damage corresponding to an earthquake of chosen intensity and obtain the level of damage suffered by each building, in particular those adjacent to the roads.
Since we know the maximum probable distance that the ejected material can reach due to the earthquake, we can predict which part of the roads will be cluttered with debris.
Thus, a buffer equal to one third of the height of buildings that suffer damage 4, and equal to two thirds of the height for those suffering damage 5, is performed. In this way, for each road section, we obtain collapses and areas that are blocked by total or partial building collapses.
Furthermore, with this method, once selected a route to be used in an emergency, we get the total cost to allow the use of the route in the post-earthquake period, with no danger of obstacles or interruptions.
This methodology could allow the decision makers to establish a priority ranking of the buildings to be adjusted to ensure the safety of the routes provided for in the Emergency Plan or to optimize the choice of routes in terms of cost optimization and execution times.

4. EXPERIMENTATION OF THE METHODOLOGY

The methodology described above has been experimented in a district of the Municipality of Cosenza (resident population of

67.239 inhabitants; municipal surface area 37.86 sq.km - Istat Data 2017), in Calabria, Italy.

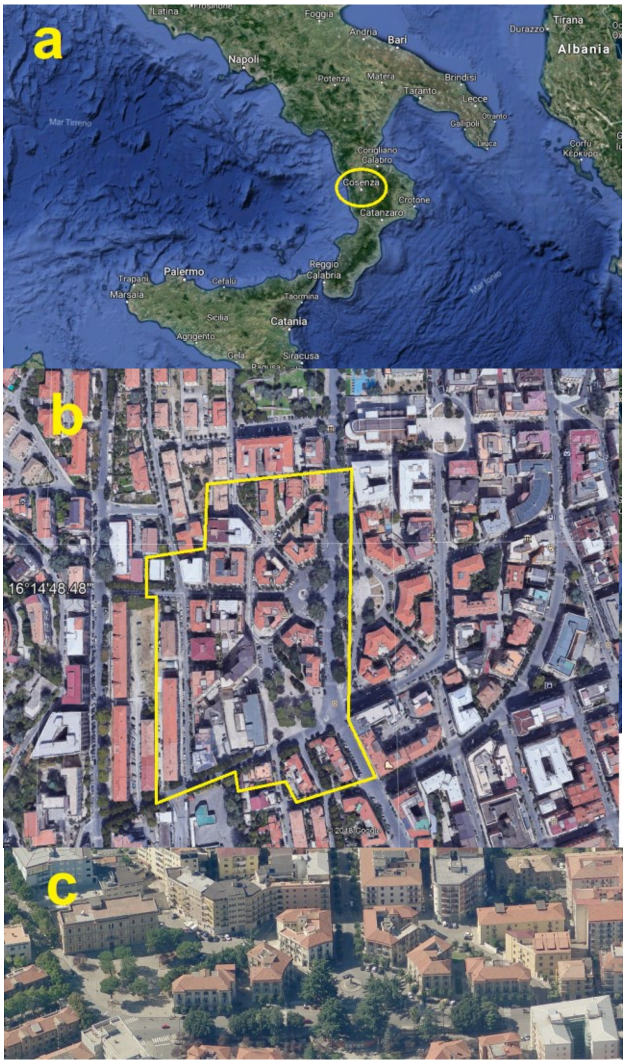

Figure 6. a) geolocation of the case study; b) neighborhood orthophoto; c) aerial view.

The municipality is the center of the urban area of Cosenza and houses a Joint Operations Centre (Civil Protection operative structure, coordinating emergency services). The whole Calabria region belongs to a highly seismic zone (zone 1); the municipality is located inside the zone 2 of the regional warning system for hydrogeological and hydraulic risk (Hydrogeological Planning Plan - PAI).

The current Civil Protection Emergency Plan (Municipality of Cosenza, 2017) identifies a series of possible Risk Scenarios on the municipal territory (high winds, storms, earthquakes, soil erosion, landslides, floods, etc..). The Plan provides, for each of these scenarios, detailed information on the expected event, on the locations where it could occur and on the elements at risk that could be involved.

In the Plan, some buildings and routes are reputed as *"strategic"*, as well as emergency areas located in different districts in the municipal territory (aimed at quickly accommodating the population and/or storing rescue resources) are considered *"sensitive points"*.

In the following case study, the neighborhood chosen is located close to some such areas: an urban park, a square and a church (Figure 6). The older buildings date back to the early 1900s and are characterized by a reinforced masonry structure. The project was drawn up immediately after the entry into force of the seismic regulations following the 1908 Messina and Reggio earthquake.

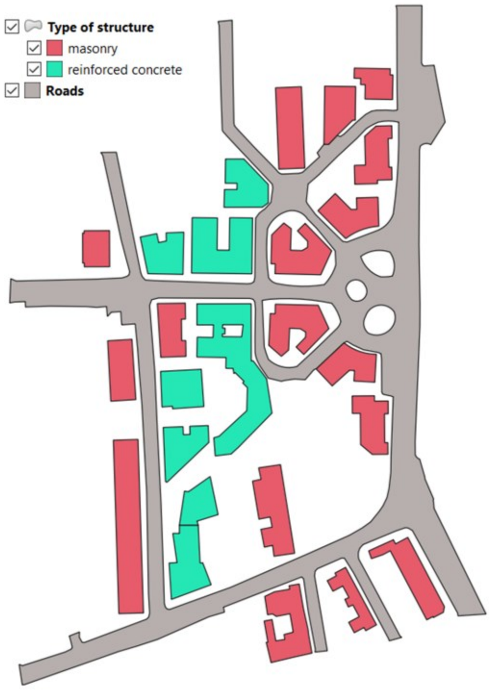

Figure 7. The structures typology of buildings.

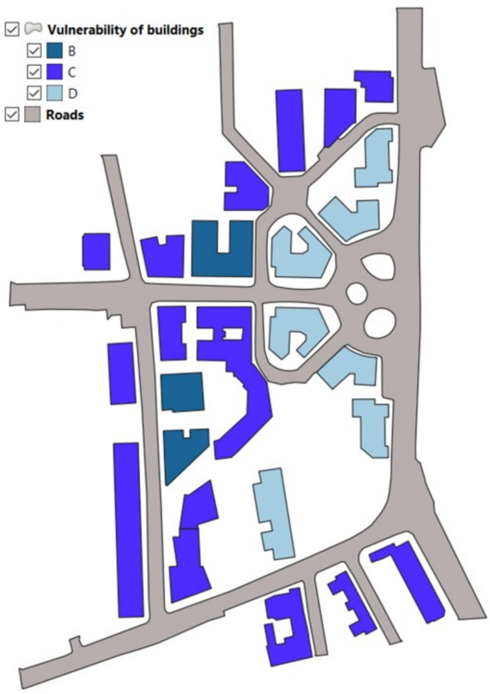

Figure 8. The vulnerability classes of buildings.

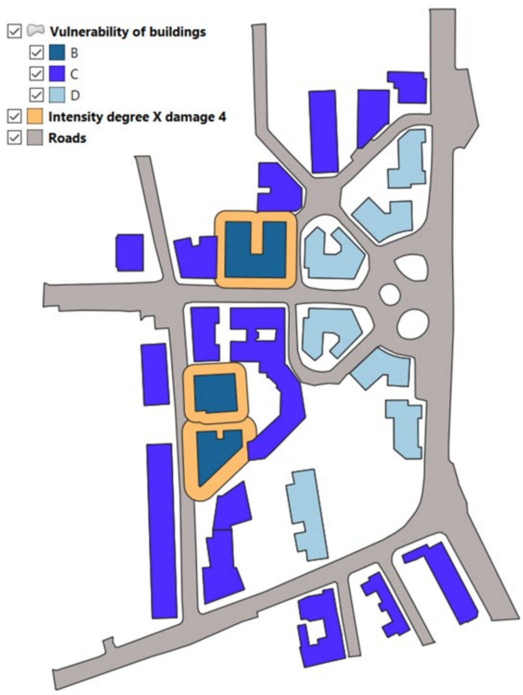

Figure 9. The scenario for intensity degree X (Damages below 4 are not considered).

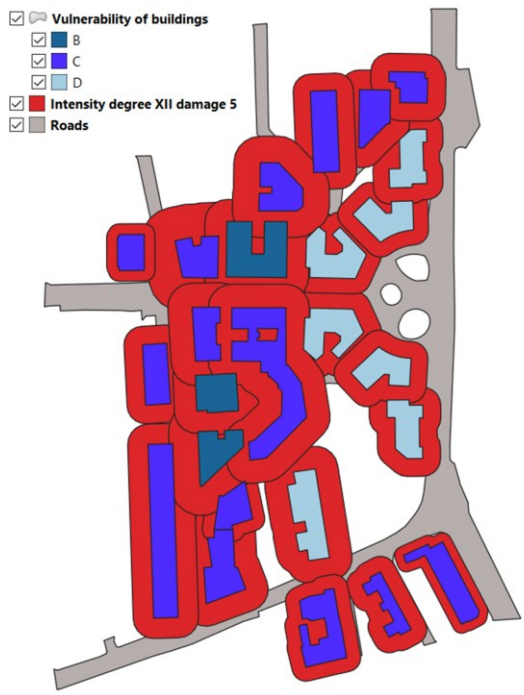

Figure 11. The scenario for intensity degree XII.

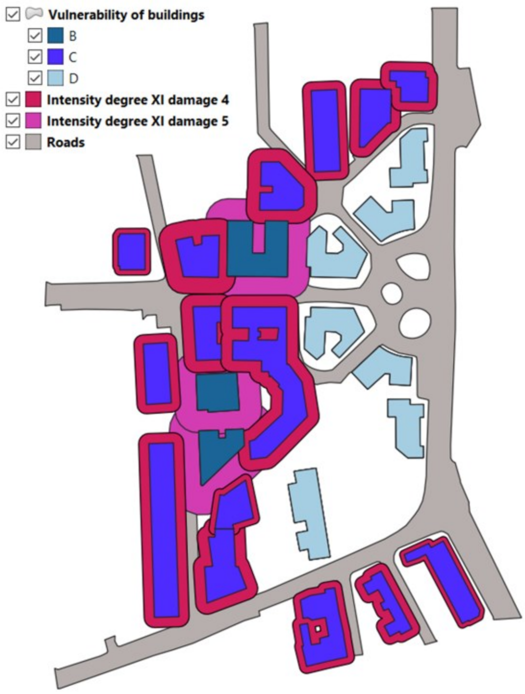

Figure 10. The scenario for intensity degree XI (Damages below 4 are not considered).

Figure 12. The scenario for intensity degree XII: in grey clear roads.

4.1 Application of the model to a case study

Within the area investigated, the routes and the adjacent buildings were identified, and the structures typology has been determined for each building. (Figure 7).

For each road section, each adjacent building was classified according to the vulnerability class (Figure 8). In particular, for each one, the global vulnerability index was defined by the corrective indices above described.

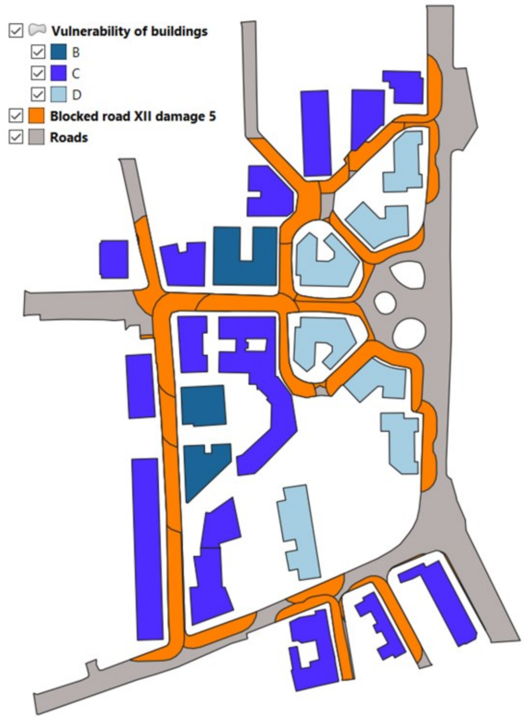

Figure 13. The scenario for intensity degree XII: clear (grey) and blocked (orange) roads.

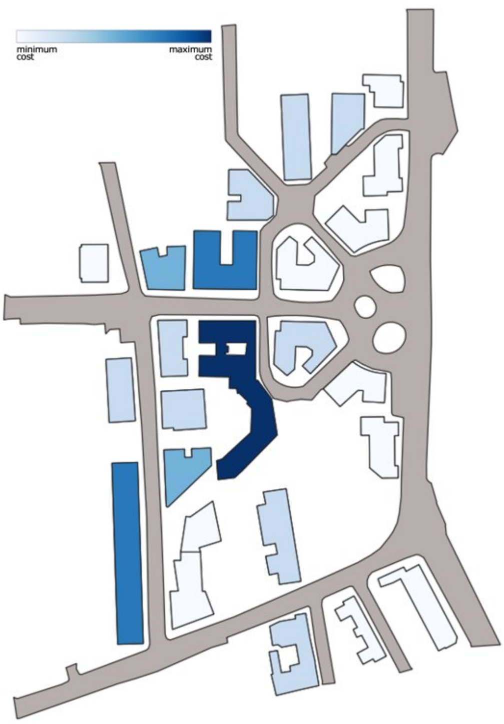

Figure 14. Adjustment costs.

Then we considered scenarios relative to X, XI, and XII intensity degrees. A buffer equal to one third of the height of buildings that suffer damage 4 has been performed (Figures 9, 10). Similarly, a buffer has been executed, equal to two thirds of the height for those suffering damage 5 (Figures 10, 11). Damages less than 4 are not considered, because they do not produce road clutter due to the ejected material (see Figure 2).

ID BUILDING	SHAPE AREA (m2)	TYPE OF STRUCTURE	VULN. CLASS	Buffer (m) for Intensity Degree and Damage				Costs (€)	
				X_4	XI_4	XI_5	XII_5	Unitary	Total
3	412,83	MASONRY	D	0	0	0	7,54	335,9	528053,83
4	390,86	MASONRY	D	0	0	0	8,14	335,9	539907,73
5	366,58	MASONRY	C	0	4,95	0	9,89	471,9	864195,89
8	385,6	REINFORCED CONCRETE	C	0	8,46	0	16,93	471,9	1555433,74
9	243,7	MASONRY	C	0	2,68	0	5,36	471,9	311348,83
10	752,39	REINFORCED CONCRETE	B	5,51	0	11,02	11,02	599,9	2512714,22

Table 7. Clutter of debris and adjustment costs for six buildings.

Through an overlay operation, the subtraction of the building buffer from the road area has been performed, in order to obtain the road stretches remaining free after collapses. If a complete interruption occurs, the road sections are broken into several parts (Fig. 12) and obstructed parts can be detected (Fig. 13).
Finally, using equation (3), a unitary cost for seismic adjustment was calculated for each building. From the unitary cost Cu, adopting a mean story height of 3 m, it was obtained the cost per unit of volume which, multiplied by the building volume, provided the total cost of adjustment of each building (Fig. 14, Table 7).

5. CONCLUSIONS

A methodology and a GIS tool have been proposed for the management of seismic emergencies in historical centers. The methodology allows to identify which damages buildings will suffer in case of an earthquake of a given degree; moreover, road obstructions are obtained for each scenario.
A case studio, regarding a neighborhood in Cosenza characterized by buildings of different epochs and structural typologies, has been presented.
The proposed GIS platform can support decision makers to plan, on the one hand, optimal connections and, on the other hand, to assign appropriate priorities for the adjustment of the various buildings, not only because of their relevance to road use but also based on cost considerations.

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