Local Geology and Seismic-Induced Damages: The Case of Amatrice (Central Italy)

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Abstract. On 24th August 2016 the first earthquake (Mw 6.2) of a long-lasting sequence struck Central Italy. The 24th August mainshock was in the surroundings of Amatrice, Central Italy, where about 300 people died. Most of the buildings were damaged and immediately after the earthquake Italian National Civil Protection (DPC) started coordinating the emergency and post-emergency activities. The latter included geological and geotechnical investigations for seismic microzonation carried out by the Centre for Seismic Microzonation (CMS) and the creation of a dedicated task force for rubbles management in the town of Amatrice. The present study presents preliminary results of the spatial correlation between the distribution of building damages generated by the 24th August earthquake, obtained by means of the Copernicus Emergency Management System (EMS) services, and the results of the seismic microzonation study of the village. We observed a spatial correlation between damages of buildings and seismic ground motion amplification, quantitatively estimated through an amplification factor (FHa). In particular, we observed an increasing trend of higher damaged buildings when FHa grows.

Keywords: Earthquake · Urban geology · Seismic microzonation · COPERNICUS Emergency Management System · Rubbles · Geomatics · LIDAR · Post-emergency management

1 Introduction

In 2016-17, Central Italy was affected by a complex seismic sequence on an area of Apennines covering large part of Lazio, Marche, Umbria and Abruzzo Regional administrative territories.

On 24th August 2016 at 01:36 (UTC) a 6.2 MW earthquake struck the Central Italy area between the municipalities of Amatrice and Arquata del Tronto (Fig. 1-b) causing about 300 victims and more than 35,000 homeless [1, 2]. Referring to the Italian Strong

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Motion Network [3] the nearest accelerometric station AMT, located about 400 m northward the Amatrice historic centre with an epicentral distance (R_{epi}) of about 8.5 km, recorded a Peak Ground Acceleration (PGA) of 0.868 g [4].

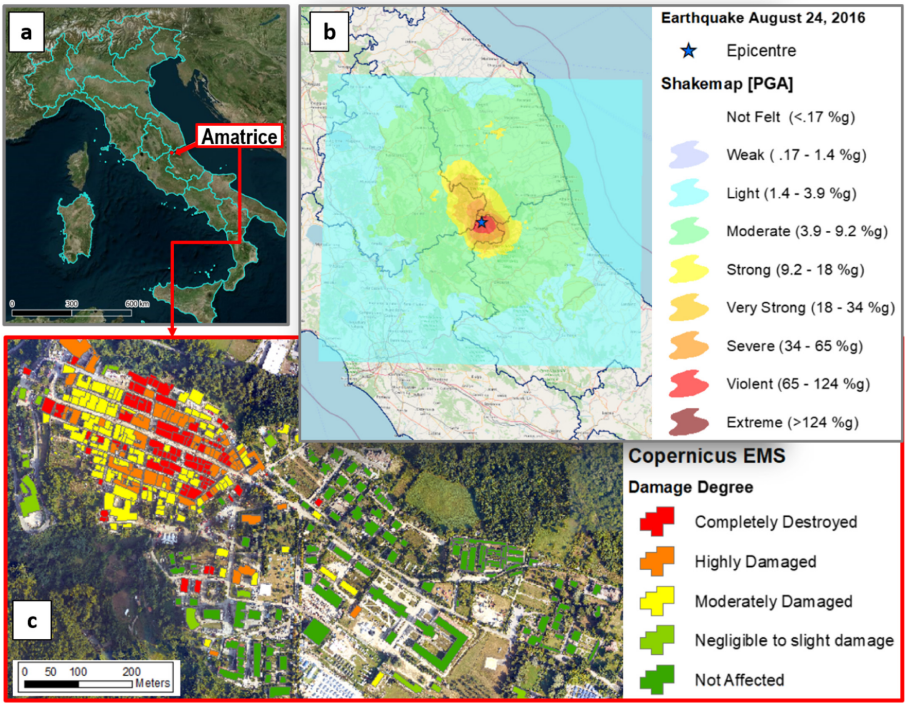

Fig. 1. a) Amatrice location (Central Italy); b) Shakemap of the earthquake occurred on August 24, 2016 (source: INGV, The Italian National Institute of Geophysics and Volcanology); c) Copernicus EMS damage grading map produced after the August 24, 2016 event (source: [5]).

Then, the sequence developed in the surrounding of Norcia, situated about 30 km northward Amatrice, with two events on 26th October (at 19:18 UTC; 6.1 MW) close Castelsantangelo sul Nera and on 30th October (at 06:40 UTC; 6.6 MW) nearby Norcia. The accelerometric recordings obtained in Amatrice station (AMT) showed for the 26th October shock ($R_{epi} \cong 33.3$ km) a PGA of 0.093 g and for the 30th October one ($R_{epi} \cong 26.4$ km) a PGA of 0.532 g.

The last phase of the sequence, was located south of Amatrice in the Montereale area and included two mainshocks occurred on 18th January 2017 at 10:14 (MW 5.7) and 10:25 (MW 5.6) recorded in AMT respectively with PGA of 0.326 g ($R_{epi} \cong$ 11.3 km) and 0.159 g ($R_{epi} \cong 14.4$ km).

The cumulative damage effect observed in Amatrice directly reflects the strong ground shaking caused by the sequence of earthquakes [1]. The 24th August Mainshock damage distribution in Amatrice was analysed by Copernicus Emergency Management

System, EMS [5] (Fig. 1-c). The *"Completely Destroyed"* and *"Highly Damaged"* buildings are constrained in the north-western part of Amatrice historic centre.

Immediately after the 24th August mainshock, Italian National Civil Protection (DPC) was in charge of emergency and post-emergency activities coordination. ENEA participated as part of EMERgency COMmittee (EMERCOM, a task force dedicated to overcome and manage Emergencies and Elimination of Consequences of Natural Disasters) to the following activities:

i) working group for determination of rubble volumes,
ii) seismic microzonation activities,
iii) macroseismic survey for the determination of earthquake intensities (QUEST),
iv) survey of co-seismic earthquake ruptures (EMERGEO).

With reference to activity i) in a previous work a method for the rapid estimation of the volumes of rubble heaps within the area of Amatrice was implemented [6]. In particular, LiDAR data were exploited to provide the geometric features (location and volume) of rubble piles distributed after the earthquake occurred on 24th August, 2016, by using an innovative procedure, based on photo-interpretation and volumes 3-D modelling. Then, a specific study on rubbles characterisation has been recently carried out [7].

With reference to activity ii), following the Ordinance n. 24 of Special Commissioner for the Earthquake, the Seismic Microzonation Center (CMS) coordinated the studies of Seismic Microzonation of Level 3 (SM3) in 138 municipalities. The Seismic Microzonation Center was founded in 2015 by the agreement between several Italian research institutions and University departments under the aegis of Italian National Research Council [8]. The seismic microzonation studies were conducted by professionals adopting the national guidelines implemented by SM Working Group [9]. Seismic microzonation has the objective of evaluating the effect of local geologic conditions on ground-shaking caused by earthquakes at the local scale.

In particular, the definition of seismic microzones focuses on ground-motion amplification factors together with areas susceptible to seismically induced instabilities like landslides, soil liquefactions or ground failures. Based on a detailed geological model of the area, the SM3 analysis required the collection of geological, geophysical, and geotechnical data and provide a detailed classification of the territory in microzones characterized by the same level of ground motion amplification expressed through an amplification factor. The ground motion amplification was evaluated by numerical simulations [10].

The amplification factors (FHa) were calculated as the ratio between the integral of acceleration elastic response spectra (5% damping) of seismic inputs (made available by CMS [8]) and the integral of simulated acceleration elastic response spectra (5% damping) of output at ground surface. Integration were performed considering three period-intervals, namely 0.1–0.5 s, 0.4–0.8 s and 0.7–1.1 s, in order to evaluate the amplification level variation as a function of structural period. The seismic input was provided for a seismic hazard level with probability of exceedance of 10% in 50 years.

In the present work, the results of SM3 study of Amatrice Municipality has been jointly analysed with the observed damage after the 24th August mainshock. In particular, the amplification factor maps of Amatrice downtown have been spatially

correlated to the building damage level distribution, focusing on the 0.1–0.5 s interval of periods that is considered representative of the fundamental period of the building stock in Amatrice.

2 Study Area

Amatrice is placed in the Central Italy section of the Apennines chain (Fig. 1-a). This area is interested, since upper Pliocene, by extensional tectonics with active seismogenic faults affecting the entire NW-SE oriented ridge [11–17].

The study of the seismic events occurred in the past as well as recent seismicity and seismotectonic studies, have revealed that Amatrice area has high seismic hazard at national level (PGA 0.25–0.275 g with probability of exceedance of 10% in 50 years).

The Amatrice basin is a morpho-structural depression filled by the Miocene siliciclastic deposits of the Laga Formation and overlaid by quaternary continental units [18]. The Laga Formation is made of alternation of sandstone and siltstone layers and represents the geologic bedrock of the area. The town lies on a fluvial terrace within the Tronto river valley. This terrace is mainly made of gravels and sands directly overlying the bedrock [18]. Like many other villages in Central Italy, urban development was directed towards the top of the hill and in the proximity of the edges of the terrace; it is the part of the mountain that allowed a better protection against attacks and control of surrounding areas as well as protection from floods in the river valley below. But these areas are also prone to ground-motion amplification effects generated by earthquakes. An example of geological cross-section elaborated through the ridge of Amatrice is reported in Fig. 2.

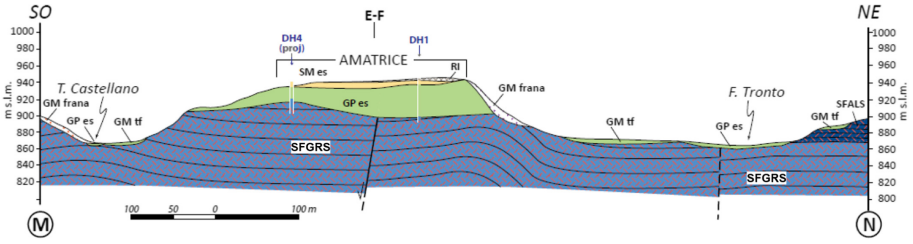

Fig. 2. SO-NE geological profile of the Amatrice Ridge. (source: [18] modified). The engineering geological units are classified according to SM Working Group [8]. Cover terrains: RI - Anthropic deposits; GPes - mixed gravels and sands in alluvial fan; GMtf - mixed gravels, sands and silts in terraced alluvial deposits; SMes - silty sands in alluvial deposits. Geological bedrock: SFALS - alternation of contrasting lithotypes, stratified and altered or fractured; SFGRS - stratified, grainy cemented lithotypes, altered or fractured.

3 Data and Materials

3.1 Dataset

The core dataset is made up of:

1. Damage Grading Map (Damaged/collapsed buildings): delimitation and classification provided by Copernicus EMS [5] (Fig. 1-c and Fig. 3-a).
2. Datasets exploited within previous studies [6, 7] on the same area (LiDAR and RGB Orthophotos) and related outputs produced (Fig. 3-b).
3. 1:5,000 Digital Cartography [19] (Fig. 3-c).
4. Seismic Microzonation - Level 3 (SM3) Map for Amatrice [18] (Fig. 3-d).

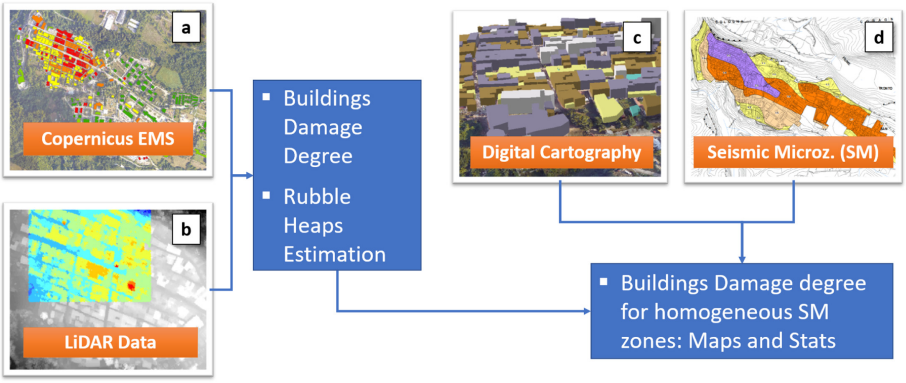

Fig. 3. Flow diagram of the procedure exploited for evaluating and mapping the relationship between building damage degree and seismic microzonation. Input data for building damage grading and rubble heaps geometries from: Copernicus EMS (a); 1 m resolution DTM from Light Detection and Ranging (LiDAR) survey and RGB orthophotos (b). The elaboration of maps and stats is obtained overlapping in GIS environment digital cartography (c) and areal distribution of SM3 amplification factors (d).

3.2 Methodology

A flow diagram of the adopted methodology, including the rubbles estimation performed in the abovementioned previous works [6, 7], is reported in Fig. 3.

In the present paper the grading map provided by Copernicus EMS in the immediate post-event phase [5] was exploited to take into account the level of damage for buildings. According to Copernicus EMS categories, buildings were classified into five levels of damage: *"Not Affected", "Negligible to slight damage", Moderately damaged", Highly damaged", "Completely Destroyed"*. These data were opportunely combined in GIS environment together with 1:5,000 digital cartography [19] and Seismic Microzonation Map (SM3) [18]. For each building, the following attributes were available in an enriched GIS layer: area, perimeter, volume, level of damage (EMS grading), SM3 amplification factor (FHa).

Detailed data about buildings vulnerability are not available. Due to the lack of knowledge, in the present study a uniform class B, according to EMS-98 European Macroseismic Scale [20], has been hypothesized for the building stock even though the masonry building quality in the area is often very poor. As most of the buildings had a height between 6 and 12 meters, their first modal shape period has been evaluated with the following formula:

$$T_1 = C_1 H^{3/4}$$

where T is the fundamental resonance period in seconds, H is the building height in meters and $C_1 = 0.050$ for masonry building. The first modal shape period is therefore approximated between 0.2 and 0.3 s (Italian Building Code NTC 2018) [21]. More data about building vulnerability could refine the results, but the saturation effect due to the strong shaking makes sense of the assumption made.

4 Results

The overlay of the SM3 and Copernicus EMS allowed to obtain statistical (Table 1) and visual (Fig. 4, Fig. 5 and Fig. 6) results.

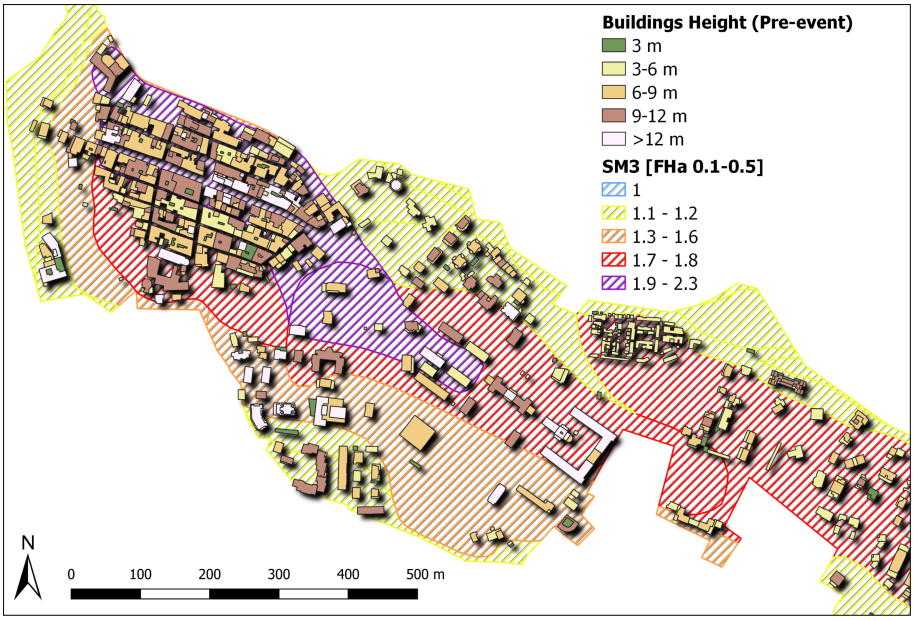

Fig. 4. Buildings' heights in the town of Amatrice (source: [19]: spatial overlay with the amplification factor values (FHa) distribution from Level 3 Seismic Microzonation (SM3) related to period interval of 0.1–0.5 s (source: [18])

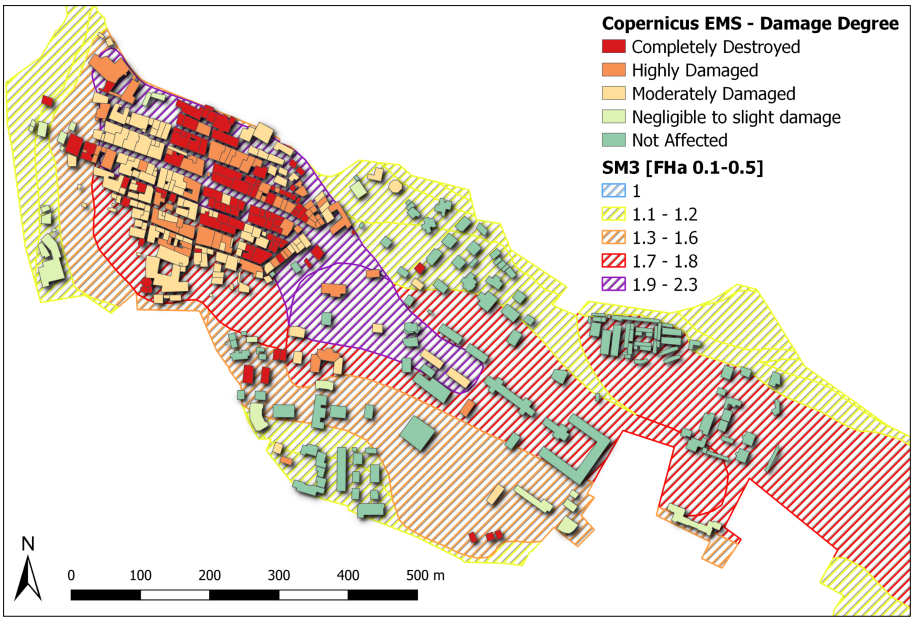

Fig. 5. Building damage degree (source: [5]) spatially overlapped to the Seismic Microzonation of Level 3 (SM3) map. FHa values are related to period interval of 0.1–0.5 s (source: [18])

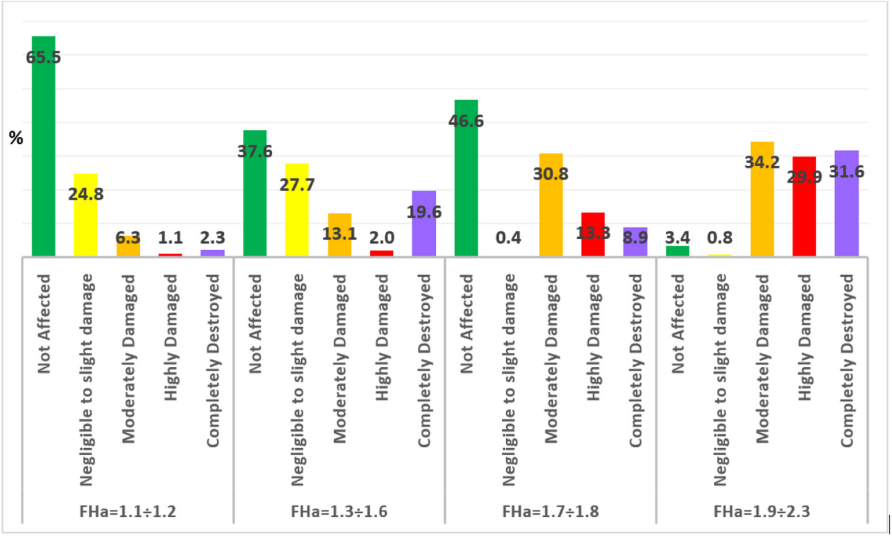

Fig. 6. Percentages of buildings stock surface, subdivided according to the five damage degree levels [5], within each different homogeneous FHa zone [18]

Table 1. Number of buildings and related areas in m^2: subdivision according to their respective damage degree levels (source: [5]) and area percentage distribution for homogeneous FHa values (period interval 0.1–0.5 s) (source: [18])

Homogeneous Amplification Factor (FHa) Zones	FHa-A Homogeneous FHa zones Area (m^2)	Damage degree	N. of buildings	BA - Building Area (m2)	% BA/BA_{tot} in relative FHa zone	% (BA/FHa-A)
1.1-1.2		*Completely Destroyed*	2	321.971	2.30	0.3%
		Highly Damaged	1	155.24	1.11	0.1%
		Moderately Damaged	4	886.21	6.32	0.8%
		Negligible to slight damage	11	3481.7503	24.82	3.3%
		Not Affected	43	9182.6762	65.46	8.7%
	153601.01		**61**	**14027.85**	100.00	**13.2%**
1.3-1.6		*Completely Destroyed*	9	2193.39	19.64	2.5%
		Highly Damaged	4	223.12	2.00	0.3%
		Moderately Damaged	8	1457.40	13.05	1.7%
		Negligible to slight damage	9	3097.47	27.74	3.5%
		Not Affected	12	4195.59	37.57	4.8%
	89845.49		**42**	**11167**	100.00	**12.8%**
1.7-1.8		*Completely Destroyed*	18	3113	8.93	1.3%
		Highly Damaged	17	4633.76	13.29	2.0%
		Moderately Damaged	64	10740.99	30.81	4.7%
		Negligible to slight damage	1	123.98	0.36	0.1%
		Not Affected	62	16255.45	46.62	7.0%
	230971.53		**162**	**34867.64**	100.00	**15.1%**
1.9-2.3		*Completely Destroyed*	68	10943.30	31.61	13.5%
		Highly Damaged	47	10363.59	29.94	12.8%
		Moderately Damaged	60	11854.09	34.24	14.6%
		Negligible to slight damage	2	292.15	0.84	0.4%
		Not Affected	7	1163.48	3.36	1.4%
	8109980		**184**	**34617**	100.00	**42.7%**
Total	**555517.84**		**449**			

In Fig. 4 are depicted the buildings heights, which are considered as proxy for estimating the building fundamental resonance period. The city centre shows a dense agglomeration of structures with an elevation between 6 and 12 m. The minority of buildings have an elevation below 6 m or above 12 m.

Figure 5 clearly shows how areas classified with higher FHa values are more densely urbanized. The spatial correlation between damages of buildings and seismic amplification, as expected, is evident. Buildings affected by higher damage levels are concentrated within the areas with higher FHa values (Table 1; Fig. 5 and Fig. 6) that, unfortunately, correspond to the densely urbanised city centre.

The present analysis highlighted a general positive correlation between the increasing trend of higher damaged buildings and growing FHa (Fig. 6). Actually, as shown in Fig. 6, this trend is straightforward for the "*Moderately damaged*" and "*Highly damaged*" classes, but not for the other two classes. The numbers for "*Negligible to slight damage*" and "*Completely Destroyed*" classes do not regularly increase with increasing FHa interval (from 1.1–1.2 to 1.9–2.3). However, if we consider the *"Completely destroyed"* class, its decreasing value within the 1.7–1.8 FHa interval is associated to a significant increase in the *"Highly damaged"* (contiguous) class, suggesting possible misclassification error among these two classes. As well, within the same 1.7–1.8 FHa interval the *"Not affected"* class is characterised by an increasing value (with respect to that of the lower 1.3–1.6 FHa interval) again associated to a very small amount of the buildings in the *"Negligible to slight damage"* class and so on. This result might be likely attributed to possible misclassification of damage level between contiguous damage classes.

5 Discussion

In some spot we have verified that Copernicus EMS attributed a *"slightly/moderately damage"* to a single construction; but the building was actually formed by two contiguous parts: one "not affected" or "slightly damaged" and the other one "completely destroyed" or "highly damaged". Some apparently anomalous results of Fig. 6 could be explained according to the hypothesis that an irregular trend can be related to the influence of factors not included in the present analysis, e.g., different vulnerability of contiguous buildings. With regards to this latter issue, further investigations are under development. More coherent results might possibly be obtained by stratifying buildings according to their vulnerability, estimated following EMS-98 classes, and performing a separate analysis for each vulnerability class. Of course, it would be worth following such an approach as long as the number of buildings within each class is statistically significant.

Moreover, some of the buildings in the South-East part of Amatrice (where FHa values are high; Fig. 5) were "not affected" or "slightly damaged". The reason is probably due to their more recent construction (seismic vulnerability of more recent buildings is still under investigation). Obviously, less damaged buildings within seismic microzones characterised by high values of FHa demonstrates that construction techniques can reduce vulnerability to seismic hazard. This should be carefully considered in the framework of urban development planning. Buildings located in seismic zones, especially the older ones, should be carefully checked in order to assess their vulnerability.

It is worth highlighting that their seismic retrofit can benefit, even totally, of financial support from the Italian Government ("Sisma Bonus", D.L. N. 63/2013 and D.L. N. 34/2019).

Geomatics, geomorphology and applied geology are increasingly interlinked as they represent the basis for innovative design/reconstruction models and adoption for modern, more efficient and smart new infrastructure in a variety of environmental contexts [6, 9, 22–25].

The advantages for central and local administrations from the exploitation of Geomatics techniques are clear, not only during the emergency management or in the recovery phases [26], but also in the framework of planning activities [27]. A number of new applications can derive from the results of the research described in the present paper, such as the advanced mapping of soil and subsoil characteristics. The classification of the territory in seismic microzones, among others, allows to identify a range of services to citizens and stakeholders. Such approach can represents the geospatial basis [28] for an effective territorial planning (urban development, exploitation of natural resources, agricultural, industrial and commercial purposes, etc.), by properly taking into account natural constraints and hazards.

The drama of catastrophic events could also represent an opportunity not only from the technical point to have new safer buildings (not necessarily preserving the original urban layout) after the reconstruction phase, but also for social and economic development. In this sense, a detailed knowledge and mapping of seismic microzones is fundamental to support the local urban planning, especially in the reconstruction phases. This is a very complex task, but the approach developed in the present study can be exploited for a proper allocation of residential and industrial areas in safer zones (even different from the original locations), whereas areas falling in more hazardous microzones could be reconverted to other uses (green infrastructures, parks, urban gardens, parking and stocking areas).

6 Conclusions

The present study exploited the levels of building damage from Copernicus EMS data [5], readily available after the 24th August 2016 earthquake, and the Seismic Microzonation study [18] within Amatrice Municipality. This has allowed to investigate the role of seismic ground-motion amplification on the observed buildings damages.

Even if very simplified assumption has been made on the seismic vulnerability of the building stock within the town, which mainly influenced the damage levels, our analysis pointed out that a significant impact was also exerted by the local geological conditions. In fact, ground-motion amplifications due to local geological conditions are well known effects and the quantitative analysis of such ground motion characteristics is fundamental for damage evaluation as well as future urban planning and reconstruction. This information can be summarized in seismic microzonation maps, where each microzone area is associated to an amplification factor (FHa). In addition, more advanced methods, including 3D numerical simulations of the Amatrice hill seismic response (like in [29]) and detailed models of the building stock vulnerability, provide quantitative insight on the specific role exerted by vulnerability and local geology on the observed damage.

Geological and geomorphological studies of urban systems and the reliable modelling of the subsoil on which they arise are continuously evolving. It is a branch of geology still under development, especially from a methodological point of view. In addition, GIS processing allows to effectively support spatial analysis opening many research and technological challenges [21–25, 30–32]. The present paper highlight that the capability to correlate seismic ground-motion amplification and the buildings damage through GIS applications, can be the driver for an efficient intervention in order to reduce building's vulnerability of existing construction, as well as new urban development models during the reconstruction phase.

In addition, an interdisciplinary and multidisciplinary approach that considers historical, geo-archaeological, geo-environmental, and seismological data can be effectively used to implement the methods of surface and subsoil geology characterisation. The use of multi-source dataset allows to perform detailed reconstructions of anthropic interventions in urban areas, as well as interactions between natural events and the human being.

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