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Sustainable planning of seismic emergency in historic centres through semeiotic tools: comparison of different existing methods through real case studies

Gabriele Bernardini[1,*], Michele Lucesoli[2], Enrico Quagliarini[3]

[1] Department of Construction, Civil Engineering and Architecture (DICEA), Università Politecnica delle Marche, Ancona, Italy: g.bernardini@univpm.it

[2] Department of Construction, Civil Engineering and Architecture (DICEA), Università Politecnica delle Marche, Ancona, Italy: m.lucesoli@pm.univpm.it

[3] Department of Construction, Civil Engineering and Architecture (DICEA), Università Politecnica delle Marche, Ancona, Italy: e.quagliarini@staff.univpm.it

- Emergency management planning for seismic emergency in historic centres is investigated.
- Emergency path availability in immediate aftermath is considered.
- 6 main semeiotic methods for path availability prediction are compared.
- A case study application allows comparing the methods reliability.
- Reliable methods should consider building-street geometry, building vulnerability and earthquake severity.

Sustainable planning of seismic emergency in historic centres through semeiotic tools: comparison of different existing methods through real case studies

ABSTRACT: Sustainable cities have to constantly face natural catastrophes, and planning actions should be oriented to quickly manage emergency conditions. Earthquake represents one of the most critical disasters. Earthquake-induced built environment modifications (i.e. building debris) affect the urban paths network availability. Historic centres are relevant scenarios because of their specific features (i.e. Heritage vulnerability; complex and compact fabric). Predicting which paths could be used by rescuers to rapidly reach damaged inhabitants could reduce losses and improve first aid actions. Sustainable semeiotic tools are proposed to quickly esteem the paths availability combining street geometrical features and building damages. Currently, no study provides insights on methods reliability. Hence, this work critically analyses methods outcomes by implementing them, for the first time, on the same real-world sample (Italian historic centres). Rapid tools (satellite images, photographic documentation) are used to compare methods previsions with effective post-earthquake paths availability. Pros and cons of each analysed method are evidenced, underlining that the approach that combines street-building geometry, building vulnerability and earthquake severity seems to give the best results. This could help Local Authorities and Civil Protection Bodies in better developing risk-mitigation strategies concerning, e.g., emergency management (rescuers' access routes definition) and urban planning (building retrofitting interventions).

Keywords: Resilient urban environment, Urban emergency planning, Historic city centres, Streets seismic damages, Evacuation, Decision support system

1 Introduction

City centres are widely prone to natural disaster, especially the historic urban parts (Santamouris, Cartalis, & Synnefa, 2015). Considering the cities resilience as a key aspect to be improved, the application of effective emergency management should be the object of more and more contributions

(Chou, Hsu, Lin, Lee, & Wei, 2017; Moretti et al., 2012). Hence, lots of them are involved in mitigating the risk due to climate events (e.g.: hurricanes, tsunamis, floods) (Kontokosta & Malik, 2018; Traore, Kamsu-Foguem, Tangara, & Tiako, 2018; Yang, Ng, Zhou, Xu, & Li, 2019) but few works focus on seismic consequence at urban scale. Historic city centres can be heavily damaged by earthquake because of the combination of extrinsic (i.e.: seismic hazard) (Kojima, Fujita, & Takewaki, 2014) and intrinsic factors (i.e.: high population density, urban fabric configuration including streets network, buildings vulnerability) (Quagliarini, Bernardini, Santarelli, & Lucesoli, 2018; Rojo, Beck, & Lutoff, 2017) characterizing the urban environment, which jointly play a relevant role for exposed population safety levels especially in relation to the immediate earthquake aftermath and the first emergency response phases (Aguado, Ferreira, & Lourenço, 2018; Staniscia, Spacone, & Fabietti, 2017; Tamima & Chouinard, 2017). Interventions on urban built-up areas should be performed by local authorities at wide scale in order to improve the population safety by preserving urban functions (Indirli, 2009). The heavy earthquake-induced damages on historic buildings emphasize the necessity to develop adequate pre-disaster risk reduction strategies aimed at a better management of emergency conditions and at organizing a rapid disaster response, while limiting the needed effort for their implementation (in terms of time and costs of strategies and intervention on the urban built environment) (Elgin, 2009; Rapone, Brando, Spacone, & Matteis, 2018).

A fundamental issue to promote similar rapid response strategies is to evaluate the urban paths network availability in immediate aftermath conditions since it effectively permits rescue teams to reach the affected area and supply first aid to injured people (Francini, Artese, Gaudio, Palermo, & Viapiana, 2018; Rojo et al., 2017). The evacuation paths network is composed by more than one urban street, linked one to each other. Thus, the path availability is ensured if each street composing the path is available.

In particular, the buildings vulnerability in a seismic event is the main factor that influences the effective street availability especially in complex or narrow urban fabric layout like the ones of

densely build-up areas and historical city centres (Aguado et al., 2018; Santarelli, Bernardini, & Quagliarini, 2018). To adopt a quick and conservative estimation of path availability (Dolce, Speranza, Bocchi, & Conte, 2018; Italian technical commission for seismic micro-zoning, 2014; Santarelli, Bernardini, Quagliarini, & D'Orazio, 2018), the path can assume two status depending on the interferences due to building debris:

1. "blocked", when debris from a considered building completely occupy the facing path section;
2. "clear", otherwise.

In this sense, the emergency plans should considered such conditions for each element of the path, so as to evidence which paths (Aguado et al., 2018; Dolce et al., 2018): will have to be avoided because they could be blocked (unavailable) by debris; will maintain their usability allowing rescuers' access to stricken areas and possible inhabitants' evacuation in safe conditions.

1.1 Methods for path availability predictions

In the last decades, literature works have widely debated semeiotic solutions to esteem the probability that debris falling from surrounding buildings could partially or totally occlude the urban streets. The proposed study provides a first attempt to organize the relevant number of different existing methods through a critical analysis of them and of their outputs. All the methods-related notations introduced in this work are reported in **Appendix A.**

Methods based on geometrical aspects are the simplest and quick-to-be applied and they could be collected in the first group visible in **Table 1**. They generally consider that hazardous interferences (leading to possible paths blockage) are connected to streets local conditions where the ratio between buildings height (h) and streets width (W) is equal or higher than 1. This approach is codified in the analyses of the Limit Condition for the Emergency (LCE) of an urban settlement (Italian technical commission for seismic micro-zoning, 2014). It is worth noticing that, in case of presence of a

courtyard between the building and the street, the courtyard width has to be added to the overall street width.

A more restrictive geometrical algorithm is proposed by Ferlito and Pizza since they propose that the path could result accessible only if the facing building height is lower than the half of street width itself so as to guarantee a free half side (Ferlito & Pizza, 2011). These methods are quick to be applied but they do not include buildings vulnerability or earthquake intensity/magnitude.

Other approaches try to jointly combine the geometrical aspects to the vulnerability of buildings assessed through rapid and low-cost methodology. The method of (Giuliani, Falco, & Sevieri, 2019) represents a first attempt to inquire street accessibility for evacuation in historical scenarios by jointly considering the importance of street itself (in case it belongs to a path with a strategic function) and its vulnerability (obtained starting to the worst macroseismic damage grade assessed among the buildings facing the street). This approach is able to define a risk hierarchy of historic street network for evacuation phases also through operative tools such as maps, but it does not directly determine a condition for paths blockage that leads to predict their inaccessibility.

A second group of works involves two other alternative approaches which try to relate different factors (i.e.: geometrical features, earthquake intensity and buildings vulnerability) proposing to assess the debris amount produced along the streets from facing buildings through empirical relationships. For each building facing the street, these approaches calculate the debris percentage on the facing street QX [%] by jointly considering the effects of the moment magnitude associated to the seismic event and the buildings vulnerability. In particular, semeiotic (e.g. macroseismic) building vulnerability methods can be applied to ensure a rapid implementation of the approach without requiring particular data from local surveys, and so reducing cost and saving time. For each building b, the multiplication between the calculated QX and the street width facing the considered building W_b [-] allows to evaluate the effective debris depth d_{ruins} [m] according to the following Equation (1):

$$d_{ruins} = QX \cdot W_b \qquad (1)$$

According to Equation (1) and the "blocked" path definition provided above, if the d_{ruins} is higher or equal than the street width, the street is considered as "blocked". Two different *debris estimation criteria* have been proposed by literature to calculate *QX*. The criterion suggested by (Quagliarini, Bernardini, Wazinski, Spalazzi, & D'Orazio, 2016), called *debris estimation criterion 1* in the following, adopts the rapid methods of (Ferlito & Pizza, 2011) to define the building vulnerability. Then, the quantity of building produced external ruins (QX_1 *[%]*) is calculated through the experimentally-based relationships reported in Equations (2) and (3):

$$V^*_1 = V_{FP} \cdot M_{ev}/M_{ev,max} \qquad (2)$$

$$QX_1(\%) = \begin{cases} 0 & if\ V^*_1 \leq 0.17 \\ 295.28V^*_1 - 49.47 & if\ 0.17 < V^*_1 < 0.51 \\ 100 & if\ 0.51 \leq V^*_1 \end{cases} \qquad (3)$$

where V_{FP} [-] is the normalized building vulnerability evaluated thanks to (Ferlito & Pizza, 2011) and M_{ev} is the earthquake moment magnitude of the event normalized for the maximum moment magnitude expected $M_{ev,max}$.

The criterion suggested by (Santarelli, Bernardini, & Quagliarini, 2018), called *debris estimation criterion 2* in the following, takes advantages from the macroseismic building vulnerability method by (Lagomarsino & Giovinazzi, 2006), and additionally considers the building height/facing street width ratio to evaluate the debris percentage. It proposes to esteem the quantity of produced external ruins (QX_2 [%]) from buildings through the experimentally-based relationships reported in Equations (4) and (5):

$$V^*_2 = V_{GL} \cdot M_{ev}/M_{ev,max} \cdot h/W \qquad (4)$$

$$QX_2(\%) = \begin{cases} 115.55V^*_2 & if\ 0 \leq V^*_2 < 0.87 \\ 100 & if\ 0.87 \leq V^*_2 \end{cases} \qquad (5)$$

where V_{GL} [-] is the normalized building vulnerability evaluated thanks to (Lagomarsino & Giovinazzi, 2006). Although they can predict the debris depth, by allowing a punctual estimation of building-facing path interferences in a detailed way, these methods reliability is connected to their experimental database dimension.

The third group of works gives the possibility of introducing in the path blockage prediction algorithm the evaluation of the damage grade suffered by buildings. The method proposed by (Francini et al., 2018) for reinforced concrete buildings and extended to masonry buildings in the conference paper by (Artese & Achilli, 2019) elaborates a methodology for planning safe routes in case of emergency predicting possible routes occlusion for Civil Protection interventions. The work takes advantages of a GIS tool and of its application to a case study. Two different buffer zone are defined to determine a maximum probable distance that the ejected material can reach, according to the following distance criteria: 1/3 of buildings height for buildings affected by 4th damage grade; equal to 2/3 of the height for buildings affected by 5th damage grade. By this way, it is possible to predict which part of the roads will be cluttered with debris. The study provides a novel buildings damage grade estimation method according to a vulnerability index evaluation given by the sum of an initial vulnerability (according to the vulnerability classes depending on the type of structure (Grünthal, 1998)) and by some additional corrective indices. Then, for each building, the related damage grade is assigned by comparing the vulnerability index with the established vulnerability thresholds (one for the 4th and another the 5th damage grade) for each macroseismic intensity level.

Street-structural unit geometrical, vulnerability and earthquake-severity aspects (through related damages) are also considered in the macroseismic damages-based methodology proposed by (Santarelli, Bernardini, Quagliarini, et al., 2018) for the paths availability in emergency condition. This model allows to relate the building vulnerability to post-earthquake damage scenario prevision based on earthquake EMS-98 intensity obtaining the related damage grades (Grünthal, 1998), according to a probabilistic approach associating the 95^{th} percentile of its cumulative distribution

function (Lagomarsino & Giovinazzi, 2006). In such conditions, the critical debris level can block the facing path according to the conditions reported by Equation (6).

$$B_{link} = \begin{cases} Blocked, \exists\ building \in path\ |^{h}/_{W} \geq 1 \wedge k95 \geq 4\ grade\ EMS98 \\ Clear,\ elsewhere \end{cases} \quad (6)$$

This methodology can use rapid detectable parameters that can be assessed by easy "in situ" surveys (external inspection, by evaluating e.g. building typology, geometrical aspects, plano-altimetric irregularity) and by "remote" inspections (e.g. by using photographic documentations and satellite sources) (Quagliarini, Lucesoli, & Bernardini, 2019).

Finally, literature works also offer other methods that try to focus on out-of-plane walls failure modes combined to fragility curves (Argyroudis, Selva, Gehl, & Pitilakis, 2015) or probabilistic and fuzzy logic analyses of the potential interaction between building and roads (Zanini et al., 2017). Anyway, such models are complex since they require accurate on-site surveys (mainly: building geometry including data from internal inspections; building materials strength) to effectively produce a good estimation of a single failure model (out-of-plane). Hence, they are not applied to this study.

Table 1 *Comparative table of considered methods to evaluate the urban path blockage where: h is the height of a building facing the street, W is the street wide and k95 is the damage grade according to (Lagomarsino & Giovinazzi, 2006).*

Inquired methods:	*Limit Condition for the Emergency (LCE)*	*Ferlito and Pizza*	*Debris estimation criterion 1*	*Debris estimation criterion 2*	*Artese Achilli*	*k95* macroseismic damages-based
Grouped by type:	(1) Geometric approaches		(2) Debris formation criteria		(3) Macroseismic damage-based approaches	
Ref.	(Italian technical commission for seismic micro-zoning, 2014)	(Ferlito & Pizza, 2011)	(Quagliarini et al., 2016)	(Santarelli, Bernardini, & Quagliarini, 2018)	(Artese & Achilli, 2019)	(Santarelli, Bernardini, Quagliarini, et al., 2018)
Blocked	h/W ≥ 1	h/(W/2) ≥ 1	druins ≥ W	druins ≥ W	Damage=4; 1/3h ≥ W Damage=5; 2/3h ≥ W	$^{h}/_{W} \geq 1 \wedge k95 \geq 4$ *grad*
Clear	h/W < 1	h/(W/2) < 1	druins < W	druins < W	Otherwise	Otherwise
Influencing factors	Geometrical ratios	Geometrical ratios	Vulnerability, Magnitude, Geometrical ratios	Vulnerability, Moment Magnitude, Geometrical ratios	Damage grade as function of: Vulnerability, Intensity; Geometrical ratios	Damage grade as function of: Vulnerability, Intensity; Geometrical ratios
Advantages from other studies:			(Ferlito & Pizza, 2011) for	(Lagomarsino & Giovinazzi, 2006) for	(Grünthal, 1998)	(Lagomarsino & Giovinazzi, 2006)

		vulnerability estimation	vulnerability estimation	

1.2 Work aims and outline

According to Section 1.1, such themes are widely debated in the research field of seismic emergency management. Indeed, they have led to the development of multiple and different approaches, but at today, it does not exist any experimental check of all these existing methods on the same sample. The literature review (Section 1.1) provides different methods but only six of them are selected to be applied in the following. Firstly, the selected methods concern the ones that fit with the research aim of this work, which is strictly limited to inquire critical condition in emergency of historical urban fabrics, and particularly focuses on masonry building typology. Meanwhile, the other methods cited in the literature section have been excluded since they could not be considered as semeiotic methods because of their significant computational commitment and for the specific data required for their application. The selected existing methods are grouped into three types and reported in **Table 1.**

The authors would point out that the main work aim is not to promote a novel methodology to assess evacuation routes availability, but to provide a first insight on the reliability of main existing semeiotic methods. In this term, the novelty of the manuscript consists in providing a first experimental evaluation of their outcomes on a real-world sample. For the first time, each method in **Table 1** is implemented on the same sample of buildings and streets. In this way, all results can be comparable. Therefore, the present work provides a further contribution about methods reliability by demonstrating their level of consistency with the real condition of streets extrapolated by available documentation about a sample recently stricken by an earthquake. The data about damages scenarios are collected indeed after the Central Italy seismic sequence in 2016. Through this process, it is possible to start to comprehend and suggest which among these methods could be better appreciated and in which cases/conditions, as supporting tool for emergency planning from Local Authorities and Civil Protection Bodies

2 Phases and methods

2.1 Phases

The paper is organised in the following phases:

- Sample collection and analysis: a sample of 50 earthquake-damaged buildings, placed in urban environment and facing urban streets, is collected. For each building, the seismic vulnerability is assessed as well as the suffered damage grade (according to the EMS-98 damage grade) and the h/W ratio are detected through photographic documentation and satellite images before and after the seismic event. In addition, satellite maps of immediate earthquake aftermath are used to esteem the real conditions of paths (blocked or clear), by considering the street space facing each considered building in the sample (Section 2.2);
- Reliability of the selected methods (**Table 1**) in predicting paths availability after an occurred event: this phase is carried out through the methods application on the considered sample. Outcomes of the methods (Section 2.3) with observed real-world conditions (real effects of an earthquake on urban paths availability) are compared to reach this goal. Then, the discussion of the final results determines which is the more accurate predictive approach among the selected.

2.2 Sample definition and needed data collection

The considered sample is composed by masonry buildings placed in a limited area affecting the historic centres of Accumoli, Amatrice, Arquata del Tronto, Capodacqua and Illica (**Figure 1**) stricken by the Central Italy seismic sequence in 2016, with the epicentre in Accumoli (RI) (42.7,13.23), on 2016/08/24 03:36:32 (UTC+2), Mw=6.0 (Seismic database: *http://cnt.rm.ingv.it/en/event/7073641/* last access 2019/04/10). The selected buildings (mainly for their various damage levels and for the availability of data about vulnerability and about the geometrical measures of streets) are subdivided in structural units (defined as independent structural

parts composing the building itself), which suffered from 1st to 5th damage grade according to EMS-98 scale (Grünthal, 1998). They were located in a restricted area with a limited range of macroseismic intensity values (from 8.8 to 9.3 registered by USGS's Shake Maps available on: https://earthquake.usgs.gov/data/shakemap/ last access 2019/04/10) and so the moment magnitude, provided above, can be reasonably considered about the same on the overall territory (according to the aforementioned shake maps).

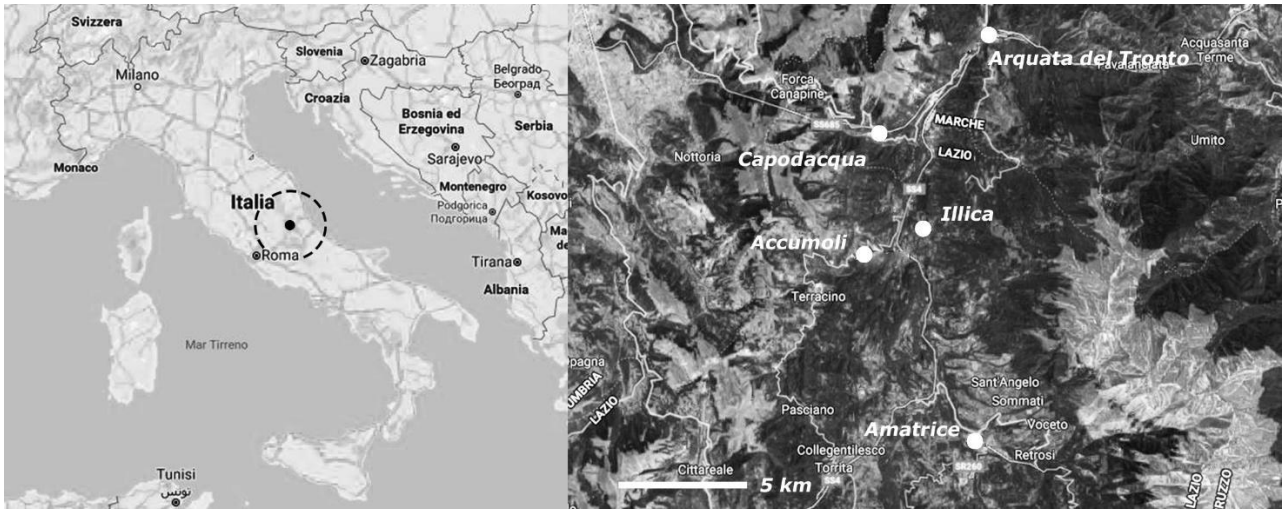

Figure 1 *Maps of Central Italy stricken area with on the left side the small towns close to the epicentral region where sample buildings are placed (image source: https://www.google.com/maps/@42.6883879,13.3319947,56567m last access on 2019/04/10).*

According to previous works (Quagliarini et al., 2016), structural units height (h) and facing streets width (W) are remotely evaluated thanks to the large availability of photographic documentation. All the planar dimensions (façades edges and streets widths) are calculated by using OpenSearch satellite images scaling tools (i.e.: Google Earth Pro version 7.3 https://www.google.com/intl/it/earth/versions/ last access 2019/04/10), aided with CAD software. In particular, façades heights are evaluated by straightening and scaling façades frontal photos according to the planar measure of the façade side length (without direct on-site measurements).

Buildings features and the other parameters required for the evaluation of the structural units vulnerability are collected through Google Street View and Google Maps (https://www.google.com/maps last access: 2019/07/12) and from post-earthquake photos available

on reliable websites (Corpo Nazionale dei Vigili del Fuoco *http://www.vigilfuoco.tv/* and Italian Civil Protection *http://www.protezionecivile.gov.it/jcms/it/multimedia.wp* last access 2019/04/10). In addition, the effective damage grade of each single building is evaluated by applying the macroseismic damage scale EMS-98 definitions (Grünthal, 1998) compared with the collected post-earthquake photographical documentation.

Finally, to detect the real conditions of urban scenarios, Satellite Grading maps of Copernicus European project (*http://emergency.copernicus.eu/mapping/ems/what-copernicus* last access 2019/04/10) are used defining if the street facing each building in the sample was blocked by debris accumulation. This last investigation takes advantages only through the visual evidence of satellite images. Therefore, it results quite impossible to strictly link the damaged building and the related debris/damage along the path in case: (a) the buildings were placed very close one to each other; (b) the collapse of facing buildings (on opposite street side) occurs. Hence, to avoid an incorrect debris evaluation due to each building, real case studies were selected by taking into account the following conditions: (a) debris generated by adjacent buildings were absent; (b) facing damaged building on opposite street side were not present. By this way, it is possible to effectively attribute debris to the considered building by avoiding incorrect estimations on path blockage due to the surrounding ones.

2.3 Comparison criteria

The methods investigated by this study are the ones reported in **Table 1**, since they are quick-to-be applied, by ensuring their sustainability for the application at urban scale due. As evidenced in Section 1, for each path, the considered methods could be able to provide binary outcomes:

- "blocked" streets, if debris completely occupy the streets section facing the considered building;
- "clear" streets, otherwise.

Real-world observations of street status are based on the same definitions.

Three situations can emerge from comparisons between the predicted result from a method application and the corresponding real-world observation:

1. correspondence between predicted and real path condition;
2. overestimation, in case the considered method predicts a "blocked" path, but the real-world observation refers to "clear" path conditions. In this case, the method prediction produces a conservative result;
3. underestimation, in cases the considered method predicts a "clear" path, but the real-world observation refers to "blocked" path conditions. In this case, the method prediction produces an "unsafe" result.

For each method, the percentages of correspondence, overestimation and underestimation cases are provided. The most reliable methods should minimize the underestimation cases to err in the side of caution, while maximizing the correspondence cases.

Finally, the two *macroseismic damages-based* approaches (the one of (Artese & Achilli, 2019) and the other of (Santarelli, Bernardini, Quagliarini, et al., 2018)) are analysed by providing a further assessment of their reliability focused only on the algorithm to determine the width of the area influenced by possible debris formation. For each method, this analysis is based on the substitution of the assessed damage grade with the the real-world detected damage grade after the earthquake occurrence. The damage grade is determined according to the EMS98 scale definitions by taking advantages of the large availability of post-earthquake photographic documentation (see Section 2.2). In this sense, this test is independent from the criteria used for the buildings damage grade prediction since it does not consider both the damage prevision and the vulnerability evaluation connected to the chosen method. In this way, the test overcomes: (a) intrisic errors due to the estimation methods application; (b) differences in the application of each method. In the following, these approaches are identified respectively as *"Observed Artese Achilli"* and "*Observed macroseismic damages-based*" methods. The last method is further investigated by subdividing the whole tested sample in the

suffered five damage grades and separately analysed in order to evidence the influence of damage grades on the urban path blockage prediction reliability according to the aforementioned situations. An investigation on specific buildings which offer differences between these methods predictions and observed results are also offered to evidence the method reliability-affecting causes.

3 Results

Appendix B reports the results of the tested sample made by 50 structural units in terms of "blocked" or "clear" paths, for each of the selected methods.

Table 2 summarizes the percentage of cases for which: predicted and effective path blockage conditions, correspond (C); the methods overestimates the path blockage, since the prediction involves a blocked path while it is available in the reality (O); the sum of correspondence and overestimation percentages (which corresponds to conservative results).

Table 2 *Percentage results of comparisons between each considered method and real-world scenario conditions are reported indicating the total percentage of cases of correspondence (C), Overestimation (O) and their sum (C+O) on the overall sample made by 50 structural units associated to their underlying urban streets.*

Methods	*Limit Condition for the Emergency (LCE)*	*Ferlito and Pizza*	*Debris estimation criterion 1*	*Debris estimation criterion 2*	*Artese Achilli*	*Observed Artese Achilli*	*k95 macroseismic damages-based*	*Observed macroseismic damages-based*
C	64%	52%	50%	60%	46%	76%	64%	96%
O	36%	48%	2%	26%	12%	2%	36%	4%
C+O	100%	100%	52%	86%	58%	78%	100%	100%

3.1 Geometric approaches: LCE and Ferlito and Pizza's methods

By comparing these methods results to the effective conditions registered after the Central Italy seismic sequence in 2016, it emerges that for the *LCE* method the 64% of cases predicts correctly the effect of debris accumulation on streets blockage and for the remaining 36% a considerable overestimation is noticed. Results from *Ferlito and Pizza's* method show a correspondence for the 52% of cases and for the remaining 48%, the method predicts blocked some paths that in real conditions are not affected by such damages and they result available for rescuers' passage.

Both methods do not lead to underestimation errors. Thus, they can be used for the emergency plan definition according to a conservative approach, by avoiding to predict available paths that can be probably blocked. Anyway, they seem to be not the most appropriate ones to select which paths could be integrated into a guidance system to conduct rapidly rescuers to heavy damages prone area or to suggest safe paths to evacuees. In fact, too many streets, especially in historic centres, could be perceived by these methods as risky or unavailable, blocked by buildings collapsed, slowing down i.e. the arrival of emergency teams.

3.2 Debris formation criteria for paths blockage

Comparing real registered situation of the considered sample to the original method *debris estimation criterion 1* by (Quagliarini et al., 2016), results suggest to avoid the implementation of this methodology in urban emergency planning operations because of its scarce capability in predicting correctly the paths blockage (in the 48% of cases the method suffers from underestimation by declaring as clear the blocked paths in real conditions). On the contrary, in the other approach *debris estimation criterion 2* by (Santarelli, Bernardini, & Quagliarini, 2018) an opposite trend emerges from its results:

- in the 60% of cases the algorithm predicts path conditions (blocked or clear) correctly;
- in the 26% of cases, the algorithm declares as blocked paths that are effectively clear from Satellite images;
- in the remaining 14% of cases, the algorithm errs predicting as not obstructed paths that in reality are blocked. These cases are essentially due to buildings that suffered very heavy structural damages (Grade 5 in the damage EMS-98 classification) but seemed to have a low vulnerability index. Such results confirm previous method (Santarelli, Bernardini, & Quagliarini, 2018) analysis on vulnerability assessment errors affecting the method.

This seems to confirm the satisfying reliability of the *debris estimation criterion 2* in comparison to the *debris estimation criterion 1*, since it limits the underestimation occurrences. However, the main difference between these two debris estimation methods seems to be embodied by the implemented buildings vulnerability assessment approaches and the capability for *debris estimation criterion 2* to influence results also by the buildings height and streets width ratio.

3.3 Macroseismic damages-based approaches

The *Artese Achilli* method application evidences a relevant percentage of cases 46% where the paths blockage is predicted correctly. This result follows the general trend of the other methods previously analysed. At the same time, although this method considers not only geometrical features but also the macroseismic damage grades as a function of buildings vulnerability and seismic intensity, it cannot be considered among the best-performing methods examined. In fact, it errs underestimating the blockage in the 42% of cases (the method predicts as clear the streets that are effectively blocked in the real-world conditions).

The reliability of general *macroseismic damages-based* approaches is also investigated by substituting the damage grade prevision method assumed by each inquired method with the results of the effective damage grade observation on a real post-earthquake scenario according to EMS98 scale (made possible thanks to the large availability of seismic damages photos). For the *Observed Artese Achilli* approach, results (**Table 2**) show that the reliability increases up the 76% of correspondences between predicted and real-world blockage of paths. However, for the majority of the remaining percentage of cases, the presence of a significant underestimation percentage (22%) seems to confirm the same results and comments to the original method application.

Otherwise, the results of the application of the *k95 macroseismic damages-based approach*, shows the punctual correspondence between the predicted availability of paths in emergency and the real-world conditions in the 64% of analysed sample cases. For the residual 36%, the methodology tends

to overestimate the path blockage. Hence, this method provides conservative results for the 100% of inquired cases.

Further confirmation of this method reliability is provided by the *Observed macroseismic damages-based* approach, which substitutes, in Equation (6), the assessed building damage grade (Lagomarsino & Giovinazzi, 2006) with the effective damage grade. Its application results register an optimization of the percentage of correspondence between the prediction capabilities of this method application and real-world observations up to the 96%, with a remaining acceptable error of 4% of overestimation cases. **Figure 2** shows a typical result obtained from this method application reported as an example.

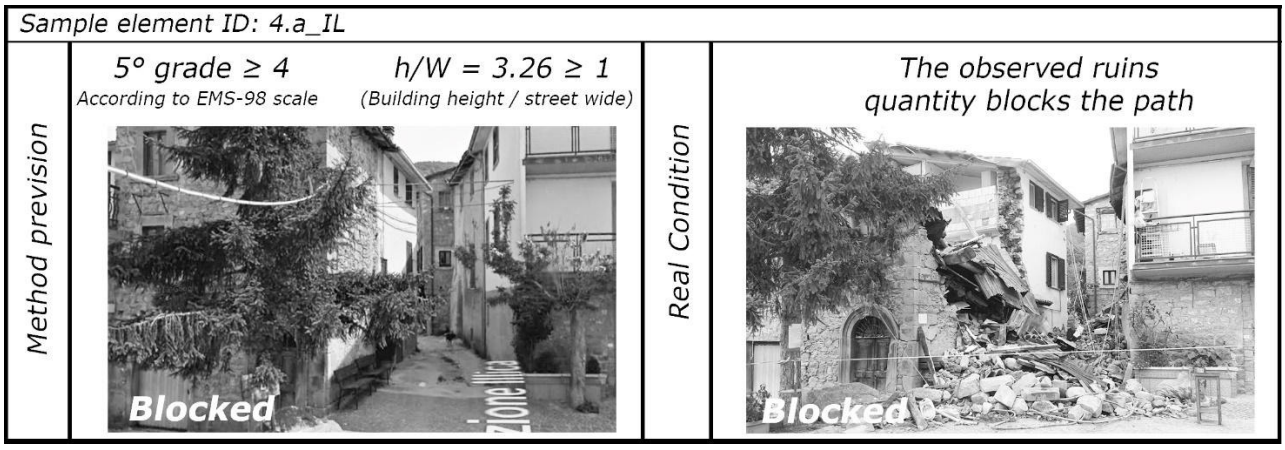

Figure 2 *Comparison between the Observed macroseismic damages-based approach prevision and real conditions of path blockage for a building in the sample (Element ID code: 4.a_IL in* ***Appendix B****): the path is effectively blocked because the observed damage is higher than the 4th grade and the ratio between building height and street width is higher than 1.*

Comparisons to the real-world images evidence that $h/W \geq 1$ is the main driver in facing path blockage especially for buildings that suffered from high damages. In addition, the sample paths affected by a facing building with a damage grade equal to 1st, 2nd and 3rd, do not embody interferences for rescuers' access, confirming the goodness of the critical limit fixed by the *macroseismic damages-based* method at the 4th grade. For paths affected by 4th and 5th facing buildings damage grades, results, shown by **Appendix B**, show that paths result blocked in the 71% of cases where buildings are affected by the 4th damage grade and in the 88% where buildings are affected by the 5th confirming

that higher the building damage grade suffered, higher the probability that paths can be blocked by debris formation.

Within the considered sample, errors in paths availability prediction are connected to only two structural units affected by the 4th damage grade (so described: *" Very heavy damage: heavy structural damage, very heavy non-structural damage; serious failure of walls; partial structural failure of roofs and floors"* (Grünthal, 1998)), as shown by **Figure 3** (concerning structural units Element ID codes 1.a_IL and 19.a_IL in **Appendix B**). In both buildings, only a limited area of the masonry façade collapsed on the facing street without leading to path blockage even if their ratio h/W is higher than one. Such buildings could be influenced by specific aspects to be investigated separately (e.g.: particular retrofitting interventions or local failure modes restricted to masonry portions). In particular, structural unit 1.a_IL (**Figure 3** A) was subject to an invasive retrofitting intervention which generates a particular failure mode. The presence of a reinforced concrete ring beam at each level with different cross sections (remarked by dotted black lines in **Figure 3** A) directed the failure mode of the masonry where a smaller reinforced concrete section was present.

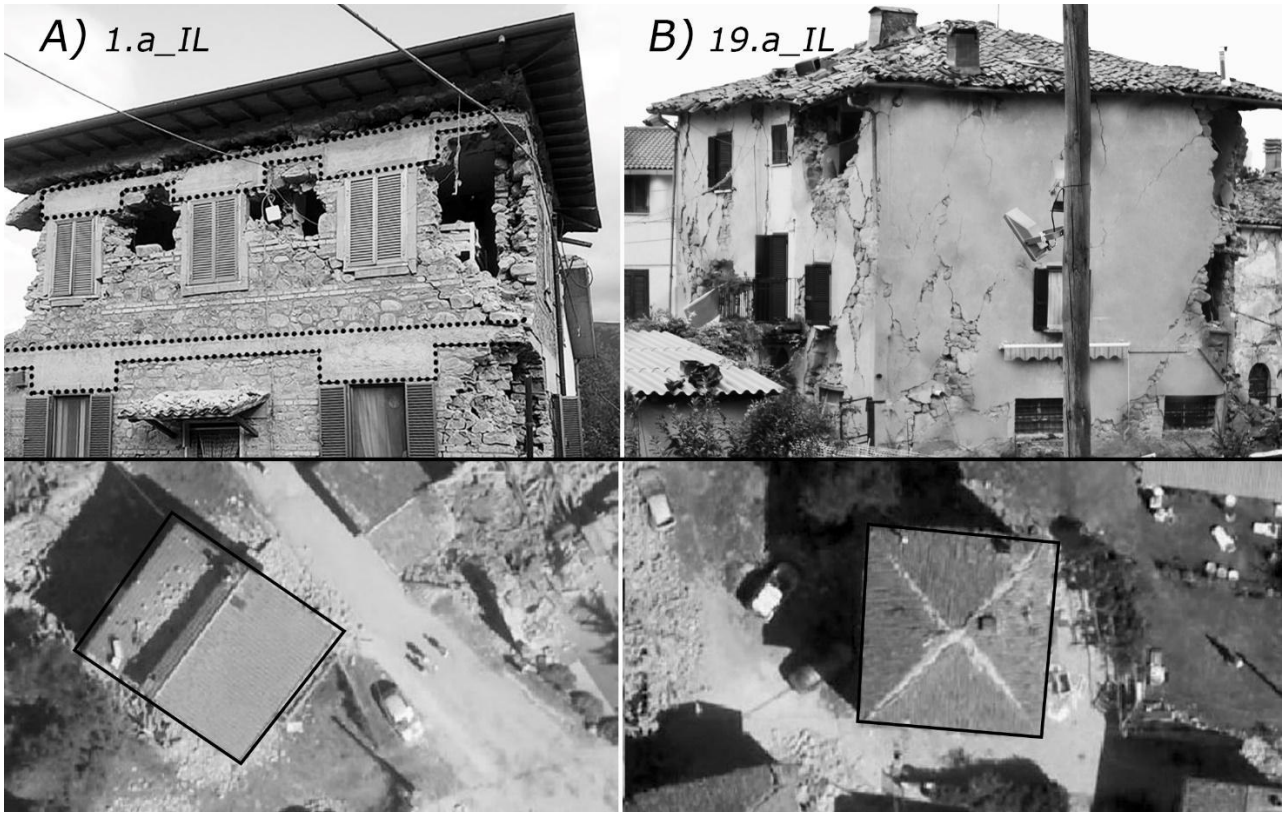

Figure 3 *Structural units with differences between real-world and predicted path availability: A) 1.a_IL on the left side and B) 19.b_IL in the right; according to Equation (6) facing streets should have been blocked but from observations they result clear; the dotted black lines in A) highlight the presence of particular retrofitting intervention (reinforced concrete rings) that could influence the failure mode. Images from https://www.repubblica.it/ and http://emergency.copernicus.eu/mapping/ems/ (last access 2019/04/10) modified by the authors.*

Structural unit 19.a_IL in **Figure 3** B shows relevant scattered cracks on its façades, since a building corner and other portions of masonry wall seem to be collapsed. Nevertheless, the scarce amount of produced debris could be due to the presence of some factors (e.g.: not visible retrofitting interventions or particular construction techniques employed on horizontal structures) that could influenced the strength of the whole structure and that could not be directly evaluable through a quick external survey.

3.4 Discussions

The comparisons among methods results and their capabilities allow to affirm that:

- The current geometrical approach *LCE* proposed by the Civil Protection (Italian technical commission for seismic micro-zoning, 2014) and the (Ferlito & Pizza, 2011) method could be perceived as too much restrictive. The first method predicts the 86% of sample paths as inaccessible while the second method reaches the 98%. Thus, emergency strategies result quite hard to be planned so as it would be hard to find the safest and fastest access route for rescuers or to suggest safe paths to evacuees. The application of such method is particularly critical for complex and compact built environment like the ones of the Historical City Centres, where the h/W ratios are generally higher than 1. The scarce reliability of the other methods is confirmed by comparing the outputs of the other applied methods with the consequences of a real seismic event, although these two approaches embody the more rapid implementation by requiring easy-to-detect parameters (i.e.: building heights and streets width);
- The *debris estimation criterion 2* developed by (Santarelli, Bernardini, & Quagliarini, 2018) could be appreciated to esteem paths availability indeed from results analysis, the method succeeds in paths occlusion prediction for the 86% of undergone sample elements. This approach could be adopted where particular geometrical restriction or situation can suggest a punctual evaluation of the availability of a street area, by contemporarily assessing the building debris quantities and the effective street width available to the rescuers' access (i.e. for rescuers' vehicles movement). Anyway, the method prediction could be enhanced by enlarging the experimental sample to better estimate factors values within the equation on path debris estimation;
- The *Artese Achilli* approach could be appreciated because of: (a) the determination of emergency paths in function of macroseismic intensity and of vulnerability index (strictly related to the typology of the building); (b) the implementation on a GIS tool that can be useful for considering the inquired buildings on both sides of the streets, from an overall point of view. Nevertheless, an underestimation of blocked paths is noticed. Applying the *Observed*

Artese Achilli with damages directly detected through post-earthquake documentation, the reliability of the proposed debris depth prediction criterion (i.e.: the buffer zone) improves sensibly.

On the other side, the original *k95 macroseismic damages-based* approach (Santarelli, Bernardini, Quagliarini, et al., 2018) could be assumed as the best one among the evaluated methodologies. In fact, the percentage of correspondences is higher not only than the *Ferlito and Pizza* and than the *LCE* method, but it also overpasses both *debris formation criteria* and the *Artese Achilli* approach. However, in respect to the first two methods, the *k95 macroseismic damages-based* approach can allow considering the earthquake severity and the building vulnerability within the scenario creation, while maintaining low-cost and easy-to-apply techniques. Finally, its higher reliability in predicting paths blockage on the other *macroseismic damage-based* method is also further validated by substituting the damages estimation system with a real damages survey from an occurred earthquake, results delivered from the *Observed macroseismic damages-based* approach. These results also demonstrate that the approach reliability can improve with the enhancement of the damages prediction method and also that they are sensibly influenced by it. However, the estimation algorithm of the area width interested by debris seems to be appreciable independently from the damage prediction.

4 Conclusions and remarks

Seismic event represents one of the most significant disaster our sustainable cities have to face. Thus, mitigation actions aimed at quickly managing that emergency should be planned to increase the population resilience and resistance. From this point of view, providing safe paths that can be used by rescuers and evacuees assumes a key role in such kind of actions. Quick-to-be applied methods for path availability prediction could be applied to support safety planners, Local Authorities and Civil Protection Bodies in earthquake scenarios development and so in planning such actions. Historic

centres are relevant scenarios to face such issues, because of their specific features (i.e. Heritage vulnerability; complex and compact urban fabric, with very high building facing narrow streets).

Thus, this work provides a first insight on some of the main current semeiotic tools, designed to esteem the availability of emergency paths aftermath the occurrence of a seismic event in a historic centre scenario. Different approaches are tested on the same case studies (historical centres) affected by real-world consequences of a recent earthquake.

Results show how most of the current methodologies (also adopted by Local Authorities and Civil Protection Bodies) that take into account only geometrical aspects (i.e. building height and street width) seem to be affected by many scenario prediction limitations. In fact, they: 1) neglect other fundamental factors altering the historic urban environment (i.e.: buildings vulnerability), as well as do not allow to provide different scenario in terms of earthquake severity; 2) can ideally consider as "blocked" the majority of possible access/evacuation routes in historical centres (because of the high ratio between building height and facing street width). Within the considered methods, the *macroseismic damages-based* approaches, that include the building vulnerability and the earthquake severity description, seem to be the most reliable ones, in particular, the method proposed by (Santarelli, Bernardini, Quagliarini, et al., 2018), in terms of possibility to predict the post-earthquake scenario. From this point of view, since this method adopts a macroseismic damages-based approach, it could be preventively used by safety planners to investigate different emergency scenarios also in terms of earthquake intensity. However, since this work investigates the reliability of path availability estimation methods through an experimentally-based approach, future works should enlarge the used sample dimension by extending the application to different contexts, by also including not only historical city centres. This operation could also provide remarks on modifications to the path availability estimation methods to better fit the experimental outcomes.

Results underlines how practitioners could be encouraged to provide future applications of semeiotic methods for path availability estimation by preferring the ones combining vulnerability, street-

building geometry and earthquake severity. In general terms, municipalities and local authorities could take advantages from the proposed method to plan preventive actions and test if emergency plans can be effective in relation to possible earthquake-induced urban fabric modifications. In the pre-disaster phase, considering different earthquake severity scenarios could lead to evaluate possible alternative evacuation plans by considering the rescuers' access routes depending on the effective conditions. Otherwise, in the immediate earthquake aftermath, the adoption of quick-to-be-applied methods could also lead to a quasi-real-time application, by taking advantage of real-world monitoring data (e.g. seismic magnitude calculation), so as to better face the disaster according to a proactive and dynamic approach.

Moreover, such results could be also used to promote specific interventions on the Building Heritage to reduce the vulnerability of critical elements into the urban fabric (i.e.: punctual retrofitting interventions on buildings where they are required). From this point of view, risk reduction strategies connected to the emergency plan could also focus on the use of available evacuation paths by the damaged population while reaching first responders and safe areas. For instance, preparedness actions towards the population could involve the spread of recommend emergency paths, while emergency wayfinding solutions could be implemented in the urban streets so as to evidence them.

5 Appendix A

Table A1. *Notation table*

Symbol	Measure	Description
h	m	Mean building height
W	m	Mean street width
QX	[%]	Generated debris percentage outside a building
b	-	Stand for the considered building
W_b	m	Refers to the mean street width facing the building b
d_{ruins}	m	Evaluated effective debris depth on street
QX_1	[%]	Generated debris percentage outside a building according to the *debris estimation criterion 1*
V^*_1	-	Buildings vulnerability index modified employed in *debris estimation criterion 1*
V_{FP}	-	Buildings vulnerability index according to (Ferlito & Pizza, 2011)
M_{ev}	-	Earthquake moment magnitude to assume as input
$M_{ev,max}$	-	Earthquake maximum moment magnitude expected in the studied region
QX_2	[%]	Generated debris percentage outside a building according to the *debris estimation criterion 2*

V^*_2	-	Buildings vulnerability index modified employed in *debris estimation criterion 1*
V_{GL}	-	Buildings vulnerability index according to (Lagomarsino & Giovinazzi, 2006)
B_{link}	-	It is the acronym for indicating the index proposed by (Santarelli, Bernardini, Quagliarini, et al., 2018)
$k95$	-	95th percentile of the cumulative distribution function of mean damage grades according to (Lagomarsino & Giovinazzi, 2006)
Mw	-	Registered moment magnitude of the Central Italy seismic event in 2016
μ_D		The buildings damage grades according to EMS-98

6 Appendix B

Table B1 Results of the case study buildings (50 structural units with their streets) application of this study. For each of them, the table shows their geometrical measures and ratios, the buildings damage grades (μ_D) according to EMS-98 and results application of: civil protection method, Ferlito and Pizza's 2011, both debris estimation criteria, the original Artese Achilli method and the Observed one, the k95 macroseismic damages-based method and the Observed macroseismic damages-based one and finally, the real scenarios conditions (C stands for "clear" and B for "blocked"). Each element ID is relates to a structural unit, according to the following criterion: the number identify the aggregate; the letter identifies the related structural unit; the capital letters stand for the urban centre of origin (IL for Illica (RI), AS for Amatrice (RI) south part, AN for Amatrice (RI) north part, CD for Capodacqua (AP), AC for Accumoli (RI), AT for Arquata del Tronto (AP)).

Element ID	*h* [m]	*W* [m]	*h/W*	μ_D	*Limit Condition for the Emergency (LCE)*	*Ferlito and Pizza*	*Debris estimation criterion 1*	*Debris estimation criterion 2*	*Artese Achilli*	*Observed Artese Achilli*	*k95 macro-seismic damages-based*	*Observed macro-seismic damages-based*	*Real scenario*
4.b_IL	7.1	3.5	2.03	1	B	B	C	B	C	C	B	C	C
4.c_IL	6.5	4	1.63	1	B	B	C	B	C	C	B	C	C
21.a_AS	7.1	5.5	1.29	2	B	B	C	C	C	C	B	C	C
21.e_AS	5.7	3.1	1.84	2	B	B	C	B	B	C	B	C	C
21.f_AS	5.5	3.1	1.77	2	B	B	C	C	C	C	B	C	C
21.g_AS	2.9	3.1	0.94	2	C	B	C	C	C	C	C	C	C
2.g_AN	3.0	3.8	0.79	2	C	B	C	C	C	C	C	C	C
1.a_CD	6.4	8.5	0.75	2	C	B	C	C	C	C	C	C	C
8.e_AC	10.2	3.5	2.91	2	B	B	C	B	C	C	B	C	C
1.b_IL	7.3	5.6	1.30	2	B	B	C	C	C	C	B	C	C
4.h_IL	6.8	1.5	4.53	2	B	B	C	B	B	C	B	C	C
9.a_IL	6.7	3.1	2.16	2	B	B	C	B	C	C	B	C	C
9.b_IL	9.2	1.9	4.84	2	B	B	C	B	B	C	B	C	C
2.c_AN	10.7	9.7	1.10	2	B	B	C	C	C	C	B	C	C
9.c_AS	7.0	2.1	3.33	3	B	B	C	B	B	C	B	C	C
9.c_IL	4.8	3.1	1.55	3	B	B	C	B	B	C	B	C	C
1.f_AS	7.5	5.7	1.32	3	B	B	C	C	C	C	B	C	C
1.b_AT	12.5	6	2.08	3	B	B	B	B	C	C	B	C	C
6.f_AN	8.7	3.7	2.35	3	B	B	C	B	C	C	B	C	C
19.a_IL	7.5	2.5	3.00	4	B	B	C	B	B	B	B	B	C

20.a_IL	7.3	3.8	1.91	4	B	B	C	C	C	C	B	B	B
9.d_AS	6.6	2.1	3.14	4	B	B	C	B	C	B	B	B	B
21.c_AS	7.1	5.5	1.29	4	B	B	C	C	C	C	B	B	B
22.a_AC	9.0	4.5	2.00	4	B	B	C	B	C	C	B	B	B
1.a_IL	8.6	5	1.72	4	B	B	C	B	C	C	B	B	C
2.e_AN	10.9	12	0.90	4	C	B	C	C	C	C	C	C	C
6.a_CD	10.1	6.7	1.51	4	B	B	C	B	C	C	B	B	B
6.b_CD	11.5	3.7	3.11	4	B	B	C	B	B	B	B	B	B
1.a_AT	16.3	4	4.08	4	B	B	C	B	C	B	B	B	B
1.d_AS	8.8	6.5	1.35	4	B	B	C	C	C	C	B	B	B
6.b_AN	10.9	3.7	2.93	4	B	B	C	B	C	C	B	B	B
6.g_AN	8.1	2.8	2.89	4	B	B	C	B	C	C	B	B	B
2.b_AN	8.9	9.7	0.92	4	C	B	C	C	C	C	C	C	C
4.a_IL	7.5	2.3	3.26	5	B	B	C	B	B	B	B	B	B
6.a_AN	5.9	3.7	1.59	5	B	B	C	B	C	B	B	B	B
6.b_AS	9.6	3.7	2.59	5	B	B	C	B	C	B	B	B	B
2.d_AN	9.4	3.5	2.67	5	B	B	C	B	C	B	B	B	B
2.a_IL	5.3	4.9	1.08	5	B	B	C	C	C	C	B	B	B
3.b_IL	3.5	6.5	0.53	5	C	B	C	C	C	C	C	C	C
4.d_IL	4.1	4	1.03	5	B	B	C	C	C	C	B	B	B
7.a_IL	3.8	8.4	0.45	5	C	C	C	C	C	C	C	C	C
1.a_AS	9.2	3.4	2.71	5	B	B	C	B	B	B	B	B	B
1.b_AS	8.2	3.4	2.41	5	B	B	B	B	B	B	B	B	B
1.c_AS	9.1	6.5	1.40	5	B	B	C	C	C	C	B	B	B
6.c_AS	10.0	2.9	3.45	5	B	B	C	B	C	B	B	B	B
21.b_AS	8.3	5.2	1.60	5	B	B	C	B	C	B	B	B	B
6.c_AN	11.9	3.7	3.22	5	B	B	C	B	C	B	B	B	B
6.d_AN	11.0	3.7	2.97	5	B	B	C	B	C	B	B	B	B
6.e_AN	12.1	3.7	3.27	5	B	B	C	B	C	B	B	B	B

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Data set https://data.mendeley.com/datasets/cfp65g3v3c/draft?a=6d9401c5-d346-48e2-a247-ae135cb42f2a

Data for: Sustainable planning of seismic emergency in historic centres through semeiotic tools: assessment of different methods through real case studies

The considered sample is composed by masonry buildings placed in a limited area affecting the historic centres of Accumoli, Amatrice, Arquata del Tronto, Capodacqua and Illica stricken by the Central Italy seismic sequence in 2016, with the epicentre in Accumoli (RI) (42.7,13.23), on 2016/08/24 03:36:32 (UTC+2), Mw=6.0 (Seismic database: http://cnt.rm.ingv.it/en/event/7073641 last access 2019/04/10). The selected buildings (mainly for their various damage levels and for the availability of data about vulnerability and about the geometrical measures of streets) are subdivided in structural units (defined as independent structural parts composing the building itself), which suffered from 1st to 5th damage grade according to EMS-98 scale (Grünthal, 1998). They were located in a restricted area with a limited range of macroseismic intensity values (from 8.8 to 9.3 registered by USGS's Shake Maps available on: https://earthquake.usgs.gov/data/shakemap/ last access 2019/04/10) and so the moment magnitude, provided above, can be reasonably considered about the same on the overall territory (according to the aforementioned shake maps). For each building in the sample, DATA sheet shows geometrical measures and ratios, the buildings damage grades according to EMS-98 and results application of: civil protection method, Ferlito and Pizza's 2011, both debris estimation criteria, k95 macroseismic damages-based and Observed macroseismic damages-based methods (EMS-98 damages by photos) and finally the real scenarios conditions (C stands for "clear" and B for "blocked"). In particular, 3 situations can emerge from comparisons between the predicted result from a method application and the corresponding real-world observation: 1. correspondence between predicted and real path condition; 2. overestimation, in case the considered method predicts a "blocked" path, but the real-world observation refers to "clear" path conditions. In this case, the method prediction produces a conservative result; 3. underestimation, in cases the considered method predicts a "clear" path, but the real-world observation refers to "blocked" path conditions. In this case, the method prediction produces an "unsafe" result. Each element ID is relates to a structural unit, according to the following criterion: the number identify the aggregate; the letter identifies the related structural unit; the capital letter stands for the urban centre of origin (IL for Illica (RI), AS for Amatrice (RI) south part, AN for Amatrice (RI) north part, CD for Capodacqua (AP), AC for Accumoli (RI), AT for Arquata del Tronto (AP)). COMPARISON sheet provides the percentage results of comparisons between each considered method and real-world scenario conditions are reported indicating the total percentage of cases of correspondence (C), Overestimation (O) and their sum (C+O) on the overall sample made by 50 structural units associated to their underlying urban streets.