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Seismic risk of Open Spaces in Historic Built Environments: A matrix-based approach for emergency management and disaster response

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ABSTRACT

Earthquakes affect the safety of the users hosted in both indoor and outdoor urban built environments, especially in Historic Built Environments (HBEs). Many full HBE-scale risk-assessment methods are defined, while methodologies oriented to local analysis of meso-scale elements, such as Open Spaces (OSs), are still limited. Nevertheless, OSs play a crucial role in the first emergency phases, like in the evacuation process, since they host emergency paths and gathering areas. The seismic risk of an OS mainly depends on the combination of the damage suffered from facing buildings and the exposure, which mainly refers to the quantification of human lives. Damage levels result from the combination of vulnerability and hazard-related issues, while exposure is essentially affected by the number of OS users, whose spatial distribution is strongly time-dependent. Methods to quickly combine these issues are needed, especially in view of the deeper insights for the implementation of risk-reduction strategies (i.e. according to simulation-based approaches). This work offers a novel methodology to quickly perform Seismic Risk Assessment and Management of an OS by correlating damage levels to exposure-related issues. The method is composed of two specific matrices, which are developed according to quick literature-based approaches prone to rapid meso-scale applications in HBEs, also by non-expert technicians. The "damage matrix" links the site hazard to the building vulnerability. The assessed damage levels are combined with the users' exposure into the "consequences matrix", to estimate the risk in emergency conditions for the OS users, thus supporting decision-makers in promoting robustness/preparedness strategies.

1. Introduction

Most of the recent earthquakes have pointed out the disproportion between their potential destructiveness, in terms of magnitude, and their devastating impacts, thus boosting a renewed interest in safety issues and prevention strategies to improve the resilience of the built environment in urban contexts [1–4]. In fact, considering casualties, devastating earthquakes have increased during the last fifty years, in view of the population pressures in built environments placed in high seismicity areas, the fragility of physical structures, and the features of modern urbanisation (e.g. unplanned modifications, urban sprawling, sudden demographic changes, etc.) [5]. In this context, meso-scale elements of the built environment (i.e. urban blocks, lots, open spaces) have a paramount role in defining the safety and the resilience of the urban system as a whole [6]. Their specific features and overall configuration in the urban layout effectively affect the ability of the built environment itself to withstand shocks and to preserve the essential assets, ensuring strategic services and functions to the hosted users even during disasters [7]. In fact, they are the basic components of macro-scale elements, such as those relating to urban layout configuration, street network, and overall building stock. At the same time, their analysis allows to quickly assess and resume the conditions of micro-scale elements that compose them (e.g. buildings, including their features in terms of type of constructions, structural resistance, etc.) as well as their interferences in the urban system.

Therefore, in the urban layout, Open Spaces (OSs) are mainly represented by squares and streets, hosting different uses and functions within the built environment, as well as playing fundamental roles during the first phases of seismic emergency and in the immediate aftermath, i.e. in the evacuation process [6,8–14]. In fact, the streets connect the built environment elements thus ensuring emergency and evacuation management operations, and squares can be possible outdoor "safe" areas for the earthquake-stricken population. Nevertheless, they have a similar characterization as outdoor areas partially or

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completely enclosed by facing buildings. As a consequence, according to previous works [3,10,12,15–17], their overall risk depends on the interactions between: (i) morphological/construction characteristics of outdoor spaces and facing buildings; (ii) their intended use and the presence of OSs users in both outdoor and indoor areas; (iii) their combined impacts on emergency and evacuation conditions, which essentially depend on the potential damage level in the OSs. In this perspective, OSs placed in Historic Built Environments (HBEs) can be affected by critical post-earthquake conditions because of the following peculiarities:

- particular configurations of the urban tissue, composed of narrow and winding streets, dense and compact built-up areas, and lacks of wide OSs which can be also used during the evacuation process [15,17]. This tissue is the result of stratified built environment layers over the time [18,19]. Although isolated buildings can exist, building aggregates prevail. Each building aggregate can be essentially identified as an urban block, thus being delimited by the OSs, and is a complex structure composed of different Structural Units (SUs). It requires specific knowledge of each SU features influencing the global seismic behaviour of the whole aggregate [20,21]. Moreover, the evolution and transformation processes during the time affect the overall seismic vulnerability of the building aggregates as well of each composing SU [22,23];
- the HBE significant vulnerability both of the elements composing squares and streets (e.g. hypogeum, pavements, underground lifelines), and of the buildings facing the outdoor spaces [17,24,25]. In particular, the buildings vulnerability represents a critical issue since it both influences the safety of HBE users during the main shock (e.g. implying direct losses in indoor conditions) and in the evacuation process (e.g. streets blockage) [17,26]. The prevalence of high vulnerable structures, such as Un-Reinforced Masonry ones in the building stock, can provoke destructive effects in the OSs [27–29]. In this perspective, their vulnerability is also affected by historic transformation processes and obsolescence, thus determining significant structural weaknesses;
- an additional large concentration of architectural heritage and monuments, that increases the fragility of the building stock due to the construction peculiarities and possible lack of maintenance and retrofitting actions [30];
- the significant exposure in terms of human lives, due to potentially high inhabitants' densities and the tourists' crowd in case of heritage sites [12,15]. Such issues also influence the OSs users' safety during the evacuation process, for instance by considering the level of knowledge of emergency procedures and the familiarity with the OSs layout [15,16].

Notwithstanding the growing interest in OSs contribution to urban resilience [3,10,12], common Seismic Risk Assessment (SRA) methodologies are mainly focused on micro-scale (single building) or macro-scale (global or national urban territory) evaluations of factors concerning hazard, vulnerability and exposure [31]. Considering the use of these risk analyses to promote Seismic Risk Management (SRM) and related risk-mitigation solutions [2,32,33], the capabilities of such application scales for decision-makers' actions respectively rely on the possibility to promote interventions on each building, and on the quick definition of risk scenario and risk-mitigation interventions at the whole HBE scale. The effectiveness of mitigation strategies is closely related to the selection of SRA models and approaches depending on the purposes, the scale of application and the level of detail in methodologies used for risk assessment [34–36]. Matrix-based approaches are commonly adopted to ensure the understanding of SRA-SRM methods and results to non-expert technicians, too. In fact, they offer a simplified framework to assist decision-makers and safety designers in ranking alternatives situations under risks and orienting urban planning to Disaster Risk Reduction (DRR) policies [37,38]. Furthermore, the type of SRA model used should match the intentions of the SRM according to a systemic perspective [39]. Considering the multidisciplinary nature of SRM tasks, they are distinguished according to the disaster's time stages in which they are applied [17,38,40–44]: pre-event phase, immediate emergency phase that includes the evacuation process, and post-event (recovery) phase.

Anyway, common approaches neglect to consider the relevant impact of the post-earthquake HBE damage on the safety of its users in the OS-scale perspective [4,12,43,45,46]. Therefore, both SRA and SRM should adopt a holistic approach in view of disaster risk factors, to improve user-related preventive measures (i.e.: preparedness of communities in the pre-disaster risk assessment; emergency management planning), as well as interventions on physical assets [42–44,47].

According to the systemic outlook to the matter [39], this work sets out a novel and integrated methodology for SRA and SRM at the meso-scale, that is focused on OSs in HBE, through a matrix-based approach. This approach is applied to combine physical elements of an OS and its exposure. To this end, literature-based methods are used to assess the risk factors, by preferring quick evaluation approaches at the OS scale. This choice ensures a rapid application of the proposed SRA-SRM methodology. According to the SRA perspective, two matrices are developed basing on a semi-quantitative standpoint. The *damage matrix* categorizes different levels of damage in the OS depending on the site hazard and the building vulnerability. The damage levels are then combined with the OS users' exposure, in terms of human lives, to derive the consequences for the OS users in relation to the evacuation process (*consequence matrix*). According to the SRM perspective, the results of the *consequence matrix* are capable of informing decision-makers regarding the risk severity and systematically suggesting the appropriate mitigation actions towards emergency planning, communities' preparedness (i.e. risk awareness, knowledge of best evacuation practices, training activities, etc.) and HBE robustness (i.e. adequate seismic retrofitting strategies by effective strengthening techniques to avoid widespread damages) [6,42,44,48,49]. These actions move toward resilience to reduce the efforts concerning response and recovery after disasters [49].

These research aims are developed under the general framework of the National Relevant Interest Research Project BE S^{2}ECURe (funded by the Italian Ministry of Education, University, and Research). The whole project combines the SRA in crowded built environments with risk assessment actions for other threats (terrorist acts, pollution, heat waves) so as to provide a performance-based approach for multi-risk resilience assessment of the built environments and its users [50]. According to such a holistic standpoint, the whole project and this work focus on the interaction of the exposed OS users with the modifications of the built environment due to disasters, specifically in this work with the post-earthquake damages of buildings facing OSs, for defining key metric elements for risk assessment and planning. OSs morphological and construction issues are linked up with the user-centred factors, thus moving towards effective and user-aware risk mitigation strategies. In this sense, this approach tries to overcome the limitation of current methodologies, which generally underestimate the users' influence during a disaster in relation to the OSs elements.

2. Material and methods

2.1. General framework for SRA/SRM matrices of OSs in HBE

According to the literature overview in Section 1, the adopted approach for proposing a novel quick and integrated methodology for SRA and SRM at the meso-scale is founded on the following assumptions:

1. It brings together the seismic risk components, that are: the hazard H, which refers to the severity of the earthquake in terms of return periods [years], according to the site hazard provided by national seismic hazard maps [7,35,51]; the vulnerability V, as the

susceptibility of the HBE elements (i.e. buildings facing the OS) to be damaged, is assessed according to existing empirical and rapid methods, by using a normalized approach (V ranges from 0 to 1) to provide input data for the damage estimation [23,52,53]; the exposure E is defined in terms of the number of human lives into the HBE before the event, and assesses the spatio-temporal distribution of OS users depending on the hosted activities in both outdoor (i.e. OS itself) and indoor areas (i.e. buildings facing the OS) [4,7].

2. On these bases, it firstly focuses on the effects of the earthquake on the HBE, by forecasting the "damage grades" of the buildings facing the OS depending on H and V combination [20,54,55]. This correlation is organized into the *damage matrix* M1. Thus, the probable damage scenarios (D) is also correlated to the presence of debris on the ground which is estimated in qualitative term according to higher damage grades [56,57].
3. In view of the point 2, according to the paramount role of OSs in the evacuation process for the OSs users' safety, the consequences on the users take into account the users-HBE interactions due to post-earthquake damage scenarios (i.e. presence of debris on the ground) [12,20,37]. A novel methodology for E assessment is provided by the authors, and such a correlation between D and E determines the risk levels of the OS through the *consequence matrix* M2.
4. Concerning the level of detail and according to a meso-scale application (e.g. many buildings can be included in the scenario to be assessed), it prefers adopting quick but reliable methodologies especially in respect to the damage assessment in HBE contexts, basing on the existing literature [23,27,58,59]. Meanwhile, easy-to-use approaches can be preferred to ensure the application of the methodology also by low trained technicians and non-expert decision-makers [21]. In this sense, matrix-based approaches for SRA and SRM are preferred [60,61], since they can express the risk level in a qualitative manner calibrated on the quantitative definition of the three risk components. Furthermore, they can provide rapid tools for multi-scenario assessment as input risk conditions vary [43,54]. Indeed, M1 and M2 allow the evaluation of optimal SRM strategies by distinguishing between: (i) robustness-increasing actions, performed by intervening on the buildings; and (ii) preparedness-increasing actions, performed through OS management and emergency planning, as well as through users' awareness improvement [42–44,47].

In view of the above, the methodology adopts the general framework of Fig. 1. All the main notations, including both symbols and acronyms, used in this work are reported in Appendix A (Table A1).

According to this overall framework and to the adoption of literature-based methodologies for SRA and SRM, criteria and calculation methods for damage and consequence matrices are respectively described in Sections 2.2 and 2.3, thus tracing the reasons for the choice and the improvement of existing assessment methodologies for H, V and E. The risk-related issues discussed below have been herein addressed with reference to the Italian context to provide direct methodologies for the matrix development and the input/output data interpretation. Nevertheless, they can be updated depending on the specific national contexts of application.

2.2. Damage matrix

The *damage matrix* has been developed in view of the OS users' interactions in post-earthquake conditions. In fact, the primary cause of earthquake-related deaths/injuries is the building damage both in a direct (e.g. total or partial failure of buildings) and indirect (e.g. being stuck by non-structural built parts such as chimneys) manner [62]. Therefore, the SRA of an OS focuses on the estimation of probable damage scenarios in order to reduce the interferences between OS users and earthquake-induced debris [15,20]. Correlating H and V allows forecasting damage grade for the buildings and, as a consequence, to estimate the debris quantities which can also imply the outdoor area unavailability during the evacuation process [21,62].

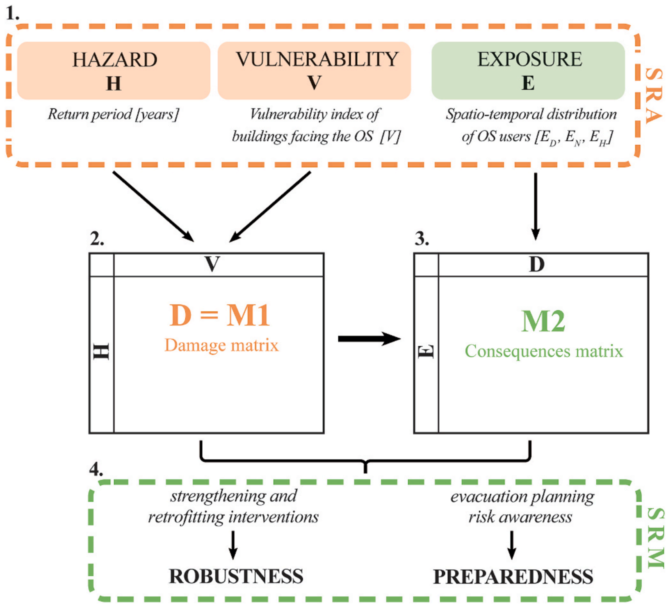

Fig. 1. Adopted framework for SRA/SRM. The numbers (1.–4.) refer to the list explained in the current section.

Concerning H, approaches based on Probabilistic Seismic Hazard Analysis allow defining different hazard scenarios of a defined geographical area, even at the municipal scale [35]. In this sense, the related models are widely adopted for the definition of national hazard maps. In the case of the Italian territory [51,63], they show the spatial distribution of expected Peak Ground Acceleration-PGA at an assigned return period in an assigned reference period of time (e.g. in 50 years) for each municipality. In respect to other quick macro seismic-based methods [64], the selection of the PGA as a descriptor of H is given according to the broad field of application to both macro and micro scale (e.g. data from microzoning activities) [35,65] and the large availability of related data within the framework of the national hazard assessments [53,66,67]. Therefore, the national hazard maps are also suitable for defining possible hazard input at the meso-scale according to the proposed SRA methodology.

Concerning V assessment approaches [36,68,69], empirical methods, such as Vulnerability Index Method (VIM) procedures [70], are commonly adopted for rapid evaluation at the macro-scale (territorial or urban), and in particular for historic city centres due to the availability of statistical evaluation of recorded data from past earthquakes [52]. In this sense, they are commonly based on semeiotic approaches suitable also for a quick meso-scale application, also in view of the possible application by low trained technicians. Empirical methods lead to the prediction of damage level depending on the correlation with H [52,68,69], by means of: (i) vulnerability curves, based on the analytical function of the mean damage (μ_D) developed by the macro-seismic method [59]; (ii) fragility functions, which represent the probability of reaching or exceeding a given damage state according to different macroseismic intensities or PGA [59,66]. In view of the above, VIM methods, such as [23,58] can be considered the most complete and reliable considering the HBE contexts application.

The higher the damage grade for the buildings, the higher the possibility that debris can block the facing outdoor areas in the OS [20,21,62,64]. Although analytical-experimental approaches (e.g. fragility curves or numerical simulations-based estimations) are provided by previous works [56,71–73], simplified methodologies based on both geometrical features and damage grades of buildings are considered [20,62]. In particular, the qualitative damage description [58,64,68] can provide rapid insights on the outdoor areas damage state affecting the evacuation from a square or towards a square (used as a gathering area) as well as the movement along a street towards a gathering area [14].

In the view of above, existing methodologies have been innovatively arranged into the *damage matrix* M1 (Fig. 2), which uses the following input data:

- return period (row category of M1), basing on the Italian building code definitions and thus considering the site PGA [74], to represent H (Section 2.2.1);
- and V (column category of M1), expressed as a normalized vulnerability index basing on the Formisano's VIM method [23], and used in the mean damage formula to obtain macroseismic vulnerability curves (Section 2.2.2) [59]. In particular, three V classes are offered, basing on vulnerability curves where the macroseismic intensity (I) is adapted in PGA values according to existing correlations [75].

As an output, the H–V combination describes the damage scenarios in terms of the damage grade (D0-D5) of the EMS-98 scale (given by the colours of the different cells) [64]:

- D5, Destruction (very heavy structural damage): Total or near-total collapse.
- D4, Very heavy damage (heavy structural damage, very heavy non-structural damage): serious failure of walls; partial structural failure of roofs and floors.
- D3, 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).
- D2, Moderate damage (slight structural damage, moderate on-structural damage): Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
- D1, 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.
- D0, No damage.

Thereby, the *damage matrix* provides the probability that buildings (belonging to a given class of V) can suffer a certain level of damage for increasing return periods.

2.2.1. *Row category (H): return period and PGA*

The correlation between return periods and damage grades has been developed starting from the correspondence of damage scenarios description of the EMS-98 scale with the limit states adopted for the performance-based assessment by the Italian Building Code [74]. The return periods are selected according to the following Limit States:

- Damage Limit State-DLS (50-years return period): structural and no structural elements are affected by negligible to slight damages that do not affect users' safety and building resistance.
- Damage Limit State-DLS (101-years return period): light cracks in very few walls and fall of both small pieces of plaster and loose stones from the upper part of buildings.
- Life Safety Limit State-LLS (475-years return period): moderate cracks and partial fall of no structural elements; substantial damage of structural elements and lack of stiffness to horizontal forces; good performance to vertical forces; critic performance near to collapse.
- Collapse Limit State-CLS (975-years return period): serious damage of no structural elements; very heavy damage to structural elements; total or near-total collapse.

Fig. 3 gives the correspondence between performance ranges and damage grades for the four return periods used in the matrix M1. This correspondence provides the first step in assigning damage scenarios within the matrix cells.

These Limit States are related to the return periods for buildings in a reference period of 50 years. Moreover, the four return periods can be related to different PGA values thanks to the Italian hazard maps [51]. However, it is not possible to associate a unique PGA to each row of the matrix since the PGA varies at the municipal scale as the return period increases. Therefore, lower (−) and upper (+) bounds have been introduced for each matrix cells to overcome uncertainties in expected damage prediction that may come from different geographical site applications. These bounds are fixed for each damage grade according to the PGA variation for each return period, as shown in the hazard maps of Fig. 4 [76].[1] Thus, the range of PGA of 475-years return period corresponds to the PGA values of the four seismic zones adopted by the seismic classification of the Italian territory.[2] The same criterion has been applied to all the other cases of return periods. The choice between these bounds depends on the expected PGA for the site under investigation according to the seismic zone to which it belongs. For instance, considering D1 and 50-years return period, the lower bound corresponds to D0 if considering the lower PGA values (seismic zone 3 and 4), while the upper bound corresponds to D2, for the highest PGA values (seismic zone 1), and D1 is associated to PGA values of seismic zone 2.

2.2.2. *Column category (V): macroseismic vulnerability curves in terms of PGA*

The Formisano's VIM method [23] is selected to calculate the building vulnerability due to: (i) the possibility to describe the earthquake scenarios in terms of PGA and thus return periods; (ii) several calibration and validation activities with respect to real-damage observations by Italian case studies [54]; (iii) the possibility to identify significant conditions in M1, in view of validating vulnerability-hazard combination for damage state assessment according to the methodology applications. In view of the HBE peculiarities introduced in Section 1, the assessment process is performed for each SU composing the building aggregates and the buildings facing the OS.

The prediction of damage is proposed according to mean damage grades ($0 \leq \mu_D \leq 5$) calculation, as reported in Equation (1) [59]:

$$\mu_D = 2,5\left[1+\tanh\left(\frac{I+6,25\ \times\ V-13,1}{Q}\right)\right] \tag{1}$$

where I is the macroseismic intensity (according to the EMS-98 scale), V is the normalized vulnerability index (thus ranging from 0 to 1) based on Formisano's VIM method, and Q is the ductility factor (assumed as equal to 2.3 for ordinary Un-Reinforced Masonry buildings). Fig. 5-a shows the adopted grouping of μ_D according to the EMS-98 scale damage grades [23].

I in equation (1) is calculated depending on the PGA, as shown in equation (2), according to the correlation law proposed by Ref. [75]:

$$\mathrm{I} = \frac{\ln(PGA)\ +\ 7,073}{0,602} \tag{2}$$

Fig. 5-b correlates the PGA values (and the corresponding I values) to the four seismic zones adopted by the seismic classification of the Italian territory, which refers to 475-years return period and so to LLS, as stated in Section 2.2.1. This scheme ensures a quick comparison based on the seismic zones.

In the perspective of the seismic classification of the Italian territory, the subdivision into three classes of V has been derived by building

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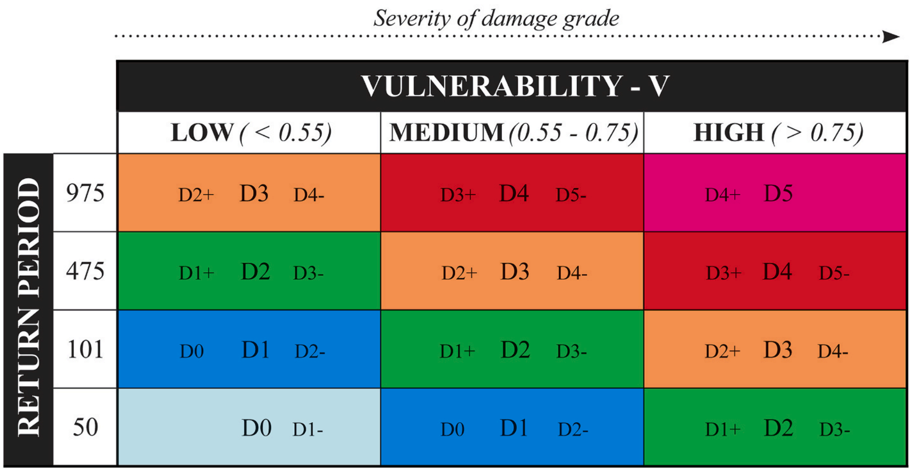
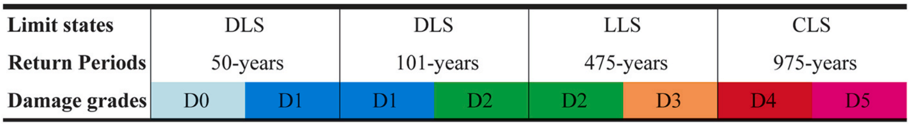
[1] According to the national regulation, the hazard map performed by the MPS04 model [76] is still valid until the update, named MPS19, will be released [63]. Notwithstanding, it maintains the same Probabilistic Seismic Hazard Assessment-based model.

[2] Available online at http://www.protezionecivile.gov.it/attivita-rischi/rischio-sismico/attivita/classificazione-sismica (accessed on 17 December 2020).



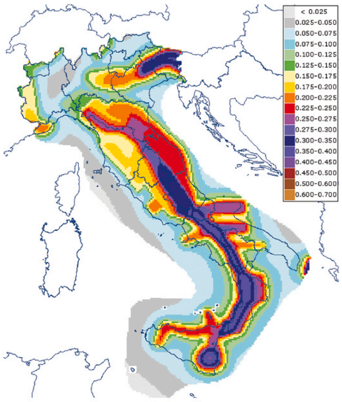
RETURN PERIOD	VULNERABILITY - V LOW (< 0.55)	 MEDIUM (0.55 - 0.75)	 HIGH (> 0.75)
975	D2+ D3 D4-	D3+ D4 D5-	D4+ D5
475	D1+ D2 D3-	D2+ D3 D4-	D3+ D4 D5-
101	D0 D1 D2-	D1+ D2 D3-	D2+ D3 D4-
50	D0 D1-	D0 D1 D2-	D1+ D2 D3-

Fig. 2. Damage matrix M1. The matrix cells represent damage scenarios based on the damage grades of the EMS-98 scale.



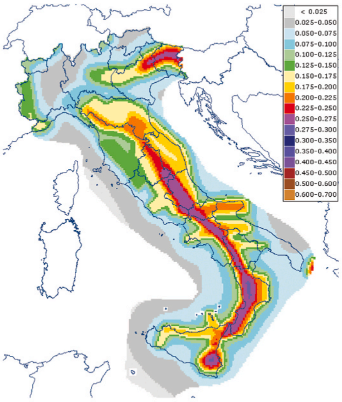
Limit states	DLS		DLS		LLS		CLS	
Return Periods	50-years		101-years		475-years		975-years	
Damage grades	D0	D1	D1	D2	D2	D3	D4	D5

Fig. 3. Correspondence between performance range of Italian building code in terms of Limit states and return period [74], and damage grades of EMS-98 scale [64].



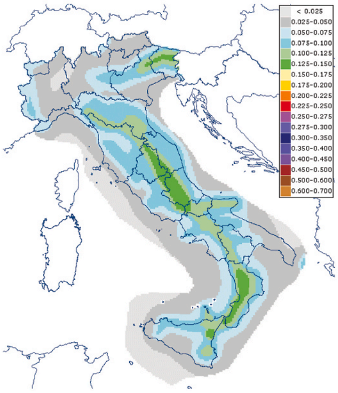
975-years return period

D	*Range of D*	*Range of PGA*
D5	D5	$PGA \geq 0.20$
	D4-	$PGA < 0.20$
D4	D5-	$PGA \geq 0.275$
	D4	$0.20 \leq PGA < 0.275$
	D3+	$PGA < 0.20$
D3	D4-	$PGA \geq 0.275$
	D3	$0.20 \leq PGA < 0.275$
	D2+	$PGA < 0.20$



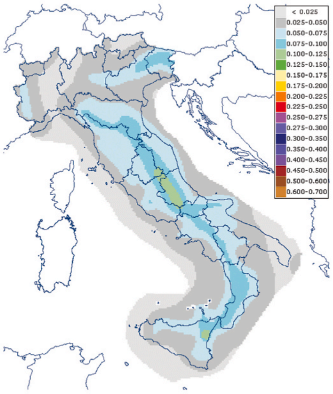
475-years return period

D	*Range of D*	*Range of PGA*
D4	D5-	$PGA > 0.25$
	D4	$0.15 < PGA \leq 0.25$
	D3+	$PGA \leq 0.15$
D3	D4-	$PGA > 0.25$
	D3	$0.15 < PGA \leq 0.25$
	D2+	$PGA \leq 0.15$
D2	D3-	$PGA > 0.25$
	D2	$0.15 < PGA \leq 0.25$
	D1+	$PGA \leq 0.15$



101-years return period

D	*Range of D*	*Range of PGA*
D3	D4-	$PGA \geq 0.10$
	D3	$0.075 \leq PGA < 0.10$
	D2+	$PGA < 0.075$
D2	D3-	$PGA \geq 0.10$
	D2	$0.075 \leq PGA < 0.10$
	D1+	$PGA < 0.075$
D1	D2-	$PGA \geq 0.10$
	D1	$0.075 \leq PGA < 0.10$
	D0+	$PGA < 0.075$



50-years return period

D	*Range of D*	*Range of PGA*
D2	D3-	$PGA \geq 0.075$
	D2	$0.05 \leq PGA < 0.075$
	D1+	$PGA < 0.05$
D1	D2-	$PGA \geq 0.075$
	D1	$0.05 \leq PGA < 0.075$
	D0+	$PGA < 0.05$
D0	D1-	$PGA \geq 0.075$
	D0	$PGA < 0.075$

Fig. 4. Upper (+) and lower (−) bounds per damage grades correlated to the range of PGA according to Italian hazard maps per return periods 975, 475, 101, 50 (http://esse1.mi.ingv.it) [76]. The damage grades colours are the same of M1 matrix Fig. 2 and 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a)

μ_D	0	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5
Damage grades	D0	D1	D2	D3	D4	D5

b)

SEISMIC ZONES *(475-years return period-LLS)*	ZONE 4	ZONE 3	ZONE 2	ZONE 1
PGA [g]	≤ 0.05	0.05 < g ≤ 0.15	0.15 < g ≤ 0.25	> 0.25
I [EMS-98]	≤ 6.8	6.8 - 8.6	8.6 - 9.4	> 9.4

Fig. 5. a) correlation between μ_D and damage grade of EMS-98 scale; b) PGA-I conversion by Ref. [75] for 475-years return period according to the four zones of the Italian seismic classification.

vulnerability curves according to the range of PGA of 475-years return period, as shown by Fig. 6. It can be noticed the following main thresholds for V classification:

- $V > 0.75$ always provokes at least D4 (or D5-) for higher PGA values (i.e. PGA>0.25, limit for seismic zone 1). According to a conservative approach, the maximum damage grade, that is referring to $V = 1$, for lower PGA values (i.e. PGA>0.05, limit for seismic zone 4) can be considered as equal to D3+;
- $0.55 \leq V \leq 0.75$ always provokes at least D3 (or D4-) for higher PGA values (i.e. PGA>0.25, limit for seismic zone 1), but not the destruction of the building, thus representing an intermediate range for the vulnerability. According to a conservative approach, the maximum damage grade, that is referring to $V = 0.75$, for lower PGA values (i.e. PGA>0.05, limit for seismic zone 4) can be considered as equal to D2+. In this sense, this V range ensures obtaining D2 and D3 values for LLS as in Fig. 3;
- $V < 0.55$ always provokes limited damage to the building (up to D3-) for the higher PGA values (i.e. PGA>0.25, limit for seismic zone 1), leading to safety conditions in LLS. Thus, these values can represent the lowest V range class.

This analysis from Fig. 6 offers the analytical explanation of the H–V combination used for M1 (i.e. row of 475-years return period). The V classification is extended to the other return periods. In this sense, it is worthy of notice that: (i) considering the seismic zones, the damage prediction is not underestimated for high PGA (zone 1–2), is not overestimated for PGA of zone 3, while may be overestimated for low PGA values (zone 4); ii) thus, a conservative approach in damage prediction can be ensured for the more hazardous zones (zones 1–2); iii) the purpose of the matrix is therefore not to provide exactly the mean damage grade, which is provided by vulnerability/fragility curves instead.

2.3. Consequences matrix

Determining E in terms of human lives (number of persons) means defining the number of OS users over the time and over the OS spaces in relation to both outdoor areas and indoor areas (i.e. facing buildings, because of the correlation between their intended use), and potential individuals' flows among OSs [4,15,20,46]. Variations in the users' number considering an OS exist at both long-term (years) and short-term (daily and weekly, up to seasonal), especially in HBEs contexts [4,15, 77]. In particular, data of short-term variations, which are due to users' activities and mobility (e.g. workers' flow; visitors' flows in touristic areas or possibility to host mass gathering events), could be well managed by safety planners in regard to OSs, thanks to the OSs spatial limitation and the possibility to directly identify the hosted functions. They are pivotal factors in such SRA-related analyses because the patterns of earthquakes casualties vary over the time of the day when the earthquake occurs, by also considering the building type and its

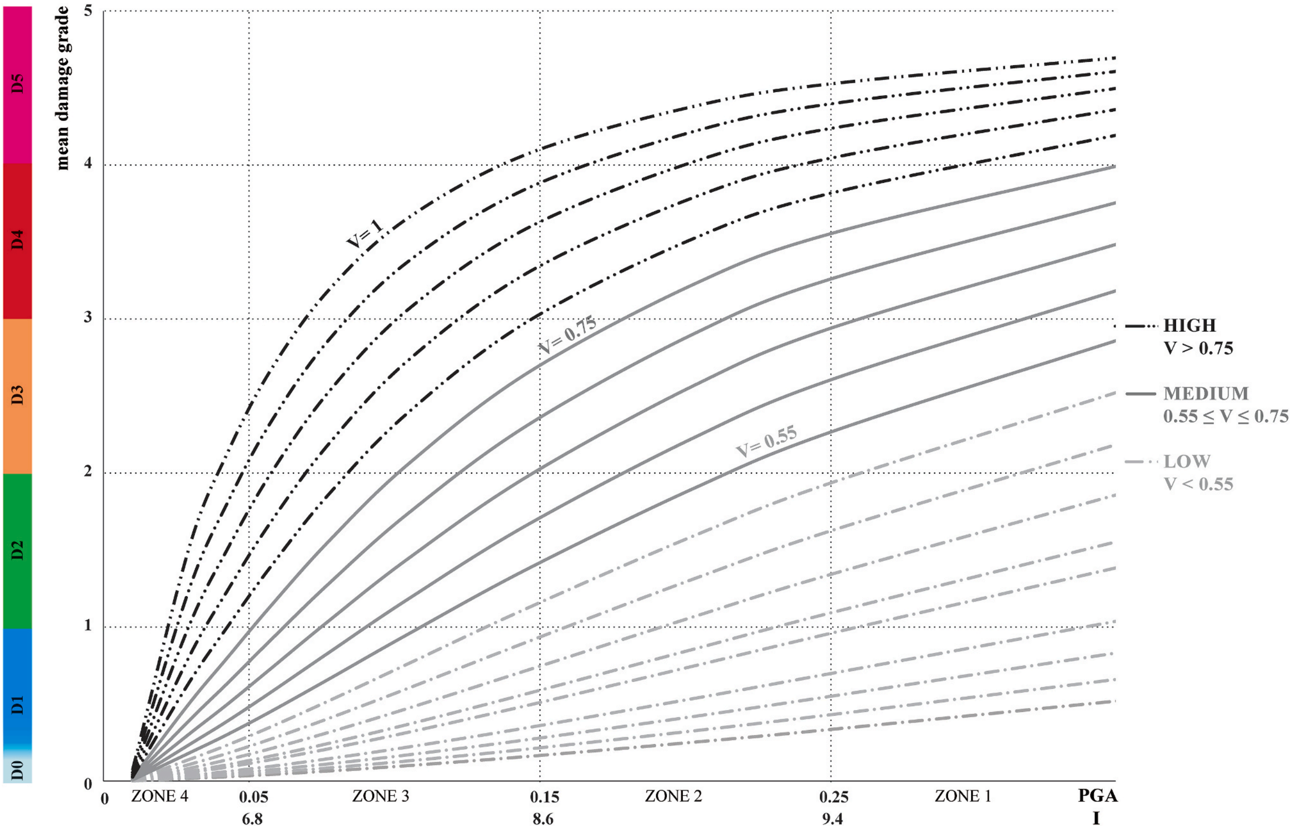


Fig. 6. V classification in three classes: vulnerability curves correlating PGA and I (see Fig. 5- b), on the x axis, and μ_D and the EMS-98 scale damage grades (see Fig. 5-a), on the y axis. Vulnerability curves are shown for V by steps of 5. The curves are shown for 475-years return period, thus allowing the comparison of x axis with the zones according to the seismic classification of the Italian territory, as well as considering the LLS.

use/function, as remarked by previous works on real-world earthquakes [45,78,79]. In general terms, the occupants of non-residential buildings seem to be more exposed to possible casualties in respect to residential ones, thus increasing possible exposure in OSs hosting public buildings, which are most frequented in daytime [29,78]. Considering historic OSs, vernacular residential buildings are also an important source of risk due to their greater vulnerability to collapse, especially in countries with a high concentration of monumental heritage such as Italy [45].

Considering the existing methodologies for human lives quantification [15,77,80], micro-scale analysis based on crowding indexes and building intended use has a rapid application and a good level of reliability in defining spatio-temporal users' patterns through the specific use/function of buildings or outdoor areas. According to previous works [4,72,77], spatial analysis may rely on: macro-scale databases, including those supported by Geographic Information System-GIS tools representations, about building stock inventory based on structural typology or on the type of activity/function inside the buildings (i.e. residential, commercial, industrial); expert judgments or on-site survey to define the aforementioned factors at the OSs scale, to move towards more reliable data. To quickly assess the building occupancy, the crowding index [persons/m^2] is multiplied by the built-up area [m^2] hosting a certain function in a building. This estimation can be also correlated to the usage-time of each function by considering ordinary (e.g. opening times for buildings open to the public; day/night-time differences for residential buildings) and extraordinary (e.g. mass-gatherings, festival, venue) conditions of the OS [15]. Some regulatory codes, which are not focused on SRA, seem to be a valid support to define the buildings occupancy. Considering the application context of this work, which considers the Italian regulation framework, the guideline UNI 10339:1995[3] defines crowding indexes related to some buildings occupancy that are to be considered as a reference to design assumptions (with respect to the indoor air quality), whereas specific information of real data is not available. National fire safety codes (for Italy [81]) can be used to derive the list of crowding indexes and criteria for the maximum crowding allowed for several buildings types [15].

Furthermore, simplified exposure modelling approaches are proposed to take into account urban buildings functions (residential, commercial, tertiary) with the related crowding index (0.02 persons/m^2 for the residential, 0.25 persons/m^2 for the commercial and 0.1 persons/m^2 for the tertiary) and the daily time-dependent distribution [82]. Moreover, this approach also provides a characterization of the OS users' distribution considering at least three age-group types of users (children by focusing on parent-assisted ones, adults, elderly), thus addressing a reference to behavioural differences, such as those due to the motion abilities depending on their individual vulnerability [15,83,84]. Classifying human lives into such users' typologies is even more important in HBEs, where a large concentration of elderly and/or of visitors and tourists can appear [15,17]. Quickly-available databases from municipal or territorial sources can be used to this end, so as to provide at least a macro-scale statistically-based overview [17,77,83].

In view of the above, the *consequences matrix* M2 shown in Fig. 7 uses the following input data:

- the exposure E (row category of M2), which depends on the number and features of the users of the OS, as well as the daytime when the earthquakes occur (holiday, night, day) (Section 2.3.1); the proposed E assessment procedure has been innovatively elaborated by the authors basing on the existing methods discussed above;
- and the given damage scenarios D (column category of M2), expressed the damage grades (D1-D5) according to M1 outputs (Section 2.3.2).

As an output, M2 provides the impact on the OS users' safety during the emergency phase and, mainly, during the evacuation process. To this end, the matrix has been populated with quantitative risk levels (expressed as a function of E × D) (Fig. 8-a) according to existing approaches [37,85]. These numerical values do not provide any specific "physical" meaning, but are merely a way to categorise the levels of severity due to possible consequences for users in the post-earthquake evacuation.

The obtained risk rating has been then organized into five thresholds (I–V) (Fig. 8-b), which qualify the severity of the scenario considering the possible users-HBE interaction due to post-earthquake damages in the considered OS [15,20,37]. The description of the scenarios has been originally elaborated for highlighting which situation can hinder OS users' evacuation and endanger their life safety in the immediate emergency phase.

2.3.1. *Row category (E): exposure of OS users*

The rows of M2 describe the probability of higher or lower impact occurring depending on the higher or lower range of E. The proposed E indexes calculation combines existing assessment procedures discussed above into a novel method that considers the spatio-temporal distribution of users and individuals' vulnerability-related issues in a comprehensive way.

The three exposure indices E_D, E_N and E_H [−] assess the exposure conditions in the OS given a certain time span, that is, respectively, daytime D, night-time N and holiday time H. They are provided using normalized rather than absolute terms, to compare different scenarios of the OS depending on the time of day when the event may occur [77]. The holiday period has also been taken into account to consider the possible increase in exposure (e.g. recurring non-working days or mass gathering conditions), especially for touristic HBEs [12,15,17].

The overall exposure index value for a time span is retrieved as the sum between E_{OA} [−], for outdoor areas (that is the OS itself under investigation), and E_{BI} [−], indoor areas (occupants of buildings facing the OS), as in Equations (3)–(5).

$$\textbf{Exposure of day} = \mathbf{E_D} = E_{BI-D} + E_{OA-D} \tag{3}$$

$$\textbf{Exposure of night} = \mathbf{E_N} = E_{BI-N} + E_{OA-N} \tag{4}$$

$$\textbf{Exposure of holiday} = \mathbf{E_H} = E_{BI-H} + E_{OA-H} \tag{5}$$

Individual vulnerability aspects are also taken into account considering three different age categories [15,82–84]: Adult (A), by including all the individuals between 15 and 65 years who are ideally autonomous in evacuation; parent-assisted Children (C), who are individuals under 14 years; and Elderly (E), who are individuals over 65 years. The impact of each age-group is associated with a specific weight (w_A, w_E, w_C) as an attempt to correct the value of the exposure index considering the aforementioned aspects related to individual vulnerability (e.g. motion during the evacuation, preparedness, risk awareness and perception) [43]. The values of the weights were obtained by applying the Analytical Hierarchy Process principles[4] [96] by comparing the three age categories (A, C, E) and justifying the relative importance between them on

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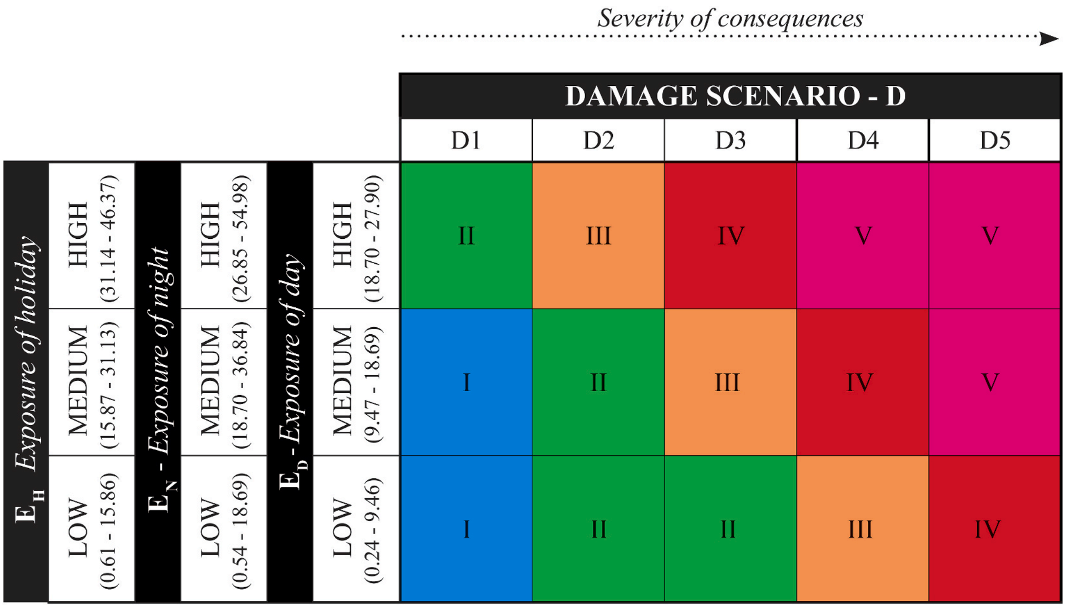
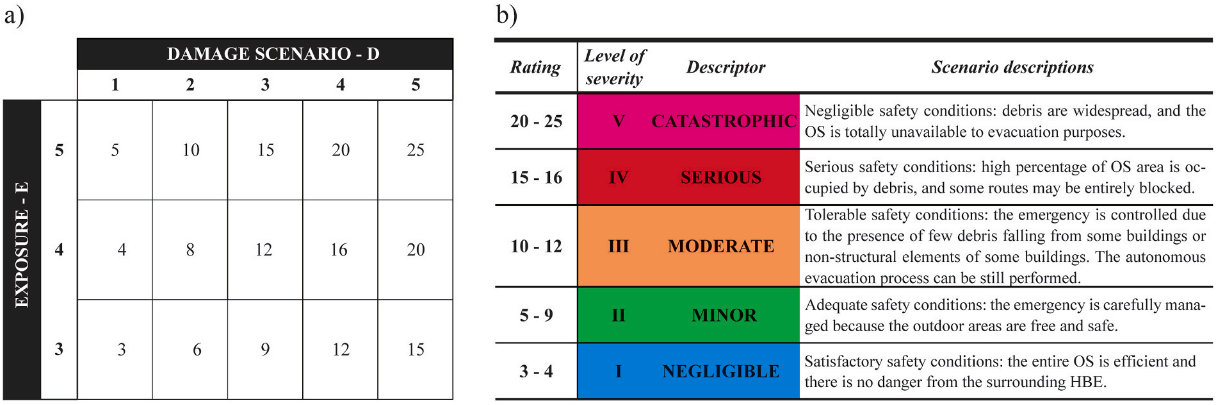
[3] The UNI 10339:1995 establishes the thermal comfort requirements in buildings, thus providing a list of crowding indices related to typical building occupancy.

[4] Available at AHP Online System (AHP-OS): https://bpmsg.com/ahp/ahp-calc.php (last access: 21/12/2020).



Severity of consequences →			DAMAGE SCENARIO - D				
E_H - Exposure of holiday	E_N - Exposure of night	E_D - Exposure of day	D1	D2	D3	D4	D5
HIGH (31.14 - 46.37)	HIGH (26.85 - 54.98)	HIGH (18.70 - 27.90)	II	III	IV	V	V
MEDIUM (15.87 - 31.13)	MEDIUM (18.70 - 36.84)	MEDIUM (9.47 - 18.69)	I	II	III	IV	V
LOW (0.61 - 15.86)	LOW (0.54 - 18.69)	LOW (0.24 - 9.46)	I	II	II	III	IV

Fig. 7. Consequences matrix M2. The levels of severity (including the colours of the cells) for the resulting scenario conditions are discussed in Fig. 8-b. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



a)

EXPOSURE - E	DAMAGE SCENARIO - D 1	2	3	4	5
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15

b)

Rating	*Level of severity*	*Descriptor*	*Scenario descriptions*
20 - 25	V	CATASTROPHIC	Negligible safety conditions: debris are widespread, and the OS is totally unavailable to evacuation purposes.
15 - 16	IV	SERIOUS	Serious safety conditions: high percentage of OS area is occupied by debris, and some routes may be entirely blocked.
10 - 12	III	MODERATE	Tolerable safety conditions: the emergency is controlled due to the presence of few debris falling from some buildings or non-structural elements of some buildings. The autonomous evacuation process can be still performed.
5 - 9	II	MINOR	Adequate safety conditions: the emergency is carefully managed because the outdoor areas are free and safe.
3 - 4	I	NEGLIGIBLE	Satisfactory safety conditions: the entire OS is efficient and there is no danger from the surrounding HBE.

Fig. 8. a) Quantification of risk levels within the matrix cells; b) Levels of severity of the consequences scenarios according to the risk rating and scenario descriptions.

the basis of objective considerations concerning evacuation process and deaths.[5] The result of the pairwise comparisons is a ranking with priority percentages for each age group, which is: $w_A = 12.2$, $w_E = 32.0$, $w_C = 55.8$. These values can be considered valid as the Consistent Ratio tends to zero.

The calculation of the exposure assessment terms used for Equations (3)–(5) are presented below. In particular, we offer the specific calculation of buildings-related exposure for daytime conditions $E_{BI,D}$ [−] according to Equation (6) and to the related sub-factors in Equations (7)–(9). Nevertheless, the same procedure can be applied to outdoor areas (E_{OA}) as well as for N and H scenarios.

$$E_{BI,D} = A \times w_A + C \times w_C + E \times w_E = (U_{OD} \times x_{\%A}) \times w_A + (U_{OD} \times x_{\%C}) \times w_C + (U_{OD} \times x_{\%E}) \times w_E \quad (6)$$

$$U_{OD} = \frac{\sum_{n=7}^{i} U'_{ODi}}{m^2_{TOT} \times I_D} \quad (7)$$

$$U'_{OD_i} = O_i \times CI_{Di} \times T_{UDi} \quad (8)$$

$$I_D = \sum_{n=7}^{i} CI_{Di} \times \sum_{n=7}^{i} T_{UDi} \quad (9)$$

In Equations (6)–(9), the following factors are included according to the scheme of Fig. 9, which can be used to organize input data for E_D assessment:

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[5] Autonomous adults are less vulnerable than all and their motion speed is about 1.30 m/s. Older individuals are more vulnerable than adults but, if autonomous, they can evacuate on their own. Moreover, they have lower speeds than adults (1.04 m/s). Parent-assisted children may be not autonomous in emergency conditions, as well as have no experience of seismic events and knowledge of evacuation procedures. Thus, they are more vulnerable than adults, and have a speed comparable to that of the elderly ($\geq$ 1.08 m/s). Therefore, they are a little more vulnerable than the elderly. According to a quick approach on age-effects assessment, the movement speed data were taken from general databases on evacuation speeds [97].

OCCUPANCY (O)		*CROWDING INDEX (CI)*		*Utilization Time T_U*			U'_{OD}	U'_{ON}	U'_{OH}
	[m²] related to the case study	*[persons/m²]*	*adopted mean value*	*Daily time H_d=(h/12)*	*Night time H_n=(h/12)*	*Holidays H_h=(h/24)*			
1	Residential	0.04* - 0.05** 0.05* (hotels bedrooms)	**0.045**	6	12	24			
2	Commercial	0.10*** , 0.20*** (shops) 0.25* (shopping centre)	**0.15**	10	0	0			
3	Recreational	0.6* - 0.7** (restaurant) 0.8* (bar)	**0.65**	6	4	6			
4	Entertainment	1.2** (without seats) 1.5* (theatre, cinema) 0.3* (museum)	**1.5**	2	4	6			
5	Religious	0.80*	**0.8**	2	2	6			
6	Hospitals (clinic)	0.12* - 0.1**	**0.12**	12	12	24			
7	Building for school	0.4*** (kindergarten) 0.45* (high school) 0.60* (university) 0.30*(laboratory)	**0.45**	8	0	0			
				I_D=15.31	I_N=12.18	I_H=21.66			

Fig. 9. Criteria adopted for the calculation of U'_{OD} (eq. (8)) within the exposure definition.

- $x_{\%A}$, $x_{\%C}$, $x_{\%E}$ [%] are the percentages of the related age group within the population of the OS in the HBE. Such data are usually available by local census data, municipality reports or observational statistics for the whole HBE[6];
- CI is the Crowding Index [persons/m^2], depending on the intended use of each area in the OS. In view of the Italian application of this work, it is based on the criteria proposed by UNI 10339 (marked with * in Fig. 9), by the Italian Fire Prevention Code (DM 3/08/2015) (marked with ** in Fig. 9), or by both of them (marked with*** in Fig. 9). These values can be used as reference values in absence of real-world data on areas occupancy. To simplify, this work adopts the mean value of those standards for the calculation, as shown in Fig. 9 (compare to "adopted mean value" column), but the safety designer could select the most reasonable or conservative value too;
- T_U is Utilization Time [h] of buildings and outdoor areas during the considered time period. It is assumed that the value depends on the estimated time of utilization of each function hosted in the OS during the day (8am–8 p.m.), night (8 p.m.–8 a.m.) and holidays (hours in a day). Thus, it depends on the specific intended use of each area in the OS (outdoor and indoor);
- O is the Occupancy, the surface area where a certain intended use is hosted in the OS [m^2]. The intended use can be assigned in regards of the main seven categories proposed in Fig. 9;
- I_D expresses the Crowding Index CI over the Daytime Utilization Time, and, according to Fig. 9. It assumes the following values for day (I_D = 15.31), night (I_N = 12.18) and holiday (I_H = 21.66) periods;
- U'_O determines the number of users per each type of intended use;
- U_O represents the normalized occupancy [−] of the OS in the given time period.

Finally, the exposure values are organized into three exposure classes (low, medium, high) for the three time periods, according to Fig. 10. These values have been obtained considering the maximum and minimum values obtainable from the previous formulas, according to Fig. 9 values and scheme.

2.3.2. Column category (D): damage scenarios and availability for evacuation purposes

Varying from left to right, columns describe the severity of the impact on the building stock under seismic events. Despite the damage prediction provided by the damage grades, the consequences scenarios proposed in Fig. 7 do not define the extent of damage, i.e. the percentage of the OS ground occupied by debris. The definition of the debris area and the width values of the street pavement free from debris can only be determined by knowing the geometric characteristics of interfering buildings and the analysed outdoor areas [26,56,57,73].

Nevertheless, the prevision of OS occlusion due to buildings failures is provided in qualitative terms considering the damage descriptions of the EMS-98 scale. Therefore, the maximum debris area is reached for D5 [56]. At the same time, according to Ref. [57], the part of the HBE streets cluttered with debris is equal to: (i) 1/3 of the height of SUs which suffer D4; and (ii) 2/3 of the height of SUs which suffer D5. Furthermore, D3 can provoke failures but only refers to non-structural elements (chimneys, pinnacles, balustrades, etc.) that are generally more vulnerable to overturn, especially in historical buildings [45,86]. As a consequence, according to M1 discussed in Section 2.2, it is assumed that the highest percentage of ground occupation by debris appears for D4 and D5, influencing the users' behaviours and motion in the evacuation process [43,56,71], because these scenarios involve the occurrence of heavy falling debris by structural parts. The consequence scenarios of IV and V

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[6] e.g., for the Italian context, please compare http://demo.istat.it/index_e.php (last access: 21/12/2020) for the resident population by age for each municipality.

E_D - *Exposure of day*

LOW	0.24 - 9.46
MEDIUM	9.47 - 18.69
HIGH	18.70 - 27.90

E_N - *Exposure of night*

LOW	0.54 - 18.69
MEDIUM	18.70 - 36.84
HIGH	36.85 - 54.98

E_H - *Exposure of holiday*

LOW	0.61 - 15.86
MEDIUM	15.87 - 31.13
HIGH	31.14 - 46.37

Fig. 10. Division into classes of values of exposure indices for day, night and holyday, to be used as input data for the rows of the consequence matrix M2. In each line, maximum and minimum values from Fig. 9 application are shown.

levels of are connected to such damage grades (Fig. 8-b), describing compromised safety urban conditions where the evacuation is partially or totally prevented due to partial or total debris obstruction. In fact, considering a street, the overall outdoor space is threatened by debris and the evacuation is prevented in the case of D4, because of the limited width in historic contexts. Considering a square, the morpho-typological configuration affects the debris impacts inside it, but the accesses to it (which corresponds to streets) can be assumed as almost certainly blocked in the case of both D4 and D5. Thus, it can be reasonably assumed that only the central area of the square could remain clear from debris.

3. Results and discussion

Although the work represents a basic step towards the OSs assessment under post-earthquake conditions, the proposed analysis approach is not to be considered a quantitative risk assessment, but as a decision support tool that can be quick-to-use for the meso-scale of the HBE. In this sense, the methodology application, as pointed out in Section 2, could be also extended to other kinds of built environments in the urban contexts, by adopting the proper exiting methodology for H, V and E estimation, also according to some main insights and future works provided in Section 3.2.

3.1. About the use of matrices for SRA and SRM

The *damage matrix* M1 is adopted for each isolated building and SU composing building aggregates facing the OS in order to highlight the probable physical damages interfering with the outdoor space as provided by scenarios of the *consequence matrix* M2. In particular, M1 may be used starting from different inputs depending on two main hypotheses HP1 and HP2 of usage under different SRA and SRM purposes, according to the methodological framework of Fig. 1.

HP1, shown in Fig. 11, refers to the use of M1 to predict the damage given a specific OS placed in a certain municipality. Thus, the expected PGA is obtained from the specific hazard map discussed in Section 2.2.1.

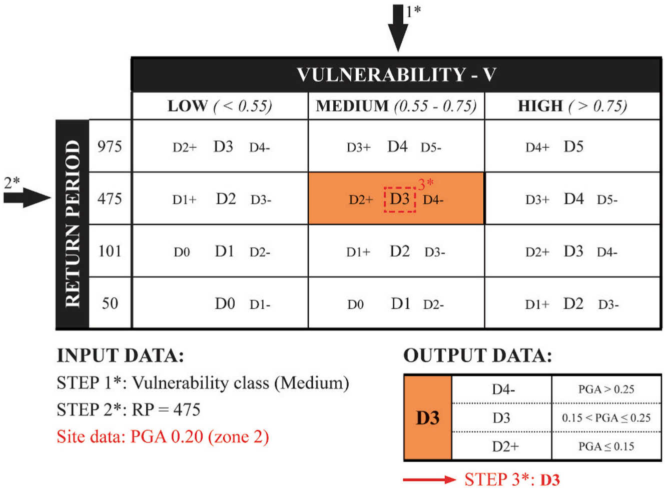

Fig. 11. Damage estimation: example of HP1 of use of the damage matrix M1. The numbers 1*, 2* and 3* refer to the three steps of the procedure.

In the Italian context, the “Spectral responses v1.03” calculation software[7] for quick application purposes [74], while more detailed PGA data referred to the specific OS surface could be derived by municipal seismic microzonation reports. The calculation procedure encompasses three steps. The first step (1* in Fig. 11) concerns the selection of vulnerability class according to the V of the SU under study. Then, the return period row is chosen (2* in Fig. 11), and it is possible to determine the corresponding damage state (3* in Fig. 11). Since the PGA value of the geographical site which belongs to the OS under study is known, the damage state can be unequivocally defined among the range of upper and lower bounds of the resulting cell.

Instead, Fig. 12 shows an example of HP2 for risk comparisons purposes, considering a given OS under different hazard conditions in terms of PGA values. In this case, the first step (1* in Fig. 12) is selecting the vulnerability class. Then, the return period is chosen (2* in Fig. 12). The intersection cell between hazard row and vulnerability column shows the possibilities of damage states according to the PGA ranges of Fig. 4.

Then, the whole OS damage grade to be considered into the *consequence matrix* is the most frequent among the SUs facing the OS. It is indeed calculated in relation to the sum of the area of SUs with the same damage grade and the total covered area, as shown in Fig. 13.

The outcomes of the M2 describe possible post-earthquake scenarios combining both consequences on the users’ and on the built environment. As shown by Fig. 14, the SRM-oriented rationale behind M2 concerns priority strategies in emergency planning orientated towards the improvement of the robustness of the built environment surrounding the OS, and of the preparedness of communities. The robustness aims are pursued according to a horizontal view of M2, that is moving from high

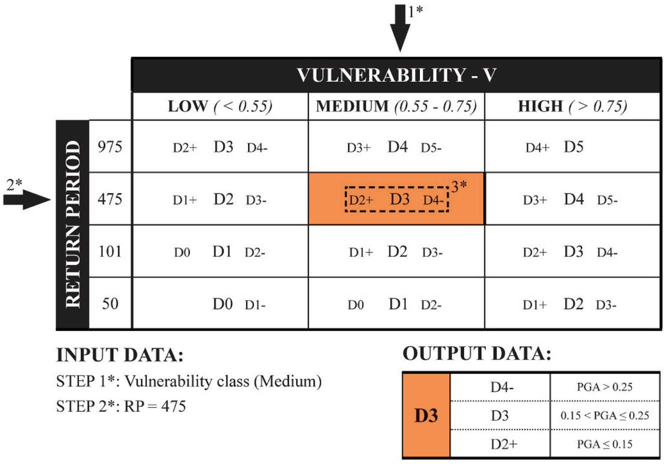

Fig. 12. Comparisons of OSs damages under different PGA conditions: example of HP2 of use of the damage matrix M1. The numbers 1*, 2* and 3* refer to the three steps of the procedure.

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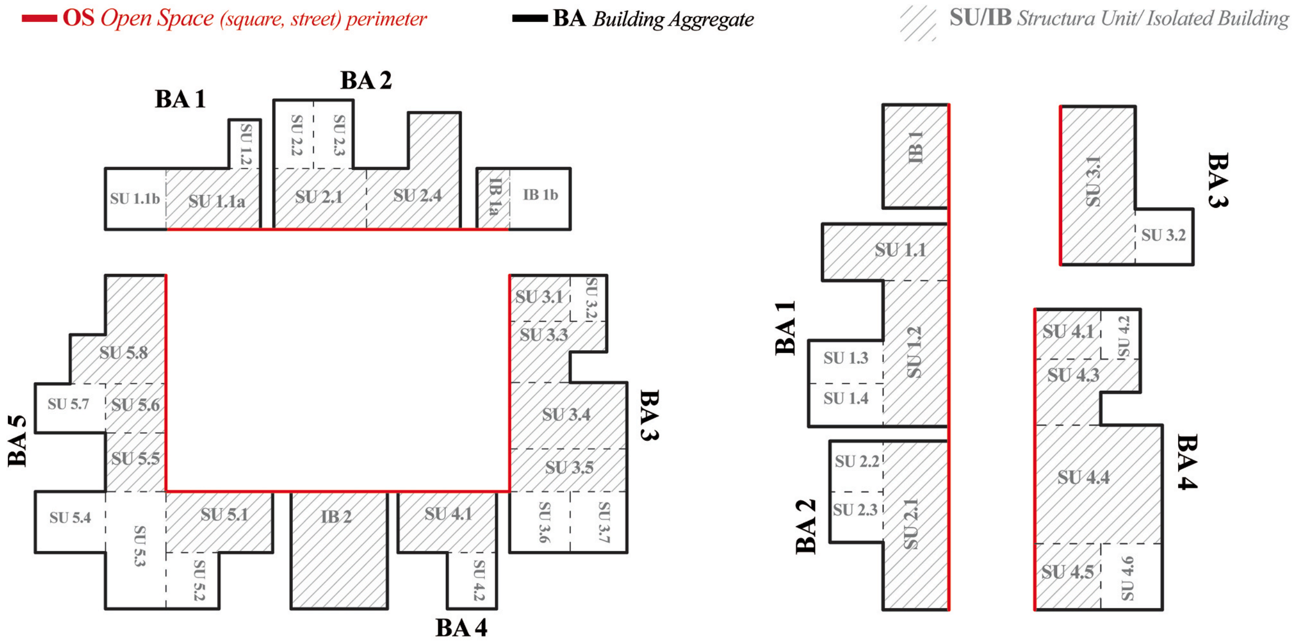
[7] Available online (last access: 22/12/2020) http://anidis.it/index.php?id=53&tx_ttnews%5Btt_news%5D=2&tx_ttnews%5BbackPid%5D=46&cHash=ba11388a6f.



Damage grades per SUs

		m²	D
BA 1	**SU 1.1a**	134	D3
BA 2	**SU 2.1**	132	D2
BA 2	**SU 2.4**	201	D3
	IB 1a	28	D3
BA 3	**SU 3.1**	65	D1
BA 3	**SU 3.3**	113	D2
BA 3	**SU 3.4**	182	D4
BA 3	**SU 3.5**	118	D1
BA 4	**SU 4.1**	140	D3
	IB 2	263	D4
BA 5	**SU 5.1**	147	D1
BA 5	**SU 5.5**	83	D1
BA 5	**SU 5.6**	70	D2
BA 5	**SU 5.8**	193	D3

→

Most frequent damage grade

	m²	
D1	413	22%
D2	315	17%
D3	**696**	**37%**
D4	445	24%
	1869	

Damage grades per SUs

		m²	D
	IB 1	114	D3
BA 1	**SU 1.1**	142	D2
BA 1	**SU 1.2**	191	D3
BA 2	**SU 2.1**	220	D3
BA 3	**SU 3.1**	235	D1
BA 4	**SU 4.1**	65	D2
BA 4	**SU 4.3**	113	D4
BA 4	**SU 4.4**	298	D1
BA 4	**SU 4.5**	86	D3

→

Most frequent damage grade

	m²	
D1	533	36%
D2	207	14%
D3	**611**	**42%**
D4	113	8%
	1464	

Fig. 13. Definition of the potential damage grade of the OS to be adopted for the consequence matrix M2 considering the application on a square (left) and a street (right). The damage grade per SU facing the OS is calculated, by also graphically marking each Building Aggregate.

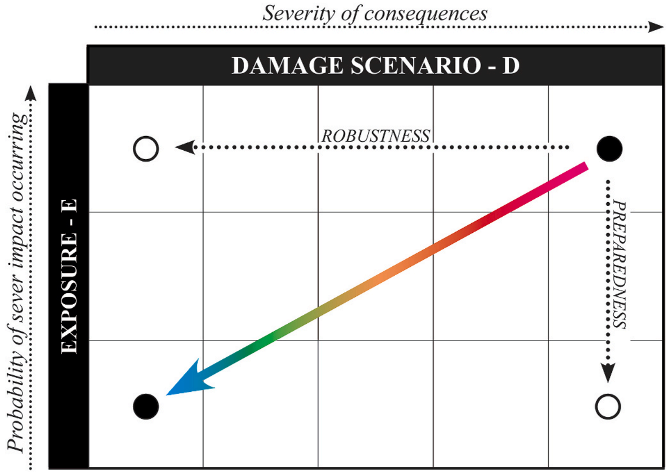


Fig. 14. Application of consequence matrix M2 for DRR strategies.

damage columns to low damage columns thanking to retrofitting interventions on OS facing buildings aimed at avoiding SUs failure [16,20]. This strategy also contributes to the emergency planning for improving the population's mobility in the evacuation process, as well as in the immediate aftermath. In fact, a lower impact of debris on outdoor spaces can fasten the individuals' movement, the rescuers' access and the possibility to leave the OS or gain it for assembly purposes [26].

From a preparedness perspective, the *consequence matrix* can be used to evaluate the maximum exposure level over the time, given a specific OS use. This analysis can be supported by a vertical view of M2, that is moving from high exposure rows to low exposure rows. The related process evaluates if modifications to the maximum occupancy of outdoor areas and buildings should be provided to limit risk in the OSs, similarly to limitations to occupancy in historic buildings given by fire safety regulations [81,87–89]. Such an approach can be mainly performed in public spaces, starting from the outdoor areas, where overcrowding in case of particular events such as mass gatherings (i.e. related to E_H) could be hence controlled. In this sense, the capabilities of M2 can be investigated by comparing the assessed exposure with exposure conditions in various time periods (day, night, holidays) to find the critical scenario in the OS. Besides, robustness-increasing actions could support a limited reduction of building occupancy in terms of future use of the spaces, thus promoting insights on the most adequate alternatives that combine such issues. At the same time, the exposure analysis underlines which scenarios could be more critical in terms of support to the hosted population, depending on individual features (e.g. presence of elderly, parent-assisted children). Thus, this procedure can be adopted as an SRM tool to plan emergency response as well as to develop effective DRR strategies for guaranteeing the safety of OS users in outdoor conditions.

3.2. *Insights and future works*

The main novelties of this work concern the scale of application and the proposal of an integrated SRA-SRM methodology through the matrix-based approach.

About the application scale, the proposed SRA deals with the single OS rather than the entire HBE or the micro-scale elements. Such an approach considers the specific risk component of the HBE, as remarked by previous works [6,10,13], and focuses on the interventions for adequate and effective DRR strategies to be implemented on the built environment elements facing the outdoor spaces of the OS.

About the proposal of an integrated SRA-SRM methodology to be applied in the OS, this work offers a valuable contribution in assisting decision-making process thanks to the combination of damage matrix and consequence matrix. The matrix-based SRA allows to graphically and easily represent the relation between risk factors, thus being a rapid procedure of verifying variation in impacts' severity depending on the input risk conditions, as remarked by previous works on HBEs SRA [61]. As also shown by Section 3.1, it provides the basis for the SRM also by non-expert decision-makers, to make them aware of the consequences of alternative scenarios by linking robustness-oriented and preparedness-oriented choices. This approach actually speeds up the overall decision-making process on emergency planning and DRR interventions. In this general context, one of the main advances of this research also concerns the development of a novel and quick-to-use exposure assessment methodology which tries to combine users' number quantification and features (i.e.: individual vulnerability in terms of their age; intended uses analysis of both indoor and outdoor areas) over time.

The holistic view of seismic risk which combines hazard, vulnerability and exposure can effectively address the existing constraints and policy challenges involved with SRM, by considering that:

1. Given the whole number of OSs in the HBE, local authorities can innovatively use the method to assess which OS is affected by the riskiest conditions in terms of damage/consequences, depending on the combinations of input risk factors (i.e. building vulnerability, hazard conditions, exposure characterization in terms of users' presences by also dividing them into age classes over the time). The use of the matrices under this assumption ensures focusing SRA/SRM efforts in the riskiest parts of the HBE, depending on the identification of "hot spots" in the urban tissue;
2. Given a certain OS in the HBE, the most relevant scenarios can be selected according to the matrix-based approach in terms of combinations of input risk factors. Such parameters provide basic input data for in-deep investigations such as those of simulation-based approaches for both users' behaviours during evacuation and rescuers' access, depending on the damage scenario, and for the decision-makers of risk-reduction strategies [43,62,90]. These tools also allow detecting specific conditions of interactions between users and elements in the OS (e.g. building, debris), rather than describing them from a general standpoint. In this sense, this action contributes to both SRA and SRM analyses;
3. According to M2 usage discussion in Section 3, the SRM perspective on the *consequence matrix* can also identify if preparedness actions can improve the OS population's safety, by also taking into account the direct support to vulnerable users in the post-earthquake OSs, or behavioural training solutions for individuals engaged in a potentially autonomous evacuation process.

In view of the above, this work contributes to a first preliminary step in the BE S^{2}ECURe project, moving towards the definition of bases for SRA and SRM-oriented metrics of the resilience of the built environments and its users [50]. According to this perspective, the provided SRA/SRM methodology could be extended to other disasters affecting the HBE, such as terrorist acts, pollution and heatwaves, according to the project context. The risk factors should be adjusted depending on the specific considered risk, while E could be easily extended to them according to the same rationale.

Nevertheless, this work just represents one of the first steps to fully comprehend a more comprehensive building of post-earthquakes scenarios, which also should take advantage of emergency and evacuation simulation tools [43]. The next research steps should firstly provide the application of the method to real case studies, to validate it. Comparisons with other SRA methodologies could be adopted to this end, as well as analyses involving real-world scenarios under earthquake conditions.

Although the *damage matrix* approach seems to be flexible enough to guarantee the retention of its overall framework, further efforts will be focused on the methodologies validation by evaluating: (i) the effectiveness of damage prediction of the adopted methodologies [23,59], which is focused on SUs; (ii) the development of other techniques focused only on the buildings façades even maintaining the assessment speediness. From this point of view, future efforts to correlate different V assessment models should be undertaken, with the aim of providing unified inputs to be used in the matrix M1, as well as of moving from a vulnerability index to another. Such a result will increase the quickness in the matrix application in real contexts. Furthermore, the potential damage assessment depending on PGA values can be supported by fuzzification techniques [91] to adapt M1 to different hazard-vulnerability coupled systems. Semi-empirical [27], probabilistic [92] and analytical methods [93–95] mainly based on the analysis of the local failure mechanisms (e.g. total or local out-of-plane, gable or corner overturning) can be addressed for further developments aimed at estimating the extension of the falling wall causing debris due to the specific triggered mechanisms.

As a consequence, existing limitations concerning the proposed consequence matrix could be overcome. In fact, the current approach adopts common characterisations for both squares and streets, regardless of their use in the emergency evacuation network. Depending on the *damage matrix* results, the consequence matrix traces possible correlation between the OS users' safety in the evacuation process, and the availability of the outdoor area by providing damage scenarios in qualitative terms on the basis of the existing approaches results [17,20,26,92]. Future works should try to provide quick but specific estimations on debris quantities as well as streets blockage or the safe squares availability for HBE users during the evacuation process (e.g. possibility to host individuals far from debris and with adequate occupant densities while waiting for the rescuers' arrival) [14,15,20]. The analysis of specific OS features can move towards the definition of recurring typological scenarios in geometrical, morphological, construction or even exposure-related terms, also thanking the application to real-world case studies. At the same time, the effects due to the vulnerability of the elements composing squares and streets (e.g. hypogeum, pavements, underground lifelines) could be also added to the damage assessment thus moving towards a more comprehensive scenario description [24,25]. Nevertheless, the quick applicability criteria pursued by the approach should be still maintained.

In view of these activities, the number of columns and rows in M1 and M2 could be additionally adapted to better distinguish the input factors levels too, given the rationale of the matrices. The H rows increase could lead to improve the OS scenario-based inclusion in terms of possible earthquakes. The V column increase could lead to more precise damage estimation, if combined to real-world validations and OS damage levels description also in quantitative terms. The E increase could rely on the inclusion of more users' typologies, also depending on familiarity and risk-awareness related issues, thus leading to improve the OS scenario-based inclusion in terms of human lives and individual vulnerability. In this regard, all these stages of research will focus on the application of behavioural simulation modelling in OSs, which can integrate these preliminary assessment conditions given by the matrixes and the activities of expert technicians for decision-makers' support.

Finally, this work provides the use of the matrices on the assumption of the Italian context. However, the proposed procedure can be replaced and adapted for other different geographical contexts. In this sense, assumptions concerning the historic heritage vulnerability and damage can be adapted, validated and calibrated in analytical terms for different geographical locations, but the general matrices framework could be maintained. Future efforts will apply the matrices to specific case studies for this purpose, thus verifying the whole capabilities of the proposed approach in view of DRR actions.

4. Conclusions

The seismic risk in an urban built environment essentially depends on the risk levels at the meso-scale, that is at each space composing the urban tissues, that are the Open Spaces (OSs), like streets and squares. These areas are the elementary spaces characterized by interactions between the exposed OS users and the post-earthquake damages (as a function of vulnerability and hazard issues), which affect the safety of the users in the OS during the earthquake and in the immediate aftermath. In this general context, OSs in Historical Built Environments (HBEs) are relevant scenarios according to the risk-increasing features of the HBE itself and of the OSs current use.

Starting from this point of view, this paper provides an integrated Seismic Risk Assessment (SRA)/Seismic Risk Management (SRM) approach by means of two matrices for the OSs in HBE, which are also innovatively combined in the methodological framework. Basing on the existing literature-based methodologies, the proposed matrices-based tool aims at improving risk reduction strategies by combining the quick damage assessment and the consequences on the OS users. The first matrix combines data from national hazard maps and quick vulnerability estimation of isolated buildings and Structural Units of building aggregates facing the OS, to predict damage grades according to EMS-98 scale. Then, the second matrix links the worst damage grade of the OS to the exposure classification, which is based on buildings occupancy types by distinguishing different time-based conditions (i.e. daytime, night-time, holiday time) and individual features (i.e. age-based categorization). The second matrix outputs investigate the possible effects on OS users in the immediate aftermath, i.e. during the evacuation process, due to the interaction between the individuals and the debris along the outdoor areas of the OS. This matrix highlights critical conditions for the identification of priority actions robustness-oriented and preparedness-oriented to reduce the OS risk.

The matrices-based assessment represents a rapid decision tool which utility lies in its simplicity and ability to reduce the complexity of the earthquake-related problems for local decision-makers, including non-expert ones. In addition, it presents a preliminary step in further investigations on OS safety, thanking simulation models, since it offers a quick tool to detect risk scenarios in the whole number of OSs placed in the HBE and inside a specific OS in the HBE.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Notations

Table A1
List of variables (symbols) and Acronyms used in the main text of this work. “-“: adimensional variables.

Notation	Unit of measure	Description
DRR		Disaster Risk Reduction
HBE		Historic Built Environment
OS		Open Space
SRA		Seismic Risk Assessment
SRM		Seismic Risk Management
SU		Structural Unit
VIM		Vulnerability Index Method
H		Hazard
PGA	g	Peak Ground Acceleration
I_V	–	Vulnerability index according to the Formisano’s VIM method
V	–	Normalized vulnerability index according to the macroseismic method
D		Damage scenario
μ_D	–	Mean damage grade calculated by the macroseismic method
I	–	Macroseismic intensity according to EMS-98 scale
E		Exposure of OS users
E_D	–	Exposure of day according to the proposed method (Section 2.3.1)
E_N	–	Exposure of night according to the proposed method (Section 2.3.1)
E_H	–	Exposure of holiday according to the proposed method (Section 2.3.1)
M1		Damage matrix
M2		Consequences matrix

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