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COMPUTER-AIDED RISK ASSESSMENT AT URBAN SCALE. MODEL DEFINITION AND VALIDATION ON A CASE STUDY.

A. Basaglia[1], A. Aprile[1], F. Pilla[2] and Enrico Spacone[3]

[1] Department of Engineering, University of Ferrara
Via Saragat 1, 44122 Ferrara, Italy
e-mail: {alberto.basaglia,alessandra.aprile}@unife.it

[2] Department of Civil, Structural and Environmental Engineering, Trinity College Dublin
College Green, Dublin 2, Ireland
e-mail: pillaf@tcd.ie

[3] Department of Engineering and Geology, University of Chieti - Pescara
Viale Pindaro 42, 65129 Pescara, Italy
e-mail: espacone@unich.it

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Abstract. *Disaster risk reduction has become a global urgent need. Similarly to other natural hazards, earthquakes may cause significant damages on a large scale. In Europe, seismic events mainly affect historical city centers, which are characterized by dense urban structure, usually constituted by ancient masonry and pre-code R.C. buildings, often in aggregate sequence. Historical city centers are very much part of the European cultural heritage and their preservation is considered a strategic issue for the EC due to their tangible and intangible values. Furthermore, it is an undisputable fact that natural disasters may have severe negative short-term economic impacts on the built environment and adverse longer-term consequences for economic growth and development. For this reason, the development of an efficient digital tool for urban seismic risk assessment and resilience enhancement becomes essential. With this aim, an original numerical procedure is proposed in this paper, based on multidisciplinary concepts combined in an innovative way. First of all, the concept of Limit States for the Minimum Urban Structure is introduced and described by means of simple mechanically based models. Then, elliptically distributed vulnerability indices are worked out by considering multidirectional seismic hazard, and 2D seismic risk assessment computation is performed. The results are implemented within the GIS software, where they are easily shown and discussed thanks to the graphical mapping tool. The proposed approach allows the definition and evaluation of a global intervention plan for resilience enhancement at the urban scale. Finally the proposed numerical procedure is applied for validation to the Italian city-center of Concordia Sulla Secchia (Italy), damaged by the 2012 Pianura Padana Earthquake (PPE). The predicted damage scenarios are compared with the actual post-seismic damage scenarios in order to evaluate the accuracy of the proposed evaluation procedure.*

1 INTRODUCTION

Disaster risk reduction is one of the biggest global challenge, as attested by the U.N. [1]. The first step to achieve disaster resilience enhancement is to propose unified guidelines for disaster management. Among all natural events, earthquakes produce most damage on a vast scale. They cause high number of casualties, severe economic damages and are a major threat for cultural heritage sites. In Europe, historical city centers represent an essential part of the cultural heritage. This immeasurable asset is a "strategic resource for a sustainable Europe" that need to be preserved [2]. Among all European countries, Italy holds the highest number of listed heritage sites as confirmed by UNESCO (*whc.ujnesco.org*). Seismic risk assessment and urban risk management improvement is the only way to avoid casualties, damages, and consequent settlements abandonment.

2 PROBLEM DEFINITION

Most authors express seismic risk, *R*, as the relationship between hazard, vulnerability and exposure, as reported in Eq. (1):

$$R_{ie|T} = |(H_i \otimes V_e) \otimes E|_T \tag{1}$$

where *H* is the hazard, i.e. the probability of exceedance of the seismic activity level of intensity *i*, during a specified recurrence period *T*; *V* is the vulnerability, i.e. the intrinsic predisposition of the *e-th* exposed element to suffer damage, resulting from a seismic event of intensity *i*; *E* is the exposure of all the *e-th* exposed elements. *H* and *E* are directly linked to the site geological properties and the social and economical value of buildings respectively. V, on the contrary can be determined with different methods [3]. Detailed approaches, highly efficient for individual buildings, become ineffective while moving to urban scale analysis. In fact, the use of less sophisticated but more practical methods is required by such complex task.

Currently, one of the main assessment methods used by researchers is the combined approach of the *Vulnerability Index* method [4, 5, 6] and the *Macroseismic* method [7, 8]. The first method determines the vulnerability of buildings as a weighted sum of 11 parameters, which represents the main features that influence the buildings' response to a seismic event. To determine the vulnerability index, a detailed inspection of buildings is required, regarding both geometrical and structural aspects. I_v, have always to fall within the range $0 \div 100$. The Macroseismic method derives from the definition of the European Macroseismic Scale, *EMS-98* [9] and related *mean damage grades*, $\mu_D \in [0 \div 5]$, and *Damage Probability Matrixes* (DPMs). Buildings are ranged into 6 vulnerability classes with an assigned *Vulnerability parameter*, V, which can be correlated with the I_v parameter of the aforementioned method, using Eq. (2). Then, using a probabilistic approach, it is possible to determine the damage level the constructions will undergo after an earthquake as well as the number of collapsed or unusable buildings and the seismic effect on the population.

$$V = 0.592 + 0.0057 \cdot I_V \tag{2}$$

This approach presents some main limitations:

a) it considers only masonry constructions;

b) it does not take into account the effects of buildings in aggregate sequence;

c) it considers the overall vulnerability as the simple sum of buildings' vulnerabilities.

Therefore, a complete methodology for seismic risk assessment and management at urban scale is still lacking.

3 MULTIDIRECTIONAL URBAN RELIABILITY ASSESSMENT (MURA-SH) METHOD

In this work, a new methodology is presented as “Multidirectional Urban Reliability Assessment - Seismic Hazard (MURA-SH)” method [10], based on the improvement of the previously described method.

3.1 Vulnerability index integration for masonry aggregates

A modified approach to the aggregate evaluation proposed by [11] is used: 5 additional parameters (see Tab. 1) are considered together with the 11 ones of the original Vulnerability Index Method [4, 5, 6]. The additional parameters take into account the building’s behaviour when inserted into an aggregate sequence. It is important to remark that contiguity of buildings can either increase or reduce the seismic vulnerability within the range of $\pm$30% of the detached building vulnerability.

Parameters		Class C_{vi}				Weight
		A	B	C	D	p_i
P12	Interactions in elevation	0	15	25	45	1.25
P13	Floor plans interactions	0	5	15	45	1.75
P14	Presence of offset ceilings	0	25	35	45	0.75
P15	Structural of typological heterogeneity	0	10	20	45	1.50
P16	Percentage difference within facade openings	0	15	35	45	1.25

Table 1: Vulnerability Index I_V additional parameters for masonry buildings in aggregate sequence

3.2 Proposed I_V – V correlation for R.C. buildings

Historical city centers often present an heterogeneous mix of masonry and R.C. constructions. In this work, a mathematical correlation between the Vulnerability Index method and the Macroseismic approach for R.C. building is proposed, as reported by Eq. (3).

$$V = 0.8568 - 0.0083 \cdot I_V - 0.000039 \cdot I_V^2 \quad (3)$$

The proposed correlation is determined following the same analytical steps described in [3] but, unlike the linear correlation used for masonry buildings, a quadratic correlation is adopted for R.C. constructions.

3.3 Vulnerability ellipses for directional risk assessment

Buildings have usually a non regular plant shape and present different structural properties in each direction. Vulnerability is considered as the sum of isotropic and anisotropic factors [12]. The isotropic factor consists of all features not related to the input direction, like building’s material quality and age. The anisotropic one includes all features dependant on the input direction, like the structural strength and stiffness as well as the boundary conditions. For this reason, each building vulnerability can be geometrically represented by an *ellipse.* Since buildings are arranged in a city according to different orientations, seismic events of similar intensities but different directions can produce different effects. In the current work, a directional risk assessment is proposed, following 3 subsequent steps:

a) Main directions x and y of the building under assessment are found out (Fig. 1a). Vulnerability indexes I_X and I_Y are then determined in both directions, by considering the different resistant areas in x and y direction. I_X and I_Y are now the semi-axes of the vulnerability ellipses (Fig. 1b);

b) An external reference system is fixed (for example, in this case, cardinal axes E-N). The angle between the x main direction and the cardinal axes E is called θ, (Fig. 1c). By considering $I_X = a$ and $I_Y = b$, the vulnerability ellipse is determined through Eq. (4):

$$\frac{(x \cdot \cos\theta + y \cdot \sin\theta)^2}{a^2} + \frac{(y \cdot \cos\theta + x \cdot \sin\theta)^2}{b^2} = 1 \tag{4}$$

c) Given a possible earthquake direction, α, vulnerability ellipses return the corresponding vulnerability value I_α for each building.

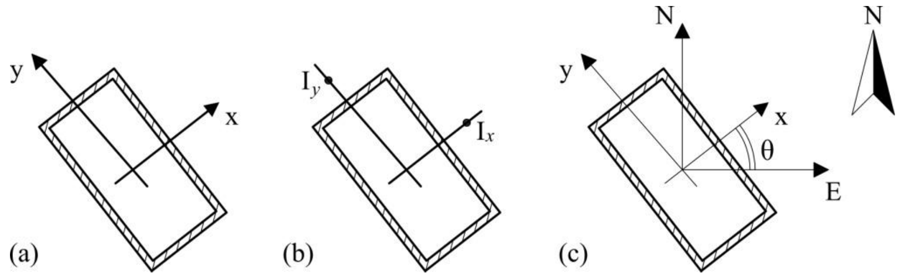

Figure 1: (a) Main directions of a building; (b) vulnerability indexes I_X and I_Y along main directions and (c) θ angle definition.

3.4 Definition of urban system reliability

The overall vulnerability of a city is not the simple sum of all buildings' vulnerability. Different constructions have different roles, which make them more or less relevant for the settlement, and their overall functioning is possible thanks to the accessibility of connection elements (routes, bridges, public open spaces, ecc). Furthermore, urban management policies must deal with the emergency phase after an earthquake, as well as with the *minimum urban structure* [13] preservation, in order to prevent the settlement abandonment. In this work, a performance-based approach for the urban system has been introduced, by adopting the definition of the *limit conditions for settlements* [14, 15]. Following this approach, the probability of the *e-th* building to undergo a certain damage level $P(D_k)|_e$, is accounted in a model that represents the overall city behavior with reference to the most significant limit conditions, expressed as CLE (emergency), CLV (life-saving) and CLD (damage).

- **CLE condition** - Only essential activities for the emergency phase are considered and the majority of the buildings can undertake even severe damages. The CLE is represented by a *series* of emergency sub-systems (see Fig. 2).

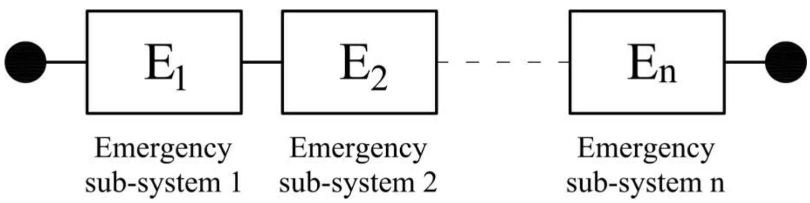

Figure 2: Urban system behaviour of the emergency limit condition (CLE)

Each *emergency sub-system* includes a strategic building, whose operation is essential in the emergency phase, and all "interfering" buildings related to it. An interfering building is an ordinary building that faces a strategic connection route (from/towards a strategic building or an emergency area). The CLE survival probability (*urban reliability*) is evaluated using Eq. (5).

$$P[\text{system survival}] = \prod_{i=1}^{n}(1 - P_i) \tag{5}$$

The component's failure probability P_i is defined according to the *importance class* c_u of buildings [16]. In particular, only the collapse, even partial, has to be prevented for interfering buildings (c_u= I, II), while any activity has to continue without interruption for strategic buildings (c_u= III, IV), see Eq. (6).

$$\begin{aligned} c_u &= \text{I, II (interfering)} \quad P_i = P(D4) + P(D5) \\ c_u &= \text{III, IV (strategic)} \quad P_i = P(D2) + P(D3) + P(D4) + P(D5) \end{aligned} \tag{6}$$

- **CLV condition -** The whole settlement is considered. The complete functionality of all strategic buildings is guaranteed, and only modest-to-long interruption of ordinary urban functions is accepted. The behaviour of the city is represented by a series-parallel combination of strategic and ordinary sub-systems (see Fig. 3). Each strategic sub-system includes an emergency system (see CLE) along with their "redundancy", i.e. other strategic systems of similar functions but not essential during the emergency phase. Ordinary sub-systems are considered in order to recover the settlement pre-seismic standard, including residential and economic activities. The CLV probability is evaluated using Eq. (7).

$$P[\text{system survival}] = \prod_{i=1}^{n}\left(\prod_{j=1}^{m} P_{ij}\right) \tag{7}$$

where P_{ij} accounts the interaction of the considered sub-systems and is defined by Eq. (6).

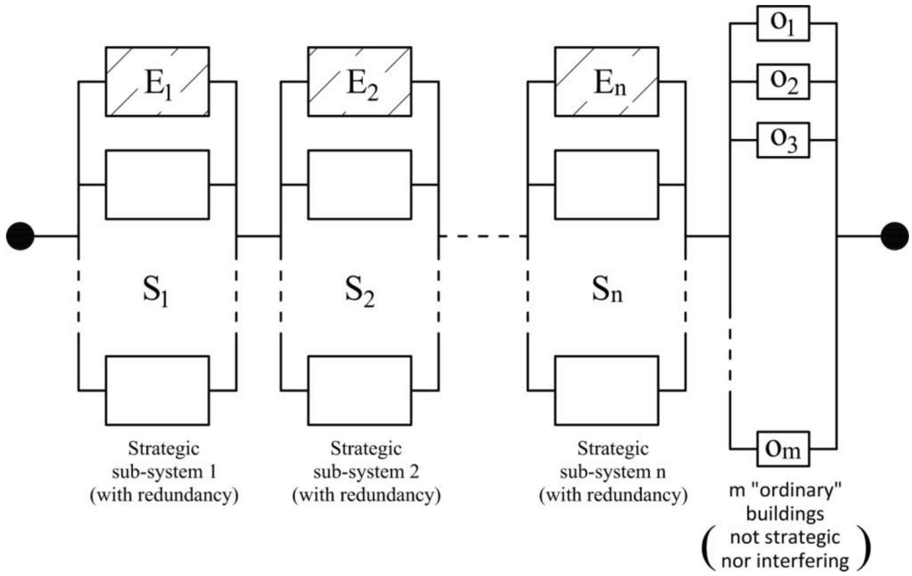

Figure 3: Urban system behaviour of the life-saving limit condition (CLV)

- **CLD condition** - Conceptually similar to the CLV, the only short-to-modest or partial interruption of ordinary urban functions is accepted. The behaviour of the city is still represented by a *series-parallel system* (see Fig. 3), and the urban reliability is evaluated using Eq. (7) where P_{ij} is defined by Eq. (8). The CLD represents the possibility for the settlement to undergo limited damage after an earthquake in order to guarantee the shorter recovery time targeted by the urban management policy.

$$c_u = \mathrm{I,II}\ \text{(ordinary)} \qquad P_i = P(D3) + P(D4) + P(D5)$$

$$c_u = \mathrm{III,IV}\ \text{(strategic)} \qquad P_i = P(D2) + P(D3) + P(D4) + P(D5)$$

4 COMPUTER-AIDED RISK ASSESSMENT

The MURA-SH method application can be time-consuming even for small settlements, mainly due to the complexity of the urban system reliability model and the multi-directional damage scenarios evaluation. The development of a computer-aided procedure for the MURA-SH numerical implementation becomes highly efficient from the computational point of view by using the MATLAB® software. The proposed numerical procedure is presented in herein.

The preliminary phase of the procedure consist on the definition of a *.txt* input file listing all the required data of the MURA-SH method. The input files format holds seven columns and as many rows as the number of buildings under assessment. The columns data contain the following information:

- Vulnerability index along *x*-main direction, I_X;
- Vulnerability index along *y*-main direction, I_Y;
- θ angle, see Eq. (4);
- Structure Identifier (ID = 0 for masonry buildings, ID = 1 for R.C. buildings and ID = 2 for other structural types);
- Local soil amplification factor related to each building, F_a,
- Importance class, c_u [16];
- Occupants' number.

All data are loaded from the input file and vulnerability ellipses are created for every building using Eq. (4). Then, a coordinates transformation from the local to the global reference system is arranged. Finally, oriented vulnerability indexes I_α are evaluated.

Indexes I_α have to be converted into vulnerability values V_α using Eq. (2) and (3) depending on the structural type. Mean damage grades, μ_D, are evaluated for increasing intensities in the range $I_{EMS-98} = 5 \div 12$ with the equations of the Macroseismic method [8], but assuming the ductility factor, Q, equal to 2.1 for masonry buildings and 3 for other buildings. This assumption is introduced to consider that masonry structures can undergo local failure modes with limited ductility, when the global behavior is not guaranteed by the structural features.

Then, damage distributions histograms are defined making use of the $Beta$ probability density function (PDF), already included in the MATLAB® library as "betapdf". Numerical integration is made within defined intervals with the MATLAB® "trapz" function. Evaluated damage probabilities are listed in matrixes for increasing intensities in the range $I_{EMS-98} = 5 \div 12$.

Total damage occurrence probability is used for losses evaluations, assessing the number of damaged or unusable buildings as well as the number of casualties and severed injured or homelessness. Equations to evaluate these data can be found in [3].

Finally, computed probabilities are combined to determine the reliability of the urban system, using equations introduced in §3.4, depending on the considered limit condition (CLE, CLV, CLD). The overall settlement reliability is evaluated for every direction α and for increasing intensities $I_{EMS-98} = 5 \div 12$. The proposed method application allows to easily predict which earthquake direction will cause the worst damage scenario, and the evolution of the settlement performance from moderate to strong earthquake intensity.

The overall MURA-SH numerical procedure is summarized in flowchart of Fig. 4.

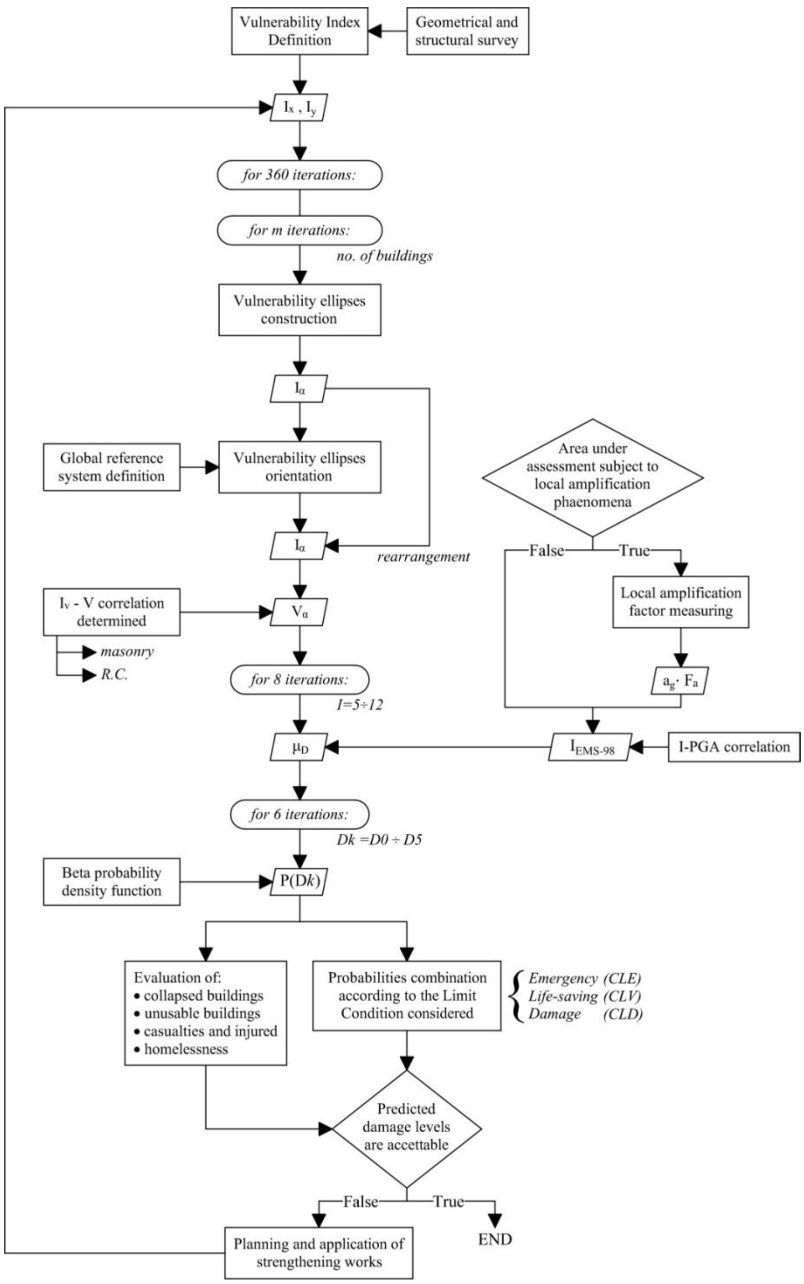

Figure 4: The MURA-SH method flowchart.

5 MODEL VALIDATION ON A CASE STUDY

Italy has recently experienced a seismic event (PPE, 2012). Among all the affected settlements, the city of Concordia sulla Secchia has a peculiar historical city center, constituted by an heterogeneous mix of masonry and R.C. constructions, built in different periods of time and mostly in aggregate sequence. The Municipal authorities of Concordia commissioned a post-earthquake survey, regarding its CLE sub-system, to the University of Ferrara, gathering geometrical and structural features of the majority of the buildings. Thanks to the available information, the MURA-SH method has been applied to the CLE sub-system of Concordia and μ_D values have been obtained for the PPE event. The PPE registered intensity that hit he city was within the range $I_{EMS-98} = 7 - 8$ (source: INGV) and the spatial distribution of seismic waves had the WNW-ESE predominant direction, i.e. 22° East (source: Italian Civil Protection).

Predicted damages were subsequently compared to the observed ones [10]. The comparison shows that, for $I_{EMS-98} = 7$, the predicted damage matches the observed damage on 15 of the 42 total number of buildings, with a positive feedback on the 36% of cases; for $I_{EMS-98} = 8$, the predicted damage matches the observed damage on 19 of the 42 total number of buildings, with a positive feedback on the 45% of cases. Maximum I_{EMS-98} registered during the PPE was equal to 8, and Concordia Sulla Secchia was the second most affected city. Therefore, it is reasonable to deduce that the actual intensity event that hit the settlement was closer to the upper bound of the measured range. The MURA-SH procedure needs to undergo more validations to improve the results accuracy. However, recognizing the task complexity, the obtained results are considered promising.

Some numerical results obtained with the MATLAB® procedure are shown in Fig. 5, where the collapse probability is represented along with the survival probability (*reliability*) of the CLE sub-system. Starting from intensity $I_{EMS-98} = 6$, the collapse probability assumes positive values and rapidly increases while the reliability drops to zero, accordingly with the CLE series system definition.

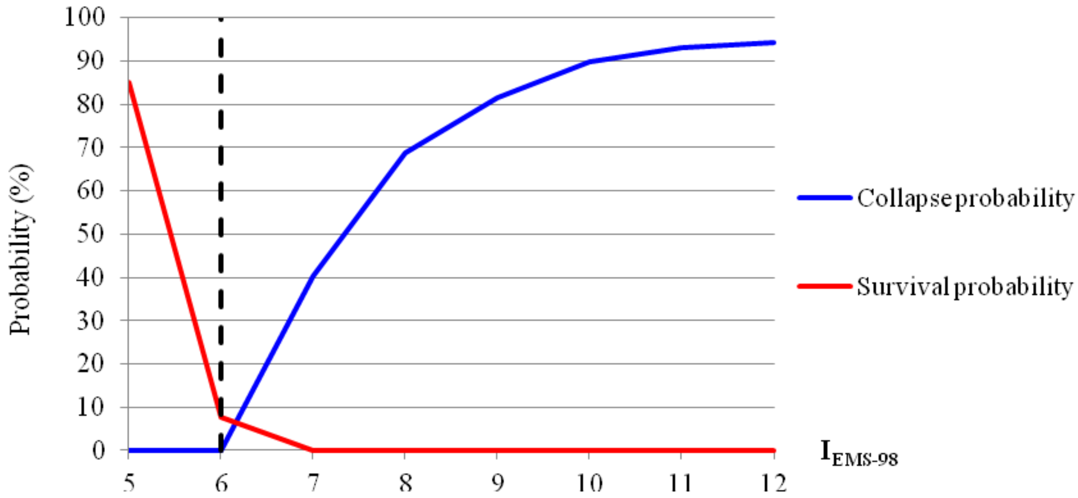

Figure 5: Collapse probability and survival probability of Concordia sulla Secchia CLE sub-system for increasing seismic intensities.

Furthermore, assessment output values can be reported directly on a city map (see Fig. 6), using the geospatial processing program ArcMap, of the Esri's ArcGIS suite (*http://desktop.arcgis.com/en/arcmap/*). With this representation it is possible to have an immediate overview of the earthquake effects for different directions and increasing seismic intensities. A unique “feature identifier”, also called FID, has to be assigned to every building in order to correctly refer corresponding output results. Assessment output values need to be previously organized in Excel files, using different sheets for increasing seismic intensities. Different colour maps can be used to represent the effects of increasing seismic intensities, and to identify most vulnerable areas.

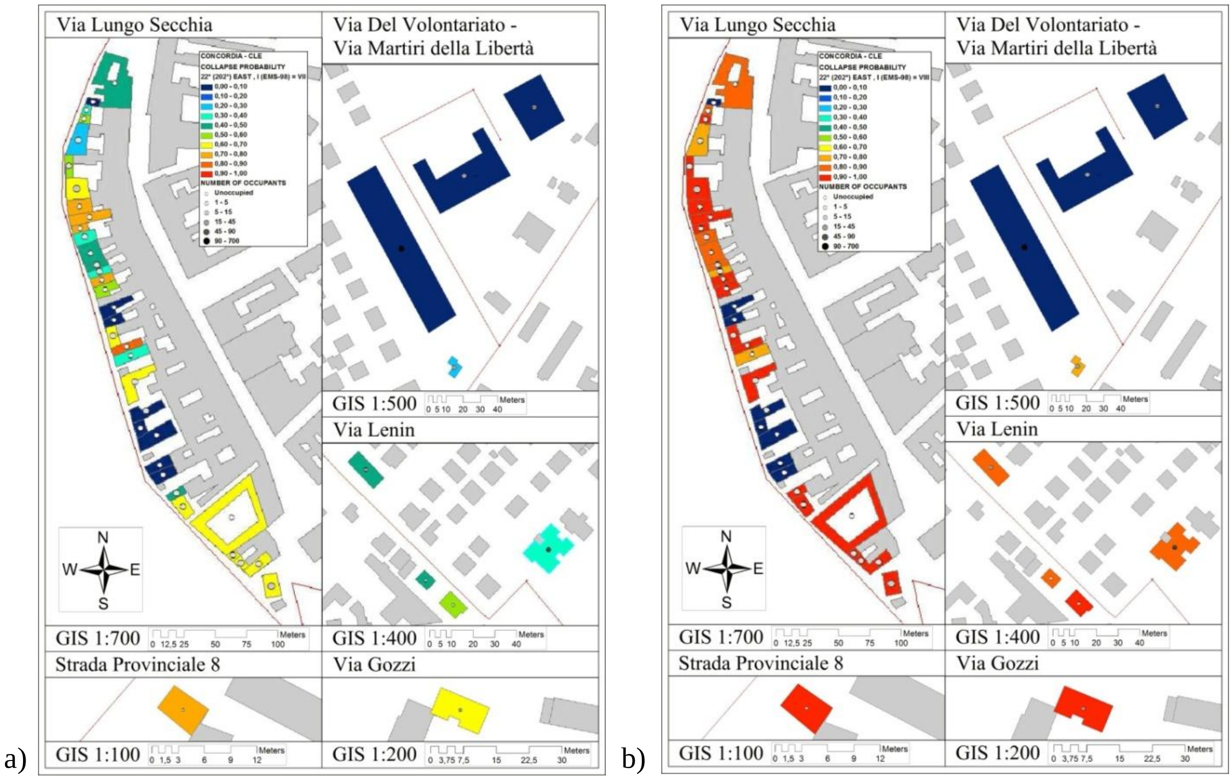

Figure 6: Mapping results of the collapse probability for the Concordia sulla Secchia CLE sub-system for (a) $I_{EMS-98} = 7$ and (b) $I_{EMS-98} = 8$.

6 CONCLUSIONS

In this work, a new methodology for the risk assessment at urban scale called MURA-SH method has been proposed. The MURA-SH method includes R.C. buildings in the evaluation, takes into account the effect of buildings aggregate sequence and performs multi-directional assessments, using the vulnerability ellipses. The MURA-SH method applies a performance-based approach to the settlement, with the definition of the urban system reliability. Thanks to its features, this method can predict whether the settlement will be able to withstand an earthquake, and what performance loss it will endure. The MURA-SH method has been implemented in a computer-aided procedure using the MATLAB® software. The obtained output results can be easily visualized with simple curves and GIS maps.

The proposed MURA-SH method has been applied on the case study of the historical city centre of Concordia sulla Secchia (Italy). The settlement experienced the PPE (2012) and a post-seismic survey of the CLE sub-system was carried out. The possibility to compare predicted damage scenarios to the observed ones has been extremely important to test the MURA-SH method accuracy. From the comparison, a matching rate of 45% ($I_{EMS-98} = 8$) was found. The procedure needs to undergo more validations to improve the results accuracy. However, recognizing the task complexity, the MURA-SH method results are considered promising.

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