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Seismic Risk Prioritization of Masonry Buildings Using the First-Level Approaches for Vulnerability Assessment

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Abstract: This paper aims to determine the seismic risk distribution of old masonry buildings located in Galata, the historical region of İstanbul. In order to obtain seismic risk prioritization of the built environment, the seismic vulnerability assessment of 40 old masonry buildings was carried out according to both the Vulnerability Index Method (VIM) based on the European Macroseismic Scale (EMS-98) and the procedure in the Specifications for Determination of Seismically Vulnerable Buildings (SDSVB 2019). In the first part of the study, using the building data gathered by the screening process on site, the vulnerability scores (VS) comprising the structural and non-structural parameters were obtained and the performance score (PS) of each building was calculated according to SDSVB 2019. Depending on the results, in order to determine the seismic priority levels, the buildings were ranked from the lowest to the highest performance score and classified in terms of their structural vulnerability. Then, in the second part of the study, the vulnerability index (VI) for each building was determined depending on the building parameters affecting the structural vulnerabilities. On the basis of vulnerability indexes, damage grades of the buildings were estimated, and accordingly, the damage distribution was acquired for the building stock. Additionally, the seismic risk distribution maps were compiled for the building inventory according to the findings achieved from both methodologies. As a result of this study, the differences between the two first-level procedures were outlined with a comparative assessment, thereby demonstrating the importance of seismic risk prioritization of the historic built environment for city-scale risk management strategies.

Keywords: Masonry buildings, Seismic vulnerability assessment, Seismic prioritization, Damage distribution

Introduction

Historical buildings around the world have been threatened by devastating earthquakes and even subjected to severe damage leading to irreversible losses in cultural assets over centuries. Thus, especially for countries highly exposed to seismic hazards, protection of the historical built environment against the impacts of destructive earthquakes has become a major concern for disaster management authorities. In this context, in order to obtain the potential damage distribution of the building stocks in historical regions, prioritization of the masonry buildings through the use of seismic vulnerability assessment methods has gained great importance within the earthquake mitigation strategies implemented in seismic-prone countries.

The seismic vulnerability assessment methodologies are mainly based on different scoring strategies that take into account the seismicity level and the structural parameters of the assessed building to determine the seismic risk distribution of large numbers of buildings. Among these, the rapid visual screening (RVS) procedure proposed by FEMA P-154 (2015) is one of the most widely-used methods for the assessment of different building typologies that aims to identify the most vulnerable buildings using the building data obtained by standardized scoring forms filled out during the screening process. Also, in the RVS procedure proposed by The

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National Research Council of Canada (NRC/IRC, 1992). The seismic vulnerability is represented by the Seismic Priority Index calculated using the structural and non-structural parameters, along with the site-specific characteristics that affect the seismic performance of the assessed building. Moreover, the method given in The New Zealand code (NZSEE, 2006) involves two levels of assessment approach through rapid visual screening and detailed seismic evaluation of the building. With the implementation of the Specifications for Determination of Seismically Vulnerable Buildings (SDSVB, 2019). The Turkish Ministry of Environments and Urbanization also set a walk-down evaluation method to be applied for the seismic vulnerability assessment of existing buildings in a regional scale. Similar to the procedures adopted in other countries, the method is based on the calculation of a building performance score taking into account the structural parameters such as the number of stories, construction quality, pounding effect and structural irregularities as well as the site topography, soil conditions and seismicity of the survey region.

Furthermore, an overview of the past research on seismic vulnerability analysis reveals that vulnerability index-based procedures also referred to as Vulnerability Index Methods (VIM) in literature, have been adopted for the large-scale seismic risk assessment of historical structures in heritage sites. As formerly proposed, VIM depends on the calculation of a vulnerability index of each building using the vulnerability parameters that represent a series of building-specific characteristics concerning the typology, construction quality, building adjacency and the structural system as well as the topography and the site conditions of the inspected area (Benedetti & Petrini, 1984). As the basis for determining the vulnerability index, the method employs the predefined vulnerability classes given in European Macroseismic Scale (EMS-98) (Grünthal, 1998).

Vulnerability index-based methodologies in the literature mainly depend on the statistical analysis of the building data regarding the typical damage observed from post-earthquake evaluation. The theory behind these methods is to represent the essential sources of building vulnerabilities that affect the structural behavior under a given seismic action and to determine the vulnerability index as a function of several parameters estimated for each assessed building (Lagomarsino & Giovinazzi, 2006; Ferreira et al. 2013). In recent index-based methodologies enhanced for seismic vulnerability assessment, additional parameters were adopted to account for the pounding effects due to the structural interactions between the adjacent buildings (Formisano et al., 2017; Chieffo et al., 2021). To investigate the physical vulnerability of the masonry buildings in Italian historic regions, Rapone et al. (2018) introduced a predictive model, directly implementing it as a case study in Scanno, Abruzzo. The proposed model was calibrated on the basis of the observed damage data from the 2009 L'Aquila Earthquake. Furthermore, Brando et al. (2021) proposed an empirical model for the buildings located in Cusco, Peru through an extensive field investigation of the historic region. Therefore, the well-documented post-earthquake building inventories have been utilized to improve and modify the existing procedures based on a vulnerability index-based approach. As can be seen from the previous studies, all the proposed methodologies have an attempt of determining the safety levels of existing buildings for the pre- and post-earthquake actions. Especially, the seismic prioritization decision is considered as a critical issue in terms of predicting and mitigating the seismic risks of heritage structures with local identity and cultural values. With this motivation, in this study, to evaluate the seismic vulnerability of the existing old masonry buildings located in the historical region of Galata, a case study was performed consisting of 40 representative buildings having similar structural characteristics that influence seismic performance. For the seismic risk prioritization of the built environment, two first-level procedures were carried out on the basis of SDSVB and VIM. As a result of this study, the seismic risk distribution maps were generated for the building inventory with respect to the findings obtained from both methodologies. Also, the importance of seismic risk prioritization of the historical built environment for city-scale risk management was revealed and emphasized with a comparative evaluation.

Methodology

The methodologies followed in this study are summarized separately in two sections. In the first section, the rapid vulnerability assessment method presented in SDSVB for masonry buildings is outlined whereas in the second section, the VIM, another rapid seismic assessment procedure introduced for masonry building stocks developed by the Italian National Group for Defense from Earthquakes (GNDT), is described.

Rapid Seismic Vulnerability Assessment according to SDSVB

In this study, the vulnerability assessment procedure introduced in SDSVB for the large existing masonry building stocks was followed. The aim of the proposed procedure is to identify, itemize, and classify the existing buildings having high-risk priorities during a forthcoming earthquake in a particular region. During the rapid visual screenings, the vulnerability parameters for each building are detected, and performance scores (PSs) depending on both the vulnerability scores (VSs) that represent each parameter and the base score (BS) that changes according to the seismic hazard zone and the number of stories are calculated. For the calculation of BS, the seismic hazard zone concerning the seismicity of the studied district is specified with the use of an online tool supported by the National Disaster and Emergency Management Authority (AFAD). Also, for the identification of VSs, different vulnerability parameters are taken into account during on-site evaluation, namely, building typology, the number of stories, apparent quality, pounding effect, irregularity in the plan, insufficient wall amount, irregular wall openings, soft story, topographic effect and insufficient structural lintels. Under the condition of vulnerability parameter existence, a vulnerability score modifier (VSM) is determined as 0 or 1 detailed with the corresponding VSs. Among the vulnerability parameters, only for the apparent quality, VSM is decided as 0.1 or 2 pointing out the good, moderate, and bad conditions, respectively. The variation of BSs concerning the different hazard zones and VSs corresponding to each vulnerability parameter according to the number of stories are listed in Table 1.

Table 1. Base scores (BSs) and vulnerability scores (VSs) for masonry buildings

	Base Scores (BS)			Vulnerability Scores (VS)										
	Seismic hazard zones			Apparent quality						Pounding effect				
No. of stories	I ($S_{DS} \geq 1.0$)	II-III ($0.5 \leq S_{DS} < 1.0$)	IV ($S_{DS} < 0.5$)	Material quality	Work manship quality	Damage	Soft story	Irregular wall openings	Insufficient wall amount	aligned Mid/Edge	not aligned Mid/Edge	Irregularity in Plan	Insufficient structural	Topog. Effects
1	110	120	130	-10	-5	-5	0	0	-5	0 /-5	-5 /-10	-5	-5	-5
2	100	110	120	-10	-5	-5	-5	-5	-5	0 /-5	-5 /-10	-10	-5	-5
3	90	100	110	-10	-5	-5	-5	-5	-10	0 /-5	-5 /-10	-10	-5	-5
4	80	90	100	-10	-5	-5	-10	-10	-10	0 /-5	-5 /-10	-15	-5	-5
5	70	80	90	-10	-5	-5	-10	-10	-15	0 /-5	-5 /-10	-20	-5	-5

After the determination of the BS, VS and VSM, PSs for each building are calculated by Eq. (1) to provide vulnerability judgment and identify the intervention priorities.

$$PS = BS + \sum [(VSM) \times (VS)] \tag{1}$$

With the completion of the calculation of PSs, the method assigns a class of seismic vulnerability for the entire building stock changing from low to high priority. At this point, the low PSs put forward the buildings having high priority which require a detailed assessment and retrofitting. As a result, in accordance with the risk levels obtained by this methodology, PSs are interpreted with caution and the outcomes are used to develop prioritization strategies in specific regions for seismic risk mitigation.

Vulnerability Index-Based Seismic Assessment Method

Among the methodologies introduced for the regional assessment of seismic vulnerability for prioritization of large numbers of buildings, in the second stage of the evaluation procedure implemented in this study, the seismic assessment of the old masonry building stock in the region was also performed using the vulnerability index-based methodology improved based on the approach proposed by the Italian National Group for the Defense against Earthquakes (GNDT, 1993). The method involves the evaluation of 15 parameters characterizing the structural vulnerabilities of the assessed building and the calculation of the vulnerability index in relation to the parameters considered in the implemented procedure (Formisano et al., 2015). Application of the method used in this study requires the completion of the vulnerability assessment form formerly introduced by Benedetti and Petrini (1984) as a rapid evaluation procedure aiming to investigate the seismic vulnerability of masonry buildings. The original assessment form includes 10 parameters to evaluate the performance of the building in relation with the construction quality and the structural and non-structural deficiencies. In addition to these parameters, the method used in this study includes 5 additional parameters accounting for the interaction effects between the structural units constructed adjacently. Therefore, with the use of the proposed assessment form based on 15 parameters described in Table 2, the information related to the structural and typological characteristics is acquired from each building in the study region.

Table 2. Vulnerability assessment form with parameters

#	Parameters	Class Score (s_i) A	B	C	D	Weight (w_i)
1	Organization of vertical structures	0	5	20	45	1
2	Nature of vertical structures	0	5	25	45	0.25
3	Distribution of plan-resisting elements	0	5	25	45	0.75
4	Location of the building and type of foundation	0	5	25	45	1.5
5	Type of floor	0	5	25	45	0.5
6	In-plane regularity	0	5	25	45	0.5
7	Vertical regularity	0	5	15	45	0.8
8	Roofing	0	15	25	45	0.75
9	Details	0	0	25	45	0.25
10	Physical conditions	0	5	25	45	1
11	Presence of adjacent building with different height	-20	0	15	45	1
12	Position of the building in the aggregate	-45	-25	-15	0	1.5
13	Number of staggered floors	0	15	25	45	0.5
14	Structural or typological heterogeneity among adjacent structural units	-15	-10	0	45	1.2
15	% difference of opening areas among adjacent facades	-20	0	25	45	1

As given in Table 2, a specific vulnerability score (s) is assigned to each vulnerability parameter, according to the estimated vulnerability class ranging between Class A and D, representing the worst and the best state of the related parameter. The weight (w) ranges between 0.25 and 1.5 depending on the significance of the inspected parameter on the structural vulnerability. Finally, the vulnerability index (I_v) of each structural unit is determined as the weighted sum of the score (s_i) of the estimated vulnerability class multiplied by the weight (w_i) corresponding to each parameter, using Eq. (2).

$$I_v = \sum_{i=1}^{15} s_i \, . \, w_i \tag{2}$$

The normalized vulnerability index (V_I) is also determined as

$$V_I = \left[\frac{I_v - \left(\sum_{i=1}^{15} s_{min} . w_i \right)}{\sum_{i=1}^{15} [(s_{max} . w_i) - (s_{min} . w_i)]} \right] \tag{3}$$

According to the vulnerability index-based approach used in this study, the potential damage state of each structural unit within the study region is predicted using the EMS-98 macroseismic intensity (I) obtained by the attenuation relationship given as

$$I = 1.45 M_w - 2.46 \ln(D) + 8.166 \tag{4}$$

where M_w and D represent the moment magnitude and source-to-site distance of the seismic action, respectively (Jaimes et al., 2015). Subsequently, determining the macroseismic intensity (I) for the specified seismic action of the study region, the mean damage grade (μ_D) of each building is calculated using Eq. (5) (Giovinazzi et al., 2006). As seen in Eq. (5), in addition to the macroseismic intensity (I), the normalized vulnerability index (V_I) and the ductility index (Q) are also used to predict the mean damage grade (μ_D) in the seismic vulnerability analysis. In order to derive the predicted damage distribution of the region, using the mean damage grade (μ_D) calculated for each structural unit, the studied buildings are classified into five discrete damage grades as no damage, slight damage, moderate damage, significant damage, severe damage and collapse denoted by D0, D1, D2, D3, D4 and D5, respectively.

$$\mu_D = 2.5 \left[1 + tanh \left(\frac{I + 6.25 V_I - 13.1}{Q} \right) \right] \tag{5}$$

Results and Discussion

In order to investigate the seismic vulnerability of the old masonry building stock located in Galata, 40 buildings having story numbers up to 5 were assessed as a case study and the results of the analyses conducted by two first-level methodologies (SDSVB and VIM) are presented.

In the initial stage of vulnerability analysis, for the implementation of the SDSVB method, the building data was collected through the walk-down survey. According to the VSs obtained on-site, PS for each building was calculated to classify the priority risk level. Herein, for the prioritization strategy of the surveyed buildings, PS ranges were classified as PS≤25, 25<PS≤55, 55<PS≤85 and PS>85 for high, moderate, low, and no risk levels, respectively. According to the given priority risk level categorization, the lowest scores show the group of buildings having high risk needing immediate intervention for further seismic evaluation.

Table 3 demonstrates a clear classification of the number of buildings according to the PS ranges. As detailed in the table, most of the entire building stock was graded as moderate (37.5%) and low (47.5%) priority risk levels. On the other hand, 5% of the entire building dataset was classified as high-risk priority while 10% was found to have no risk priority. It is noticeable from the table that the group of buildings within the high-priority risk range was composed of the ones with the higher number of stories. In the calculation of the PS according to the method implemented here, the BSs and VSs vary as the number of stories changes. Therefore, the number of stories appeared to be the main influential parameter affecting the seismic risk level of the assessed building.

Table 3. Distribution of the number of stories in the building dataset with respect to PS ranges

No. of stories	PS≤25 *High*	25<PS≤55 *moderate*	55<PS≤85 *low*	PS>85 *no risk*
1	-	-	-	-
2	-	-	2	3
3	-	-	3	1
4	-	4	8	-
5	2	11	6	-
Σ No. of buildings	2	15	19	4
% of buildings	%5	%37.5	%47.5	%10

For determining the critical deficiencies in the studied region and investigating the effect of vulnerability parameters on the seismic risk priority, the distribution of each parameter with respect to PSs is presented in Table 4. Since all inspected buildings in the study area were constructed adjacently, the pounding effect was extensive as expected. Furthermore, for the high-risk priority building group, as can be seen, the existence of the other four parameters (insufficient wall amount, irregular wall amounts, irregularity in plan and topographic effect) caused a drastic change in the seismic risk level.

Table 4. Distribution of vulnerability parameters with respect to PS ranges.

PS Ranges	Soft story	Insufficient wall amount	Apparent quality	Irreg. wall openings	Topographic effect	Irreg.in plan
0<PS≤25	0.0	50.0	0.0	100.0	50.0	50.0
25<PS≤55	40.0	73.3	6.7	20.0	13.3	6.7
55<PS≤85	26.3	10.5	0.0	0.0	5.3	5.3
PS>85	50.0	0.0	0.0	0.0	0.0	0.0

With the completion of the steps of the SDSVB assessment, vulnerability analysis was also carried out by the VIM based on EMS-98. According to the procedure, V_I was calculated considering 15 vulnerability parameters representative of both the structural and non-structural characteristics of the assessed building. The distribution of the VIs estimated for the building stock was illustrated in Figure 1. The results of the distribution revealed that VIs ranged in between 0.16 and 0.42 having a mean value calculated as 0.25.

In order to reveal the effect of each vulnerability parameter on the seismic risk evaluation, the distribution of the estimated vulnerability classes (A, B, C and D) within the entire building stock was determined as shown in Figure 2. Considering the classes C and D, it is apparent from the figure that P1 and P6 representing the parameters related to the organization of vertical structures and in-plane irregularity, respectively, significantly penalized the seismic vulnerability performance of the buildings.

Moreover, since the masonry building stock was entirely composed of adjacent units, the percent distribution of vulnerability classes for the parameters regarding the pounding effects (P11 to P15) had a remarkable impact on the vulnerability analysis. Also, Figure 2 justifies that the adjacent buildings with the same heights, having the same opening ratio on the facades (P11 and P15) had a positive effect on the seismic performance.

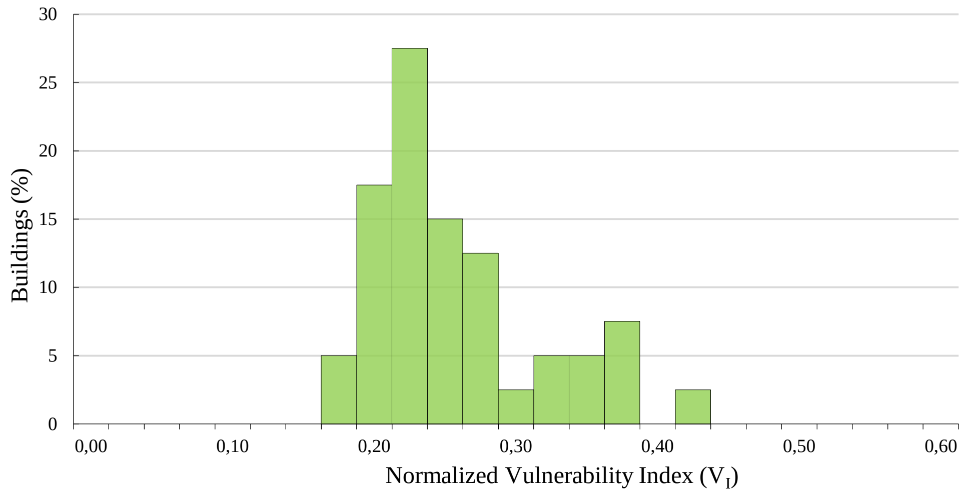

Figure 1. Distribution of the buildings with respect to normalized vulnerability index (V_I)

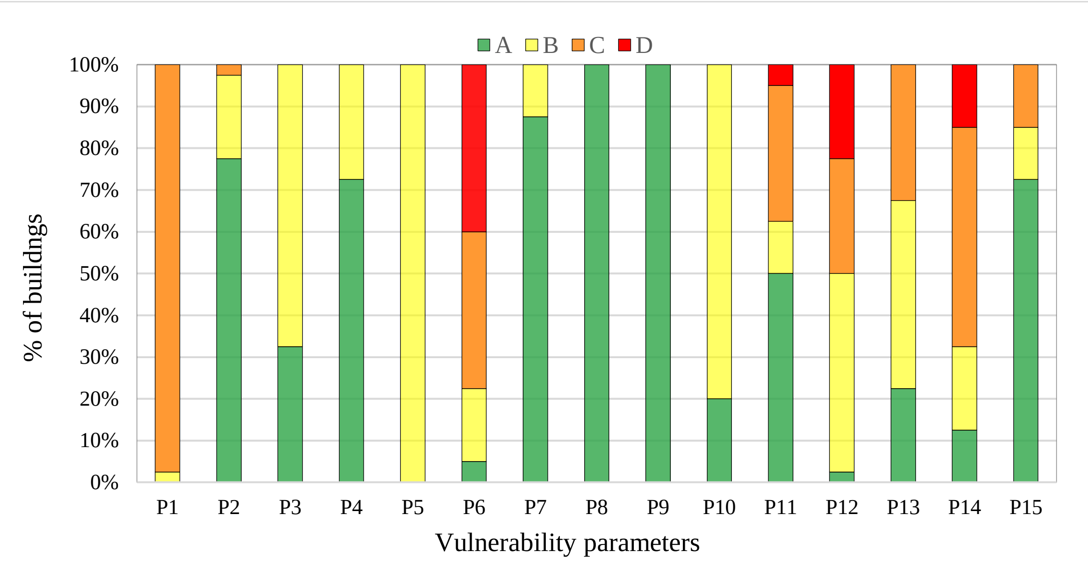

Figure 2. Distribution of vulnerability classes with respect to vulnerability parameters

The damage distribution related to the mean damage grades (μ_D) and the PSs of the building aggregate are represented in Figure 3. Following the procedures of VIM, μ_D mainly depends on EMS-98 based macroseismic intensity (I) and the normalized vulnerability index (V_I). Hence, the macroseismic intensity level concerning the seismicity of the assessed region was obtained as XI for the moment magnitude, Mw=7 and source-to-site distance of D = 20 km. The mean damage grade distribution given in Figure 3(a) implies that the entire building stock was clustered within the ranges of D1, D2 and D3 corresponding to the slight, moderate and significant damage grades, respectively. The results revealed that the majority of the surveyed buildings (77.5%) was found to sustain moderate damage (D2). On the other hand, it is forecasted from the findings that 10% of the buildings experienced slight damage (D1), whereas 12.5% suffered significant damage (D3). In Figure 3(b), PS distribution obtained by SDSVB confirmed that the majority of the surveyed buildings were graded as having moderate and low priority risk levels, as also detailed in Table 3 previously.

When the results were compared in Figure 3, moderate damage grade (D2) was correlated to the PS ranges comprising both the moderate and low priority levels. From the correlation between the degree of damage and PS, the results based on SDSVB appeared to be on the safer side. It is an expected result that this procedure, which also allows the compensation of potential errors that might be encountered during the evaluation of large numbers of buildings through visual screening in a limited time, would remain on the safer side.

In order to discuss the results obtained by the two first-level procedures, the spatial distributions showing the seismic performance of the buildings in terms of μ_D and PSs were illustrated in Figure 4.

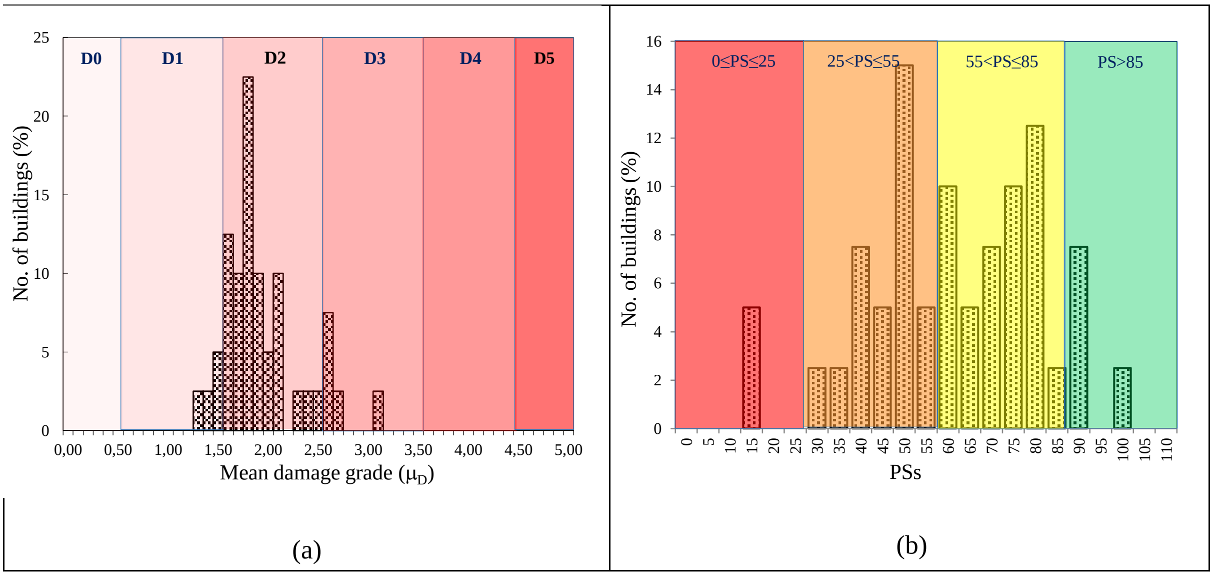

Figure 3. The damage distribution related to (a) the mean damage grades (μ_D) and (b) PSs of the masonry buildings

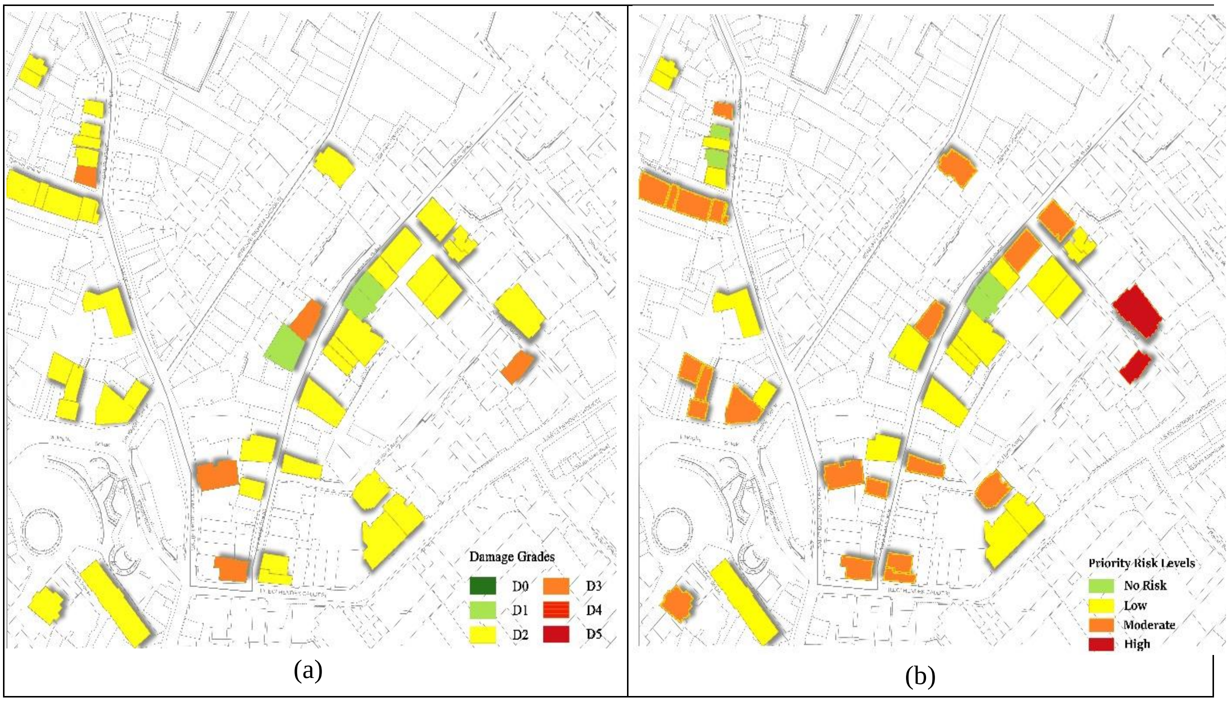

Figure 4. Spatial distribution of the seismic performance of the buildings with respect to (a) mean damage grades and (b) PSs.

To sum up the results, the spatial distribution of the seismic performance of the buildings is demonstrated in Figure 4. In the analysis conducted by VIM, the damage grades were ranked in between the damage classes of D1 and D3. On the other hand, the PSs calculated with respect to SDSVB were found to be ranked in all priority categories varying from no risk to high risk level for the entire building stock. Considering the location of the buildings, the results of both first-level assessment methods on the building basis was also observed to be consistent. Taken as a whole, when Figure 4 is examined comparatively, the most critical buildings having the highest priority level in the region were also expected to suffer moderate and significant damage grade. Additionally, the buildings predicted as having slightly and moderate damage levels were classified in low and moderate seismic priority risk categories. Besides, closer inspection on the findings of SDSVB revealed that, buildings having high-risk priority were affected by the existence of more than one vulnerability parameter in a single structural unit. Particularly, the most vulnerable buildings were the ones located at the corners having insufficient wall amount and irregularity in plan.

Conclusion

This study aimed to reveal the seismic vulnerability of the masonry buildings located in Galata, a historic district of Istanbul, by carrying out two first-level procedures based on SDSVB and VIM. By the review and discussion of both methods within a case study composed of 40 masonry buildings, the differences between the interpretations of the findings about the seismic prioritization of the buildings were set out.

With the given two conceptually different methods, the expected damage grade and seismic prioritization levels, indicating the seismic performance of the buildings, were obtained for the same masonry building aggregate. First, the results obtained were examined in terms of their statistical distribution and then, their spatial distributions were derived for the surveyed region. As a result, a significant correlation was attempted to be achieved between the expected damage grades under possible earthquake effects determined by VIM and seismic risk prioritization levels obtained by SDSVB.

Contributing to literature as a component of the seismic risk mitigation approaches, this study emphasized the importance of outcomes of the structural vulnerability assessment of existing buildings for the pre-earthquake preparation and management strategies and underlined that the resiliency of cities is improved through seismic risk prioritization.

Recommendations

This article will serve for future studies on the seismic vulnerability assessment to make decisions for the prioritization of strengthening activities of the built environment. Also, this study will contribute to the strategic planning and decision-making procedure governed by local authorities, especially for the historical regions.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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