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A HYBRID PROCEDURE FOR SEISMIC VULNERABILITY ASSESSMENT OF URBAN AREAS

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Abstract: *The seismic vulnerability assessment of existing urban areas provides fundamental information about the process of reduction of seismic risk in different phases of planning and emergency management. This contribution presents the salient aspects of a comprehensive hybrid approach to large-scale seismic vulnerability and risk assessment of existing urban areas. The developed methodology combines the advantages of the vulnerability index method in assessing the seismic vulnerability for large-scale datasets of buildings with a detailed analytical approach based on the nonlinear static pushover method, which allows the determination of the capacity curves and the specific limit states of the buildings. The proposed methodology includes all phases leading to the final risk estimation, starting from the stage of data collection and detection of buildings characteristics and ground type to the vulnerability index evaluation, and the execution of non-linear analysis of the selected buildings, to the definition of vulnerability–peak ground acceleration curves, to the derivation of the vulnerability curves for the selected urban area. The outcome of the research is risk representation in terms of the damage and seismic risk indexes. The application of the methodology is demonstrated through the computation of seismic vulnerability and risk assessment of a Croatian settlement located near Split along the Adriatic coast. The presented procedure has provided the seismic vulnerability indices, the damage indices, the critical accelerations for different limit states, and the indices of seismic risk for different return periods. The results have been integrated into a web GIS map that enables the visualization of both vulnerability and risk of the selected area. The findings of the developed methodology are shown to have important operational outcomes in the seismic risk management of the investigated area.*

1. Introduction

An insufficient seismic resistance of buildings represents main reason for human losses and material damage during a seismic event. The seismic vulnerability assessment of existing urban areas provides fundamental information about the process of reduction of seismic risk in different phases of planning and emergency management. The assessment of seismic performance of buildings, such as seismic vulnerability, structural capacity and damage state, is a demanding task, especially in old cities that have been gradually growing and expanding over the course of centuries. It requires expensive experiments or complex nonlinear methods that precisely model the dissipation of energy in earthquake. Analysis of whole buildings is carried out by a non-linear static (pushover) method or an incremental dynamic analysis. Both approaches allow to monitor the level of damage and determine the collapse load.

The assessment of the seismic resistance of a large number of buildings in cities is much more demanding because it is not possible to carry out a nonlinear analysis for all buildings. Therefore, in order to effectively manage earthquake risk, the large scale seismic vulnerability assessment is usually performed by simplified methods.

The approaches for the evaluation of structural vulnerability can be generally classified as empirical, analytical, or hybrid. Among them, empirical methods are often used for the first screening of buildings and vulnerability classification at the urban scale, primarily due to the reduced computational efforts in comparison with more complex detailed approaches. Empirical methods, such us the vulnerability index method and the damage probability index method are based on qualitative evaluations and can be used for setting priorities in reconstruction or undertaking measures of prevention, mitigation, preparedness, and response in a process of a seismic risk management.

In this paper, the hybrid seismic risk assessment procedure is adopted. The developed methodology combines the advantages of the vulnerability index method, proposed by Benedetti and Petrini (1984), in assessing the seismic vulnerability for large-scale datasets of buildings with a detailed analytical approach based on the nonlinear static (pushover) method, Fajfar and Eeri (2000), implemented in Eurocode 8 (2004, 2005), which allows the determination of the capacity curves and the specific limit states of the buildings. The application of the methodology is demonstrated through the computation of seismic vulnerability and risk assessment of a Croatian settlement located near Split along the Adriatic coast.

2. Procedure for seismic vulnerability and risk assessment

The procedure for seismic vulnerability and risk assessment is structured as follows:

- Documentation of architectural, structural and material features by examining building codes, historical and archival sources, on-site visual inspection and thermographic imaging;
- Creation of a database of buildings and visualization of input data by the web map in the GIS environment;
- Geophysical survey of the soil type;
- Definition of seismic hazard for the test site using available seismic hazard maps of Croatia and the results of geophysical survey;
- Seismic vulnerability assessment by vulnerability index method for the sample of the buildings;
- Extrapolation of the results for the seismic vulnerability index for the entire test site;
- Non-linear static analysis of the relevant buildings located in the test site and determination of the peak ground accelerations for damage limitation (DL), significant damage (SD) and near collapse (NC) states;
- Development of vulnerability–peak ground acceleration curves for three limit states (DL, SD, NC) for the test site;
- Development of vulnerability curves that establish relations between damage, vulnerability and peak ground acceleration for the test site;
- Risk evaluation in terms of seismic damage the index of seismic risk for three return periods;
- Visualization of hazard, vulnerability indices, damage indices and indices of seismic risk of the buildings in the web map.

3. Characteristics of the area

3.1. Building characteristics

The methodology has been applied to the area of Kaštel Kambelovac, a small Mediterranean urban settlement along the Croatian side of the Adriatic Sea and consisting of a historical core constituted by stonemasonry. The historical core was erected between the 15th and the 19th century, while the periphery outside of the historical core includes more modern buildings. In particular, five main categories of construction data of the modern buildings have been recognized: before 1948, 1949–1964, 1964–1982, 1982–2005, and modern buildings erected from 2005 onwards. All these buildings exhibit different seismic performance depending on the period of construction and applied technical regulation.

The buildings located in the historical centre (Figures 1, 2) consists of walls made of stone blocks and mortar joints with thickness from 45 cm to 75 cm. The wall textures are variable: roughly shaped stone blocks of various size alternate to masonry consist of blocks of homogeneous size, well-shaped or cut. The quality of mortar is overall poor. Floors are made of timber beams and wooden floor coverings. Confining elements are lacking, and connections between the walls and floors are generally weak. Some of these buildings were reconstructed and monolithic reinforced concrete plates replaced the wooden floors.

Outside of the historical centre, the buildings (Figure 3) were mostly made as masonry structures consisting of stone, concrete, or brick blocks, unreinforced or reinforced with RC confining elements (only with ties or with ties and columns) depending on the construction period and technical regulations. Generally, the masonry buildings constructed before 1964 are not earthquake-resistant because they have been built as unreinforced masonry structures (Nikolić et al, 2021, 2022). Since 1964, seismic regulations required horizontal confining elements and rigid horizontal diaphragms or horizontal and vertical confining elements and rigid horizontal diaphragms depending on the seismic zone and the number of floors. After 1980, stricter regulations for the construction in earthquake areas were applied and the use of unreinforced masonry was not allowed in the areas of medium and high seismicity. Buildings erected from 2005 onwards are seismically resistant structures due to the application of modern design standards based on the Eurocode 8, firstly implemented through the pre-standards (HRN ENV 1998-1:2005) and finally by introducing the full European standard (Eurocode 8, 2011) in the Croatian national legislation (HRN EN 1998-1:2011).

Figure 1. Historical centre of Kaštel Kambelovac.

Figure 2. Buildings in the historical centre.

Figure 3. Buildings outside of the historical centre.

3.2. Seismic hazard of the area

The seismic hazard for Croatia is presented in terms of the horizontal peak ground acceleration a_g with two maps for the return periods of 475, 225 and 95 years. The a_g in the Kaštela area, is equal to 0.22 g, 0.17 g, and 0.11 g for the return periods of 475, 225, and 95 years, respectively, and ground type A. The seismic hazard for soil types different from A increases. The characterization of soil type at the area has been determined by a geophysical survey which shown that the average shear wave velocity $v_{S,30}$ is higher than 800 m/s along three examined lines (Da Col et al, 2021). Considering that the investigated test site is relatively small, the soil type A was considered for all buildings in the test area.

4. Seismic vulnerability assessment

4.1. Application of vulnerability index method

The vulnerability index method is used to calculate the vulnerability index for the building based on the calculation of 11 geometrical, structural and non-structural vulnerability parameters of the building (GNDT-SSN, 1994). They consider the influence of the type and quality of the structural system, the shear resistance in two horizontal directions, the position and the foundations, the properties of floors, the configuration in plan and elevation, the maximum wall spacing, the roof's typology and weight, the existence of non-structural elements, and the state of preservation. Four possibilities for each parameter were decided: from "A", indicating an optimal state, to "D", indicating a poor state. Furthermore, the method numerically scores each option. The relative importance of each parameter in the overall vulnerability is computed by using weight coefficients relating to each parameter. Vulnerability index $_{Iv}$ is obtained in a form:

$$I_V = \sum_i s_{vi} w_i \tag{1}$$

where s_{vi} is the numerical score for each class, and w_i is the weight of each parameter. The vulnerability index is normalized in a 0–100% range; the low index indicates high seismic resistance and low vulnerability, while a high vulnerability index is characteristic of the buildings with low seismic resistance and high vulnerability. The present study includes the modifications of the GNDT method considering the replacement of light timber floors with heavier RC floors, which are often used in the reconstruction of old masonry buildings (Nikolic et al, 2021). The upper value of the vulnerability index I_v is 438.75.

The vulnerability indices for 111 buildings with known architectural, structural, and material features (75 in the old city centre and 35 outside of the centre) were calculated by the vulnerability index method. The vulnerability indices were included into a web map based on the GIS and shown in Figure 4.

Figure 4. Vulnerability index map of the area.

4.2. Evaluation of PGA by static non-linear analysis

The present study aims to evaluate seismic risk in terms of the damage index and the index of seismic risk using information about vulnerability of the buildings obtained by vulnerability index method. In order to calculate the damage index, the relation between the vulnerability index and the seismic capacity represented by PGA for the sample of 18 buildings has been established. Non-linear static (pushover) analysis has been applied for the calculation of PGA for three limit states (damage limitation, significant damage and near collapse) which are defined according to HRN EN 1998-1:2011, for the yield displacement, ¾ of ultimate displacement and ultimate displacement, respectively. Vulnerability index-peak ground relations enable the calculation of the damage index of the building, but also the calculation of the index of seismic risk for each limit states.

Eighteen buildings (Figures 5 and 6) in the settlement were modelled using 3MURI software (2019) following the equivalent frame model approach based on the structural response along two horizontal axes in the positive and the negative direction, accidental eccentricity equal to ±5% of the maximum floor dimension and three distribution of lateral forces (uniform, linear and modal).

Pushover analysis was conducted on ten buildings in the historical centre (Figure 5) that have historical or cultural value and 8 buildings outside of the historical centre, that are typical for the constructions built of concrete or brick hollow blocks after 1948 and can be classified according to the construction period. They belong to the following categories: (1) Type 1—unreinforced concrete masonry built before the first seismic regulation in 1964; (2) Type 2—concrete masonry with horizontal RC confining elements typical for the period between 1964 and 1980; (3) Type 3—confined concrete masonry with horizontal RC ties and RC columns built between 1980 and 2005, and (4) Type 4—confined brick masonry with horizontal RC ties and RC columns, which are seismically resistant structures due to the applications of modern design standards based on Eurocode 8. The buildings have rigid RC slabs, while the roof is mainly wooden with roof tiles. Since two configurations of buildings prevail in terms of height, with two floors and a roof and three floors and a roof, two buildings of different storeys were selected for each period of construction for detailed pushover analysis. Therefore, two different elevation configurations have been analysed: (a) P + 1 which consists of ground, one floor, and a roof; and (b) P + 2 which consists of ground, two floors, and a roof (Figure 6).

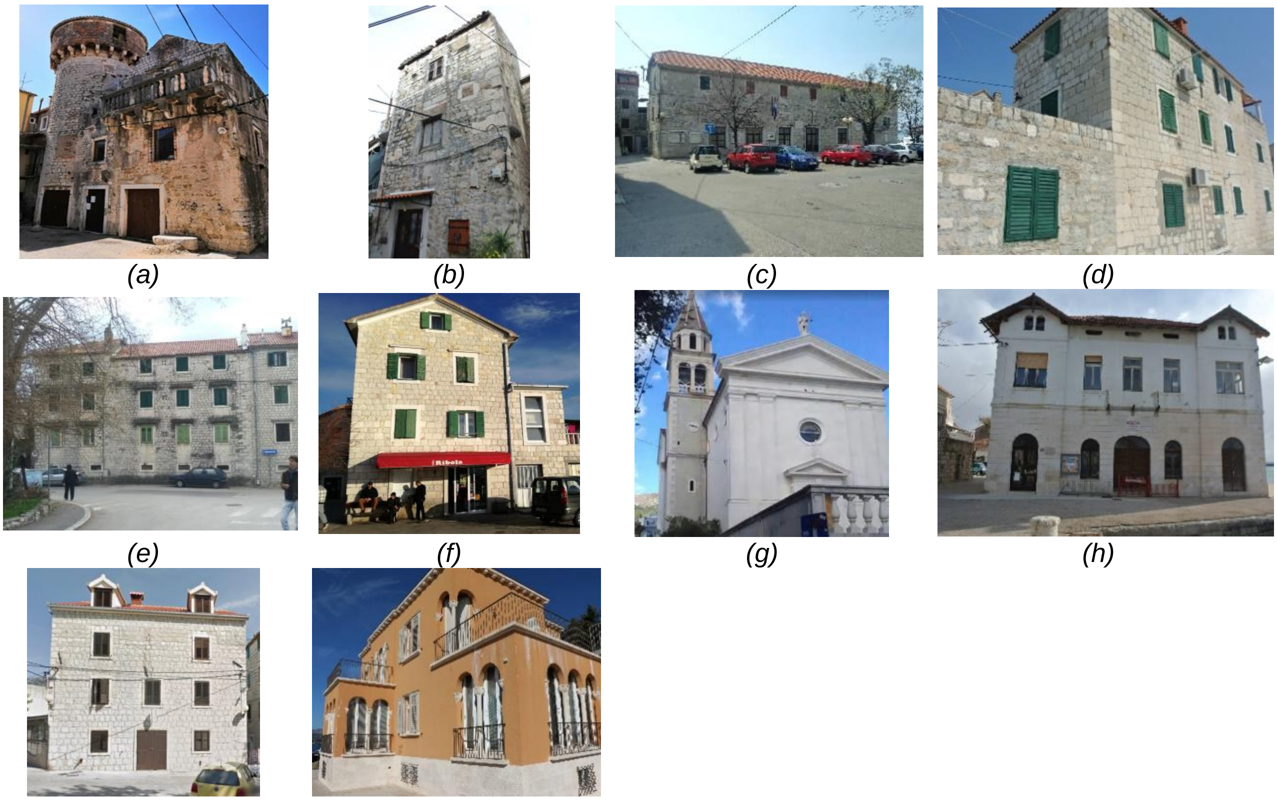
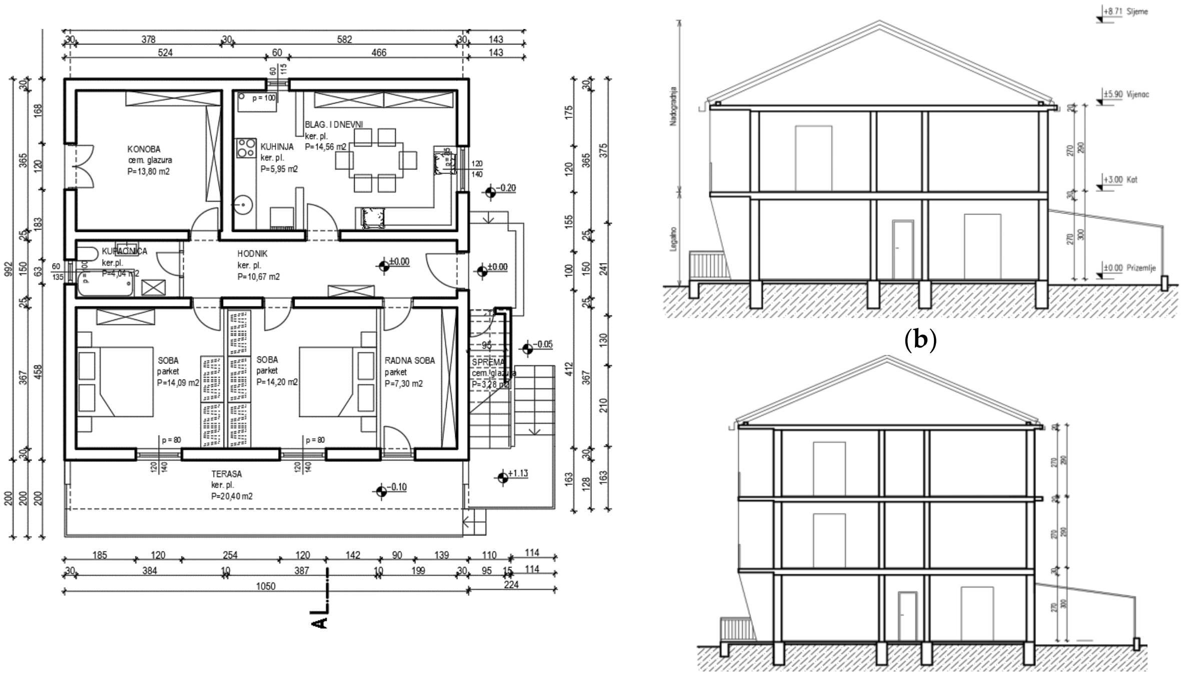

(a) *(b)* *(c)* *(d)*
(e) *(f)* *(g)* *(h)*
(i) *(j)*

Figure 5. Analysed buildings in the historical centre (a) Cambi Tower; (b) Cumbat Towers; (c) Public Library; (d) Folk Castle; (e) Dudan Palace; (f) Perišin house; (g) St. Mihovil Church; (h) rowing club; (i) residential building; (j) ballet school.



(a) (c)

Figure 6. Typical configurations outside of the historical centre: (a) plan; (b) section view P + 1; (c) section view P + 2.

Peak ground accelerations for the DL, SD, and NC limit states were computed in the x and y directions. The lowest PGA values were identified for each building and limit state. The critical PGA results and vulnerability indices for the considered buildings are presented in Table 1.

Table 1. Vulnerability index and critical PGA of the buildings.

No	Building	I_v [%]	PGA_{DL} [g]	PGA_{SD} [g]	PGA_{NC} [g]
1	Cambi Tower	76.9	0.030	0.059	0.078
2	Kumbat Towers	65.2	0.057	0.087	0.103
3	Public Library	59.0	0.028	0.061	0.079
4	Folk Castle	58.7	0.081	0.061	0.080
5	Dudan Palace	50.1	0.051	0.068	0.083
6	Perišin house	48.7	0.058	0.061	0.121
7	St. Mihovil Church	40.5	0.057	0.086	0.102
8	Rowing club	40.2	0.064	0.110	0.141
9	Residential building	34.8	0.081	0.095	0.152
10	Ballet school	23.9	0.103	0.142	0.183
11	Type 1 building P+2	29.1	0.083	0.114	0.142
12	Type 1 building P+1	29.1	0.061	0.144	0.173
13	Type 2 building P+2	13.4	0.098	0.145	0.175
14	Type 2 building P+1	13.4	0.115	0.187	0.220
15	Type 3 building P+2	6.0	0.065	0.158	0.189
16	Type 3 building P+1	6.0	0.075	0.175	0.206
17	Type 4 building P+2	4.3	0.103	0.188	0.243
18	Type 4 building P+1	2.6	0.130	0.218	0.270

4.3. Vulnerability index - PGA relations

The results for 18 analysed buildings presented in Table 1 are used to establish the vulnerability index - PGA relation for the DL, SD, and NC limit states at the entire test site. Figure 7 shows a cloud of points representing the relationship between the vulnerability index calculated on the basis of 11 parameters I_v and the critical

PGA associated with the DL, SD, and NC limits. The relationships I_V–PGA_{DL}, I_V–PGA_{SD} and I_V–PGA_{NC} represented as exponential functions were shown in Figure 7. They are used to approximate the yield (damage limitation), significant damage, and collapse PGA for the entire test site. The values of yield and collapse accelerations are the basis for deriving vulnerability curves. The quality of the approximation of the PGA obtained by the pushover analysis and those represented by trend lines for the three limit states are validated by standard deviation. Significantly better quality of PGA approximations has been achieved for the NC and SD limit states than for the DL state. The derived trend lines are used to estimate PGA for three limit states of the buildings using their vulnerability index.

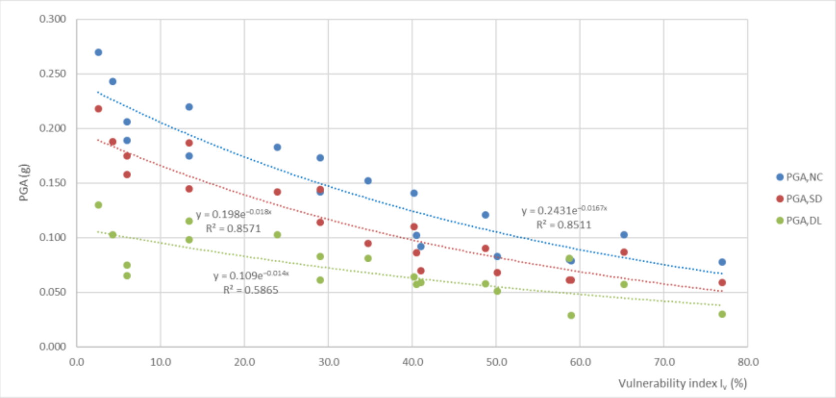


Figure 7. Trend lines I_V–PGA_{DL}, I_V–PGA_{SD}, and I_V–PGA_{NC}.

4.4. Vulnerability curves

The basis for defining vulnerability curves are vulnerability indices, yield peak ground acceleration PGA_y, and collapse peak ground acceleration PGA_c, obtained by the pushover analysis for analysed buildings. Yield acceleration PGA_y is assigned to PGA_{DL} and collapse acceleration PGA_c to PGA_{NC} limit states, respectively. As PGA_y and PGA_c depend on the vulnerability index I_v, the values of PGA_y, associated with damage $d=0$, and PGA_c, associated with damage $d=1$, can be calculated for each value of I_v.

Figure 8 shows the vulnerability curves used for the estimation of the damage index of the buildings at the investigated area (Nikolić et al, 2022).

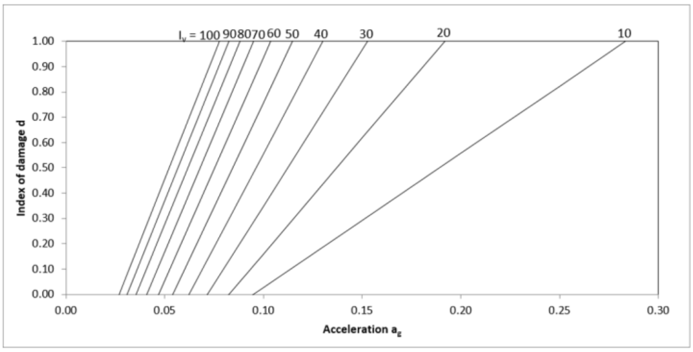
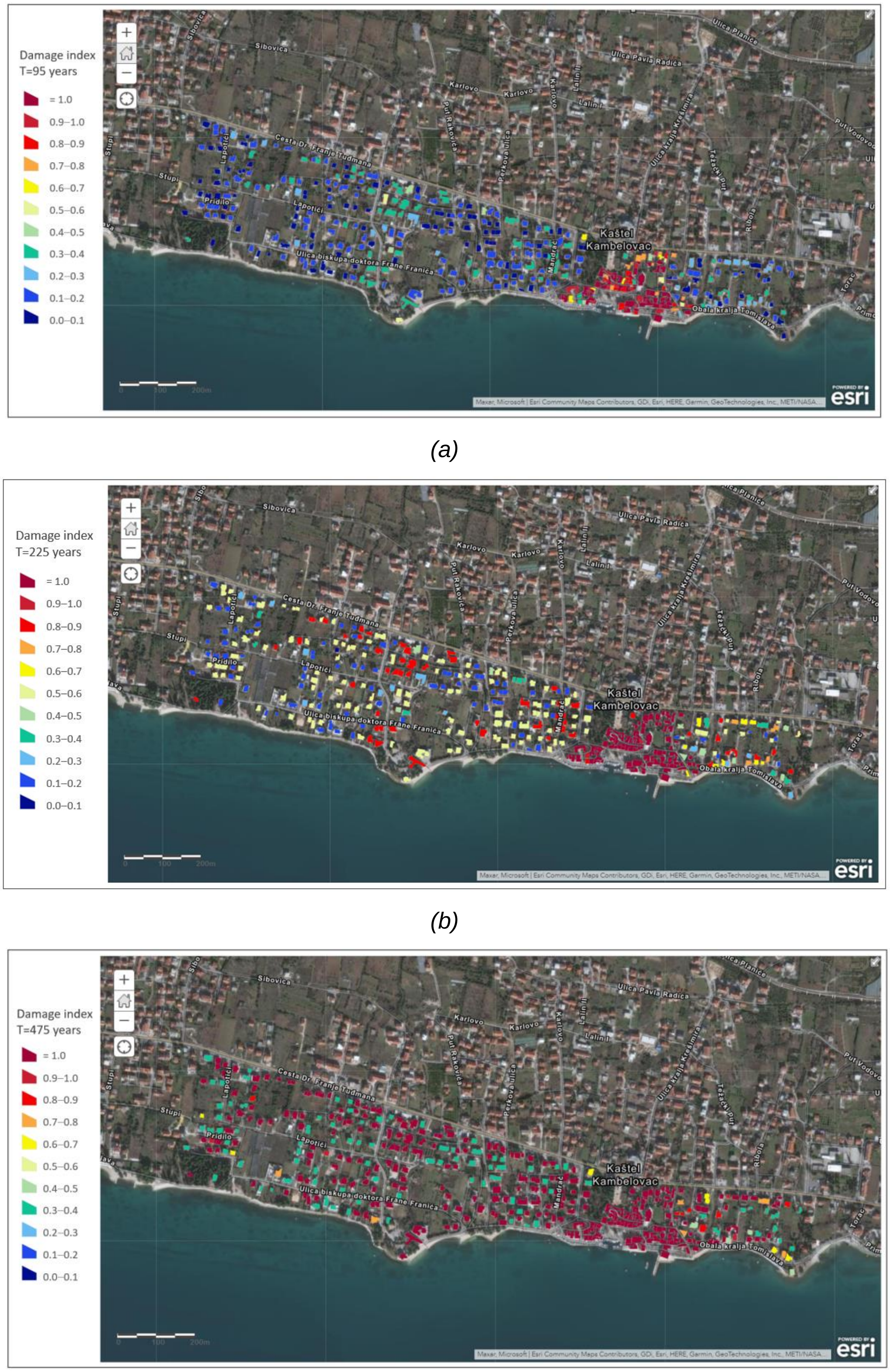


Figure 8. Vulnerability curves for the observed area.

4.5. Damage index maps

The spatial distribution of the damage is represented by the damage index maps of the investigated area for the given intensity of the earthquake. Three seismic scenarios corresponding to return periods of 95, 225, and 475 years and demand PGA of 0.11 g, 0.17 g, and 0.22 g, respectively, have been chosen. The damage to the buildings for different scenarios is presented in Figure 9.



(a)

(b)

(c)

Figure 9. Damage index distribution: (a) T=95 years; (b) T=225 years; (c) T=475 years.

4.6. Index of Seismic Risk

The index of seismic risk is calculated as the ratio of the PGA_C associated to the structural capacity and the demand ground acceleration PGA_D in a form:

$$\alpha_{PGA,C} = \frac{PGA_C}{PGA_D} \tag{2}$$

The capacity of the structure represents the minimum value of PGA for which a certain limit state is achieved. In this paper, the capacity of the structure for the structural collapse (i.e., NC limit state) is analysed. Therefore, PGA_C is equal to PGA_{NC}. Demand ground acceleration PGA_D is obtained from the seismic hazard map for the selected return period as $PGA_D = a_g S$, where a_g represents horizontal PGA on type A soil which also includes importance of the building ($a_g = \gamma_I a_{gR}$) and S is a soil parameter. In this study, the soil type A with soil parameter S=1 was considered for all buildings in the test area.

Indices of seismic risk are used to validate the safety of the structure, $\alpha_{PGA} > 1$ refer to safe structures, while the values $\alpha_{PGA} < 1$ refer to non-safe structures. The indices of seismic risk for the NC limit state of the buildings for three return periods are presented in Figure 10.

(a)

(b)

(c)

Figure 10. Risk maps in terms of index of seismic risk: (a) T=95 years; (b) T=225 years; (c) T=475 years.

5. Conclusions

The paper presents a comprehensive hybrid approach to large-scale seismic vulnerability and risk assessment of existing urban areas. The methodology combines the vulnerability index method which is used to assess the vulnerability of a large number of buildings with a detailed analytical approach based on the nonlinear static pushover method, which allows determination of the capacity curves and detection of the specific limit states of the buildings. The methodology has been applied to a small Mediterranean urban settlement Kaštel Kambelovac, placed along the Croatian Adriatic coast.

The pushover analysis performed for 18 buildings with different structural and material characteristics (old historical stone masonry buildings and unconfined and confined buildings built of concrete or brick hollow blocks) provided valuable results of their behaviour up to the failure, as well as peak ground accelerations for specific limit states. Presented methodological approach was resulted with the relationship between the vulnerability index and peak ground accelerations of damage limitation, significant damage, and near collapse states as well as vulnerability curves that serve to determine the damage index of the buildings for a specific seismic action. Finally, the seismic risk in terms of the damage index and the index of seismic risk was represented for the chosen urban settlement. The developed seismic risk maps have important operational outcomes in the seismic risk management of the investigated area.

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