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RECENT ADVANCES IN SEISMIC VULNERABILITY ASSESSMENT OF CROATIAN COASTAL URBAN AREA

Željana Nikolić (1) *, Elena Benvenuti (2), Luka Runjić (3), Nenad Mladineo (4), Marko Mladineo (5)

(1) *Full Professor, University of Split, Faculty of Civil Engineering, Architecture and Geodesy, zeljana.nikolic@gradst.hr*
(2) *Full Professor, University of Ferrara, Engineering Department, elena.benvenuti@unife.it*
(3) *Researcher, University of Split, Faculty of Civil Engineering, Architecture and Geodesy, luka.runjic@gradst.hr*
(4) *Professor, University of Split, Faculty of Civil Engineering, Architecture and Geodesy, nenad.mladineo@gradst.hr*
(5) *Associate Professor, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, marko.mladineo@fesb.hr*

Abstract

The seismic vulnerability assessment of existing urban areas provides fundamental information about reducing seismic risk in different phases of planning and emergency management. This contribution presents recent advances in seismic vulnerability assessment in Croatian coastal areas at various scales, starting with a detailed analytical approach at the building scale to large-scale evaluation at the building level and the level of the homogeneous zones. The investigation was performed in the town of Kaštela. This typical coastal settlement has expanded over past centuries, resulting in a heterogeneous distribution of the buildings built in periods with different technical regulations. A detailed nonlinear-linear analysis of important buildings (historical, public) has been performed providing evidence of their collapse behaviour. A comprehensive hybrid approach to large-scale seismic risk assessment, combining seismic vulnerability indices with critical PGAs for different limit states, has been applied to define vulnerability curves that relate vulnerability index, damage index, and peak ground acceleration. The outcome of the present analysis is the large-scale risk representation in terms of the damage and seismic risk indexes at the building level. The level of seismic risk to the community depends on several other parameters whose activation reduces the resilience to extraordinary events. Considering the characteristics of the observed pilot site, additional criteria for the risk assessment of homogenous zones are introduced, such as communal infrastructure, road network, construction density, inhabitation density, importance factor (public building, school, etc.), and status of protected historical buildings. The proposed methodology addresses seismic risk assessment at the level of homogeneous zones and utilizes Spatial Multi-Criteria Decision Making and PROMETHEE method. The presented approach to seismic risk assessment has important operational outcomes in the seismic risk management of the investigated area.

Keywords: seismic vulnerability assessment, hybrid approach, nonlinear-linear analysis, vulnerability index, damage, seismic risk index, PROMETHEE method.

1. Introduction

An insufficient seismic resistance of buildings is a main reason for human losses and material damage during a seismic event. 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 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 monitoring the level of damage and determining the collapse load.

The assessment of the seismic resistance of most buildings in cities is much more demanding because it is not possible to carry out a nonlinear analysis for all of them. Therefore, to effectively manage earthquake risk, the large-scale seismic vulnerability assessment is usually performed by simplified methods. In this paper, seismic vulnerability is assessed at different scales, starting with analytical approach at the building scale to large-scale assessment at the building level and large-scale assessment at the level of the homogeneous zones.

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The proposed methodology applies a comprehensive hybrid approach to large-scale seismic risk assessment at the building level [1, 2], combining seismic vulnerability indices with critical PGAs for different limit states. The aim is defining vulnerability curves to relate vulnerability index, damage index and peak ground acceleration. The developed methodology combines the advantages of the vulnerability index method, proposed by Benedetti and Petrini [3], in assessing the seismic vulnerability for large-scale datasets of buildings with a detailed analytical approach based on the nonlinear static (pushover) method, implemented in Eurocode 8 [4, 5], which allows the determination of the capacity curves and the specific limit states of the buildings.

The level of risk of the community depends on several other parameters whose activation reduces the "resistance" of the community in seismic event. The most common parameters (criteria) relevant for the influence of the earthquake to the community are grouped into area characteristics (geology, soil, slope, historical earthquake events, fault line, etc.), the characteristics of human intervention in space (land use, built communal infrastructure and roads, etc.) and social characteristics such as housing density, social purpose of buildings (Occupancy Category), social structure, etc.). The large-scale assessment of seismic risk at the level of homogeneous zones has been performed by using the multi-criteria analysis [6] that is commonly used to evaluate and compare quantitative and qualitative criteria in completely different units and the order of magnitude. In this level of processing, the previously analyzed buildings, whose seismic performance has been represented in terms of vulnerability, damage and risk indexes, are grouped into spatial units defined as “homogeneous zones”. Since homogeneous zones have complex characteristics, the parameters for vulnerability and hazard, are coupled with the inclusion of additional criteria in order to assess the level of seismic risk to the community.

The methodology has been applied to a small coastal urban settlement, Kaštel Kambelovac (Fig.1), on the Croatian side of the Adriatic Sea near Split. The settlement consists of a historical core constituted by stonemasonry and the periphery outside of the historical core. The historical core was erected between the 15th and 19th centuries, while the periphery includes mostly modern buildings. In particular, five main categories of construction data of 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 performances depending on the period of construction and applied technical regulation.

Figure 1. Historical center of Kaštel Kambelovac with typical buildings.

2. Seismic risk assessment at the building level

A comprehensive hybrid approach to large-scale seismic risk assessment, combining seismic vulnerability indices with critical peak ground accelerations (PGA) for different limit states, has been applied to define vulnerability curves that allow to relate vulnerability index, damage index, and PGA.

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.

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The parameters 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. Finally, the vulnerability index I_v is calculated in a form $I_V = \sum_i s_{vi} w_i$, 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; a 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. Vulnerability indexes of the buildings located in the test site are presented in Fig. 2 [2].

Figure 2. Vulnerability index map of the test site.

An important step in seismic risk assessment is representation of seismic risk in terms of the damage index and the index of seismic risk. In this paper a hybrid empirical-analytical procedure that combines seismic vulnerability indices with critical PGA have been developed. For this purpose, detail non-linear pushover analysis for 18 buildings has been performed by 3MURI software [7]. 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 different limit states of buildings (damage limitation PGA_{DL}, significant damage PGA_{SD}, and near collapse PGA_{NC}). Vulnerability index - PGA relations (Fig. 3) enable the calculation of the damage index of the building, but also the calculation of the index of seismic risk for each limit states.

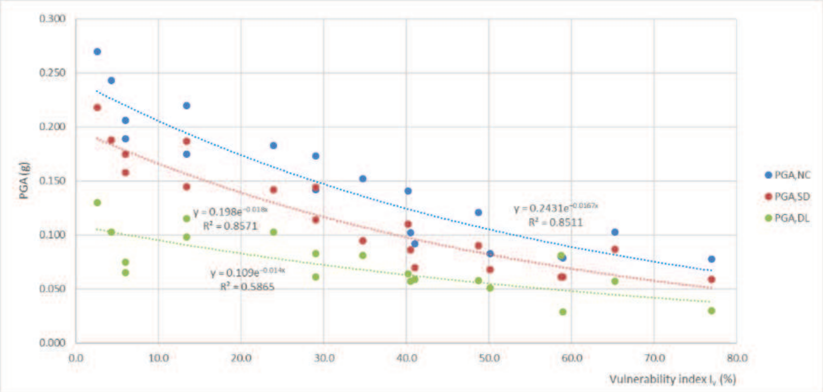

Figure 3. Vulnerability index – PGA relations (I_v–PGA_{DL}, I_v–PGA_{SD}, and I_v–PGA_{NC}).

The vulnerability curves allow to correlate the vulnerability index, damage index and peak ground acceleration. The basis for defining vulnerability curves in the presented investigation are vulnerability indices I_V, yield peak ground acceleration PGA_y, and collapse peak ground acceleration PGA_C, obtained by the pushover analysis for 18 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. Fig. 4 shows the vulnerability curves used for the estimation of the damage index of the buildings at the investigated area [2].

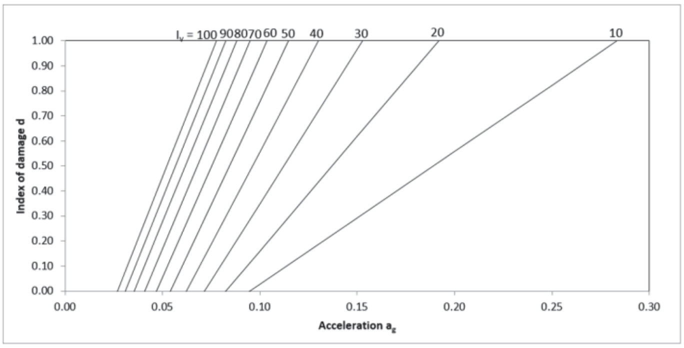

Figure 4. Vulnerability curves for the test site.

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 Fig. 5.

(a)

(b)

(c)

Figure 5. Damage index distribution: (a) T=95 years; (b) T=225 years; (c) T=475 years.

The index of seismic risk is calculated as a ratio of the PGA_C associated to the structural capacity and the demand ground acceleration PGA_D in a form $\alpha_{PGA,C} = PGA_C / PGA_D$. 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. Indices of seismic risk are used to validate the safety of the structure, $\alpha_{PGA,C} > 1$ refer to safe structures, while the values $\alpha_{PGA,C} < 1$ 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 Fig. 6.

(a)

(b)

(c)

Figure 6. Distribution of index of seismic risk: (a) T=95 years; (b) T=225 years; (c) T=475 years.

3. Seismic risk assessment at the level of homogeneous zones

The large-scale assessment of seismic risk at the level of homogeneous zones has been performed to evaluate and compare quantitative and qualitative criteria in completely different units and the order of magnitude. The previously analysed buildings, whose seismic performance has been represented in terms of vulnerability, damage and risk indexes, are grouped into spatial units defined as “homogeneous zones”. The homogenous zones are created considering specific urban characteristics, areas surrounded by the main roads and terrain height. The parameters for vulnerability represented by vulnerability index and seismic hazard in each zone are coupled with the inclusion of additional criteria in order to assess the level of seismic risk to the community. Additional criteria are communal infrastructure -electricity supply, communal infrastructure - water supply and drainage, Road network, construction density (distance between buildings), inhabitation density, importance factor of the buildings (public, school, etc.) and existence of protected historical buildings.

A methodology for seismic risk assessment of the area at the level of the homogeneous zones is based on Spatial Multi-Criteria Decision Making based on PROMETHEE method [8], coupled with the Geographic Information System [6].

The advantage of the Spatial Multi-Criteria Decision-Making system is the ability to generate criteria evaluations from GIS analysis. In this research, GIS analyses have been made to aggregate criteria evaluations for each homogenous zone for the following additional criteria: communal infrastructure, road network, construction density, inhabitation density, importance factor (public building, school, etc.), and historical buildings.

Criterion Communal infrastructure can be presented as a unified indicator or, for easier quantification, can be divided into individual content, such as: electricity supply, water supply and sewerage, gas network, telecommunications network, etc. Road network is part of the built infrastructure, but it is also treated as a special criterion due to its importance, because firefighter’s accesses are very important element of the system for assessing the vulnerability of urban units. Construction density or distance between buildings as a way of building is an important criterion from the aspect of the organization of the rescue, especially in cases of earthquakes of higher intensity. Inhabitation density is a very common criterion used to have an insight into the expected number of victims or vulnerable persons. Data for this criterion can be generated from a digitized view of the census or from communal databases. The importance factor is a criterion that selects buildings that have social importance (content) such as schools, churches, and kindergartens. Another criterion is dictated by the presence of important historic buildings in a particular homogeneous zone. GIS analysis of these criteria is presented in Fig. 8.

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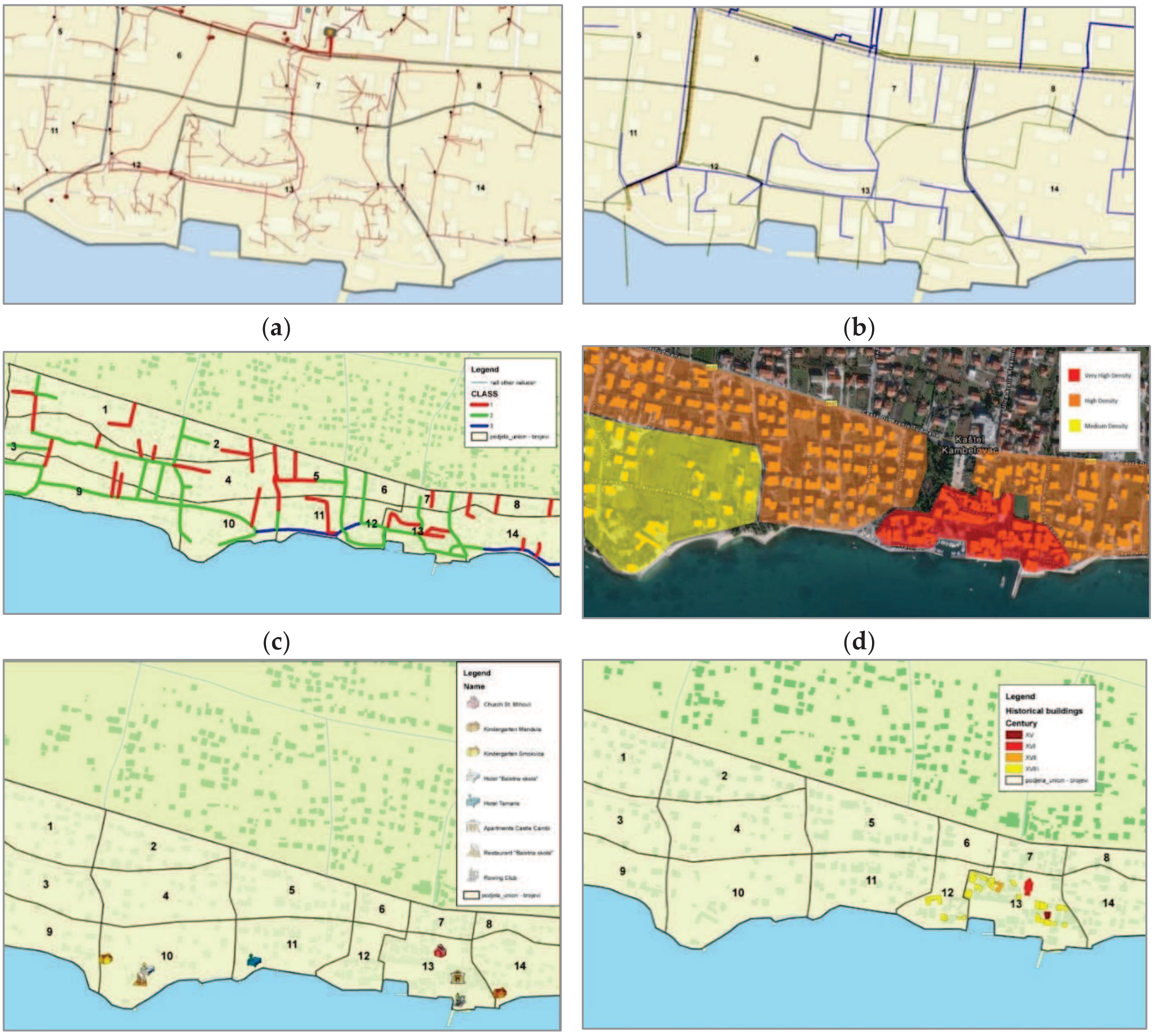

(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 8. GIS analysis of additional criteria: (a) electricity supply; (b) water supply and drainage; (c) road network; (d) construction density; (e) importance factor (public, school, etc.); (f) historical buildings.

The PROMETHEE method combines all above mentioned criteria with ease, mutually compares homogeneous zones and evaluates the risk for each zone. Visual representation of the results has been made in GIS, where green represents low risk and red represents high risk (Fig. 9).

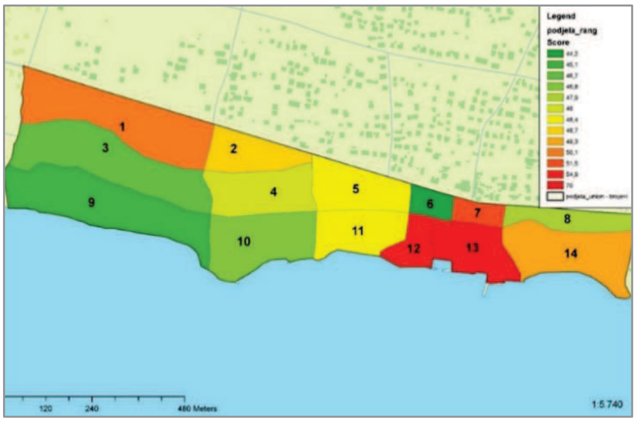

Figure 9. Seismic risk assessment for homogenous zones (green represents low risk, red represents high risk).

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4. Conclusion

This paper presents a methodology for seismic vulnerability assessment at different scales. This methodology utilizes a comprehensive hybrid approach specific for large-scale seismic vulnerability and risk assessment of existing urban area at the building scale. Moreover, vulnerability index method and non-linear static pushover analysis are used for representation of vulnerability index, damage index and index of seismic risk for the Croatian coastal settlement Kaštel Kambelovac. Spatial Multi-Criteria Decision Making based on PROMETHEE method, coupled with the Geographic Information System are used to assess seismic risk to the community at the level of the homogeneous zones introducing additional criteria which influence to the earthquake consequences in the observed zones. Finally, the various homogenous zones are ranked in terms of proneness to seismic risk. The obtained results provide an important basis for systematic take-over and planning of priorities in rehabilitation of vulnerable urban areas. Performed analyses furnish, indeed, useful information for decision makers and public authorities to prioritizing future interventions and planning the operational capacity of civil protection to rescue and recovery after harmful events.

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