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SEISMIC STRESS TEST OF BUILDING STOCK IN SLOVENIA

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Abstract

The physics-based assessment of seismic risk and its unbiased perception in the community is necessary to enhance community seismic resilience. As a step towards this objective, a seismic stress test of building stock in Slovenia was performed last year. The stress test outcome was negative, which was communicated to the Ministry by means of a preliminary seismic performance certificate of building stock at the national level. The seismic stress showed that the seismic risk in Slovenia is too high. About 20% of citizens live in buildings for which the seismic risk expressed by median estimates of time-based risk measures is beyond the acceptable long-term risk. The real estate value of these buildings is estimated at 18 billion euros. Consequences of a major earthquake (M_w=6.4) close to Ljubljana were simulated informatively by the physics-based method. It was realised for the first time in Slovenia that such an earthquake would likely cause a national catastrophe. The median number of fatalities and direct losses due to damaged building stock was estimated, respectively, to about 600 and 10.5 billion euros, which is more than 20% of Slovenia gross domestic product. It was recommended that seismic resilience in Slovenia is enhanced in two phases: the preparatory and implementation phase. The former phase also foresees seismic performance certificates to improve risk communication and risk management enabled by the novel grading system.

Keywords: Seismic stress test, building stock, scenario-based assessment, seismic performance certificate of building stock, seismic performance certificate of a building, IKPIR application, Slovenia.

1. Introduction

The perception of seismic risk in communities is biased. Citizens and some other stakeholders responsible for earthquake-resistance of the built environment are not aware that major earthquakes can cause very severe ground motions. Recent earthquakes in Croatia represented natural experiments to test whether the perception of ground shaking and seismic vulnerability in Slovenia is correct or not. Many people in Ljubljana were quite shocked and afraid because of the shaking felt in Ljubljana due to the Petrinja earthquake, but the horizontal peak ground accelerations in Ljubljana were very low, between 1% to 3% g [1]. It was also realised that some engineers' beliefs are also false but in the opposite direction. For example, on the evening of December 29th 2020 the opinion of the head of certified engineers was broadcasted on television, as summarised online the next day [2]. By answering on how much damage would be caused if an earthquake of a magnitude similar to the one from the Petrinja earthquake hit Ljubljana, the head of certified engineers concluded that there would be some damage, but mainly on chimneys, roofs, and on some buildings that are not earthquake resistant. Diametrically opposite false beliefs about seismic vulnerability showed once more that the unbiased perception of seismic risk is not possible to be achieved by evidence because major earthquakes are fortunately rare.

The problem of a false perception of seismic vulnerability and risk drives incorrect decision-making towards community seismic resilience. This issue can be solved by providing physics-based seismic risk information to all stakeholders. For this purpose, the seismic stress test methodology was developed [3]. The methodology goes beyond conventional risk assessment because it also includes a novel grading system for evaluating and communicating short-term and long-term risks [4]. As such, it can also be used as a tool for long-term risk management.

The simplified version of the seismic stress test was recently applied to building stock in Slovenia [5]. The methodology was developed as a part of the basic research project Seismic stress test of built environment sponsored by Slovenian Research Agency.

In the paper, the seismic stress test methodology is summarised. The stress test outcome is then presented for the time-based earthquake consequences and the scenario-based consequences assuming that the earthquake M_w=6.4 occurs 5 km north of the centre of Ljubljana. The proposed actions for enhancing the seismic resilience of Slovenia in the long-term are briefly presented and discussed.

2. Development of seismic stress test of building stock in Slovenia

The seismic stress test methodology of building stock in Slovenia is an adjusted version of the methodology developed for critical infrastructures [3]. The workflow of the adjusted methodology foresees four phases: (1) Preassessment, (2) Assessment, (3) Decision, and (4) Report phase. Some phases are divided into several steps, which results in a total of six steps, presented in the following.

Phase 1: Preassessment

Step 1: Data collection. The objective is to collect the data needed to perform the seismic stress test: building stock data, occupancy data, seismic hazard data and the results of any potential previous stress tests. The data is used to develop the exposure model, the building stock fragility model, the seismic hazard model and the consequence model.

Step 2: Definition of risk measures and acceptance criteria. Seismic risk measures that are going to be used in risk evaluation and the corresponding acceptance criteria are defined in this step. The acceptance criteria are defined based on guidelines from standards, as well as by considering the society's financial capacity and results of previous stress tests. In addition, informative risk measures may be defined. The informative risk measures are those that are not going to be considered in risk evaluation but will be used informatively. Moreover, this step may also include an analysis of the uncertainty in defining the acceptance criteria.

Phase 2: Assessment

Step 3: Risk assessment. This step includes the estimation of seismic risk for each building and the classification of buildings into risk classes (A-G) defined based on the acceptance criteria. Seismic risk estimation includes seismic hazard analysis, seismic fragility analysis and consequence analysis. However, the risk evaluation is performed from the point of view of the acceptance criteria. Each building is classified into the risk class. Because of the uncertainties, the building stock risk classification is based on many simulations. After performing all simulations, the number of buildings in each risk class is estimated with a selected level of confidence. Results are presented in terms of seismic performance certificate of building stock at the national level. Additionally, the informative risk measures are quantified. In this case, as well, the simulation-based approach for risk assessment can be used. In this study, all simulations were performed with IKPIR application.

Phase 3: Decision

Step 4: Determination of critical buildings. The critical buildings are determined based on the allocation of buildings into the risk classes performed in Step 3. The critical buildings are those classified into the risk classes associated with long-term intolerable risk (risk classes C-G). Only risk classes A and B are considered long-term acceptable.

Step 5: Development of risk mitigation guidelines. Risk mitigation guidelines developed in this step recommend measures for building stock strengthening, reducing uncertainties related to the estimation of risk and definition of acceptance criteria, and other measures that may gradually enhance community seismic resilience.

Phase 4: Report

Step 6: Presentation of the results. The outcome of the stress test and the guidelines are presented to the entity that requested the seismic stress test.

The described workflow was executed for the purpose of the seismic stress test in Slovenia [5]. The Ministry of the Environment and Spatial Planning, Ministry of Education, Science and Sport, and Ministry of the Interior provided the building stock and occupancy data. However, the seismic hazard data was obtained directly from the national hazard analysis [6] and SHARE hazard analysis [7] using the logic tree approach for the risk estimated.

For simplicity, only three time-based risk measures were considered in the stress test. The annual probability of exceeding the complete damage state and the expected annual loss addressed seismic risk at the building level. The third risk measure was defined as the number of buildings exceeding the long-term intolerable risk to communicate seismic risk at the building stock level. The acceptance criteria for each of these risk measures included three risk boundaries (i.e. the values of acceptable risk) corresponding to the negligible risk, long-term tolerable risk and short-term tolerable risk, whereby the latter referred to the maximum risk tolerated within the next 30 years. Such a definition of acceptable risk is the consequence of the novel decision model [4]. In addition, three informative risk measures were defined to be used in a scenario-based risk assessment: the number of buildings in each of the designated damage states, the number of fatalities, and the direct seismic loss.

Two seismic hazard models were taken into account in the case of time-based risk assessment [6,7]. Due to the lack of building data, the peak ground acceleration (PGA), which is a building-independent ground-motion intensity measure, was considered. The informative scenario-based risk assessment involved only one ground motion model [8], which enables PGA spatial simulation based on a selected magnitude, epicentre and other fault parameters

The exposure model was defined based on limited knowledge of the building stock. It consisted of twenty building classes considering the impact of the load-bearing structure material, the year of construction, and the number of storeys. Most of the building classes consisted of masonry or reinforced concrete buildings. All buildings with the real estate value above 50,000 € according to the mass real estate valuation model and all buildings occupied by people were considered in the stress test. The building stock database included about 500,000 buildings or parts of buildings, representing 97% of the entire building stock value.

The building stock fragility was modelled stochastically. Four damage states were taken into account, representing slight damage (DS1), moderate damage (DS2), extensive damage (DS3) and total damage (DS4) [9]. For each of the twenty building classes and each damage state, an interval for the median fragility curve was defined based on existing studies (e.g. [9,10]). The fragility of a particular building within a given building class was then considered uncertain. The median fragility of a building was thus modelled as a random variable centred around the median fragility of the building class. Moreover, the effects of the soil type, design level, and conservatism in the seismic load considered in the reference studies were taken into account by adjusting the adopted fragility curves.

The consequence model was developed separately for buildings and people. In the case of buildings, an economic loss was assigned to each of the four damage states, as recommended in [9]. The consequences on the people were modelled by the number of fatalities, by taking into account the damage state, the building occupancy and the fatality rate as a function of the building class [5].

An important element of the stress test was also the risk evaluation and communication model, taking into account the novel grading system [4]. It is foreseen that a grade from A to G is assigned to each risk measure based on the comparison of the estimated risk and acceptance criteria. As already mentioned, grades A and B correspond to long-term tolerable risk, while the lower grades correspond to long-term intolerable risk. However, each grade from C to G is associated with a different short-term risk tolerance, which enables that the grade is gradually reduced over time if the risk is not sufficiently reduced in a predefined period. The grading system can thus be understood as a risk management tool.

3. Outcome of seismic stress test: Time-based seismic risk assessment

The seismic stress test outcome in terms of time-based consequences is presented herein only by classifying the building stock into the risk classes based on the probability of exceedance of complete damage state (DS4) for a period of 50 years. The results are presented in terms of a seismic performance certificate of building stock at the national level (Figure 1). The building stock classification into the risk classes is presented by the number of buildings or parts of buildings for each risk class. Because the seismic risk assessment is uncertain due to the use of building class fragility functions, the results are presented by the median values and the 5th and 95th percentiles. Figure 1 shows that about 100,000 buildings or parts of buildings are classified in risk class C, D, E or F, for which the risk is not long-term acceptable. There are no buildings in risk class G. This risk class is reserved for the next periodical execution of the stress test. The real estate value corresponding to risk classes C-F is about 20% of the estimated value of all building stock in Slovenia. Based on the central population register, about 400,000 people (about 20% of the population) live in buildings for which risk is not acceptable in the long-term. In risk class F, there are from 5.4 thousand to 18.5 thousand buildings or building parts. These buildings and building parts require immediate actions towards the improvement of earthquake resistance. Because only risk classes A and B refer to the acceptable long-term risk, it can be concluded that the Republic of Slovenia is not safe against earthquakes in the long-term. Thus the outcome of the seismic stress test is negative, and actions for enhancing seismic resilience are proposed.

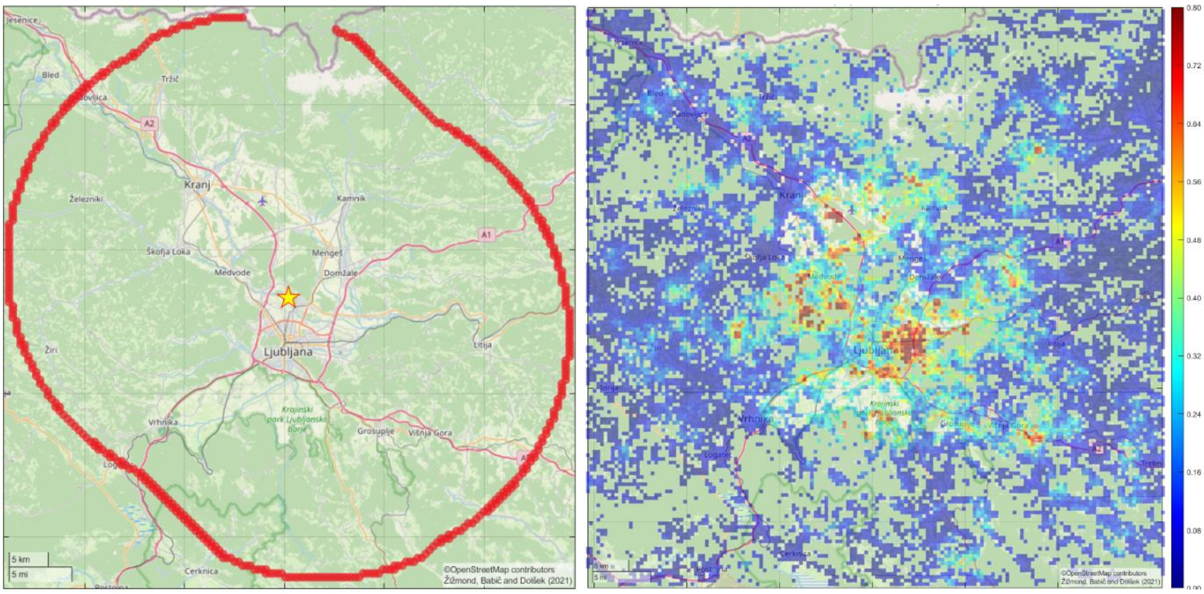
Risk classes	**Number of buildings or parts of buildings × 10^3**		
	5th percentile	**50th percentile**	95th percentile
A	182.4	**229.0**	268.7
B	173.4	**192.7**	212.9
C	48.1	**64.4**	83.6
D	6.8	**10.6**	15.5
E	8.2	**13.5**	21.6
F	5.4	**10.0**	18.5
G	0	**0**	0

Figure 1. The number of building or parts of buildings for risk classes A-G based on a target probability of exceedance of damage state of complete damage (DS4). In addition to median estimates, the 5th and 95th percentile values are also shown.

4. Informative outcome of seismic stress test: Scenario-based seismic risk assessment

Scenario-based risk assessment is much easier to be communicated to the stakeholders because it simulates consequences in the case of a critical earthquake event. However, the outcome of scenario-based risk assessment is considered informative because the critical earthquake event was selected arbitrarily by assuming magnitude M_w=6.4 and an epicentre approximately 5 km north of the centre of

Ljubljana (see Figure 2a). The magnitude of the event corresponds to the magnitude of the earthquake which hit Petrinja on 29th December 2020, whereas the location of the epicentre of the assumed event roughly corresponds to the epicentre of the Ljubljana earthquake from 1895. This simulation was performed for the purpose of the conference. In the stress test [5], a critical earthquake event was approximately simulated by ground motions from the 1895 Ljubljana earthquake.



a) b)

Figure 2. a) The assumed location of the epicentre (yellow star) and the exposure area of influence of the critical earthquake scenario, b) maps of one simulation of the spatially correlated PGA compatible with assumed epicentre and activated fault

Ground-motion fields of the considered critical earthquake were simulated 500 times. PGA on rock soil was considered as the ground-motion intensity measure. The intra- and inter-event variation and spatial correlation of PGA were taken into account. The PGAs on rock soil were multiplied by the soil amplification factors based on the draft of the new Eurocode 8. An example of a ground-motion field is presented in Figure 2b. The PGA ground motion field is presented only for the areas with buildings where the soil type is defined.

In addition to the PGA ground-motion fields, the building capacities for different damage states were simulated for each building using the uncertain building class fragility model. For each of 500 ground-motion fields, 20 sets of PGA capacities were simulated for each damage state and each building from the building exposure model. Consequently, 10,000 damages states were estimated for each building. The spatially distributed average damage of building stock is presented in Figure 3 for two simulations. The direct loss due to buildings' damage state was then assessed, and the expected fatalities were estimated. It was considered that 5-15 % of buildings in DS4 collapsed depending on the building class, and assumed that the collapse of the building is fatal for 10 % of the people inside of the building.

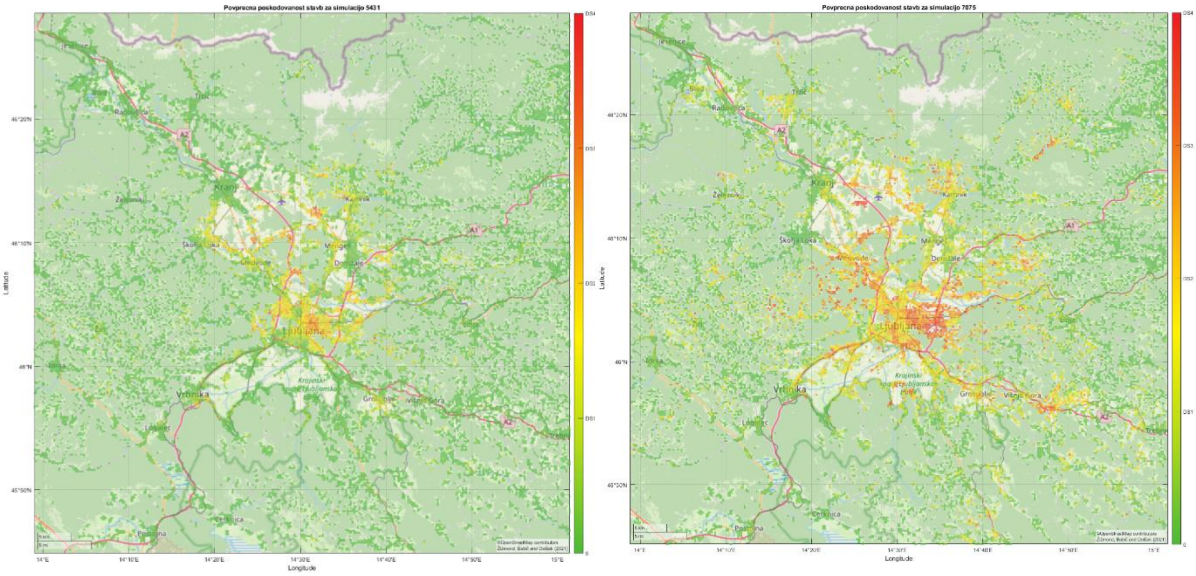
For the considered critical earthquake, it was found that 151,000 buildings or building parts are located within 30 km from the projection of the fault rupture area to the surface. The real estate value of the exposed building stock is approximately 45 billion euros. The exposed area is populated by 700,000 people.

The consequences of the critical earthquake are presented in Table 1. Due to the uncertainty associated with seismic action and the capacities of the buildings, the results are presented for three percentile values (5th, 50th (median) and 95th percentile). The direct seismic loss due to building stock damage was estimated between 3.6 (5th percentile) and 21.7 (95th percentile) billion euros, with the median loss equal to 10.5 billion euros. The median value of fatalities was estimated to 568, while the fatalities for a 90 percent confidence level were observed in the interval from 99 to 1662. The results of the simulation show that the consequences of the considered earthquake event would be catastrophic not only for the Ljubljana region but for the entire Slovenia. The amount of fatalities, displaced people and losses would be enormous. Namely, in the buildings that would achieve damage state DS4, between 8,605 and 123,384 people (median 45,377) are registered, which is a rough estimate of the displaced people due to the considered earthquake event. The direct seismic losses would be between 7 % and 45 % (median 22 %) of the gross domestic product from 2019.

The informative outcome of the seismic stress test showed that the consequences of such a major earthquake are very likely to be catastrophic. Probably Slovenia would need decades to recover, which would reduce the societal well-being of the citizens of the Republic of Slovenia, regardless of help from other countries.

Table 1. Results of the simulation of the critical earthquake (M_w=6.4, 5 km north of Ljubljana centre).

	5th percentile	50th percentile	95th percentile
No. of buildings in DS1	19,928	24,274	27,948
No. of buildings in DS2	24,354	38,233	48,684
No. of buildings in DS3	6,317	17,268	29,596
No. of buildings in DS4	1,638	8,404	22,982
Number of fatalities	99	568	1,662
Direct seismic loss due to building damage (in euros)	3.6 billion	10.5 billion	21.7 billion



a) b)

Figure 3. The spatial distribution of average damage of building stock for the simulations refers approximately to a) 5th percentile of direct losses and b) 50th percentile of direct losses.

5. Proposed actions for enhancing seismic resilience in Slovenia

Based on the outcome of the stress test, four groups of actions were recommended to the Ministry of Environment and Spatial Planning: (1) actions to strengthen the building stock, (2) actions to reduce uncertainty in the seismic risk estimation, (3) actions to improve public awareness of seismic risk, and (4) actions to provide financial incentives for enhancing seismic safety. It was proposed that the actions are introduced in two phases: the preparatory and implementation phase. The preparatory phase is foreseen for five years, while the implementation phase is foreseen until 2050.

Each group of actions has a different purpose, but the groups are interconnected. Herein we focus briefly only on the seismic performance certificate of building, which is one action that helps to improve the public perception and awareness about the seismic risk but can be used together with other actions. The seismic performance certificate of a building partially solves the issue of uncertainty in the seismic risk estimation at the national level. However, the certificate could also be used to plan the owner contribution to the fund for financial incentives for enhancing seismic resilience at the national level. Thus, it was recommended that a seismic performance certificate of a building is developed and implemented in the preparatory phase of enhancing the seismic resilience of Slovenia.

An example of the graphical part of the proposed seismic performance certificate of a building [5] is presented in Figure 4. It is obvious that the grades are harmonised with the energy performance certificate. However, the grading system is novel because grade reduction is introduced due to the adopted concept of long-term and short-term risk tolerance [4]. The results correspond to an older school building in Ljubljana [5,11], for which the certificate was obtained on the basis of a detailed seismic analysis. However, note that at least four levels of details for calculating risk measures used in the building certificate were already developed (e.g. [11], [12]).

From the seismic performance certificate of the building, it can be concluded that the building is classified in risk class D, which means that the risk is intolerable in the long-term. Therefore the outcome of the stress test is negative. The certificate foresees that the initial grade D will be reduced over time (Figure 4). Based on the proposed methodology ([4],[5]), grade D will be reduced to grade E in 1 year, into grade F in 11 years and finally to grade G in 21 years. If the final grade G is reached, even the short-term risk would be considered intolerable. In such cases, immediate actions should be taken so that the seismic risk is reduced.

As a consequence of the Petrinja earthquake, quite some Ljubljana citizens asked for information about the earthquake-resistance of their homes. For that purpose, informative seismic performance certificates of buildings were issued based on the seismic stress test of building stock in Slovenia. However, because the level of detail of seismic risk assessment of building stock is low, the certificate in such cases foresees the interval of grades and not only one grade, as presented in Figure 4.

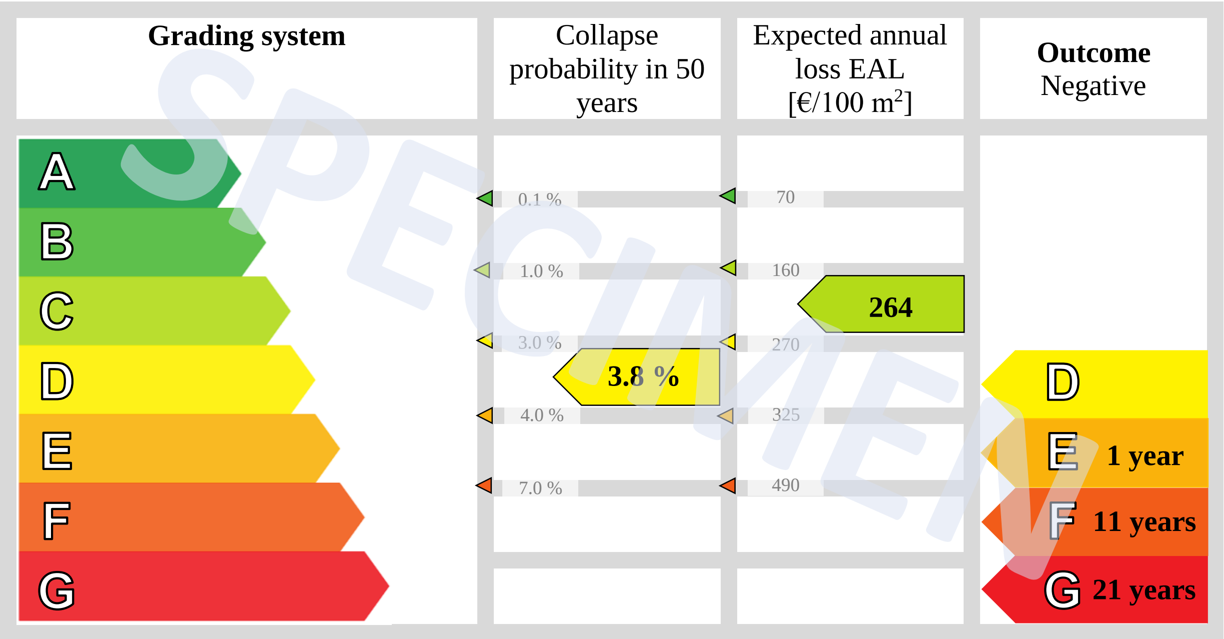


Figure 4. An example of seismic certificate of a school building in Ljubljana with the consideration of two seismic risk measures: collapse probability in 50 years and expected annual loss per 100 m^2 of floor area with the risk boundaries and the outcome of a stress test and the grade reduction ([5], [10]).

6. Conclusions

The seismic stress test of the building stock in Slovenia was developed slightly before the 2020 earthquake hit Zagreb. Since then, the seismic stress test outcome was delivered and presented to the Ministry of Environment and Spatial Planning of the Republic of Slovenia. Soon after the Petrinja earthquake, the results were again communicated to the stakeholders through media and in the Slovenian Parliament. After a five-hour debate, the Committee on Infrastructure, Environment and Spatial Planning unanimously decided that the Government of the Republic of Slovenia should prepare by the end of the year a resolution on strengthening earthquake resistance in the Republic of Slovenia. It is hoped that the resolution will be prepared in a broad context, which will enhance seismic community resilience comprehensively. In such a context, the physics-based simulations of seismic risk and related digitalised seismic performance certificates are key factors for establishing unbiased seismic risk perception and communication and provide a basis for risk management towards community seismic resilience.

6. Acknowledgements

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