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Seismic stress test of the building stock of the University of Ljubljana

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Abstract

The lack of interest in replacing or strengthening unsafe buildings is primarily due to limited personal experience with the damage caused by major earthquakes. However, while strong earthquakes are rare, the seismic risk can be significant due to their potentially catastrophic consequences. To help establish an unbiased perception of seismic risk in society, we conducted a seismic stress test of the building stock of the University of Ljubljana (UL). The UL provided data that we improved by inspecting selected buildings and/or available project documentation. The developed exposure model of the UL building stock was then complemented by a seismic hazard model, a seismic fragility model and a consequence model. All models were coupled into the seismic stress test framework based on the seismic risk analysis. In this paper, the seismic stress test framework is briefly summarized with an emphasis on the exposure model. This is followed by the presentation of the results of the study. We show that the seismic fatality risk at the UL is too high. The average annual return period for loss of life among students is only six years, which exceeds the fatality risk of a code-conforming building stock by a factor of 26. Moreover, the expected annual losses are too high. The expected annual cost of repairing seismic damage to UL's building stock was estimated at EUR 1 million, representing about a quarter of UL's Development Fund.

Key words: Seismic stress test, building stock, seismic hazard, seismic fragility, seismic risk

1 Introduction

The probability of the occurrence of strong earthquakes is not negligible in Slovenia. Such earthquakes can cause heavy damage to existing building stocks and fatalities [1]. Recent earthquakes in our surroundings are also a reminder that stronger earthquakes are a reality (e.g. in L'Aquila in 2009, Durrës in 2019, Zagreb and Petrinja in 2020). Due to the lack of personal experience, many people believe that Slovenia's seismic risk is very low. To establish an unbiased perception of seismic risk among individuals and society, the seismic stress test of the built environment, which is based on the seismic risk analysis, can be performed (e.g. [2, 3]).

When conducting stress tests against extreme earthquakes, it is useful to use probabilistic analysis methods to evaluate adverse events with a certain degree of probability and account for all possible scenarios that contribute to seismic risk. A recent seismic stress test of the Slovenian building stock [3] showed that earthquakes threaten 88 to 228 thousand lives, if considering only the residents of the Republic of Slovenia (RS). Therefore, it is necessary to raise awareness about the consequences of strong earthquakes, especially in critical infrastructures. One such critical infrastructure is the building stock of the University of Ljubljana (UL). For this purpose, a seismic stress test has been performed for the UL building stock, as well as for the so-called updated UL building stock, which is a hypothetical building stock consisting of code-conforming buildings.

The following section presents the UL building stock by describing the exposure model used in seismic risk assessment. A framework for a seismic stress test is then presented in Section 3. The global outcome of the seismic stress test is given in Section 4, which is followed by the conclusions.

2 Building stock of the University of Ljubljana

The UL is the central higher education and scientific research institution in the RS. Its building stock can thus be classified as a critical infrastructure. For the sustainable operability and development of UL, human resources development is crucial, which could only be achieved if the UL activities are carried out in functional and safe facilities. In developing the UL building stock database, the publicly available data were first investigated [4]. As the study progressed, a collaboration with UL was established. Based on UL's data, we concluded that the university's building stock included 156 buildings or 228 building parts. Despite all the information, the knowledge about the buildings, based on publicly available databases and the university database, was not sufficient for conducting a comprehensive seismic stress test. Nevertheless, the information collected was considered sufficient for the first (i.e. low) level of building knowledge, as discussed later in Section 2. During the building stock database development, it was realised that the quality of information varies significantly from building to building.

Therefore the second and third level of building knowledge were introduced. The second level of building knowledge includes a visual inspection of the building and review of the project documentation, while the third level of building knowledge also comprises the results of previously conducted seismic analyses [5, 6, 7].

The initial building stock database was then established. The largest proportion of UL buildings are located in the city of Ljubljana (i.e. 119). Thirty-nine buildings are located in other municipalities in Slovenia, as shown in Figure 1a. Based on the UL building stock analysis, we found that the real estate value of many buildings is relatively low. Therefore, it was decided to perform the seismic stress test only for the most important facilities, including all buildings intended for educational or scientific research activities estimated to at least 70,000 EUR. In this way, the majority of auxiliary facilities were excluded. The remaining UL building stock, which we refer to as the characteristic building stock, comprises 102 buildings. Although many UL buildings were omitted in the seismic stress test, the total real estate value of UL's characteristic building stock amounts to 99.8 % of the estimated total real estate value of UL's building stock. In order to develop the exposure model, the list of UL's enrolled students and employees was evaluated based on the data for the 2019/2020 academic year. The obtained list of enrolled students showed that there are currently 37,615 students enrolled at the UL. UL employees defined the other part of the population model. Their number has fluctuated slightly over the past few years. At the end of 2019, the number of employees was set to 6,296.

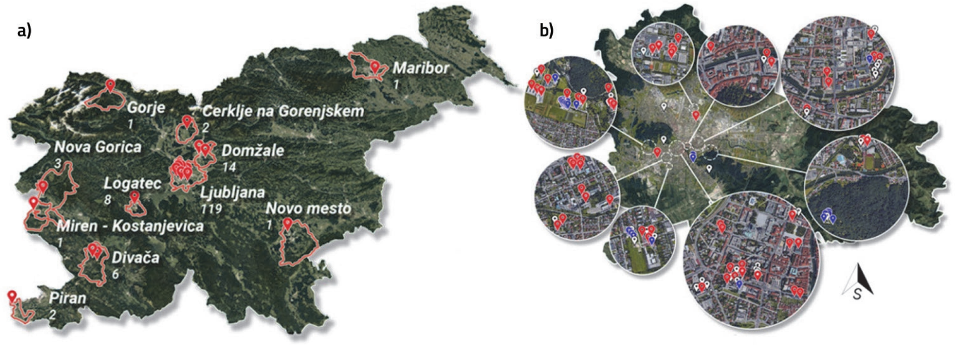

Figure 1. Demonstration of (a) the number of UL buildings by municipalities and (b) the characteristic building stock of the UL in the Municipality of Ljubljana. Higher and lower importance buildings are presented respectively by red and white characters, while the other UL buildings are marked as blue

In order to gain a better insight into the characteristic building stock of the UL, the predominant material of the load-bearing structures and the years of construction of the buildings were analysed. These building characteristics were used for evaluating the seismic vulnerability of buildings, if the building knowledge was at the first level. It was found that the predominant material of the load-bearing structure of most of the facilities of the building stock is either masonry or reinforced concrete. The latter material is used for almost 60 % of the characteristic UL building stock. There are also quite a few buildings where the load-bearing structural material is defined as a combination of building materials. In these cases, it is likely that the material is a combination of masonry and concrete construction. Other materials can be assigned to particular buildings, but to a lesser extent. Based on these assumptions, it was concluded that the proportion of buildings that are either masonry or concrete is about 94 % of the characteristic building stock. Moreover, the year of construction is noted in the characteristic building stock database, as the seismic resistance of buildings has changed significantly over time. Therefore, buildings were divided into five construction periods that relate to different standards for earthquake resistant design. Unfortunately, the UL building stock is relatively old, as half of the buildings in the characteristic building stock were built before 1964, when the standard for earthquake resistant design was first introduced. Interestingly, quite a few buildings have been constructed in the last twenty years, but these buildings represent only 9.8 % of the characteristic building stock. A more detailed analysis shows that most of the 26 faculties/academies of UL have buildings which were not designed to be earthquake resistant.

Note that for the simplicity of writing, the characteristic building stock is termed from now on as the existing building stock, although it comprises only the most relevant buildings of the UL as discussed in this section. We will also define the so-called updated building stock, which comprises the same buildings as the existing building stock but their seismic capacity is upgraded to be earthquake-resistant according to Eurocode 8 requirements.

3 Overview of the seismic stress test methodology

The seismic stress test methodology includes the seismic hazard model, the building stock exposure model, which consists of three levels of building knowledge, the seismic fragility model of the building stock and the consequence model on buildings and people. Building Knowledge Levels 1 and 2 do not foresee conducting a seismic performance analysis of the building. Thus we developed a parametric model for estimating the building's pushover curve considering limited information about the building. Based on the result of the model, we then determined an equivalent system with one degree of freedom (SDOF) [8], which enables a nonlinear dynamic analysis (e.g. [9, 10]). Such an approach makes it possible to perform accurate seismic risk studies, although the input data are subject to epistemic uncertainty.

3.1 Seismic hazard model

The seismic hazard model consists of seismic hazard curves based on official probabilistic seismic hazard analysis [11] and ground motions at buildings' locations. The peak ground acceleration at the surface (PGA) of soil type A was used as the intensity measure. As this is a measure independent of the building's properties, a single seismic hazard curve was applied to all buildings in similar locations with the same soil type. Therefore, seismic hazard curves for soil type A were determined for six locations where the facilities are located. The effect of soil was taken into account with the soil factor according to Eurocode, while the ground motion randomness was simulated with fifteen accelerograms, which differ according to the type of soil on which they were recorded (soil type A, B, C, D).

3.2 Building stock exposure model

The majority of building stock is described by publicly available data (i.e. Building Knowledge Level 1), which includes the year of construction, building category of occupancy, net floor area, load-bearing structure material, number of floors above ground level and height of the building. In Slovenia, such data can be acquired from the real estate register – REN [4]. Building Knowledge Level 2 provides additional data about the building obtained by onsite inspection and/or reviewing the building permit's project documentation. In this case, the parametric pushover curve data becomes more reliable, which is reflected in the building's seismic fragility analysis. However, Building Knowledge Level 3 foresees developing a detailed nonlinear numerical model and estimating the structural capacity in terms of load-bearing and deformation capacity. The pushover analysis is usually used for this purpose [8], according to the SIST EN 1998-1: 2005 standard. In this way, additional data about the building are obtained, which are essential for analysing the building's seismic fragility.

3.3 Seismic fragility model

A novel parametric model to estimate pushover curves for Building Knowledge Levels 1 and 2 was developed. For brevity, the model is not described in this paper. However, it allows an approximation of the pushover curve (Figure 2a) without performing a pushover analysis. The obtained pushover curve is then used to define the equivalent SDOF model [8] and to perform the incremental dynamic analysis (IDA) [12] (see Figure 2b). The limit-state ground motion intensities are then used to estimate the fragility curves (Figure 2c). The parametric model for pushover curves has several advantages compared to building class fragility functions (e.g. [13]). One of them is that the seismic loading for evaluating the seismic hazard curve is consistent with the seismic hazard at the facilities' site, which is often not the case if a building's fragility is simulated by predefined fragility curves. However, the major advantage of the novel parametric model for pushover analysis is its ability to simulate the pushover curve of a strengthened building or an equivalent new (i.e. code-conforming) building. Thus it can be used as a tool to simulate the effect of strengthening or replacement of a building on the fragility curve and the building stock seismic risk. In this study, the fragility curves were calculated for four damage states determined by the HAZUS methodology [14]: the slight damage state (see Figure 2, green), the moderate damage state (yellow), the extensive damage state (red), and the complete damage state (black).

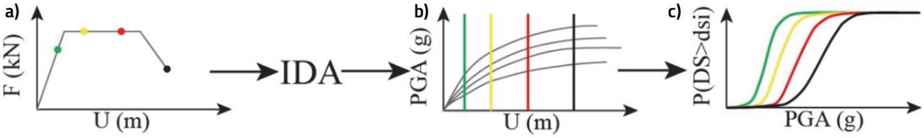

Figure 2. Schematic presentation of the: a) parametric pushover curves, b) the corresponding IDA curves, c) fragility curves related to four damage states

3.4 Earthquake consequence model on buildings

In this paper, time-based risk assessment is performed. Therefore, the consequence model includes risk indicators such as the exceedance probability of damage states ()) for a period of 50 years and the expected annual losses (e.g. in EUR/100 m^2 net floor area). The novel fragility model made it possible to simulate the earthquake consequences for a hypothetically updated building stock that reflect the seismic performance of an earthquake-resistant building stock designed according to SIST EN 1998-1. Consequently, the UL existing building stock's seismic performance was not compared to the target seismic risk indicators, but to the assessed risk indicators in the hypothetically updated building stock case, which is considered consistent with the current legislation. For brevity, the details about the updated building stocks development are not presented.

A simplified seismic loss estimation method developed for the seismic stress test of the building stock of RS [3] was also used to estimate seismic losses of the existing and updated UL building stock. The standardised repair costs (relative to the reconstruction cost) for all four damage states and building reconstruction cost were defined and coupled with the fragility curves and the seismic hazard curve. The loss estimation thus involves several steps. In the first step, the probability of achieving damage states for a given PGA is calculated from the fragility curves (Figure 3a). The standard repair cost (losses) for a given damage state is then multiplied by a probability of experiencing the damage state, given PGA (Figure 3b). This process is repeated for all consider damage states. The resulting losses are then summed in order to obtain the expected loss given the level of PGA, which is termed the loss curve (Figure 3c). The loss curve can then be coupled with the seismic hazard curve (Figure 4), which results in the expected annual losses. The above description for the estimation of expected losses refers to a single building. By repeating it for all buildings and summing the results, the excepted losses for a building stock are obtained.

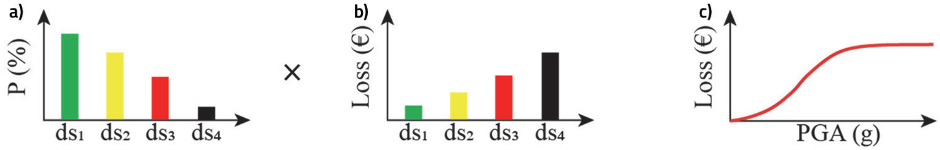

Figure 3. **a) the probability of exceedance of each damage state at a given PGA, b) the value of expected losses associated with damage states, c) the loss curve, representing expected losses as a function of PGA**

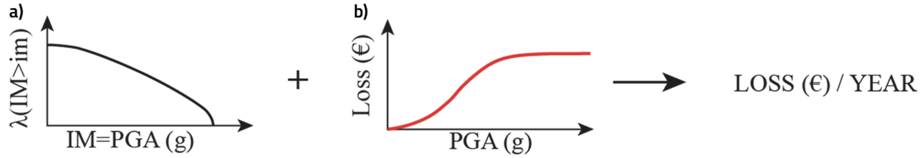

Figure 4. **Determining the expected annual losses by coupling: a) the seismic hazard curve, b) the loss curve**

3.5 Earthquake consequence model on people

The nominal occupancy of the buildings in the UL building stock is known. The UL determined the nominal number of people in the buildings by clearly distinguishing between the number of employees, and the number of students enrolled relative to each UL member. An hourly building occupancy model was then developed (Figure 5c), to estimate the number of people in the UL building stock at each hour throughout the year. In the case of the time-based consequence model, the equivalent annual number of people in each building was estimated by assuming that the probability of an earthquake occurring at any time during the year is equally probable.

The calculation of the expected annual number of fatalities is similar to calculating the expected annual losses. However, in addition to the exceedance probability of the selected damage states for a given PGA (see Figure 5a), the probability of a building collapse for a given damage state must also be known (see Figure 5b). In the performed stress test, it was considered that there is a 5 to 15 % chance that a building will collapse in the case of damage state 4 (Figure 5b) [14]. These probabilities are multiplied and the obtained probabilities are summed and multiplied by the equivalent annual number of people and by the proportion of the fatalities given the collapse of a building, assumed to be 0.1. The result is the expected number of fatalities given a designated PGA. The expected annual number of fatalities is then calculated by coupling the expected number of fatalities given the level of PGA and the seismic hazard curve. If the procedure is repeated for all UL building stock buildings, the expected number of fatalities refers to the UL building stock population.

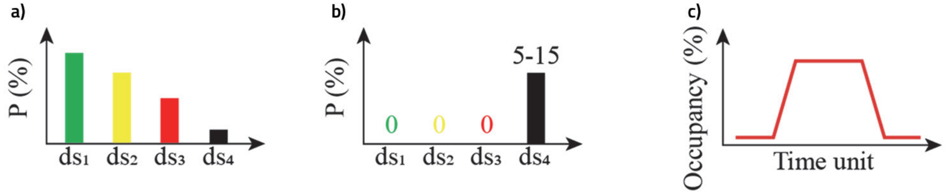

Figure 5. a) the probability of exceeding the damage states given the level of PGA, b) the probability of collapse of a building given the damage state, c) the percent of occupancy at a given time unit

4 Results od the seismic stress test

The seismic stress test results are presented for the UL building stock in terms of time-based seismic risk indicators of people and buildings' consequences. First, the return period for a fatality event and the average expected number of fatalities over 50 years were evaluated. The consequences on buildings were assessed by the expected annual loss for the UL building stock and the probability of exceeding each damage state over a 50-year period. However, only the expected annual loss and the complete damage state's exceedance probability are presented in the following.

The stress test results show that UL building stock is not earthquake resistant. The mean return period for a fatality among students is only about 6 years. Although employes have a lower chance of being fatally injured, the return period for a UL employee fatality is about 26 years. If annual fatality indicators are transformed into a period of 50 years, the expected number of deaths is about eight and two, respectively, among students and employees. The total expected number of deaths in 50 years due to seismic hazard is estimated to be about ten, undoubtedly due to the obsolete building stock. The outcome of the seismic stress test is thus negative. The stress test was also performed for the updated building stock to get an insight into the tolerable level of risk. If the UL building stock were to be renewed, the return period for student fatality would increase to 158 years. This means that student lives in the UL existing building stock are endangered 25 times more comparing to an updated building stock. The return period for the employee fatality also increases to approximately 411 years. The UL employees are thus also at much more risk than they would be in an updated building stock.

In order to classify the UL building stock according to risk classes for loss of life, 16 risk classes were defined based on intervals of return periods for loss of life (see Figure 6). The figure shows that there is one building in the existing building stock with a return period for a fatal event of less than 30 years. Such a low return period for loss of life from an earthquake is unacceptable because, for most updated buildings, the return period for loss of life is significantly increased. Most new buildings are classified in the interval of return periods between 60,000 and 120,000 years, while most existing buildings fall in the interval of return periods between 1000 and 2000 years.

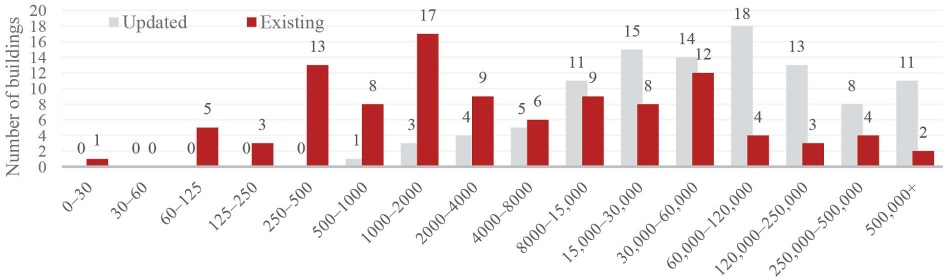

Figure 6. Classification of buildings of the existing and updated UL building stock into classes of return periods for the fatality event

The outcome of the seismic stress test is negative also in terms of expected losses. The estimated expected annual loss is about 1,000,000 EUR. This risk indicator can be understood as the average annual repair cost resulting from earthquake damage in the long term. The value is not negligible as it represents about a quarter of the annual government funding UL receives for development [15]. However, the expected annual losses in the updated UL building stock case are reduced to 83,400 EUR, representing only 8 % of the existing buildings stock's expected losses. It can also be concluded that the UL building stock's seismic resilience is too low due to the high expected annual losses.

Additionally, the UL building stock facilities were classified into nine intervals of expected annual losses (see Figure 7). It should be noted that almost half of the buildings of the existing stock are in classes with an expected annual loss of more than 4,000 EUR, while there are only two such buildings in the updated building stock (1.9 % of the building stock). A significant reduction in the expected annual losses can be seen in the updated building stock, with almost 76 % of all buildings being in classes with an expected annual losses of less than 1,000 EUR.

The probability of exceeding the damage states is calculated for a period of 50 years. The results of the analysis for the exceedance of the complete damage state () are shown in Figure 8. It can be observed that the risk of exceeding the complete damage state is significantly reduced for the updated building stock. The exceedance probability between 6 % and 25 % in the case of the complete damage state can be observed for 33 buildings of the existing building stock. In the case of the updated building stock, the exceedance probability for practically the same number of buildings (i.e. 30) is only between 0.1 % and 0.4 %. It can be concluded that the probability of exceeding the state of complete damage is exceeded about 60 times for the existing building stock.

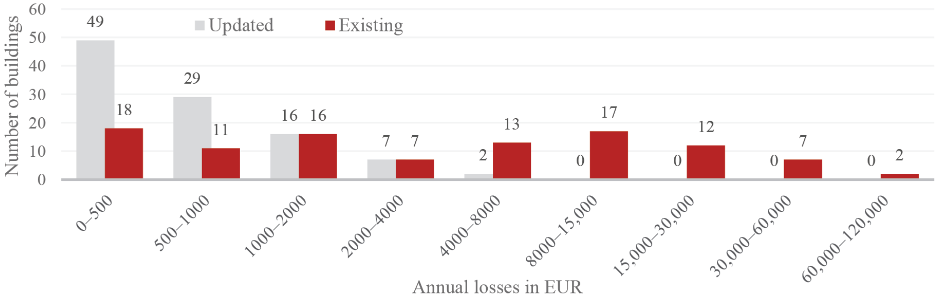

Figure 7. Classification of buildings of the existing and updated building stock into classes of expected annual losses in EUR

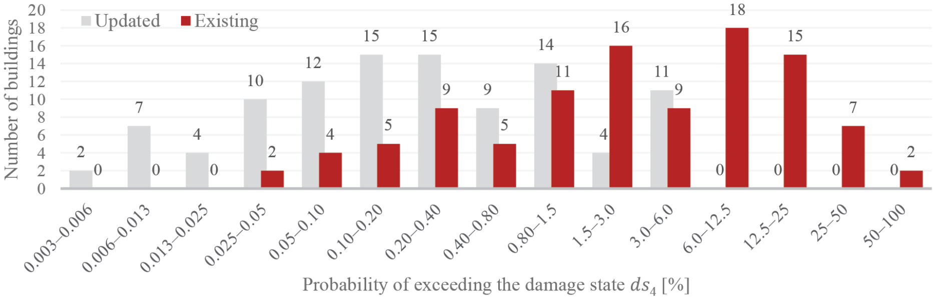

Figure 8. Classification of buildings of existing and updated building stock according to the probability of exceeding the complete damage state, for a period of 50 years

5 Conclusions

The seismic stress test of the UL building stock was performed during the summer of 2020 as an application of basic research conducted within the project Seismic stress test of the built environment sponsored by Slovenian Research Agency. The study gained attention among the Deans and the Rector of UL after the Petrinja earthquake, which caused some minor damage to UL building stock although the PGA in Ljubljana was measured in the interval between 1 % to 3 % g. The stress test results were presented to the UL management, and the decision was made to establish the systematic approach for enhancing the seismic resilience of the UL and improve the seismic stress test by considering Building Knowledge Level 3 approach for all critical buildings.

Such a decision was inevitable because the seismic stress test results showed that the expected annual number of fatalities in a code-conforming building stock would be lower by a factor of 25, while the expected annual monetary losses of a code-conforming building stock would decrease by a factor of 12. Fortunately, the awareness of the problem is growing, which is reflected in the intention of the Republic of Slovenia's Government to start the construction of three new faculties by 2022 [16].

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