

Earthquake Risk of Schools in Croatia: Focus on the Exposure Model

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Abstract

Given that several regions of the Republic of Croatia are exposed to moderate and high seismic hazard, earthquake risk assessment is of particular interest to the government and the community, as it is a key aspect of implementing prevention and mitigation strategies. Schools, in particular, are part of the community's critical infrastructure, and their safety and earthquake resistance are of utmost importance. After the earthquakes struck Croatia in 2020, it became clear that schools are not safe places, as more than 400 schools were affected by these events. The project EARS was initiated with the aim of creating a reliable earthquake risk model for schools, assessing the risk, and prioritizing the seismic retrofitting of buildings, in both the short and long term.

This paper presents the initial steps in creating a detailed earthquake risk model for elementary schools in Croatia, specifically the exposure model. First, a GIS-based database is created, including multi-level data. The lowest level of data (LD1) covers all schools and includes basic information such as geographic location, seismic hazard at the site, construction/retrofit period, importance in civil protection, number of students and staff, and school area. The next level (LD2) adds basic structural information, while the highest level (LD3) includes detailed structural data. Based on this multi-level database, school facilities in areas of high seismic hazard will be mapped, the number of exposed children will be determined and the main structural typologies of school buildings will be identified. Moreover, schools already damaged by the 2020 earthquakes and their retrofit interventions will be systematically recorded, providing essential input for subsequent vulnerability analyses. This newly created exposure model will serve as the basis for a detailed nationwide earthquake risk assessment of schools and for prioritizing interventions, which is planned for the next phases of this project.

Keywords: exposure, schools, GIS, database, building features.

1- INTRODUCTION

Croatia is located in a seismically active region of southern Europe, where strong earthquakes have occurred in the past resulting in casualties and significant destruction of the built environment. Therefore, earthquake risk assessment is of particular interest to the government and the community, as it represents a very important aspect for the implementation of prevention and mitigation strategies. Since schools are a vital part of community infrastructure, their safety and seismic resilience are crucial. Furthermore, they are attended by children, the most vulnerable group of the population, and very often schools are designated as shelters for the population after a disaster. After the earthquakes struck Croatia in 2020, it became clear that schools are not safe places, and the authorities were strongly pressured by parents to start solving the problem. It is interesting to mention that 214 schools were damaged in the Zagreb earthquake, and 192 schools in the Petrinja earthquakes (Figure 1). Let us just recall the fortunate circumstances that the Zagreb earthquake, which caused a great extent of damage, was only moderately strong, considerably weaker than predicted for the location, and that it occurred on early Sunday morning during the COVID-19 lockdown, when the children were not in school, while the Petrinja earthquakes occurred during school vacations.

Considering the facts mentioned above, it can be concluded that many schools in central Croatia cannot be considered safe. This can also be extrapolated for the rest of Croatia, because, according to the available data from the data management system of the Ministry of Science, Education and Youth of Croatia, more than half of all schools were built before the adoption of the first seismic regulations.



Figure 1- Aftermath of the 2020 earthquakes: a) Archdiocesan Gymnasium in Zagreb; b) Secondary School in Petrinja

Many countries in seismically active parts of Europe and the wider region have made school earthquake safety a major priority. Only a few examples include Italy, Greece, Portugal, and Turkey. After the 2002 Molise earthquake in Italy, which killed 27 pupils [1] Italy launched a national prevention plan, established research networks such as ReLUIIS and EUCENTRE in cooperation with Civil Protection [2], and developed tools like the DaDO database and WebGIS platforms to improve vulnerability and risk assessment [3–6]. Greece recently introduced the “SafeSchools” program, which uses seismic sensors, real-time data, and early warning software to estimate damage and support rapid decisions on evacuation and building safety [7–10]. Portugal has focused on prioritizing schools for retrofitting and developing risk mitigation plans [11], while Turkey invested €270 million between 2019 and 2024 to strengthen 350 schools and improve safety for about 280,000 students and staff.

Despite the extensive damage to buildings in the education sector due to earthquakes in 2020 [12–16], Croatia did not take measures towards seismic risk mitigation of the educational sector, nor did the research community devote itself to the problem of earthquake-(un)resistant schools nor to improve the models needed for reliable earthquake risk assessment. In Croatia, the areas of the strongest seismic activity are also the areas with the largest population, and thus also of special economic and social importance (e.g., the area of Zagreb, Split, Dubrovnik, and Rijeka): more than 30% of the territory, i.e., around 60% of the population, is exposed to strong earthquakes with expected catastrophic consequences [17,18]. Besides, almost a third of the housing stock was built before the adoption of any regulations that take earthquake action into account. Moreover, buildings were designed for seismic forces that were several times lower before the adoption of Eurocode standards than today, which can be extrapolated to public buildings as well.

The research project EARS (Development of an Earthquake Risk Model for Schools in the Republic of Croatia), funded by the Croatian Science Foundation, was initiated with the aim of creating a reliable earthquake risk model for schools, assessing the risk and prioritizing the seismic retrofitting of buildings, in both the short and long term. As the project officially started in April 2026 and is planned to last 5 years, this paper will only describe the initial activities of the project.

2- INVENTORY OF ELEMENTARY SCHOOLS IN CROATIA

According to data from the Ministry of Science, Education and Youth for 2024/2025, there are 2,501 schools in total, of which 1,996 relate to regular elementary schools. According to Croatian regulations, attending an 8-year education in an elementary school (i.e., homeschooling is not allowed) is obligatory for all children, and the majority of children attend state-owned schools. Therefore, there are many school buildings spread across the country, attended by more than 300,000 pupils (Figure 2).

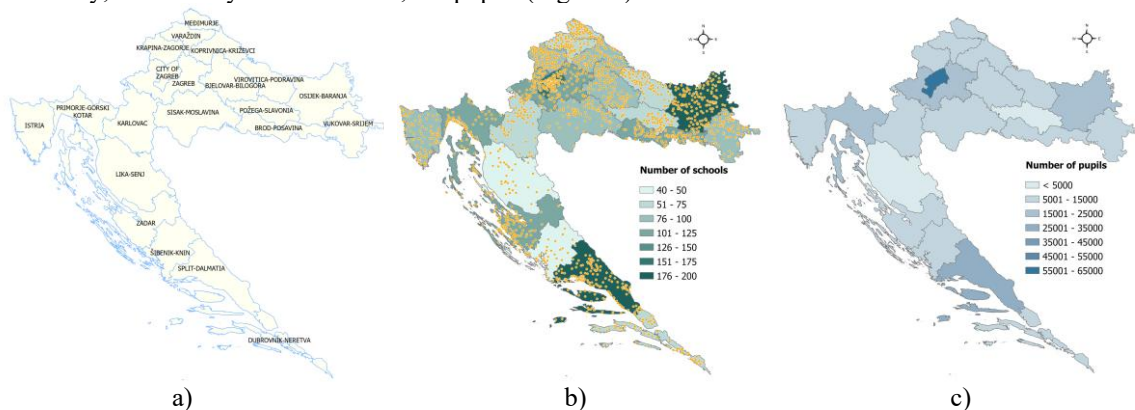


Figure 2- Elementary schools in Croatia: a) counties, b) geolocations and number of schools by counties, and c) number of pupils by counties (right)

Regarding the number of schools, around 10 % of the schools are located in the Split-Dalmatia County, which comprises a few large islands, followed by Osijek-Baranja County in the east (9%) and the City of Zagreb (8 %). More than one-fifth of all pupils attend schools in the City of Zagreb, while in some counties large in area, such as Lika-Senj and Požega-Slavonia, there are fewer than 5,000 pupils.

As may be seen in Figure 3, some areas of the country are exposed to moderate/high seismic hazard. The hazard map created by the Department of Geophysics, Faculty of Science [19] is currently the only official information on seismic hazard in Croatia, due to the lack of detailed microzonation studies that should be conducted for a comprehensive seismic hazard assessment. Since seismic microzonation is not available, the USGS vs30 (average shear wave velocity) model based on the topographic slope [20–23] can be used to estimate amplification effects.

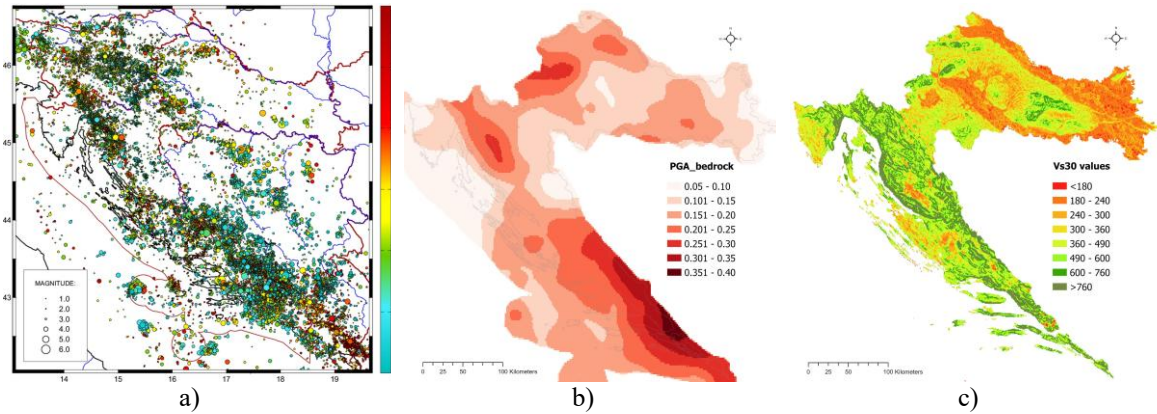


Figure 3- Seismic hazard information: a) map of epicenters of earthquakes from the Croatian Earthquake Catalogue (1908–2019), $M \geq 1.0$ [24], b) peak ground acceleration (PGA) [g] of type soil A for return period (RP) of 475 years (a probability of exceedance of 10% in 50 years) [19], and c) the values of vs30, based on the USGS topographic slope model for Croatia [20–23] (right)

Figure 4 shows counties according to seismic hazard (color of the polygon), and the number of exposed pupils on the left map and the number of exposed buildings on the right map (height of a polygon). The seismic hazard is shown as the mean PGA values on the bedrock in a county.

If the number of pupils and schools in the areas with moderate/high seismic hazard is analyzed, two counties stand out – the City of Zagreb and Split-Dalmatia County. However, the county with the highest hazard, Dubrovnik-Neretva County, also has approximately 10,000 pupils, while the moderately hazardous areas of Zagreb County and Primorje-Gorski Kotar County have more than 24,000 and nearly 19,000 pupils, respectively.

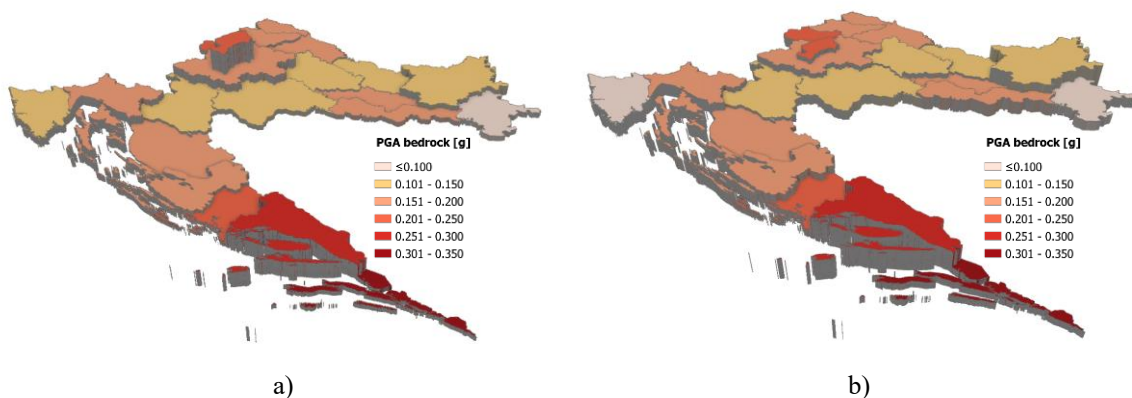


Figure 4- Counties by seismic hazard, shown by polygon color, and exposure indicators, represented by polygon height: a) number of exposed pupils, and b) numbers of exposed buildings

Clearly, earthquake risk should be among the top priorities. The basis for reliable risk assessment is good data on schools, especially on structural parameters, which will be reflected in the exposure model.

One of the first steps in developing the exposure model is creating the GIS-based database architecture. Given the large number of elementary schools (around 2,000), data collection is conducted at three levels, using available data from the Ministry of Science, Education and Youth, local authorities, and completed

projects (e.g., the Zagreb Earthquake Risk Project), along with field research and computer-based research (e.g., using Google Street View).

- Level 1 (LD1) – this lowest level of data covers all schools and includes basic data such as geographic location, seismic hazard at the site, construction/retrofit period, importance in civil protection, number of students and staff, and school area.
- Level 2 (LD2) – adds basic structural information (structural material, structural system type, number of storeys) to LD1. The goal is to gather LD2 data for the majority of schools – depending on the availability of the data, but especially for schools located in seismically active areas of Croatia (Central Croatia, Croatian Littoral, and the southern part of the country).
- Level 3 (LD3) – includes LD1, LD2, and detailed structural data, such as plan and elevation irregularities, floor plan shape, floor and roof structure, and aggregate position, based on GEM taxonomy [25,26]. LD3 data will be collected for 10 pilot schools, where a monitoring system will be installed in the later phases of the project. This system will enable real-time damage assessment in earthquake shaking. Data will also be gathered for all elementary schools in Zagreb, with efforts to include other schools in seismically active areas as well.

As the project has started very recently, only LD1 data have been collected from the management system of the Ministry of Science, Education and Youth of Croatia, which will be presented in brief in the following text. LD2 and LD3 attributes will be collected from multiple sources, including archival documentation from schools and local authorities, as well as field and online surveys.

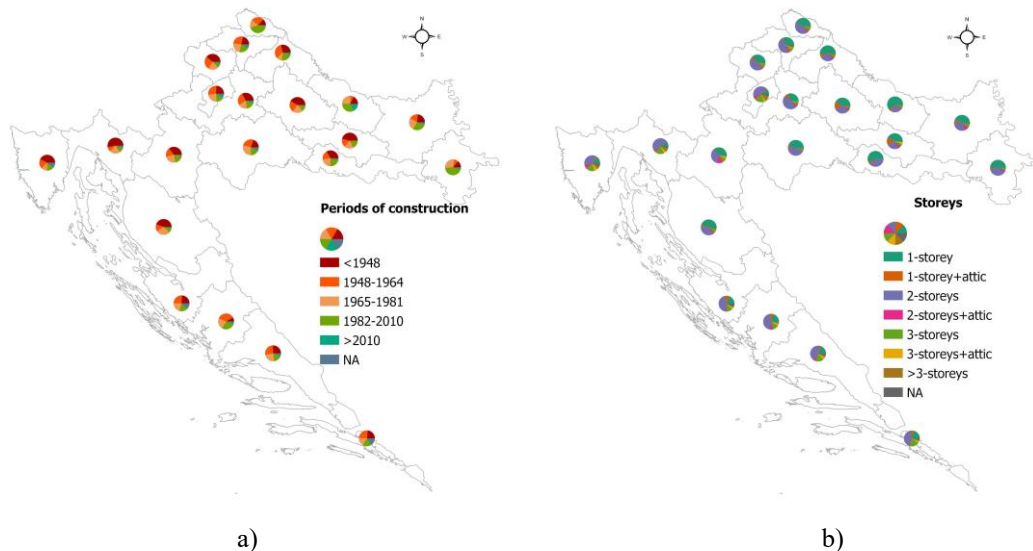


Figure 5- County-level exposure data: a) buildings by construction periods, and b) buildings by number of storeys,

Regarding the construction period (Figure 5 left), 29 % of all schools were constructed before 1948, 22 % in the period from 1948-1964, 22 % in the period 1965-1981, 20 % in the period 1982-2010, 3 % after 2010, and for the remaining schools, the data is not available. It may be observed that 52 % of the school buildings were built before the seismic codes were drafted in the region. Unfortunately, the majority of the schools in all counties with the highest seismic hazard in the country were also built before 1965.

If the number of storeys is analyzed (Figure 5 right), 33 % of the buildings are single-story buildings, while an additional 5 % have an attic. Two-storey buildings account for 39% of the stock, with an additional 5% comprising two storeys plus an attic. Buildings with three storeys represent 11%, while a further 3% have three storeys and an attic. Only 3% are higher than 3 stories, while for the remaining schools, data is not available.

The activity of collecting LD2 and LD3 data has already begun for the City of Zagreb, however, it has not yet been systematized as it also includes extensive documentation.

3- OBSERVED DAMAGE IN PAST EARTHQUAKES

As shown in the previous chapters, many school buildings are located in areas with moderate/high seismic hazard and some of them have already been damaged by earthquakes. Impacts of the $M_w 5.4$ Zagreb earthquake have been presented in detail in [12,14,16], so the focus here will be on school performance. Among the more

than 500 damaged educational and research institutions, schools were the most affected (about 200 buildings). Fortunately, all of these institutions were closed on the day of the event, because it was Sunday in the midst of the COVID-19 pandemic. Figure 6 shows the distribution of buildings across the city according to usability tags (colors) and gross floor area (columns). The usability tags were defined as: (i) green (no structural damage observed; U1: entry is allowed without limitations, and U2: can be used with recommendation for short-term countermeasures), (ii) yellow (potential structural damage observed; PN1: temporarily unusable, require additional inspection, and PN2: can become usable after performing urgent interventions) or (iii) red (structural damage, no entry is allowed; N1: unusable due to external risks, and N2: unusable due to damage) color.

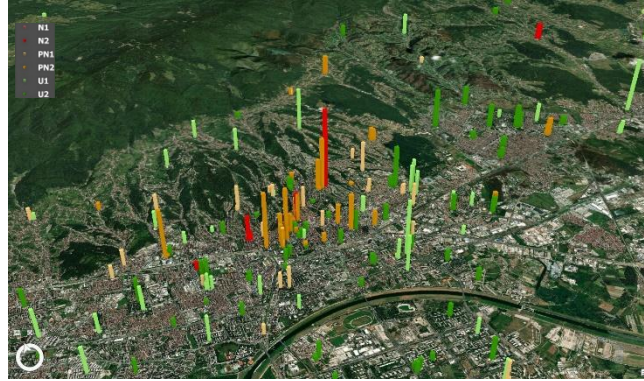


Figure 6- Damage to buildings according to usability tags (colors) and gross floor area (columns) on 3D aerial view of the City of Zagreb

Among the affected schools, 8 buildings have been red-tagged – 7 in Zagreb and 1 in Krapina-Zagorje County, while 81 have been yellow-tagged. Yellow- and red-tagged buildings required additional engineering review.

All the red-tagged buildings in Zagreb were unreinforced masonry (URM). A few examples of damage may be observed in the Figure 7.



Figure 7- Damage to elementary school buildings: Vugrovec-Kašina (top) [27] and Petar Zrinski [28] (bottom)

One of the buildings that has undergone extensive post-earthquake retrofit was the elementary school Petar Zrinski.

It is a URM building built in 1889 as one-storey building (Figure 8) with a 5 m high storey, and in 1922 a second storey was added with the same materials. In 1956, an annex to the building was constructed in reinforced concrete, comprising only columns and floor systems (without beams or walls). In that intervention,

additional openings were made in the original longitudinal structural walls. All of this weakened the original structure. It is important to mention that the school is categorized as an individually protected heritage building.

In the scope of preliminary investigations to fully assess the extent of the damage, a geodetic survey of the building's vertical alignment was carried out. After processing the survey data, significant deviations from the building's verticality were observed, the largest at the location of the annex. Therefore, it was decided that the 1956 extension, where the largest displacements were measured, should be removed and a new building constructed in its place.

The school building also suffered other significant damage: horizontal and diagonal cracks were recorded on all longitudinal and transverse walls of the original old building; cracks were recorded on all lintels; deviations of the façade walls from their vertical axis were recorded, partly as a consequence of the earlier subsidence of the southern part of the building due to unstable foundations; the central staircase connecting the floors deviates from the school's street-side outline by more than 10 cm, with the greatest deviation at the level of the second floor. Damage caused by differential settlement, identified in previous investigations prior to the 2020 earthquake, is also noted.

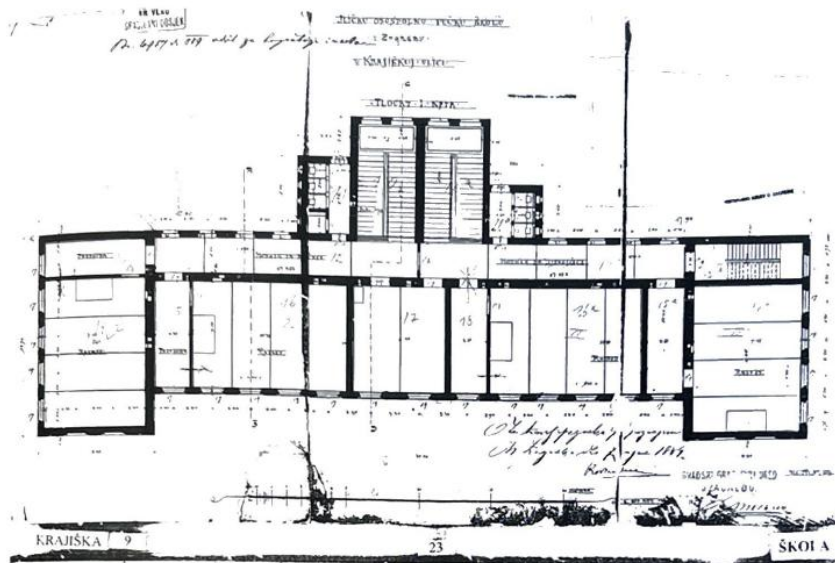


Figure 8- Elementary school Petar Zrinski in Zagreb: layout from the archive documentation, 1889 [28]

The building was retrofitted to Level 3 according to the Croatian Technical Code for Structures [29]. The proposed retrofit strategy was based on a set of coordinated interventions intended to restore structural integrity, improve global seismic behavior, and ensure more reliable interaction between the existing masonry walls, floors, and foundations. The concept includes subsoil improvement and foundation strengthening in reinforced concrete where required, repair and injection of damaged masonry, strengthening of lintels above openings, replacement of deteriorated secondary timber beams with steel ones, and the introduction of reinforced concrete floor slabs to provide stiffer and more effective diaphragm action. Additional measures include strengthening the basement vaulted structure, applying reinforced concrete jacketing to selected walls, tying wall intersections to improve continuity, and filling wall niches in order to reduce local weaknesses. Taken together, these measures aim to create a more regular, connected, and earthquake-resistant structural system while retaining the essential characteristics of the historic building. The more detailed description of the intervention may be found in [28].

Regarding the Mw6.4 earthquake near Petrinja, the impacts were thoroughly described in [15]. As in the Zagreb earthquake, the most severely damaged buildings were unreinforced masonry (URM) structures built before the first seismic codes. Among the educational facilities, 192 schools and 10 higher education buildings were damaged by the earthquake. Fortunately, because of the public holiday, the schools were closed on the day of the main event. An example of damage to schools is given in Figure 9. The Petrinja Elementary School, a valuable URM heritage building, sustained extensive damage with significant damage to load-bearing walls, and collapse of gable walls, a number of spandrels, and of partition walls. The roof structure also partially collapsed. Despite the field inspection experts' recommendation to demolish the building, it was retrofitted due to its high cultural value.

The post-earthquake retrofit included strengthening the walls using an FRCM system and shotcrete. Collapsed walls were removed and reconstructed as confined masonry. The floor layers on the ground were

removed and replaced with a new, lightly reinforced concrete base slab, waterproofing, thermal insulation layers, and the final floor layers. The floor structure was removed down to the level of the brick vault, and a lightweight concrete slab is to be constructed over all the underlying layers. The timber ceiling joists below the attic were removed and replaced with new ones. On the underside, a 15 cm suspended ceiling is to be installed, consisting of mineral wool and gypsum plasterboards fixed to a suspended metal substructure. On the upper side, a new composite reinforced concrete slab was constructed. The roof structure was removed and rebuilt within the same dimensions as the existing one. All partition walls on each floor were removed and replaced with new gypsum-board walls in accordance with the new functional layout [30,31].



Figure 9- Damage to Petrinja Elementary School [27]

Another typology of buildings often built after WWII was the dual system comprising reinforced-concrete infilled frames and unreinforced masonry walls of solid brick, with the ribbed floors with closely spaced joists that are load-bearing in only one direction. Before 1964, when the first seismic code was drafted, it was typical for RC columns in frames to lack the minimum transverse reinforcement, so brittle shear failure in the concrete may be expected. Some of these buildings were also damaged in the 2020 earthquakes, particularly those belonging to the higher education sector. These buildings were retrofitted so that the original dual structural system was transformed into a wall system [30,31]. One such school is currently undergoing a retrofit in Zagreb, so more detailed data will be available in the next phases of the project.

4- CONCLUSIONS

This paper presents the initial steps of developing a new exposure model for elementary schools in the Republic of Croatia. It is shown that among approximately 2,000 schools, 52% were constructed without any seismic considerations. About one-third of all buildings are single-storey buildings, while 39 % are two-storey buildings (in addition, 5 % of both types have an attic also). If the seismic hazard is analyzed, approximately 12 % are located in zones with PGA on the bedrock for the return period of 475 years, higher than 0.25 g, while an additional 55% of the buildings are located in zones with PGA on the bedrock for the return period of 475 years, higher than 0.15g. All the information is stored in the newly created GIS database, which will serve as the foundation for earthquake risk assessment.

This research is being conducted through the project EARS (Development of an Earthquake Risk Model for Schools in the Republic of Croatia), funded by the Croatian Science Foundation, with the aim of developing an advanced system that will contribute to mitigating the earthquake risk for schools, consisting of a new advanced web platform for schools based on a GIS system, along with a newly developed risk assessment methodology and a new risk model. Unfortunately, recent earthquakes have demonstrated that Croatia is in urgent need of it.

5- ACKNOWLEDGMENT

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6- REFERENCES

- [1] Dolce M. The Italian national seismic prevention program. Proceedings of the 15th World Conference on Earthquake Engineering 2012.
- [2] Sabetta F. Seismic Risk Assessment and Reduction in Italy. NED University Journal of Research 2019;1:55–75. <https://doi.org/10.35453/nedjr-stmech-2019-0005>.
- [3] Di Ludovico M, Cattari S, Verderame G, Del Vecchio C, Ottonelli D, Del Gaudio C, et al. Fragility curves of Italian school buildings: derivation from L'Aquila 2009 earthquake damage via observational and heuristic approaches. Bulletin of Earthquake Engineering 2023;21:397–432. <https://doi.org/10.1007/s10518-022-01535-4>.
- [4] Faravelli M, Borzi B, Onida M, Cattari S, Alfano S, Masi A, et al. An Italian platform for the seismic risk assessment of school buildings. Procedia Structural Integrity, vol. 44, Elsevier B.V.; 2022, p. 107–14. <https://doi.org/10.1016/j.prostr.2023.01.015>.
- [5] Perrone D, O'Reilly GJ, Monteiro R, Filiatrault A. Assessing seismic risk in typical Italian school buildings: From in-situ survey to loss estimation. International Journal of Disaster Risk Reduction 2020;44. <https://doi.org/10.1016/j.ijdr.2019.101448>.
- [6] Cattari S, Alfano S, Manfredi V, Borzi B, Faravelli M, Di Meo A, et al. National risk assessment of Italian school buildings: The MARS project experience. International Journal of Disaster Risk Reduction 2024;113:104822. <https://doi.org/10.1016/j.ijdr.2024.104822>.
- [7] Karatzetzou A, Apostolaki S, Riga E, Pitilakis K, Lekkas E. Hierarchical policy for seismic intervention of school buildings at urban scale. Structures 2023;48:669–80. <https://doi.org/https://doi.org/10.1016/j.istruc.2022.12.080>.
- [8] Fotopoulou S, Karafagka S, Petridis C, Manakou M, Riga E, Pitilakis K. Vulnerability Assessment of School Buildings: Generic Versus Building-Specific Fragility Curves. Journal of Earthquake Engineering 2023;27:2994–3023. <https://doi.org/10.1080/13632469.2022.2121791>.
- [9] Karafagka S, Riga E, Oikonomou G, Karatzetzou A, Fotopoulou S, Pitilakis D, et al. RiskSchools: a prioritization-based system for the risk assessment of school buildings combining rapid visual screening smartphone app and detailed vulnerability analysis. Bulletin of Earthquake Engineering 2024;22:2951–80. <https://doi.org/10.1007/s10518-024-01889-x>.
- [10] Karafagka S, Riga E, Oikonomou G, Karatzetzou A, Fotopoulou S, Pitilakis D, et al. AN INNOVATIVE APP AND PLATFORM FOR THE SEISMIC RESILIENCE ASSESSMENT OF CRITICAL INFRASTRUCTURE. WCEE2024, Milan: 2024.
- [11] Ribeiro FL, Candeias PX, Correia AA, Carvalho AR, Costa AC. Risk and Resilience Assessment of Lisbon's School Buildings Based on Seismic Scenarios. Applied Sciences (Switzerland) 2022;12. <https://doi.org/10.3390/app12178570>.
- [12] Government of Croatia World Bank report. CROATIA Rapid Damage Assessment and Needs 2020. 2020.
- [13] Government of Croatia World Bank report. Croatia December 2020 Earthquake Rapid Damage and Needs Assessment. 2021.
- [14] Atalić J, Uroš M, Šavor Novak M, Demšić M, Nastev M. The Mw5.4 Zagreb (Croatia) earthquake of March 22, 2020: impacts and response. Bulletin of Earthquake Engineering 2021;19:3461–89. <https://doi.org/10.1007/s10518-021-01117-w>.
- [15] Atalić J, Demšić M, Baniček M, Uroš M, Dasović I, Prevolnik S, et al. The December 2020 magnitude (Mw) 6.4 Petrinja earthquake, Croatia: seismological aspects, emergency response and impacts. Bulletin of Earthquake Engineering 2023;21:5767–808. <https://doi.org/10.1007/s10518-023-01758-z>.
- [16] Šavor Novak M, Uroš M, Atalić J, Herak M, Demšić M, Baniček M, et al. Zagreb earthquake of 22 March 2020 – Preliminary report on seismologic aspects and damage to buildings. Gradjevinar 2020;72:843–67. <https://doi.org/10.14256/JCE.2966.2020>.
- [17] Atalić J, Šavor Novak M, Uroš M. Seismic risk for Croatia: Overview of research activities and present assessments with guidelines for the future. Gradjevinar 2019;71:923–47. <https://doi.org/10.14256/JCE.2732.2019>.
- [18] Atalić J, Šavor Novak M, Uroš M. Seismic risk for Croatia: Overview of research activities and present assessments with guidelines for the future. Gradjevinar 2019;71:923–47. <https://doi.org/10.14256/JCE.2732.2019>.
- [19] Herak M, Allegretti I, Herak D, Ivančić I, Kuk V, Marić K, et al. Seismic hazard map of Croatia. 2011.
- [20] Allen TI, Wald DJ. On the use of high-resolution topographic data as a proxy for seismic site conditions (VS30). Bulletin of the Seismological Society of America 2009;99:935–43. <https://doi.org/10.1785/0120080255>.

- [21] Heath DC, Wald DJ, Worden CB, Thompson EM, Smoczyk GM. A global hybrid VS30 map with a topographic slope-based default and regional map insets. *Earthquake Spectra* 2020;36:1570–84. <https://doi.org/https://doi.org/10.1177/8755293020911137>.
- [22] Wald DJ, Allen TI. Topographic Slope as a Proxy for Seismic Site Conditions and Amplification. *Bulletin of the Seismological Society of America* 2007;97:1379–95. <https://doi.org/10.1785/0120060267>.
- [23] Yong A, Thompson EM, Wald D, Knudsen K, Odum J, Stephenson W, et al. Compilation of VS30 Data for the United States. Reston, VA: 2016. <https://doi.org/10.3133/ds978>.
- [24] Dasović I, Herak M, Prevornik S. A. Introduction: The earthquake and its effects – A.1 On earthquakes and seismology – in general. In: Uroš M, Todorčić M, Crnogorac M, Atalić J, Šavor Novak M, Lakušić S, editors. *Earthquake Engineering - Retrofitting of Masonry Buildings*, Zagreb: University of Zagreb Faculty of Civil Engineering; 2021, p. 15–36.
- [25] Brzev S, Scawthorn C, Charleson AW, Allen L, Greene M, Jaiswal K, et al. GEM Building Taxonomy Version 2.0. GEM Technical Report 2013;02:188. <https://doi.org/doi:10.13117/GEM.EXP-MOD.TR2013.02>.
- [26] Silva V, Yepes-Estrada C, Dabbeek J, Martins L, Brzev S. GED4ALL - Global Exposure Database for Multi-Hazard Risk Analysis – Multi-Hazard Exposure Taxonomy. GEM Technical Report 2018-01. GEM Foundation, Pavia, Italy, 2018.
- [27] CCEE. GIS-based building usability database. Croatian Center for Earthquake Engineering, Faculty of Civil Engineering, University of Zagreb, 2024.
- [28] Maglov A. Retrofit of the Elementary School Petar Zrinski in Zagreb (in Croatian). In: Kovač D, Pojatina J, Tarnik K, Todorčić M, editors. *Seismic Retrofits and Reconstructions*, Zagreb: Croatian Center for Earthquake Engineering – Intervention Service; 2025, p. 293–316.
- [29] Official Gazette of Republic of Croatia. Technical Code for Structures (NN 17/17, 75/20, 7/22). 2017.
- [30] Salaman A, Stepinac M, Matorić I, Klasić M. Post-Earthquake Condition Assessment and Seismic Upgrading Strategies for a Heritage-Protected School in Petrinja, Croatia. *Buildings* 2022;12. <https://doi.org/10.3390/buildings12122263>.
- [31] Ivanišević N, Matorić I, et al. Building Retrofit Design for Comprehensive Rehabilitation - Design of Structural Strengthening (in Croatian). PASE ZAGREB Consulting d.o.o., 2023.
- [32] Uroš M, Demšić M, Baniček M, Pilipović A. Seismic Retrofitting of Dual Structural Systems—A Case Study of an Educational Building in Croatia. *Buildings* 2023;13. <https://doi.org/10.3390/buildings13020292>.
- [33] Šavor Novak M, Uroš M, Demšić M, Jevtić Rundek R, Pilipović A, Atalić J. Detailed Structural Typology of Existing Substandard Masonry and Reinforced Concrete Buildings in the City of Zagreb, Croatia. *Buildings* 2024;14. <https://doi.org/10.3390/buildings14113644>.