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SCENARIO-BASED SEISMIC RISK ASSESSMENT OF SCHOOL BUILDINGS IN THE SKOPJE AREA, NORTH MACEDONIA

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Abstract

The Republic of North Macedonia (RNM) is characterized by a moderate to high seismic hazard. Combined with the vulnerability of the existing building stock, the impact of earthquakes continues to be substantial. The implementation of risk mitigation strategies at regional or national levels includes the seismic assessment of a wide range of buildings. Given the significant social and economic impact of school buildings, especially in the Skopje region, a scenario-based seismic risk assessment of school buildings in this area is presented here.

The RNM is divided into 8 regions and 80 municipalities (urban and rural), 10 of which constitute the City of Skopje, the country's capital. Out of approximately 1119 primary and secondary school buildings, 193 are located in the Skopje region, serving 81,993 students and 8,961 teaching and administrative staff, according to official data from the beginning of the 2022/23 school year.

The ground motion field, representing the shaking intensity in the study area, is defined using the characteristics of the seismic rupture from the July 26, 1963, Skopje earthquake (magnitude 6.1, hypocentral depth 5 km, epicentral intensity IX). The exposure model is developed by utilizing structural attributes from previous studies and current replacement cost estimates. For buildings where structural typology data is unavailable, taxonomies are assigned with weighted values based on statistical analysis and expert judgment. Lastly, for the vulnerability component, taxonomy strings from the GEM vulnerability database are applied through a mapping scheme.

The analysis are carried out using the OpenQuake Engine, and the results are ultimately presented in terms of damages and losses.

Keywords: seismic risk assessment, scenario-based hazard, school buildings, damages, losses

1. Introduction

In recent years, raising awareness about seismic risk has become a critical issue for all seismically active regions, including the Republic of North Macedonia (RNM). The development of earthquake loss models and the implementation of risk mitigation strategies at regional or national levels require comprehensive seismic assessments of different building portfolios. Among these, school buildings hold particular importance due to their critical social and economic roles during and after earthquake events. This research focuses on structuring and implementing a framework for a regional, scenario-based seismic risk assessment of school buildings in the territory of RNM and applying it to a specific region in RNM, the Skopje region.

The Skopje region is the most densely populated among the eight regions of RNM [1]. It accommodates approximately one-third of the country's total population, highlighting the critical importance of seismic risk assessment for buildings in this area. Although there have been several attempts to assess the seismic risk of school buildings across RNM [2, 3, 4, 5, 6], no comprehensive study covering all schools has been conducted to date.

The approach given herein evaluates the potential damages and structural losses to school buildings from a scenario-based hazard modelled after the 1963 Skopje earthquake, the most credible earthquake for this region. All analyses are conducted using the state-of-the-art software, the *OpenQuake engine* [7, 8].

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2. Methodology for regional seismic risk analysis of school buildings

Studies on large building portfolios are generally scarce for the territory of RNM. One notable exception is the recent study focusing on the City of Skopje is [9], which presents a methodology for assessing seismic losses in the aggregated local building inventory. This study considers two hypothetical seismic events as well as a probabilistic hazard approach. Beyond RNM, research on deterministic seismic risk assessment for large building portfolios has explored various aspects of this approach. An example is the study on risk and resilience of Lisbon's school buildings based on seismic scenarios [10], and an analysis of school buildings in two regions of Metro Manila, Philippines [11]. Additionally, in [12] several regional scenario-based assessments are presented, providing valuable insights on the methodology development.

In line with common practice, the proposed framework for the school buildings in RNM consists of the following steps:

1) Scenario-based hazard analysis conducted considering the fault rupture of the 1963 Skopje earthquake and local site conditions;
2) Exposure modelling of the school buildings including a taxonomy mapping scheme;
3) Choosing the appropriate vulnerability/fragility functions;
4) Damage analysis due to the given scenario hazard;
5) Structural loss analysis due to the given scenario hazard.

These steps are applied specifically to the Skopje region but can also be applied to any region of RNM, provided that information on the most credible earthquake and building portfolio is available. This framework represents an initiative of outputting information with potential for their integration into a national seismic risk assessment map in the future.

3. Application of the proposed methodology to the Skopje region

According to the State Statistical Office of the Republic of North Macedonia [1], at the beginning of the 2022/23 academic year, there were 1013 primary and 135 secondary schools (as administrative entities) active, with 252,341 pupils and 30,312 teaching staff.

In general, RNM is comprised of 8 regions and 80 municipalities, 10 of which constitute the City of Skopje, the country's capital. The municipalities are divided into rural and urban municipalities. Information regarding schools for each region is presented in Table 1, in which the information regarding the Skopje region is highlighted in grey.

Table 1. General information on RNM municipalities, population and schools per region.

Region	Number of municipalities	Number of urban municipalities	Number of rural municipalities	Population based on the latest census in 2021 **[1]**	Number of primary schools	Number of secondary schools	Number of primary and secondary school buildings, SY2022/23 [MES]	Number of pupils, SY2022/23 [MES]	Number of teaching staff and administration, SY2022/23 [MES]
Eastern	11	8	3	150,234	94	13	107	17,903	2,573
Northeastern	6	3	3	152,982	99	8	107	22,747	2,693
Pelagonia	9	5	4	210,431	181	16	197	29,798	3,598
Polog	9	2	7	251,552	149	13	162	37,237	4,779
Skopje	**17**	**9**	**8**	**607,007**	**162**	**31**	**193**	**81,904**	**8,909**
Southeastern	10	6	4	148,387	120	7	127	18,412	2,334
Southwestern	9	5	4	177,398	125	10	135	24,286	3,208
Vardar	9	5	4	138,772	82	9	91	20,054	2,218
	80	**43**	**37**	**1,836,713**	**1012**	**107**	**1119**	**252,341**	**30,312**

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As shown in Table 1, this region accounts for approximately 33% of the total population of RNM, while hosting 17% of the total number of school buildings and 32% of the overall number of pupils and staff. This highlights the importance of seismic risk assessment for buildings in this area. Furthermore, according to the zoning map of Macedonia adopted for National Annex to MKS EN 1998-1:2012 Eurocode 8, with a return period of 475 years and a 10% probability of exceedance in 50 years, the expected PGA for this region is 0.25g [13]. The spatial distribution of the school building stock in this region is presented in Figure 1.

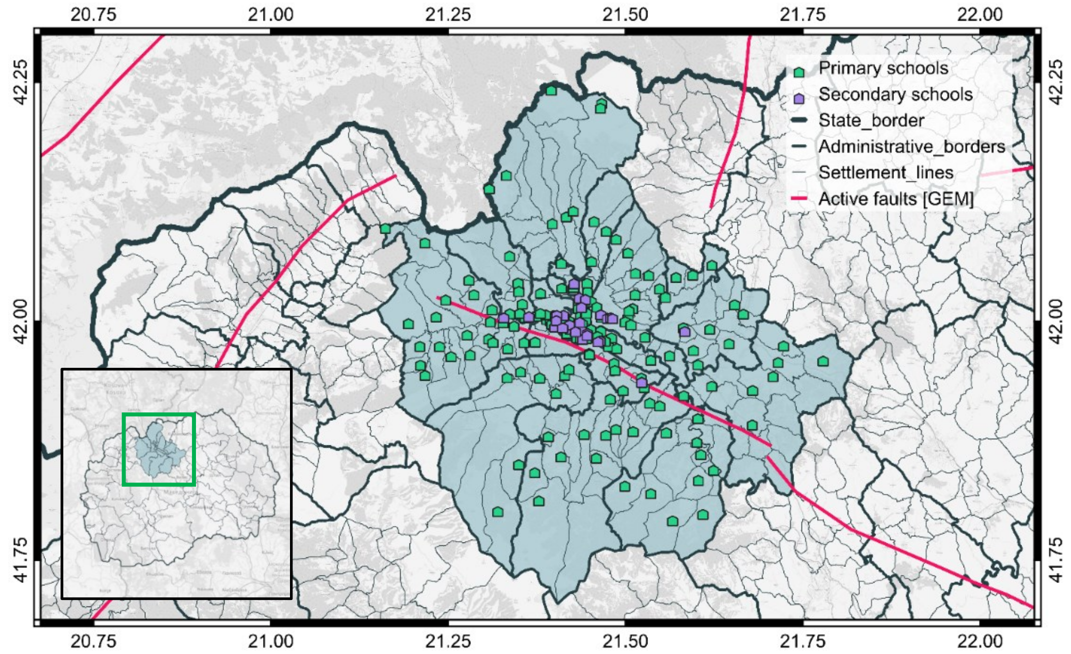

Figure 1. Spatial distribution of primary and secondary school buildings in Skopje region.

3.1. Scenario hazard and site characterisation

The territory of RNM lies on the Eurasian tectonic plate, centrally located within the Balkan Peninsula. Seismic activity in RNM is categorized into three main seismic zones that extend in a north-south direction: the West-Macedonian seismic zone, the Vardar seismic zone, and the East-Macedonian seismic zone, (Figure 2). The neotectonic faults map of RNM is also presented in Figure 2.

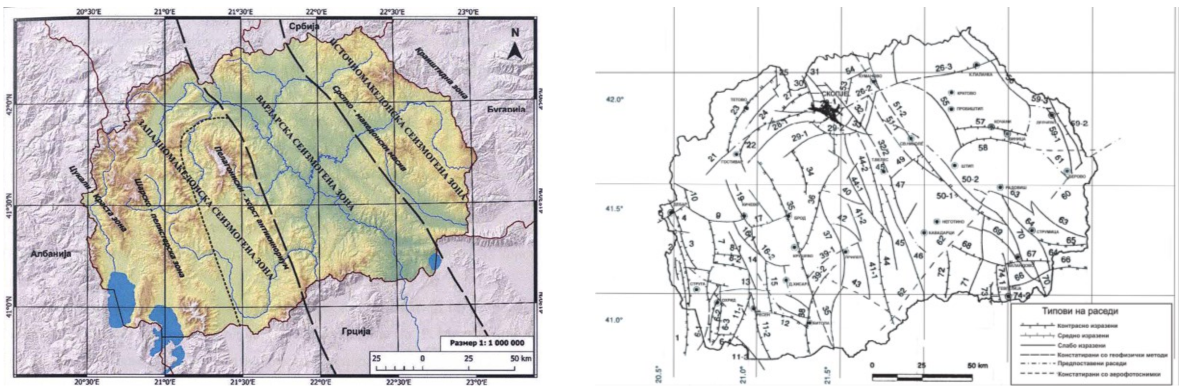

Figure 2. Main seismogenic zones and neotectonic units in RNM [14] (*left*); Map of neotectonic faults in the Republic of Macedonia [15] (*right*).

The Skopje region is located in the Skopje epicentral area and is closely associated with the seismic activity of the Skopje depression. This depression represents a neotectonic feature imposed on older geological structures of the Vardar seismic zone, extending partially into both the West- and East-

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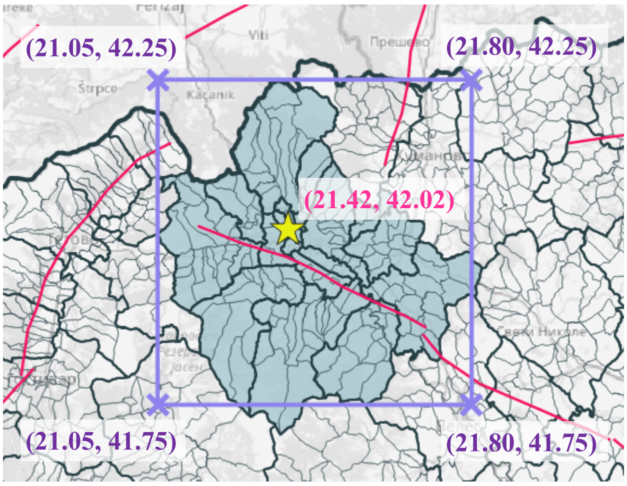
Macedonian zones. The Skopje depression is characterized by the intersection of faults with varying orientations, which has led to significant tectonic activity. The strongest earthquakes in this epicentral area are caused by the uplift and horizontal displacement toward the Skopska Crna Gora Mountain in the northern part of the region, relative to the Vodno mountain in the southern part of the region, along the Skopje-Kyustendil fault [14].

There have been three significant earthquakes with a magnitude of Mw > 6.0 in this region, all causing extensive destruction to the housing and infrastructure in the city of Skopje. The first occurred in the year 518, followed by another in 1555. The most recent earthquake, the one in 1963, will be utilized in this study to determine the hazard of the study area in a deterministic manner. This analysis will later be applied in the seismic risk assessment of damages and losses.

The 1963 Skopje earthquake had a local magnitude 6.10, hypocentral depth 15km and epicentral intensity IX according to [14]. In past studies, the hypocentral depth has also been reported as 5 km [16, 17]. This earthquake caused 1,070 deaths, more than 3,300 seriously injured people and left about 76% of the population without shelter, [18]. In addition to the large number of destroyed and damaged residential buildings, among the most damaged and destroyed typologies were public buildings. According to [19], 8 primary and 11 secondary school buildings were destroyed, and 22 primary and 13 secondary school buildings were severely damaged. All buildings of the University of Skopje were seriously damaged, which led to their forced demolition.

Since its occurrence, many studies have investigated the fault mechanism of this earthquake [16, 17, 20, 14]. The fault is generally considered to be of a strike-slip type, with [16] initially identifying its fault planes as approximately oriented either NW-SE or NE-SW.

In this study, the fault kinematics is modelled according to [14]. Technical information on earthquake and fault, along with the study area polygon, are provided in Figure 3.



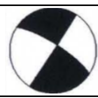
Date	26.07.1963
Time	04:17:11.7
Longitude	42.02
Latitude	21.42
Local magnitude	$M_L = 6.10$
Moment magnitude	$M_W = 6.01$
Depth	$h = 15.0km$
Strike	303° WNW
Dip	77° NNE
Rake	-1°
Type of rupture	Normal-left-lateral
Beach ball diagram	

Figure 3. Study area and characteristics of the seismic rupture for 1963 Skopje earthquake according to [14].

To model the local site effects, information on the local site conditions (Vs_{30}), is obtained from USGS [21]. The Vs_{30} values are provided at a resulution of 0.00833° in both longitudonal and latitudonal directions. In total, there are 5,550 data points available for analysis. The *Institute of Earthquake Engineering and Engineering Seismology (IZIIS)* of Skopje has conducted seismic microzonation for several parts of RNM, and Skopje in particular, defining the ground geophysical parameters. The availability of these data will server for a better interpretation of local site effects, however, they will remain as a resource for potential future work for now.

The Ground Motion Prediction Equations (GMPEs) used in this study generally follow the logic tree established by [22]: AkkarBoomer2010 [23] (w=0.3), BooreAttkinson2011 [24] (w=0.25), Bindi2017 [25] (w=0.20) and CauzziFaccioli2008 [26] (w=0.25).

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All the above-mentioned information regarding rupture mechanism, GMPEs and site conditions are input into the *Scenario Calculator* of the OpenQuake engine to compute ground motion fields (GMFs) for several intensity measures (IMs), which indicate the shaking intensity of the study area. To account for the aleatory variability associated with the GMPEs, a truncation level of 5 is utilized and 100 GMFs are generated for each GMPE, resulting in a total of 4000 realizations (4GMPEs*100GMFs). The average GMF for the IM of PGA is presented in Figure 4.

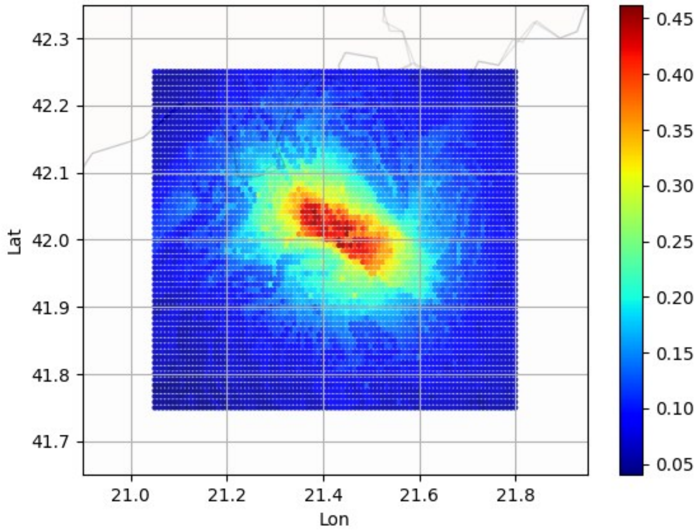

Figure 4. The average ground motion field for IM=PGA.

3.2. Exposure modelling of the school building stock

When conducting a seismic risk analysis, either in general or using the OpenQuake engine, the risk calculator requires an exposure model that includes: a metadata section containing general information about the exposed assets, a taxonomy section, and a cost conversion [27]. The general information on school buildings for the Skopje region is gathered from two sources:

- *Ministry of Education and Science (MES) of RNM* [28] – Provision of administrative information, such as the total number of school facilities, their full names and addresses, level (primary/secondary), status (central/regional), number of pupils, and number of employees at the beginning of the 2022/23 academic year. This information was available upon request.
- *Agency for Real Estate Cadastre (KAT) of RNM* [29] – Provision of the number of stories and net areas for all school buildings located in urban areas, as well as for some located in rural areas. This information is publicly available in.

3.2.1. School building taxonomies

Regarding the taxonomy, to ensure a unified characterization of the considered buildings, they are classified according to the GEM Building Taxonomy v3.2 [30]. It is important to mention the lack of data sources for most school buildings in the country in general, and for the Skopje region in specific. There are no official databases that provide accessible technical information and collecting these data through field and visual inspection on a building-by-building basis is a significant challenge, especially when there is no adequate funding. Therefore, the only available source of technical information is previous research studies and projects focused on school buildings. These available research studies and projects, along with the classification of the school buildings covered in them according to the GEM Building Taxonomy, are presented in [31]. For only Skopje region, the following sources are used for the classification of school buildings:

- The 2001 project of the IZIIS, supported by UNICEF Macedonia: *Physical and psychological management of earthquake related emergency situations in schools in the Republic of Macedonia* [32] [33].

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- *Individual seismic risk assessment of school buildings* at the request of the municipalities or the school administration for one of the following reasons: the school board noticed significant damage in the structural parts of the schools and wanted to ensure that the damage was not structural, or the school board decided to make structural changes to the building (such as floor or story expansion, rearrangement of floor areas, improvement of roof structures, etc.). These individual assessments are all conducted by IZIIS.

These sources provide technical information for only *65* out of 193 school buildings, accounting for approximately *34%* of the total. Some of the attributes that are available for these school buildings include: the lateral load resisting system (LLRS), material type and construction technology; number of stories above ground and below ground, and the height of the ground floor level above grade; year of construction or retrofit; shape of the building plan; structural irregularities in plan and elevation; material of the external walls; roof shape, covering, and system; floor system material and type; and foundation system.

According to [34], the most relevant attributes for seismic risk are considered to be the LLRS and material, date of construction, height and wall material. Less important attributes include roof shape and material, ground floor hydrodynamics and plan orientation, and foundation type. Attributes considered irrelevant in seismic risk assessment include wall openings, presence of basement, and ground floor level.

Initially, in this research, school buildings are classified by systematizing all available attributes, including both the most relevant to seismic risk and some less significant ones. As a result of considering a substantial number of attributes, more than fifty unique building classes were identified. A representation of the identified typologies for the most important attributes is provided in Figure 5.

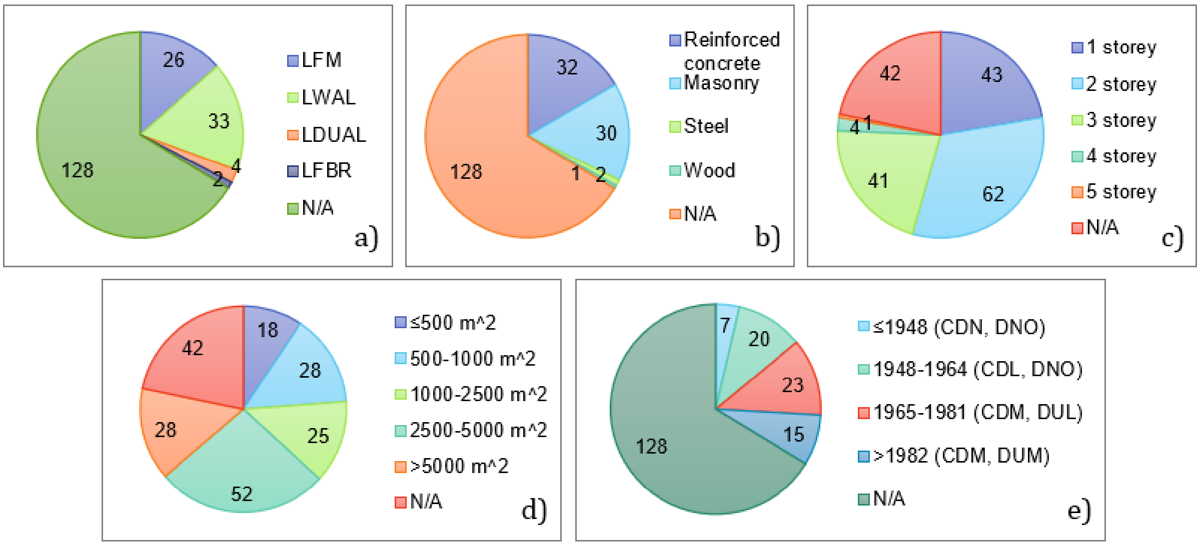

Figure 5. Pie charts representing the identified typologies for each main attribute: a) LLRS; b) Material type; c) Number of stories above ground; d) Area; and e) Date of construction. *Note: Abberivations are as per* [30].

The date of construction attribute is linked to the code and ductility level of the structure. A state-of-the-art concept regarding the genealogy of codification in the territory of RNM is presented in [35]. However, this concept differs from the one proposed in [36], which is considered in [37, 38] for exposure modelling of buildings in the territory of RNM in the European Seismic Risk Model (ESRM20) [39]. The difference lies in the classification of buildings constructed after 1981: they are categorized as *high code* (CDH) by the first source, and as *moderate code* (CDM) by the latter.

Nevertheless, considering that the vulnerability and fragility functions for school buildings utilized here are derived from the ESRM20, the categorization based on [36] is adopted for the code levels of the

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buildings, whereas the categorization for ductility level is taken from [35]. These categorizations are given in Figure 5/e.

Since the exposure model here includes all school buildings in the Skopje region, it is noted that *67%* of the buildings lack information about their structural typology because they have not been studied in previous research. Among these, *86* buildings (roughly *45%* of the total) have only general information available, such as location, area, number of stories, and the number of pupils and staff, as provided by MON and KAT. Additionally, there are *42* buildings (roughly *21%* of the total) for which only partial general information is available, such as location and the number of pupils and staff (MES).

The overall dataset of school buildings is composed of three types of datasets with varying levels of epistemic uncertainty. To address this shortcoming – and considering that not all of the fifty unique building classes in the first group are numerically significant, as some differ only in attributes irrelevant to seismic risk – a taxonomy mapping scheme is utilized.

The step-by-step process of exposure modelling is presented in Figure 6 through a workflow diagram. Data that is automatically read from the resources are shown in green, while actions taken to classify the buildings are marked in blue. Mathematical calculations made during the process are marked in yellow.

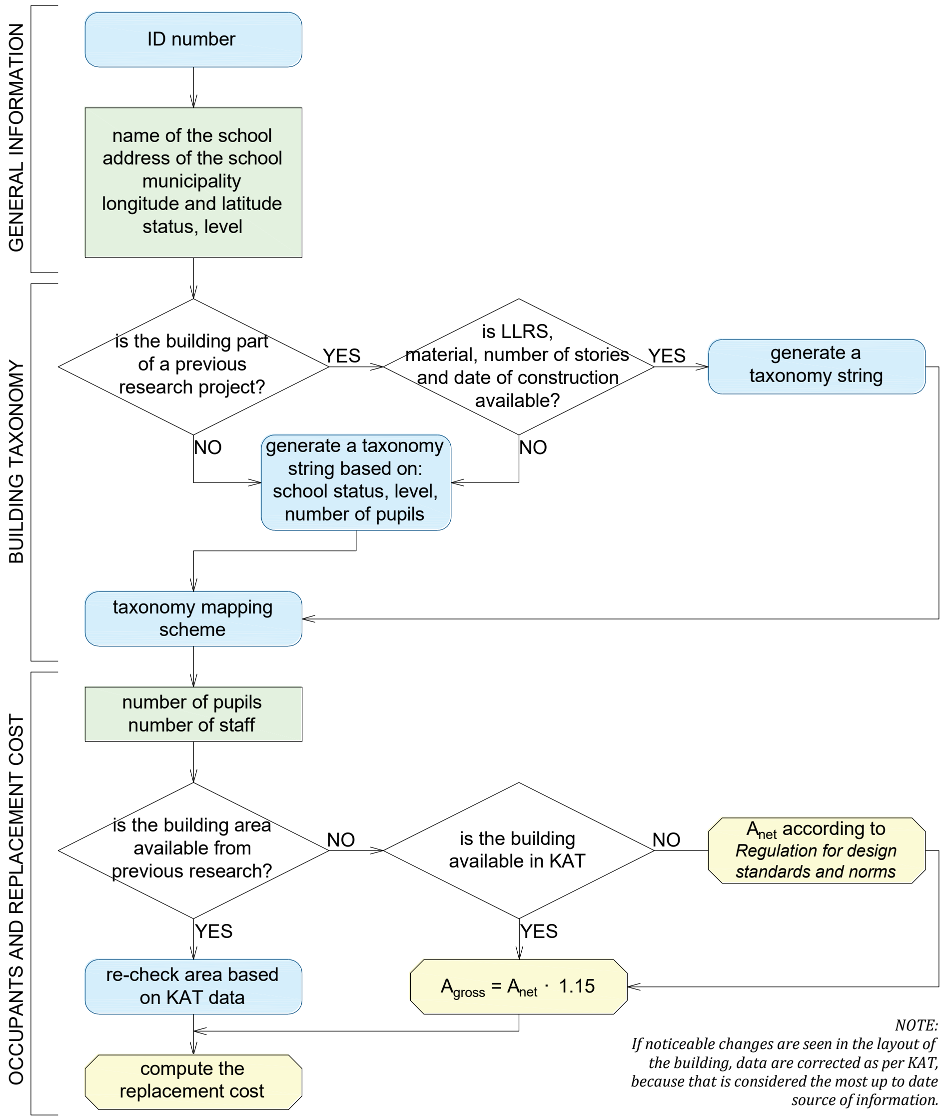

Figure 6. Workflow for exposure modelling of school buildings.

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For buildings with partial taxonomy strings (45%) or those entirely lacking them (21%), assumptions regarding the unavailable data are primarily based on the school status and level, and number of pupils. These assumptions are based on the statistical analysis from the classification of school buildings from previous research and individual assessments and engineering judgement, enabling the assignment of appropriate taxonomy strings. For buildings with already defined strings, the mapping scheme is used only as a connector with a suitable vulnerability/fragility function.

One of the most important types of information that is missing for most structures is the year of construction or retrofit. This will remain an epistemic uncertainty that can be mitigated by conducting more detailed inspections.

3.2.2. Replacement cost

The replacement cost in this research is defined *per asset* and per *unit area*. The area of each school building is determined either through a previous research project, obtained from KAT, or assumed based on the *Regulation for Design Standards and Norms* published in the Official Gazette of RM (no. 60/12, 29/15, 32/16, 114/16) and the Official Gazette of RNM (no. 211/20), as shown in Figure 6.

The structural replacement cost of school buildings is assumed to be 50,220.00MKD/m^2 equivalent to 800€/m^2. This value is taken as a reference value for construction of school buildings, given in the official *Price list for engineering services for building construction*, published in the Official Gazette of RNM (no. 259/22, 2022). The overall area of the school buildings for the Skopje region amounts to *544,225m²*, whereas the total replacement cost is *€435,380,000.*

Although it is well understood that buildings constructed with different materials and technologies, as well as those in different areas, should have varying unit prices per area, this study considers only the most conservative scenario for the sake of simplicity.

3.3. Fragility and vulnerability models

The fragility and vulnerability models considered in this research are those developed for the European Seismic Risk Model (ESRM20) [39]. Notably, these models also serve as the basis for the fragility and vulnerability of Europe employed in the Global Seismic Risk Model [40].

For the fragility models, four damage states are defined: DS1 (slight), DS2 (moderate), DS3 (extensive) and DS4 (complete), where their thresholds are illustrated in Figure 7.

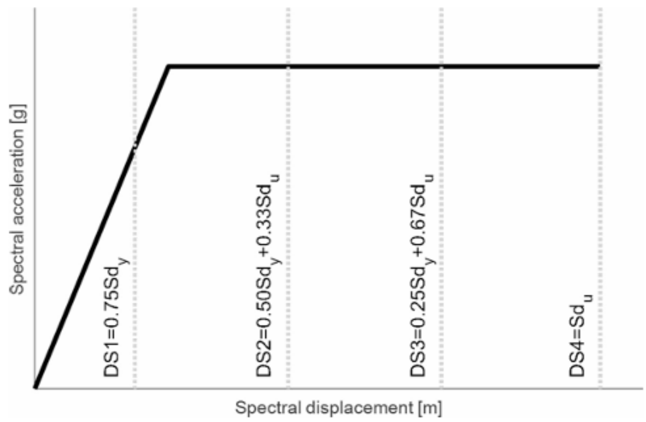

Figure 7. Damage thresholds according to [41].

Using damage-loss models, the fragility functions are converted into vulnerability models. For losses due to damage, the following damage ratios, representing the ratio of repair cost to replacement cost, are adopted: 0.05 for slight damage, 0.15 for moderate damage, 0.6 for extensive damage, and 1.0 for complete damage [39].

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4. Risk analysis of school buildings in Skopje region

Considering the input provided in the previous subsections, scenario damages and losses were computed using the OpenQuake engine for the exposed school buildings of Skopje region.

4.1. Scenario damage

The damage of school buildings was assessed using the *Scenario Damage Calculator* from the OpenQuake engine. The output of this analysis provides the probability (expressed as a fraction) of each building reaching a specific damage state per ground motion field. The mean damage distributions for all the assets, along with the corresponding standard deviations, are presented in Figure 8.

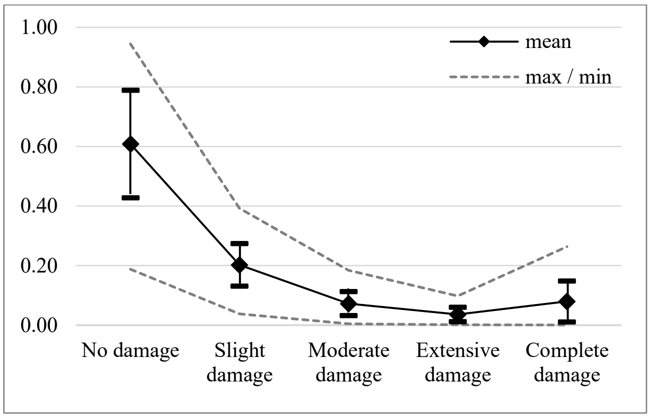

Figure 8. Mean and standard deviation of damage distribution statistics for the current conditions.

From this figure, we can observe that the majority of buildings show *no damage* due to the imposed earthquake. The probability of any asset reaching one of the other damage states is generally less than 20%.

Referring to the observed damage during the 1963 Skopje earthquake, as referenced earlier from [19], 8 primary and 11 secondary school buildings were destroyed, and 22 primary and 13 secondary school buildings were severely damaged. There were also other school buildings that sustained moderate or slight damage state. However, this situation is not reflected in the graph if a similar earthquake were to strike today. The reason for this discrepancy is that the exposure model is primarily based on data from the year 2001, which is 38 years after the earthquake occurred. During these years, school buildings were not only repaired and retrofitted, but two new seismic design building codes were also introduced (JUS39/64 and later JUS31/81). The 1963 Skopje earthquake significantly increased awareness among both the public and governmental authorities, and this is reflected in the results presented in this study.

The damage statistics indicate that the most vulnerable buildings are those located near the earthquake epicenter. This is expected, as Figure 4 shows higher PGA values in that region. Regarding the building taxonomies, the highest probabilities of complete damage (0.20-0.26) are observed in schools primarily belonging to RC and masonry structures with 2 or 3 stories.

4.1.1. Scenario losses

The losses of school buildings were assessed using the *Scenario Loss Calculator* from the OpenQuake engine. In this study, only structural losses were observed, and results are presented in the form of loss maps and statistics.

The mean structural loss of school buildings in the Skopje region is estimated at *€76,054,600*. This represents approximately *17%* of the total area of the schools. While this percentage may not seem very high, it is still significant. The losses are concentrated in only some of the school buildings, as most of the school buildings, as previously noted, do not exceed the no damage and slight damage state.

The aggregated mean losses at the municipality and settlement levels are presented in Figure 9.

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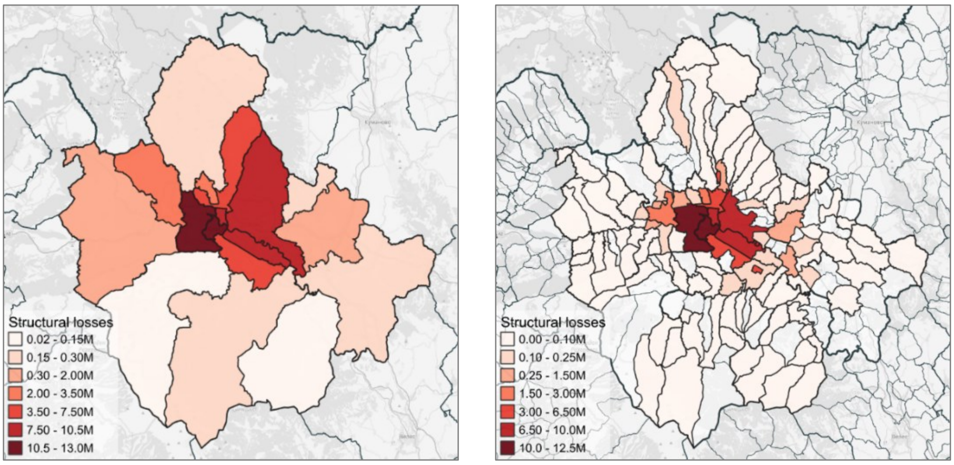

Figure 9. Aggregated structural losses (€) at municipality level (left) and settlement level (right).

The largest structural losses are observed in the municipalities of Karpos and Centar, followed by Cair, Gazi Baba, and Aerodrom. These municipalities are located closer to the epicentre of the earthquake event, and a similar trend was noted during the damage assessment. Located in these municipalities, structural losses exceeding €1 million are observed in 27 school buildings, both RC and masonry structures, primarily with three stories. These buildings typically accommodate more than 200 pupils and have areas exceeding 3500m².

5. Conclusions

This research addressed the scenario-based seismic risk assessment of school buildings in the Skopje region, focusing on the 1963 Skopje earthquake. The total area of school buildings in the amounts to 544,225m², with a total replacement cost of €435,380,000. The study outcomes include damage and loss statistics for individual schools, as well as aggregated data at the municipality level.

The majority of buildings exhibit *no damage* or only *slight damage* due to the imposed hazard. The probability of reaching moderate to severe damage states remained below 20% for most buildings, with a 20-26% probability of complete damage observed in only 12 buildings near the earthquake's epicentre. These were predominantly RC and masonry structures with two or three stories.

The total expected structural loss amounts to approximately 17% of the total school area, equivalent to an estimated €76,054,600.

Finally, it is important to note that significant uncertainties associated with assessing damage and losses based on a single event, as highlighted in [42]. While estimating seismic risk from a single earthquake scenario (deterministic approach) is valuable for raising public awareness and informing decision-makers, a probabilistic seismic risk assessment would be a more proper method for prioritizing risks, planning mitigation, and supporting insurance decisions.

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