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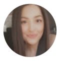

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Hierarchical policy for seismic intervention of school buildings at urban scale

Anna Karatzetzou(1,2)*, Stefania Apostolaki(1), Evi Riga(1), Kyriazis Pitilakis(1), Efthymios Lekkas(2)

(1) Aristotle University of Thessaloniki, P.O.B. 424, 54124, Thessaloniki, Greece

(2) National Kapodistrian University of Athens, Greece

*Correspondence to: Anna Karatzetzou (akaratze@civil.auth.gr, phone number: +30 2310 994209)

ORCID IDs of authors:

Anna Karatzetzou: https://orcid.org/0000-0002-4658-457X

Stefania Apostolaki: https://orcid.org/0000-0002-3377-0322

Evi Riga: https://orcid.org/0000-0001-5310-0505

Kyriazis Pitilakis: https://orcid.org/0000-0003-2265-0314

Efthymios Lekkas: https://orcid.org/ 0000-0002-9336-8490

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Abstract

Seismic risk assessment involves many uncertainties starting from the exposure model and the evaluation of site-specific seismic hazard, and ending with the actual estimation of the expected damages and losses. Seismic risk is also explicitly related to a reliable decision-making process in order to improve pre- and post-earthquake management and resilience. In the case of seismic risk assessment of a large number of critical buildings, like school buildings, at community or regional scale, it is important to establish a reliable and efficient hierarchical policy in order to allow the decision-making regarding the necessary pre- and post- seismic event retrofitting and structural strengthening actions to be undertaken, starting from the identification of the most vulnerable buildings, which need a second order seismic analysis prior to any retrofitting and strengthening action. To this regard, the aim of the present paper is to develop an adequate retrofit optimization framework based on a two-level ranking process for the quick identification of the most vulnerable school buildings, for which a more detailed vulnerability and risk assessment should follow. The herein proposed framework is an efficient and simple tool for prioritization, policy-making and scheduling of seismic prevention projects. The proposed methodology is applied to the school buildings of the municipality of Thessaloniki, Greece. The results of the application indicate that about 3.5% of the total studied school buildings may require further investigation for retrofitting and strengthening.

Keywords: ESHM13; ESRM20; earthquake; seismic risk; school buildings; prioritization

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

Availability of data and material

Not applicable

Code availability

All calculations have been undertaken with the OpenQuake Engine, an open-source software for hazard and risk assessment that is available from: https://github.com/gem/oq-engine

1 Introduction

Greece is among the countries with the highest seismic hazard worldwide. This has resulted in a quite early introduction of seismic code provisions, which started in 1939 and took a first official form in 1959 (Greek Seismic Code, 1959). Since then, the code has been upgraded several times with the last one dated in 2003. However, even today, according to the Hellenic Statistical Authority (ELSTAT) about 70% of buildings in Greece are built with low seismic code (before 1985) or without any code at all.

As in most countries around the world, upgrading and retrofitting the existing building stock to comply with modern safety requirements and recent development of seismic codes is very difficult from technical, financial and legal point of view. The situation is different for public buildings and in particular critical buildings like schools and hospitals. For these buildings, citizens and governmental authorities are very sensitive to potential losses after an earthquake and consequently quite favorable to undertake necessary measures to improve their resilience and safety. In literature, there are several studies concerning urban scale earthquake risk assessment of buildings (Milutinovic et al., 2003, Marasco et al., 2021, Lu et al., 2017). However, a comprehensive, easily applied in practice strategy for the definition of the most vulnerable school buildings in Greece and the priorities for intervention, in other way a hierarchical policy for upgrading and strengthening/retrofitting, is still missing. The work presented in this paper aims to fill this gap, proposing a practical and efficient methodology that defines priorities for seismic intervention of Greek school buildings. In particular, the objective is to develop a risk management framework for the prioritization of seismic strengthening of school buildings in Greece that are found to have inadequate resistance according to the current seismic design specifications. The decision for targeting school buildings prior to other public buildings is mainly justified by the relatively high level of losses related with schools during several recent seismic events. Just to mention few recent examples, in October 2002 in Italy, twenty-seven children and one teacher lost their lives due to the collapse of a primary school in San Giuliano during the M5.7 earthquake (Maffei and Bazzurro, 2004). In Greece, the Thessaloniki 1978 M6.5 earthquake caused extensive damages to 35 school buildings. The M7.0 earthquake of October 30th, 2020 in Samos island, caused extensive damages to 11 out of the 44 school units (Papadimitriou et al., 1999).

Additionally, in 2020 the Greek government officially expressed its intent to improve the safety of all school buildings in the country through the targeted project, which proposes the use of the two-level seismic inspection process adopted currently in Greece. The first level is a Rapid Visual Screening (RVS) procedure similar to FEMAR-154 (2015) for a first scanning and ranking of the school buildings that should be strengthened. The second level uses a form that is quite similar to the 1984 UNDP/UNIDO-RER/79/015 format (Penelis et al., 1984).

In literature, there are several prioritization methodologies for buildings like the ATC 1978 and the NZSEE 2003, which include procedures for ranking priorities. It should be noted that a direct comparison between the various methodologies, is not an easy task as each methodology is certainly associated with important uncertainties, limitations, specific assumptions, different input data etc. Grant et al. (2007) studied school buildings in Italy and proposed a multiple-level framework for the identification of the most vulnerable school buildings based on steps of increasing detail and reducing the size of the building inventory. Okada et al. (2000) and Kabeyazakawa et al. (2000) proposed multi-level procedures for the seismic vulnerability assessment of school buildings in Japan. All existing in literature methodologies adopt several indices, most of which are based on the difference between the seismic design hazard at the time of construction and the seismic demand, according to a current seismic code (NZSEE 2003, Grant et al. 2007, Crowley et al. 2008, Gattesco et al. 2011). According to Petruzzelli and Iervolino, 2021, such indices account for both vulnerability and hazard.

Like other procedures in literature (Di Pasquale et al., 2001, Goretti and Di Pasquale, 2004 and Grant et al., 2007), the herein proposed procedure includes a first phase for screening the building population in order to select a percentage of them, which is likely to need further investigation. This first phase is based on an approximate seismic hazard evaluation of the buildings, comparing the design with the demand seismic hazard for each building. The second phase is a more refined analysis, which involves a more detailed vulnerability assessment, prioritizing the school buildings that need strengthening. The main differences with other existing methodologies in literature are: (i) the expression of the seismic hazard in terms of Peak Ground Accelerations (PGA) and not in terms of spectral values, because the use of spectral values presupposes the knowledge of the fundamental period of the studied school building. Of course, many authors (Verderame et al., 2009, Asteris et al., 2017, Marasco and Cimellaro, 2021, Crowley and Pinho, 2006) have recently proposed accurate mathematical formulations to estimate the fundamental period of buildings based on certain characteristics (e.g., number of storeys, type of construction). Nevertheless, in this study the authors decided to express the hazard in such a way that it does not depend on the characteristics of the structure and therefore in a way that it can be determined directly even on large scale applications. (ii) The use of the European Seismic Hazard (ESHM13) and Risk (ESRM20) models (Woessner et al., 2015, Crowley et al., 2021), to define the seismic demand and the fragility of the studied schools, respectively. The proposed ranking and hierarchical policy is based on ordinary large scale and rather simple risk-assessment methods that do not necessarily require inspection or building-specific vulnerability studies covering the whole school building stock in a municipality or a city.

2 Seismic design codes in Greece

Considering that the proposed methodology makes use of the seismic capacity and demand of school buildings that have been designed and constructed in the last 70 years, it is necessary to shortly present the evolution of the seismic design codes in Greece in order to understand the changes and how these changes affect the classification of the school building stock. The first guidelines for earthquake - resistant design in Greece, though not in the form of a code, were published in 1939 in the journal "Technical Chronicles", no 184, 1939. These guidelines included a seismic zonation map, which was later reformed and included in Roussopoulos (1949, 1956). The 1956 version of the map divides the Greek territory into 5 seismic zones. Different seismic coefficients (pseudo-static approach) are provided for each zone for three types of soil conditions (soft, medium and hard soil), ranging between 0.01g and 0.16g. This zonation formed the basis for the first seismic code in Greece, which was published in 1959, including three seismic zones and three soil categories, with seismic coefficients (design seismic ground accelerations) ranging from 0.04g to 0.16g. The 1984 revision of the seismic code did not affect the seismic zonation. The next seismic code, NEAK, which was regulated in 1992 and implemented in 1994, includes four seismic zones with peak ground acceleration (PGA) ranging between 0.12g and 0.36g, regardless of the soil type. This seismic zonation map was slightly modified in 1995 to upgrade some cities to a higher seismic zone. The same zonation was adopted by the 2000 version of the code (EAK, 2000). Finally, in the 2003 version of EAK, the zone of 0.12g was removed and three seismic zones remained with PGA between 0.16g and 0.36g, again regardless soil conditions. The 2003 zonation of EAK is also being used as seismic map for rock-site conditions in the Greek National Annex of Eurocode 8 (CEN, 2004). At this point, we should stress that the current EC8 seismic code adopts a soil factor S, which amplifies seismic ground motion for sites other than rock, while the Greek codes NEAK and EAK assumed that all sites located within the same zone have the same PGA for seismic design regardless of soil type.

Modern codes classify buildings in importance classes. Each importance class is associated with an importance factor, which multiplies the design peak ground acceleration. The concept of the importance of the structures was introduced in Greek seismic codes in 1984, with an importance factor equal to 1.5 for school buildings, which was changed to 1.15 in EAK 2000.

Finally, up to 1994 the seismic design was based on maximum allowable stresses, and after 1995, on ultimate strength. For the transfer from the permissible stresses design methods that existed before 1994 to the permissible force methods that were applied in Greece after 1995, a factor of 1.75 is proposed by the current intervention regulations in Greece (KAN.EPE., 2013).

This short description of the historical evolution of the seismic design codes in Greece allows us to classify the school buildings in four categories, depending on the year of their construction, as follows:

1. <1959 "No code" : Buildings built prior to 1959 with no seismic code regulations
2. 1959 – 1984 "Low code": Buildings designed with the seismic regulations of 1959
3. 1985 – 1994 "Moderate code": Buildings designed with the seismic regulations of 1984
4. ≥1995 "High code": Buildings designed with the seismic regulations of 1995, 2000 and 2003

This classification will be used throughout the present prioritization scheme described in detail in the following Section 3.

3 Methodology

The proposed hierarchical policy for seismic retrofit optimization and prioritization of upgrading interventions of school buildings in Greece is developed in two stages: The first one, which is making a first-order ranking of the school buildings based on a simplified approach, is in fact a technically efficient precursor of the second stage, where the buildings identified as more vulnerable in the first stage are further analyzed using more advanced techniques. The methodology is actually proposing the way that the ranking should be accomplished.

Stage 1: Priorities for seismic rehabilitation over a large school building inventory.

The first stage of seismic risk assessment ranking concerns a large school building inventory covering a whole community. It is based on easily accessible technical information, namely the location and the age of construction for each school building. Therefore, at this stage, we maintain the technical basis of the prioritization at a lower level, emphasizing mainly on the hazard and the seismic demand for each school building.

In the present study, and contrary to other methodologies (e.g. Crowley et al., 2008), we have chosen the seismic hazard to be expressed in terms of Peak Ground Acceleration (PGA) and not through spectral acceleration and/or displacement values, because the use of spectral values presupposes the knowledge of the fundamental period of the studied school building. Petruzzelli and Iervolino (2021) also propose the use of the PGA values, when the fundamental period of the building is not available (or if the structure has a particularly low period of oscillation). In addition, in the Greek design codes prior to 1995 response spectra are not available.

The output of Stage 1 is a ranking of the school buildings in decreasing order of potential risk. The comparison at this stage is made between the demand given by the current standards with the acceleration used considering the standards in use at the time of the construction of the school building. Then, using few simple criteria like the available budget for strengthening interventions in a given period of time, we define the buildings that have the first priority in retrofitting, in other words the more vulnerable ones. The whole process at this stage does not require technical on-site inspection neither specific engineering studies of the various buildings under consideration. The only parameters needed are the knowledge of the year of construction, the geographical location and if possible, the available budget for the retrofitting in a certain time period.

The procedure that is followed at Stage 1 has as follows:

1. **School mapping**: All school buildings are mapped in a Geographic Information System (GIS) with their coordinates (x,y).

2. **Taxonomy I (age)**: Categorization of the school building stock in four categories, depending on the year of their construction (<1959 "No code", 1959 – 1984 "Low code", 1985 – 1994 "Moderate code", ≥1995 "High code").

3. **Mapping of PGA_{DS}**: Evaluation and mapping in GIS of the design Peak Ground Accelerations (PGA_{DS}), which are depicted from the age of construction and the code level at that time. At this phase, we also consider increase of PGA_{DS} due to the importance of the structure. More specifically, for the school buildings that were built between 1984 and 1999, we adopt an importance factor equal to 1.5, whereas for those that were built after 1999, we consider an importance factor equal to 1.15. It is reminded that seismic codes before 1984 did not take into account the importance of the buildings in seismic design and risk assessment. In addition, for pre-1995 constructions, a factor of 1.75 is applied, i.e. the PGA_{DS} values are multiplied by 1.75. This factor is proposed by the current intervention regulations in Greece (KAN.EPE., 2013), for the transfer from the permissible stresses design methods that existed before 1995 to the permissible force methods that were applied in Greece after 1995.

4. **Mapping of PGA_{DM}**: Probabilistic seismic hazard analysis for the region where school buildings are located using OpenQuake engine (Pagani et al., 2014; Silva et al., 2014) in order to evaluate and map in GIS the demand Peak Ground Acceleration, PGA_{DM} for different return periods.

5. **Evaluation of $\mathbf{RF_1}$**: Calculation for each school building of the first ranking risk coefficient, $\mathbf{RF_1}$, evaluated as the ratio between demand PGA (PGA_{DM}) from the hazard map for selected return period and the effective design PGA (PGA_{DS}) from the seismic code applied in each case.

$$RF_1 = PGA_{DM} / PGA_{DS} \tag{1}$$

$\mathbf{RF_1}$ is therefore a measure of the PGA deficit between the demand PGA and the design PGA. If $\mathbf{RF_1}$ is greater than unity, the seismic demand of the considered existing building is larger than the one considered at the time of construction, and thus the structure is potentially vulnerable to earthquakes. The ranking of schools based on $\mathbf{RF_1}$ is a rapid screening of the whole school building exposure in large scale determining the relative seismic risk of the building stock, based only on the design PGA at the time of construction and the presently required demand PGA based on the updated hazard analysis and the selection of the mean return period for the seismic risk assessment. This first ranking does not need the knowledge of specific features of individual buildings, making a broad assumption of uniform code compliance. This first order risk rating provides an indication of the risk level of all school buildings in a certain municipality or region compared to current seismic regulations. Therefore, the output of this first stage screening may result in a number of schools, say *k*, that should be further assessed in the second assessment stage, which is described in the next paragraph. In this second stage, only schools with $\mathbf{RF_1} > 1$ will be selected.

Stage 2: Priorities for seismic rehabilitation over a smaller school building inventory resulting from Stage 1.

At this second stage, the selected *k* school buildings from the previous step are examined in more detail in order to determine the priorities for seismic rehabilitation. The necessary input data are now more detailed, but still in a limited number, including construction material properties, lateral loading resisting system and the height of the buildings. As previously, this process does not require on-site inspection and specific studies of the buildings. The data can be retrieved through open access web mapping platforms, such as Google Maps and OpenStreetMap, complemented with a good engineering judgement. This approach is effective in reducing the inventory down to a manageable size. The selected buildings are classified according to their main attributes necessary for the determination of their seismic vulnerability. Besides the previously mentioned ones an extra parameter is the ductility level. The herein adopted taxonomy (**Taxonomy II**) follows the international building taxonomy scheme proposed in GEM (Brzev et al., 2013) (Table 1). The values of each attribute are provided in Table 1. Level 1 is a level of detailing whereas Level 2 provides additional details to describe an attribute.

Next, a damage analysis is performed using again OpenQuake software for the seismic demand assessed in the first stage (i.e. PGA_{DM} values).

In that way we calculate the distribution of damage and the second ranking risk coefficient **RF_2** (Equation 2), which is the sum of the probabilities of exceedance at “extensive damage” and “complete damage” damage states (**Evaluation of RF_2**).

$$RF_2 = P(DS_{extensive} + DS_{complete}) \tag{2}$$

The **RF_2** risk coefficient is used to prioritize the *k* school buildings for seismic intervention by sorting the buildings with descending values of RF_2.

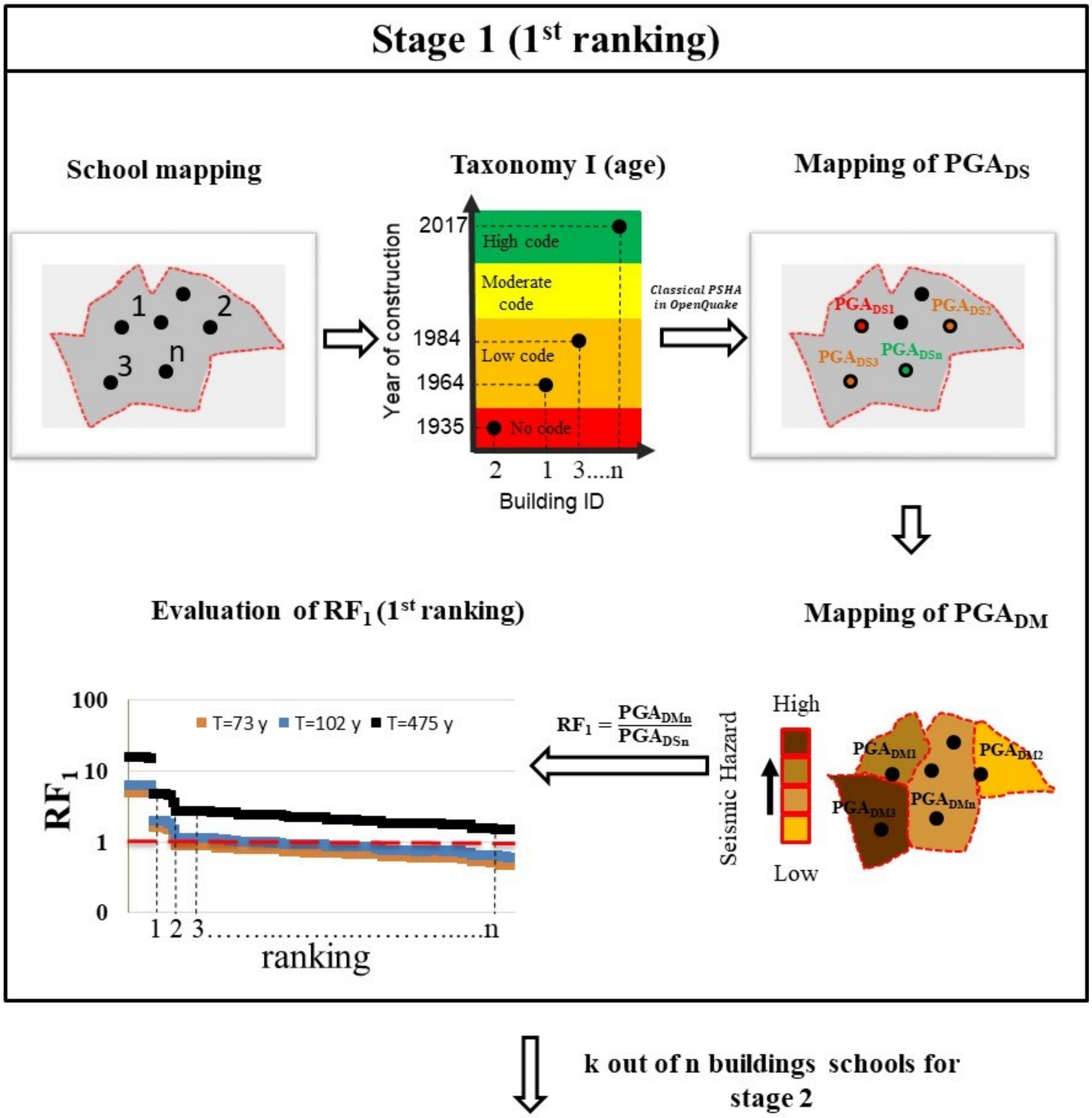
RF_2 alone cannot define the most vulnerable school buildings that require retrofitting and strengthening. It is necessary to define one or more thresholds that may allow the identification of those cases in which structural retrofitting is first and second priority. The definition of the thresholds depends, besides the computed **RF_2** values, on several other parameters of technical and socioeconomic character, like the available time and budget, availability of backup school facilities etc. The synthesis of all these parameters will finally define the percentage of school buildings to be retrofitted first and, most importantly, which these schools are. In the present application, we assume that the school buildings having at least 10% probability of exceedance of excessive and complete damages, or in other words buildings with **RF_2** greater than 10%, belong to the first priority for retrofitting. This threshold may be considered as the threshold that defines the number of school buildings for which the community disposes the necessary resources to proceed to retrofitting and strengthening measures in a given period of time. Needless to say that a decision of this kind also depends on the total number of school buildings in the community area and the available experience from past earthquakes and damages. In our case the selected threshold of 10% is also based on previous seismic risk assessment studies for the building stock of Thessaloniki city (Riga et al., 2021) and observation of recorded damages during the M6.5 1978 earthquake that hit the city. In general, this threshold can be modified on a case-by-case basis, depending on the location of the schools, their number and structural characteristics and of course on the available resources for seismic interventions.

The interesting thing in the proposed ranking and hierarchical policy is that it is based on ordinary large scale and rather simple risk-assessment methods that do not necessarily require inspection and building-specific vulnerability studies covering the whole school building stock in a municipality or a city. The first ranking requires knowledge of the construction year and geographical location alone, while the second ranking makes use of some extra building data, which are also easily available. Of course, the user should be capable of using some software tools like OpenQuake (Pagani et al., 2014; Silva et al., 2014).

Figure 1 describes the proposed hierarchical policy for the optimization of seismic interventions of school buildings.

Table 1. GEM Building Taxonomy (Brzev et al., 2013) used to classify the school buildings.

ATTRIBUTE	**ELEMENT CODE**	**LEVEL 1 VALUE**	**ELEMENT CODE**	**LEVEL 2 VALUE**
MATERIAL	CR	Concrete, reinforced	PC	Precast concrete
	MUR	Masonry, unreinforced	CL99	Fired clay unit, unknown type
	MR	Masonry, reinforced	ST99	Stone, unknown technology
	MCF	Masonry, confined	ADO	Adobe blocks
	MATO	Material, other	CB	Concrete blocks, unknown type
	W	Wood	STDRE	Dressed stone
	S	Steel		
LATERAL LOAD-RESISTING SYSTEM (LLRS)	LWAL	Wall	DNO (CDN)	Non-ductile (Period of construction: before 1959)
	LDUAL	Dual frame-wall	DUL (CDL)	Ductile, low (Period of construction: 1960-1985)
	LFM	Moment frame	DUM (CDM)	Ductile, medium (Period of construction: 1986-1995)
	LFINF	Infilled frame	DUH (CDH)	Ductile, high (Period of construction: 1996-present)
HEIGHT	H	Number of storeys above ground	HBET	Range of number of storeys above ground
			HEX	Exact number of storeys above ground
	SOS	Soft Storey Buildings		


Stage 1 (1st ranking)
School mapping
1
2
3
n
Taxonomy I (age)
Year of construction
2017
1984
1964
1935
High code
Moderate code
Low code
No code
2
1
3....n
Building ID
Classical PSHA in OpenQuake
Mapping of PGA_DS
PGA_DS1
PGA_DS2
PGA_DS3
PGA_DSn
Mapping of PGA_DM
High
Low
Seismic Hazard
PGA_DM1
PGA_DM2
PGA_DM3
PGA_DMn
RF_1 = PGA_DMn / PGA_DSn
Evaluation of RF_1 (1st ranking)
100
10
1
0
RF_1
T=73 y
T=102 y
T=475 y
1 2 3..............................n
ranking
k out of n buildings schools for stage 2

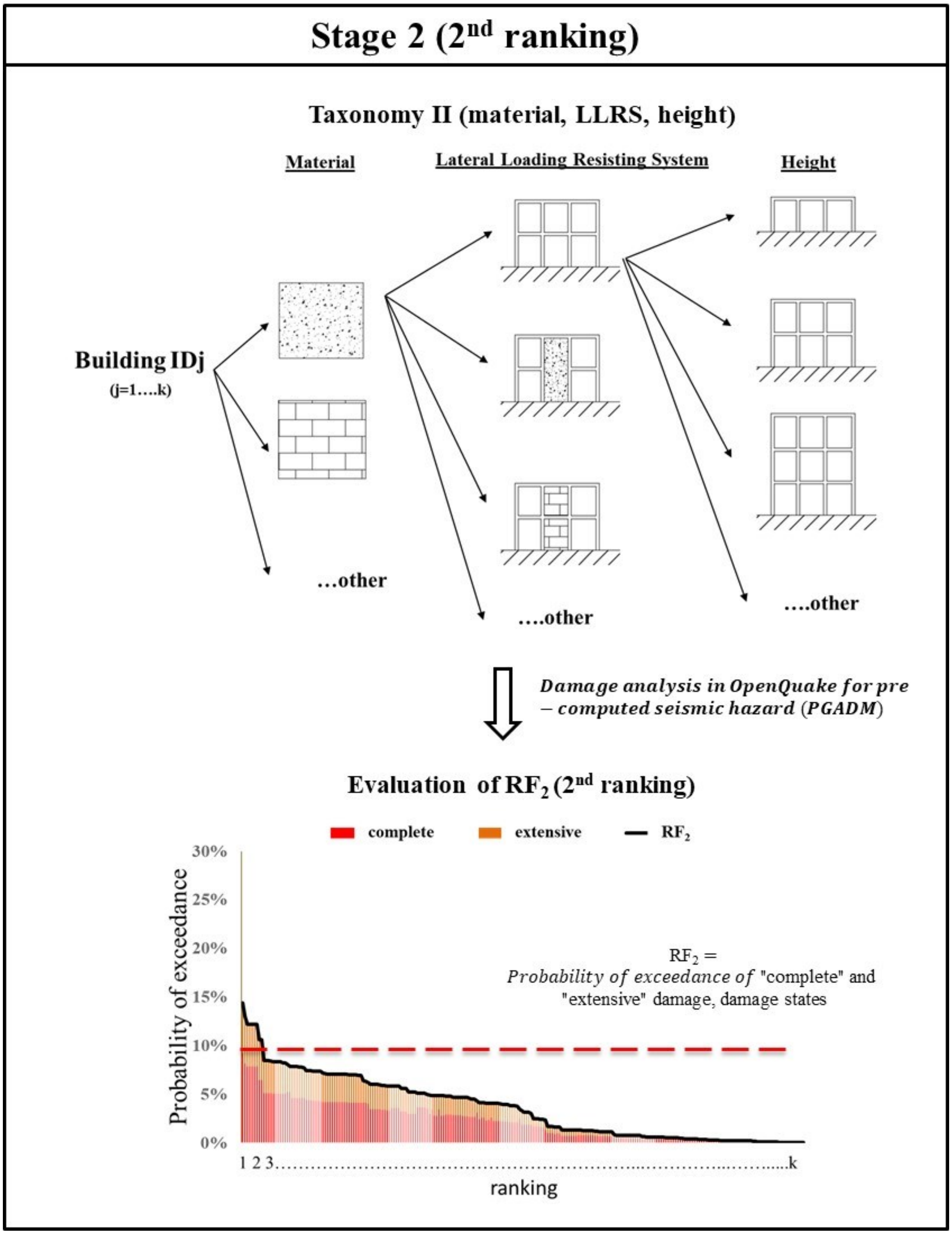


Figure 1 Description of the hierarchical policy of seismic interventions of school buildings

4 Application to the school buildings of Thessaloniki

The proposed methodology is applied to the school buildings of Thessaloniki city, Greece, which is the second-largest city in Greece. Thessaloniki has a long history of destructive earthquakes. The most recent major earthquake in Thessaloniki happened in June 1978 with a magnitude of $M_w=6.5$. The earthquake caused extensive damages to 35 school buildings.

4.1 Stage 1: Evaluation of Risk Factor RF_1 (1st ranking)

School mapping

The first step is the definition of the study area with the school buildings on a GIS map as shown in Figure 2, creating in this way a database of the studied school buildings and their locations. Figure 2 shows one point for each one of the 101 school building aggregates, comprising in total 239 individual school buildings.

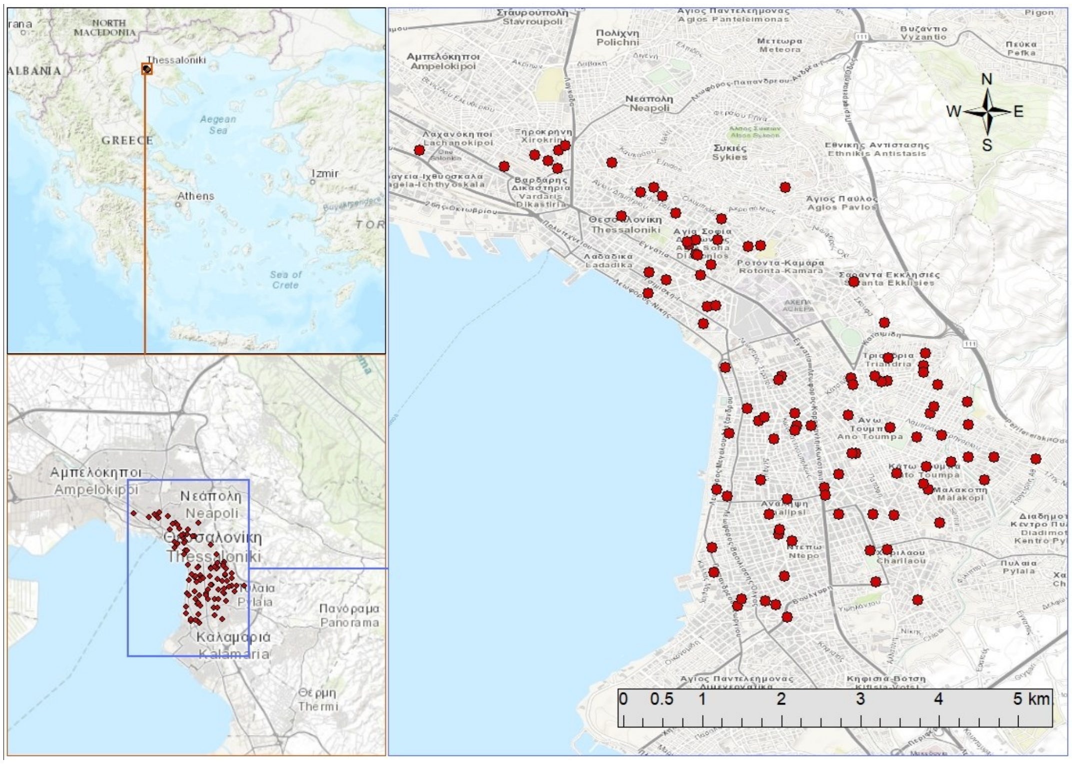


Figure 2 Location of the study area on the map of Greece and mapping of the studied school building aggregates (in red).

Taxonomy I (age)

Classification of the school buildings to four categories ("No code", "Low code", "Moderate code", "High code") according to their year of construction period (**Taxonomy I, Figure 3**). For each category, the design Peak Ground Acceleration (PGA_{DS}) is known as depicted in Table 2. For the studied school buildings, it results that about 21%, 31%, 19%, 29% of the total number of buildings, belong to the "No code", "Low code", "Moderate code" and "High code" category, respectively.

Table 2 Assumed design Peak Ground Acceleration (PGA_{DS}) for each code level class

Code level	No code	Low code	Moderate code	High code
PGA_{DS} (g)	0.01 - hard soil	0.06 - hard soil		0.16
	0.04 - medium soil	0.08 - medium soil		
	0.08 - soft soil	0.12 - soft soil		

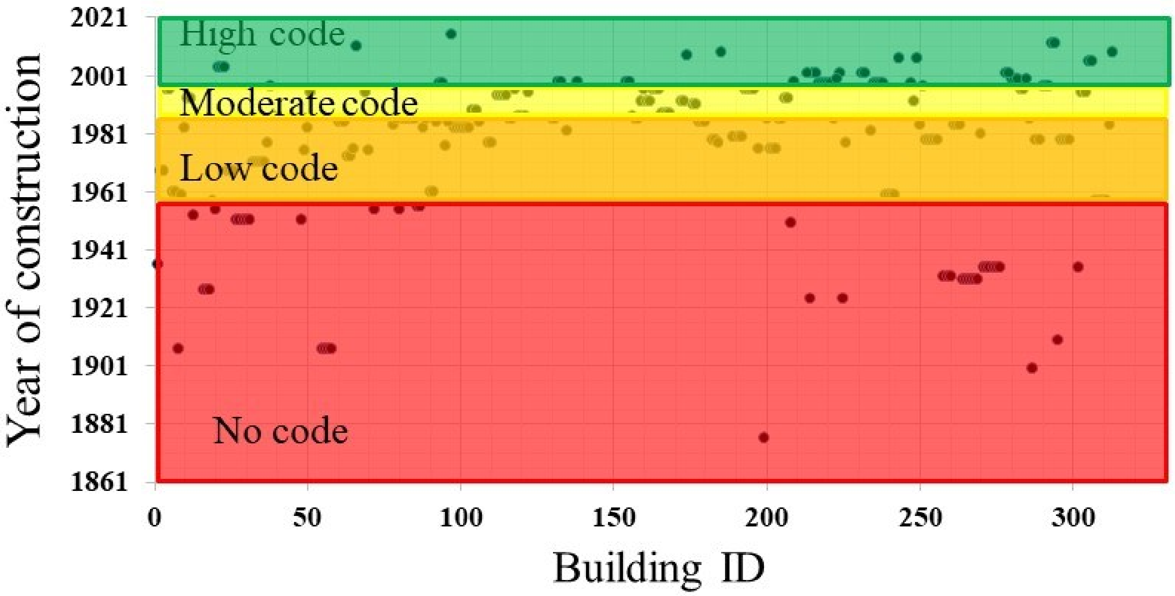


Figure 3 Classification of the school buildings to the four categories ("No code", "Low code", "Moderate code", "High code") according to their year of construction (Taxonomy I)

Mapping of PGA_{DS}

According to the age of construction of each school building and the relevant seismic building code, we define the design Peak Ground Acceleration (PGA_{DS}) as depicted through histograms in Figure 4. The number under each histogram indicates the number of buildings within the school building aggregate, while the bar chart coloring follows the PGA_{DS} values. With warm colors, we depict the lower PGA_{DS} values.

Mapping of PGA_{DM}

Next, we perform a probabilistic seismic hazard analysis (PSHA) using the European Seismic Hazard Model ESHM13 (Woessner et al., 2015) and an appropriate detailed $V_{s,30}$ model (Figure 5, Riga et al., 2021) which has been developed based on measured $V_{s,30}$ values available from the microzonation study of Thessaloniki (Anastasiadis et al., 2001). We then select an appropriate return period, in order to evaluate the demand Peak Ground Acceleration (PGA_{DM}) for all school buildings and generate the hazard map for the studied region.

In the present application, we evaluated the seismic hazard for the study area for mean return periods T equal to 73, 102 and 475 years. Figure 6 illustrates the seismic demand PGA_{DM} for the whole area for the selected return periods of 73, 102 and 475 years. Maps for other intensity measures can also be produced.

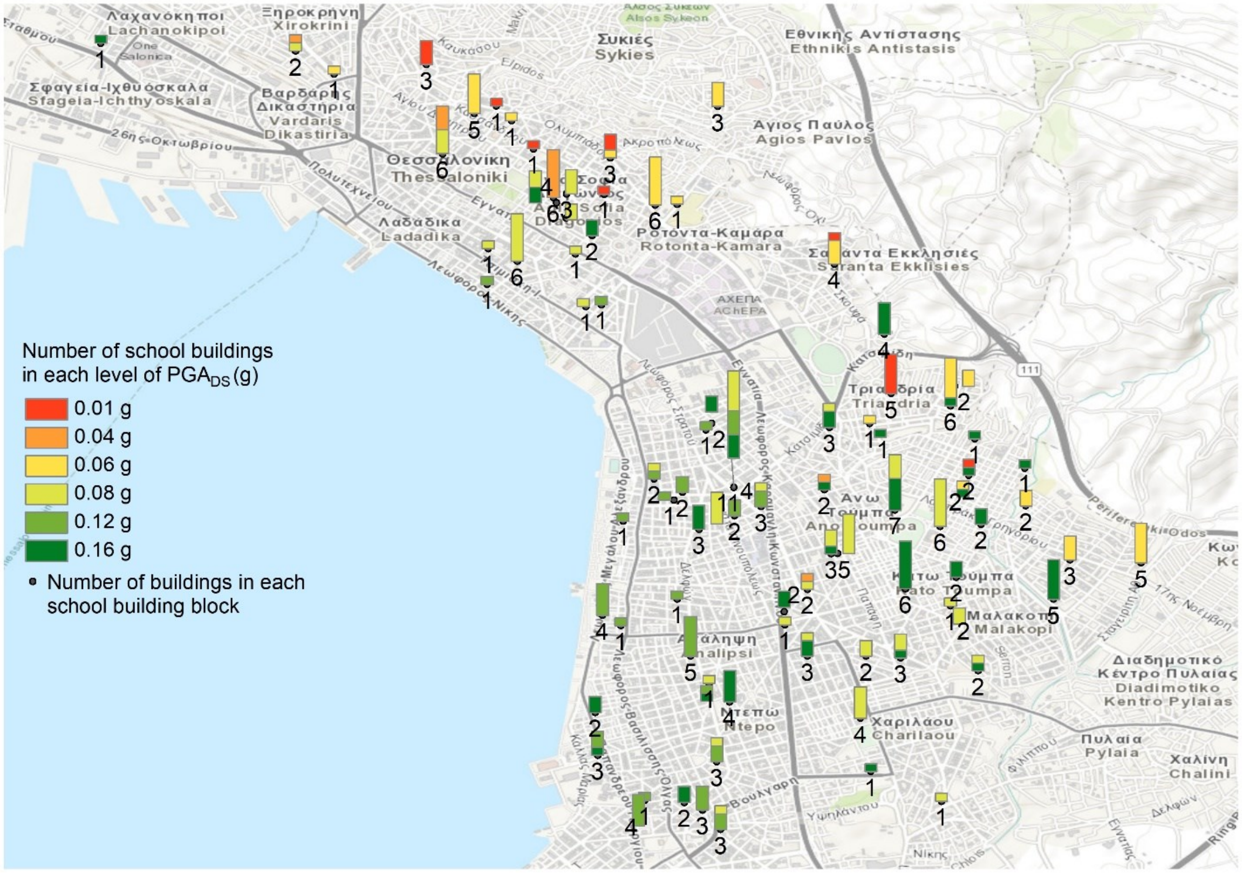


Figure 4 Design Peak Ground Acceleration (PGA_{DS}) for all studied school buildings. Each school building aggregate is depicted through a histogram. The number under each histogram indicates the total number of buildings within the school building aggregate, while the bar chart coloring follows the PGA_{DS} values for each building.

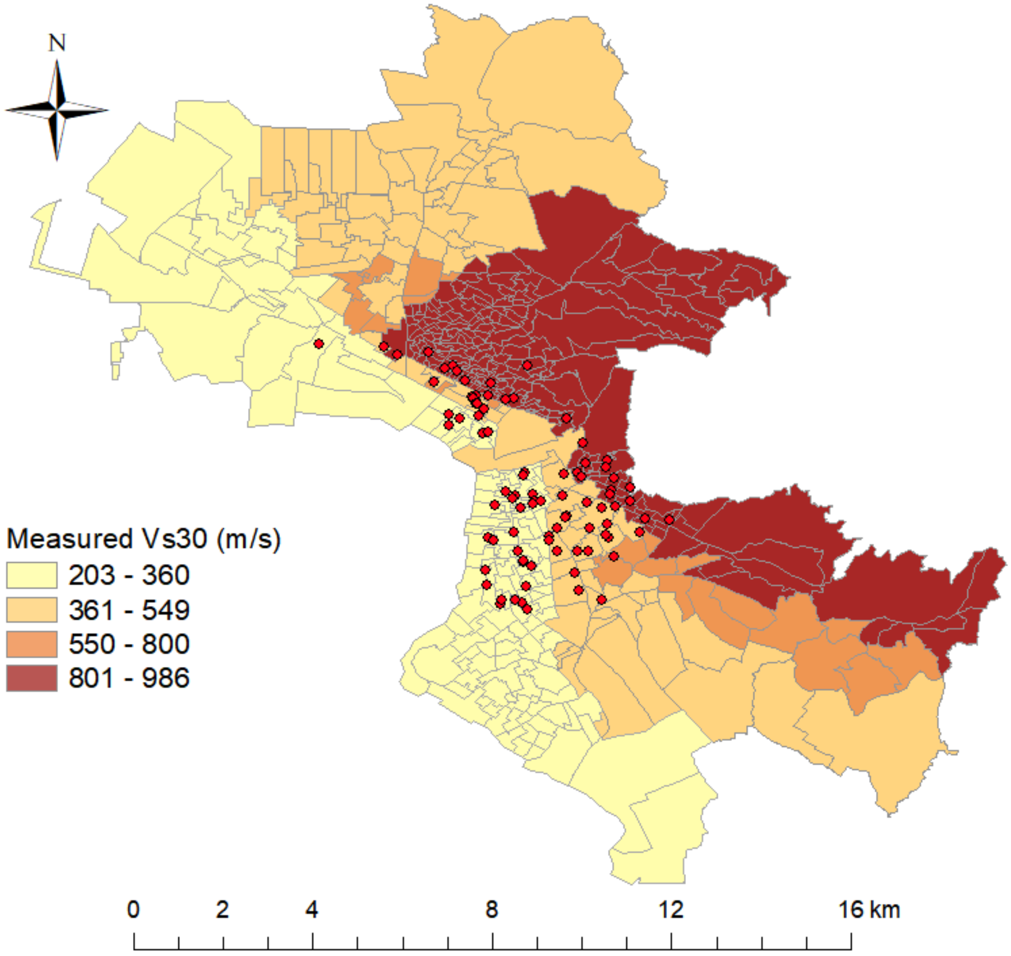


Figure 5 Local site conditions adopted in the present application. Adopted $V_{s,30}$ model for Thessaloniki, (Riga et al., 2021) based on measured $V_{s,30}$, of the studied school building aggregates (red points)

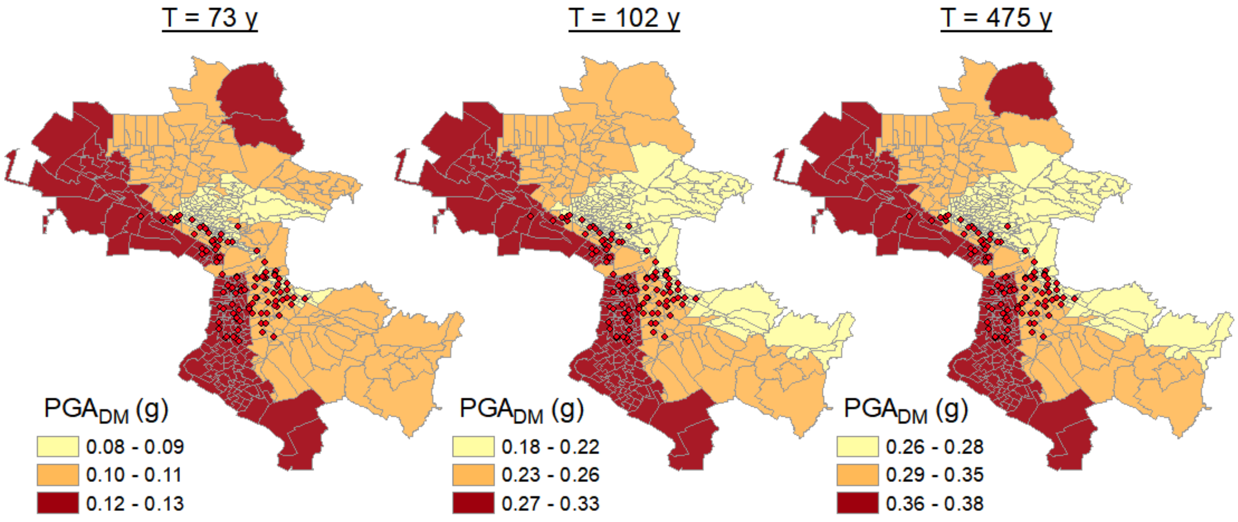


Figure 6 Spatial distribution of demand Peak Ground Accelerations PGA_{DM} in the study area for the selected mean return periods T of 73, 102 and 475 years, using the $V_{s,30}$ model. The red points are the herein studied school building aggregates of the studied area.

Evaluation of RF_1

Finally, a first order ranking is achieved by calculating the risk coefficient factor **RF_1** depicted in Figure 7. The 239 studied schools are ranked from the highest value of **RF_1** to the lowest value of **RF_1**. When **RF_1** is larger than the unity, the requirement in terms of current seismic demand (in terms of PGA values), is greater than the design Peak Ground Acceleration (PGA) at the year of the construction.

It is observed that for return periods of 73 and 102 years the majority of the school buildings (approximately 222 out of 239) have a value of **RF_1** approximately equal to or less than 1. In contrast, for the 475-year return period, **RF_1** for all school buildings is greater than 1. Obviously, the mean earthquake return period that will be chosen to assess the seismic behavior of school buildings is the most critical factor that affects **RF_1**. It is worth noting that for the 15 buildings with the highest **RF₁** value, **RF₁** is much higher than unity for all studied return periods. These buildings are old masonry buildings or reinforced concrete buildings that were built without any seismic regulation.

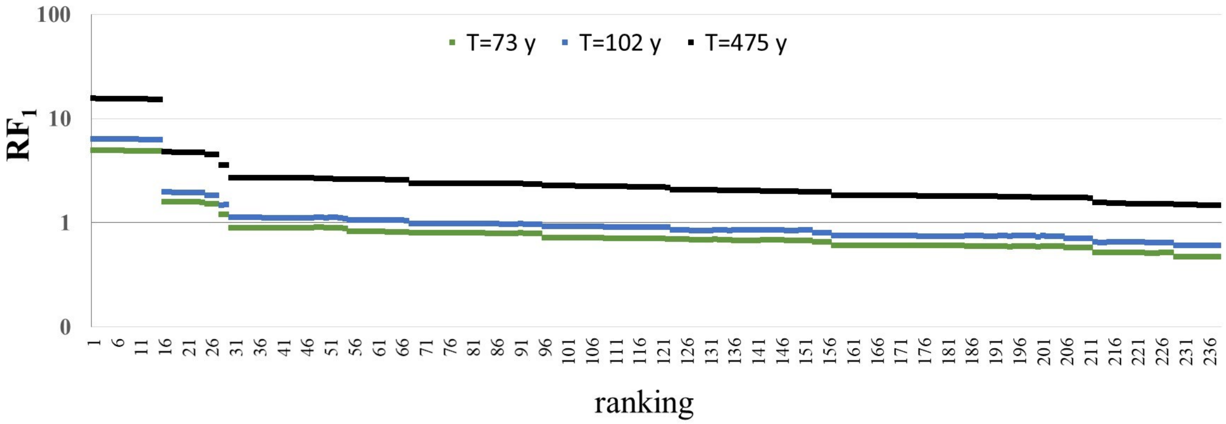


Figure 7 Risk factors RF_1 for the studied school buildings for the selected mean return periods T = 73 (green curve), T= 102 (blue curve) and T= 475 (black curve) years. In the x-x axis, the 239 studied schools are ranked in decreasing order of RF_1

4.2 Stage 2: Evaluation Risk Factor RF_2 (2nd rating)

Taxonomy II

In order to proceed to the second and more detailed ranking, we select the *k* school buildings which pass the first ranking, i.e., the buildings with $RF_1>1$ for a mean return period T= 475 years. For this return period, all buildings in our example have RF1 values greater than one. All school buildings are therefore classified into different building classes following the GEM international building taxonomy scheme (Brzev et al., 2013), according to main construction material, lateral load resisting system, number of storeys (i.e. height) and ductility level, which, is assumed to be a function of the construction time. In our study, the Directorate of Urban Planning & Architectural

Studies of the Municipality of Thessaloniki provided the required data for the studied school buildings. However, it is possible to obtain this information through open access web mapping platforms, such as Google Maps and OpenStreetMap, or through in situ virtual inspection.

Figure 8 shows the most common typologies of the studied school buildings (31 in total) in the Municipality of Thessaloniki and the classification of the school buildings in Thessaloniki based on the four selected attributes, namely, the material, the Lateral Load-Resisting System (LLRS), the height and the ductility level (Brzev et al., 2013).

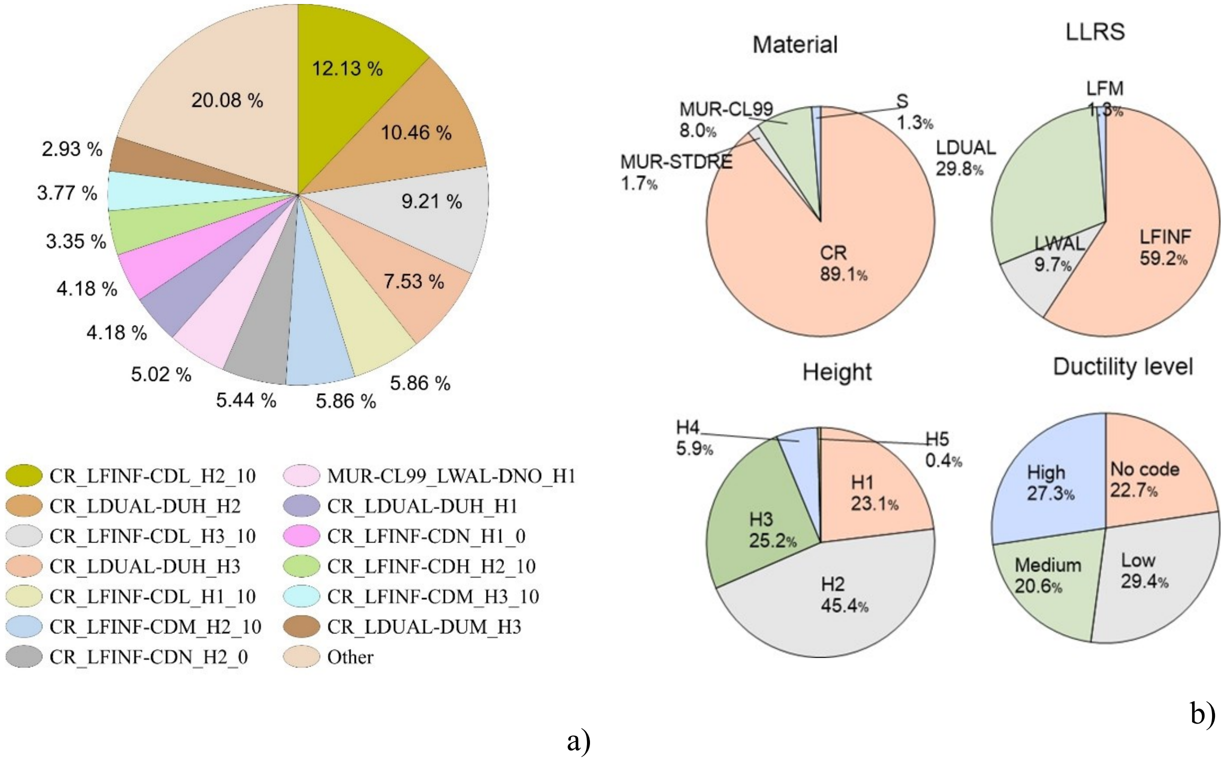


Figure 8 a) School building typologies in the municipality of Thessaloniki. b) Classification of the school buildings in Thessaloniki based on the four selected attributes according to the GEM Building Taxonomy of Table 1.

Evaluation of RF$_2$

Next, using OpenQuake engine, for the pre-computed in Stage 1 PGA_{DM} values (Figure 6) for a return period T=475 years, we evaluate the distribution of damage for each school building.

At this step, we select a reliable and appropriate vulnerability model. The uncertainties that the utilized vulnerability model can introduce into the vulnerability assessment of a building stock are many (Riga et al., 2017).

In the present study, for the studied schools, we adopted the ESRM20 fragility and vulnerability models (Crowley et al., 2021, Romão et al., 2021), which are considered appropriate for large scale applications and have been developed specifically for probabilistic seismic risk and vulnerability analysis. The ESRM20 fragility and vulnerability models utilized herein result from numerical analyses performed on equivalent single-degree-of-freedom (SDOF) systems. The performance thresholds for the four selected damage states are presented schematically in Figure 9. The calculated probabilities of exceedance of each damage state are based on the selected damage thresholds, of course taking into account the seismic demand.

Damage state	**Threshold**
Slight damage (DS1)	0.75 S_{dy}
Moderate damage (DS2)	0.50 S_{dy}+0.33 S_{du}
Extensive damage (DS3)	0.25 S_{dy}+0.67 S_{du}
Complete damage (DS4)	S_{du}

S_{dy}- Spectral displacement at yield
S_{du} - Spectral displacement at ultimate capacity

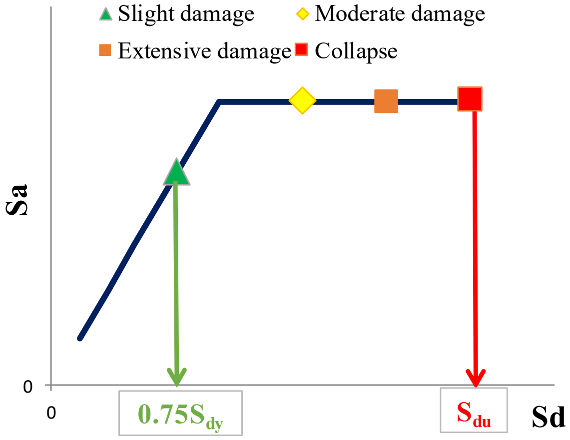


Figure 9 Thresholds for the selected damage states (Crowley et al., 2021, Martins and Silva, 2021)

After evaluating the damages for the selected seismic scenario (herein T=475 years), we calculate, for each school building, the second risk factor coefficient $\mathbf{RF_2}$, which is the sum of the probabilities of exceedance of "complete damage" and "extensive damage" damage states. The threshold value that allows the identification of the buildings for which structural retrofitting is required or not, is considered here equal to 10%.

Figure 10 shows (black line) the Risk Factors $\mathbf{RF_2}$ for the selected mean return period of 475 years. The horizontal axis depicts, with decreasing order of $\mathbf{RF_2}$, the school building inventory coding and the vertical axis the probability of exceedance of each damage state according to Figure 9. $\mathbf{RF_2}$ risk factor is the sum of the probabilities of exceedance at "extensive damage - DS3" and "complete damage – DS4" damage states. The red dashed line shows the threshold value L2, equal to 10%, that defines the school buildings for which structural retrofitting is required. School buildings having an $\mathbf{RF_2}$ value equal or higher than 10% are considered as more vulnerable and need retrofitting. In the current application, 9 school buildings are above the 10% threshold and thus require structural retrofitting.

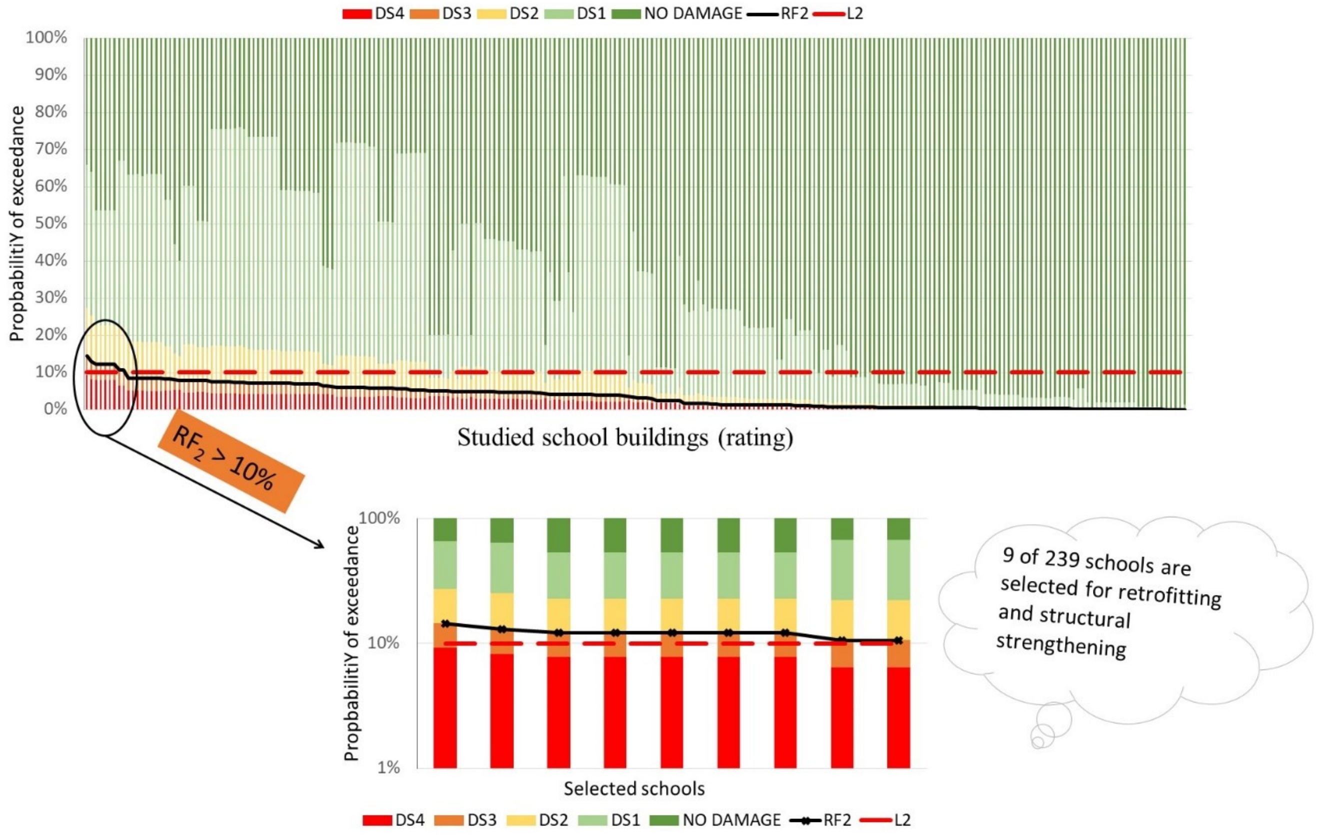


Figure 10 $\mathbf{RF_2}$ for all studied 239 school buildings in Thessaloniki city, considering a return period equal to T=475 years. 9 out of 239 school buildings (about 3.5%) exceed the threshold of 10% probability of exceedance of the sum of damages states DS3 and DS4 (extensive and complete damages). The black line shows the $\mathbf{RF_2}$ values the red dashed line shows the threshold of 10%. Each bar of the histogram represents one school building.

5 Conclusions

We described a methodology of a prioritization scheme for a simple, yet efficient, hierarchical policy for retrofitting and strengthening needs of school buildings at community scale. The proposed scheme is based on a two-level ranking process to allow the quick identification of the most vulnerable school buildings and concerns a first order vulnerability assessment that could be utilized in large scale applications. For the most vulnerable school buildings, a more detailed, building-specific, vulnerability and risk assessment should follow.

More specifically, at the first level, the ranking of schools is based on peak ground acceleration "deficit" between the design one at the construction time and the presently required based on the hazard analysis. This first ranking does not consider any specific feature of individual buildings; it only provides an indication of the risk level of all exposed school buildings in a certain municipality or region. For that, it only requires the knowledge of the construction year and the geographic coordinates of the buildings. The output of this phase is RF_1, which is a measure of the PGA deficit between the demand PGA and the design PGA. If RF_1 is greater than unity, the seismic demand of the considered existing building is larger than the one considered at the time of construction, and thus the structure is potentially vulnerable to earthquakes. Therefore, this first stage screening result in a number of schools, k, that should be further assessed in the second assessment stage.

The selected k school buildings, which are classified as vulnerable in the first level ranking, are examined in more detail in the second ranking level, which makes use of some extra building data, namely the construction material, the lateral load resisting system and the ductility level of the building. This information is necessary to select the appropriate fragility curves of each building typology and perform the risk analysis using the OpenQuake tool for the selected seismic return period. In this stage we calculate the distribution of damage and the second ranking risk coefficient RF_2, which is the sum of the probabilities of exceedance at "extensive damage" and "complete damage" damage states. The RF_2 risk coefficient is used to prioritize the k school buildings for seismic intervention by sorting the buildings with descending values of RF_2. Therefore, in order to define the most vulnerable school buildings, it is necessary to define one or more thresholds that may allow the identification of those cases in which structural retrofitting is first and second priority. The definition of these thresholds depends, on several other parameters of technical and socioeconomic character. The synthesis of all these parameters will finally define the percentage of school buildings to be retrofitted first and, most importantly, which these schools are. In the present application, we assume that the school buildings having at least 10% probability of exceedance of excessive and complete damages, or in other words buildings with RF2 greater than 10%, belong to the first priority for retrofitting. This threshold can be modified on a case-by-case basis, depending on the location of the schools, their number and structural characteristics and of course on the available resources for seismic interventions. It is important to note, that despite their uncertainties, both rankings are based on large scale risk-assessment methods that do not necessarily require inspection and building-specific studies of the various school buildings.

The methodology is applied to 101 school building aggregates comprising in total 239 isolated school buildings of the Thessaloniki Municipality in Greece. According to the proposed hierarchical policy the most vulnerable school buildings have been identified. These buildings represent about 3.5% of the total stock of the school buildings in Thessaloniki (9 out of 239) that require further and more detailed structural analysis to define the retrofitting and strengthening measures to be applied.

The proposed hierarchical policy, despite its simplicity, provides an efficient tool to identify the school buildings that need retrofitting and seismic upgrade to meet the present safety requirements, reducing the large initial inventory down to a more manageable size for policymaking and scheduling of seismic prevention projects for school buildings.

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Data and resources

OpenQuake Engine is available for download at https://www.globalquakemodel.org/oq-get-started. The main datasets and OpenQuake input files of ESRM20 are online available at https://gitlab.seismo.ethz.ch/efehr. The results of the ESHM13 are open to access and download at hazard.efehr.org, whereas those of the ESRM20 are distributed by risk.efehr.org

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