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Risk and Resilience Assessment of Lisbon's School Buildings Based on Seismic Scenarios

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Featured Application: Based on the risk estimates obtained in this study, the Lisbon City Council defined short- and medium-term risk mitigation plans, starting with a detailed inspection and assessment of the more vulnerable school buildings, in order to mitigate seismic risk on the city council-managed public schools.

Abstract: The safety and resilience of school buildings against natural disasters is of paramount importance since schools represent a reference point for communities. Such significance is not only related to the direct consequences of collapse on a vulnerable part of the population, but also due to the importance of schools in the post-disaster recovery. This work is focused on the risk and resilience assessment of school buildings in Lisbon (Portugal) under seismic events. The results of this study, in which a subset of 32 schools are analyzed, are used to define a prioritization strategy to mitigate the seismic risk of the Lisbon City Council school building portfolio and to assess the overall resilience of the school network. Numerical modeling of the school buildings is performed in order to estimate losses in terms of the built-up area of the schools and recovery times associated with different seismic scenarios, which are probabilistically defined specifically for the sites of the buildings, accounting for the local soil conditions and associated amplification effects. Based on the obtained risk estimates, which are compared to reference values established on international guidelines and specialized literature, the Lisbon City Council and LNEC jointly defined a short- and medium-term risk mitigation plan, starting with a detailed inspection and assessment of the most vulnerable school buildings and continuing to the implementation of retrofitting measures.

Keywords: seismic risk; resilience; risk mitigation; scenario-based analysis; numerical modeling; decision-making; emergency and recovery planning

Citation: Ribeiro, F.L.; Candeias, P.X.; Correia, A.A.; Carvalho, A.R.; Costa, A.C. Risk and Resilience Assessment of Lisbon's School Buildings Based on Seismic Scenarios. *Appl. Sci.* **2022**, *12*, 8570. https://doi.org/10.3390/app12178570

Academic Editors: Adolfo Crespo and Nuno Almeida

Received: 12 July 2022
Accepted: 16 August 2022
Published: 27 August 2022

1. Introduction

Measuring community resilience is recognized as an essential step towards reducing disaster risk and being better prepared to withstand and adapt to a broad array of natural and human-induced disasters [1]. Moreover, given the increasing concentration of people, activities, and resources in urban areas, the concept of community resilience gained increasing attention in the scope of city management [2].

Schools play a critical role, both in the education and development of a community and in the response and recovery of a natural disaster. Although schools were identified as a highly vulnerable component of a city building stock [3], they should be able to remain operational after a disaster so that they may allocate key post-event services, such as medical aid, temporary shelter, among others. As a consequence, school buildings are usually set as a priority for assessment and resource allocation for structural retrofitting [4].

Recently, the Comprehensive School Safety Framework (CSSF) [5] proposed an integrated approach to reduce disaster risk and promote resilience in the education sector [6]. Furthermore, some of the world disaster reduction campaigns led by the United Nations International Strategy for Disaster Reduction (UNISDR) were carried out together with various partner organizations under the theme of "Disaster Risk Reduction Begins at School" [7].

Recent earthquakes confirmed the significant vulnerability of school buildings. In fact, about 19,000 children died during the 2005 Kashmir earthquake (M_w = 7.6) in Pakistan, most of them due to the collapse of school buildings that were affected to a much higher proportion than other buildings [8]. A medium-sized earthquake (M_w = 6.4) in 2003 caused the collapse of three new schools and a dormitory building in Bingöl, Turkey, in which 100 people were killed [9]. During the 2003 Boumerdès (Algeria) earthquake (M_w = 6.8), 564 out of 1800 schools were severely damaged [10]. The 2002 Molise, Italy earthquake (M_w = 5.6) killed 27 children and one teacher due to the collapse of a school building [11], representing 93% of the total number of deaths.

Moreover, a significant portion of the school building portfolio was designed prior to the existence of seismic design provisions and/or constructed according to obsolete structural codes, which include little to no provisions for earthquake resistance and detailing.

Although the vulnerability of school buildings was studied in the past [3,4,9,12–18], in Portugal, school buildings were only studied starting in 2007 [19–21], and no regional or national strategy exists to mitigate seismic risk.

Taking as an example the Portuguese public secondary (10th to 12th grade—similar to high school in the US) education school building portfolio in mainland Portugal, it currently includes about 400 schools [19]. Of these, 23% were built before the end of the 1960s, just before or shortly after the publication of the first seismic design code provisions, the Code for Building Safety against Earthquakes, RSCCS (Decree No. 41658, 1958), and 46% were built in the 1980s, with a significant proportion predating 1983, when the Code for Safety and Actions for Building and Bridge Structures, RSAEEP (Decree-Law No. 235, 1983), and the Code for Reinforced and Prestressed Concrete Structures, REBAP (Decree-Law No. 349-c, 1983), came into force. Regarding Lisbon's schools for secondary education and second and third cycles of basic education, 38% were built before the end of the 1960s and 28% were built in the 1980s [22]. This highlights the importance of assessing the Portuguese school building portfolio. As far as the authors are concerned, a national systematization of school buildings and their structural characteristics is not publicly available in Portugal.

The Portuguese National Laboratory for Civil Engineering (LNEC) developed a research study on the seismic risk and resilience of public schools managed by the Lisbon City Council (CML). This paper describes the methodology and the main outcomes regarding the study of a subset of 32 schools, represented in Figure 1, that correspond to the secondary education and second and third cycles of basic education schools that are managed by CML. This group of schools includes the bigger and more complex schools of the CML school building portfolio. Based on the outputs of this research study, which was completed in 2021 [22], CML and LNEC jointly defined a risk mitigation intervention for this group of schools, whose main principles are also presented in this paper. The analysis of 77 elementary schools and kindergartens that are part of the CML school buildings portfolio is programmed for the near future.

This relatively low number of schools (109 schools that are managed by CML) allows for a comprehensive and detailed risk assessment of each school building to be carried out. This detailed assessment provides information on the structural safety and seismic performance of the buildings, as well as useful knowledge for the optimization of a structural retrofitting intervention for specific seismic scenarios.

Nevertheless, the risk assessment methodology should not require a numerical and computational cost that hinders its application to a broad portfolio of buildings. In other words, the risk assessment methodology should perfectly balance between complexity and engineering-based outcomes [6]. The risk assessment should allow for defining seismic risk prioritization strategies and identifying the archetype of buildings that require more detailed evaluations/analyses, as well as provide quantitative seismic risk estimates for one or more selected buildings in the database and design structure-specific risk-mitigation strategies, such as structural retrofitting.

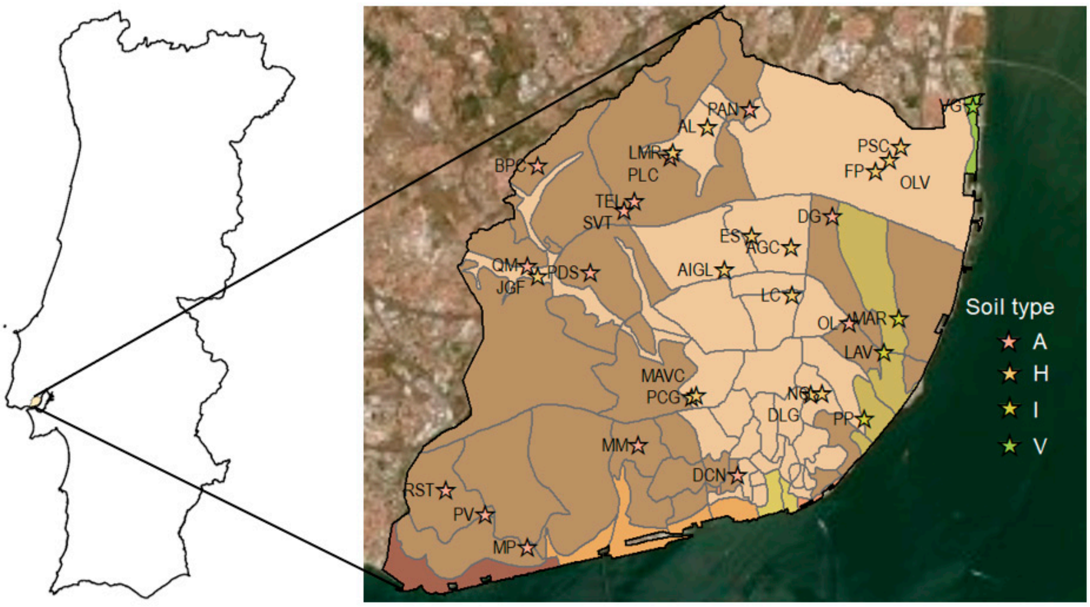


Figure 1. Identification of the CML's 32 schools of secondary education and second and third cycles of basic education, using the Lisbon's soil layer produced by LNEC.

Nonlinear numerical models of the school buildings were developed based on the available information, namely design projects and drawings provided by CML or collected from other sources, such as the Atlas of Portuguese School Architecture [23], as well as visual inspections carried out by the LNEC team. The nonlinear response of the buildings in this research work is simulated using the SeismoStruct software [24], while the performance for various seismic intensity levels is obtained with the Capacity Spectrum Method (CSM) [25], which is one of the reference methods for seismic performance assessment of existing building structures in international guidelines.

The research presented in this paper allowed for the defining, for each school, of a performance matrix that represents the fulfillment of the levels of seismic performance established for the various seismic intensity levels according to predefined performance objectives. These performance objectives are defined based on international guidelines (VISION 2000) [26] and specialized literature [27].

The evaluation of seismic risk parameters, namely estimated losses in terms of the built-up area, both expected annual losses and losses in a 50-year period, and recovery times for each school, which can be defined as the number of interdiction days of the school buildings due to earthquake damage, allows for the ranking of schools on the basis of their seismic risk and vulnerability. Additionally, a resilience analysis was developed, consisting of the estimation of the post-earthquake school building portfolio functionality as a function of time after the seismic event, for a set of seismic scenarios.

The assessment based on the speed of recovery is one of the reference methods used to evaluate resilience [28]. Other methods are the assessment against thresholds that reflect program objectives, assessment against principles of good resilience, and assessment against peers (benchmarking). The post-earthquake school building functionality is of paramount importance to the development of an integrated emergency response plan at the city level.

Based on the results of this study, CML defined an intervention plan, both for the short- and medium-term, for the seismic risk mitigation of these school buildings. This plan starts with a detailed inspection and assessment of the most vulnerable school buildings, which includes in situ tests of materials, inspection of geometry and detailing, dynamic characterization of the buildings (vibration periods, mode shapes, and equivalent damping), and soil and foundation surveys. This information will assist in the development of a cost-effectiveness analysis of various retrofitting solutions.

In the following section, a literature review on the seismic risk and vulnerability assessment and mitigation of school buildings is presented. Afterward, in Section 3, Lisbon's school building portfolio is characterized and the archetype typologies used in this study are presented. In Section 4, the risk and resilience assessment methodology is detailed, while in Sections 5 and 6 the risk and resilience outputs are presented and discussed, respectively. Finally, in Section 7, conclusions and future developments are outlined.

2. State of the Art on Seismic Risk Assessment and Mitigation for School Buildings

2.1. Background Codes and Guidelines

Risk-mitigation strategies designed by governmental agencies should be based on a rational understanding of the risk of large building groups—or portfolios—at a country level (or in a smaller region). In this context, various risk assessment methodologies and prioritization schemes for buildings based on their relative seismic vulnerability/risk are available in the scientific literature and/or international standards/guidelines.

The procedure proposed in the guidelines by the Applied Technology Council [29] uses a strength-based approach to define an earthquake capacity ratio, comparing the actual strength of the building to the code requirement for new buildings. Adjustments are also adopted to consider in situ material properties and insufficient detailing (compared to modern design). Such a capacity-to-demand ratio is defined as the earthquake capacity ratio, and it is calculated as the minimum of the component-by-component strength ratios.

The New Zealand Society for Earthquake Engineering (NZSEE) defines an evaluation procedure based on various levels with increasing detail of analysis, similar to the one proposed by Grant et al. [30]. The initial evaluation procedure (IEP) in the NZSEE guidelines, published in 2017 [31], aims to provide a broad indication of the seismic rating of a building based on a sidewalk survey. The evaluation is expressed in terms of the ratio (%NBS) of the displacement capacity of the building for the life safety limit state over the minimum capacity required for a new building for the same limit state. A baseline %NBS is calculated using specifically tabulated coefficients relating to year of design, strengthening interventions, importance of the structure, assumed ductility capacity, site hazard, presence of near-fault effects, soil type, etc. It is assumed that the capacity of the building cannot be lower than the minimum specified by the code valid for the year of design, if any.

Furthermore, the procedure introduced by the Federal Emergency Management Agency [32] is based on a rapid visual screening of buildings and a two-level approach for a fast assignment of a seismic vulnerability index (which requires no mechanical-based calculation from the user). FEMA P-155 describes the rationale behind the scoring system, which is directly connected to the probability of collapse of archetype building categories. Such a method is based on the HAZUS framework (and typological force–displacement curves) to define the building categories and to derive a seismic-only assessment.

Finally, Part 3 of Eurocode 8 (EN 1998-3) [33] consists in the current European basis for the seismic assessment of existing buildings. Although it proposes a series of recommendations for the assessment of building structures, a practical framework that integrates the analysis methods that are referred to in this document is yet to be developed.

Referring to the education sector, a consistent effort was put forward by the World Bank in addressing these aspects with the implementation of the Global Program for Safer Schools (GPSS) [34]. Launched in 2014, the GPSS contributes to the Comprehensive School Safety Framework [5,35] by financing and advising governments to implement safer school programs worldwide. As outlined in the Sendai Framework [36], "while the drivers of disaster risk may be local, national, regional or global in scope, disaster risks have local and specific characteristics that must be understood for the determination of measures to reduce disaster risk" [sic]. This is particularly valid in countries where risk data scarcity remains a major issue [37], and where there is a tendency to perform risk assessments with models from other regional contexts.

In 1997, Alaska's Department of Education, among others, produced surveying forms to assess the structural conditions of buildings and the associated seismic vulnerabilities, with a focus on school buildings. Such forms mainly consist of checklists investigating areas of potential concern for seismic vulnerability. The Italian National Group for Earthquake Defence (GNDT) also provided a seismic vulnerability index [38,39] based on simple assessment forms, including, among other parameters, the structural material, the typology of the lateral load-resisting system (LLRS), the quality of the building materials, and the overall construction, and the existing damage level (if any).

In 2017, the Italian "Guideline for the seismic risk classification of constructions" was approved (Decree-Law No.58, 2017), proposing a methodology to define the seismic risk classification of buildings based on a simplified calculation of their seismic performance and expected annual loss (EAL). These guidelines, commonly known as SISMABONUS, define a technical procedure to calculate tax deductions by improving the seismic performance of buildings through strengthening interventions. The proposed procedure is simple and allows practitioners to deal with the evaluation of EAL without having to perform a sophisticated probabilistic seismic risk assessment. A letter-based classification is used to define the seismic risk class to which a building belongs.

2.2. Empirical Approaches for Risk and Vulnerability Assessment

Risk and vulnerability assessments are most commonly derived: (i) from expert opinions (expert/judgmental-based); (ii) from statistical processing of post-earthquake reconnaissance data (empirical/observational); or (iii) through analytical/numerical simulations.

Risk quantification of large school portfolios through the development of empirical risk mitigation prioritization approaches led to the development of rapid surveying forms and rapid assessment procedures that were proposed by different authorities and organizations, such as the World Health Organization (WHO) and the United Nations (UN), with special focus on developing countries. For instance, Dhungel et al. [40] collected and assessed the physical condition of 1381 school building units in Nepal by mobilizing the school teachers. School vulnerability, calculated on the basis of empirically weighing different factors (e.g., structural material, number of stories, and shape of the roof), was used to estimate the possible damage, casualties, and injuries caused by earthquakes of different seismic intensities. Different statistical methods were used for fragility derivation of the Nepalese school building portfolio, for instance by Giordano et al. [41], based on the World Bank's data collected after the 2015 Gorkha sequence.

Other empirical risk assessment frameworks were also developed in countries with high risk of seismic activity, as is the case of Peru, where a project was funded by the government of Japan and the Global Facility for Disaster Reduction and Recovery [34], Turkey, with the Istanbul Seismic Risk Mitigation and Emergency Preparedness (ISMEP) Project, initiated in 2006, as well as Indonesia, where the Indonesia School Programme to Increase Resilience (INSPIRE) tried to develop an advanced, harmonized, and science-based risk assessment framework for school infrastructure in Indonesia, subjected to cascading earthquake–tsunami hazards [6]. The INSPIRE seismic risk prioritization index aims at providing a simple method to derive a prioritization scheme, minimizing the subjectivity involved in the calculation. This work combines the INSPIRE metric, which allows for empirically assessing the seismic risk and defines prioritization strategies for risk mitigation, and the Papathoma Tsunami Vulnerability Assessment (PTVA) index [42]. This is a step forward in defining a multi-hazard risk assessment methodology. Such a multi-level framework is implemented for 85 reinforced concrete (RC) school buildings in Banda Aceh, Indonesia, the most affected city by the 2004 Indian Ocean earthquake–tsunami event.

However, conducting empirical studies may be unfeasible in data-scarce regions [37], such as Portugal, where the return periods of seismic action are significantly large. For this reason, the development of numerical studies, such as the ones referred to in the following paragraphs, based on the characteristics of local buildings, are deemed necessary.

2.3. Analytical Approaches for Risk and Vulnerability Assessment

Analytical risk and vulnerability assessments are an alternative to overcome the limitations of empirical methods [43]. Ideally, these methods should include all the sources of uncertainty, e.g., geometry, material properties, static loads, ground motion, etc. [44]. However, analytical fragilities based on numerical analyses, such as Finite Element Method (FEM) analyses, are generally time consuming, as multiple FEM models need to be generated and analyzed to include aleatory uncertainty. Despite this negative aspect, the development of numerical models and analysis of the buildings allow for a deeper understanding of their performance and, therefore, for the development of more optimized retrofitting designs for mitigation of seismic risk.

A recent research project entitled "*Progetto Scuole*", whose main objective was to assess the seismic risk of a number of representative school buildings, was carried out at the Eucentre Foundation (Pavia, Italy), in collaboration with the University School for Advanced Studies IUSS, in Pavia, Italy [45,46]. Three schools, representative of the Italian school building portfolio, were selected to be analyzed in detail through advanced numerical models developed using information collected during in situ inspections and calibrated with the results of ambient vibration measurements. Two site locations were also chosen to perform probabilistic seismic hazard analysis and select hazard-consistent ground motion record sets adopting the seismicity model used for the calculation of the Italian national seismic hazard map. Expected Annual Losses (EAL), including both structural and non-structural building components, were estimated following the procedure proposed in FEMA P-58. Losses were then used as a performance parameter to quantify the seismic vulnerability of the school buildings.

Table 1 reports the EAL obtained by O'Reilly et al. [46] for the three buildings under study, namely the Reinforced Concrete (RC), the Unreinforced Masonry (URM), and the Precast Concrete (PC) buildings. The EAL values computed following the FEMA P-58 methodology were below 1% for all typologies at the considered site locations. The authors stated that these loss values appear to be in line with typical values of recent quantification studies on existing Italian buildings. URM school buildings were demonstrated to be the most vulnerable, out of the three considered, when assessing the expected losses with respect to increasing seismic intensity. Moreover, the authors computed the damage to non-structural elements and showed that it tends to dominate the EAL, constituting between 70% and 90% of the total, depending on the structural typology.

Table 1. Expected annual loss ratios obtained by O'Reilly et al. [46] for three buildings representative of the Italian school building portfolio.

Expected Annual Loss Ratios (%)	RC	URM	PC
High seismicity site	0.35%	0.48%	0.30%
Medium seismicity site	0.28%	0.33%	0.13%

Additionally in Italy, the ASSESS project [47] defined a 3-level methodological approach for defining priorities in inspection and retrofitting school buildings in order to reduce seismic risk in the Friuli Venezia Giulia region (NE Italy).

Jeswani et al. [4] developed a seismic risk assessment and mitigation analysis of more than 1000 public school buildings in the Manila Metropolitan region in the Philippines. The authors quantified different risk contributions and identified cost-drivers that can be targeted for performance-based risk management of large school portfolios.

Anelli et al. [48] proposed a cost–benefit index and an innovative resilience indicator that helps to identify the best prioritization strategy for retrofit interventions. Jaimes and Niño [49] also proposed a cost–benefit methodology, based on numerical analysis of the buildings, to assess possible interventions, such as retrofitting or reconstruction of structures focused on mitigation of direct physical losses due to seismic actions.

López et al. [12] contributed to the development of a national risk-reduction program in Venezuela, starting with the assessment of the seismic performance of two typical schools, which were analyzed through nonlinear pushover analysis. Their performance was then extrapolated to the inventory of schools in Venezuela. A practical retrofitting intervention plan was studied, based on the addition of auxiliary structures to support the seismic loads, leaving the existing structures to support only the gravity loads.

It is worth noting that the problem of building collapse under severe earthquakes is not the only one related to the effect of earthquakes on structures. In fact, as stated by López et al., moderate earthquakes can induce severe damage on buildings, with high consequences in terms of indirect losses. In fact, a large percentage of earthquake-induced losses are also related to the damage of non-structural elements [50]. The poor seismic performance of non-structural elements is generally the consequence of the omission of proper seismic design and detailing, and expertise on how to effectively perform it. For example, significant damage to ceiling systems, partitions, shelves, and ornaments in heritage URM buildings was reported by Perrone et al. [50] following the 2016 Central Italy earthquake.

Calvi et al. [51] conducted an exhaustive review of typical non-structural damage observed in school buildings after major seismic events around the world and highlighted that ceiling systems, partitions, lighting systems, and bookshelves are generally the most vulnerable elements. The main reasons identified were the lack of proper anchorage of the various elements and, in many cases, the absence of clear seismic design methodologies and prescriptions to implement them.

The results of previous studies, such as Giordano et al. [52], provide quantitative evidence that for seismically active regions, the seismic retrofit of structures is a financially advantageous investment, since the reduction in future earthquake-induced loss exceeds the upfront cost of the intervention. However, for most building owners, the investment required for retrofitting remains an issue since it is considered too high and is not associated with an immediate and tangible benefit. In this context, Giordano et al. [52] proposed an incremental seismic retrofitting for Nepal, in which the total investment is spread over time in a gradual and cost-effective way, thus allowing for more flexibility in implementing effective risk management actions at a regional and national scale.

Finally, it is worth highlighting that a school infrastructure is not limited to the school buildings, but includes other infrastructures, such as power and water supply, as well as accessibility to the school [53]. Additionally, the school community further includes the attributes of the local stakeholders, as well as how they interact and support each other in normal conditions. Within the SAFER project [53], educational community resilience is assessed based on four dimensions: (i) school infrastructure, (ii) school community, (iii) school governance, and (iv) school curriculum.

2.4. Assessment of the Portuguese School Building Portfolio

In Portugal, the first initiative that systematically addressed the rehabilitation and retrofitting of secondary education school buildings started in 2007. This initiative was managed by a public–private entity called *Parque Escolar*, EPE [19]. Its mission consisted of the upgrading and safeguarding of the Portuguese school building heritage by restoring its physical and functional effectiveness. Structural strengthening, namely in what concerns seismic retrofitting, was particularly evidenced in this program [19]. The program stages 1 and 2, launched in 2007 and 2008, intervened in 106 schools throughout Portugal. School buildings that were intervened as part of the *Parque Escolar* initiative are thus associated with a risk significantly lower than the one associated with the remaining school buildings.

Some Portuguese regions received more attention, such as the Algarve region in the south of Portugal. In fact, Ferreira et al. [20] started to study the educational infrastructure in Algarve by developing a seismic risk assessment, in which the seismic response of buildings was considered following a vulnerability index based on EMS-98. More recently, Estevão et al. [21] led the PERSISTAH (Projects of earthquake resilient schools in Algarve (Portugal) and Huelva (Spain)) project, which aims to develop tools for diagnostic, evaluation, management, and rehabilitation of primary schools in both Algarve (south of Portugal) and Huelva (south of Spain) regions. The project created a ranking methodology for the vulnerability of primary schools, named "school-score".

Apart from these projects, no national strategy exists in order to assess the seismic risk of educational infrastructure. Thus, it is of paramount importance to study, on a first stage, the functional and structural condition of Portuguese school buildings and, on a second stage, to define intervention plans to mitigate the identified risks. This paper summarizes the assessment developed as part of one of these research studies, which focused on the school buildings that are managed by Lisbon's City Council [22].

3. Characterization of 32 School Buildings in Lisbon

The first consistent national program related to the construction of educational infrastructures started at the beginning of the military dictatorship (1930–1933). Later, the 1938, 1947, and 1958 plans implemented common programs, based on the values of modernist architecture in agreement with the ideals of the *Estado Novo* (dictatorial) regime, resulting in the construction of technical schools as a major outcome. The expression of normalization becomes particularly relevant from the beginning of the sixties with the adoption of several standardized building typologies, as well as the design of school-based and technical-based models at the end of the sixties. Buildings built between the 1970s and 1990s are mainly based on prefabrication processes and followed the program for the execution of preparatory and secondary (1980) schools. These schools follow a typified strategy through a common infrastructure around the country.

The *Parque Escolar* program [19] proposed a chronological organization of Portuguese school buildings in three periods: from the end of the 19th century to 1935, from 1936 to 1968, and from 1968 to the present. Following this organization, among the 32 CML schools represented in Figure 1 that are part of this research study, only one was built before 1935, whereas eleven where built in the period between 1935 and 1968. Finally, twenty schools were built after 1968. These schools correspond to the secondary education, and second and third cycles of basic education schools that are managed by CML and include the bigger and more complex schools of the CML school buildings portfolio.

The analysis of the 32 public schools, started by the systematization of the available information, namely the one coming from: (i) design and/or construction drawings provided by CML; (ii) information contained in publications about the national school buildings portfolio, namely the annexes of the "Atlas of School Architecture in Portugal" [23]; and (iii) visual inspections of schools, carried out by LNEC, in which some small-scale tests were carried out (drilling) to assess the position of structural elements and construction materials.

The schools were then divided into the following structural typologies, corresponding to groups that differ in the type of structural analyses to be developed. The typologies are:

- Composite masonry–concrete structure ("composite MC")
- Composite concrete–masonry structure ("composite CM")
- Reinforced concrete structure ("RC")
- 3×3 reinforced concrete pavilion ("3×3")
- *Vale Rosal* reinforced concrete pavilion ("VR")
- Compact 24T reinforced concrete pavilion ("C24T")

These six typologies are represented in Figure 2 with examples of schools from each of the typologies. These different typologies correspond to different construction periods. It should be noted that the distinction between the first two typologies lies in the relative contribution of the masonry elements to resist horizontal actions, such as earthquakes. In the first case (composite masonry–concrete structure), the masonry elements represent a significant portion of the primary elements resisting horizontal actions. On the other hand, in the second typology (composite concrete–masonry structure), the masonry elements essentially possess the function of supporting the gravity loads coming from the slabs, being the resistance to horizontal actions conferred by the reinforced concrete elements. Although the difference between the two can be diluted within each construction period, this differentiation is essential to define a consistent and accurate methodology for analyzing the seismic structural response of the buildings.

Composite Masonry–Concrete (“composite MC”)

Escola Básica Eugénio dos Santos

Composite Concrete–Masonry (“composite CM”)

Escola Básica Paula Vicente

Reinforced Concrete (“RC”)

Escola Secundária Marquês de Pombal

3 × 3 reinforced concrete pavilion (“3 × 3”)

Escola Básica Alto do Lumiar

Compact 24T reinforced concrete pavilion (“C24T”)

Escola Básica Marvila

***Vale Rosal* reinforced concrete pavilion (“VR”)**

Escola Básica São Vicente de Telheiras

Figure 2. Examples of the identified structural typologies of the school buildings.

In terms of what concerns the reinforced concrete buildings, the 3×3, VR, and C24T typologies all correspond to framed reinforced concrete structures based on a modular system (possibly prefabricated). This system consists of regular frames with spans around 4.5 m. The number of frames in the two directions form different building configurations (e.g., three spans of 4.5 m in each direction of the 3×3 typology) and justify the definition of these three different typologies, thus facilitating the analysis and interpretation of results. Otherwise, typology “reinforced concrete structure” (RC) includes structures that do not fit into the aforementioned typified categories and, consequently, require an individualized analysis. Although these RC buildings are mostly frame structures, they are not based on modular, or typified, building structures.

Among these typologies, two main building construction techniques can be identified. First, buildings typically from before 1960, mainly unreinforced masonry buildings with timber floors or reinforced concrete slabs, have rubble stone or brick masonry walls made with lime or cement mortar and two to three unconnected layers across the thickness. In the most recent buildings, it is also possible to find some vertical elements (columns) and horizontal elements (beams) made of reinforced concrete. The poor connections between orthogonal walls and the presence of floors providing a weak diaphragm restraining effect may contribute to the poor seismic response of URM buildings [54].

Second, a large percentage of school buildings are made of reinforced concrete, which is one of the most representative building typologies in Portugal. A common feature in these buildings, namely in those constructed under non-existent or low-seismic design codes, is the lack of adequate seismic detailing and design philosophies now included in modern design standards around the world. The columns were generally designed only for gravity loads with low shear and flexural capacity. The lack of shear reinforcement in the joints, combined with the increase in forces due to the interaction between the RC frame and masonry infills, often caused the shear failure of beam-to-column joints in similar buildings around Europe [55]. Furthermore, in RC buildings, poor connection detailing is also associated with the collapse of infill wall panels.

Table 2 presents the list of schools and corresponding construction dates, typologies, built-up areas, approximate number of students, as well as individual IDs that are represented in Figure 1. The detailed characterization of the typologies and their respective application to schools can be checked in the full report of this research study [22]. Among the 32 schools, there are four schools (greyed out in Table 2) that were excluded because they did not respect the basic assumptions of the study requested by the CML or because there was no information available to allow their analysis.

Table 2. Structural typologies and basic information of the 32 school buildings under study.

School	ID	Construction Date	Typology	Area (m^2)	~No. Students
Escola Básica Alto do Lumiar	LMR	1986	3 × 3	4810	535
Escola Básica Damião de Góis	DG	1977	3 × 3	4810	365
Escola Básica Professor Delfim Santos	PDS	1972	3 × 3	7221	1040
Escola Básica Olaias	OL	1983	3 × 3	4810	585
Escola Básica Piscinas	PSC	1991	3 × 3	2700	680
Escola Secundária Lumiar	LMR	1984	3 × 3	6625	725
Escola Secundária Restelo	RST	1989	3 × 3	7366	1100
Escola Básica Pintor Almada Negreiros	PAN	1998	VR	4086	520
Escola Básica Telheiras	TEL	1995	VR	4086	595
Escola Básica São Vicente—Telheiras	SVT	2009	VR	6202	730
Escola Básica Marvila	MAR	1995	C24T	3810	330
Escola Básica Professor Lindley Cintra	PLC	2009	C24T	3810	530
Escola Básica Olivais	OLV	1995	C24T	3810	535
Escola Básica Bairro do Padre Cruz	BPC	1998	RC	2785	350
Escola Secundária José Gomes Ferreira	JGF	1997	RC	9028	1000
Escola Básica Fernando Pessoa	FP	1969	RC	5086	800
Escola Secundária Marquês de Pombal	MP	1962	RC	12,570	400
Escola Básica Luís António Verney	LAV	1963	RC	4500	420
Escola Básica Luís de Camões	LC	1956	RC	2062	500
Escola Básica Manuel da Maia	MM	1947	RC	8500	365
Escola Básica Quinta de Marrocos	QM	1978	RC	2785	585
Escola Básica Almirante Gago Coutinho	AGC	1982	Composite CM	2264	450
Escola Secundária Dona Luísa de Gusmão	DLG	1947	Composite CM	2662	990
Escola Básica Paula Vicente	PV	1949	Composite CM	3772	430
Escola Básica Nuno Gonçalves	NG	1950	Composite MC	3209	910
Escola Básica Patrício Prazeres	PP	1953	Composite MC	4201	475
Escola Básica Eugénio dos Santos	ES	1949	Composite MC	3475	830
Escola Artística Instituto Gregoriano de Lisboa	AIGL	1955	Composite MC	472	475
Escola Básica Vasco da Gama	VG	1999	RC	3491	620
Escola Artística de Dança do Conservatório Nacional	DCL	1994	Composite MC	550	150
Escola Profissional Ciências Geográficas	PCG	1964	Composite MC	-	90
Escola Secundária Maria Amália Vaz de Carvalho	MAVC	1933	Composite MC	9684	1180

Figure 3 (left) shows the total number of schools in each typology. The typology with the highest number of schools (9) is the RC typology. The remaining typologies that include reinforced concrete structures (3 × 3, VR, and C24T) total 13 schools. The composite structures, which correspond to the oldest ones, include 10 schools: 3 schools with a composite concrete–masonry structure and 7 schools with a composite masonry-concrete structure.

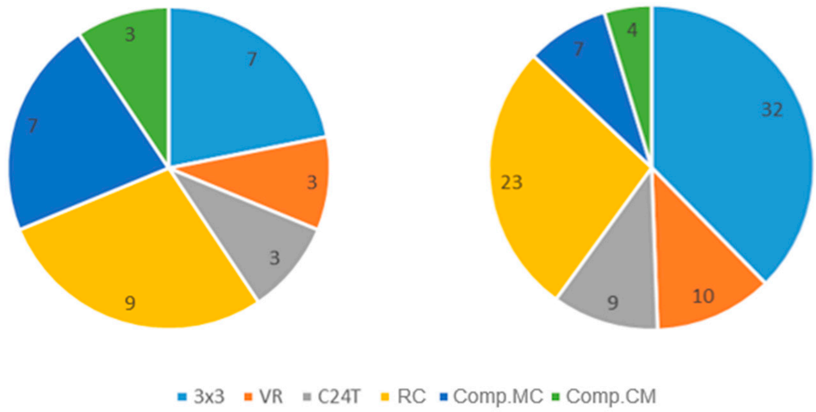


Figure 3. Total number of schools in each structural typology (total: 32 schools) (**left**); total number of main buildings in each structural typology (total: 85 main buildings) (**right**).

Figure 3 (right) shows the total number of buildings, classified as main buildings, by structural typology. As can be seen, the 3 × 3, VR, and C24T typologies are the ones that include a larger number of buildings. This is due to the existence, in each of these schools, of a significant number of separate buildings, which function as classroom/administrative buildings and, as such, are considered as independent main buildings. On the other hand, the schools with composite building typologies, which are typically constituted by a single building, are the ones with a smaller number of main buildings. Nevertheless, composite typologies require a much more time-consuming and complex analysis of their seismic performance, as described later in this work.

4. Seismic Risk and Resilience Assessment Methodology

In terms of assessing the seismic performance of buildings and their structural and non-structural elements, one of the most comprehensive performance-based earthquake engineering (PBEE) methodologies was initially conceived by Cornell and Krawinkler [27] and then adopted by the Pacific Earthquake Engineering Research (PEER) Center. The PEER PBEE framework includes a number of analysis stages and variables, illustrated in Figure 4. Firstly, hazard analysis is conducted based on the rupture and local site details D, yielding the definition of the intensity measure IM to be used in the subsequent analysis. Secondly, structural analysis is carried out, relating the intensity measure of the seismic action to the structural response, which is characterized by an engineering demand parameter EDP. Thirdly, damage analysis allows for the definition of a relationship between structural response (EDP) and a damage measure DM. Finally, loss analysis is conducted to provide information for a final consequence analysis of performance measures referred to as decision variables (DV), such as the expected losses and probability of collapse.

In this work, the analysis of the seismic performance of schools and the definition of an intervention plan to mitigate the seismic risk is based on the following fundamental steps, illustrated in Figure 5. First, the main buildings of the school under analysis are characterized according to the previously mentioned structural typologies, creating groups that differ in the type of structural analysis to be carried out. Second, seismic action is characterized, based on a probabilistic study of the seismic hazard [56], at each school location taking into account site effects due to soil conditions, which are quantified based on the available information at LNEC [57]. Afterwards, seismic response assessment is performed using different numerical modeling procedures. Nonlinear numerical models of two of the schools, represented in Figure 6, are developed in the Seismosoft's SeismoStruct software, Version 2021—Release 3 [24], allowing for the evaluation of the structural behavior and the nonlinear response of each main building for different seismic intensity levels, which serves to calculate the expected losses in terms of the school's built-up area and recovery times (number of days of interdiction).

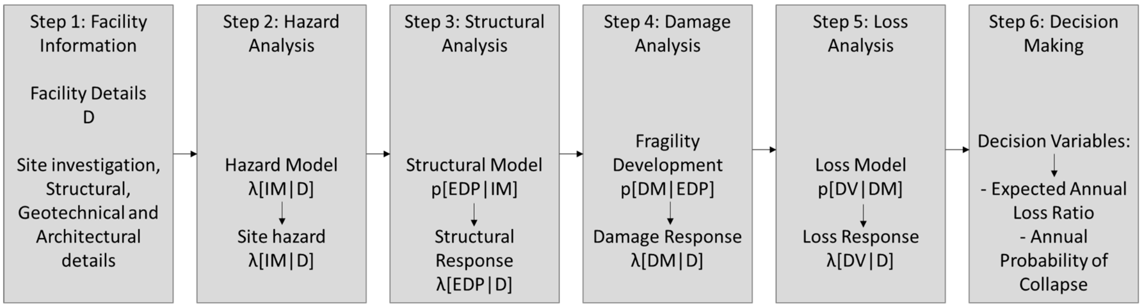


Figure 4. Illustration of the four stages of the PEER PBEE framework (adapted from [27]).

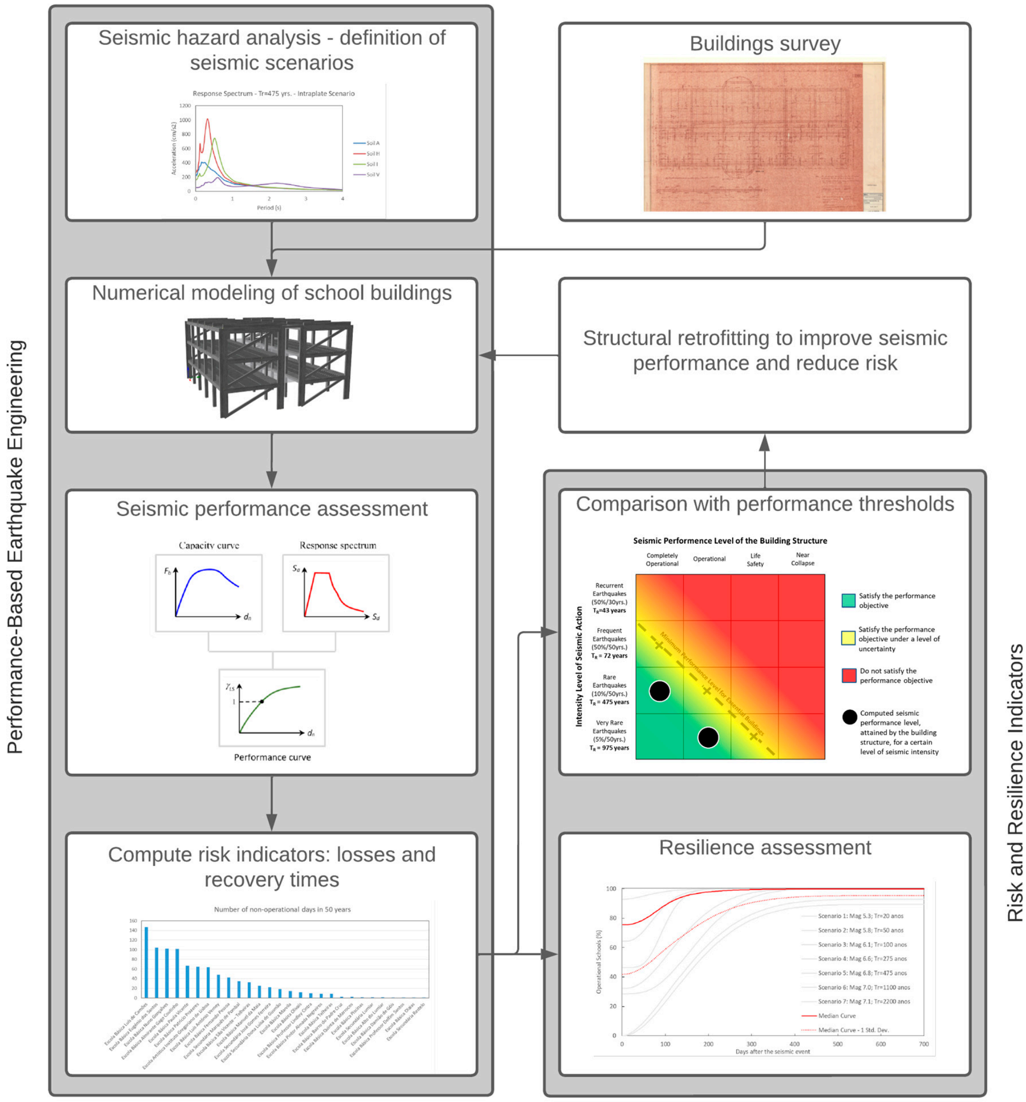
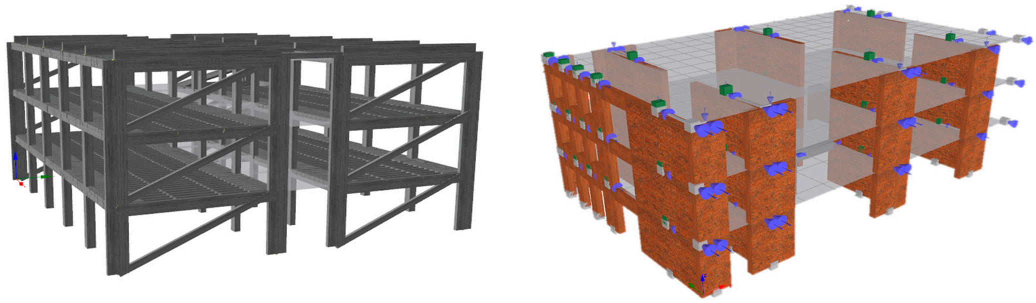


Figure 5. Overview of the assessment methodology employed for the Lisbon City Council school building portfolio.



(**a**) EB Luís António Verney (RC) (**b**) EB Eugénio dos Santos (Comp. MC)

Figure 6. Nonlinear numerical models for structural response assessment at different levels of seismic action intensity for a: (**a**) RC structure; and (**b**) composite masonry–concrete structure.

Numerical models of RC buildings are based on force-based beam–column frame elements with fiber-discretized sections. Each beam–column element has seven integration points along its length and 150 uniaxial fibers defined in their cross sections, which are assigned stress–strain phenomenological models. Concrete fibers are assigned the model proposed by Mander et al. [58], while fibers associated with reinforcing steel bars are assigned the Giuffre–Menegotto–Pinto [59] model. The confinement effects provided by the lateral transverse reinforcement are incorporated through the rules proposed by Mander et al. [58] whereby constant confining pressure is assumed throughout the entire stress–strain range. In what concerns composite structures, masonry piers and spandrels are modeled through equivalent nonlinear frame elements with fiber sections. The uniaxial masonry fiber response is based on the Seismostruct parabolic masonry model, which consists of a uniaxial material model for masonry that is based on the hysteretic rules of the constant confinement concrete model [58]. Material parameters assumed for the aforementioned models vary among schools. Whenever possible, material parameters are taken from the school project drawings or complementary information. Otherwise, material parameters needed to be assumed following similar school buildings specifications or typical construction practices at the time of the construction of each school, based on specialized literature [54]. Detailed information on the material model parameters may be found in Ribeiro et al. [22]. The nonlinear response of each building is assessed through a nonlinear static (pushover) analysis using a lateral load that is proportional to the fundamental mode of vibration of the structure.

Subsequently, the evaluation of the seismic performance of the structure, based on a pre-established performance objective in accordance with specialized literature and international regulations, is carried out, which enables filling in a seismic performance matrix, which will be introduced next. Moreover, individual assessment sheets for the main building of each school, with the information collected, description of the models, and analysis assumptions adopted, results and recommendations are prepared in order to systematize the results in an easy-to-follow way for non-expert decision makers.

Based on the results, it is possible to define intervention plans for the mitigation of seismic risk in schools, which integrates structural retrofitting. This requires the reassessment of the seismic performance in order to optimize the retrofitting solution based on the risk mitigation objectives and gains.

Structural seismic response is defined herein through capacity curves, as shown in Figure 7, which allow for the detailed assessment of the structural response for increasing seismic intensity levels. The capacity curve represents the structural response as a function of the seismic loading. In Figure 7, four structural response limit states (EL1 through EL4) are represented. Each of these limit states corresponds to the upper bound of a performance level. The description of these four limit states is presented in Table 3.

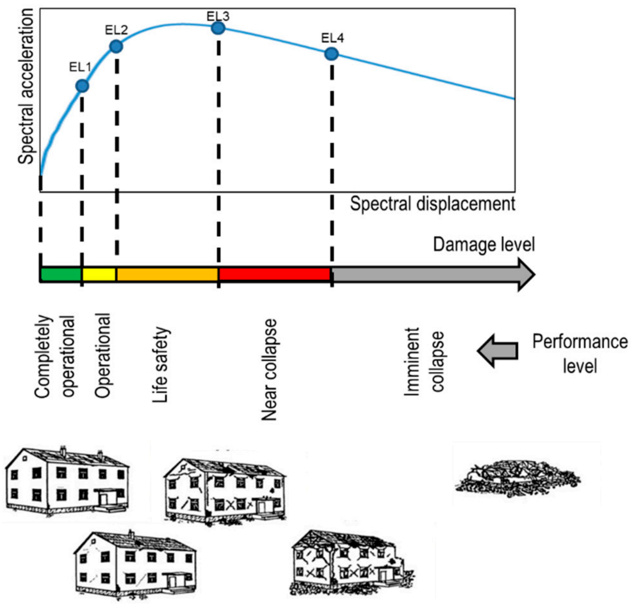


Figure 7. Illustrative capacity curve in the acceleration–displacement (Sa–Sd) format and identification of damage and performance levels, as well as response limit states.

Table 3. Definition of seismic response limit states.

Limit State	Description	Structural Response Indicator
Completely operational (EL1)	Until this point, continuous service (school operates without any functionality loss) after earthquake is expected, with negligible structural and non-structural damage.	Accounts for 70% of the spectral displacement associated with the operational limit state (EL2).
Operational (EL2)	Structure is safe for occupancy and most operations can resume immediately after earthquake. Repair is required to restore some nonessential services. Damage is light.	Spectral displacement associated with the elastic limit of the capacity curve.
Life safety (EL3)	Life safety is generally achieved. Structure is damaged to a moderate level but remains stable. Some building systems or contents may be protected from damage. Extensive repair operations are necessary to rehabilitate the structure and restore full functionality. In some cases, rehabilitation may not be economically viable.	Spectral displacement associated with 3/4 of the spectral displacement value associated with the near collapse limit state (EL4). Note: in the case of shear failures in columns, this limit state corresponds to the point at which such brittle failure occurs.
Near collapse(EL4)	Although structural collapse is prevented, non-structural elements may fail. Structural damage is severe. Repair operations, if viable, are costly and generally long (depending on the allocated resources).	Displacement associated with the point at which the base shear force (or spectral acceleration) decreases by 20% relatively to the maximum base shear force (or the maximum spectral acceleration). Note: In the case of shear failures in columns, this limit state is associated with a spectral displacement equal to 4/3 of the spectral displacement associated with the life safety (EL3) limit state.

The joint analysis of the seismic response of the building structure, defined through its capacity curve, with the expected seismic action for the location, which depends on the geological–geotechnical conditions of the site, allows for the assessment of the performance of the structure. This performance point is computed using the Capacity Spectrum Method (CSM), which is recommended by the current international guidelines [25]. The CSM is used to determine the response of each structure to 32 levels of seismic action intensity. The plot of the structural response for each of these 32 seismic intensity levels defines the hazard curve in terms of structural displacement, represented in Figure 8. This curve relates the spectral displacement of the structure with the seismic intensity, defined herein through its return period.

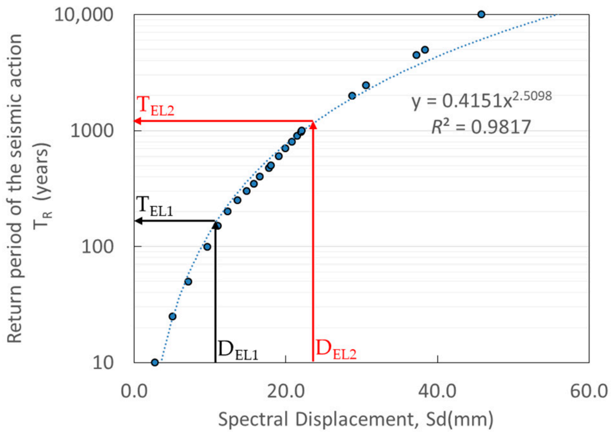


Figure 8. Structural response hazard curve—graphical representation of the procedure for calculating the return periods associated with the exceedance of the structural response limit states EL1 and EL2.

The structural response hazard curve is then used to determine the intensity of the seismic action, i.e., the return period, leading to the exceedance of the limit states (EL) represented in Figure 7 and described in Table 3. Figure 8 illustrates graphically the computation of the return periods T_{EL1} and T_{EL2} associated with the exceedance of EL1 and EL2, respectively.

The return periods of the seismic action associated with the exceedance of the defined structural response limit states are then compared against well-known thresholds, such as the ones proposed in VISION 2000 [26].

Schools are considered in this study as part of the third (γ_{III}) class of importance, according to NP EN 1998-1:2010, which corresponds to an essential performance objective. This classification takes into account the type of occupation of the schools and their importance in the post-earthquake response, namely their use in the allocation of key post-event services. Therefore, Table 4 presents the minimum objectives, in terms of performance levels, associated with four seismic intensity levels. As can be seen, the minimum performance levels for essential buildings are more demanding than the performance levels applicable to ordinary buildings (e.g., residential buildings).

Table 4. Definition of performance objectives for current and essential buildings (adapted from [26]).

Intensity Level of Seismic Action	Return Period of Seismic Action	Probability of Exceedance	Minimum Seismic Performance for Ordinary Buildings	Minimum Seismic Performance for Essential Buildings
Recurrent	43 years	50% in 30 years	Completely operational	-
Frequent	72 years	50% in 50 years	Operational	Completely operational
Rare	475 years	10% in 50 years	Life safety	Operational
Very rare	975 years	5% in 50 years	Near collapse	Life safety
Maximum considered	2475 years	2% in 50 years	Imminent collapse	Near collapse

In order to facilitate the visualization of the results, the seismic performance of the school buildings was represented in the form of a performance matrix, as shown in Figure 9, that graphically represents the seismic performance achieved by each structure for four levels of seismic intensity. This representation allows for verification of whether the structural seismic performance meets the minimum requirements for this type of structure (essential performance objective).

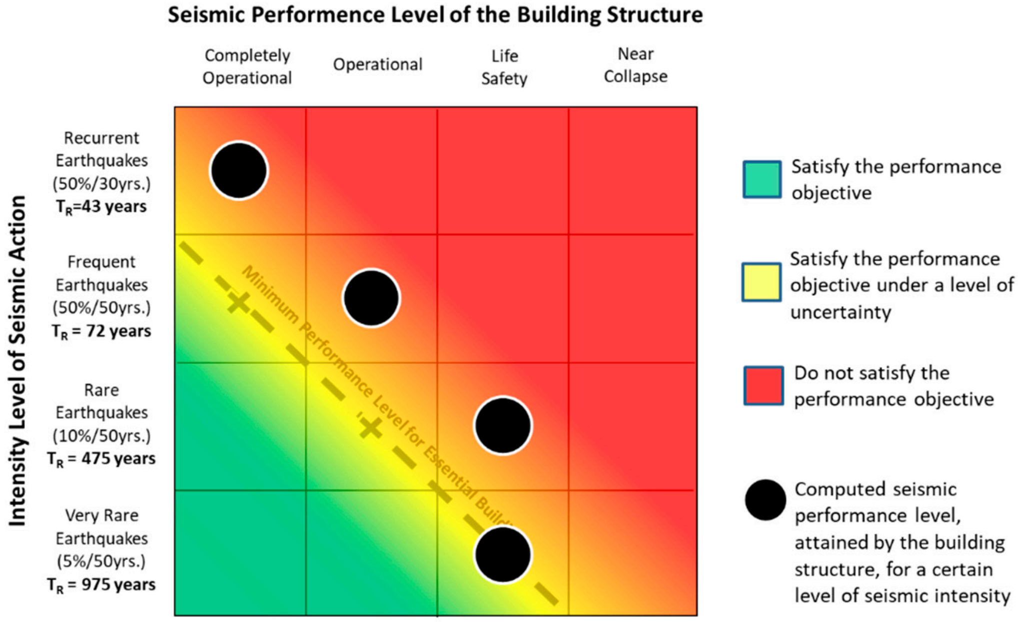


Figure 9. Seismic performance matrix with identification of the admissible and non-admissible zone (matrix of the school *ES José Gomes Ferreira*).

The methodology employed herein also yields estimates of losses and recovery times, which are fundamental to assess the risk and resilience of the school network, under different seismic scenarios. Losses are computed based on the return periods that lead to the exceedance of the defined limit states. The expected losses, per year (AEL—Annual Expected Loss), and over 50 years (TEL—50 years life Time Expected Loss) are thus computed by:

$$\text{AEL }(\%) = \sum P_{ELi} \times DF_{ELi} \tag{1}$$

$$\text{TEL }(\%) = \sum \left(1 - (1 - P_{ELi})^{50}\right) \times DF_{ELi} \tag{2}$$

where P_{ELi} corresponds to the probability that the structure equals or exceeds the EL_i limit state and DF_{ELi} corresponds to the damage factor (estimated loss ratio as a function of built-up area) associated with the EL_i limit state. The probability P_{ELi} corresponds to the inverse of the return period associated with limit state EL_i. It should be noted that the computation of the expected loss over a 50-year period assumes that: (i) over this time period, the current state of schools is, at least, maintained by rehabilitation/recovery interventions, guaranteeing that no aggravation on seismic vulnerability occurs; and (ii) the probability of the occurrence of a seismic event is uniform over that time period.

The sum of the expected losses, in terms of lost areas, over a 50-year time period in the various CML schools, allows for the computation of a global risk indicator. This corresponds to the expected loss index, computed as:

$$I_v(\%) = \Sigma(TEL_k \cdot A_k)/\Sigma A_k \tag{3}$$

where k varies between 1 and the number of schools and A_i is the area of each school.

Following a similar approach, the recovery time, RT_{Eli}, expressed through the number of interdiction days due to the occurrence of earthquakes, is also estimated. The estimated loss values and the number of interdiction days associated with each limit state are shown in Table 5. These values are defined based on the literature and existing risk assessment frameworks [60,61].

Moreover, expected losses and recovery times are also computed for seven different seismic scenarios, presented in Table 6, that vary in the moment magnitude scale (M_w), between 5.3 and 7.1. All seismic scenarios considered in this research study are intraplate seismic scenarios, which correspond to the most relevant types of scenarios, as demonstrated in previous LNEC studies [56,60]. These intraplate seismic scenarios are based on earthquakes occurring along the Lower Tagus Valley, which corresponds to Lisbon's nearest seismogenic source [56,62–64].

Table 5. Definition of damage factor and recovery times associated with response limit states.

Limit State	EL1	EL2	EL3	EL4	Ref.
DF_{ELi}	1%	10%	75%	100%	Sousa and Campos Costa [60]
RT_{ELi}	1 day	60 days	240 days	720 days	HAZUS v.4.2.3 [61]

Table 6. Magnitudes and return periods associated with seven intraplate seismic scenarios.

Scenario	Return Period (Years)	Magnitude (M_w)
1	20	5.3
2	50	5.8
3	100	6.1
4	275	6.6
5	475	6.8
6	1100	7.0
7	2200	7.1

This approach provides results associated with different earthquake intensities and corresponding different probabilities of occurrence, which help stakeholders (in this case CML) to identify vulnerable assets that need to be strengthened and suggest potential leverage points for intervention useful for decision making and planning of emergency responses, depending on the earthquake intensity.

It is worth noting that the estimates obtained for each scenario assume that all available resources are allocated, without any limitation, thus not depending on the socioeconomic and political context that affect the decision making in a post-earthquake scenario. As a consequence, these estimates only depend on the expected damage level and associated recovery times of the school building portfolio.

Both the probabilistic seismic hazard analysis and the seismic scenarios defined in this study for CML's schools are based on a hazard model that integrates the seismogenic zones defined in the ERSTA project, Seismic and Tsunami Risk Study of Algarve [65]. The action determined for Lisbon is then amplified, taking into account the specific geotechnical characteristics of the soils where the CML schools are located. These ground characteristics are determined based on the soil map produced by LNEC [57], which was built using the systematization of hundreds of geotechnical surveys. The 32 schools being studied in this research work are thus assigned a given soil type, as shown in Figure 1. Among the total number of schools, 14 are located in soil type A, which corresponds to stiff rock foundation. The other 14 are located in soil type H, whereas 3 are located in soil type I. Finally, only one school is located in soil type V, which corresponds to one of the softest soils in LNEC's soil cartography. A detailed description of each soil type may be found in previous LNEC studies [22].

Based on the ground type associated with each school, the seismic action at the bedrock is propagated to the surface using equivalent linear stochastic analysis. The details of this procedure can be obtained in [66]. The surface response spectra, deduced through equivalent linear Frequency Response Functions (FRF), associated with the four ground types considered, are represented in Figure 10 for seismic scenario 5 (return period of 475 years).

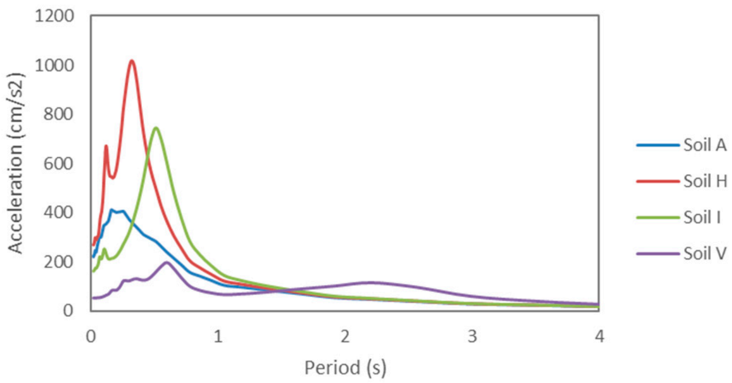


Figure 10. Response spectra associated with seismic scenario 5 (return period of 475 years) for the four ground types.

5. Risk Indicators and Intervention Prioritization

5.1. Current Situation

As referred to in the previous section, based on the return periods that lead to the exceedance of the response limit states, it is possible to compute the expected losses and recovery times associated with annual and 50-year time periods. The expected losses, as a function of the built-up areas (percentages and gross values correspond to red and blue bars, respectively) of school main buildings, are shown in Figure 11. To facilitate the reading of the results, Figure 12 shows the values of the expected losses in 50 years, in terms of the percentage of the school's main building areas, in decreasing order.

School	AEL (%)	AEL·A_i (m^2)	TEL (%)	TEL·A_i (m^2)	Typology	Area (m^2)	No.students	
Escola Básica Alto do Lumiar	0.01	0	0.33	16	3x3	4810	535	Reinforced concrete schools, of modular construction; framed structure with columns and beams; possible flat slabs
Escola Básica Damião de Góis	0.01	0	0.29	14	3x3	4810	365	
Escola Básica Professor Delfim Santos	0.01	0	0.29	21	3x3	7221	1040	
Escola Básica Olaias	0.01	0	0.29	14	3x3	4810	585	
Escola Básica Piscinas	0.01	0	0.33	9	3x3	2700	680	
Escola Secundária Lumiar	0.01	0	0.33	22	3x3	6625	725	
Escola Secundária Restelo	0.01	0	0.29	21	3x3	7366	1100	
Escola Básica Pintor Almada Negreiros	0.04	2	1.74	71	VR	4086	520	
Escola Básica Telheiras	0.04	2	1.74	71	VR	4086	595	
Escola Básica São Vicente – Telheiras	0.17	11	6.00	372	VR	6202	730	
Escola Básica Marvila	0.06	2	2.73	104	C24T	3810	330	
Escola Básica Professor Lindley Cintra	0.04	2	1.95	74	C24T	3810	530	
Escola Básica Olivais	0.05	2	2.27	87	C24T	3810	535	
Escola Básica Bairro do Padre Cruz	0.01	0	0.51	14	RC	2785	350	Reinforced concrete schools, not included in the previous typologies
Escola Secundária José Gomes Ferreira	0.11	10	4.25	383	RC	9028	1000	
Escola Básica Fernando Pessoa	0.27	14	7.75	394	RC	5086	800	
Escola Secundária Marquês de Pombal	0.19	23	6.29	791	RC	12,570	400	
Escola Básica Luís António Verney	0.35	16	8.73	393	RC	4500	420	
Escola Básica Luís de Camões	0.70	15	28.80	594	RC	2062	500	
Escola Básica Manuel da Maia	0.12	10	4.69	399	RC	8500	365	
Escola Básica Quinta de Marrocos	0.01	0	0.42	12	RC	2785	585	
Escola Básica Almirante Gago Coutinho	0.49	11	20.85	472	Comp. CM	2264	450	Schools with composite masonry-concrete or concrete-masonry structures
Escola Secundária Dona Luísa de Gusmão	0.09	2	4.06	108	Comp. CM	2662	990	
Escola Básica Paula Vicente	0.91	34	12.24	462	Comp. CM	3772	430	
Escola Básica Nuno Gonçalves	0.71	23	23.80	764	Comp. MC	3209	910	
Escola Básica Patrício Prazeres	0.31	13	12.25	514	Comp. MC	4201	475	
Escola Básica Eugénio dos Santos	0.73	25	24.38	847	Comp. MC	3475	830	
Escola Artística Instituto Gregoriano de Lisboa	0.33	2	12.88	61	Comp. MC	472	475	
	AEL_{total} (m^2) = 220		TEL_{total} (m^2) = 7103					
	Ip/year = 0.2%		**Ip/50yrs = 5.4%**					
Escola Básica Vasco da Gama					RC			Not analyzed
Escola Artística de Dança do Conservatório Nacional					Comp. MC			
Escola Profissional Ciências Geográficas					Comp. MC			
Escola Secundária Maria Amália Vaz de Carvalho					Comp. MC			

Figure 11. Expected losses as a function of the built area of the schools.

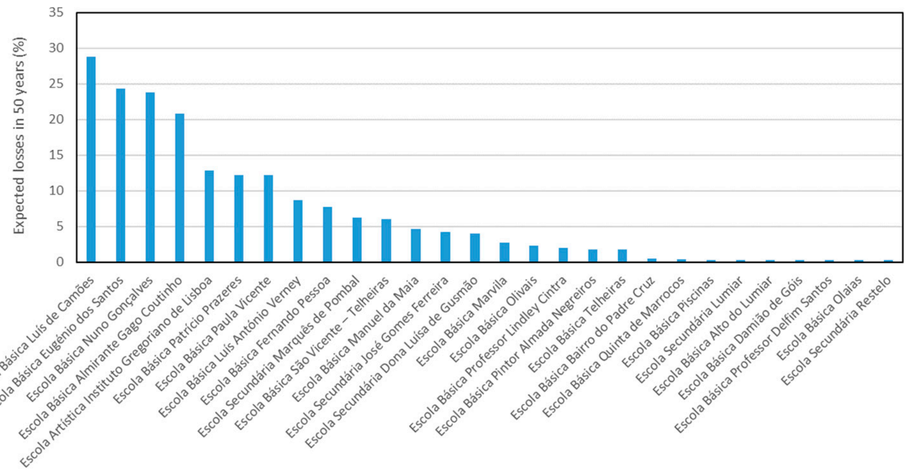


Figure 12. School ranking according to expected losses over 50 years (as a percentage of school area).

It is possible to verify that four schools register expected losses in 50 years greater than 20% of its area, while in three other schools the expected losses are greater than 10%. These schools are mostly of composite MC or CM typologies. The exception is the school *Luís de Camões*, which is a reinforced concrete school presenting a structural deficit to withstand the expected seismic action level. It is considered that these seven schools have a high level of expected losses (AEL = 0.7%), a value that is more than three times higher than the value of the general building stock in Lisbon, obtained in previous LNEC studies [60,67], which is 0.2%. Nevertheless, the global annual expected loss of the 28 analyzed schools is also 0.2%, as shown in Figure 11. Thus, the global seismic behavior of schools is in line with the seismic behavior of Lisbon's building stock. This loss value is also close to the one mentioned in the literature for the Italian school buildings portfolio [46], which reflects a greater relative seismic vulnerability of Lisbon's analyzed school buildings portfolio, taking into account that the seismicity of Italy is higher than that of the Lisbon territory.

Keeping the current conditions, the expected loss over 50 years is 5.4% of the total area of the schools. Although a loss of 5.4% of the total school building portfolio under analysis cannot be considered negligible, it is not a very large value. This observation is related to the fact that the vast majority of schools have an adequate performance regarding limit states 3 and 4, whose associated losses are potentially substantial. Thus, this loss value is concentrated in a relatively small number of schools. Furthermore, the seismicity expected in Lisbon is moderate, which leads to the fact that the probability of exceeding the most severe limit states is relatively low.

The composite building structure schools present a generally less satisfactory performance, as can be seen in Figure 11. The structural system of these schools and the current demands in terms of seismic performance contribute to the fact that the performance objectives are not achieved for most of these schools. It should be recalled, however, that most of them were built before the enforcement of the regulations that consider seismic action in structural design.

In what concerns the scenario-based analysis, the calculation of losses associated with each scenario corresponds to the computation of the seismic performance level achieved by each school building for the seismic intensity associated with that scenario. Once determined, the total loss for each scenario corresponds to the sum of losses for each school, given the occurrence of the seismic scenario under analysis. Table 7 shows the expected losses for each seismic scenario. For an earthquake with magnitude 6.6 and a return period of 275 years, the expected loss is approximately 9.1%, while for an earthquake with a magnitude of 7.1 (return period of 2200 years), the expected loss is 17.7% of the total area of the schools. It should be recalled that these values correspond only to direct losses due to the damage induced by the seismic action in the building structures and do not include indirect losses.

Table 7. Expected losses for the considered seismic scenarios.

Scenario	Return Period (Years)	Magnitude (M_W)	Expected Loss (%)
1	20	5.3	0.3%
2	50	5.8	1.9%
3	100	6.1	4.4%
4	275	6.6	9.1%
5	475	6.8	12.1%
6	1100	7.0	13.5%
7	2200	7.1	17.7%

5.2. Mitigation Simulation

A conceptual strengthening intervention is implemented in the most vulnerable school buildings in order to mitigate the seismic risk of the school building portfolio. The structural systems of the four schools with estimated losses above 20% in 50 years are considered to be strengthened so that negligible losses and recovery times are obtained in 50 years. The estimated losses and recovery times associated with the entire school building portfolio are then reassessed based on the improved results achieved by these four most vulnerable schools.

With this mitigation intervention, the highest losses are now concentrated in the group of three schools that record losses of approximately 12% (see Figure 12). Recall that, without mitigation, the highest losses were above 20% (in the four schools that were strengthened in the test mitigation intervention).

Table 8 shows the expected losses for each seismic scenario, obtained considering these mitigation interventions, as well as the relative difference of the estimated losses in the current situation. It can be seen that, for seismic scenarios 4 to 7, i.e., scenarios with magnitudes larger than 6.6, an average loss reduction of 47.5% is obtained. For lower magnitude scenarios, the loss reduction is not as effective. This observation is due to the fact that a small number of schools do not comply with the most demanding limit states (limit states 3 and 4), thus concentrating the losses due to high intensity earthquakes on this relatively small number of schools. As a consequence, an intervention for these schools results in an effective reduction in the expected losses. On the other hand, for lower intensity seismic scenarios, the expected losses are spread through a larger number of schools, since the performance targets associated with functionality (limit states 1 and 2) are not met for a much larger number of buildings. As a consequence, intervention in just four of the buildings leads to a less effective loss reduction.

Table 8. Expected losses and loss reduction with and without a test strengthening intervention in four schools for the considered seismic scenarios.

Scenario	Expected Loss w/o Strengthening (%)	Expected Loss w/ Strengthening (%)	Loss Reduction (%)
1	0.3%	0.3%	0%
2	1.9%	1.2%	36%
3	4.4%	3.6%	19%
4	9.1%	5.0%	45%
5	12.1%	5.8%	52%
6	13.5%	6.4%	53%
7	17.7%	10.6%	40%

With this test mitigation intervention, and for an earthquake with a magnitude of 6.6 and a return period of 275 years, the expected loss is now approximately 5.0% (9.1% without strengthening), while for an earthquake with a magnitude of 7.1 (return period of 2200 years) the expected loss is now 10.6% (17.7% without strengthening).

This hypothetical mitigation intervention shows that, by strengthening a relatively low number of schools, it is possible to effectively reduce the expected losses and, thus, to mitigate the seismic risk for the school building portfolio.

6. Resilience Assessment

6.1. Current Situation

In addition to calculating the estimated losses, recovery times of each school due to seismic damage were also computed, which enables the assessment of their post-earthquake functionality. In particular, it allows for the estimation of which schools would be closed after an earthquake and, consequently, the need to relocate students for a significant period of time after the earthquake.

This section presents the results in terms of the estimated number of days each school would be closed due to seismic damage, either annually or over a 50-year period, as well as the corresponding resilience indicator "relocated students x month" (SMD). From the sum of the product of the annual probabilities of exceeding each limit state by the corresponding interdiction days, the Annual Expected Interdiction days (AEI) for each school is obtained. The calculation of the interdiction days over 50 years (TEI) is done similarly to the calculation of expected losses over a similar time frame. These values are shown in Figure 13. To facilitate the reading of the results, Figure 14 presents the number of interdiction days in 50 years, in decreasing order.

School	AEI (days)	TEI (days)	SMD (std·month)	Typology	Area (m^2)	No.students	
Escola Básica Alto do Lumiar	0.0	1.5	26	3x3	4810	535	Reinforced concrete schools, of modular construction; framed structure with columns and beams; possible flat slabs
Escola Básica Damião de Góis	0.0	1.3	16	3x3	4810	365	
Escola Básica Professor Delfim Santos	0.0	1.3	45	3x3	7221	1040	
Escola Básica Olaias	0.0	1.3	25	3x3	4810	585	
Escola Básica Piscinas	0.0	1.5	34	3x3	2700	680	
Escola Secundária Lumiar	0.0	1.5	36	3x3	6625	725	
Escola Secundária Restelo	0.0	1.3	47	3x3	7366	1100	
Escola Básica Pintor Almada Negreiros	0.2	8.8	153	VR	4086	520	
Escola Básica Telheiras	0.2	8.8	175	VR	4086	595	
Escola Básica São Vicente – Telheiras	0.9	32.6	792	VR	6202	730	
Escola Básica Marvila	0.3	14.3	158	C24T	3810	330	
Escola Básica Professor Lindley Cintra	0.2	10.0	177	C24T	3810	530	
Escola Básica Olivais	0.3	11.8	210	C24T	3810	535	
Escola Básica Bairro do Padre Cruz	0.0	2.3	27	RC	2785	350	Reinforced concrete schools, not included in the previous typologies
Escola Secundária José Gomes Ferreira	0.6	22.7	756	RC	9028	1000	
Escola Básica Fernando Pessoa	1.4	42.4	1132	RC	5086	800	
Escola Secundária Marquês de Pombal	1.0	34.2	456	RC	12,570	400	
Escola Básica Luís António Verney	1.8	47.9	670	RC	4500	420	
Escola Básica Luís de Camões	3.6	147.1	2452	RC	2062	500	
Escola Básica Manuel da Maia	0.6	25.2	307	RC	8500	365	
Escola Básica Quinta de Marrocos	0.0	2.1	42	RC	2785	585	
Escola Básica Almirante Gago Coutinho	2.4	101.7	1526	Comp. CM	2264	450	Schools with composite masonry-concrete or concrete-masonry structures
Escola Secundária Dona Luísa de Gusmão	0.4	18.8	621	Comp. CM	2662	990	
Escola Básica Paula Vicente	4.5	66.6	955	Comp. CM	3772	430	
Escola Básica Nuno Gonçalves	3.3	102.2	3100	Comp. MC	3209	910	
Escola Básica Patrício Prazeres	1.5	64.9	1028	Comp. MC	4201	475	
Escola Básica Eugénio dos Santos	3.3	104.3	2887	Comp. MC	3475	830	
Escola Artística Instituto Gregoriano de Lisboa	1.6	64.0	1013	Comp. MC	472	475	
Escola Básica Vasco da Gama				RC			Not analyzed
Escola Artística de Dança do Conservatório Nacional				Comp. MC			
Escola Profissional Ciências Geográficas				Comp. MC			
Escola Secundária Maria Amália Vaz de Carvalho				Comp. MC			

Figure 13. Expected number of interdiction days and "relocated students x month" indicator (SMD).

Figures 13 and 14 show that four schools are expected to register a number of interdiction days in 50 years above 3 months, while three other schools will be closed for more than 2 months in 50 years. Regarding the SMD indicator, three schools have a value greater than 2400. The values presented here can serve as a basis for developing a response plan for seismic events at the municipal level.

A post-earthquake resilience assessment is performed by calculating the recovery times associated with each school given the occurrence of seven different seismic scenarios. For each scenario, the performance level achieved by each main building allows for the computation of the number of interdiction days and, consequently, the recovery time. Consequently, it is possible to determine the number of schools closed as a function of the time after the earthquake.

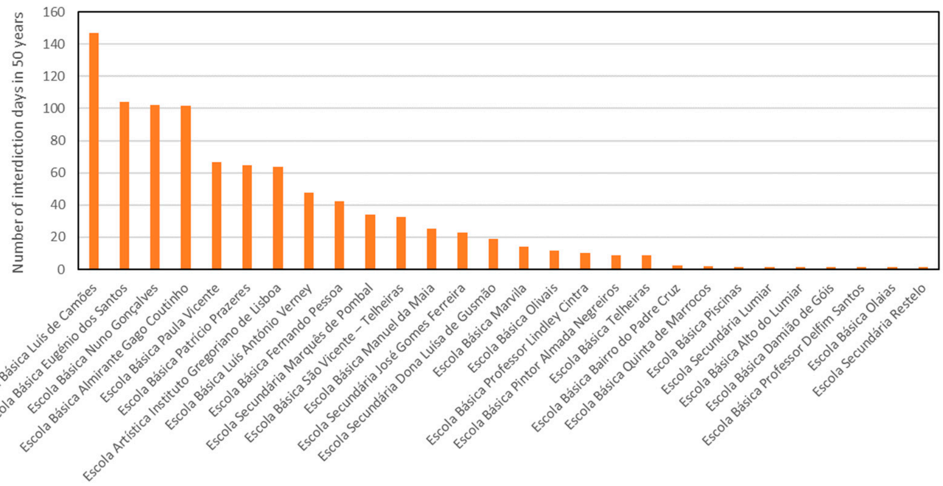


Figure 14. School ranking according to the number of interdiction days over 50 years.

Figure 15 shows the resilience curves of the schools analyzed for seven different seismic scenarios, as well as the median curve (weighted by the probability of each seismic scenario) and median minus one standard deviation. These curves relate the number of operational schools as a function of time after the seismic event. For instance, for Scenario 1, the lowest intensity of the seven scenarios considered, only 7% of the analyzed schools are expected to be closed the day after the earthquake (for inspection, planning and execution of the cleaning, rehabilitation, or reinforcement intervention). The remaining schools did not exceed the first limit state (completely operational); therefore, no inspection is required and they may continue to function immediately after the earthquake. On the other hand, for Scenarios 6 and 7, the most intense that are considered, all 28 schools will be closed for at least 1 day. However, after 240 days, only about 25% of the schools will remain closed. Over time, schools will be incrementally reopened, by meeting the proper conditions or due to rehabilitation actions, until all schools are operational again, which is anticipated to take place in a maximum period of two years (730 days).

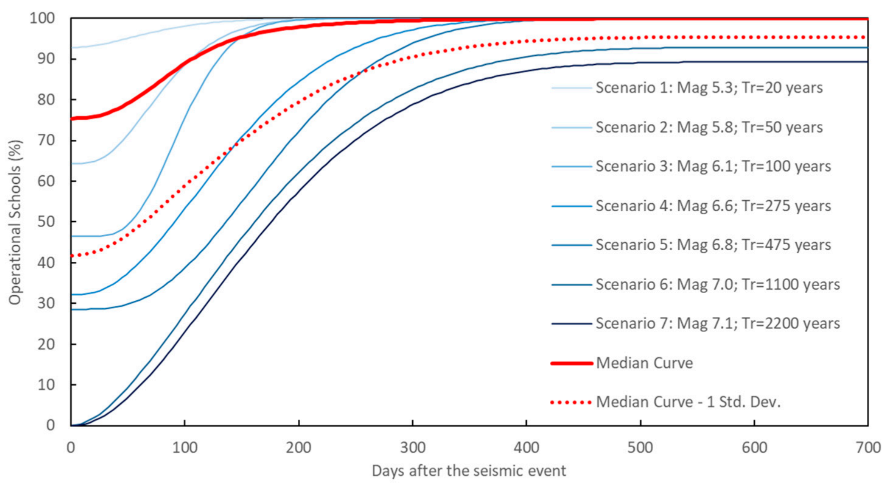


Figure 15. Resilience curves of the school buildings portfolio (28 schools) for seven seismic scenarios.

This data may assist in the development of individual emergency plans and of an integrated emergency response plan that addresses the need to relocate students after an earthquake event. The analysis of the remaining CML schools (under development), as well as complementary systems, namely accessibility, will provide additional data for future analyses of the resilience of the CML school network.

6.2. Mitigation Simulation

Similarly to what was done for the expected losses, the number of interdiction days and, consequently, the recovery times were reassessed considering that the four schools with estimated losses above 20% in 50 years are virtually strengthened so that a negligible number of interdiction days in 50 years are expected for these schools.

Under these considerations, the maximum number of interdiction days in any school is now around 65 days in 50 years (see Figure 14), whereas before the intervention, the four most vulnerable schools recorded a number of interdiction days in 50 years above 100 days.

Figure 16 presents the resilience curves of the school building portfolio considering the test strengthening intervention in the referred four schools. Blue lines represent the resilience curves with strengthening, whereas the same colors used in Figure 15 are kept for the curves associated with the current situation (without strengthening). Figure 16 illustrates that a global increase in the number of operational schools after an earthquake is obtained with this intervention. This means that not only a smaller number of schools will be closed after the seismic event, but also that the complete functionality of the entire system will be attained earlier after the earthquake.

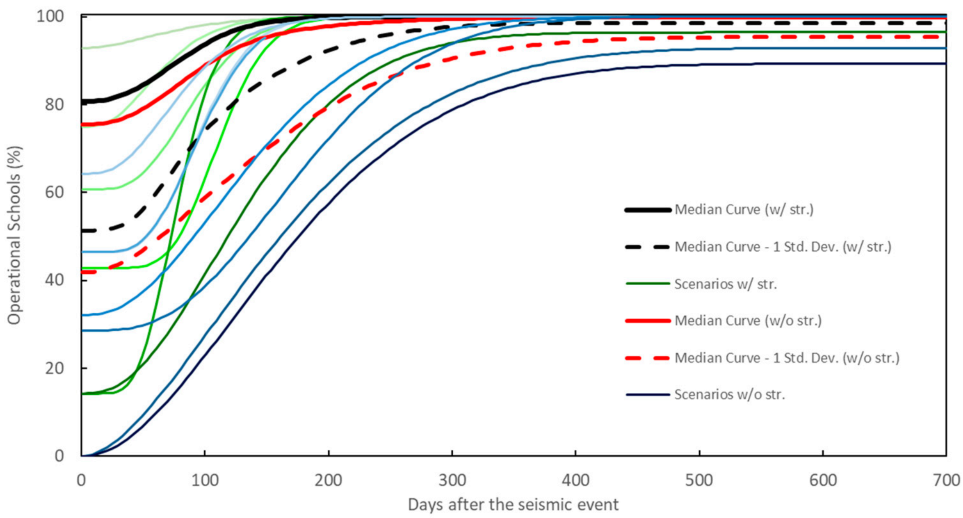


Figure 16. Resilience curves of the school buildings portfolio (28 schools) for seven seismic scenarios, with and without a test strengthening intervention in four schools.

Nevertheless, it should be noted that the test mitigation intervention was focused on the most vulnerable schools, based on the expected losses. To optimize the improvements regarding the functionality of the school building portfolio, an intervention based on the improvement of the seismic performance of the buildings should be carried out concerning operational performance levels (limit states 1 and 2), meaning that a larger number of buildings should be subjected to intervention.

7. Conclusions

The integrated management of the school buildings portfolio is fundamental, particularly in regard to the definition of a global strategy for the mitigation of seismic risk, including interventions in the most vulnerable schools. This research work addressed the risk and resilience of 32 schools in Lisbon (Portugal) under seismic events, which are probabilistically defined specifically for the sites of the schools, accounting for the local soil conditions and associated amplification effects. The final outcomes of the study are the definition, for each school, of a seismic risk profile, including a performance matrix that graphically represents the achievement or the failure to meet the seismic performance targets established for various seismic intensity levels. Risk parameters are also estimated, namely estimated losses in terms of the area of the schools and the number of interdiction days, which provide a global view of the effects of seismic events on the school portfolio and allow for the ranking of schools according to these risk and resilience indicators.

Based on the results of this study, a short- and medium-term intervention plan was developed jointly by CML and LNEC to mitigate the seismic risk of these schools.

The results obtained in this study yielded the following main conclusions:

- Overall, the seismic performance of these schools is in line with that of the housing stock in the city of Lisbon, obtained in previous LNEC studies;
- considering all schools analyzed, the level of expected losses is 5.4% of their built-up area for a time period of 50 years; this seismic risk value is close to the one mentioned in the literature for the Italian school buildings portfolio, which reflects a greater relative seismic vulnerability of the analyzed school buildings portfolio, taking into account that the seismicity of Italy is higher than that of the CML territory;
- four schools are associated with expected losses, due to the occurrence of earthquakes over a period of 50 years, greater than 20%, while other three schools register expected losses greater than 10%. These seven schools are considered to have a high level of expected losses;
- modular structural typologies, namely 3 × 3, C24T, and Vale Rosal typologies, as well as most of the other reinforced concrete schools, show a satisfactory seismic performance in regard to the established performance objectives. This fact is related to the regulations to which these buildings were designed, namely in the period when seismic design was included in the Portuguese design codes;
- composite typology schools present a generally less satisfactory performance. In fact, their construction system and the current demands in terms of seismic performance objectives, which are much more demanding than those (if any) present in the design codes that were in force at the time these structures were built, lead to this undesirable deficit of a capacity to withstand expected seismic loads;
- for a seismic scenario with magnitude $M_w = 6.6$ and a return period of 275 years, the expected losses are approximately 9.1%, while for a scenario with a magnitude $M_w = 7.1$ (return period of 2200 years) the expected losses are 17.7% of the total area of the schools;
- it is estimated that four schools will have recovery times greater than 3 months in 50 years and three other schools will be closed for more than 2 months in 50 years. Regarding the indicator "relocated students × month", three schools present a value greater than 2400 "relocated students x month" in 50 years;
- a hypothetical mitigation intervention was analyzed, which showed that, by strengthening a relatively low number of schools, it is possible to effectively reduce the expected losses and recovery times and, thus, to mitigate seismic risk on the school building portfolio. This highlights the importance of considering an accurate prioritization scheme in the selection of the most effective intervention strategy.

Based on the obtained results, CML and LNEC defined a plan for seismic risk mitigation through the retrofitting of the most vulnerable schools. Specific studies for the seven schools will be conducted in the short-term, including in situ tests of materials, dynamic characterization of the buildings (vibration periods, mode shapes, and equivalent damping), soil characterization and foundation surveys, as well as the development of cost-effective retrofitting design solutions. Moreover, it is envisioned to develop a guide for reducing nonstructural seismic vulnerabilities, as well as the production of dissemination material addressed to students, teachers, and parents to enhance the level of community awareness and preparation for seismic events.

Currently, other 77 Lisbon school buildings, which correspond to the remaining CML school buildings, are under assessment. At the same time, the LNEC is taking part in the detailed assessment and retrofitting cost-benefit analysis of the most vulnerable buildings identified in this work. Additionally, extension of the study to other regions of Portugal with significant seismic hazards, namely the remaining municipalities of the Lisbon Metropolitan Area, is being planned. As for future developments, it is envisioned to include non-structural elements and indirect losses in the risk assessment methodology. Although non-structural elements are expected to influence the performance and losses associated with the initial damage states, their influence on the ultimate capacity of the structure, i.e., on significant damage and collapse limit states, still remains an open topic.

Author Contributions: The work presented in this paper resulted from the multidisciplinary work developed by the research team of the Earthquake Engineering and Structural Dynamics Unit (NESDE) of LNEC. The seismic hazard scenarios and corresponding response spectra were developed by A.R.C. The characterization of the building stock, systematization of information, visual inspections of the buildings, and numerical modeling was carried out by F.L.R., P.X.C., and A.C.C. The performance assessment, including the implementation of the Capacity Spectrum Method was conducted by the previous three researchers, together with A.A.C. All the authors collaborated on the design of the study methodology, as well as on the contacts with the Lisbon City Council in order to communicate the outcomes of the study and assist in the definition of an intervention plan. Finally, all authors contributed to the writing of this paper, which was led by the first author. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Lisbon City Council through a project established with the Buildings Department of LNEC, LNEC Proc. 0305/1201/2231501.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the throughout support of the Lisbon City Council in the development of the study, as well as to the collaboration of all the school building managers that made the visual inspections possible. The authors would also like to acknowledge the contribution of the Buildings Department of LNEC in the systematization of the information both from the Lisbon City Council and other sources, namely the Atlas of School Architecture in Portugal.

Conflicts of Interest: The authors declare no conflict of interest.

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