SEISMIC AND STRUCTURAL RISK ASSESSMENT OF AN EDUCATIONAL BUILDING FOR COMMUNITY SUSTAINABILITY: A CASE STUDY IN ZARUMA, ECUADOR

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ABSTRACT

Zaruma, an Ecuadorian city with a mining tradition, has natural conditions of steep slopes and environmental and socio-economic impacts related to old and illegal mining operations. Different geodynamic events (e.g. seismic movements, settlements and sinkholes) have caused structural damage to essential buildings such as the ‘San Juan Bosco’ School. This research aims to assess the seismic vulnerability of reinforced concrete buildings of the ‘San Juan Bosco’ School through the analysis of national and international seismic codes for the proposal of rehabilitation works that guarantee the sustainability of the structure. The study included technical visits to observe the current damage to the structures. The structural characteristics of the buildings were identified using auscultation and concrete coring. The gathered data and an analysis of the site’s seismic hazard allowed for a structural assessment of the buildings carried out using national (NEC) and international (ASCE/SEI) codes. Subsequently, rehabilitation alternatives were proposed for each building according to national and international (FEMA) standards. The structural system, composed of moment-resisting concrete frames, presents potential vulnerabilities owing to impact (collision) and torsion attributed to its overhangs. The structural assessment revealed that all blocks comply with the drift limits stipulated by ASCE 41-13 (below 2%); only block B5.6 exceeds these limits (2.25%). Recommended rehabilitation strategies include mass reduction (removal of upper floors, representing a dead load of 700 kg/m^2 and a live load of 400 kg/m^2) and removal of short columns (decreased window width). These interventions are intended to facilitate education, thus benefiting the Zaruma Mining District community.
Keywords: seismic rehabilitation, building inspection, structural evaluation, reinforced concrete.

1 INTRODUCTION

The Earth has been subjected to several destructive natural hazards throughout geological time, of which one of the most dangerous is earthquake [1]. This natural phenomenon is an essential manifestation of the strength of tectonic forces caused by the thermal state of Earth’s interior [2]. Most of the energy in subduction zones generates massive earthquakes [3]. As the boundary between the Nazca Plate and the South American Plate, earthquakes occurred off the coasts of Ecuador and Colombia in 1942 (Mw 7.8), 1958 (Mw 7.7), 1979 (Mw 8.2), and 2016 (Mw 7.8) [4].

Earthquake damage to structures and infrastructure results in the loss of functionality, economic losses, fatalities, and injuries [5]. Deaths and injuries depend mainly on the scale of damage to structural and non-structural components [6]. In Turkey, more than 150,000 people died and 900,000 buildings were damaged during earthquakes in the last century [7].

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240251

Engineers design structures using the guidelines provided by seismic-resistant codes, which include some unknowns and assumptions [8]. If well-designed according to modern codes (e.g. ANSI/AISC 341-16, NBC-2015), such structures can withstand large structural damage with a low risk of collapse in the event of a strong earthquake, thus avoiding unnecessary casualties [9]. It is essential to assess seismic vulnerability for realistic preparedness, response-action strategies, and effective seismic hazard management [10].

Essential facilities (e.g. schools and hospitals) play a strategic role under normal conditions, and their role is even more important and critical during a disaster [11]. Uninterrupted use of essential facilities is crucial for the functionality of a community or city. However, recent studies have highlighted the high seismic risks of these buildings [12].

Most countries on the west coast of South America are prone to major seismic catastrophes owing to their location on the Pacific Ring of Fire [3]. Previous earthquakes have confirmed that Ecuador is one of the most vulnerable countries in South America. The earthquake in Pedernales (Mw 7.8) affected the coastal provinces of Manabí, Esmeraldas, Guayas, and El Oro, where fatalities and injuries have been reported [4]. In addition, 875 schools were affected by the earthquake with different levels of damage [13].

Zaruma is a mining town with a unique geological mining heritage. It is located in the western foothills of the Andes Mountains, in the El Oro Province (southwestern Ecuador (Fig 1(a))), with an area of 659.40 km^2 and a population of 24,097 inhabitants [14] (Fig. 1(b)).

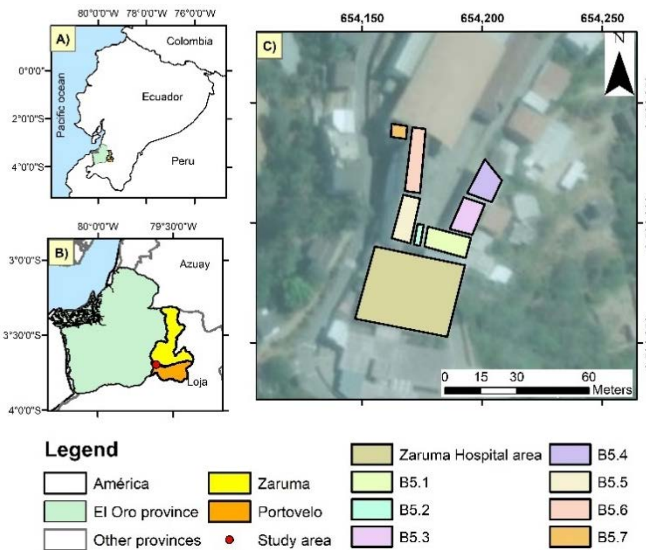

Figure 1: Geographical location map of the study area. (a) El Oro province within Ecuador; (b) The study area concerning the Zaruma canton; and (c) Structures analysed in the 'San Juan Bosco' School, next to the Humberto Molina Hospital.

Geodynamic events such as subsidence are associated with informal mining activities and earthquakes in Zaruma [15]. Seven subsidence events occurred between 2016 and 2022, most notably the 'La Inmaculada' school (2016) and the Avenida Colón subsidence (2021). Meanwhile, within a radius of 250 km from Zaruma, there were 22 earthquakes greater than Mw 5.5, including two earthquakes in 1995 (Mw 6.5 and 7.0; 217 km away) and in 2017 in

Balao (Mw 5.5; 80 km away). The latter caused the closure of several essential facilities (e.g. Humberto Molina Hospital and 'San Juan Bosco' School) [16].

Zaruma, Portovelo, and Atahualpa cantons have 65 Education Centres, including 'San Juan Bosco' School. The Educational Centre began in 1993 and is located south of Zaruma, where it continues to function. Currently, this school has approximately 1,000 students at the primary and secondary levels, ensuring a continuous, safe, and functional learning environment within the students' education.

Throughout the years, buildings have suffered damages related to inadequate structural design, informal construction, improper performance of certain non-structural elements, and the occurrence of earthquakes near Zaruma. The evaluation and diagnosis of the structural system of the existing 'San Juan Bosco' School facilities will serve as a basis for the adaptation or diagnosis of other educational centres. With this structural analysis, rehabilitation alternatives can be proposed to ensure the safety of students, teachers, and staff in general within the school. Moreover, educational centres serve as complexes in emergency situations, such as community resilience. The continued operation of the educational centre generates a positive economic and social impact, generating employment and a suitable environment for education in the long term.

Therefore, the following research question arises: How to respond to the vulnerability of the 'San Juan Bosco' School blocks by evaluating buildings using engineering techniques? This research aims to assess the seismic and structural risks of the buildings of the 'San Juan Bosco' School through inspection field visits and analysis in specialised software for the proposal of engineering solutions that guarantee the socio-educational sustainability of the Zaruma community.

2 GENERAL DESCRIPTION OF THE INFRASTRUCTURE

All blocks of the educational unit had three levels, consisting of two concrete slabs and a steel panel or Eternit roofing. Fig. 1(c) shows the layout of the blocks in the school, and Table 1 lists the building characteristics.

3 MATERIALS AND METHODS

The methodological procedure proposed in this research consists of reviewing information on the 'San Juan Bosco' School and gathering field data (e.g. in situ measurements in buildings and sampling for the laboratory) for the current structural evaluation, incorporating the geodynamic conditions of Zaruma. Solutions for reopening the rehabilitation works of the 'San Juan Bosco' School were analysed.

This study was divided into three phases (Fig. 2): (1) information gathering through fieldwork and sampling; (2) conducting structural assessment under current conditions; and (3) proposing rehabilitation alternatives to decision-makers.

3.1 Data analysis

3.1.1 Baseline inspection

The inspection was carried out through several visits to the study area ('San Juan Bosco' School) based on the international standard American Society of Civil Engineers and Structural Engineering Institute ASCE/SEI 41-13 [17]. This initial survey determined the external and internal dimensions of the buildings and structural elements, which were then used for structural evaluation using specialised software. Flexometer and tape were used to determine the exterior and interior dimensions of the buildings.

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Table 1: Physical-structural data collected during field visits to the buildings that integrate the 'San Juan Bosco' School.

Block (location in school)	Construction year	Building features	Image
B5.1 (South)	1993	➢ No structural plans and no engineers were involved ➢ It has three levels (two slabs and one roof) ➢ Area: 109.74 m^2 ➢ Height: 10 m ➢ Moment-resisting concrete frames (MRCF) ➢ Two-way ribbed slab ➢ Losa nervada en dos direcciones	
B5.2 (South)	1993	➢ Staircase sector (B5.1 and B5.5) ➢ Width: 1.40 m ➢ Area: 14.81 m^2 ➢ Height: 8.91 m	
B5.3 (Southeast)	1994	➢ It has four levels (one ground floor, two slabs and one roof) ➢ Area: 76.06 m^2 ➢ Height: 10.35 m ➢ MRCF	
B5.4 (East)	1994	➢ It has three levels (a ground floor, a slab and one roof) ➢ Area: 84.94 m^2 ➢ Height: 10.35 m ➢ MRCF	

Table 1: Continued.

Block (location in school)	Construction year	Building features	Image
B5.5 (Southwest)	1994	➢ Involvement of an architect ➢ It has four levels (one basement, two slabs and one roof) ➢ Area: 117.71 m^2 ➢ Height: 13.24 m ➢ MRCF	
B5.6 (West)	Late 90s	➢ It has four levels (one basement, two slabs and one roof) ➢ Area: 165.29 m^2 ➢ Height: 14.45 m ➢ MRCF	
B5.7 (West)	Late 90s	➢ Staircase sector (B5.6) ➢ Width: 1.45 m ➢ Area: 14.28 m^2 ➢ MRCF	

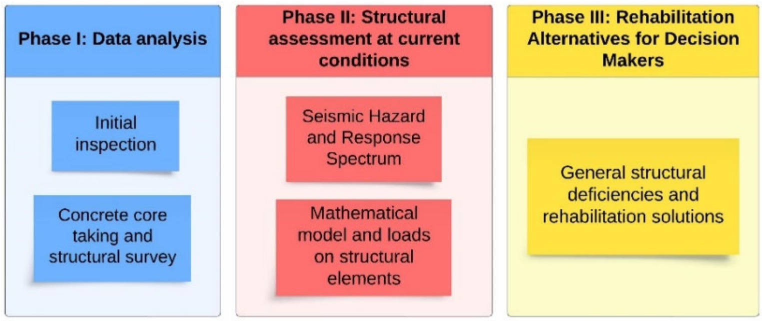

Figure 2: Proposed three-phase methodological scheme followed in this research within the study area. It includes the process of data collection in the field, the analysis of these data in software, and the proposal of rehabilitation alternatives.

3.1.2 Concrete coring and structural surveys

For structural characterisation, concrete cores were taken, and reinforcing steel was surveyed. Nine concrete cores were obtained from the columns, beams, slabs, and walls in the selected blocks (B5.1, B5.3, B5.6). This test was performed in accordance with the American Society for Testing and Materials (ASTM C39/C39M-23) [18]. These three buildings of the 'San Juan Bosco' School were chosen for three reasons: (i) the buildings had more upper floors; (ii) the top floor of each building was built and extended without structural consideration (extra weight was added to the structural members that were not considered in the initial designs); and (iii) there was a limited budget for testing.

The survey of reinforcing steel was carried out by auscultation of the structural elements (beam, column, and foundation). This auscultation made it possible to determine the type and quantity of reinforcing steel in the structural elements (the same blocks were chosen for taking concrete cores). Flexometer and digital Vernier calipers were used for this purpose.

3.2 Structural assessment under current conditions

3.2.1 Seismic hazard and response spectrum

Before the structural assessment, a seismic hazard characterisation was carried out based on the Ecuadorian Construction Norm (NEC, by its acronym in Spanish), promulgated by the Ministry of Urban Development and Housing of Ecuador (MIDUVI, by its acronym in Spanish) [19]. Zaruma is in Seismic Zone III, corresponding to a seismic hazard factor of 0.30g.

Chapter 2/Appendix C of ASCE/SEI [20] determines the elastic response spectrum. Because the school buildings are 20–30 years old, the BSE-1E parameter was selected as the seismic parameter for structural evaluation.

3.2.2 Mathematical model and loads on the structural elements

The columns and beams of the buildings were modelled using frame elements, whereas the floor slab was modelled using shell elements. The materials used for the various structural elements are:

- Compressive strength (B5.1): f'c = 180 kg/cm^2 for beams, columns and slabs.
- Concrete modulus of elasticity (B5.1): Ec = 202,500 kg/cm^2

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- Compressive strength (in other blocks): f’c = 290 kg/cm^2 for beams, columns and slabs.
- Concrete modulus of elasticity (in the other blocks): Ec = 257,000 kg/cm^2.

According to MIDUVI [19], the stiffness of the elements is as follows:

- Beams (bending) = 0.50EcIg; where Ig: inertia moment
- Columns = 0.80EcIg (compression)
- Walls (bending) = 0.60EcIg

The columns were embedded in the base of the building. The gravity loads used for the structural analysis are detailed below:

Slabs

- Total dead load ≈ 700 kg/m^2
- Classroom live load = 200 kg/m^2
- Live load on first floor = 500 kg/m^2
- Live load on upper floors = 400 kg/m^2

Steel roofs

- Total dead load ≈ 20 kg/m^2
- Live load = 70 kg/m^2

The load combinations used for the structural analysis, based on the requirements of ASCE/SEI 7-16 [21], were as follows:

- 1.1(D + 0.25 L) + E; where D: dead load, L: live load, and E: earthquake load.
- 0.9 D + E

3.3 Rehabilitation alternatives for decision-makers

As described in the previous section, three-dimensional mathematical models developed in SAP2000 [22] were used for the structural analysis, which was performed according to the guidelines contained in ASCE/SEI [20].

Similarly, a table was prepared showing the general weaknesses of the blocks of the ‘San Juan Bosco’ School as well as the structural rehabilitation alternatives recommended by MIDUVI [19] and the Federal Emergency Management Agency (FEMA) [23].

4 RESULTS

4.1 Baseline inspection and structural characterisation

Block B5 (consists of the blocks described in Table 1) has experienced several problems (1993 to date). From interviews with various professionals and school officials, it is known that block B5.1 experienced shear failure in a pair of columns during an earthquake in 1995. The columns were subsequently repaired by adding three walls in the north–south direction. Subsequently, during the extension of the block (construction of an additional floor with a steel panel roof), the block experienced tilting in the east–west direction. Therefore, this block was rehabilitated by constructing two spread footings in the east–west direction. It is important to note that this block was adjacent to Humberto Molina Hospital.

Block B5.6 has significant cracks in several walls in the basement crawl space. There are also small cracks, some of which are very fine, in other blocks. In recent years, some sectors of Block B5 have been disabled (e.g. the basement of Block B5.6). Table 2 summarises the dimensions, structural reinforcement, and compressive strength obtained during the initial inspection.

Table 2: Dimension of the structural elements within the buildings of the 'San Juan Bosco' School. The results of the structural reinforcement of the analysed elements are presented, as well as the compressive strength of the concrete coring.

Block	**Dimensions (mm × mm)**	**Structural reinforcement**	**Strength (f´c) (MPa)**
B5.1	➢ Column: 325 × 500 ➢ Beam: 330 × 500 ➢ Slab: 200	Column ➢ Longitudinal: 4ø22 ➢ Stirrups: ø8/190 mm ➢ Corrugated rod Beam ➢ $A_{sl,SUP}$: 2ø20 + 1ø14 ➢ $A_{sl,INF}$: 2ø20 ➢ A_{st}: 1 est. ø8/120mm	Column: 21.3 Beam: 13.6 Slab: 18.5
B5.2	➢ Column: 300 × 500 ➢ Beam: 200 × 300 ➢ Slab: 200	-	-
B5.3	➢ Column: 330 × 350 ➢ Beam: 280 × 400 ➢ Slab: 200	Column ➢ Longitudinal: 8ø18 ➢ Stirrups: 2ø8/125 mm Beam ➢ $A_{sl,SUP}$: 2ø18 ➢ $A_{sl,INF}$: 2ø18 ➢ A_{st}: 1 est. ø8/190mm	Column: 21.6 Beam: 32.6 Slab: 27.3
B5.4	➢ Column: 300 × 300 ➢ Beam: 200 × 200 ➢ Slab: 200	-	-
B5.5	➢ Column type 1: 350 × 350 ➢ Column type 2: 400 × 500 ➢ Column type 3: 400 × 600 ➢ Beam: 300 × 500 ➢ Slab: 200		
B5.6	➢ Column: 430 × 600 ➢ Beam: 300 × 500 ➢ Slab: 300	Column ➢ Longitudinal: 8ø20 ➢ Stirrups: 2ø8/220 mm Beam ➢ $A_{sl,SUP}$: 2ø20 ➢ $A_{sl,INF}$: 2ø20 ➢ A_{st}: 1 est. ø8/190mm	Column: 27.2 Wall: 14.2 Slab: 36.9
B5.7	➢ Column: 300 × 300 ➢ Beam: 200 × 300 ➢ Slab: 200	-	-

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4.2 Structural analysis of the blocks

For the preliminary evaluation of the 'San Juan Bosco' School's structures, the methodology proposed by ASCE/SEI 41-13 [20], and the results of the concrete coring and structural survey conducted during Phase I were used.

Table 3 and Fig. 3 show the period and modal analysis results for each school block, respectively. Buildings have potential seismic deficiencies. Consequently, in the event of severe earthquakes acting on a structure, there are indications that the buildings could perform inadequately. The limit states that could develop in the structural elements were masonry and column shear failures.

Table 3: Results of period (T) obtained for the school blocks.

Block	Period (s)		
	T1	T2	T3
B5.1	0.62	0.55	0.47
B5.3	0.78	0.75	0.69
B5.4	0.79	0.68	0.55
B5.5	0.87	0.74	0.67
B5.6	0.54	0.74	0.38

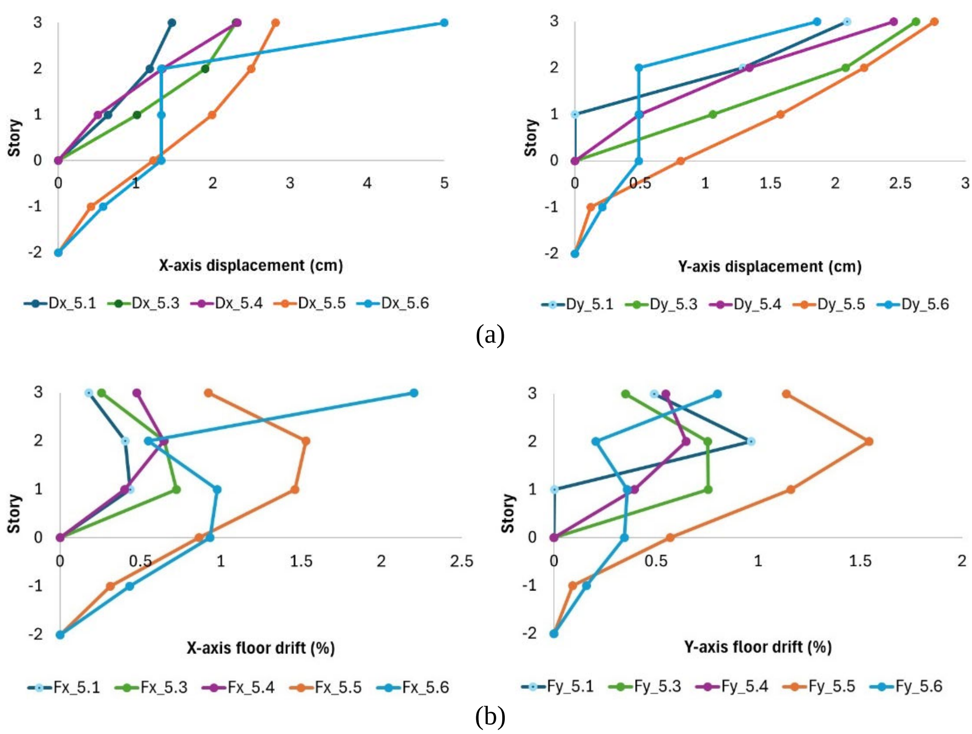

Figure 3: Modal analysis of buildings 5.1, 5.3, 5.4, 5.5, 5.6 of the 'San Juan Bosco' School (a) displacements in the X–Y axes; (b) drifts in the X–Y axes.

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Table 4: Proposed seismic deficiencies and rehabilitation alternatives for the analysed buildings of the 'San Juan Bosco' School. *(Source: Adapted from FEMA [23].)*

Category	**Deficiency**	**Addition**	**Improve**	**Reduce**	**Remove**	**Block**
Informal construction	Low concrete compressive strength	Walls	Increase element size	Remove upper floors	-	B5.1
Structural configuration	Torsion	Braced or moment-resisting frames		-	-	B5.5 B5.6
	Knocking possible	-	-	-	Slab edge and beams	B5.1 B5.4 B5.5 B5.6
	Soft or weak story	Walls	Sleeving columns	-	-	B5.1
	Inadequate shear strength	-	Increased column cross-section	-	-	All of them
Component detail	Short column	-	Decrease window width or close space	-	-	All of them
Non-structural elements	Cracks or fissures Slender walls	Pillars	Sealing cracks Apply mortar	-	Walls	All of them

4.3 Rehabilitation alternatives

In general, most blocks exhibit similar seismic deficiencies. Table 4 shows the structural defects and the recommended structural rehabilitation alternatives. Likewise, the table presents the weaknesses of non-structural elements (e.g. masonry walls) and their rehabilitation techniques.

The rehabilitation proposals in Table 4 were obtained and adapted from the FEMA. In informal buildings, as in B5.1, B5.3 and B5.6, the removal of upper floors or the reinforcement of some structural elements is suggested. This was applied in the Humberto Molina Hospital in Zaruma, in buildings B3 and B4, according to Rojas et al. [16] for its rehabilitation and reopening. Alternatives to avoid torsion and knocking in buildings B5.1, B5.4, B5.5 and B5.6, reinforce the columns and walls, and remove the edges of the slabs. A similar situation was observed in buildings and houses in Pedernales (Manabí, Ecuador) because of structural problems caused by the April 2016 earthquake (irregularities in elevation, and short columns) [24].

5 CONCLUSION

Ecuador has high seismic activity that affects the stability and functionality of its buildings, as in the case of the ‘San Juan Bosco’ School in Zaruma. This infrastructure has been operational for 30 years. In this study, the reinforced concrete blocks of the ‘San Juan Bosco’ School (B5.1, B5.2, B5.3, B5.4, B5.5, B5.6, B5.7) were examined through field visits, material tests (laboratory and field), and comparison with national (NEC) and international (ASCE/SEI) standards. This made it possible to determine the vulnerability and level of seismic performance of the structural system of school buildings to propose structural rehabilitation strategies using the techniques recommended by FEMA.

The school has yet to undergo the necessary adaptations or maintenance during its years of operation. Regarding the structural design of the elements, the following conclusions can be drawn:

- The strength of the concrete in the columns, beams, and slabs analysed is low in some blocks (B5.1, approximately 180 kg/cm^2) and needs to meet the minimum requirements stipulated in NEC (210 kg/cm^2).
- The auscultated rebars are corrugated in all the blocks; therefore, it is concluded that the yield stress of the reinforcing steel used is 4,200 kg/cm^2. Consequently, the yield strength met the minimum requirements stipulated in the NEC and ASCE/SEI codes (4,200 kg/cm^2).
- The minimum number of elements complied with the minimum requirements stipulated in the current codes (1% in columns and 0.33% in beams).
- The stirrups of the elements had 90° hooks. Consequently, the hooks used did not meet the seismic requirements stipulated in the current codes (135° hooks).

This structural characterisation, evaluation, analysis, and proposal of rehabilitation alternatives in the blocks will facilitate decision-making by the Risk Management Secretariat authorities, Education Ministry, and Zaruma Municipality. ‘San Juan Bosco’ School is vital for educating approximately 25,000 people. The data collected are a basis for supporting and seeking assistance from policymakers to make decisions on the assignment of resources and the prioritisation of the analysis and seismic-resistant reinforcement of schools in the area.

The methodology presented in this study will serve as a model to be replicated in other educational centres (schools and colleges) in Ecuador with the same or worse conditions than the Zaruma Hospital. Because Ecuador is a country with constant geodynamic risk and has educational structures with many years of service, which are not properly maintained or were built with previous standards, its application in these cases is necessary and immediate. Replicating it in essential facilities in other countries is also possible; however, it is necessary to review the national standards and seismic spectra in each case.

The present study shows a limited number of concrete cores, which depend on the budget of the current research project. In addition, it is possible to extend this study by investigating other blocks of the 'San Juan Bosco' School. Furthermore, the realisation and interpretation of shear/moment diagrams should be completed to observe the behaviour of the elements under seismic conditions.

ACKNOWLEDGEMENTS

This work was supported by the research project, 'Propuesta de Geoparque Ruta del Oro y su incidencia en el desarrollo territorial', with Code CIPAT-02-2018 from ESPOL Polytechnic University. To Computers & Structures Inc. (CSI) for the trial version of the SAP 2000 software, which was used to carry out the structural analyses of the school.

REFERENCES

[1] Pal, S.C., Saha, A., Chowdhuri, I., Ruidas, D., Chakrabortty, R., Roy, P. & Shit, M., Earthquake hotspot and coldspot: Where, why and how? *Geosystems and Geoenvironment*, **2**(1), 100130, 2023. https://doi.org/10.1016/j.geogeo.2022.100130.

[2] Hasterok, D., Halpin, J.A., Collins, A.S., Hand, M., Kreemer, C., Gard, M.G. & Glorie, S., New maps of global geological provinces and tectonic plates. *Earth-Science Rev.*, **231**(1), 104069, 2022. https://doi.org/10.1016/j.earscirev.2022.104069.

[3] Zhu, W., Ji, Y., Qu, R., Xie, C. & Zeng, D., Slab metamorphism and interface earthquakes in Peru: Implications from three-dimensional hydrothermal variation in the subducted Nazca plate. *Tectonophysics*, **823**(1), 229212, 2022. https://doi.org/10.1016/j.tecto.2022.229212.

[4] Jiménez, C., Saavedra J.M. & Moreno, N., Seismic source characteristics of the 2016 Pedernales-Ecuador earthquake (Mw 7.8). *Phys. Earth Planet. Inter.*, **312**(1), 106670, 2021. https://doi.org/10.1016/j.pepi.2021.106670.

[5] Sajan, K.C., Bhusal, A., Gautam, D. & Rupakhety, R., Earthquake damage and rehabilitation intervention prediction using machine learning. *Eng. Fail. Anal.*, **144**(1), 106949, 2023. https://doi.org/10.1016/j.engfailanal.2022.106949.

[6] Wyss, M., Speiser, M. & Tolis, S., Earthquake fatalities and potency. *Nat. Hazards*, **119**(1), pp. 1091–1106, 2023. https://doi.org/10.1007/s11069-022-05627-x.

[7] Günaydin, M., Atmaca, B., Demir, S., Altunişik, A.C., Hüsem, M., Adanur, S., Ateş, Ş. & Angin, Z., Seismic damage assessment of masonry buildings in Elazığ and Malatya following the 2020 Elazığ-Sivrice earthquake, Turkey. *Bull. Earthq. Eng.*, **19**(1), pp. 2421–2456, 2021. https://doi.org/10.1007/s10518-021-01073-5.

[8] Dogan, G., Ecemis, A.S., Korkmaz, S.Z., Arslan, M.H. & Korkmaz, H.H., Buildings damages after Elazığ, Turkey earthquake on January 24, 2020. *Nat. Hazards*, **109**(1), pp. 161–200, 2021. https://doi.org/10.1007/s11069-021-04831-5.

[9] Fang, C., Qiu, C., Wang, W. & Alam, M.S., Self-centering structures against earthquakes: A critical review. *J. Earthq. Eng.*, **27**(1), pp. 4354–4389, 2023. https://doi.org/10.1080/13632469.2023.2166163.

[10] Kamranzad, F., Memarian, H. & Zare, M., Earthquake risk assessment for Tehran, Iran. *ISPRS Int. J. Geo-Information*, **9**(1), 430, 2020. https://doi.org/10.3390/ijgi9070430.
[11] Anelli, A., Vona, M. & Santa-Cruz Hidalgo, S., Comparison of different intervention options for massive seismic upgrading of essential facilities. *Buildings*, **10**(1), 125, 2020. https://doi.org/10.3390/buildings10070125.
[12] Anelli, A., Santa-Cruz, S., Vona, M., Tarque, N. & Laterza, M., A Proactive and resilient seismic risk mitigation strategy for existing school buildings. *Struct. Infrastruct. Eng*., **15**, pp. 137–151, 2019. https://doi.org/10.1080/15732479.2018.1527373.
[13] Carrillo, J., Arteta, C.A. & Vera, X., Post-earthquake safety assessment of schools after the 2016 Ecuador M7.8 earthquake. *Soil Dyn. Earthq. Eng*., **179**, 108561, 2024. https://doi.org/10.1016/j.soildyn.2024.108561.
[14] Carrión-Mero, P., Solórzano, J., Chávez, M.Á., Blanco, R., Morante-Carballo, F., Aguilar-Aguilar, M. & Briones-Bitar, J., Evaluation of geomechanical features and stability for the recommendations and rehabilitation of the Humberto Molina Hospital, Zaruma, El Oro, Ecuador. *WIT Transactions on Ecology and the Environment*, vol. 241, WIT Press: Southampton and Boston, pp. 455–466, 2020.
[15] Carrión-Mero, P., Solórzano, J., Morante-Carballo, F., Chávez, M.Á., Montalván-Burbano, N. & Briones-Bitar, J., Technical closure of the Humberto Molina Astudillo Hospital and its implications for sustainability, Zaruma-Ecuador. *Int. J. Sustain. Dev. Plan*., **17**, pp. 363–373, 2022. https://doi.org/10.18280/ijsdp.170202.
[16] Rojas, P.P., Moya, C., Caballero, M., Márquez, W., Briones-Bitar, J. & Morante-Carballo, F., Assessing and mitigating seismic risk for a hospital structure in Zaruma, Ecuador: A structural and regulatory evaluation. *Int. J. Saf. Secur. Eng.*, **13**, pp. 597–610, 2023. https://doi.org/10.18280/ijsse.130402.
[17] American Society of Civil Engineers, *ASCE/SEI Seismic Evaluation and Retrofit of Existing Buildings*, ASCE: Reston, VA, 2014.
[18] ASTM International, ASTM C39/C39M-23 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. https://www.astm.org/c0039_c0039m-23.html. Accessed on: 16 Jun. 2024.
[19] Ministry of Urban Development and Housing, MIDUVI NEC-SE-DS: Peligro Sísmico, Diseño Sísmo Resistente. https://www.habitatyvivienda.gob.ec/documentos-normativos-nec-norma-ecuatoriana-de-la-construccion/. Accessed on: 16 Jun. 2024.
[20] American Society of Civil Engineers, *ASCE/SEI 41-1 Seismic Evaluation and Retrofit of Existing Buildings*, ASCE: Reston, VA, 2014.
[21] American Society of Civil Engineers, *ASCE/SEI 7-16 Minimum Design Loads for Buildings and Other Structures*, ASCE: Reston, VA, 2006. https://sp360.asce.org/personifyebusiness/Merchandise/Product-Details/productId/232121003#:~:text=(7-05)-. Accessed on: 16 Jun. 2024.
[22] Computers & Structures Inc., *SAP 2000: Integrated Finite Element Analysis and Design of Structures*. https://www.csiamerica.com/products/sap2000. Accessed on: 16 Jun. 2024.
[23] FEMA, *Techniques for the Seismic Rehabilitation of Existing Buildings, FEMA 547, 2006*, FEMA. https://www.fema.gov/node/techniques-seismic-rehabilitation-existing-buildings. Accessed on: 16 Jun. 2024.
[24] Villalobos, E., Sim, C., Smith-Pardo, J.P., Rojas, P., Pujol, S. & Kreger, M.E., The 16 April 2016 Ecuador earthquake damage assessment survey. *Earthquake Spectra*, **34**(3), pp. 1201–1217, 2018. https://doi.org/10.1193/060217EQS106M.