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Original Research

Indicator-Based Assessment of Seismic Vulnerability Factors in Spanish Colonial Heritage Churches in Bohol, Philippines

Reymarvelos Oros[1,2,*], Joel Opon[1,2,3]

1. Center for Structural Engineering and Informatics, MSU – Iligan Institute of Technology, Iligan City
2. Research Institute for Engineering and Innovative Technology, MSU – Iligan Institute of Technology
3. Department of Civil Engineering and Technology, MSU – Iligan Institute of Technology

* Correspondence: reymarvelos.oros@g.msuiit.edu.ph (R.O); joel.opon@g.msuiit.edu.ph (J.O)

ABSTRACT

This study evaluates the seismic vulnerability of three 19th-century Spanish colonial heritage churches in Bohol, Philippines—Santa Monica (Alburquerque), San Nicolas de Tolentino (Dimiao), and San Agustin (Panglao)—which serve as notable examples of unreinforced masonry construction that endured the 2013 Bohol earthquake. A proxy indicator-based approach was employed to quantify key parameters influencing seismic behavior, including wall slenderness, plan regularity, buttress adequacy, and belltower rigidity. Statistical analyses, such as mean, standard deviation, and coefficient of variation, were used to examine variability among indicators and identify those contributing most to seismic susceptibility. The results demonstrate the applicability of indicator-based methods for assessing heritage structures where detailed geometric and material data are unavailable. Differences in wall proportions, connections, and architectural configurations reveal variations in historical construction practices and their implications for lateral load resistance. This indicator-based approach offers an efficient means of characterizing the seismic vulnerability of unreinforced masonry heritage buildings using measurable parameters. Overall, the findings provide a methodological basis for informed heritage conservation, risk reduction, and structural assessment, contributing to a broader understanding of how architectural form and construction typology affect the seismic resilience of Spanish colonial churches in the Philippines.

Keywords: seismic vulnerability, heritage churches, unreinforced masonry, indicator-based assessment, cultural heritage conservation

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1. INTRODUCTION

The Philippines, situated along the Pacific Ring of Fire, ranks among the most seismically active regions worldwide, where recurrent earthquakes continue to endanger the built environment. Particularly at risk are unreinforced masonry (URM) heritage structures erected prior to the implementation of modern seismic design standards [1-4]. Among these are Spanish colonial churches constructed during the 18th and 19th centuries, which stand as enduring testaments to Philippine history, culture, and faith. Their massive stone masonry walls, vaulted ceilings, and slender belltowers, inherently lack the capacity to resist earthquake-induced forces. The 2013 Bohol earthquake (Mw 7.2), as an example, vividly demonstrated the structural fragility URM churches, resulting in the extensive damage and collapse of numerous heritage churches across the province [5-6]. These losses emphasize the need to balance cultural preservation with structural resilience through a rigorous understanding of the current condition and seismic response of heritage structures to guide effective conservation and retrofitting interventions.

Research on the seismic vulnerability of heritage masonry structures has advanced globally, using empirical, analytical, and numerical approaches like extensive structural monitoring, kinematic analysis, and finite element method [7-10]. However, such approaches often require detailed material characterization, geometric documentation, or computational resources that may not be available for historical buildings. To address these challenges, indicator-based assessment methods have been introduced to evaluate seismic vulnerability using measurable proxy geometric and architectural parameters derived from field observations and available documentation [11-12]. These methods offer a practical and non-invasive alternative for assessing heritage structures, especially in data-limited contexts like many parts of the Philippines.

This study applies a novel indicator-based approach to evaluate the seismic vulnerability of three 19th-century Spanish colonial churches in Bohol, Philippines. By quantifying key structural characteristics — such as wall slenderness, plan regularity, buttress adequacy, and belltower rigidity — the study identifies the critical parameters affecting seismic vulnerability. The findings demonstrate that measurable, indicator-based assessment offers a practical and scalable framework for evaluating the seismic vulnerability of unreinforced masonry heritage churches, thereby advancing heritage conservation and disaster resilience through evidence-based risk evaluation of historically significant structures in earthquake-prone regions.

2. MATERIALS AND METHODS

This study employed a quantitative, indicator-based approach to assess the seismic vulnerability of three 19th-century Spanish colonial churches in Bohol, Philippines—Santa Monica (Alburquerque), San Nicolas de Tolentino (Dimiao), and San Agustin (Panglao). The methodology integrates systematic literature review, structural plan investigation, and proxy indicator-based evaluation to quantify structural parameters influencing the seismic vulnerability of heritage unreinforced masonry (URM) buildings.

2.1. Church Description

The selected churches were chosen based on the availability of engineering plans, their relatively intact structural condition following the 2013 Bohol earthquake, and their representativeness of 19th-century Spanish colonial ecclesiastical architecture. These factors ensure the reliability of geometric and material data necessary for the vulnerability assessment. Moreover, their cruciform layouts, unreinforced masonry construction, and baroque-inspired details exemplify the typical structural and architectural characteristics of heritage churches in the Philippines, making them suitable case studies for understanding seismic behavior within this typology. Each church features thick load-bearing walls, high vaulted ceilings, and *mamposteria*, i.e., stone masonry composed of irregular stones bonded with mortar and clad with coralline limestone using lime mortar [13]. Although minor cracking in the churches was observed during the earthquake, all three remained structurally intact, making them appropriate case studies for seismic vulnerability evaluation.

Architectural drawings (Figures 1-3) of the three churches were obtained from the National Museum of the Philippines. These plans provided geometric and dimensional information necessary for computing the proxy indicators. Measurements of wall thickness, wall height, openings, buttress spacing, and belltower dimensions were extracted from the drawings. Since the study focused on non-destructive and data-driven assessment, no field measurements or material testing were conducted.

2.1.1. Parish Church of Santa Monica

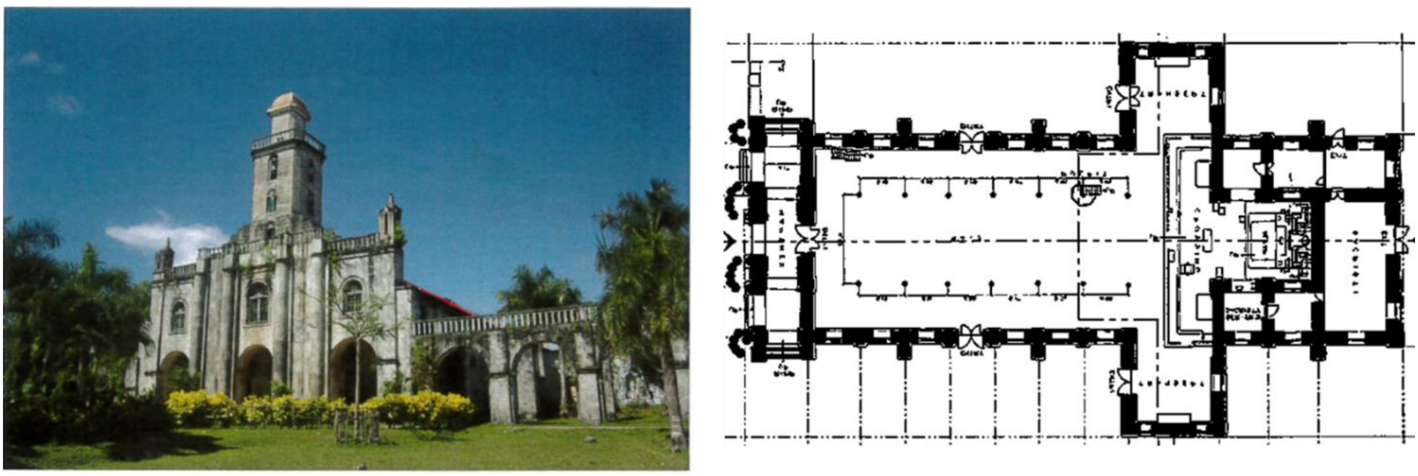
The Parish Church of Santa Monica in Alburquerque, completed in the late 19th century, stands as a notable example of Spanish colonial ecclesiastical architecture in the Philippines. The church follows a cruciform plan (Figure 1(b)) with wide transepts, thick unreinforced coral stone masonry walls, and a neoclassical façade accentuated by classical pilasters and cornices. Its bell tower, integrated into the façade, functions as both an architectural focal point and a liturgical feature (Figure 1(a)). During the 2013 Bohol earthquake, the structure sustained only minor damage and was later restored in accordance with national heritage conservation standards [14].

2.1.2. Parish Church of San Nicolas de Tolentino

Located in the municipality of Dimiao, the Parish Church of San Nicolas de Tolentino is a well-preserved example of Baroque-inspired colonial architecture that embodies the artistic and religious sensibilities of the Spanish missionary period. The church features similar cruciform layout, thick unreinforced masonry walls, and side buttresses providing lateral stability (Figure 2). Despite its age, the structure sustained only minor damage during the 2013 Bohol earthquake and was later restored in compliance with national heritage conservation protocols [14].

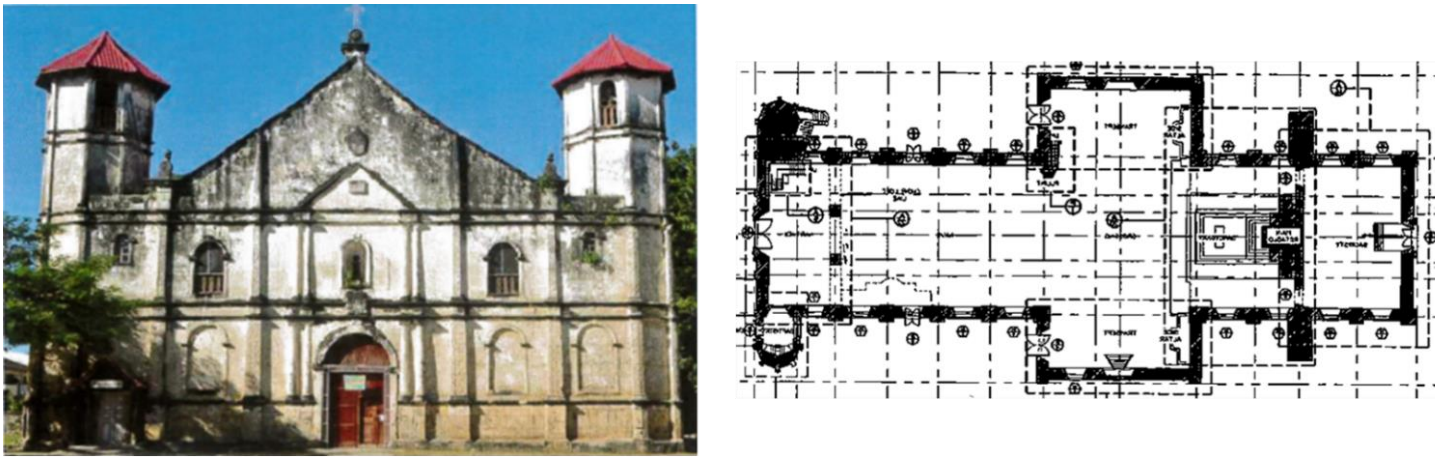
2.1.3. Parish Church of San Agustin – Panglao

The San Agustin Church in Panglao Island, Bohol, follows the same cruciform layout (Figure 3) as the other churches and is primarily constructed from locally sourced coralline limestone, reflecting Spanish colonial building traditions in coastal areas of the Philippines. Architecturally, it is distinguished by its prominent portico façade and intricately frescoed ceilings that blend European religious motifs with Filipino artistic expression. During the 2013 Bohol earthquake, the church sustained moderate structural damage, including masonry cracks and partial detachment of ornamental elements. Subsequent restoration and retrofitting works were carried out to enhance its structural integrity and ensure the preservation of its cultural and historical value [14].



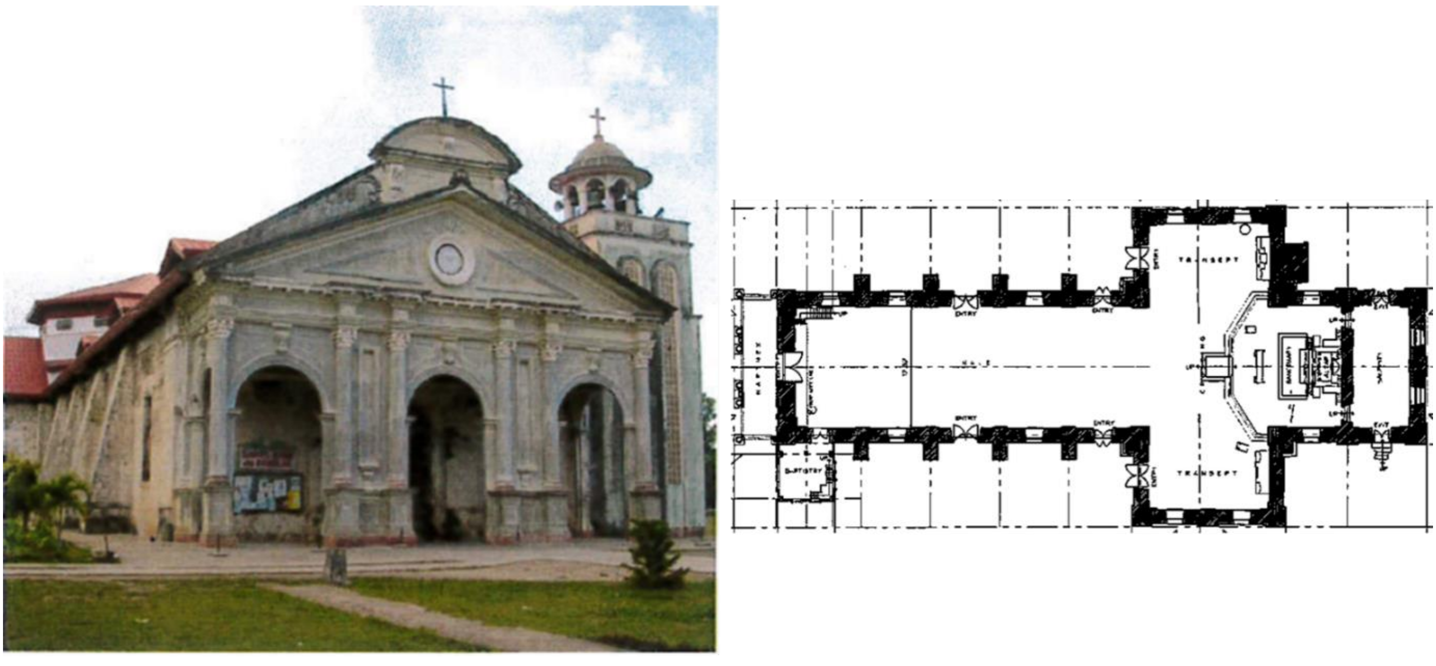
(a) (b)

Figure 1. (a) Façade and (b) floor plan of the Parish Church of Santa Monica – Alburquerque, Bohol (Courtesy of National Museum of the Philippines).



(a) (b)

Figure 2. (a) Façade and (b) floor plan of the Parish Church of San Nicolas de Tolentino – Dimiao, Bohol (Courtesy of National Museum of the Philippines).



(a) (b)

Figure 3. (a) Façade and (b) floor plan of the Parish Church of San Agustin – Panglao, Bohol (Courtesy of National Museum of the Philippines).

2.2. Indicator Selection

The identification of vulnerability indicators was guided by a systematic review of peer-reviewed journal publications in Scopus and Web of Science. Vulnerability indicators refer to measurable or observable parameters that reflect the susceptibility of structural components to seismic damage. In this study, they serve as the basis for evaluating how specific building features influence the overall susceptibility of heritage churches. From the review, twelve indicators (see Table 1 in Results and Discussion) were selected, categorized, and adapted to the context of Bohol's Spanish colonial churches.

These indicators are organized into six main categories that capture the structural configuration and behavior of unreinforced masonry (URM) churches during earthquakes: (1) Vertical structures (V1–V2) represent the load-bearing walls that primarily resist gravity loads and influence the building's global stability; (2) Lateral systems (L1–L2) account for mechanisms that resist horizontal seismic forces; (3) Geometry (G1–G2) considers the church's overall plan and elevations, which affect stiffness distribution and potential torsional responses; (4) Connections (C1–C2) involve the interaction between key components (e.g., walls, vaults, and roofs), whose deficiencies often lead to partial or total collapse; (5)Buttress conditions (D1–D2) are evaluated because these elements play a vital role in counteracting lateral thrusts, particularly in the nave and apse regions; (6) Lastly, belltower characteristics (B1–B2) are included due to their geometric slenderness and frequent separation from the main structure, making them highly vulnerable to out-of-plane failures.

Since some indicators cannot be directly measured, relevant proxy measurements are instead used. A detailed description of each indicator, along with its proxy variables, is provided in Table 1. Note that for these proxy measurements, there is no absolute threshold, so they are evaluated relative to each other.

The Type of Vertical Resisting System (V1), measured as the ratio of total wall area to building footprint, reflects the massiveness of a church's vertical structural components [7-9,11,15-16].

The Organization of Vertical Structures (V2) is quantified as the ratio between wall areas in the short and long directions of the building. This indicator assesses the uniformity of wall distribution, which is crucial for ensuring symmetrical lateral resistance and minimizing torsional effects during seismic events [7-11,15-16].

The Roofing System (L1) indicator reflects the contribution of the roof to seismic demand, specifically in relation to its height above the ground and the resulting increase in lateral seismic forces [7-11,15-16]. This indicator captures the structural implication of roof elevation—since a higher roof position results in a greater mass located farther from the base. This elevated mass not only increases the inertial forces during an earthquake but also amplifies the overturning moment acting on the structure [20].

The Plan Regularity (L2) indicator, expressed as the ratio between the shorter and longer plan dimensions, assesses the geometric symmetry of a structure [7-12,15-16]. Regular building footprints generally promote uniform seismic response, while irregular plans can lead to torsional behavior and concentration of stresses. The Slenderness of Walls (G1), defined as the ratio of wall height to thickness, serves as a key indicator of susceptibility to out-of-plane failure, which is one of the most common seismic failure modes in URM structures [21-22]. For this indicator, the proxy measurement is the ratio of wall thickness to height.

The Presence of Wall Openings (G2) is assessed by the ratio of the area of openings—such as windows and doors—to the total wall area. This indicator is critical in seismic vulnerability assessment, as excessive or poorly distributed openings weaken masonry walls, reduce their stiffness, and create potential points of failure during ground motion [7-8,11,16,23]. The indicator Connection to Orthogonal Walls (C1) evaluates the proportion of the wall height that is structurally tied to perpendicular walls, which is essential for the box-type behavior of masonry structures during seismic events [23]. Strong interconnections between orthogonal walls allow the load to be redistributed and prevent out-of-plane collapse [21-22].

The Connection to Diaphragms (C2) indicator assesses the extent to which vertical wall elements are structurally tied to horizontal components—such as flat diaphragms, roof trusses, or tie beams. This connection is essential in heritage masonry churches to prevent the thrusting effect of the roof system onto the walls, which can cause separation, cracking, or collapse under seismic forces [7,16,23]. By anchoring walls to flat diaphragms, the overall structure can act as an integrated unit, improving seismic energy distribution and enhancing stability.

The Adequacy of Buttress (D1) indicator evaluates the structural sufficiency of buttresses in resisting lateral forces by analyzing the ratio of buttress thickness to the center-to-center spacing between buttresses [25-27].

The Resistance of Buttress (D2) indicator evaluates the ability of buttresses to resist lateral seismic forces, which is particularly crucial for unreinforced masonry structures [25-27]. This is quantified by the ratio of the buttress width to its height, a geometric proxy that reflects structural rigidity. In general, wider buttresses offer greater stability and improved lateral resistance due to their lower tendency to overturn or deform under seismic loads. Therefore, this indicator provides insight into the lateral support function of buttresses, which is especially important in historical churches where such features are integral to the overall stability of tall, heavy walls.

The Belltower Slenderness (B1) indicator, which this study employed by computing its inverse, i.e., base-width-to-height ratio, assesses the vertical vulnerability of church belltowers [28-30]. Thus, a lower ratio signifies a more slender and seismically vulnerable structure, while a higher ratio suggests a broader, more stable form. Slender towers are particularly susceptible to seismic excitation due to their higher centers of mass and reduced lateral resistance.

The Belltower Rigidity (B2) indicator is defined as the ratio of the area of resistive walls in the tower to its base area, reflecting the ability of the tower to resist lateral forces through its masonry shell [28-30]. A higher value indicates a stiffer and potentially more stable structure under seismic loads, while a lower value suggests greater vulnerability to lateral deformation or collapse.

2.3 Indicator Evaluation

The seismic vulnerability of the heritage churches was assessed using a set of proxy indicators designed to represent key structural characteristics of unreinforced masonry buildings [7–11,15–16]. This proxy indicator-based approach offers the advantage of relying primarily on geometric measurements, making it suitable for historical structures where detailed material properties or structural documentation are often unavailable. Each church was assessed using the defined vulnerability indicators in Table 1. Proxy values were calculated according to the defined formulas for each indicator. Statistical analyses—including the mean, standard deviation, and coefficient of variation—were employed to characterize the variability of the indicators and identify which parameters most strongly reflect potential seismic vulnerability. The mean represents the average value of each indicator, while the standard deviation (SD) quantifies the dispersion of the data. The coefficient of variation (COV), computed as $\mathrm{COV} = \frac{\mathrm{SD}}{\mathrm{Mean}} \times 100\%$, expresses the relative variability in percentage terms, enabling comparison among indicators with differing scales. For example, if an indicator yielded values of 1.0, 1.2, and 0.8 for three churches, the mean would be 1.0 and the SD 0.2, giving a COV of 20%. A higher COV indicates relatively strong geometrical differences, suggesting that the indicator contributes more significantly to the differences in seismic performance among the churches.

Under a condition of high COV, the indicator values show large variability across the churches, suggesting that the churches differ substantially in how that specific vulnerability factor manifests. A high COV does not imply that one church is definitively more vulnerable overall; rather, it indicates that the indicator contributes unevenly to potential vulnerability and therefore warrants closer examination to understand why some churches score differently on that factor.

3. RESULTS AND DISCUSSION

Table 1 shows the indicator values for the three churches and their descriptive statistics (i.e., mean (average value), standard deviation (degree of variation from the mean), and coefficient of variation (SD expressed as a percentage of the mean)). Figure 4 presents a bar chart to visually compare the vulnerability indicator values for the three heritage churches across the twelve indicators.

3.1.1. Type of Vertical Resisting System (V1)

Among the three heritage churches, San Nicolas and San Agustin exhibited relatively high values of 0.2282 and 0.2296, respectively, while Santa Monica had a notably lower value of 0.1667 (Table 1). The higher ratios observed in San Nicolas and San Agustin indicate the presence of more extensive wall systems, which may enhance vertical load-bearing capacity and stiffness [17-19]. However, this also implies greater seismic mass, which could increase inertial forces during ground motion if not properly distributed or restrained [20]. In contrast, Santa Monica's lower wall-to-footprint ratio suggests a lighter structure, which may be advantageous in terms of reduced seismic demand, but could also mean thinner or less continuous walls, potentially compromising overall stability and lateral resistance.

Table 1. Quantitative vulnerability indicators for the heritage churches based on proxy measurements.

Vulnerability Indicators	Proxy Measurement	Values for Each Church			Mean	SD	CV (%)
		Santa Monica	San Nicolas	San Agustin			
V1. Type of Vertical Resisting System	Total wall area divided by building footprint	0.1667	0.2282	0.2296	0.2082	0.0359	17.25
V2. Organization of Vertical Structures	Ratio between the wall areas in the short and long directions	0.2615	0.1352	0.2368	0.2112	0.0669	31.68
L1. Roofing System	$\frac{h_r h_w}{h_r h_w + h_w^2}$ where h_r = height of roof and h_w = height of wall	0.6610	0.6223	0.6637	0.6490	0.0232	3.573
L2. Plan Regularity	Ratio between the lengths of the shorter and longer sides	0.3244	0.2371	0.2393	0.2669	0.0498	18.65
G1. Slenderness of Walls	Ratio between wall's thickness to its height	0.1884	0.1245	0.2354	0.1828	0.0556	30.43
G2. Presence of Wall Openings	Ratio between the area of openings to the total wall area	0.0854	0.0462	0.1426	0.0914	0.0485	53.09
C1. Connection to Orthogonal Walls	Ratio of structurally connected wall height to total wall height	0.6667	0.6667	1.0000	0.7778	0.1925	24.74
C2. Connection to Diaphragms	Ratio between length of wall connected to a flat diaphragm, trusses, or ties to the total length of wall	1.0000	0.1811	0.3204	0.5005	0.3577	71.48
D1. Adequacy of Buttress	Thickness of buttress over center-to-center spacing of buttress	0.0800	0.0477	0.1764	0.1014	0.0669	66.03
D2. Resistance of Buttress	Width over the height of buttress	0.2198	0.2636	0.2368	0.2401	0.0221	9.197
B1. Belltower Slenderness	Base width over height	0.3806	0.2363	0.3488	0.3219	0.0758	23.55
B2. Belltower Rigidity	Area of resistive walls of the tower divided by tower base area	0.3715	0.1455	0.0344	0.1838	0.1718	93.46

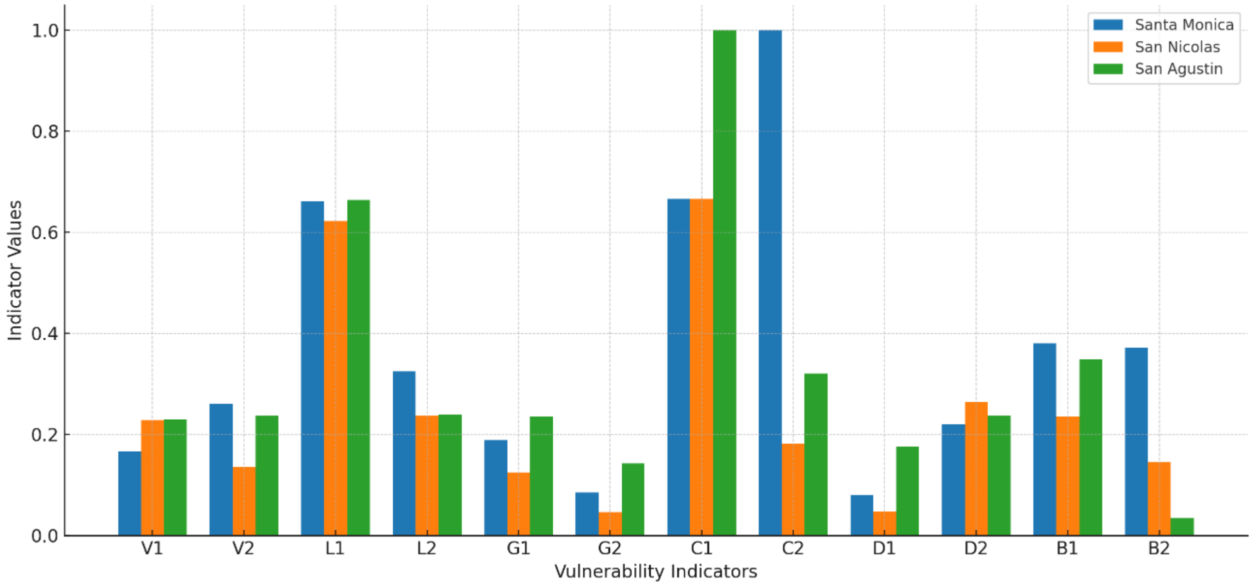


Figure 4. Vulnerability indicator values of the three Bohol churches.

Statistical analysis shows a mean value of 0.2082 with a standard deviation of 0.0359 and a coefficient of variation of 17.25%, indicating moderate variability among the three churches. While massive walls can offer superior gravity load resistance, they must be supported by effective lateral load paths to ensure seismic resilience.

3.1.2. Organization of Vertical Structures (V2)

The three churches exhibited notable variation in this parameter. Santa Monica recorded the highest ratio at 0.2615, indicating a more balanced wall distribution, while San Agustin followed closely at 0.2368. In contrast, San Nicolas had a markedly lower value of 0.1352, suggesting that its walls are disproportionately concentrated in one direction, i.e., the longitudinal axis. The mean value across the churches was 0.2112, with a standard deviation of 0.0669 and a coefficient of variation of 31.68%, indicating significant variability in the structural configuration. Among the three, Santa Monica shows the most favorable configuration in terms of potential seismic performance, as a more uniform wall layout promotes symmetrical load paths and reduces the risk of torsional response [20]. San Agustin, while slightly less balanced, remains within a comparable range. On the other hand, San Nicolas's low ratio indicates a potentially critical deficiency; walls concentrated in one direction offer limited resistance in the orthogonal direction, which may result in uneven displacements and torsional stresses during lateral shaking.

3.1.3. Roofing System (L1)

The results show closely grouped values among the three churches: San Agustin with the highest at 0.6637, followed by Santa Monica at 0.6610, and San Nicolas at 0.6223. The overall mean of 0.6490, with a low standard deviation of 0.0232 and a coefficient of variation of just 3.57%, reflects a high degree of similarity in roof elevation across the churches. This minimal variability suggests that the churches have comparable wall heights and roof positions, resulting in relatively uniform seismic mass distribution at the upper levels. The slightly higher value observed in San Agustin indicates a marginally taller roof profile, suggesting a greater mass that can increase lateral seismic forces, and the added height also raises the overturning moment demand on the structure.

3.1.4. Plan Regularity (L2)

Among the three churches, Santa Monica exhibited the highest plan regularity with a ratio of 0.3244, followed by San Agustin (0.2393) and San Nicolas (0.2371). These values suggest that Santa Monica has a more compact and balanced layout, while the other two churches are more elongated. The computed mean across the churches was 0.2669, with a standard deviation of 0.0498 and a coefficient of variation of 18.65%, indicating moderate variability in plan configuration. From a seismic perspective, Santa Monica's more regular plan geometry is advantageous as it supports balanced distribution of inertial forces and reduces the likelihood of torsional vibrations [20]. In contrast, the elongated shapes of San Nicolas and San Agustin may result in uneven lateral displacements and increased vulnerability at corners or transitions between plan segments.

3.1.5. Slenderness of Walls (G1)

Among the three churches, San Agustin recorded the highest proxy value at 0.2354, indicating relatively short and thick walls. Santa Monica (0.1884) presented a moderate value, while San Nicolas had the lowest proxy ratio at 0.1245, reflecting taller or thinner walls that are less stable under lateral loading. The overall mean proxy ratio was 0.1828, with a standard deviation of 0.0556 and a coefficient of variation of 30.43%, which indicates substantial variability in wall proportions across the churches. This variation has significant implications for seismic performance. The high slenderness observed in San Nicolas de Tolentino is particularly concerning, as such walls have a higher tendency to buckle or overturn under lateral seismic forces, especially in the absence of adequate anchorage or transverse support like a buttress system. Santa Monica, with moderate proxy ratio of wall thickness to height, may still be vulnerable, though to a lesser extent. San Agustin, having the highest proxy ratio, demonstrates more favorable proportions for resisting both in-plane and out-of-plane actions.

3.1.6. Presence of Wall Openings (G2)

Among the three churches, San Agustin had the highest ratio of openings at 0.1426, indicating a considerable reduction in effective wall area. Santa Monica followed with a moderate value of 0.0854, while San Nicolas had the lowest proportion of openings at 0.0462, suggesting more solid and continuous wall panels. The average ratio across the churches was 0.0914, with a standard deviation of 0.0485 and a high coefficient of variation of 53.09%, signifying considerable disparity in wall perforation among the structures. The notably high ratio in San Agustin raises significant concern, as openings reduce a wall's ability to carry both in-plane and out-of-plane seismic loads.

3.1.7. Connection to Orthogonal Walls (C1)

The highest value was observed in San Agustin, with a ratio of 1.000, indicating full connectivity between vertical wall elements through thickened corners. In contrast, both Santa Monica and San Nicolas exhibited lower and equal values of 0.6667, suggesting that some walls lack effective perpendicular connections. The mean ratio across the churches was 0.7778, with a standard deviation of 0.1925 and a coefficient of variation of 24.74%. This moderate variation implies differing construction practices. San Agustin's superior performance under this indicator reflects a more cohesive wall layout, which is expected to enhance its ability to withstand seismic loads through improved stress transfer mechanisms. The lower connectivity in the other two churches, however, may pose a risk of separation at wall junctions, especially during strong ground motion.

3.1.8. Connection to Diaphragms (C2)

Based on the data, the churches exhibit variable levels of diaphragm connectivity, with a mean ratio of 0.5005, a standard deviation of 0.3577, and a coefficient of variation of 71.48%, indicating significant disparity across the buildings. Santa Monica shows the highest value of 1.000, indicating that all its vertical walls are effectively anchored to flat diaphragms, thereby minimizing thrust effects. In contrast, San Agustin and San Nicolas have markedly lower values of 0.3204 and 0.1811, respectively, suggesting incomplete diaphragm-wall connections—likely due to vaulted or arch-type roofing systems that lack continuous horizontal ties. This inconsistency is a concern, as inadequate diaphragm connections increase the risk of outward wall displacement or loss of structural cohesion during seismic events [24].

3.1.9. Adequacy of Buttress (D1)

Among the three churches, the computed values varied significantly, with San Agustin showing the highest adequacy ratio at 0.1764, followed by Santa Monica at 0.0800, and San Nicolas with the lowest at 0.0477. The overall mean is 0.1014, while the standard deviation is 0.0669, resulting in a coefficient of variation of 66.03%. This high variability suggests a considerable inconsistency in buttress design and spacing among the churches, which could have been affected by other factors like slenderness of walls (G1). The notably higher value in San Agustin implies more robust lateral support provided by its buttresses, which is advantageous in resisting out-of-plane wall displacements during seismic events. In contrast, the much lower values for Santa Monica and especially San Nicolas may reflect insufficient buttress dimensions or widely spaced configurations that reduce their effectiveness under seismic loads.

3.1.10. Resistance of Buttress (D2)

Among the three heritage churches, the values for this indicator are closely aligned, with San Nicolas registering the highest value at 0.2636, followed by San Agustin at 0.2368, and Santa Monica at 0.2198. The calculated mean is 0.2401, with a relatively low standard deviation of 0.0221 and a coefficient of variation (CV) of 9.20%. This low CV indicates minimal variability in buttress resistance, suggesting a consistent architectural approach or structural convention across the churches when it comes to buttress design. Such uniformity may point to shared influences in construction techniques during the period these churches were built.

3.1.11. Belltower Slenderness (B1)

Based on the data, Santa Monica had the most compact belltower with a B1 ratio of 0.3806, followed by San Agustin at 0.3488, and San Nicolas with the slenderest tower at 0.2363. The average ratio across the churches is 0.3219, with a standard deviation of 0.0758 and a coefficient of variation (CV) of 23.55%, indicating moderate variability in slenderness. These results show that San Nicolas' belltower, having the lowest base-width-to-height ratio, is potentially the most vulnerable to seismic forces, particularly to overturning or lateral swaying. Santa Monica, by contrast, with the highest B1 ratio, may exhibit better performance under dynamic loads due to its broader base relative to its height. Nevertheless, the towers' structural independence relative to the main church structure should also be accounted in evaluating the vulnerability of the belltowers.

3.1.12. Belltower Rigidity (B2)

Among the three churches, Santa Monica had the highest rigidity at 0.3715, followed by San Nicolas at 0.1455, while San Agustin had a low value of 0.0344. With a mean rigidity of 0.1838, a standard deviation of 0.1718, and a coefficient of variation (CV) of 93.46%, this indicator showed the greatest variability among all those assessed. Such disparity points to inconsistent belltower design and construction practices across the churches, with direct implications for seismic safety. Santa Monica's tower, having the most substantial resistive wall area relative to its base, is likely to perform better under lateral loading. San Nicolas, while less stiff, maintains a moderate degree of resistance. However, San Agustin's tower exhibits extremely low rigidity, indicating very thin or fragmented wall sections that are highly susceptible to seismic damage, including cracking, rocking, or full structural failure. This result raises serious concerns for San Agustin, especially when combined with its relatively high wall slenderness (G1) and high proportion of wall openings (G2).

3.2. Overall Evaluation

The comparative evaluation of the three heritage churches—Santa Monica, San Nicolas, and San Agustin—reveals varying levels of seismic vulnerability on a per indicator basis. San Nicolas de Tolentino shows the highest seismic vulnerability among the three churches due to several unfavorable structural features. Its unbalanced wall distribution, high wall slenderness, weak diaphragm connections, and insufficient buttress support indicate limited lateral resistance and low structural redundancy. Despite having fewer wall openings and moderate belltower rigidity, these advantages could be insufficient to counteract overall weaknesses.

Santa Monica Church demonstrates generally favorable performance, with more balanced wall distribution, high plan regularity, and strong diaphragm connectivity contributing to improved seismic stability. However, its moderate wall thickness and limited buttress support suggest potential vulnerability under strong shaking. Its compact and rigid belltower is a notable strength, though the lighter wall system may still require enhanced lateral confinement. San Agustin Church exhibits mixed characteristics—robust walls, strong inter-wall connectivity, and sufficient buttress strength indicate good overall resistance, but high wall openings, weak diaphragm connections, and particularly low belltower rigidity significantly reduce its seismic reliability. While the main structure may perform adequately, the belltower remains highly vulnerable to seismic failure. While the indicator-based assessment provides a systematic means to identify potential structural weaknesses, it is subject to inherent uncertainties stemming from reducing complex structural characteristics into quantifiable ratios, and from the lack of detailed as-built documentation or material testing typical in heritage structures. Variability in construction practices, undocumented modifications, and degradation over time further contribute to uncertainty in the vulnerability assessment. To address these uncertainties, integrating indicator-based assessment with advanced analytical and empirical methods is essential. Future evaluations should incorporate, for example, detailed material characterization, laser scanning or photogrammetry-based geometric documentation, and physics-based numerical simulations to validate and refine indicator-derived results. Collaborative efforts between engineers, architects, and heritage conservators can ensure that both structural safety and cultural integrity are preserved in developing intervention strategies. Moreover, establishing a comprehensive digital archive of heritage church data—covering geometry, materials, and damage history—would enhance the accuracy of future assessments and facilitate comparative studies across regions. By strengthening the connection between quantitative assessment and conservation practice, this integrative approach promotes a more resilient, evidence-based framework for safeguarding the Philippines' Spanish colonial heritage against future seismic hazards.

4. CONCLUSION

This study applied an indicator-based assessment to evaluate the seismic vulnerability of three 19th-century Spanish colonial heritage churches in Bohol—Santa Monica, San Nicolas de Tolentino, and San Agustin. By quantifying geometric and architectural parameters such as wall slenderness, plan regularity, buttress adequacy, and belltower rigidity, the study demonstrated the practicality of proxy indicators in assessing unreinforced masonry (URM) heritage structures where detailed material or structural data are unavailable. Statistical analyses revealed that certain parameters, particularly wall slenderness, wall openings, and diaphragm connectivity, exhibit higher variability among the churches, indicating their greater influence on the variability of potential seismic performance.

The results underscore that despite similarities in construction typology and materials, variations in geometry and structural configuration could significantly affect how each church may respond to seismic loads. While the indicator-based method cannot replace comprehensive numerical or experimental analysis, it offers a valuable preliminary tool for prioritizing conservation and retrofitting interventions, especially in data-limited heritage contexts.

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5. APPENDIX

Values of Parameters for Vulnerability Indicator Computation

Parameters	Values		
	Santa Monica	San Nicolas	San Agustin
Length of door openings (m)	18.66	17.11	20.86
Wall area (m^2)	302.52	374.49	302.97
Plan area (m^2)	1814.7	1641.29	1319.35
Length of door openings in the short direction (m)	6.22	8.36	3.16
Length of door openings in the long direction (m)	6.22	5.1	12.64
Wall area in the short direction (m^2)	26.18	13.00	21.87
Wall area in the long direction (m^2)	100.11	96.13	92.36
Roof height, h_r (m)	15.52	18.12	14.17
Wall height, h_w (m)	7.96	11	7.18
Length of shorter side (m)	23.67	17.85	16.1
Length of longer side (m)	72.96	75.27	67.29
Thickness (m)	1.5	1.37	1.69
Area of wall openings (m^2)	149.76	147.49	204.95
Total perimeter (m)	220.34	290.46	200.13
Gross area of wall (m^2)	1753.91	3195.06	1436.93
Number of thickened corners	8	8	12
Total number of corners	12	12	12
Length of flat ceiling (m)	220.34	52.61	64.12
Total perimeter (m)	220.34	290.46	200.13
Center-to-center spacing of buttresses (m)	12.5	23.67	7.2
Thickness of buttress (m)	1	1.13	1.27
Height of buttress (m)	7.96	11	7.18
Width of buttress (m)	1.75	2.9	1.7
Height of belltower (m)	11.85	20.65	17
Base width of belltower (m)	4.51	4.88	5.93
Belltower area of the base (m^2)	21.87	11	30.37
Belltower resistive walls (m^2)	8.13	1.6	1.05

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