

BIM-BASED EARTHQUAKE RISK ANALYSIS: ASSESSING BUILDING DAMAGE AND ECONOMIC LOSS USING GEM TAXONOMY

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ABSTRACT: This study presents a Building Information Modeling (BIM)-based approach for earthquake risk assessment that integrates the Global Earthquake Model (GEM) structural taxonomy to evaluate potential building damage and associated economic losses. The analysis focuses on four reinforced-concrete building complexes (a total of four buildings) at Institut Teknologi Bandung (ITB), West Java, which are located near the active Lembang Fault. Three-dimensional building exposure models were developed using BIM to represent key structural parameters, including building height, material composition, construction type, and floor configuration. These exposure models were combined with seismic hazard data characterized by peak ground acceleration (PGA) corresponding to a Mw 7.0 scenario earthquake to estimate damage probabilities using GEM-recommended fragility curves for comparable reinforced-concrete building typologies and associated vulnerability functions. The results indicate that approximately 30–40% (mean \approx 35%) of the assessed buildings are expected to experience moderate damage under the selected earthquake scenario, with average direct economic losses ranging from USD 31,000 to USD 45,000 per building, reflecting uncertainties in fragility and vulnerability modeling. Overall, the proposed approach demonstrates the capability of BIM to enhance multi-dimensional exposure representation and to improve the accuracy of post-disaster economic loss estimation within the context of a limited campus-scale case study, thereby supporting resilience planning and risk informed decision making at the institutional level.

Keywords: Building Information Modeling; Seismic Risk Assessment; 3D exposure modeling; Lembang Fault.

1. INTRODUCTION

Natural disasters generate significant losses, including fatalities, structural and infrastructural damage, economic disruption, and the loss of livelihoods [1]. Among these hazards, earthquakes are particularly devastating due to their capacity to produce widespread destruction and high casualty rates. Data suggest that approximately 95% of earthquake-related fatalities are attributed to building collapse [2]. Recent events, such as the 2021 M_w 6.2 Mamuju–Majene earthquake and the 2022 M_w 5.6 Cianjur earthquake, have highlighted the vulnerability of the built environment in Indonesia. For instance, the Mamuju–Majene event caused more than 100 fatalities and damaged over 7,800 houses [3].

The physical vulnerability of buildings to seismic hazards is influenced by several factors, including ground motion intensity, structural typology, structural configuration, and building age [4]. A key aspect of seismic risk assessment is the classification of buildings into taxonomy categories that represent varying levels of structural fragility [5, 6,7]. Each taxonomy class is defined by a specific

combination of structural characteristics that determines how a building responds to seismic loading. Therefore, detailed information on building taxonomy is essential for exposure modeling and the estimation of direct physical losses.

Building Information Modeling (BIM) provides a comprehensive digital representation of buildings that integrate both spatial and non-spatial attributes. BIM facilitates the standardized extraction of data related to structural elements, geometry, materials, and spatial relationships. These capabilities make BIM an effective tool for taxonomy classification and exposure analysis. While some institutions and countries have developed their own taxonomy standards for risk assessment, this study employs the internationally recognized taxonomy system developed by the Global Earthquake Model (GEM) [8,9].

Exposure assessment, defined as the identification and characterization of elements at risk, is a fundamental component of earthquake risk modeling [10]. Conventional exposure models typically rely on two-dimensional (2D) data, where building footprint area is used as a proxy for asset

value [11,12]. However, 2D data often lacks critical geometric attributes, such as building height, number of floors, and internal layout. These missing parameters reduce the accuracy of building volume estimation and economic valuation. In contrast, three-dimensional (3D) BIM models provide detailed information on building height, structural complexity, and functional characteristics, thereby improving the accuracy of exposure assessments [13].

In disaster risk management, 3D visualization has been proven to be more effective than traditional 2D maps for communication, planning, and public awareness [14,15]. Additionally, the use of BIM has expanded beyond architectural design and facility management to include asset maintenance and administration, and disaster risk reduction more broadly [16,17,18,19,20]. Advances in surveying technologies, such as point cloud acquisition, now enable the development of detailed BIM models for existing structures, including public and educational facilities [21,22].

Despite these advancements, several challenges remain. One key limitation is the lack of comprehensive digital models for many existing buildings. Structural damage assessments still rely heavily on manual field surveys and empirical models, which are time-consuming and subject to observer bias [23]. BIM offers a promising solution because it can integrate multi-source information within a unified digital environment, enabling more efficient decision-making and improved risk estimation [24], [25].

However, existing studies have not fully explored the integration of BIM with standardized global taxonomy systems such as GEM for exposure modeling, nor have they systematically evaluated the implications of using BIM-derived 3D data compared with conventional 2D approaches. This gap is significant, especially in seismically active regions where building inventories are incomplete or inconsistent. Previous studies often focus on either BIM-based structural assessment or taxonomy classification, with limited work combining both within a unified seismic risk framework.

The originality of this study lies in its development of a methodological framework that links BIM-derived structural attributes with GEM taxonomy classes to generate spatially explicit and structurally informed exposure models. By comparing BIM-based 3D exposure estimation with traditional 2D footprint-based models, the study provides empirical evidence on the benefits and limitations of each approach and offers insights for improving seismic risk assessment practices.

Given this context, there is a clear need for spatially explicit building models that incorporate structural taxonomy to support robust exposure analysis. This study proposes a methodology that utilizes 3D BIM models to extract building taxonomy

and calculate exposure values, and it includes a comparative analysis against conventional 2D-based exposure models. The objective is to demonstrate the added value of BIM in improving the quality of earthquake risk assessments, particularly in seismically active regions with limited building data infrastructure.

To achieve this objective, the study integrates BIM modeling with the GEM taxonomy framework within the context of the Institut Teknologi Bandung (ITB) campus, which is located near the active Lembang Fault Zone. This integration enables detailed spatial and structural analysis at both the individual building scale and the district scale. The combined use of BIM and the GEM taxonomy provide a data-driven and scalable approach that enhances the accuracy, consistency, and applicability of exposure modeling in academic and urban environments. The contributions of this study include: (1) a systematic workflow for deriving GEM taxonomy attributes from BIM models; (2) a comparative evaluation of 2D and 3D exposure estimation; and (3) empirical insights on the implications of BIM integration for seismic risk modeling.

2. RESEARCH SIGNIFICANCE

This study offers a significant contribution to seismic risk assessment by integrating BIM with the standardized GEM taxonomy to generate spatially explicit and structurally informed exposure models. The originality of this work lies in the development of a systematic workflow that links BIM-derived building attributes, including height, geometry, structural typology, and configuration, to internationally recognized taxonomy classes. This approach enables a more consistent and detailed representation of building characteristics compared to traditional exposure datasets.

In contrast to conventional 2D footprint-based exposure models, which often rely on limited geometric information, this study utilizes 3D BIM data to improve the estimation of building volume and vulnerability. By conducting comparative analysis between 2D and 3D exposure assessments within the ITB campus, this study offers valuable insights for enhancing the accuracy, consistency, and applicability of seismic risk modeling, particularly in areas where detailed building inventories are limited.

3. MATERIALS AND METHODS

3.1 Study Area

This study was conducted on the ITB campus using BIM data from four campus buildings. The study site was selected due to its close proximity to the Lembang Fault, one of the most active seismic

faults in West Java. The Lembang Fault extends approximately 29 km from Padalarang to Jatinangor. ITB's main campus is located in the northern part of Bandung City, approximately 2–3 km from the mapped fault trace, placing the campus within a high seismic hazard zone. Historical seismic investigations indicate that the Lembang Fault is capable of generating earthquakes with magnitudes ranging from M_w 6.8-7.0 [26 27].

3.2 Research Workflow

This study was conducted through a series of sequential stages designed to meet the research objectives. In the first stage, BIM data for selected ITB campus buildings were analyzed, focusing on various building types, including multi-story, high-rise, and heritage buildings that had already been modeled in BIM format. In the second stage, building taxonomy was defined based on the geometry of the BIM models, following the GEM taxonomy classification. The third stage involved assessing exposure values based on two key components: (1) the 3D BIM geometry and (2) construction cost estimates derived from the building footprint and number of floors, multiplied by predetermined coefficients. Subsequently, seismic risk estimation was performed using the open-source OpenQuake engine using version 3.16.4 and QGIS dekstop 3.32.1 ,which supports probabilistic hazard and risk assessment [28].

The OpenQuake calculator simulates seismic hazard over a given time period T by generating a Stochastic Event Set (SES). For each fault defined in the source model, the number of events over time T is sampled from a probability distribution as defined by:

$$SES(T) = \{k \times rup, k \sim Prup(k|T) \forall rup \text{ in } Src \forall Src \text{ in } SSM\} \quad (1)$$

Here, k represents the number of occurrences sampled from the rupture probability distribution $Prup(k|T)$, and $k \times rup$ indicates that rupture rup occurs k times within the simulated period. This framework enables comprehensive risk modeling under uncertainty and enables informed decision-making for earthquake resilience planning. Building on probabilistic hazard simulations, seismic risk is assessed by integrating hazard, exposure, and fragility to estimate expected damage and losses

$$R = H \times E \times F \quad (2)$$

H (Hazard) = represents the probability and intensity of seismic events, E (Exposure) = denotes the assets and their associated economic values, and F (Fragility) = the probability of exceeding a set of limit states, given an intensity measure level.

3.3 BIM Data

BIM served as primary data source for extracting detailed geometric and structural information. Its ability to integrate spatial and non-spatial attributes make it suitable for exposure modeling and vulnerability assessment. The BIM models provided accurate 3D visualization, enabling interpretation of building architecture, structural layout, and material configuration. From these models, building taxonomy classes were assigned according to the GEM framework.

For the purposes of this study, the buildings were categorized into three groups based on age, architectural style, and historical significance (Figure 1): Modern buildings (CADL and SBM Freeport), Older buildings (West GKU), Heritage buildings (West Hall).

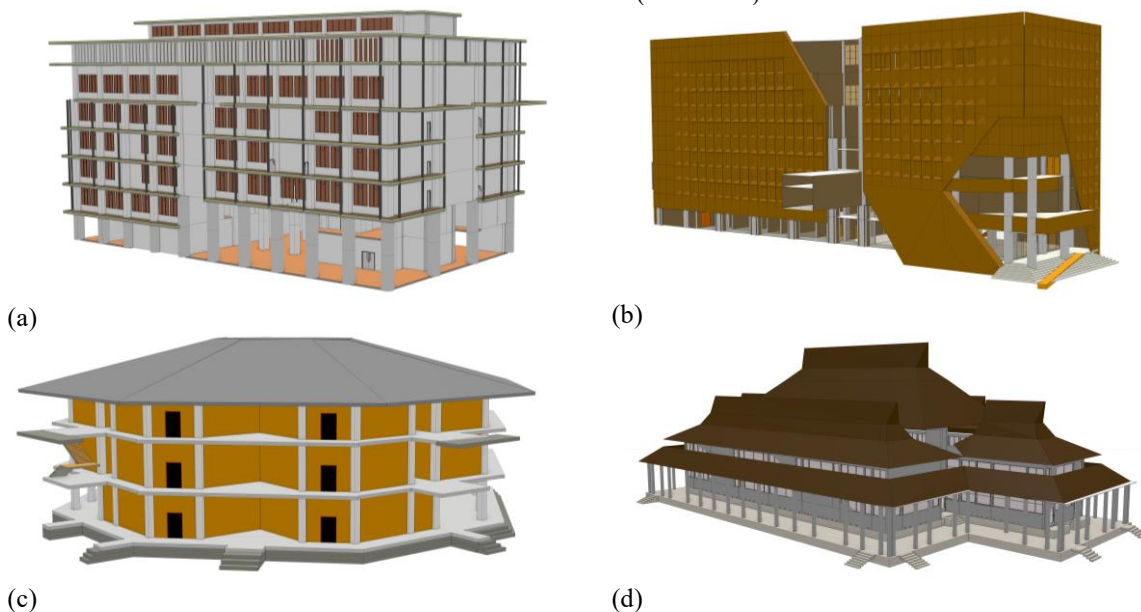


Fig. 1. Visualization of BIM data for the four selected buildings: (a) CADL, (b) SBM Freeport, (c) West GKU, and (d) West Hall.

These buildings were purposively selected to represent structural diversity across the campus, thus allowing for a broader understanding of seismic risk under varied construction typologies. The selection was intended to reflect the range of vulnerabilities that may exist due to differences in design standards, construction methods, and usage functions.

Building Information Modeling provides rich geometric data, transforming this geometry into an analytical model suitable for structural analysis, particularly for lateral load resistance, involves significant interpretation and the introduction of explicit assumptions[29,30,31]. The lateral load-resisting system (LLRS) was inferred solely from BIM visualization and geometric inspection, consistent with exposure modeling practices in OpenQuake and the Global Earthquake Model (GEM) Building Taxonomy. Shear wall systems were identified by vertically continuous reinforced concrete walls or cores, while moment-resisting frame systems were identified by regular beam-column layouts and the absence of dominant wall elements. Plan and vertical regularity were assessed through floor-by-floor BIM inspection. The inferred LLRS represents a taxonomy-level approximation. [32,33,34].

The use of these BIM models contributes to the development of a contextually relevant taxonomy framework for higher education institutions in Indonesia. Furthermore, it supports the generation of a precise exposure database, which enhances both individual building assessments and aggregate loss estimations.

3.4 Exposure Data

Each building was geo-referenced using precise geographic coordinates and assessed for its potential exposure to earthquake hazards.

The BIM models provided key exposure attributes, such as total building area and number of floors, which are used to estimate the structural value of each asset. The exposure value, defined as the estimated asset value, was calculated by multiplying the total geometric area from the BIM model with the unit construction cost per square meter (m²), as defined by the official standards of the Bandung City Government USD 354, Exposure values represent structural replacement costs only, excluding non-structural components and contents. Two approaches were applied to estimate the asset value:

1. A Geometry-Based Approach

This approach uses the total building area derived from BIM geometry. The estimated asset value is calculated as:

$$\text{Estimated Asset Value} = \text{Unit Cost per Area} \times \text{Total Building Area (BIM)} \quad (2)$$

2. Floor Coefficient-Adjusted Approach

This approach adjusts the estimated asset value by incorporating vertical complexity through an empirical floor coefficient.

$$\text{Estimated Asset Value} = \text{Unit Cost per Area} \times \text{Ground Floor Area} \times \text{Floor Coefficient} \quad (3)$$

Floor coefficients reflect typical construction multipliers for multi-floor buildings. For instance, coefficients of 1.09 and 1.12 apply to buildings with two and three floors, respectively. The complete list of coefficients is provided in Table 1.

Table 1. Coefficients used as proxies for estimating floor-based adjustments in building asset valuation.

| Number of Floors | Coefficients |
|------------------|--------------|
| 1 | 1 |
| 2 | 1.09 |
| 3 | 1.12 |
| 4 | 1.135 |
| 5 | 1.162 |
| 6 | 1.197 |
| 7 | 1.236 |
| 8 | 1.265 |

3.5 Seismic Hazard Data

Seismic hazard data were sourced from the Indonesian Center for Earthquake Studies (Pusat Studi Gempa Nasional/PuSGeN), which provide national earthquake source models covering the Lembang Fault, the Cimandiri Fault, and the Sunda Subduction Zone. For the vulnerability assessment, this study adopted fragility functions from the GEM Global Seismic Risk Model which providing standardized fragility curves applicable across various building typologies [35-36].

The seismic hazard analysis followed the Probabilistic Seismic Hazard Analysis (PSHA) framework, which quantifies the likelihood of different ground motion intensities while incorporating uncertainties in seismic source characteristics, recurrence intervals, and ground motion attenuation. PSHA estimates the probability that parameters such as Peak Ground Acceleration (PGA) or spectral acceleration (Sa) exceed defined thresholds within specific time frames [37,38].

Unlike Deterministic Seismic Hazard Analysis (DSHA), which only considers the maximum credible earthquake from the nearest fault, PSHA integrates contributions from all potential seismic sources across a range of magnitudes, locations, and recurrence intervals. This probabilistic approach

yields a more comprehensive hazard characterization and is widely used for risk-informed decisions in building code development, urban planning, and disaster insurance pricing [39,40].

The PSHA methodology consists of two main components:

1. Seismic Source Modeling

Active faults, seismotectonic zones, and magnitude-frequency distributions were characterized using PuSGeN’s regional earthquake source model, which includes the Lembang Fault, the Cimandiri Fault, and the Sunda subduction interface [35].

2. Ground Motion Modeling

Ground Motion Prediction Equations (GMPEs) were applied to estimate ground shaking level at specific sites. Local site conditions in Bandung were incorporated using Vs30 values, representing the average shear-wave velocity in the upper 30 meters of the soil profile [41].

The integration of seismic source and ground motion models was carried out using Monte Carlo simulations and semi-analytical methods, producing hazard curves for varying ground motion intensities. These curves form the basis for the building risk assessments presented in this study [42, 43].

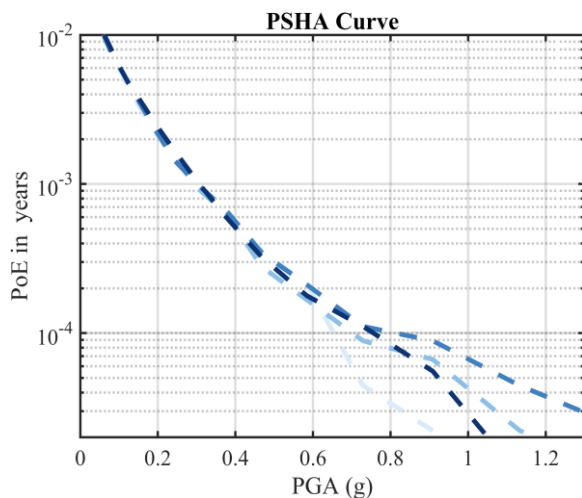


Fig. 2. Logic tree-based hazard curves

4. RESULT

4.1 Building Taxonomy

The analysis showed that seven out of the thirteen building taxonomy elements defined by the GEM framework can be identified using BIM-based visualization and geometric information. These identifiable elements include: (1) building orientation, (2) building height, (3) plan-shape configuration, (4) structural irregularities, (5) exterior walls type, (6) roof type, and (7) floor geometry.

From the BIM geometric data, attributes such as building height and number of floors can be extracted directly.

The spatial visualization also enables the assessment of buildings footprint shapes, spatial arrangement among buildings, and overall structural configuration. In addition, the BIM models support the identification of exterior wall types, roof forms, and floor geometries.

However, four GEM taxonomy elements cannot be inferred geometric data alone. These include: (1) the material of the lateral load-resisting system, (2) the date of construction or retrofit, (3) the building function or occupancy, and (4) the foundation system. These elements require additional metadata, which are only available if recorded explicitly during the planning or construction stages within a comprehensive BIM environment. Using the available taxonomy information, GEM taxonomy codes were assigned to the four buildings, as presented in Table 2.

Table 2. Summary of building classifications according to the GEM taxonomy

| Building | Taxonomy | Description |
|--------------|------------------|--|
| CADL | CR/LDUAL+DUH/H:8 | Concrete reinforced (CR), Dual frame-wall system (LDUAL), ductile, 8 storeys |
| West GKU | CR/LFINF+DUH/H:3 | Concrete reinforced (CR), Infilled frame [LFINF], ductile, 3 storeys |
| SBM Freeport | CR/LDUAL+DUH/H:6 | Concrete reinforced (CR), Dual frame-wall system (LDUAL), ductile, 6 storeys |
| West Hall | W/LWAL+DUL/H:1 | wood (W), with wall system (LWAL), Low ductility (DUL), 1 storey |

4.2 Building Damage Assessment Using BIM Geometry and Floor Coefficients

Seismic damage assessment was performed for four buildings on the ITB campus using two exposure estimation approaches: a BIM geometry-based method and a floor coefficient-adjusted method. Asset values were converted from Indonesian rupiah to U.S. dollars using the exchange rate of 28 August 2025 (1 USD = 16,436 IDR).

While the two approaches yield different asset valuations (Table 3), the resulting damage patterns are consistent. Probabilistic simulations for a one-year period indicate that all buildings are most likely to experience slight damage, regardless of the exposure estimation method. The probability distributions of damage states derived from both approaches are presented in Figure 3, which highlights the dominance of the slight damage category across all buildings.

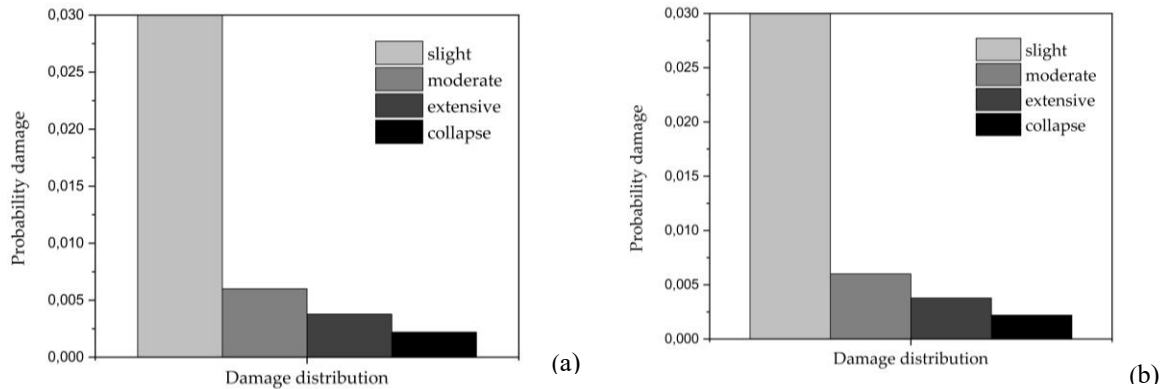


Fig. 3. Probability distribution of building damage levels derived from the seismic risk model: (a) geometry-based, and (b) floor coefficient-adjusted.

Table 3. Asset risk statistics for earthquake-induced

| Taxonomy | Lon | Lat | Losses (FC) | Losses (G) |
|--------------------|-----------|-----------|-------------|------------|
| CR/LWAL+D UC/HEX:6 | 107.60877 | - 6.88826 | 89 | 432 |
| CR/LFM+DN O/HEX:3 | 107.60886 | - 6.89033 | 241 | 475 |
| CR/LWAL+D UC/HEX:8 | 107.60957 | - 6.88831 | 80 | 625 |
| W+WLI/HEX:1 | 107.60983 | - 6.89240 | 31 | 31 |

building damage.

*FC= floor coefficient, G=geometry

4.3 Economic Loss Assessment for Building Damage

Economic losses due to earthquake hazards were estimated for return periods ranging from 5 to 1,000 years using two exposure models: a floor coefficient-adjusted approach and a BIM geometry-based approach. For short return periods (5–10 years), both simulations indicate negligible expected losses,

reflecting the low probability of damaging events over shorter time horizons.

As return periods increase, economic losses rise progressively under both exposure models, demonstrating a clear positive relationship between seismic recurrence interval and expected loss. The loss–return period curves derived from the floor coefficient-based and geometry-based exposure models are presented in Figures 4a and 4c, respectively. Although the absolute loss magnitudes differ between the two approaches, the overall trend remains consistent, with substantially higher losses associated with longer return periods.

Event-based aggregation of losses further reveals that a limited number of seismic events dominate the overall economic risk. In particular, the aggregated risk by event analysis identifies a single dominant event (rup_id 6001) contributing both the highest losses and the highest occurrence frequency under the floor coefficient-based exposure model, as illustrated in Figure 4b. Comparable patterns are observed in the geometry-based simulation (Figure 4d), highlighting the influence of high-impact events on total economic loss estimates.

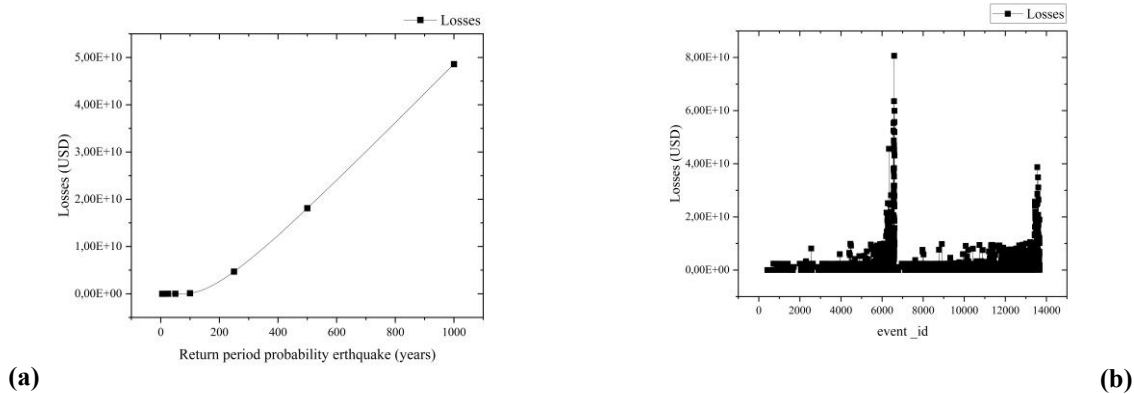


Fig 4. Economic loss estimates from seismic risk simulations. (a) Economic loss vs Return period (b) and Economic loss vs Geometric based Event ID

West Hall. These results indicate that geometry-based estimation provides a more detailed representation of building exposure, which is particularly relevant for earthquake risk analysis requiring floor-level spatial and structural resolution to support mitigation planning and risk-informed decision-making.

The first model employed a geometry-based asset estimation approach using the full BIM model. It incorporated detailed information for each floor based on the 3D structural and visual representation of the building. This approach is more comprehensive because it fully utilizes the geometric information embedded in the BIM model, including floor area, volume, and configuration. As a result, every part of the building, from the ground floor to the upper levels, was proportionally represented in the asset estimation. This model produced higher asset values, namely USD 3,453,769 for CADL, USD 1,088,995 for West GKU, USD 1,809,787 for SBM Freeport, and USD 661,281 for West Hall. These results provide a more realistic depiction of potential economic risk by accounting for the full physical complexity of each building. Therefore, the first model can be considered more representative in the context of earthquake risk analysis, particularly when spatial and structural precision at the floor level is essential for supporting effective mitigation and planning.

6. CONCLUSION

This study presents a BIM-based methodological framework for earthquake risk assessment that enables systematic extraction of seismic exposure parameters in accordance with the Global Earthquake Model (GEM) taxonomy. The results show that seven taxonomy parameters can be directly derived from BIM geometry, with one additional parameter inferred from non-geometric attributes, demonstrating the methodological feasibility and consistency of BIM for exposure modeling.

In terms of impact, integrating BIM with the OpenQuake engine allows for stochastic risk simulations that more realistically represent structural damage and economic losses compared to traditional two-dimensional, coefficient-based methods. The three-dimensional representation of buildings in BIM is particularly effective in capturing vertical structural complexity in multi-story buildings, thereby improving the accuracy of exposure characterization and loss estimation.

However, this study also identifies a key limitation related to the use of generalized taxonomy classifications and fragility functions. The GEM taxonomy codes applied provide simplified building representations and do not explicitly account for critical structural attributes such as foundation systems, retrofit conditions, detailed lateral load-resisting mechanisms, and material properties, which significantly influence seismic performance.

To address these limitations, future research should focus on refining taxonomy definitions and fragility models by leveraging the detailed structural information available in BIM. With improved data quality and alignment with national building standards, BIM has the potential to support the development of a more robust, data-driven taxonomy framework. Consequently, this study supports the institutional adoption of BIM as a standard tool for earthquake risk assessment and seismic risk mitigation planning, enabling more accurate, scalable, and policy-relevant risk analyses.

7. ACKNOWLEDGMENTS

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