

RESEARCH ARTICLE

Health Infrastructure Service Management Using Nonlinear Pushover Analysis Based on Earthquake Response Spectrum

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Abstract

This study aims to determine the inter-floor shift due to earthquake spectrum response using nonlinear pushover analysis in a clinic building located in the Cimandiri Fault Zone as a basis for healthcare infrastructure management. This is very important because healthcare infrastructure is a place that must be available in any condition, even after an earthquake disaster. The Sukabumi area is an area located in the Cimandiri Fault Zone, so buildings in this area must be specifically designed to remain intact during disasters, especially earthquakes that often cause building damage. The research object that is the case study in this study is a 4-story clinic building that uses a reinforced concrete structure. The method used in the earthquake spectrum response analysis refers to SNI 1726:2019 and SNI 2847:2019, which have available spectral response webs, while the nonlinear pushover analysis uses the ATC-40 and FEMA-440 methods implemented in ETABS. The results of the analysis show that the inter-floor shift on the second and third floors exceeds the specified service limits, so it can be stated that the clinic building structure service in this case study requires damage control (DO). This can be seen based on the analysis results that the inter-floor shift of 201 mm in the X direction and 190 mm in the Y direction can cause moderate damage that can be repaired, so that health infrastructure service management is very necessary. Controlling recurrent damage due to earthquakes can be done with three retrofit scenarios consisting of the addition of shear walls, column coating, and steel reinforcement. The three scenarios are assessed and ranked based on the reduction of shifts, repair duration, and functional disruption. The addition of shear walls is the main recommendation without disrupting functionality, while column coating and the addition of steel reinforcement can disrupt health service operations. Retrofit scenarios can be recommended to support a sustainable health service infrastructure system in earthquake-prone areas. Earthquake spectrum response is a key factor that needs to be reviewed in building damage analysis as a basis for risk control management of health service infrastructure.

Keywords: Infrastructure management, Spectrum response, Healthcare infrastructure, Sustainable infrastructure, Earthquake

1. Introduction

Earthquakes cause shaking of the ground surface over a certain distance through the propagation of ground vibrations, known as the earthquake response spectrum. This is what causes damage to the ground surface, including buildings standing near the earthquake zone. Damage to the health care infrastructure is often caused by earthquakes (Mavrouli et al., 2023), (Spiridonov et al., 2025). Health care facilities, particularly hospitals and clinics, are vital infrastructure elements in the discourse of safety due to seismic response, especially in sustainable urban development (Poudel et al., 2024). When an earthquake occurs and even afterward, the facility must function as a service center for first emergency response, coordinating rescue operations, and supporting recovery (Yamamoto et al., 2022), therefore, this infrastructure must be protected from damage so that operations can continue to function properly. However, in fact, based on post-earthquake disaster reports such as those in Haiti in 2010 (Contreras et al., 2025), the Tōhoku earthquake in 2011 (Galloway, 2020), and the Türkiye–Syria earthquake in 2023 (Şentürk, 2025), it shows that many hospitals collapsed and could not operate even though they were desperately needed (Qu et al., 2023). Globally, this underscores the importance of robust, earthquake-resistant healthcare infrastructure to continue operating according to its function; therefore, a comprehensive understanding of the

performance of building structures in the earthquake spectrum response area is very important (Ramesh et al., 2025), so healthcare infrastructure management is needed.

Indonesia is geographically located in the Pacific Ring of Fire region, with intense seismic and volcanic activity due to the interaction of several major tectonic plates, including: the Indo-Australian, Eurasian and Pacific Plates (Sabah and Sil, 2023). The Meteorology, Climatology, and Geophysics Agency (BMKG) noted that more than 10,000 earthquakes occur every year, with 200 of these events having a magnitude of more than 5.0 (Supendi et al., 2023a). The 5.6 magnitude Cianjur earthquake in 2022 caused hundreds of fatalities and injuries, and caused severe damage to over 6,000 buildings. (Supendi et al., 2023b). The Sukabumi area, which is the case study in this research, is the area directly affected by the earthquake, because it is located along the active Cimandiri fault, which is one of the most seismically active faults in West Java (Pasari et al., 2021). Based on the above background, an evaluation of the health service system in Indonesia is necessary. Soil type, depth, and impoundment play a significant role in the distribution of ground motion, in addition to activities such as tectonics and local geological conditions.

Recent studies further indicate that the Cimandiri Fault is an active left-lateral strike-slip fault with an estimated slip rate of approximately 3–5 mm/year, reflecting continuous tectonic strain accumulation capable of generating damaging

earthquakes (Pasari et al., 2021). In the Sukabumi area, this fault system is expressed through several active segments, including the Loji, Cidadap, and Nyalindung segments, which directly traverse or closely border urban zones of Sukabumi City, thereby increasing seismic exposure to critical infrastructure (Pasari et al., 2021). From a structural perspective, many hospital and healthcare buildings in Sukabumi Regency were constructed prior to the enforcement of modern Indonesian seismic design codes, often characterized by limited ductile detailing, inadequate lateral load-resisting systems, and high vulnerability of non-structural components under strong ground motion (BMKG). The object of this study is a four-story clinic building consisting of one basement and three above-ground floors, located along the South Ring Road (Jalur Lingkar Selatan), Sukabumi City, which represents a typical existing healthcare facility situated in close proximity to the active Cimandiri Fault. Given the documented spatial variability of site response, active fault segmentation, and the strategic role of healthcare facilities, a seismic zoning map of the Cimandiri Fault affecting Sukabumi City is therefore presented to contextualize the seismic hazard and structural risk faced by the investigated building.

1.1 Research Trends and Knowledge Gap

Padalu and Surana's 2024 study examined non-linear pushover analysis, creating a standard approach for evaluating reinforced concrete structures using ATC 40, FEMA 356, and FEMA 440 (Padalu and Surana, 2024). ATC-40 and FEMA-356 established nonlinear static (pushover) analysis procedures as a standard framework for performance-based evaluation of reinforced concrete structures by relating structural capacity curves to discrete damage-state performance levels, and FEMA-440 later refined these displacement-based methods to improve the accuracy and consistency of seismic performance assessments. (Kuria and Kegyes-Brassai, 2023), (Alwaeli et al. 2020), and (Guettala et al. 2025) demonstrate effectiveness in terms of displacement requirements and structural performance categories. Several of these studies focused solely on identifying structural and material issues. However, the theoretical findings obtained have not been applied to support risk decision-making. The relationship between drift ratio, ductility, and capacity spectrum is often overlooked in existing research (Anwar et al., 2024). Therefore, facility management and decision-making lack the quantitative tools needed to prioritize strengthening and maintenance of critical buildings.

1.2 Problem Statement

SNI 1726:2019, which refers to seismic design, and SNI 2847:2019, which refers to concrete structures, are still widely used in hospital and clinic designs, even though these design standards are outdated (Miyamoto et al., n.d.), (Paikun et al., 2022). This situation impacts the safety of visitors and patients inside because the building structure does not meet minimum standards during an earthquake (Paikun and Kurniawan 2022) in their study described that a health facility in a small area in Sukabumi adjacent to the Cimandiri fault must remain active during an earthquake. Research by (Asadi et al. 2020) stated that decision-making in risk is still inadequate and a solution is needed for this. (Kerle 2024) also supports this view that risk management relies on post-disaster visualization, because only qualitative methods are used in disaster risk management. Based on these conditions, improvements are needed in earthquake-prone areas.

1.3 Research Objective and Scope

The general objective of this study is to apply nonlinear pushover analysis within an earthquake risk management framework for healthcare facility infrastructure to ensure the continuity of medical services during and after seismic events. Specifically, the study aims to employ nonlinear pushover analysis to comprehensively assess the seismic performance of healthcare facility structures, to interpret those performance results into risk classifications relevant to the continuity of healthcare operations, and to formulate strengthening and intervention prioritization strategies based on technical parameters such as drift, estimated repair duration, and levels of functional disruption to support managerial decision-making.

The scope of this research focuses on technical evaluation and development of risk management decision-making. The technical focus of this research is nonlinear pushover modeling and analysis. The managerial focus of this research focuses on facility managers and policymakers, as well as assessing the operational impacts on healthcare delivery. The research method provides a quantitative approach to planning, maintenance, and resource allocation post-earthquake recovery efforts (Li et al., 2025). The limitations of this research are limited to facilities and structural forms.

1.4 Novelty and Expected Outcomes

This research expands on the ATC-40 and FEMA-440 seismic evaluation studies (Abate et al., 2025). Furthermore, this research provides a technical decision-support framework for risk mitigation and prevention. It also supports post-earthquake maintenance and resource allocation. This research also serves as a link between EDPs and risk management indicators to provide structural evaluation of operations.

The novelty of this research lies in the implementation of a nonlinear structure within a managerial framework. The results provide policy and technical recommendations for strengthening the resilience of health services in disaster-prone areas such as earthquakes.

2. Conceptual and Methodological Framework

2.1 Conceptual Framework Overview

This research conceptual framework combines structural engineering and construction management to manage earthquake risk mitigation in health-prone areas (Khalqillah et al., 2025), (Lamonge et al., 2024) proposed engineering output indicators including capacity curves, target displacement, and interstory drift. This research conceptual framework consists of three layers. The first layer assesses structural performance through nonlinear and linear analysis in accordance with existing standards. Then, the second layer evaluates the structural response to assess functional and operational risks, including damage, downtime, and service disruption. The third layer develops tools to support decisions and create multi-criteria strategies that consider effectiveness and operational sustainability (Pokkuluri et al., 2025).

2.2 Framework Description

Drift data and performance classification are linked to the Performance-Risk Matrix, which estimates post-earthquake recovery times (Vania et al., 2025). The DC classification process ranges from two to six weeks, while IO indicates minimal disturbance, and LS indicates longer recovery times (Baquedano-Juliá et al., 2024). The risk matrix is categorized into high, medium, and low as an ongoing effort (Sunhadji et al., 2022).

During the strengthening phase, existing options such as shear walls can theoretically reduce drift by around 30-40 percent (Chen et al., 2023). Column reinforcement with

RC/FRP is used to increase ductility (Villar-Salinas et al., 2021). Finally, steel bracing can reduce torsion and deformation (Gao et al., 2020). These reinforcement options are considered based on their effectiveness, construction, and implementation time (Daniel & Ghiaus, 2023), which ultimately results in a Retrofit Prioritization Matrix (Pokkuluri et al., 2025).

The final stage involves establishing post-intervention monitoring as a mechanism for ongoing evaluation and implementation in facility maintenance (Zhao et al., 2025). This framework is more clearly presented in Figure 1. This cycle is expected to improve safety, reliability, and economic efficiency over a sustainable period (Hoffmann & Blab, 2012).

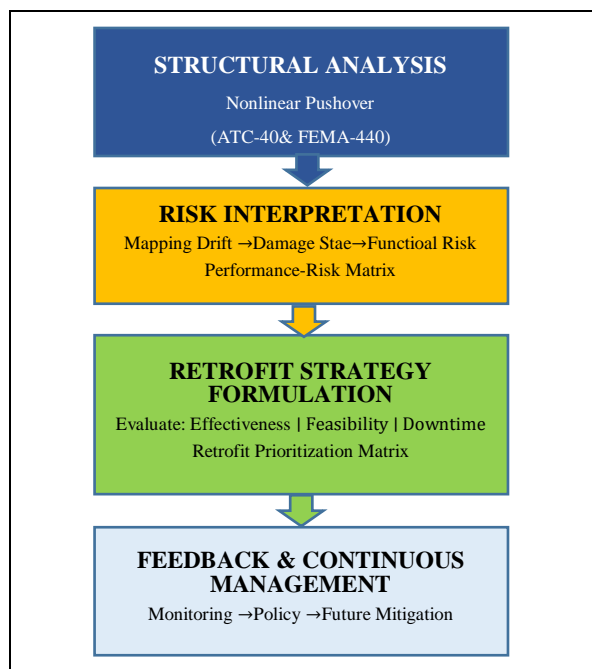


Fig. 1. Graphical representation

2.3 Contribution of the Framework

The framework proposed in this study connects nonlinear pushover techniques with administrative decision-making techniques in natural disaster risk management systems, including Sukabumi. This framework can be implemented in various facility infrastructures, not only healthcare facilities but also educational, political, and other public access facilities. Furthermore, according to Mukherjee et al. (2023), this framework can also be useful for government agencies in assisting with building resilience investment decisions when budgets are limited.

This research can also theoretically provide a basis for linking nonlinear structural capacity assessments through a framework developed for critical healthcare facilities (Hughes et al., 2021). This framework consists of a systematic structural evaluation, hazard characterization, formulation of reinforcement strategies based on hazard identification, and finally, periodic and continuous monitoring (Elgamal et al., 2003).

This study describes a systematic and comprehensive approach to conceptual and procedural aspects, including research design, data collection, computational modeling, linear and nonlinear analysis, and conversion into risk management system parameters. To ensure the framework can be replicated and used appropriately, this study emphasizes methodological rigor. This study sequentially applies seismotectonic characterization, nonlinear response

analysis, and risk management to healthcare infrastructure located in earthquake-prone areas (Nursanto and Fadhilah, 2024).

3. Research Methods

This study uses a quantitative approach, combining engineering and managerial aspects, to assess infrastructure resilience (Wang et al., 2025). The goal is to link nonlinear pushover analysis with hazard planning strategies for healthcare infrastructure, enabling understanding within the context of emergency management during disasters (Gernay & Khorasani, 2019).

Data collection, computational modeling, nonlinear evaluation, hazard interpretation, and formulation of structural mitigation and strengthening strategies constitute the design of this study (Saleh, 2025). This reinforced concrete community health center building in Sukabumi was selected as a case study due to its proximity to the Cimandiri Fault, making it categorized as a high-hazard zone (Mase et al., 2023). SNI 1726:2019, SNI 2847:2019, ATC-40 (1996), and FEMA-440 (2005) are used as technical standards to assist researchers in providing a conceptual evaluation framework (Khotimah et al., 2024; Octaviani et al., 2024).

3.1 Case Study Description and Data Collection

This case study evaluates a three-storey reinforced-concrete clinic in Sukabumi, Indonesia, located within the active Cimandiri fault zone; the facility functions as an outpatient and emergency medical center and is assigned an importance factor of 1.4 under SNI 1726:2019 (Andika and Roesdiana, 2025). Primary data were collected from architectural and structural drawings, site inspection, and material documentation. Key modeling inputs for the ETABS analyses included a special moment-resisting frame (SMRF) with reinforced-concrete columns and beams (Abhinand and Pandikkadavath, 2025); concrete strength $f'_c = 25$ MPa and steel yield $f_y = 400$ MPa (Amir et al., 2020); dead and live loads per SNI 1727:2020 with an assumed occupancy load of 3.0 kN/m² for healthcare use (Syamsi et al., 2025); and seismic parameters of $PGA = 0.4g$, soil type SD, and spectral accelerations $S_5 = 1.2g$ and $S_1 = 0.6g$ (Kan et al., 2025).

3.2 Structural Modeling and Linear Analysis

A three-dimensional computational representation of the structure was developed using ETABS version 19, incorporating the complete spectrum of loading scenarios prescribed by Indonesian seismic code SNI 1726:2019 (Kuncara, 2023). Linear static evaluation was used to validate the existing structure, then identify the lateral pattern displacements resulting from operational freedom, and finally used to determine the basic vibration period.

The dynamic modal evaluation showed 0.71 seconds and 0.68 seconds for longitudinal and transverse respectively, then the structural response was dominated by translational motion from the opposite direction. The computed foundation reaction forces and relative story displacements were compared against regulatory limits, specifically the drift threshold not exceeding two percent of floor-to-floor height (Xie et al., 2019). While most floor levels demonstrated compliance with code provisions, localized violations observed at the uppermost level indicated potential stiffness irregularities characteristic of soft-story behavior, thereby justifying the necessity for subsequent nonlinear capacity assessment.

3.3 Nonlinear Pushover Analysis Procedure

Nonlinear pushover analysis was performed using ETABS with two different control methods (Oscar D Gaxiola-Camacho et al., 2021), namely:

- ATC-40 Capacity Spectrum Method (CSM)
- FEMA-440 Displacement Coefficient Method (DCM)

For beams and columns using plastic hinges, refer to the FEMA-356 standard for flexural behavior (M3) (Soltani et al., 2023). Building structures that experience monotonically increasing lateral loads in both main directions can experience global instability.

The capacity curves (base shear vs roof displacement) were produced using the nonlinear pushover analysis and later transformed into acceleration–displacement response spectra (ADRS) to ascertain the structural performance point. The goal displacement in each primary direction was assessed in accordance with the ATC-40 recommendations, and between Immediate Occupancy (IO) and Life Safety (LS) as per FEMA-440 (Oscar D. Gaxiola-Camacho et al., 2021), and between Immediate Occupancy (IO) and Life Safety (LS) per FEMA-440 (Fitriyah et al., 2025). The evaluation process assesses the inter-story displacement ratio in the X and Y directions, then compares it to the Immediate Occupancy (IO) and Life Safety (LS) thresholds established in their respective standards. This procedure establishes a framework for assessing the extent of damage and the need for deformation, which forms the basis for risk interpretation and subsequent repair planning.

3.4 Risk Assessment and Functional Mapping

The relationship between functional risk indicators and damage operability is mapped in Figure 2



Fig 2. Drift–Damage–Function–Downtime Framework

The framework in Figure 2 shows the relationship between structural displacement, damage condition, functional impact, and estimated downtime. Structural drift is a primary indicator of damage severity, implying that "the greater the drift, the greater the damage." The FEMA P-58 (2018) and HAZUS (2015) risk-based assessments serve as the framework for this study (Zhou et al., 2025). Damage state is categorized as light, moderate, severe, and total failure, a categorization based on FEMA P-58/HAZUS (Majdi and Vacareanu, 2021). Functional Impact focuses on the functionality of the structure during a disturbance, in this case an earthquake. This section also categorizes the structure's function as still operational, its function as reduced to unusable, and its function as completely unusable. The last one is Expected Downtime, this is about how long the building cannot operate after an earthquake disaster, this downtime is influenced by the FEMA P-58 recovery model, HAZUS data, and previous theories or studies.

3.5 Retrofit Strategy Formulation

Retrofit decision-making requires a multi-criteria A multi-criteria framework is used to assist retrofit decision-making. This framework requires consideration of both structural performance improvements and managerial feasibility. These two aspects are significantly interconnected and must be incorporated into this multi-criteria framework. The criteria used in this framework utilize parameters such as effectiveness, feasibility, and disruption (Ongpeng et al., 2022). Each criterion is analyzed to identify its characteristics, allowing for the differences between the two parameters (Table 1).

Table 1. Evaluation Criteria Framework for Retrofit Alternatives

Criterion	Description	Evaluation Parameters	Assessment Scale	Criterion
Effectiveness	Improvement in lateral stiffness and drift reduction	% drift reduction, increased ductility	High / Moderate / Low	Effectiveness
Feasibility	Constructability and resource efficiency	Material availability, construction complexity, cost ratio	High / Moderate / Low	Feasibility
Operational Disruption	Impact on facility operations during retrofit	Downtime duration, accessibility, service continuity	High / Moderate / Low	Operational Disruption

3.6 Integration into Risk Management Framework

Entering the final stage, integrating the Risk Management Framework (Arefi et al., 2025). In decision-making, there is a Performance Targeting dimension, where this dimension maintains the construction during shocks during the earthquake and prevents serious damage from the disaster. In Maintenance Planning, this dimension prioritizes plans for strengthening the construction, this is applied because health services must continue to operate during the reconstruction process. In Policy Integration, this dimension is used as a policy discussion to determine which parts of the health service must be improved first. The fourth dimension, Continuous Improvement, emphasizes post-construction sustainability, with monitoring as an evaluation in subsequent reconstruction.

3.7. Validation and Limitations

Model validation was performed by examining the consistency of capacity curves and plastic hinge formation patterns with comparable reinforced concrete frame structures in the existing literature. The predicted drift ratios and performance points agree well (within $\pm 10\%$) with benchmark studies conducted at similar seismic intensities. However, this study acknowledges several limitations:

- It uses a single-case model and does not include cost-benefit quantification.
- The downtime estimates are scenario-based rather than empirically verified.

Future research should address these limitations by incorporating downtime history analysis, cost evaluation, life cycle analysis, and risk optimization on multiple buildings to enhance generalizability. Despite these limitations, the methodological validation strengthens the applicability of the proposed framework for integrating seismotectonic data and structural performance analysis into a practical earthquake risk management system for critical healthcare infrastructure.

3.8. Research Flow

This research uses a comprehensive and systematic procedure to connect structural and managerial analysis. This procedure begins with problem formulation, where problem identification is carried out related to nonlinear pushover. Then, a literature review is conducted to strengthen the theoretical basis of what will be done and clear boundaries of what must be done related to nonlinear pushover. Then, a problem formulation is also carried out based on the identified problems related to nonlinear pushover. After the first stage of data collection, the data is modeled in ETABS, followed by a linear analysis and then a nonlinear pushover analysis following ATC-40 & FEMA-440. The main outputs are capacity curves, inter-story displacement profiles, and drift ratios (Suranto et al., 2021). The final stage is to develop a

decision support framework. The procedure is described in more detail in Figure 3.

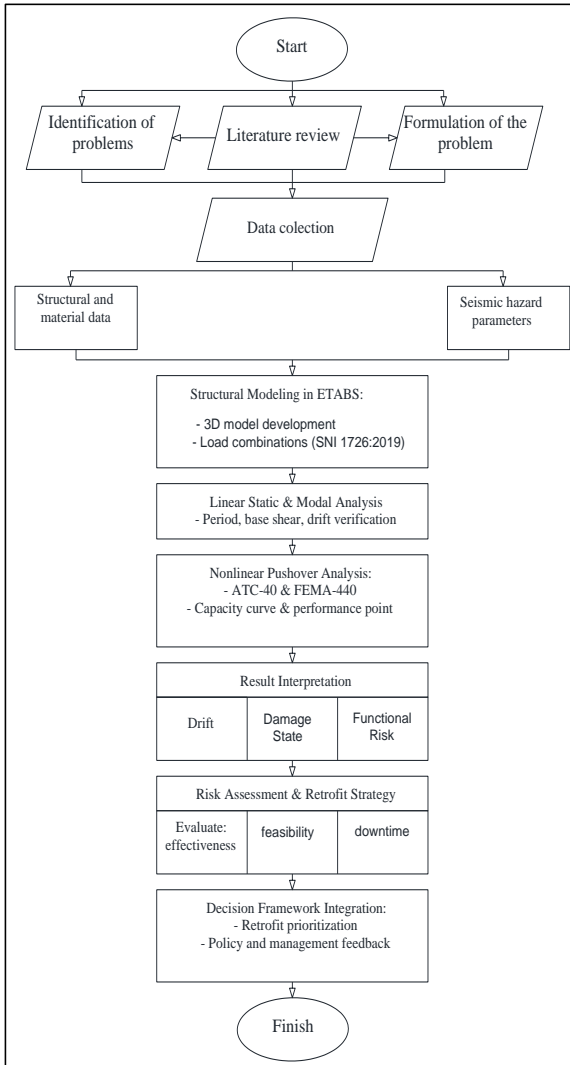


Fig. 3. Research flow

4. Results and Discussion

4.1 Structural and Seismic Parameters

The structure analyzed in this study is a three-storey reinforced-concrete healthcare facility located in Sukabumi, West Java—an area traversed by the Cimandiri Fault Zone, one of Indonesia’s most active seismic regions. This geographic setting makes the building a relevant example for evaluating the earthquake resilience of essential infrastructure.

The hospital is designed with a special moment-resisting frame (SMRF) system to ensure adequate ductility during strong ground shaking. Each floor has a uniform height of 4 meters, giving the building a total height of 12 meters, as shown in the architectural elevations in Figure 4. The primary lateral-load-resisting components consist of reinforced-concrete columns measuring 0.45×0.45 m and beams measuring 0.30×0.75 m, built using 25 MPa concrete and 400 MPa reinforcing steel. The structure demonstrates a regular distribution of mass and stiffness, helping to reduce potential torsional irregularities during seismic excitation.

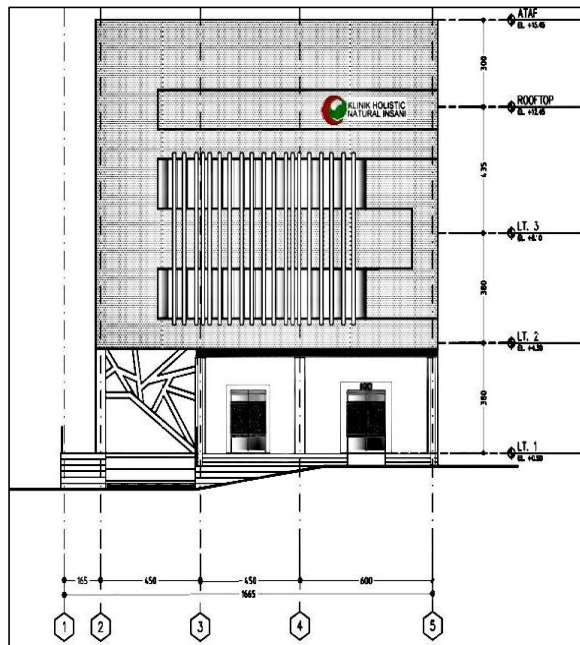


Fig. 4. Front view of the research object (source: primary data from the clinic building)

The seismic input was defined following SNI 1726:2019 and FEMA P-1050. Regional spectral accelerations from the Indonesian hazard map give $\alpha_{\square} = 1.20g$ and $\alpha_{\square} = 0.60$ g. The site, classified as stiff soil (Class D), uses coefficients $\alpha_{\square} = 1.2$ and $\alpha_{\square} = 1.6$. With the building’s occupancy category IV (essential facility), the importance factor is $\alpha_{\square} = 1.4$. Table 2 of the original report lists these coefficients and their adjusted values.

Table 2. Design seismic parameters for the Sukabumi site (SNI 1726:2019)

Parameter	Symbol	Value (g)
Mapped spectral acceleration (short)	S_S	1.20
Mapped spectral acceleration (1 s)	S_1	0.60
Site coefficient (short)	F_a	1.20
Site coefficient (long)	F_v	1.60
Adjusted short-period acceleration	$S_{MS} = F_a S_S$	1.44
Adjusted 1-s acceleration	$S_{M1} = F_v S_1$	0.96
Design spectral acceleration	$S_{DS} = \frac{2}{3} S_{MS}$	0.96
Design long-period acceleration	$S_{D1} = \frac{2}{3} S_{M1}$	0.64

According to these values, the site falls under Seismic Design Category E, indicating a requirement for high-ductility detailing and explicit nonlinear performance verification.

The design response spectrum is developed using code-defined expressions such as Equation 1.

$$S_a(T) = \begin{cases} S_{DS}(0.4 + 0.6), & 0 \leq T \leq T_0 \\ S_{DS}, & T_0 < T \leq T_S \\ \frac{S_{D1}}{T}, & T > T_S \end{cases} \quad (1)$$

Where $T_0 = \frac{0.2S_{D1}}{S_{DS}} = 0.13s$ and $T_S = \frac{S_{D1}}{S_{DS}} = 0.67s$. For the building’s fundamental period ($T_1 \approx 0.71s > T_S$) the corresponding spectral acceleration is $S_a = S_{D1}/T_1 \approx 0.90g$.

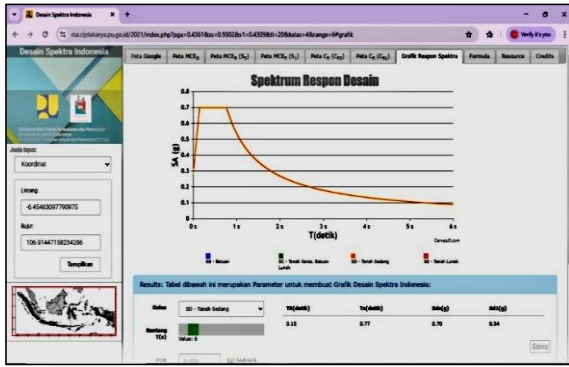


Fig. 5. Design response spectrum for the Sukabumi site, derived from the Indonesian Seismic Design Spectrum

The spectral coordinates obtained from the analysis confirm the severe seismic demands characteristic of the Sukabumi area. Based on the response spectrum, the β value is close to 1 g, indicating that ground motion at the design level requires a lateral force nearly equal to the building's own weight. This suggests a lack of ductility that could lead to substantial structural damage. The combination of stiff soil amplification, a high PGA value, and a significance factor of 1.4 further reinforces the need for improved restraint details and structural redundancy.

4.2 Structural Modeling and Linear Analysis

Based on the development of a structural model using ETABS V19 as a three-dimensional finite element representation to capture the global dynamic behavior of the building structure, consisting of beams, columns, and floor systems modeled as line elements and structural frames of the building based on their actual dimensions and material properties. Seismic masses are distributed evenly across each story to reflect realistic loading conditions, and floor diaphragms are assumed to act rigidly. Dead and live loads were applied according to SNI 1727:2020 (Al Ihsyan and Syahputri, 2024), while seismic actions were assigned using the response-spectrum method based on the design spectral parameters derived for the Sukabumi site.

Boundary conditions were defined as fully fixed at the base, assuming shallow foundations on stiff soil consistent with the site classification. The structural system was modeled as a ductile SMRF, corresponding to a seismic response modification factor $\beta = 8$. The modal analysis was performed to obtain the structure's fundamental translational and torsional modes, followed by linear static and dynamic evaluations for code compliance.

Modal and Static Response. Table 3 presents the principal results of the modal analysis. The first translational modes occur in orthogonal X and Y directions, while the third mode corresponds to torsional vibration. The computed periods demonstrate good agreement (within 10%) with the empirical estimation $T = 0.09 \cdot h^{0.75}$ prescribed in SNI 1726:2019, where $\beta = 0.0466$ for reinforced-concrete moment frames.

Table 3. Modal analysis results

Mode	Direction	Description	Period T (s)	Effective Mass (%)
1	X	First translational	0.71	72.8
2	Y	First translational	0.65	74.2
3	Torsional	Rotation about vertical axis	0.58	10.3

The corresponding base shear obtained from linear dynamic analysis under design-level excitation was 1,120 kN in the X direction and 1,015 kN in the Y direction. The computed story drifts are summarized in Table 4.

Table 4. Interstorey Drift under Design-Level Excitation

Storey	Max Drift (X) (%)	Max Drift (Y) (%)	Code Limit (%) (SNI 1726:2019)
3	0.28	0.25	2.0
2	0.31	0.27	2.0
1	0.36	0.29	2.0

All drift ratios are below the permissible limit of 2%, indicating that the building structure behaves elastically under design-level shaking. The modal shape is dominated by lateral translation, not torsion, which is consistent with the standard floor plan configuration, indicating adequate lateral stiffness without excessive flexure.

A linear response analysis indicates that the reinforced concrete clinic building meets the elastic deformation criteria, indicating balanced stiffness in both horizontal directions. However, the X-direction exhibits a longer period of 0.71 seconds. Investigations of the existing building revealed the absence of shear walls, indicating the need for additional reinforcement, necessitating a nonlinear capacity analysis. A drift ratio of <0.4% indicates high stiffness, indicating that service-level performance requirements can be met.

4.3 Nonlinear Pushover Analysis

To evaluate the building's inelastic performance under severe ground motions, a nonlinear static (pushover) analysis was conducted using the same finite-element model developed in ETABS. The lateral load pattern was assigned proportional to the fundamental mode shape, representing uniform mass participation in the primary direction of response. The analysis proceeded incrementally until the base shear reached its peak and the global stiffness of the structure degraded significantly, defining the ultimate limit state.

Plastic hinges were defined at beam and column ends in accordance with FEMA 356 moment–curvature relationships for reinforced-concrete members. The resulting capacity curves, base shear versus roof displacement, represent the progressive stiffness degradation as the structure yields and approaches collapse.

The capacity curves for the X- and Y-directions are shown in Figure 6.

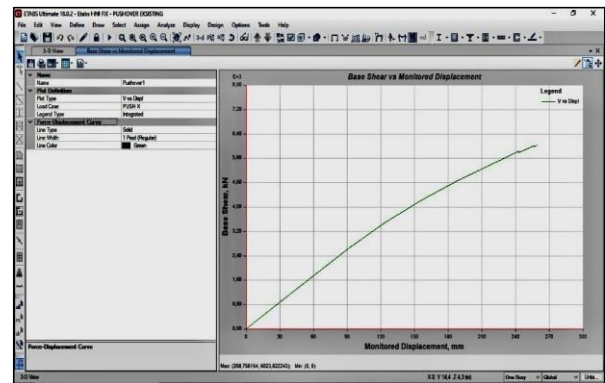


Fig. 6. Pushover capacity curves in X and Y directions showing nonlinear response up to collapse

Both curves exhibit an initial linear–elastic range followed by a gradual reduction in stiffness after yielding. The ultimate base shear capacity in the X direction is approximately 10,872 kN at a roof displacement of 290 mm, while in the Y direction it reaches 26,334 kN at only 3 mm, indicating significantly higher lateral stiffness along the Y axis due to the presence of shear walls.

The curves were transformed into capacity spectra (base shear versus roof displacement normalized by effective modal mass) and intersected with the demand spectrum obtained from the response parameters β and β . The

intersection delineates the performance point at which structural capacity matches seismic demand. The results of

the ATC-40 and FEMA-440 procedures are summarized in Table 5.

Table 5. Comparison of ATC-40 and FEMA-440 in performance

Direction	Method	Target Displacement (mm)	Base Shear (kN)	Ductility (μ)	Performance Level
X	ATC-40	201	9,832	4.2	Life Safety
X	FEMA-440	190	9,720	4.0	Life Safety
Y	ATC-40	45	25,650	2.0	Immediate Occupancy
Y	FEMA-440	42	25,540	1.9	Immediate Occupancy

Both assessment methodologies produce consistent results, reinforcing the reliability of the modeling approach used in this study. The structure satisfies the Life Safety (LS) performance level in the X direction, which means that collapse is avoided even though significant structural damage may occur. As a result of the lateral wall elements' increased stiffness and overstrength, the Y direction, on the other hand, achieves Immediate Occupancy (IO) performance. Energy absorption and ductility. According to Equation 2, the yield displacement in the X direction is roughly 48 mm, resulting in a global ductility ratio.

$$\mu = \frac{\Delta_u}{\Delta_y} = \frac{290}{48} \approx 6.0 \quad (2)$$

This result surpasses the minimum ductility criterion ($\mu \geq 4$) for special moment-resisting frames specified in SNI 2847:2019.

The majority of plastic hinges form at the beam ends of the first and second stories, according to the energy dissipation pattern shown in the area under the pushover curve. This is a common reaction in reinforced-concrete frames with significant interaction from shear walls. Only after significant roof displacements (>200 mm) do column hinges appear, indicating a strong-column-weak-beam mechanism that sustains ductile performance. The nonlinear results also show a distinct difference between the building's ductility-controlled and stiffness-controlled directions. The confining effect of the lateral walls keeps the structure mostly elastic in the Y direction. Damage under design-level shaking is therefore negligible, in line with an Immediate Occupancy performance level.

The X direction, on the other hand, experiences considerable inelastic deformation, necessitating roof-level drifts greater than 1.6% and exhibiting plastic hinge formation at several beam ends. This pattern shows temporary functional disruption in accordance with Life Safety standards, along with moderate but repairable damage.

While the results indicate that the building will maintain its structural integrity during a significant seismic event when

interpreted within a risk-based framework, inspection and repair are required, necessitating a brief evacuation, resulting in the temporary suspension of infrastructure services. A key finding of this study is the need for increased stiffness and redundancy in the X-direction building structure due to the anisotropic seismic response characteristics of the structural frame, which is partially reinforced with masonry walls without shear walls.

The overall results of this nonlinear pushover analysis provide an analytical basis for risk mapping and retrofitting strategies by confirming that the structure meets ductility requirements while identifying directional vulnerabilities, which will be discussed in Section 4.4.

4.4 Performance Interpretation and Risk Mapping

4.4.1 Performance Level Assessment

Based on the nonlinear analysis described in Section 4.3, two distinct performance behaviors were identified: 1) Immediate Occupancy (IO) in the Y-direction, with a required drift remaining below 0.8%; 2) Life Safety (LS) in the X-direction, with a maximum drift of approximately 1.6%

Referring to ATC-40 and FEMA 440, these levels correspond to elastic performance conditions and are subject to controlled damage for reinforced concrete framing systems. Although the IO condition is only associated with superficial effects that do not compromise building functionality, the LS condition typically involves localized cracking, limited reinforcement yielding, and minor non-structural damage.

The plastic hinge analysis revealed that the interstory drift ratio indicates that the structure will maintain overall stability during a design-level earthquake, but there will be damage that compromises the building's structural integrity, although repairable. The structural parameters within standard performance categories are quantitatively represented in Table 6.

Table 6. Performance Classification and Expected Damage Characteristics

Direction	Performance Level	Peak Drift (%)	Structural State	Expected Damage	Expected Functionality
X	Life Safety (LS)	1.6	Moderate yielding in beams	Repairable cracking; partial spalling	Temporary service interruption
Y	Immediate Occupancy (IO)	0.8	Elastic response	Hairline cracks only	Fully operational
Combined	–	–	Stable global behavior	No collapse	Serviceable after inspection

The findings show a clear directional imbalance: the Y-axis is overly rigid, while the X-axis affects seismic performance because there are no shear walls. This anisotropy frequently occurs in healthcare facilities that were first built using force-based codes, where drift vulnerability is hidden by strength adequacy.

4.4.2 Functional Risk Interpretation

In order to link engineering results with operational impact, the results were examined using the Performance-Risk Matrix framework of Performance-Based Earthquake Engineering (PBEE). According to the FEMA P-58 methodology, the structural drift (Δ) and hinge formation

states are linked to damage states (DS) and expected downtime (DT).

A damaged state brought on by structural drift has an impact on functionality and causes anticipated downtime.

The mapping produces the subsequent functional scenarios:

- Damage State 2 (Moderate) \rightarrow drift \approx 1 %–2 % \rightarrow localized cracking, some ceiling/facade damage \rightarrow 1–4 weeks downtime.
- Damage State 1 (Minor) \rightarrow drift $<$ 1 % \rightarrow no significant non-structural damage \rightarrow immediate reoccupancy.

While the IO state in the Y-direction is connected to DS 1, the LS state in the X-direction is connected to DS 2.

Based on empirical correlations from HAZUS 2015 and FEMA P-58 (2018), the facility's expected functional downtime for full service restoration is estimated to be between two and six weeks. During this time, structural repair requirements are limited to localized concrete patching and rebar anchorage, while recovery actions mostly focus on non-structural repairs like ceilings, partitions, and mechanical, electrical, and plumbing (MEP) systems.

4.4.3 Performance–Risk Matrix

A risk-performance matrix was developed to integrate these results into a decision-oriented format. This matrix combines exceedance probability, performance status, and functional consequences to facilitate maintenance prioritization, as described in Table 7.

Table 7. Performance–Risk Matrix for the Case-Study Hospital

Seismic Intensity	Probability of Exceedance (50 yr)	Structural Performance	Functional Risk Level	Recommended Action
Frequent (Service-Level)	20 %	IO	Low	Routine inspection only
Design-Basis	10 %	LS (X) / IO (Y)	Medium	Strengthening of X-direction frame
Maximum Considered	2 %	CP tendency (X)	High	Immediate retrofit required

The risk increases with increasing earthquake intensity. Predicting the pattern of risk increase, classifying low, moderate, and high risks that occur during an earthquake, can be determined through the performance matrix. It is known that low risks will occur during the planned earthquake, but high risks will occur during the maximum earthquake; therefore, additional reinforcement is needed in the X-direction of the building structure.

The vertical axis indicates earthquake intensity, while the horizontal axis visualizes the functional shutdown categories, with a gradient between green and red indicating low to high risk levels, as shown in Figure 7. Therefore, a temporary shutdown is necessary to build a more stable building. This is intended to prepare for strategic planning, emergency operations, and retrofit resource allocation. The solution to this situation is to prepare an emergency room in the form of a backup medical tent.

The integration of analysis into asset management is carried out not only for diagnostic purposes but also as a tool to support strategic risk decisions. This integration utilizes ISO 22301 and FEMA 356 standards, which are used for solution sustainability. Table and Figure 7 demonstrate the relationship between engineering assessments and resilience policy strategies. Then it can also improve the ability of medical services to remain open and active in conditions before and after the earthquake disaster.

4.5 Retrofit Strategy Formulation and Decision Integration

In formulating a retrofit strategy and integrating decisions, several factors must be considered. First, identify structural vulnerabilities, determine the direction of fragility at X, then determine the limits of drift and ductility to achieve life-safety levels. Furthermore, the earthquake caused moderate damage, meaning it can still be used before and after the earthquake, and the damage can still be repaired.

The requirements for this retrofit program refer to increased stiffness and resiliency in earthquake-prone areas. This aims to minimize disruption during the retrofit. The basic concept of this retrofit is based on SMR and PBRD, the main principles of which are cost minimization, feasibility, and sustainability in earthquake-prone areas for healthcare services.

There are three conceptual retrofit options: first, the addition of steel jacketing to the columns in the X direction. Second, the addition of reinforced concrete shear walls on the perimeter. Third, the installation of concrete steel bracing. These options can be selected based on parameters such as effectiveness, cost minimization, downtime, and ease of reconstruction. This is clearly presented in Table 8.

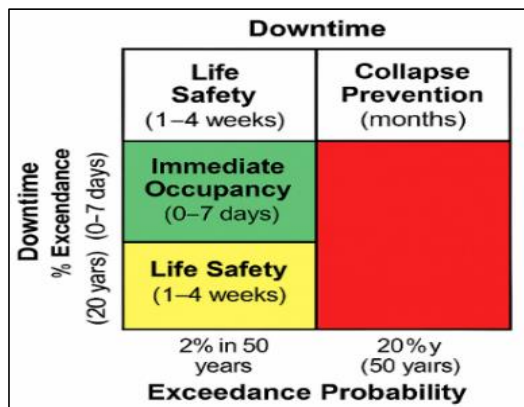


Fig. 7. Performance–risk matrix

Table 8. Comparative Evaluation of Retrofit Alternatives

Retrofit Option	Structural Effectiveness	Construction Feasibility	Cost Impact	Expected Downtime	Overall Assessment
RC Shear Wall (new panels)	High (↑ stiffness +50%)	Moderate (major intervention)	High	4–6 weeks	Effective but intrusive
Steel Jacketing of Columns	Moderate (↑ ductility +30%)	High (local intervention)	Medium	2–3 weeks	Balanced and practical
Concentric Steel Bracing	High (↑ stiffness +40%)	High (prefabricated elements)	Medium	2–3 weeks	Optimal balance of cost and performance

These findings indicate the best choice for steel bracing, with rapid reconstruction in the event of earthquake damage, minimal disruption to existing medical services, and improved structural stiffness. This assessment included effectiveness with a value of 40%, feasibility with a value of 25%, cost with a value of 20%, and downtime with a value of 15%. These scores were then combined to create an equation by combining all the criteria obtained, which was used to determine the final retrofit option.

$$P1_i = 0.4E_i + 0.25F_i + 0.25C_i + 0.15D_i \quad (3)$$

The results are presented in Table 9, which displays the work index equation for each retrofit option..

Table 9. Performance index scores and retrofit prioritization

Retrofit Option	(PI) Score	Priority Rank
Steel Bracing	0.88	1
Column Jacketing	0.83	2
RC Shear Walls	0.71	3

The identified problem was a weak X-direction, necessitating increased stiffness and ductility. The solution to this problem was column jacketing, which added local ductility. Steel bracing was then added to the side sections, adding stiffness. This solution further resulted in improved performance, from life safety to immediate occupancy, shifting from simply protecting the building to ensuring it remained usable and operational before, during, and after the earthquake. Downtime was also reduced to less than three weeks.

These findings have implications for risk-based planning, where earthquake metrics can be utilized in prioritization and budgeting. Furthermore, operational continuity, reduced downtime during construction, resulted in a retrofit schedule without service disruption. The policies used were based on standards aligned with BNPB 2020–2045 and SDGs 11.

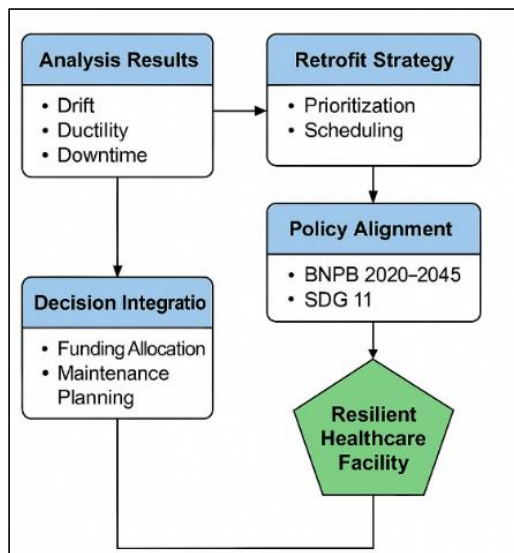


Fig. 8. Integrated decision framework for seismic retrofit

The decision-making framework is presented in Figure 8, which first identifies the techniques to be used, then formulates the policies to be used, and finally, implements managerial steps. Based on these findings, the integration of engineering and management can create a robust, effective and flexible profit plan for the services required by hospitals (health services).

5. Conclusion

The findings indicate that the building has reached the Life Safety (LS) level according to FEMA-440 and the Damage Control (DO) level according to ATC-40. This indicates that the building can still be repaired. Meanwhile, there is a Performance-Risk Matrix that helps determine retrofits and assists with maintenance, this condition is carried out by paying attention to the suitability of the structural response relationship to functional consequences. Furthermore, the findings also indicate weaknesses in the X-direction frame, there is an increase in stiffness in the column jacketing or the installation of shear-wall infill.

This study provides a decision-support framework for building earthquake-resistant healthcare infrastructure by fusing engineering analysis with management considerations. In addition to evaluating structural behavior, the model converts technical results into practical recommendations for preserving service continuity, allocating resources as efficiently as possible, and influencing institutional policy. In line with SDGs 9 (Industry, Innovation, and Infrastructure) and 11 (Sustainable Cities and Communities), these results support sustainable infrastructure governance. In order to

support ongoing improvements in seismic resilience, future work should extend the framework to a variety of facility types, include time-history and cost analyses, and make use of digital monitoring systems.

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