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SEISMIC FRAGILITY ANALYSIS OF FIXED AND ISOLATED BASE REINFORCED CONCRETE BUILDING STRUCTURES IN INDONESIA

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ABSTRACT

Indonesia has had seismic codes for earthquake-resistant structure designs since 1970 and has been updated five times to the latest in 2019. In updating the Indonesian seismic codes, seismic hazard maps for design also update, and there are changes to the Peak Ground Acceleration (PGA). The Indonesian seismic design uses the concept of building performance levels consisting of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). In relation to these performance levels, some cases have shown that buildings suffer from huge damage compared to their performance targets after an earthquake. Considering this issue, the current study aims to analyze the performance of the seismic isolation system design (isolated) on existing target buildings (fixed) and analyze seismic fragility with the PGA intensity according to Indonesia's seismic hazard maps of 0.1–1.5g. The target building used in this study is a prototype design eight-story medium-rise residential building that uses the reinforced concrete moment frame structure. The analysis uses Nonlinear Time History Analysis (NLTHA) for the design and Incremental Dynamic Analysis (IDA) for seismic fragility. Both analyses use 11 selected ground motions based on soil classification, magnitude, fault distance, and earthquake source mechanism. The NLTHA results reveal that using a seismic isolation system can increase the target building's performance level from LS to IO. A comparison of the IDA results depicts a trend of significant performance improvement. That is, with the same performance level target and risk category, the isolated base structure can be used at 1.46–3.20 times higher PGA than the fixed base structure. The fragility analysis results show that the fixed base structure has a 30% safety margin and a 62.5% isolated base structure from the PGA design. The obtained results are useful for assessing existing buildings or considering a new building's performance.

Keywords: Seismic isolation, fragility curve, incremental dynamic analysis, performance level.

1. INTRODUCTION

As a country prone to earthquakes, Indonesia has had seismic codes for earthquake-resistant structure designs since 1970 and has been updated five times to the latest in 2019. In updating the Indonesian seismic codes, seismic hazard maps also update. There are changes to the Peak Ground Acceleration (PGA) values that can decrease or increase based on the research developments related to seismic hazard maps in Indonesia (Irsyam et al., 2017). Under these conditions, an analysis is needed to determine the effect of changing the earthquake's intensity on the structure's behavior. The analysis that can be used is

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seismic fragility analysis. This analysis can provide an overview of the structure's behavior towards damage limits with different earthquake intensities. It is useful for evaluating structures at various intensity values, such as PGA (Rajkumari et al., 2022).

The Indonesian seismic design uses the concept of building performance levels comprising Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). In relation to this performance, some studies found that, after an earthquake, buildings suffer from more damage than their performance targets. This problem often occurs because of the poor quality of the construction materials used and the workmanship involved (Pribadi et al., 2021). A seismic isolation system is one of the technologies that can be used to increase the building performance level. In Indonesia, several buildings had been built using this system, but the usage has remained relatively low (Imran et al., 2021).

Regarding seismic fragility analysis, no study in Indonesia has researched this analysis on seismic isolation systems. A study on the fragility analysis of the isolation system in Indonesia is needed to see its behavior if the earthquake intensity increases much compared to the design earthquake intensity. Based on the background description, the main objective of this study is to analyze the seismic isolation system design to improve the performance level of existing target buildings and the seismic fragility of fixed and isolated base structures with a PGA intensity according to Indonesia's seismic hazard maps of 0.1–1.5 g.

2. DATA

The target building is a typical construction design for a high-seismicity area by the Indonesian Ministry of Public Works and Housing (Table 1 and Figure 1). The target building was chosen because it is a typical design that is widely used and has a life safety performance target that is still possible to improve and to see how significant performance increases using an isolation system.

Table 1. Target building information.

Parameters	Information
Occupancy	Residential (risk category: II)
Structure system	Special moment frame reinforced concrete with shear wall
Number of stories	8 stories
Total height	27.4 m = 3.6 m + (3.4 m x 7)
Building codes	Indonesian seismic codes (SNI 1726:2019)
Seismic parameters design	$\boldsymbol{S_{DS}}$ = 1.00 g; $\boldsymbol{S_{D1}}$ = 0.68 g; site class D
Concrete strength (f_c')	Beam and slab = 30 MPa; column and shear wall = 35 MPa
Yield strength of rebar (f_y)	longitudinal, shear, and cross tie = 420 MPa
Number of type members	Column type = 1; beam type = 5; shear wall type = 1; sslab type = 1

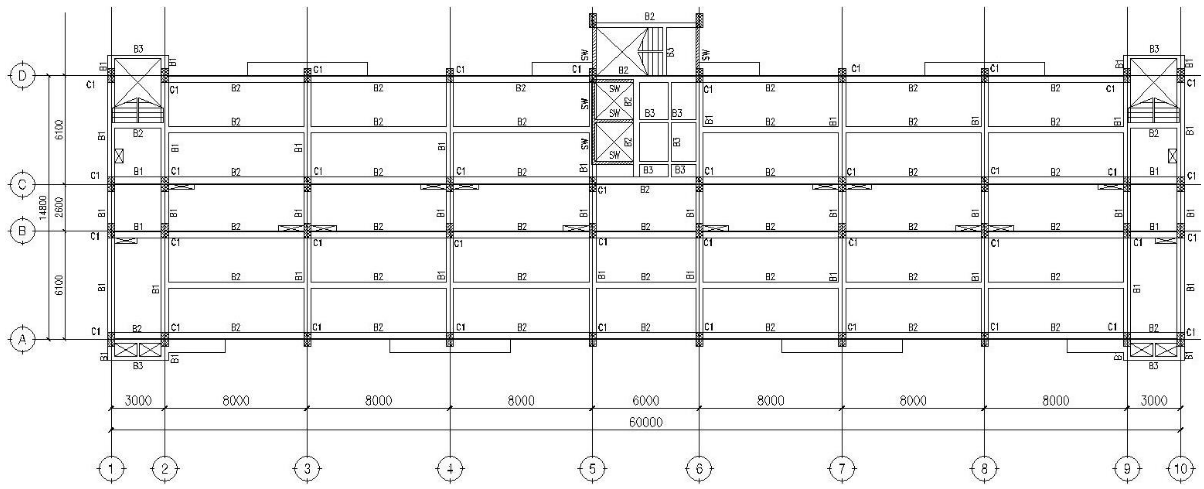


Figure 1. Target building typical structure plan.

3. METHODOLOGY

3.1. Seismic Isolation

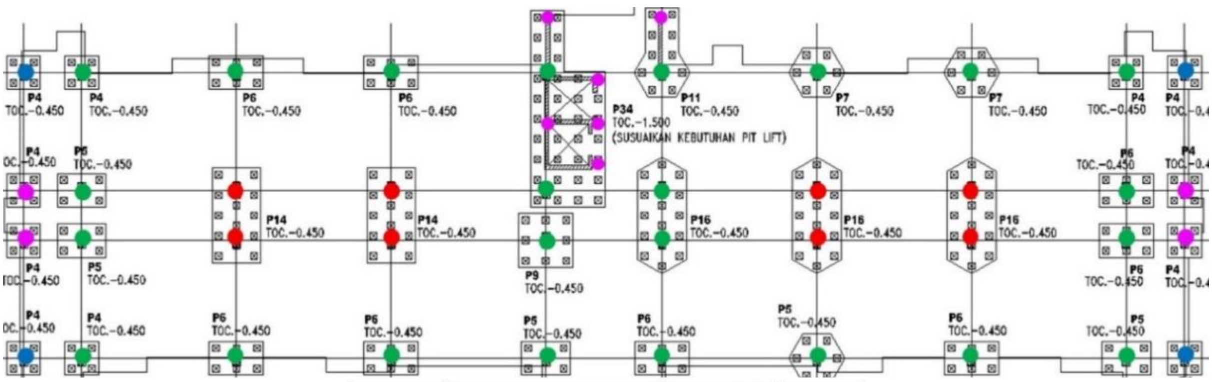
Seismic isolation design was conducted on the target building without changing the structural design. The target building structures have been designed with seismic codes so that some design parameters can be used, such as the total building mass and base shear coefficient. In this study, three types of isolators were used, namely natural rubber bearing, lead rubber bearing, and sliding rubber bearing. The parameters used in seismic isolation design were base shear coefficient (α_1) of 0.1 was obtained, natural periods (T_f), shear coefficient of the damper (α_s), and design displacement of the seismic isolation system (D_d).

$$T_f = 2\pi\sqrt{\frac{m}{K_f}} \qquad (1) \qquad\qquad D_d = \frac{gS_{D1}T_f}{4\pi^2 B_D} \qquad (2) \qquad\qquad \alpha_s = \frac{Q_y}{mg} \qquad (3)$$

Where m is the total mass of the building, and K_f is the stiffness of the seismic isolation system. The total structural mass of the upper structure is 8774.14 tons. S_{D1} is design spectral acceleration at a period of 1, and B_D is the damping coefficient related to effective damping (β). The Japan Society of Seismic Isolation (JSSI) has a range of values for seismic isolation design parameters as shown in Table 2. In addition to the design parameter values discussed earlier, there are also force requirements governing stability such as the wind load (F_{wind}) which must be lower than the characteristic shear strength (Q_y). By calculating the service load (dead load, superimposed dead load, live load, wind load, and earthquake load) following Indonesia codes (SNI 1726:2019) and design parameters following Japanese standards (JSSI), the results of the seismic isolation design can be seen in Figure 3 and Table 2 for the design parameters.

Table 2. Design parameter result.

Design parameters	General value in Japan	Design result	Status
Base shear coefficient ($\boldsymbol{\alpha_1}$)	0.05 – 0.20	0.1	OK
Design displacement ($\boldsymbol{D_d}$)	30 – 50 cm	39 cm	OK
Natural periods ($\boldsymbol{T_f}$)	3 – 5 s	3.5 s	OK
Shear coefficient of damper ($\boldsymbol{\alpha_s}$)	0.02 – 0.10	0.02	OK
Wind load ($\boldsymbol{F_w}$) < characteristic shear strength ($\boldsymbol{Q_y}$)	> 1265.88 kN	1717.6 kN	OK



Legend	Type	Type code	Number
	Lead Rubber Bearing	LL070G4-E	8
	Lead Rubber Bearing	LL065G4-E	24
	Natural Rubber Bearing	NH060G4	4
	Elastic Sliding Bearing	SL050GC	10
Total			46

Figure 2. Seismic isolation design

3.2. Concept Modeling and Analysis

The modeling and analysis of reinforced concrete building structures were performed using three-dimensional modeling. The beam, column, and shear wall elements were modeled as line elements, and the slab was modeled as a rigid diaphragm. The infill wall was modeled as a gravity load without contributing to the lateral stiffness. Modeling of plastic hinges and acceptance criteria for each structural element is carried out per ASCE 41-17. The nonlinear behavior of reinforced concrete elements was modeled by the Takeda hysterical model. In the IDA analysis, the earthquake's intensity will be greater than the design earthquake, so in the isolation system, displacements will exceed the design displacements. In the building design plan, there is a retaining wall around the isolation system, the distance between the seismic isolation system and the retaining wall is determined at shear strain (γ) 300% of the height of the total rubber thickness. This value is the assumption of rubber conditions that have not yet been broken and are still performing quite well. The gap between the seismic isolation system and the retaining wall is 500 mm and was modeled as a gap element. The defined stiffness only affects when the deformation exceeds the defined seismic gap. This study used the stiffness value based on the experimental test results of Miwada et al. (2012) as 104.6 kN/mm.

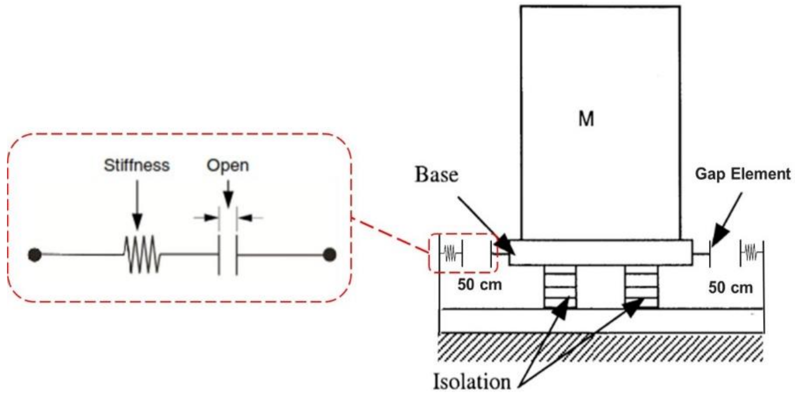


Figure 3. Concept of seismic gap model for pounding effect.

3.3. Incremental dynamic analysis (IDA)

The IDA in this research uses the Nonlinear Time History Analysis (NLTHA) principle, carried out on several intensity measurements in the form of PGA with intervals of 0.1–1.5 g based on Indonesian seismic hazard maps. For damage measurement in the form of inter-story drift ratio maximum (IDR_{max}) which is referring to performance level IO of 1.0%, LS of 2.0%, and CP of 2.5% (Xue et al., 2008; Ibrahim & El-Shami, 2011). Based on the SNI 1726:2019 for performing the NLTHA, 11 ground motions are required as the minimum number of ground motions. The ground motions were selected referring to Indonesian deaggregation maps data which explains the source magnitude (M) and distance (R) for each earthquake source mechanism and soil classification map, 11 ground motions were chosen for analysis, as shown in Figure 4. Furthermore, the resulting IDA from 11 ground motions can be statistically evaluated to be the equivalent dispersion, δ_{eq}, which can be calculated by Equation (4).

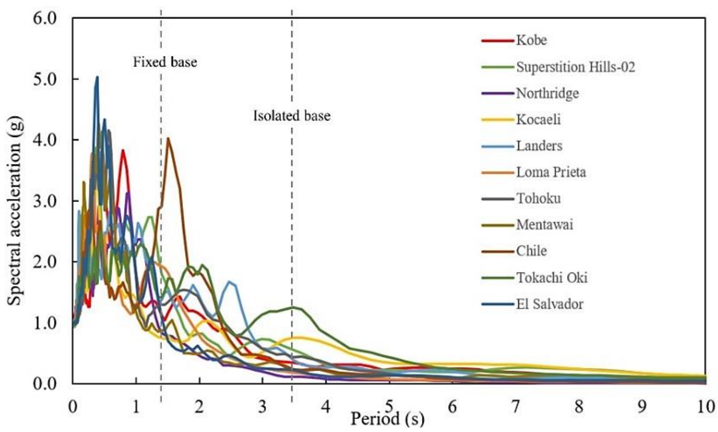


Figure 4. Selected ground motion scaled at PGA of 1.0 g.

$$\delta_{eq} = \frac{\ln(IDR_{max})^{84\%} - \ln(IDR_{max})^{16\%}}{2} \qquad (4)$$

Using the formula from Nagae et al. (2006), the probability of the IDR_{max} exceedance against the idr limit of each performance level can be calculated by Equation (5).

$$P[IDR_{max} > idr] = 1 - P[IDR_{max} \leq idr] = 1 - \Phi\left(\frac{\ln(idr) - \ln(IDR_{max})^{50\%}}{\delta_{eq}}\right) \quad (5)$$

The IDA is only performed in the weak direction of the building, which in this work, is the X-direction. The structure herein was modeled in three full dimensions; hence, the IDA will require much time when using the 11 ground motions and do it on fixed and isolated bases. The weak axis analysis is also sufficient for representing the worst possible conditions.

4. RESULTS AND DISCUSSION

The fragility curve in Figures 5 denotes the relationship of the Probabilities of Exceedance (POE) at each performance level in the PGA range of 0.1–1.5 g. Based on ASCE 7-16, a reliability target is determined based on the building risk category. The target reliability is also called the target probability of failure or the POE. The building risk category was related to the target value because it showed a level of building risk according to its occupancy. The risk target classification based on occupancy is determined by the government in the seismic codes, which, in this case, is the Indonesian government in SNI 1726:2019.

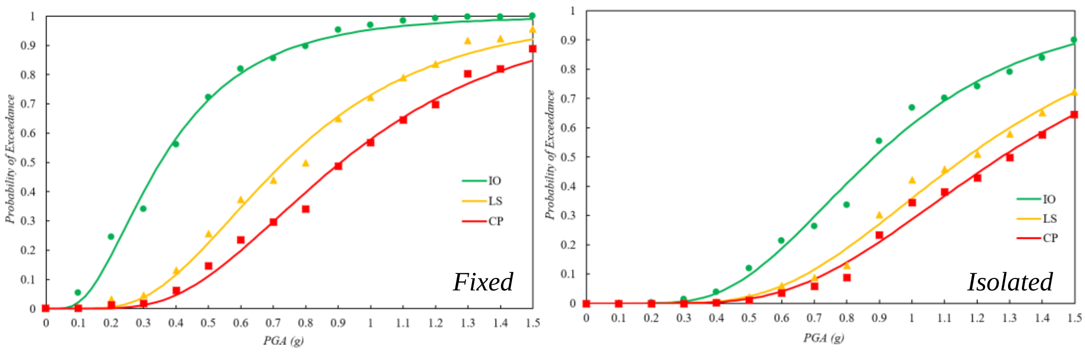


Figure 5. Fragility curve result

Table 3. PGA values range of performance levels at target reliability.

Risk category	Occupancy (SNI 1726:2019)	POE (ASCE 7-16)	PGA limit					
			Fixed base structure			Isolated base structure		
			IO	LS	CP	IO	LS	CP
I-II	Residential Office Factory	25 %	≤0.23 g	>0.23 g ≤0.52 g	>0.52 g ≤0.65 g	≤0.65 g	>0.65 g ≤0.87 g	>0.87 g ≤0.95 g
III	Prison Meeting hall Sport Centre	15 %	≤0.18 g	>0.18 g ≤0.43 g	>0.43 g ≤0.54 g	≤0.56 g	>0.56 g ≤0.75 g	>0.75 g ≤0.81 g
IV	Hospital School Disaster shelter	9 %	≤0.15 g	>0.15 g ≤0.37 g	>0.37 g ≤0.47 g	≤0.48 g	>0.48 g ≤0.65 g	>0.65 g ≤0.70 g

Table 3 explains the performance level of the target building at several PGA levels. The target building was designed using DBE (2/3 MCE_R) PGA = 0.40 g with risk category II. The performance was LS for a fixed structure and IO for an isolated structure. A comparison of the PGA limit value on each target reliability and risk category showed the significance of using an isolated structure, which can be employed on a PGA larger than that of fixed structures with a ratio of 1.46–3.20.

The results also indicate the safety margin level of the design results. Fixed and isolated structures were designed with different performance targets. The fixed base structure was designed with LS targets, while its isolated base was designed with IO targets. Limit values were used for each performance target. The safety margin for the fixed base structure was 0.52 g / 0.40 g = 1.3 (30%), while that for the isolated base structure was 0.65 g / 0.40 g = 1.625 (62.5%).

5. CONCLUSIONS

This study analyzed the design of a seismic isolation system for a target building and determined the seismic fragility with a PGA intensity according to Indonesia's seismic hazard maps of 0.1–1.5 g. The following conclusions can be drawn based on the results of the performed analyses:

- The design results using the seismic isolation system showed increased performance in the target building. Based on the NLTHA, the target buildings with an LS performance level can increase to IO, as evidenced by the decrease in the IDR_{max}value from above 1.0% to below 0.5%. The IDA result comparison also showed a trend of significant performance improvement. That is, with the same performance level target and risk category, seismic isolation can be used at 1.46–3.20 times higher PGA than that of the fixed base structure.
- The fragility analysis results using the IDA were very effective in determining the fragility and the reliability of the response structure. For fragility, the fixed base structure showed a 30% safety margin and a 62.5% isolated structure from the PGA design. The safety margin is defined as the range of structural performance targets still being achieved before the performance target decreases.

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