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Comparative Analysis of Earthquake Loss Estimation Using HAZUS Method with Modified Building Capacity Curve

(Analisis Perbandingan Estimasi Kerugian Gempa Bumi Menggunakan Metode Hazus dengan Modifikasi Kurva Kapasitas Gedung)

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ABSTRACT

Based on the World Bank publication in 2019, one of the strategies to improve disaster financial resilience is the availability of loss estimation data. As one of the vulnerable countries affected by earthquake disasters, Indonesia does not yet have a widely used pre-disaster estimation model. Model adoption is one of the strategies used to improve disaster resilience in Indonesia. The HAZUS method is a model FEMA (Federal Emergency Management Agency) developed to estimate earthquake losses in the US. The adoption process in Indonesia requires adjustments to the EDP (Engineering Demand Parameter) used in the HAZUS model. The EDP in the HAZUS model consists of capacity curves, fragility curves, and repair cost coefficients. The statistics of buildings affected by earthquakes in Indonesia from 2000 to 2020 show that residential houses are the most affected buildings. This study aims to obtain comparative results of the HAZUS model structural element loss estimation with modified data of local capacity curve pushover results in Indonesia. The study was conducted by performing a pushover analysis on a case study of a residential building to obtain a capacity curve. In this study, the EDP analyzed was only the EDP of the capacity curve. The case study was conducted at housing cluster X in West Bandung Regency, West Java, using house type T94/120 as the case study structure. The results of the capacity curve comparison show that the capacity curve of the local house from the pushover analysis has lower stiffness and ductility. The comparison of loss estimation for single hazard scenarios shows that the modified curve method has the most conservative loss estimation than HAZUS in the hazard of earthquake return periods of 100, 250, 500, and 750 years. The annual loss estimation shows that the modified capacity curve provides the most conservative or 37.5% larger in annual loss estimation.

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1. INTRODUCTION

As a country that frequently experiences earthquake disasters, Indonesia has low resilience to earthquake disasters [1]. The low level of resilience means that Indonesia needs a lot of time and resources to recover from post-disaster conditions. Based on data from the National Disaster Management Agency (BNPB), in the period 2000-2021, 1,471,355 residential houses; 23,552 educational facilities; 2326 health facilities; 18,085 worship facilities; and 6,286 office facilities were identified as earthquake damages, as shown in Figure 1.

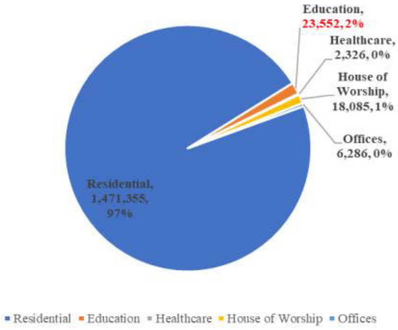


Figure 1. Data on building damage due to earthquakes in Indonesia 2000-2021 [2]

The massive damage resulted in the need for resources to carry out reconstruction, among which the financial aspect is quite important. Through the World Bank publication, the availability of loss estimation data is one of the strategies to improve resilience in the financial aspect [3]. Loss estimation can be done pre-disaster with an estimation model. Indonesia, with its high earthquake vulnerability, does not yet have a pre-disaster estimation model for buildings. Adopting an estimation model is a strategy to accelerate the availability of loss estimation. Several earthquake loss estimation models have been developed, one of which is the most widely applied HAZUS model [4]. The HAZUS loss estimation model is a building loss estimation model based on building performance against earthquake hazards developed by FEMA in the United States in 1992 and still used today for annual earthquake loss estimation [5]. The advantage of the HAZUS model is that it simplifies the process of determining building performance which is determined based on the classification of structural type, floor height. Determination of building performance that previously required pushover analysis through complex procedures and consumed a lot of resources (time, energy, and cost) to obtain data and modeling of existing buildings, is simplified with Engineering Demand Parameters (EDP) that have been provided by the HAZUS model through research that has been carried out previously on the types of structures defined. Specifically, the EDPs were used to develop structural analysis variables, namely capacity curves and fragility curves. This advantage allows the loss estimation process to be carried out quickly with minimal use of resources.

However, there are limitations that the EDP in the HAZUS model does not reflect building characteristics, especially in typical buildings outside the United States [6]. Some studies show a wide range of deviations from EDP HAZUS to local existing structural parameters [7], [8]. This prompted the need to adjust EDP HAZUS with local parameters in Indonesia in the model adoption process. The model adjustment step is also driven by reflecting on previous earthquake events in Indonesia, which shows that the construction of building structures in Indonesia is the main factor causing earthquake damage and losses [9], [10].

Several HAZUS model adoption studies in Indonesia have been conducted but on public facilities (schools and hospitals) and only focused on comparing the scope of structural analysis variables, not yet reaching the comparison of loss values [11], [12]. This study aims to compare the results of the HAZUS model structural element loss estimation with the modified data of local capacity curve pushover results in Indonesia. The case study was conducted in X housing cluster in West Bandung Regency, West Java. It is expected that this loss estimation comparison study can contribute to the adoption of the HAZUS model as an effort to improve disaster resilience in the financial aspect.

2. MATERIALS AND METHODS

The loss estimation comparison study was conducted with the data collection and quantitative analysis process shown in the research flow chart in Figure 2. In this study, the loss estimation reviewed was limited to the loss of residential structural components, where the loss of nonstructural components was not reviewed in this study. The study started with data collection. The data collection consisted of two groups of data. The first group of data is structural data of the existing building under review in the form of geometry, dimensions and structural reinforcement data of the residential houses under review. The second group of data is general house property data consisting of site plan data, area, and number of floors of the house under review. In this study, a case study of 1 typical house in housing cluster X is used, which will be explained in more detail in the case study subchapter.

The building property data group is used for the analysis of structural component loss estimation, where the data is used in the selection of EDPs based on the HAZUS model structural classification. There are 2 types of EDPs selected, namely EDPs for compiling capacity curves and EDPs for compiling fragility curves, which will be explained in more detail in the HAZUS method subchapter. The selected EDPs are further processed to obtain annual loss estimates and for certain hazard scenarios.

In the existing structure data group, it is used to develop a 3-dimensional (3D) structural model. From the 3D structural model data, it is further used for pushover analysis whose output is the capacity curve of residential buildings. From the output of the capacity curve, further processing is carried out with the HAZUS fragility curve EDP to obtain an estimate of annual losses and for certain hazard scenarios. By analyzing the capacity curves of local buildings in Indonesia, a comparative analysis of the capacity curves and an analysis of the earthquake loss estimation generated by the different capacity curves were conducted.

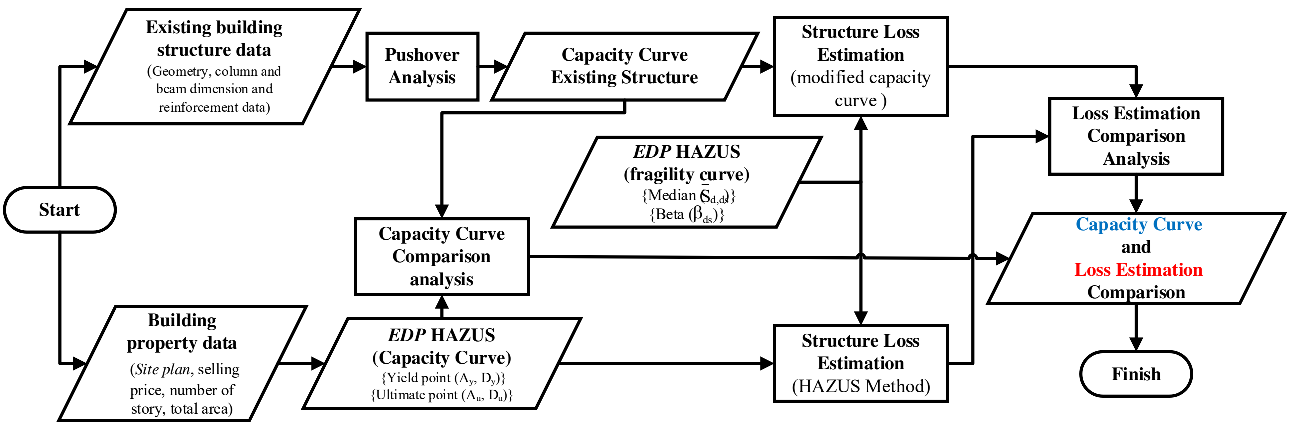


Figure 2. Flowchart of the comparative study of HAZUS model loss estimation with modified data of local house capacity curves in Indonesia

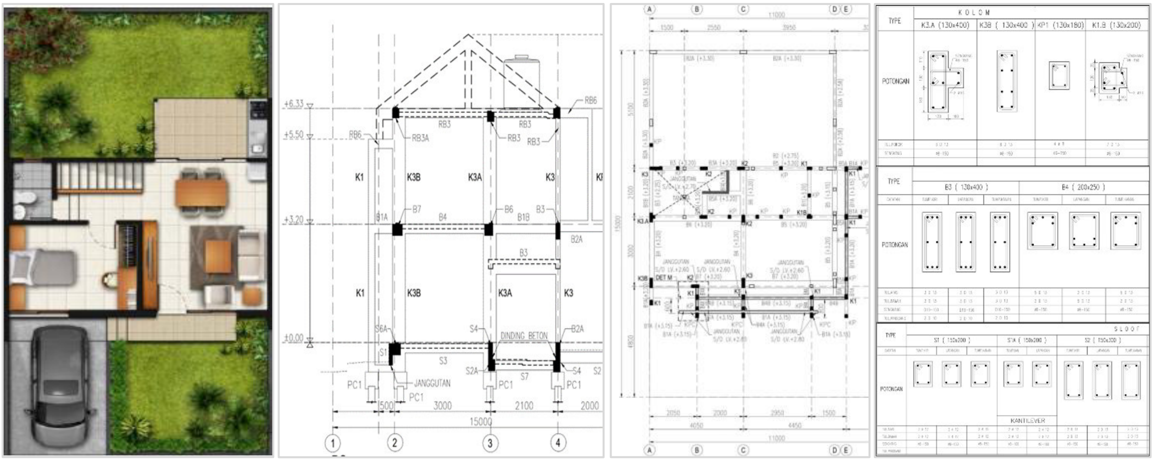
2.1. Case Study

The case study in this research is a housing cluster X in West Bandung Regency (KBB), West Java. The X cluster under review has a high earthquake risk due to the presence of the Lembang Fault in KBB. The Lembang Fault is one of the faults that is observed to be active. This fault has a length of 29km, stretching from Mount Manglayang to Padalarang across KBB, with fault measurement lines along 0km to 20km in KBB, where this fault has a movement of 2-3 mm per year which is categorized as slow movement, but will accumulate energy that can be released to cause a large earthquake [13].

Figure 3. Housing cluster X research case study

Table 1. House property data for cluster X case study

No	Type of house	Building area (m^2)	Land area (m^2)	Total unit	House Price
1	T94/120	94	120	290	Rp. 2.048.294.100
2	T99/165	99	165	61	Rp. 2.523.906.900
3	T133/220	133	220	23	Rp. 3.084.200.490
4	T145/260	145	260	6	Rp. 3.617.139.240



(a) (b) (c) (d)

Figure 4. Case study typical house data (a) typical architect's plan, (b) building cut, (c) typical structural plan, (d) typical structural details

Cluster X has a total of 380 housing units consisting of 4 types of house types, namely 290 units of type T94/120, 61 units of type T99/165, 23 units of type T133/220, and 6 units of type T145/260 with property data shown in Figure 3 and Table 1. Based on the data on the types of housing units, this study uses type 94/120 as the housing structure under review because it has the highest percentage of units, 76% of the total housing units in Cluster X. All buildings in cluster X were built starting in 2020.

The T94/120 house consists of 2 floors, with a first-floor height of 3.20m and a second-floor height of 3.13m shown in Figures 4a and 4b for the architect's plan. For structural data, the plan, dimensions and quality of the column and beam structures are shown in Figure 4c. For the quality of the structure, data is obtained from the housing development team, the quality of concrete is f'_c = 18.68MPa and the quality of steel reinforcement is f_y = 240MPa. Based on the structural data, the structural system in this case study is identified as Reinforced Masonry Walls (RM1) in accordance with FEMA 454 structural criteria, which is also used as a reference in the HAZUS model [14].

2.2. HAZUS Method

The HAZUS (Hazard United States) method was developed by FEMA in 1992 to estimate earthquake losses for various infrastructures (buildings, roads, and lifeline infrastructures) at different levels (local, state, and regional) based on Geographic Information Systems (GIS) and can be implemented by users with various expertise[5]. For general building stock, the HAZUS model has four main analysis stages, consisting of hazard analysis, structural analysis, damage analysis, and loss analysis as shown in Figure 5. Hazard analysis outputs the demand spectra curve, structural analysis outputs the building capacity curve, damage analysis outputs the probability of damage based on the fragility curve, and loss analysis outputs the loss value from the estimated probability level. For each stage will be explained further in the following subsections.

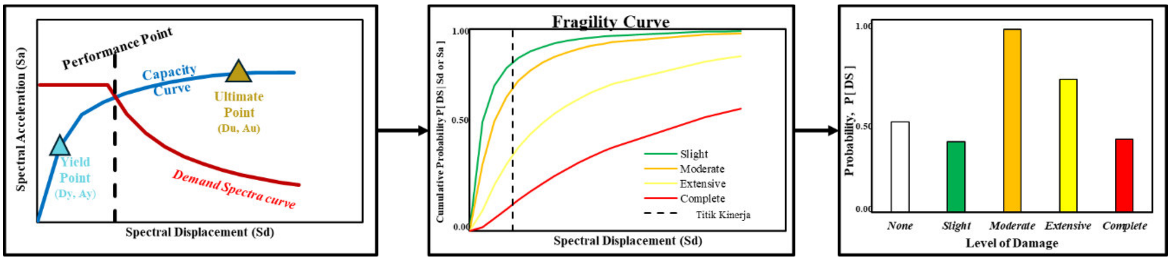
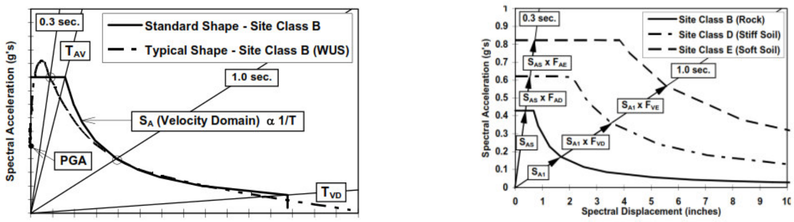


Figure 5. HAZUS Model Schematic [5], [15]

2.2.1. *Hazard Analysis*

The HAZUS model that uses demand spectra as the hazard at the observed location is shown in Figure 6b. The demand spectra curve is created based on the response spectrum parameterized by the response spectra Sa (short-period spectral acceleration), and S1 (1-second spectral acceleration), and a specific site class as presented in Figure 6a.

For application in Indonesia, the earthquake acceleration for Sa and S1 can be obtained through the 2017 Earthquake Hazard and Source Map data, specifically for the 2500 year return period provided [16]. The HAZUS method can calculate annual losses. To calculate the annual loss, it is necessary to estimate the loss value of the building with a hazard scenario of 8 earthquake return periods (100, 250, 500, 750, 1000, 1500, 2000, 2500 years)[5].



(a) (b)

Figure 6. HAZUS model hazard analysis [5] **(a) standardized response spectrum, (b) standardized demand spectrum**

Due to the limited data on Indonesian earthquake parameters, this study adopted the Eurocode equation in determining the earthquake magnitude at unavailable return periods as shown in Equation 1, where a_g = seismic acceleration value sought, a_{gR}= reference value of earthquake acceleration, T= return period value of the earthquake parameter being sought, T_R = reference value of the known return period of the earthquake parameter, and k= seismic coefficient taken as 0.3 [17]. In the preparation of the standard form of spectrum response, this study follows the procedure of SNI 1726: 2019[18].

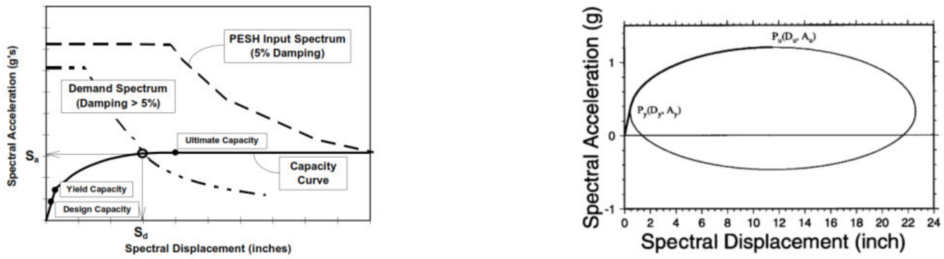
$$\frac{a_g}{a_{gR}} = \left(\frac{T}{T_R}\right)^2 \tag{1}$$

The response spectrum parameters are converted to demand spectra (spectral displacement) parameters using Equation 2, where SD = spectral displacement (mm), SA = spectral acceleration (g), and T = period for a given value (sec).

$$S_D = 9.8 \times S_A \times T^2 \tag{2}$$

2.2.2. Structure Analysis

In the structural analysis, HAZUS uses simplified building capacity performance based on building type, code level, and building height. The building capacity curve is superimposed on the demand spectra to obtain the building performance as shown in Figure 7a.



(a) (b)

Figure 7. HAZUS model capacity analysis [5], [19]

The building capacity curve is created using the yield capacity points provided, and the ultimate capacity can be seen in the HAZUS manual with different code levels (high code, moderate code, low code, pre code) [5]. Code level determination is based on the development of local building codes in Indonesia, where high codes are in the range > 2012, medium codes are in the range 1991-2012, and low codes are in the range 1970-1990 [11], [20]. The capacity curve is created by connecting two points provided as a transition from the elastic to the nonlinear plastic state with an elliptical shape shown in Figure 7b [19]. The EDP capacity curve used in this study is shown in Table 2. Since the case study building was built above 2012, the EDP used is the high code level.

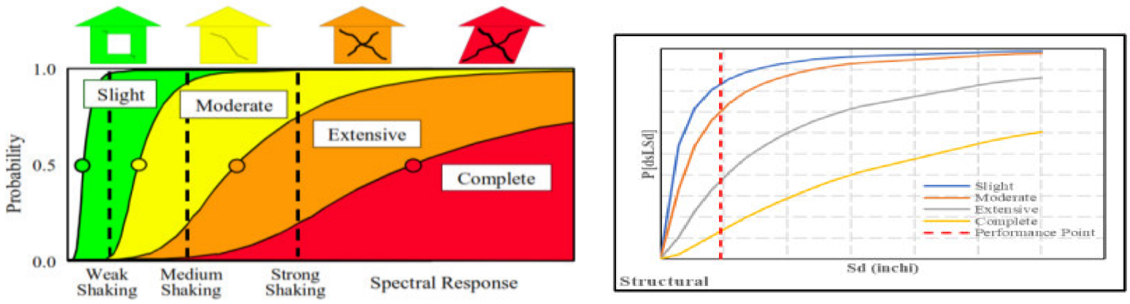
Table 2. EDP HAZUS capacity curve used [5]

Type of structure	**Level of code**	**Capacity curve EDP**			
		Yield point		**Ultimate point**	
		D_y (mm)	**A_y (g)**	**D_u (mm)**	**A_u (g)**
Reinforced Concrete Reinforced Masonry Bearing Walls, low rise ***(RM1L)***	*High Code*	16.231	0.533	259.817	1.066

2.2.3. Damage Analysis

The building fragility curve compiled in the damage analysis is shown in Figure 8a. The fragilization curve is a lognormal probability function for structural and non-structural damage conditions (slight, moderate, extensive, and complete) that will be reached or exceeded when the spectral displacement of the building is reached (S_d) given is shown in Figure 8b. Each fragility curve is characterized by the median ($\bar{S}_{d,ds}$), and lognormal standard deviation (β_{ds}) as shown in Equation 3, where P[ds||S_d] is the exceedance probability value of the spectral displacement and damage level under review, and Φ is the cumulative normal standard distribution function[5].

$$P\left[ds \mid S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \times ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \quad (3)$$



(a) (b)

Figure 8. Damage analysis in HAZUS model[5], [12]

The values of and can be found in the HAZUS manual for structural and non-structural components with each damage condition [5]. The fragility curve EDP used in this study is shown in Table 3. The output of this fragility curve is the probability value of damage at each level of damage at the Sd value obtained from the building performance point of the pushover analysis.

Table 3. HAZUS fragility curve EDP used

Type of structure	**Level of code**	**fragility curve EDP**							
		Slight		**Moderate**		**Extensive**		**Complete**	
		$\bar{S}_{d,ds}$ (mm)	β_{ds}	$\bar{S}_{d,ds}$ (mm)	β_{ds}	$\bar{S}_{d,ds}$ (mm)	β_{ds}	$\bar{S}_{d,ds}$ (mm)	β_{ds}
Reinforced Concrete Reinforced Masonry Bearing Walls, low rise ***(RM1L)***	*High Code*	18.29	0.84	36.58	0.86	109.73	0.92	320.04	1.01

2.2.4. Loss Analysis

The HAZUS method calculates the direct economic loss components due to the earthquake, which include building repair costs, building contents losses, building inventory losses, relocation costs, revenue losses, rental income losses, and wage losses. All loss components are calculated based on the previous stage of analysis. The structural repair cost ($CS_{ds,i}$) is calculated in Equation 3, where BRCi is the building replacement cost, PMBTSTR $_{ds,i}$ is the probability of the structure being damaged at each level of structural damage for the single hazard scenario under review, $RCS_{ds,i}$ is the ratio of structural repair cost expressed in % BRC_i.

$$CS_{ds,i} = BRC_i \times \sum_{i=1}^{33} PMBTSTR_{ds,i} \times RCS_{ds,i} \quad (3)$$

The values of the structural repair cost ratio, $RCS_{ds,i}$ used in this study for residential buildings are shown in Table 4. In this study, the variable $RCS_{ds,i}$ is adopted in the loss calculation of the modified capacity curve of the case study building.

Table 4. Structure Repair Cost Ratio value, $RCS_{ds,i}$ (in % BRC_i)

Building Occupancy Code	Occupancy	Structure damage level			
		Slight	*Moderate*	*Extensive*	*Complete*
RES1	*Single-family Dwelling*	0.5	2.3	11.7	23.4

In the calculation of annual losses, the calculation procedure begins by calculating the value of structural losses through Equation 3 with 8 hazard scenarios of earthquake return periods (100, 250, 500, 750, 1000, 1500, 2000, 2500 years). The loss value of each return period is plotted between the probability and loss value as shown in Figure 9. In the plot result, the annual loss value is defined as the area of the inner shading of the graph plot result. Annual losses can be calculated through Equation 4, where Pi is the probability value calculated through the 1 year/return period equation, and Li is the loss value calculated for each return period hazard scenario.

$$Annualized\ Losses = (P_{2500} \times L_{2500}) + \left[(P_{2000} - P_{2500}) \times \left(\frac{L_{2000} + L_{2500}}{2}\right)\right] + \left[(P_{1500} - P_{2000}) \times \left(\frac{L_{1500} + L_{2000}}{2}\right)\right] + \left[(P_{1000} - P_{1500}) \times \left(\frac{L_{1000} + L_{1500}}{2}\right)\right] + \left[(P_{750} - P_{1000}) \times \left(\frac{L_{750} + L_{1000}}{2}\right)\right] + \left[(P_{500} - P_{750}) \times \left(\frac{L_{500} + L_{750}}{2}\right)\right] + \left[(P_{250} - P_{500}) \times \left(\frac{L_{250} + L_{500}}{2}\right)\right] + \left[(P_{100} - P_{250}) \times \left(\frac{L_{100} + L_{250}}{2}\right)\right] \quad (4)$$

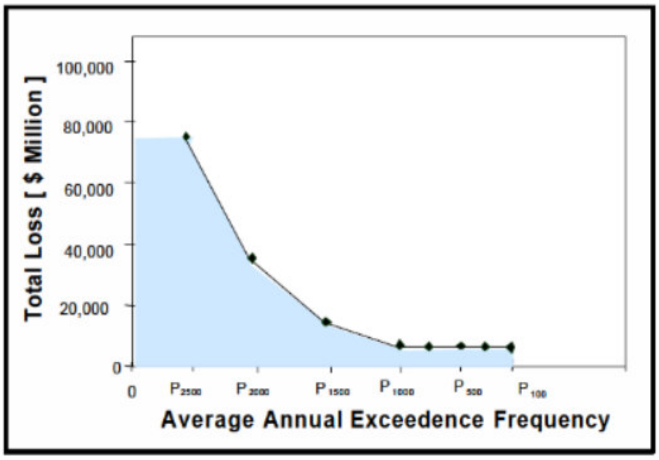


Figure 8. HAZUS model annual loss analysis [5]

2.3. Pushover Analysis

Pushover analysis is an analytical procedure to determine the collapse behavior of a building against an earthquake, also known as the nonlinear static method or static push load method, where this analysis requires a computer program to be able to realize it on a real building, except for a simple structure [21]. One of the computer programs for pushover analysis can use the Structural Analysis Program Software (SAP2000) [22]. The purpose of the pushover analysis is to evaluate the seismic behavior of the structure under earthquake loading, i.e. to obtain the actual ductility factor and the actual earthquake reduction factor of the structure. From this analysis, a capacity curve is obtained that shows the relationship of base shear to transition, which shows a change in structural behavior from linear to nonlinear. This is in the form of a decrease in stiffness indicated by a decrease in the slope of the curve due to the occurrence of plastic joints in the columns and beams [23].

In the modeling of the house building in this study, the existing house is modeled as a Reinforced Masonry (RM1) structure, where the wall stiffness is modeled as an equivalent diagonal strut structure. The calculation of the equivalent diagonal structure is done through Equation 5 to Equation 6, where λ1 is the coefficient to determine the equivalent width of the wall strut, E_{me} is the elastic modulus of the brick press, E_{fe} is the elastic modulus of the supporting frame material, t_{inf} is the thickness of the wall, h_{inf} is the height of the wall, I_{col} is the moment of inertia of the column, L_{inf} is the length of the wall, and a is the width of the equivalent strut structure width of the wall [24]. The calculation criteria of the equivalent structure are shown in Figure 9. Meanwhile, the parameter model for the plastic joint properties of beams, columns, and wall struts adopts the parameters of ASCE-41 [25].

$$\lambda_1 = \left(\frac{E_{me} \times t_{\inf} \times \sin(2\theta)}{4 \times E_{fe} \times I_{col} \times h_{\inf}} \right)^{0.25} \tag{5}$$

$$a = 0.175 \times \left(\lambda_1 \times h_{col} \right)^{-0.4} \times L_{\inf} \tag{6}$$

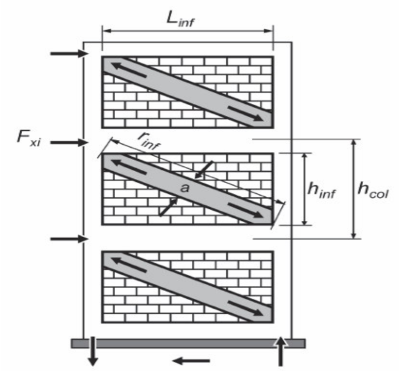


Figure 9. Modeling of a Brick Wall Support [26]

3. RESULTS AND DICUSSION

3.1. 3-dimensional model of the case study house

Based on structural and architectural data, the T94/120 residential structure shown in Figure 10 was modeled. The position of the beam and column structure followed the architectural plan. The gravity loading of the structure is carried out based on the function space of the architectural plan. Modeling of the wall strut structure was carried out based on the location of the wall based on the architectural plan with the results of the strut width calculation.

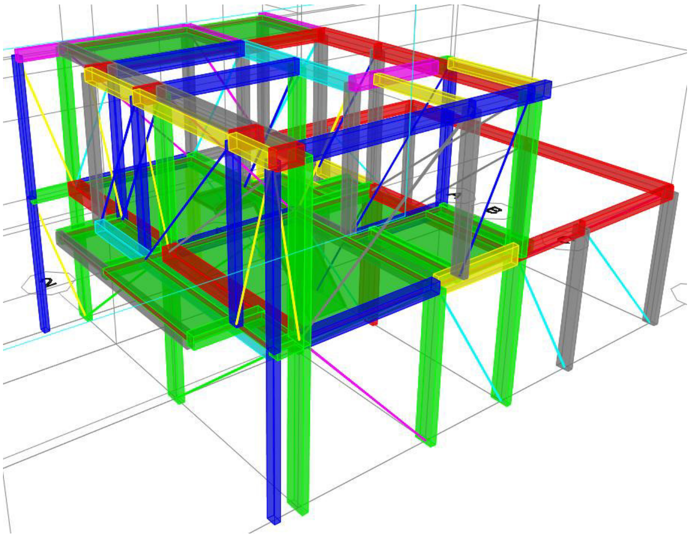
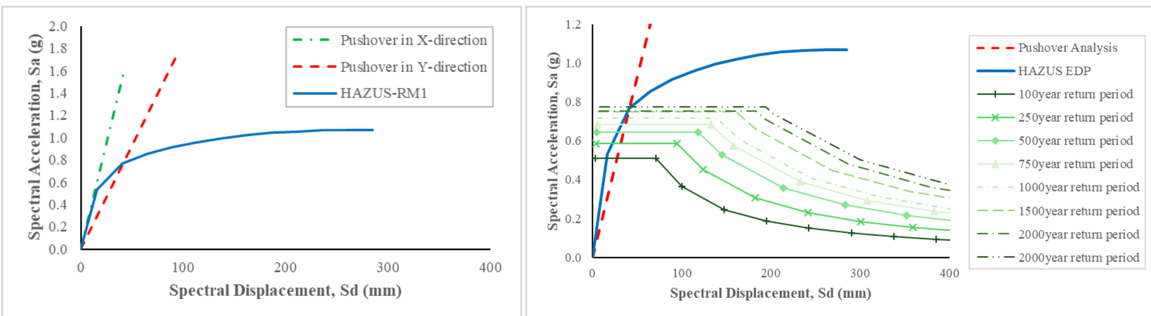


Figure 10. Case study structure model of house T94/120 of housing cluster X

3.2. Capacity Curve Comparison

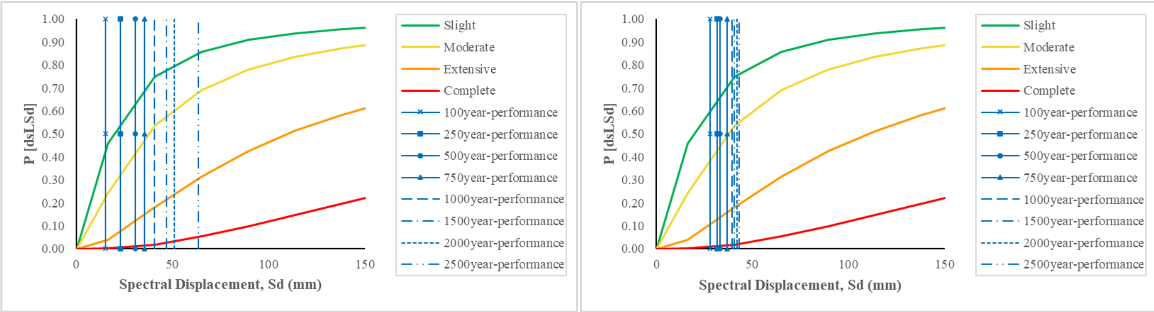
The results of pushover analysis and HAZUS method are shown in Figure 11a. The pushover analysis was conducted in two directions of the building, X-direction and Y-direction. The Y-direction pushover results have a capacity curve with lower stiffness than the X-direction results. In determining the building performance for loss analysis, the Y-direction capacity curve is used with the consideration that the resulting performance results are more conservative.

In the comparison of the HAZUS method capacity curve with the pushover results, it shows that the pushover result curve has a lower ductility than the HAZUS EDP, where the HAZUS EDP has a longer transition area from the yield limit to the ultimate limit, when compared to the pushover results. This indicates that the typical structural characteristics of residential houses in Indonesia are different from the typical structural characteristics of residential houses in the United States in the context of the RM1 structural type. In Figure 11b, the building performance is determined based on the capacity curve against 8 return period hazard scenarios to determine the single hazard loss and annual loss for each method (HAZUS and modified capacity curve).



(a) (b)

Figure 11. Comparison of capacity curves, (a) comparison of HAZUS capacity curves and case study pushover results, (b) determination of building performance points



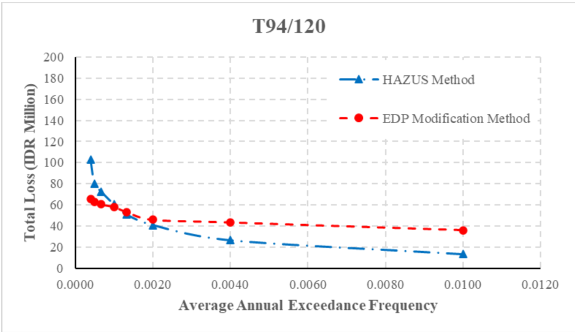
(a) (b)

Figure 12. Comparison of damage analysis on fragile curves (a) HAZUS method (b) capacity curve modification case study

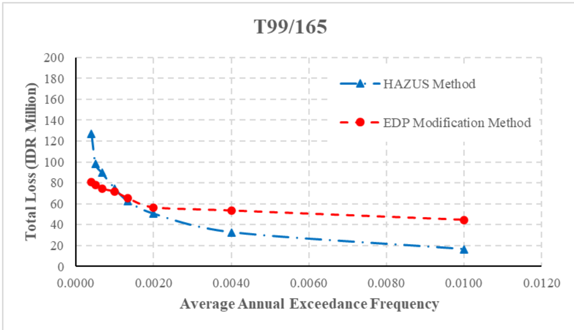
The results of the building performance are plotted on the capacity curve, which in this study in both methods uses the HAZUS fragility curve EDP shown in Figure 12. In the HAZUS method performance plots obtained performance that has a wider range of spectral displacements so that more diverse probability values are obtained shown in Figure 12a. While in the modified capacity curve method, the plot results show that the spectral displacement range has a narrower range which implies that it also has a probability value that is more likely to be uniform shown in Figure 12b. The results of the probability values from the plot on the fragility curve are used to calculate single hazard losses and annual losses through Equations 3 and 4.

3.3. Comparison of Loss Estimates

Comparison of loss estimation values for each hazard scenario and annual loss estimation for each type of house in cluster X and also for each method is shown in Figure 13. In the comparison of loss estimation for a single hazard scenario, data visualization was conducted on the case study of T94/120 residence shown in Figure 13a. The comparison of estimates for each hazard scenario shows that the modified capacity curve method has a greater estimate than the HAZUS method in hazard scenarios with return periods of 100, 200, 500, and 750 years. While in the hazard scenarios of return periods of 1000, 1500, 2000, and 2500 years the HAZUS method has a greater estimated value than the modified capacity curve method. This is consistent in other house types according to the initial study design, where in other house types using the T94/120 analysis results are representative. In Figures 13b to d, the estimated losses for each hazard scenario are shown, which has a similar loss trend for each return period as T94/120. Figure 14 shows a comparison of annual loss calculations based on Equation 4 for each method for each house type. In the annual loss comparison, it shows that the EDP modification method provides a 37.5% greater annual loss prediction consistently for each house type compared to the HAZUS method. This shows the urgency of applying local EDP in estimating losses, because if only fully adopting the HAZUS method, the estimates will be underestimated.



(a)



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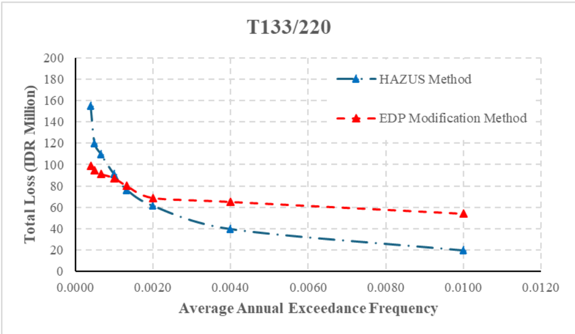
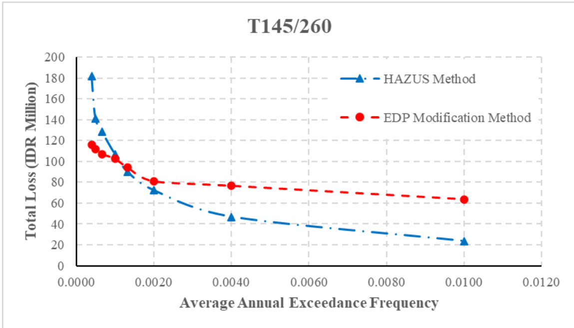


(c)



(d)

Figure 13. Comparison of Loss Estimation in single hazard scenario for each house type (a) T94/120; (b) T99/165; (c) T133/220; (d) 145/260

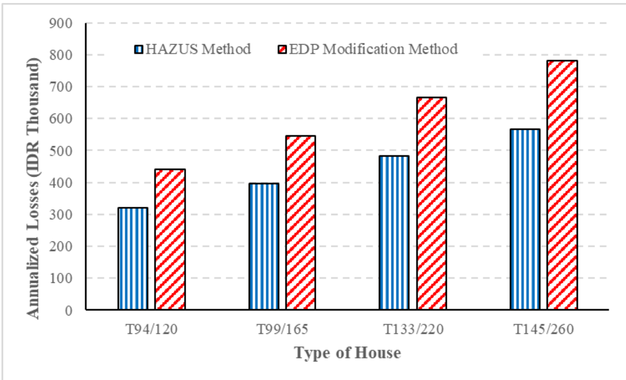
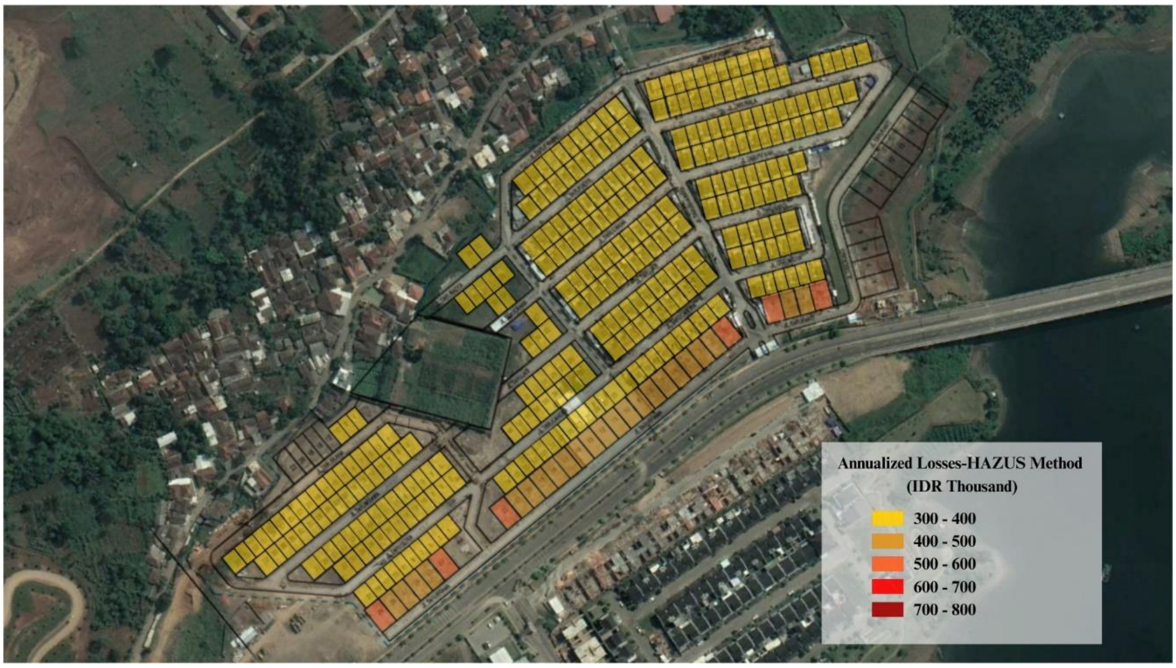
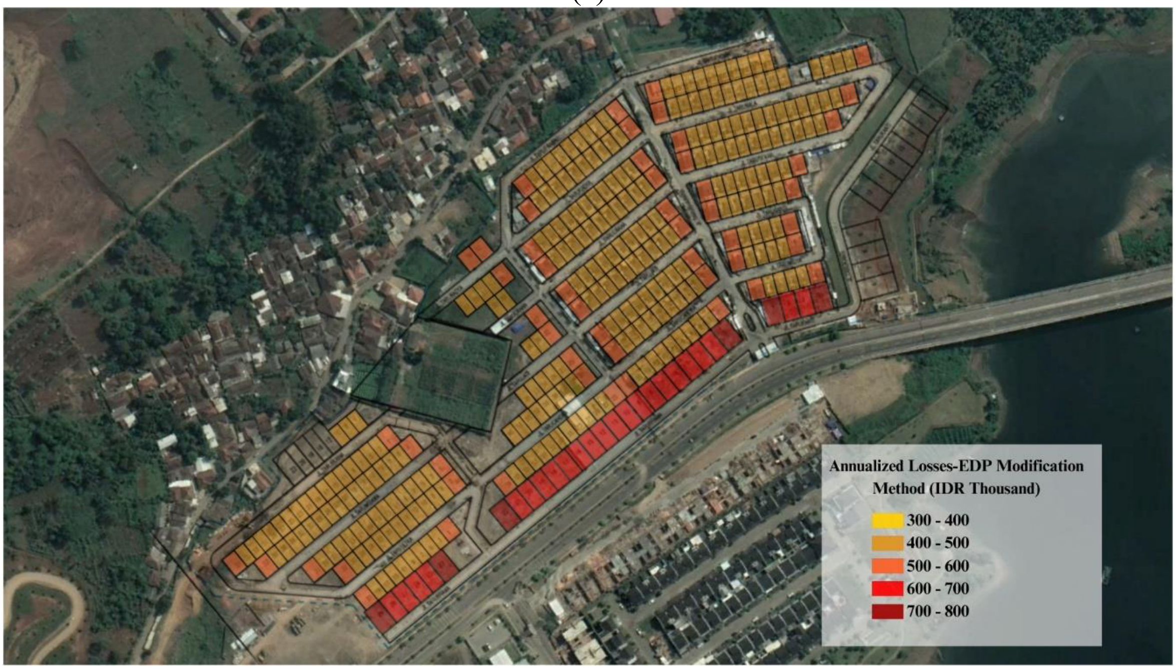


Figure 14. Comparison of Estimated Annual Loss for each type of house

In the annual loss estimation, data visualization was also carried out on the scope of cluster X which is shown in Figure 15. In the comparison of annual losses, it shows that the annual loss estimation of the modified capacity curve method has a greater estimated value, shown in Figure 15a, compared to the HAZUS method loss estimation shown in Figure 15b. Although the estimation results in single hazard show a balanced deviation trend between the two methods, the deviation in the modified capacity curve method has a significant contribution in the calculation of annual losses. This indicates the importance of adjusting the HAZUS EDP to local characteristics when adopting the application in Indonesia, because the local EDP produces a more conservative annual loss estimation value. The annual loss estimation value can be utilized in budgeting planning by the government and can also be utilized for the insurance premium estimation approach.



(a)



(b)

Figure 15. Comparison of Estimated annual Loss, (a) HAZUS method, (b) modified capacity curve

This study is limited to the EDP modification of the capacity curve in the study of the potential adoption of loss estimation using the HAZUS method in Indonesia. In the next study, modification of EDP fragility curve and modification of RCS_i coefficient with local data can be conducted. The development study can contribute to getting a fuller picture of the potential adoption of HAZUS in Indonesia.

4. CONCLUSION

Based on the comparison study of HAZUS method capacity curve modification, it shows that local structural data adjustment is required for adoption in Indonesia. The results of the capacity curve comparison of a typical case study of a residential house show that the local house capacity curve has lower stiffness and ductility compared to the HAZUS capacity curve EDP. In the loss estimation comparison, for the single hazard scenario, the results varied for both methods, but the annual loss estimation showed that the modified capacity curve gave a more conservative annual loss estimation. This shows the importance of local EDP adjustments in the process of estimating earthquake losses. Future research can be carried out to study the EDP modification of the fragility curve and the modification of the RCS_i coefficient with local data, which through this research illustrates the importance of EDP adjustments, specifically on the EDP of the building capacity curve.

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