An Implementation of the HAZUS Method for Estimating Potential Damage of Residential Houses at Pacitan Sub-district, East Java, Indonesia due to Earthquake

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Abstract. Indonesia is not only known as an archipelago that is rich in natural resources but also known as a disaster-prone country. Because of its location in four major Eurasian, Indo-Australian, Pacific, and Philippine tectonic plates, natural disasters such as earthquakes, floods, landslides, volcanic eruptions, droughts, forest fires, and tsunamis often occur throughout the region. In 2006, a large earthquake shocked the densely populated Yogyakarta Province and its surrounding areas. This earthquake caused huge fatalities and damaged thousands of buildings and infrastructures. The Pacitan region is geographically close to Yogyakarta, and is located only 120 km from the epicenter of the quake. Therefore, awareness of disaster mitigation is a critical action in reducing disaster risks. In addition, the Pacitan Regency is a hilly and mountainous region covering a total area of 1,389.87 km. Its territory also includes karst regions and lowland areas. A preliminary research utilizing the HAZUS method was conducted for assessing the damage probability of residential houses at an earthquake-prone area of Pacitan sub-district. The indicative results show that the unreinforced masonry (URML) types are the most destructive followed by Wood, light frame (W1), reinforced masonry low-rise (RM2L), and reinforced masonry mid-rise (RM2M) when applied across three scenarios of earthquake with magnitudes of 6, 6.5, and 7, respectively.

1 Background

According to USGS 2018 [13] over the past decade, Indonesia has experienced numerous earthquakes above a RS of 6 magnitude (Fig. 1). In 2018, a destructive earthquake [2, 3, 4] occurred in Banten (6.1 RS). Even smaller events such as the case in Banjarnegara in April 2018 measured at 4.4 had the potential to devastate hundreds of houses. In August 2018 an

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earthquake in with RS 7 magnitude inflicted numerous fatalities and incurred serious economic losses. Due to these numerous and anticipated future events, there is a need to learn more about earthquake characteristics and apply risk assessments of buildings and diminish the possibility of hazard threats.

Fig.1. The earthquake > 6 magnitude occurrence over past decade in Indonesia [13]

An earthquake occurrence causes severe damage in buildings due to several factors, such as the mechanism of the earthquake, the geologic condition of the seismic wave, magnitude of the earthquake, depth of earthquake, and site effect [17]. Concerning its geology, Pacitan is likely to be hit by a huge earthquake either from the sea or the active faults producing a potential severe damage. Based on the seismic history, Pacitan was hit by a large earthquake of 7.5 magnitudes in 1859 followed by a small tsunami. Another earthquake event was also recorded at 7.2 RS in Pacitan in 1937 with an intensity VII – IX MMI [5].

From previous studies [9, 12], a series of earthquakes have considerable effects because of a lack of awareness of the earthquake and poor implementation of the earthquake resistant building concept. Moreover, the limited references to the national standards/codes in building practices in Indonesia [10] produce poor detailing, using a wide variety of material quality and construction methods, improper structural designs can increase destructive impacts caused by an earthquake event. The adage has long been said that earthquakes do not kill people, but buildings do. The damage and the collapse buildings due to the incapacity of structures to anticipate the ground motion during peak ground acceleration can have serious disastrous impacts.

Given these conditions, it is timely to conduct a vulnerability assessment and study of the existing residential houses in Pacitan in order to discover the expected losses before an earthquake occurs. The destructive effect of the earthquakes can be reduced by adopting a damage ratio model, such as the well-known HAZUS method. This method was developed by the Federal Emergency Management Agency (FEMA) in the United States, which can help to determine the damage and loss assessment of hazards, especially earthquakes. Therefore, this research focuses on applying the HAZUS method for estimating potential losses from buildings during an earthquake in the Pacitan Sub-district area.

2 Theoretical Review

FEMA developed the HAZUS method in 1997 to provide a platform for risk assessment of various hazards mainly earthquakes, flooding and cyclone. It also identifies and visualizes hazards and vulnerabilities which can help the government authorities to ensure that settlements are up to standards and also assists in preparing in post-disaster planning, recovery, and reconstruction [6]. Exhaustive data are required for this method such as general building stocks, utilities, building specifications, types of occupancy, and configurations of the house. A general building stock inventory is created by using census track characteristics as the unit for grouping of buildings. The main aim is to group the building into pre-defined classes of buildings in the HAZUS method so that a seismic hazard map can be produced by inputting seismic micro-zonation details. This methodology also makes it easier to find out the probabilities of damage under various ground shaking conditions.

The ground shaking at a point due to the energy released from an epicenter is represented as a demand spectrum. The demand spectrum is a relationship between the Spectral Acceleration (S_A) and Spectral Displacement (S_D). A point of the spectral acceleration at a given time period is derived from ground motion prediction equations, which use various parameters such as rock types, distance from epicenter, local soil condition, etc.

The ground motion prediction equation adopted by Dauglas [7] was derived by Laurendeau et al. [8] regarding earthquake data with the shallow crustal mechanism. The ground motion is derived in the following equations:

$$\ln SA = FM + FD + FS \quad (1)$$

$$FM = a_1 + a_2 [M - M_h] + a_3 (M - M_h)^2 \text{ for } M \leq M_h \quad (2)$$

$$FM = a_1 + a_4 [M - M_h] \text{ for } M > M_h \quad (3)$$

$$FD = [b_1 + b_2 (M - 4.5)] \ln R + b_3 [R - 1] \quad (4)$$

$$R = \sqrt{R_{rup}^2 + h^2} \quad (5)$$

$$FS = c_1 \cdot \ln [V_{s,30}/800] \quad (6)$$

where S_A is in g, $a_1 = -0.033598$, $a_2 = 0.49784$, $a_3 = -0.14873$, $a_4 = 0.22496$, $M_h = 5.6$, $b_1 = -0.95495$, $b_2 = 0.20938$, $b_3 = -0.014$, $h = 1.36$, $c_1 = -0.34393$, $\phi = 0.65621$ (intra event), $\tau = 0.53412$ (inter event) and $\sigma = -0.84611$ (total).

Shear-wave velocity value (V_s) is one of the essential parameters for analyzing the dynamic properties of soil. These different soil types are listed in Table 1 [16].

Table 1. Site classes of different shear wave velocity (UBC, 1997)

Site class	Description	Shear-wave velocity (V_s) - m/s
A	Hard rock	$V_s > 1500$
B	Rock	$760 < V_s < 1500$
C	Very dense soil and soft rock	$360 < V_s < 760$
D	Stiff soil profile	$180 < V_s < 360$
E	Soft soil profile	$V_s < 180$

Spectral displacement (S_D) is affected by spectral acceleration (S_A) and Time period (T) [6], the ground motion is:

$$S_D = 9.8 \times S_A \times T^2 \quad (7)$$

where,

S_D = spectral displacement,

S_A = spectral acceleration,

T = time period in seconds.

The yield values and ultimate values of every building types (URM, RM, W) for low-code seismic design level are shown in Appendix 1. According to Kircher et al. [8], probabilities of a damaged state are determined by cumulative damage probabilities and it is shown in the Eq. 8 as follows:

$$P(d_s|S_d) = \phi \left[\frac{1}{\beta_{ds}} \ln \left(\frac{S_d}{S_{d,ds}} \right) \right] \quad (8)$$

where,

$P(d_s|S_d)$ = the probability of reaching or exceeding a slightly damaged state (S_d),

$S_{d,ds}$ = the threshold of spectral displacement,

β_{ds} = the standard deviation of the natural logarithm of spectral displacement for damage state d_s ,

ϕ = the standard normal cumulative distribution function.

The probability of each damage state is calculated by substituting the value of peak building response and the damaged state median of a specific damage state. The parameters of structural fragility curve for URM, RM, and W building types are given in Appendix 2. The probable levels of expected damage vary from building type-to-type and level of different seismic design levels. After calculating commutative damage probabilities, discrete damage probabilities are calculated from the following formula shown in Table 2 [6].

Table 2. Probabilities of damage based on the HAZUS method

No	Damage state	Damage probability
1	Complete damage	$P[C] = P(C S_d)$
2	Extensive damage	$P[E] = P(E S_d) - P(C S_d)$
3	Moderate damage	$P[M] = P(M S_d) - P(E S_d)$
4	Slight damage	$P[S] = P(S S_d) - P(M S_d)$
5	No damage	$P[N] = 1 - P(E S_d)$

3 Research Methodology

The location of the study is in Pacitan sub-district, which is the capital city of Pacitan, East Java, Indonesia. Pacitan Sub-district has the highest population of the district [18]. Moreover, based on the geological formation [19], Pacitan sub-district is in an alluvium (Qa) formation, which is dominated by sedimentary layers. Therefore this research is focused on this area. The main aim of this study is to estimate the probability of damage of

residential buildings subjected to an earthquake in Pacitan Sub-District by using the HAZUS method for preparedness and mitigation purposes. There is no precise damage assessment model that can be developed in Indonesia, especially one that can be applied to the Pacitan Sub-district. Given this reason, the HAZUS method was adopted and applied to this research to reduce the devastating effect of the earthquakes.

The research plan begins with the collection of primary data and secondary data. The primary data is building inventory data collected by the purposive sampling method with a census track and generating the building footprint map. The secondary data are collected from GIS maps, satellite images, administrative data, ground motion, and seismic data. The demand spectrum is generated from Laurendeau et al [8] attenuation function [7] by using three hypothetical earthquake scenarios (6, 6.5, 7 Magnitudes). The yield and ultimate capacity values of building types are published in the HAZUS manual book. This research utilizes the quantitative approach to measure the damage probability using this method. It generates five scenarios levels, i.e., no damage, slight, moderate, extensive, and complete.

4 Results and Discussion

Pacitan Sub-district is located at -8.1955698 latitudes and 111.099692 longitudes. As an administrative area [18], Pacitan Sub-district consists of 25 villages. In terms of geographic position, in the west of Pacitan Sub-district is Pringkuku Sub-district, in the north of Pacitan Sub-district is Arjosari Subdistrict, in the East of Pacitan Sub-district is Kebonagung Sub-district, and in the south of Pacitan Sub-district is Indonesian Ocean.

Fig. 2. Research administrative map in Pacitan Sub-district 2018
(Source: GIS 10.2, Modification of Pacitan Administrative Map)

Fig. 2 shows the administrative map of the research area in the Pacitan Sub-district. The red block depicts the residential blocks in Pacitan Sub-district, which is the main focus of this research. According to the field survey, the dwelling houses in Pacitan Sub-district are dominated by mud-brick houses and the majority are single story houses [11]. This kind of building is categorized as a non-engineered building. In terms of the HAZUS method, there are four types of structures in Pacitan Sub-district as shown in Fig. 3, i.e.: unreinforced masonry (URM) low-rise, reinforced masonry (RM2L) low-rise, reinforced masonry (RM2M) mid-rise, and wooden structure (W1). In Indonesia, non-engineered buildings are constructed in small towns and villages [13] and are generally built according to tradition, types suiting local culture, and materials available in the area. It is also determined by the owner and influenced by societal preferences at the time of construction.

Fig. 3. Type of houses in Pacitan Sub-district (fieldwork), (a) Reinforced Masonry Low-rise -RM2L, (b) Wood-W1, (c) and (d) Typical unreinforced masonry low-rise (Source : Fieldwork)

The building type strengthened with reinforced masonry (RM) is mostly located in the central city like Ploso Village, Baleharjo Village, Tanjungsari Village, Pacitan Village, and Pucangsewu Village. Other villages in the coastal area are nearby the Grindulu River and are dominated by unreinforced masonry structures and wood structures.

A residential house adopted from the earthquake-resistant design concept on their structures is presented in Fig. 3 (a) which is classified as reinforced masonry. In practice, the reinforced masonry wall is strengthened with reinforced concrete members on all four sides [11] consisting of bond-beams or tie-beams and tie-columns and interconnected connections, which is the critical point of strength. Whilst Fig. 3 (b) presents a wood-type building. Other Fig. 3 (c) and Fig. 3 (d) are categorized as a

typical unreinforced buildings because the structures only made from mud-brick without the column, sloop, or even the beam.

This paper presents preliminary results based on generating the discrete damage probabilities in a specified location at Ploso Village due to the limited process of data completion. The main goal of this research is to analyze the discrete damage of 25 villages in that area. It should be noted that the HAZUS method has four main parameters to estimate the damage probabilities, such as seismic hazard, demand spectrum (ground motion), capacity curve of building types, and damage function.

For the demand spectrum considering the hypothetical earthquake scenarios of magnitude 6, 6.5, and 7 with its epicenter located at 8.018°S 111.051°E, with deep-focus earthquake occurs 19.7 km below the earth's surface are used for calculating the demand spectrum using ground motion prediction equation given by Laurendeau et al. [8]. The distance from the epicenter to the study area (Ploso Village) is 22 km. The average of the shear wave velocities of the site is 278.965 m/s, which can be found in USGS [15]. The calculation of discrete damage probabilities starts from generating the demand spectrum using a ground motion prediction equation. The spectral acceleration is shown in Fig. 4 determined by Eq.1 to Eq.6.

Fig. 4. Spectral acceleration vs. period adopted from Laurendeau's attenuation function

Fig. 5. Spectral acceleration vs. spectral displacement

Fig. 5 shows the higher magnitudes produced by the higher spectral accelerations as well as the spectral displacements considering Eq. 7. The lower magnitude provides the lower spectral acceleration. Then the generation of peak building response considers the

demand spectrum and building types in Pacitan sub-district based on the HAZUS manual book, and highlights the capacity curve values given in Appendix1. The relationship between the demand spectrum and capacity curves for three hypothetical earthquake scenarios is depicted in Fig. 6.

Fig. 6. Intersection of demand spectrum and capacity curve

It should be noted that a peak building response (performance point of structure) is the corresponding to the values of the spectral displacement in intersection points of the capacity curves and the demand spectrum. This means that the structures experience shaking until it reaches its performance point (peak building response) followed with the maximum damage occurred. Fig. 6 shows the capacity curves of four buildings identified in Pacitan Sub-district overlaid in the demand spectrum to calculate the peak building response. According to Fig. 6, the highest value of peak spectral displacement indicates that RM2M and RM2L types about 1.16 in. for 7 magnitudes while the lowest number of peak magnitudes is W1 and URML at 0.3 in. for 6 magnitudes. Then the generation of fragility curve is carried out to get the probabilities of damage.

Fig. 7. Percentage of Damage Probabilities

The probabilities of damage states are generated from the total of damage probabilities using the equation in Eq. 8. The probability of damage for each building types can be shown in Fig. 7. There are five damage states in the percentage of damage probabilities comprising no damage, slight, moderate, extensive, and complete. The types of buildings in Pacitan Sub-district consist of four classes (RM2M, RM2L, W1, and URML). These are generated in three scenarios magnitude of the earthquake (6, 6.5, and 7). The probabilities of discrete damage can be determined by using the formulas in Table 2.

Fig. 7 presents the higher number of earthquake magnitudes providing the greater levels of damage in every type of building. On the other hand, the lower magnitudes of the earthquake, the greater number for no damage levels shown Fig. 7 also indicates the URML type is severer among other types, it is shown from the amount of complete damage level, extensive damage level, and moderate damage level are higher than other types, in three different magnitudes of earthquake. Besides, level of no damage for the URML type has the lowest number among others in three different magnitudes (6, 6.5, and 7) are 62.38%, 42.06%, and 24.98% respectively. The detail results of analysis are listed in Table 3.

Table 3. The Level of damage probabilities of building types

Magnitude 6		Complete	Extensive	Moderate	Slight	No Damage	Damage
	URML	0.53%	3.58%	13.10%	20.41%	62.38%	38%
	W1	0.02%	0.59%	6.65%	21.87%	70.86%	29%
	RM2L	0.05%	3.43%	12.70%	12.60%	71.22%	29%
	RM2M	0.01%	0.055%	2.58%	6.91%	90.45%	10%
Magnitude 6.5		Complete	Extensive	Moderate	Slight	No Damage	Damage
	URML	1.87%	8.26%	22.16%	25.65%	42.06%	58%
	W1	0.15%	2.11%	15.23%	32.51%	50.00%	50%
	RM2L	0.12%	5.25%	16.44%	14.60%	63.58%	36%
	RM2M	0.07%	0.543%	10.03%	15.41%	73.95%	26%
Magnitude 7		Complete	Extensive	Moderate	Slight	No Damage	Damage
	URML	4.99%	14.87%	29.67%	25.49%	24.98%	75%
	W1	0.63%	5.51%	26.30%	36.89%	30.66%	69%
	RM2L	1.16%	15.35%	28.29%	17.48%	37.72%	62%
	RM2M	0.12%	0.873%	13.00%	17.48%	68.53%	31%

The W1 is the second highest vulnerable structure with the number of no damage level are higher than URML type at 70.86%, 50%, and 30.66% in different magnitudes (6, 6.5, and 7) respectively. Fig. 7 and Table 3 also show that the number of slight damage level for W1 is greater among others. However, the level of complete damage, extensive damage, and moderate damage are still lower than the URML type. The amount of all level damage probabilities for the RM2L has almost similar with the W1 type, but the level damage for the RM2L is lower than the W1. The values of no damage level for the RM2L are 71.22% for magnitude 6, 63.58% for magnitude 6.5, and 37.72% for magnitude 7, respectively. The RM2M type has the smallest severe damage shown in Fig.7 and Table 3 with the number of none damage level is higher than others in different magnitude (6, 6.5, and 7) are 90.45%, 73.95%, and 68.53% respectively. By this it means, the RM2M has the strongest structure.

Overall, it is clear that the URML has highly vulnerable among others followed by the W1, the RM2L, and the RM2M. It is shown that the lower number of none damage level, the greater vulnerable of building generated. This percentage of the damage level result

seems lesser than expected because the values of the capacity curve and the fragility curves provided in the HAZUS manual book based on United States (US) building types that might be different with the structures of building types in Indonesia. Therefore, this preliminary research needs to be more deeply analyzed by using modifications and some approaches in HAZUS parameters to acquire the appropriate and optimal result.

5 Concluding remarks

The HAZUS method adopted in this research is helpful to estimate the damage and loss due to earthquake hazard in Indonesia, especially in Pacitan. The result indicates the URML is the severest vulnerable, which has the lowest percentage of none damage level are 62.38%, 42.06%, and 24.98% in earthquake magnitudes 6, 6.5, and 7, respectively. The second highest damage is W1, which has number of no damage level at 70.86%, 50%, and 30.66% in different magnitudes (6, 6.5, and 7), respectively. Continued to the RM2L, which actually has almost similar rate number with the W1 type. The percentage of none damage to the RM2L in magnitude 6, magnitude 6.5, and magnitude 7, respectively are 71.22%, 63.58%, and 37.72%. Then the lowest vulnerable structure is the RM2M type, which has the highest amount of no damage level in three different magnitudes at 90.45% for magnitude 6, 73.95% for magnitude 6.5, and 68.53% for magnitude 7. The RM2M demonstrates having sufficient strength in resisting earthquake. In addition, the number of damage levels for each building type are lower than expected, therefore more in-depth analysis is desirable to achieve more rational targets.

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Appendix 1

Table A1. Building capacity curve - Low Code [6]

W1	Yield capacity	D_y (in)	0.24	A_y (g)	0.2
	Ultimate Capacity	D_u (in)	4.32	A_u (g)	0.6
URML	Yield Capacity	D_y (in)	0.24	A_y (g)	0.2
	Ultimate Capacity	D_u (in)	2.4	A_u (g)	0.4
RM2L	Yield Capacity	D_y (in)	0.16	A_y (g)	0.133
	Ultimate Capacity	D_u (in)	1.6	A_u (g)	0.267
RM2M	Yield Capacity	D_y (in)	0.35	A_y (g)	0.111
	Ultimate Capacity	D_u (in)	2.31	A_u (g)	0.222

Appendix 2**Table A2.** Structural fragility curve parameters - Low Cow Seismic Design Level [6]

Building properties			Interstory Drift at				Spectral Displacement (inches)							
Type	Height (in)		Threshold of Damage State				Slight		Moderate		Extensive		Complete	
	Roof	Model	Slight	Moderate	Extensive	Complete	Medium	Beta (b)	Medium	Beta	Medium	Beta	Medium	Beta
W1	168	126	0.004	0.0099	0.0306	0.075	0.5	0.93	1.25	0.98	3.86	1.02	9.45	0.99
URML	180	135	0.003	0.006	0.015	0.035	0.41	0.99	0.81	1.05	2.03	1.1	4.73	1.08
RM2L	240	180	0.004	0.0064	0.0161	0.0438	0.72	1.05	1.15	1.07	2.89	1.09	7.88	0.91
RM2M	600	450	0.0027	0.0043	0.0107	0.0292	1.2	0.84	1.92	0.81	4.81	0.77	13.12	0.92