

Maximum Acceleration Based on Probabilistic Seismic Hazard Analysis at Koni Mamuju Building Mamuju, West Sulawesi

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Abstract

Maximum Acceleration Based on Probabilistic Seismic Hazard Analysis at Koni Mamuju Building Mamuju West Sulawesi. This research evaluates the seismic risk at the Koni Mamuju Building in West Sulawesi by Probabilistic Seismic Hazard Analysis (PSHA) utilising the USGS earthquake catalogue and EZ-FRISK software. Analysis was conducted assuming a 2% exceedance probability over 50 years (equivalent to a return period of 2,475 years). The bedrock Peak Ground Acceleration (PGA) was determined to be 0.684 g (pre-scaling: 1.026 g, scaled by a factor of 2/3). Surface acceleration rose to 0.800 g after doing site response analysis with DEEPSOIL V7, indicating a local amplification factor of roughly 1.17. The response spectrum indicated a peak spectral acceleration S_a (0.2 s) of 1.341 g, signifying substantial seismic demand on short-period structures. Hysteretic loop analysis revealed a maximum shear stress ratio of 0.3162 at a strain of 0.33 at a depth of 15 m (NSPT = 14, clay layer), signifying vulnerability to cyclic deformation and possible liquefaction. The findings indicate that Mamuju is situated in a high seismic hazard zone, necessitating conservative structural design that considers soil amplification effects and short-period spectral demands in accordance with SNI 1726-2019.

Keywords: PSHA, Land Acceleration, Melting, Mamuju Earthquake

INTRODUCTION

Indonesia is one of the most seismically active places in the world because it is located at the intersection of three main tectonic plates: the Indo-Australian, Eurasian, and Pacific plates. West Sulawesi has seen some very bad earthquakes, the worst of which was the Mamuju earthquake on January 14, 2021, which had a magnitude of 6.2 and caused a lot of damage and deaths. So, it is very important to know how likely earthquakes are in this area in order to develop safe and strong infrastructure. The need for understanding was well expressed by President Lyndon Johnson in a directive to the Special Assistant for Science and Technology, Donald F. Hornig (Finn, 2010). Analysis of the match of PGA values from the donovan method with the data *Accelerograph*, (Kata L et al., 2023). Research using *Probabilistic Seismic Hazard Analysis* (PSHA), is still rarely carried out, especially for the West Sulawesi region, as well as soil movements which are generally still limited to bedrock design. Some previous studies related to PSHA include research conducted by Makrup and Munafi (2016), this study predicts the acceleration of earthquake earth vibrations found in soil using PSHA, but in the Semarang and Solo areas.

Liquefaction happens when the ground shakes and causes saturated sandy soils to briefly lose their shear strength and act like a fluid. Structures built on soils that can turn into liquid are very likely to settle unevenly, fail to support themselves, or collapse. Before any liquefaction study can be done, it is important to accurately describe the seismic hazard at a site because the potential for liquefaction is directly related to the strength of the ground motion during an earthquake. Deterministic (DSHA), probabilistic (PSHA), or code-based methods can be used to figure out how the ground moves at a spot. Probabilistic Seismic Hazard Analysis (PSHA) is regarded as the most comprehensive approach, as it amalgamates inputs from all conceivable earthquake sources, accounting for both the frequency and uncertainty of seismic occurrences (Cornell, 1968). There is still not much research on PSHA for West Sulawesi; most of the studies that are out there are about Sumatra, Java, or Lombok. Makrup and Muntafi (2016) utilised probabilistic seismic hazard assessment (PSHA) with spectral matching to create synthetic ground motions for Semarang and Solo. Anugrayanti et al. (2021) conducted an empirical analysis of peak ground acceleration and earthquake intensity at Mamasa, West Sulawesi. Hanindya et al.

(2023) utilised Deterministic Seismic Hazard Analysis (DSHA) to evaluate the liquefaction potential at Anutapura Hospital, Palu, Central Sulawesi.

Peak Ground Acceleration (PGA), which is the highest ground acceleration, is one of the most important signs of how much damage an earthquake could cause (Edwiza, 2008). PGA values can be ascertained instrumentally via accelerographs or empirically through Ground Motion Prediction Equations (GMPEs), such as those developed by Esteva, Donovan, McGuire, Fukushima-Tanaka, and Kanai, each calibrated for distinct tectonic environments and distance intervals (Januarti, 2022; Kusumawardani et al., 2020; Ulfiana et al., 2018). The correctness of any empirical approach is contingent upon area geological conditions; in Mamuju, the tectonic context exhibits similarities to those of North Sulawesi, particularly in plutonic rock geology.

This study uses PSHA to measure the seismic risk for the Koni Mamuju Building, which is in Mamuju, West Sulawesi, at $2^{\circ}40'24.58''$ S, $118^{\circ}51'27.59''$ E. The 2019 SNI code is used to make earthquake time histories, and site response analysis is done to send bedrock motion to the ground surface. This information is then used to build structures and assess liquefaction.

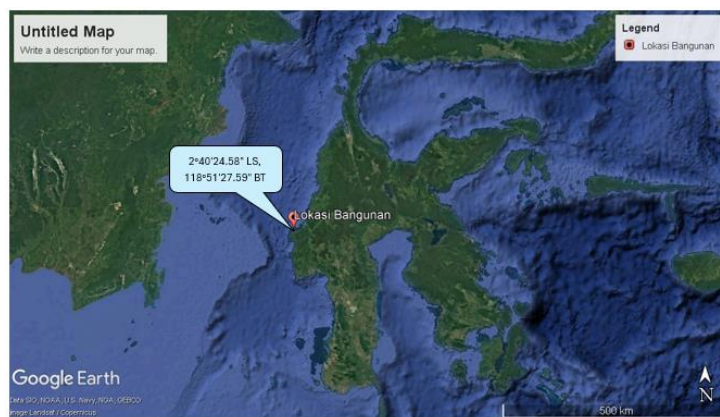


Figure 1. Location of the research building, Mamuju, West Sulawesi

There aren't many accelerometer networks that can measure earthquake time histories because of a lack of resources. If there are no instrumentation records, DSHA can be used with the Ground Motion Prediction Equation (GMPE) and spectral matching at the site's dominant frequency to generate time histories. To determine the potential for liquefaction at a specific location, the artificial earthquake acceleration time history must be transmitted through the soil profile to the necessary analysis depth, which is usually 30 m below the surface of the ground (SNI 1726-2019).

METHODS

This study employs a quantitative, experimental approach using secondary data from earthquake catalogs and geotechnical software to calculate the probabilistic seismic hazard at the Koni Mamuju Building site. Historical earthquake data — including event magnitude, hypocentral depth, and epicentre location — were obtained from the USGS earthquake catalog for the period 1900–2025. Supplementary local earthquake data were obtained from the National Earthquake Study Centre (PusGen) of Indonesia.

The dataset includes all events with moment magnitudes between M_w 4.0 and M_w 9.0 occurring within a 500 km radius of the city of Mamuju. This radius encompasses the major seismogenic sources relevant to the site, including the Palu-Koro Fault, the Mamuju segment of the Sulawesi Fold-and-Thrust Belt, and the Sulawesi subduction zone. Geological parameters such as fault slip rates and subduction interface coupling coefficients were sourced from the PusGen 2017 national seismic source model.

The PSHA workflow employed the following software tools::

- a. Google Earth Pro – site coordinate identification and 3D source geometry visualization.
- b. Zmap7 – seismicity analysis to determine the magnitude of completeness (M_c), seismicity rate parameter (a -value), and Gutenberg-Richter b -value.

- c. EZ-FRISK – probabilistic seismic hazard computation integrating 3D earthquake source models, occurrence rates, and Ground Motion Prediction Equations (GMPEs).
- d. Seismomatch – spectral matching of selected accelerograms to the target Uniform Hazard Spectrum (UHS).
- e. DEEPSOIL V7 – one-dimensional nonlinear site response analysis to propagate bedrock motion to the ground surface.

The PSHA procedure followed these sequential steps:

- a. Earthquake source identification: subduction zones and active fault segments were modelled in three dimensions within EZ-FRISK. Geometric parameters (dip angle, depth range, and rupture area) were assigned based on PusGen 2017 source data.
- b. Seismicity analysis: the Gutenberg-Richter recurrence parameters ($a = 5.82$, $b = 0.91$) and magnitude of completeness ($M_c = 4.5$) were determined from the declustered earthquake catalog using Zmap7. These values were input into EZ-FRISK to define source activity rates.
- c. Hazard computation: using EZ-FRISK, the seismic hazard was computed at the site by integrating all source contributions with the selected GMPEs (Boore-Atkinson 2008 for shallow crustal events; Zhao et al. 2006 for subduction interface events). The analysis was performed at a 2% probability of exceedance in 50 years (return period = 2,475 years), in accordance with SNI 1726-2019. The output is the Uniform Hazard Spectrum (UHS).
- d. Ground motion record selection: three actual ground motion time histories (AGMTH) were selected from the PEER Ground Motion Database based on the dominant magnitude (M) and distance (R) from the hazard deaggregation results.
- e. Spectral matching: the three selected accelerograms were matched to the UHS target spectrum using Seismomatch software. Goodness-of-fit was evaluated by the root-mean-square error (RMSE) between matched and target spectra, following SNI 1726-2019 requirements.
- f. Site response analysis: the matched bedrock time histories were propagated through the site soil profile to the surface using DEEPSOIL V7, employing a nonlinear equivalent-linear formulation. Input soil parameters (shear wave velocity V_s , unit weight, and modulus reduction/damping curves) were derived from borehole SPT data at the Koni Mamuju Building site.
- g. Second spectral matching: the surface response spectrum was compared with the SNI 1726-2019 design spectrum and adjusted using F_a (short-period) and F_v (long-period) site amplification coefficients.

The PSHA and DSHA approaches are complementary: PSHA characterizes the overall probabilistic hazard across all return periods and magnitudes, while DSHA defines a single controlling scenario (maximum credible earthquake) critical for nonlinear time-history analysis. Together, they ensure that structural designs are both probabilistically calibrated and scenario-resilient. EZ-FRISK was selected over open-source alternatives such as OpenQuake due to its established use in Indonesian practice and direct compatibility with the PusGen 2017 source model format. The analytical workflow is fully reproducible using the input parameters documented in this study.

RESULTS AND DISCUSSION

Probabilistic Seismic Hazard Analysis (PSHA)

This study conducted an earthquake hazard analysis utilising the Probabilistic Seismic Hazard Assessment (PSHA) approach. Seismic hazard assessment utilising EZ-FRISK software. This study's seismic analysis of earthquake dangers was confined to probability surpassing 2% over a 50-year lifespan of the building, equating to a return period of 2475 years. Figure 2(A) illustrates the outcomes of the uniform-hazard-spectrum reaction. danger deaggregation is the analysis of diverse sources of earthquake danger impacting a site to forecast the predominant distance and magnitude. This methodology employs probabilistic methodologies, accounting for all potential outcomes for each earthquake source depending on its properties. This study's deaggregation computation is confined to earthquake dangers at the PGA period and 0.2 seconds, with a probability surpassing 2% throughout the building's 50-year lifespan, as existing earthquake rules have adopted these criteria. The deaggregation procedure seeks to estimate the significant earthquake for the area in question. This can produce average magnitude and average distance, which will be beneficial for picking actual soils with properties similar to the desired circumstances. The objective of this deaggregation computation is to recommend the suitable ground movement for the constructed construction. The outcomes of the deaggregation analysis are illustrated in Figure 2 (B).

Table 1. Probability of a uniform hazard response outcome exceeding 2% in 50 years

<i>Time</i>	<i>2/3 Axial Spectral (g)</i>
0	0,684
0,5	1,346
0,1	1,341
0,2	1,175
0,3	1,145
0,4	1,127
0,5	0,943
0,75	0,697
1	0,559
2	0,256
3	0,171
4	0,130

Table 1 presents the results of this investigation, illustrating the correlation between the acceleration of time (period) and the spectrum (g) in the examined area. The 0-second interval is referred to as PGA (Peak Ground Acceleration). The Peak Ground Acceleration (PGA) value in the bedrock at the study site, with a 2% likelihood of being exceeded over 50 years, is 1.026 g. Upon multiplying by 2/3, the PGA value in the bedrock at the research site, with a 2% risk of exceedance over 50 years, is 0.684 g. Figure 2 (A) illustrates a graph of the uniform spectral hazard response in this study.

The Dangers of Deaggregation

Hazard deaggregation is the analysis of diverse sources of earthquake hazards impacting a site to ascertain the predominant distance and magnitude. This strategy employs a probabilistic methodology, considering all potential scenarios of each earthquake (earthquake source) relative to the subduction earthquake source at the survey location, specifically Mamuju, West Sulawesi, as seen in Figure 2 (B).

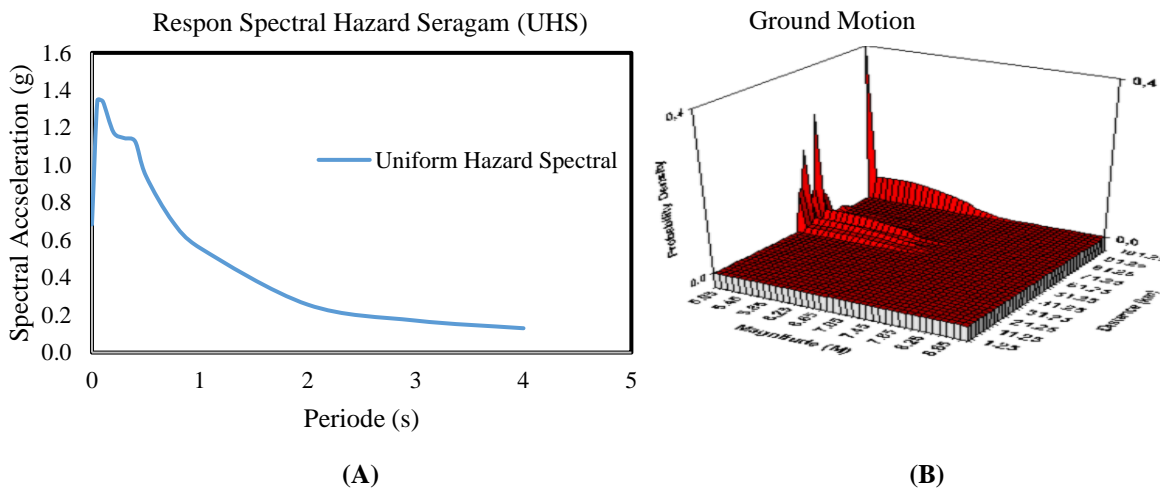


Figure 2. A and B: Target Spectrum Response (UHS) (A) and Hazard Deaggregation Results (B)

The actual time history closest to M and R, which is the dominant result of *Probabilistic Seismic Hazard Analysis*, is the *time historical record*. Since it is used for the analysis of building structures, the actual time history selection consideration must represent the high, medium and low frequency contents, this is as stated by previous researchers.

Spectral Matching

The temporal history data obtained from the Peer Ground Motion Database site, which correlates to the features and causes of the earthquake at the site under evaluation, can be employed in the spectrum matching procedure. Data from the Time history acquired from the Peer Ground Motion Database is shown in Table 2 below.

Earthquake waves are temporal phenomena that induce ground motion during an artificial earthquake and subsequently transmit from the bedrock to the surface. The location for study is the Mamuju Region in West Sulawesi. To propagate

earthquake waves from the bedrock to the surface, data from the soil layer obtained from the drilled logs at the site is necessary, as illustrated in Figure 2.

Table 2. Data Time History

Earthquake Names	Year	Station name	MD (Mw)	RD (Km)	Hypocenter depth (km)
Danau Mammoth-06	1980	Bishop – Paradise Inn	5,94	23,86	14,00

Sumber: <http://ngawest2.berkle.edu/spctras/31964/searches/31964/searches/new>

Table 2 presents the earthquake time history data utilised for the Matching procedure. This data originates from the Mammoth Lakes-06 earthquake in 1980, documented at the Bishop Paradise Lodge station. The earthquake registered a magnitude of 5.95 at a depth of 23.86 kilometres. Figure 3 (Artificial time history) illustrates the documented seismic time history. This study employed SeismoMatch software for the Spectral Matching analysis. The data utilised in the matching procedure comprises historical data employed to align the target with the corresponding scourge response, as illustrated in Figure 3 (Matching) of the SeismoMatch programme results. The outcomes of the SeismoMatch matching are presented in Table 3.

Table 3. SeismoMatch Matching Results

Time(s)	Suitable Acelegram (g)	Original Acelegram (g)
0,000	0,0152	-0,000000
0,005	0,0153	-0,000020
0,015	0,0154	-0,000030
0,020	0,0155	-0,000070
0,025	0,0156	-0,000060
0,030	0,0157	-0,000160
0,035	0,0158	-0,000240
0,040	0,0159	-0,000310
0,045	0,0160	-0,000310
0,050	0,0161	-0,000300
0,055	0,0162	-0,000310
0,060	0,0162	-0,000390
↓	↓	↓
10,985	0,0023	-0,000020
10,990	0,0021	0,000000
10,995	0,0020	0,000000

Figure 3 illustrates the spectral response matching procedure, depicting the original acceleration spectral response of the Mammoth-06 Lake Earthquake (1980). The target spectral response is the scattering spectrum derived from the seismic hazard analysis conducted at the location examined in this study, specifically in Mamuju, West Sulawesi.

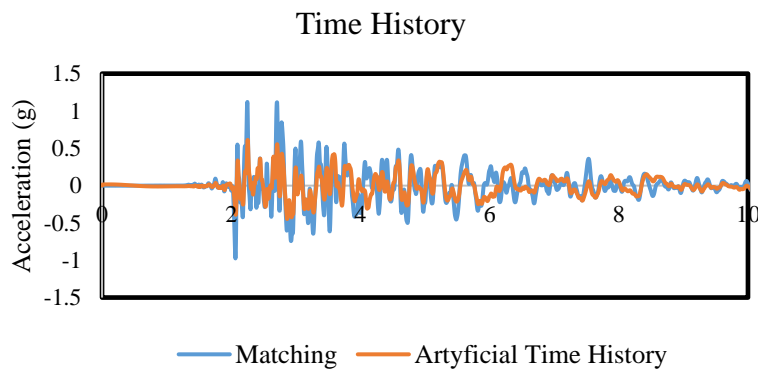


Figure 3. Comparison of time on probability exceeding 2% in 50 years in bedrock

Soil Dynamics Response Analysis

An analysis of soil-dynamics reaction was conducted to ascertain the magnitude of earthquake acceleration experienced at the surface. The analysis conducted involves ascertaining the characteristics of soil dynamics and wave propagation from the bedrock to the surface. The soil characteristics utilised were derived from soil testing findings presented as soil log data at the research site, specifically the Koni Mamuju Building in West Sulawesi. This research is situated at the coordinates 2°40'24.58" S, 118°51'27.59" E. This study does an examination of soil properties by inputting soil dynamics parameters for each stratum. Soil dynamics parameters can be derived from the correlation of borehole data represented as N-SPT through equations developed by geologists. Assessment of soil dynamic response to derive soil dynamic parameters and wave propagation from bedrock to the soil surface. This analysis is conducted through soil testing (SPT) in the field to acquire Ground Motion, Spectral Response, and Shear Stress Ratio. The outcomes of the computation of soil dynamics parameters are derived from Table 4.

Table 4. Results of Calculation of Soil Dynamics Parameters

Layer Number	Depth (m)	Thickness (m)	Unit Weight (Kn/m ³)	NSPT	Fast Propagation of Sliding Waves (m/s)
Lempung	3	2	18	5	153,670
Shores	10	6	19	7	179,479
Pasir	12,8	2	18	9	201,281
Shores	15	2,5	18	14	235,205

Wave propagation will be executed vertically from the bedrock to the earth surface utilising wave propagation theory, facilitated by DEEPSOIL V7 software. The computation of the shear wave velocity (Vs) derived from the N-SPT test in the Mamuju region, correlating Vs with the spectral response per soil layer, illustrates a graph depicting Ground Motion, Spectral Response, and Shear Stress Ratio relative to soil depth, with a 2% probability over 50 years. The average of the outputs from this equation yields the propagation speed of the disposable shear wave (Vs) utilised for the analysis with DEEPSOIL V7 Software in bar 4, as follows.

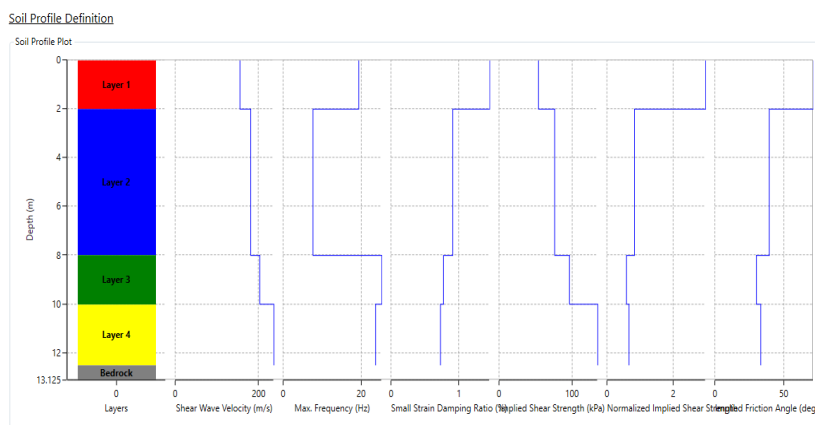


Figure 4. BH 3 Soil Profile

History of Acceleration Time

The propagation of waves from the bedrock to the ground surface is carried out after the analysis process on the history of the bedrock time. In this process, dynamic parameters are fed into each layer of the software. The time history of surface acceleration is multiplied by the bedrock. Based on the results of wave propagation, the peak acceleration value increases at the surface after propagation from the bedrock. This increase is called the amplification factor. This factor can change according to local soil conditions. The output of DEEPSOIL V7 also obtained the response of the acceleration spectrum, speed, and displacement at the ground surface, which can be seen in Figure 5 as follows

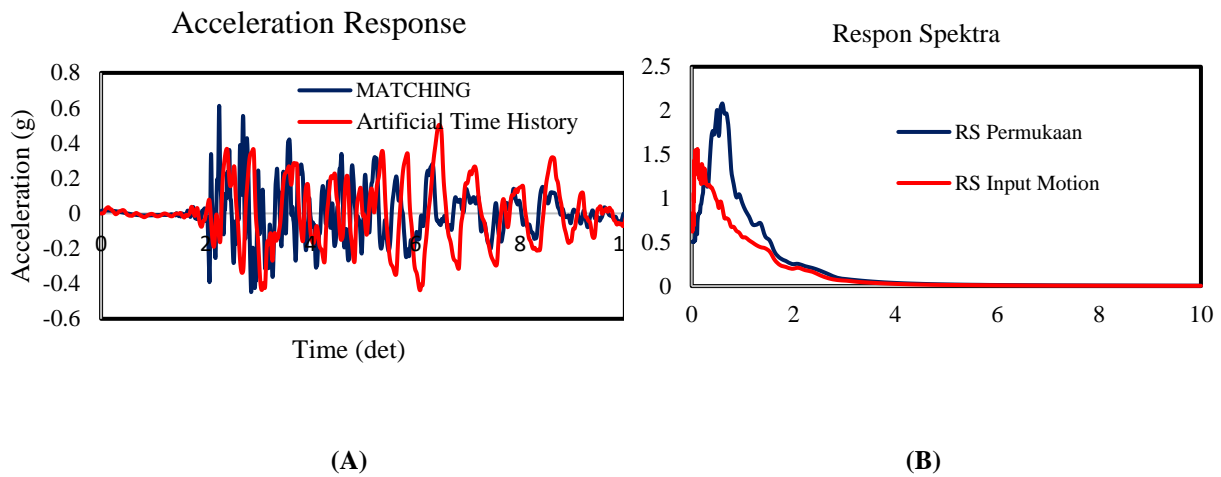


Figure 5. A and B: Results of Analysis of Earthquake Acceleration Response per Soil Layer (A) and Spectral Response in the Mamuju Region (B)

The results of the acceleration analysis due to the influence of soil profile and 78 soil parameters on each layer show that amplification occurs. The amplification that occurred on the original historical time data from the Mammoth earthquake source and the matching results with the earthquake source at Mamuju resulted in a range value of 0.800 g at ground level. Meanwhile, Figure 4 B shows the response of the original spectrum to the response of the spectrum on the surface, which, from the results of the soil dynamics analysis, has increased.

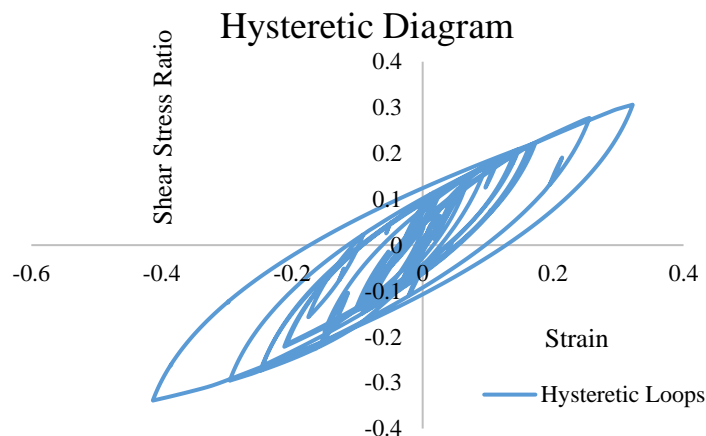


Figure 6. Hysterical Circles in Mamuju District

The Hysterical Loop in Figure 5 above shows a graph of the acceleration relationship with the period in the spectral response per layer and a graph of the relationship between the stress ratio and its regression in the hysterical loop. Hysteretic loop areas show soil damping due to cyclic loads. This means that the wider the damping surface of the soil layer, the larger it will be. The largest shear stress ratio value is 0.3162 at a stretch of 0.33 at a depth of 15.84 meters with an NSPT value of 14 in clay soils. This, of course, will affect the soil environment in terms of liquefaction susceptibility.

CONCLUSION

This study performed a Probabilistic Seismic Hazard Analysis (PSHA) for the Koni Mamuju Building in Mamuju, West Sulawesi. The bedrock PGA at 2% probability of exceedance in 50 years is 1.026 g (MCER) and 0.684 g (design level, $2/3 \times$ MCER), placing the site firmly in a high seismic hazard zone consistent with the PUSGEN 2017 national hazard

map. Surface PGA increased to 0.800 g following DEEPSOIL V7 site response analysis, corresponding to a local amplification factor of ~ 1.17 , driven by the soft clay and loose sand deposits ($V_s < 200$ m/s) in the upper 15 m. The maximum spectral acceleration $S_a(0.2 \text{ s}) = 1.341$ g (bedrock design level) indicates severe short-period demand; surface spectral values are higher, implying that structures with natural periods below 0.5 s face the greatest seismic risk. The highest shear stress ratio of 0.3162 at a shear strain of 0.33% at 15 m depth (N-SPT = 14, sandy layer) indicates liquefaction susceptibility and warrants detailed evaluation per SNI 1726-2019 Annex B.

The findings have direct practical implications for structural design in Mamuju: (1) the design spectrum must account for ground amplification by applying site-class-specific coefficients F_a and F_v per SNI 1726-2019; (2) short-period structures require conservative base shear design; and (3) foundation design must consider liquefaction mitigation strategies for the 15 m sand layer. Overall, the PSHA results confirm that Mamuju requires a conservative, site-specific seismic design approach.

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