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Microzonation Site Effects and Shear Strain during Earthquake Induced Landslide Using HVSR Measurement in Ulu Mana Sub-District, South Bengkulu Regency Indonesia

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Abstract: The Ulu Manna area is classified as an area with high landslide potential because of its location and geological structure, which is hilly. The risk of landslides in the Ulu Manna area due to earthquakes in weak areas can be studied using ground shear strain (GSS). This study aimed to provide information on the potential of landslides in the Ulu Manna area, South Bengkulu Regency Indonesia. The data was collected using the Horizontal-to-Vertical Spectral Ratio (HVSR) method. The study area is 195.8 km^2 and consists of 32 data collection points. The data processing was performed using WinMASW 5.2 HVSR and ArcGIS Desktop 10.8.2 software to obtain dominant frequency values, amplification values, subsurface soil vulnerability index values, maximum soil acceleration values, and soil shear strain values. The soil shear strain values obtained are on the order of 10-4 to 10-3, meaning that the dynamic characteristics of the soil in the study area are elastic-plastic. This plastic-elastic nature characterizes the area as an area with high landslide potential.

Keywords: Ground Shear Strain; HVSR; Local Site Effects; Microzonation; Soil Vulnerability Index.

Introduction

Indonesia is located in the convergence of the three world's major tectonic plates: Indo-Australia, Eurasia, and Pacific Plates. In the Sumatra area, Indo-Australia Plate collides with Eurasia Plate due to the density difference between the oceanic crust (Indo-Australia Plate) and the continental crust (Eurasia Plate) (Bock et al., 2003). The boundary between plates and the rock mass above it is called a subduction zone interface or subduction zone (Natawidjaja, 2007).

Continuous thrust from the Indo-Australia Plate to the Eurasia Plate causes energy accumulation at the bottom of the Eurasia Plate in the convergence of both plates. If the accumulated energy is released, an earthquake will occur in the sea area of Bengkulu. Several great-scale earthquakes that shook the sea area of Bengkulu were on 4 June 2000 (Mw 7.9) (Ambikapathy et al., 2010) and 12 September 2007 (Mw 7.9) (Lubis et al., 2013). Apart from the recent events on 4 June 2000 and 12 September 2007, historical records show that Bengkulu Province has been stricken by earthquakes several times, and significant damage was reported, as shown in Figure 1.

The island of Sumatra is characterized by three tectonic systems, from west to east: the Sumatra Subduction Zone, the Mentawai Fault Zone, and the Sumatran Fault Zone. These three tectonic systems have generated high seismic activity, which impacts ground movement. Consequently, many researchers have

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studied the tectonic system positions for their high earthquake risk.

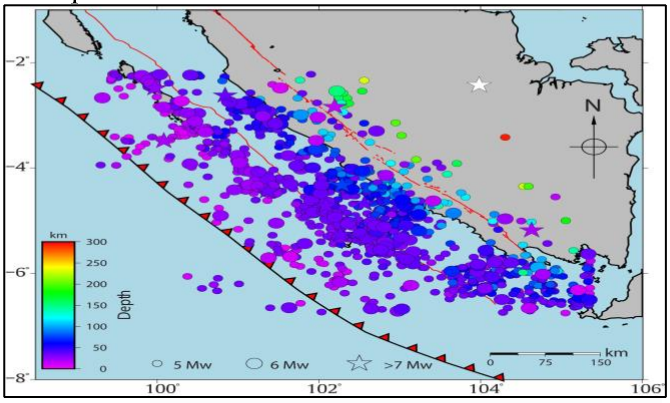

Figure 1. The Historical Seismicity around Bengkulu Province (Mw > 5.0 and 1922–2022)(USGS, 2022).

Some researchers have studied the landslide phenomena around the world (Sassa et al., 1996; Sato and Harp, 2009; Delgado et al., 2011; Chousianitis et al., 2014; Martino et al., 2019). Landslides can occur due to predisposing and stirring factors, e.g., regional geomorphological, gravity, geotechnical, climatic, geological, and seismotectonic conditions (Ogila, 2021).

Landslides are complex phenomena and require various surveying tools (e.g., drilling, inclinometers, INSAR, geophysics, and global positioning systems) to understand their origins, mechanisms, and impacts. Non-destructive classical exploration geophysical methods (e.g., refraction seismic, electrical resistivity tomography) are widely applicated in slope stability studies (Pazzi et al., 2019), to allow relatively precise characterization of the geometry of unstable zones. However, this method is expensive, time-consuming, and challenging to implement, especially in difficult areas. This limitation can be overcome by applying the Horizontal-to-Vertical Spectral Ratio (HVSR) method, which is more straightforward, cheaper, and quicker to implement than the methods above. This technique has previously been used around the world to analyze unsteady regions under an analysis of spectral response (Hellel et al., 2013).

Some research in this field has focused on the main development challenges causing local soil instability in the study area. Microzonation becomes vital for large and developing cities as population agglomeration increases resulting in rapid and unplanned development (Molnar et al., 2020).

This work discussed the phenomenon of local landslides in the Ulu Mana sub-district area based on field observations and HVSR measurement data collected directly in the field in areas affected by landslides and their interpretation.

Method

Data Observation and Location

In the Ulu Manna area, data from 32 points have been collected directly in the field. Locations of data collection points include important public infrastructure such as community settlements, government offices, and schools. The ambient noises were recorded with a three-component seismometer (PASI Gemini-2), which has a very reliable 2 Hz frequency response. The microtremor survey was carried out in the northeastern part of South Bengkulu Regency, namely in the Ulu Manna area, where there were clear signs of landslides. Data collections were mainly carried out in landslides and outside areas affected by landslides.

A field observation was conducted to make the distribution pattern of data points. The distribution was used to characterize different regions based on the spectral sensitivity. Following the SESAME instructions (SESAME, 2004), the data collection time was 30 minutes with a sampling frequency of 200 Hz. We used Win-MASW 5.2 HVSR software to estimate the horizontal-vertical spectral ratio.

HVSR Method

Kanai (1957), introduced the ambient noise method to estimate the seismic response from soft to hard and rocky soils. Later, Nogoshi (1971) proposed the HVSR method, and Nakamura (1989) popularized it worldwide. This method estimates the resonant frequency of the ground by using ambient noise in the environment where the data is collected Using a single sensor or sensor network, the method calculates the spectral ratio of the horizontal and vertical components of the noise recording to determine the shear wave velocity stratification. (Nakamura, 1989).

Numerous site effect and seismic microzonation studies have utilized the HVSR method since it is straightforward and quick to perform. (Layadi et al., 2016; Gosar, 2017). In particular, this method is used widely in many geological research, for instance, mapping of geological stratigraphy (Tebbouche et al., 2017) and sedimentary basin (Issaadi et al., 2021), ground characterization (Panzera et al., 2019), and ground structure interaction (Pazzi et al., 2016).

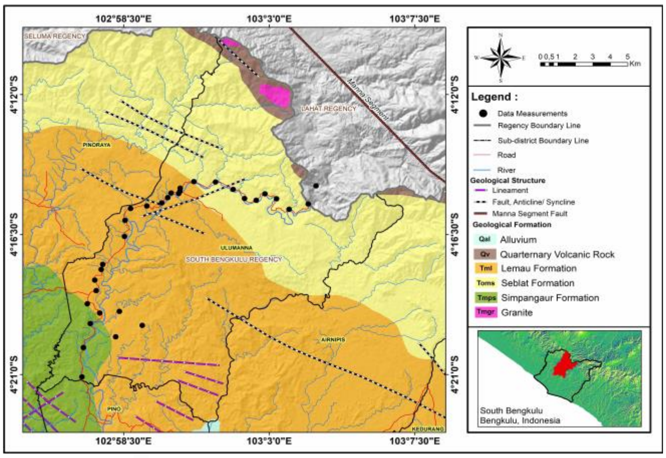

Figure 2. P The geological map of research area and data measurement points

In addition, this method is applied to the definition and characterization of landslides, where different spectral responses are associated with different landslide zones (stable and unstable) (Iannucci et al., 2020). According to Ma et al., (2019), based on the HVSR curve, each landslide zone is characterized by its specific response pattern. Unstable areas are characterized by horizontal polarization, where ground motions can be amplified in the direction marked by the peak maximum. This directivity is influenced by geological and topographical factors that polarize the ground motion in one main direction. However, the results obtained in the current work demonstrate the capability and efficiency of the HVSR method to analyze and identify directivity phenomena in site responses, especially in the presence of unstable slopes.

Seismic Vulnerability Index

Every site has a unique frequency influenced by the underground conditions: thickness, density, and compactness of the subsurface rock layer. With ratio comparison, a dominant parameter can depict a site's degree of vulnerability (K_g). The seismic susceptibility index (K_g) from Nakamura (Asnawi et al., 2020) can be calculated by Equation (1).

$$K_g = \frac{{A_0}^2}{f_0} \tag{1}$$

Where Kg is the seismic vulnerability index, A_0 is the HVSR peak spectral amplification factor, and f_0 is the subsurface natural dominant frequency (Hz). Kg is helpful for determining a site with weak and lousy ground resistance. Kg also can be used to determine earthquake vulnerability levels and damage potential that can be aggravated by macroseismic and ground shaking (Gosar, 2017).

The seismic susceptibility index (K_g) is based on the dynamic properties of soil. Nakamura (1997) said that the value of K_g could be used to estimate ground weakness and earthquake damage before a destructive earthquake occurs. In addition, Nakamura (2000; 2008) stated that the K_g value can be used to calculate the damage/load on buildings and soil during an earthquake. With the K_g value, it is possible to assess the site's susceptibility to strong ground movements selectively. The parameter can be calculated for grounds and structures as it relates to the natural period and the amplification factor.

Ground Shear Strain

The ground shear strain (GSS) parameter represents the soil strain during an earthquake. A higher ground shear strain value reflects a higher probability that a surface sediment layer can stretch. These strains and shears cause deformations such as landslides and liquefaction (Nakamura, 1989).

In contrast, a lower ground shear strain shows that a limited ground layer deformation can occur. If a ground layer acceleration is accelerated, the value of surface shear strain can be estimated hypothetically with seismic susceptibility index (K_g) and peak ground acceleration (α_{max}) (Nakamura, 2000; Nakamura, 2008; Farid and Hadi, 2018). GSS value can be calculated by Equation (2) as follows:

$$\gamma = K_g \times 10^{-6} \times \alpha_{max} \tag{2}$$

Where γ is shear strain, K_g is seismic susceptibility index, and α_{max} is peak ground acceleration. Kanai's attenuation (Douglas, 2021) as written in Equation (3) was used to calculated the peak ground acceleration.

$$\alpha_{max} = \frac{1}{\sqrt{T_g}} \times 10^{0.61M - \left(1.66 + \frac{3.6}{R}\log R\right) + \left(0.67\frac{1.83}{R}\right)} \tag{3}$$

Where T_g is ground shaking period, M is an earthquake magnitude moment, and R is an earthquake hypocenter distance. Based on equation (3), effective strain was estimated from the multiplication of K_g and α_{max} at the bedrock level. The result is the index to indicate deformation vulnerability in the data measurement area. Ground shear strain can trigger a deformation in soil later closed to the surface: landslide deformation.

Figure 3.a shows the signal from the three-component microtremor recording data, and Figure 3.b shows the H/V curve, which contains the fundamental frequency values and amplification from the selected location.

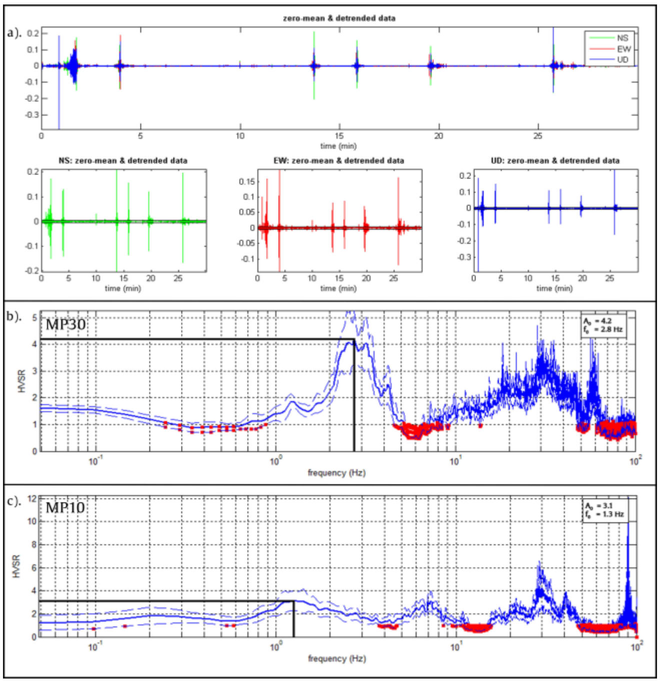

Figure 3. a). The example of microtremor signal record obtained in the field which is a combination of three component: NS, EW, and UD. In addition, the example of analyzed microtremor data (b) The MP 30 measurement points, and (c) The MP10 measurement points.

Table 1. The variation of soil characters and the value of seismic ground shear strain (Ishihara, 1982).

Ground Shear strain	10^{-6} 10^{-5}	10^{-4} 10^{-3}	10^{-2} 10^{-1}
Soil Conditions Phenomenon	Wave propagation, vibration	Crack, settlement	Landslide, compacting soil, liquefaction
Nature of soil dynamics	Elasticity	Elasto-plasticity	Collapse

Result and Discussion

Microtremor measurements were processed using WinMASW 5.2 HVSR software. The microtremor data processing results were mapped using the default inverse distance weight (IDW) interpolation technique from spatial data analysis in ArcGIS Desktop 10.8.2.

Figure 4. shows the microzonation map of Ulu Manna A_0. In general, the amplification value (A_0) 1.0 – 4.0 dominates in the Ulu Manna District, especially in the Simpangaur, Lemau, and Seblat formations. Some areas with higher amplification values are found in the Lemau and Seblat formations. These areas tend to have low soil density. According to Gosar (2017) a high amplification value indicates a greater impedance contrast between sediment and subsurface bedrock in the study area. The microzonation of f_0 based on the geophysical survey is depicted in Figure 5. It can be observed that the dominant frequency (f_0) of the investigated sites generally ranges from 1.1 to more than 19.6 Hz. The relatively larger dominant frequency indicates a thin sediment thickness (Gosar, 2017).

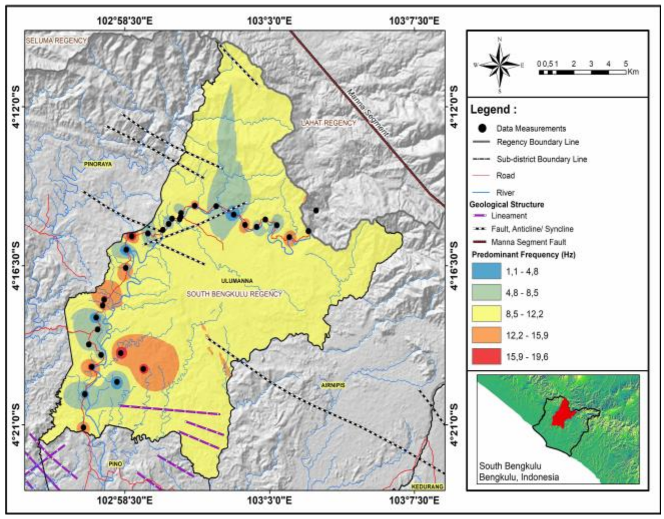

Figure 4. The Microzonation map of Ulu Manna Fundamental Resonance Frequency (f_0).

Parameters A_0 and f_0 are further analyzed to produce a seismic hazard map (K_g). The ease at which the surface soil structure resists deformation during an earthquake is described by the Seismic Susceptibility index (Kg). The susceptibility index value in the Ulu Manna area ranges from 0.4 to 11.7. Overall, most Ulu Manna areas have low seismic susceptibility index values (Figure 6). The smaller the seismic susceptibility index value of an area, the smaller the region's vulnerability to earthquake hazards.

In this study, we used Kanai method to calculate the peak ground acceleration. Based on the equation, the dominant period of the ground (T_g), the intensity of the earthquake (M), and the distance from the point of measurement to the hypocenter of the earthquake (R) are factors which influence the maximum ground acceleration value. The greater the magnitude of the earthquake, the greater the value of the maximum acceleration. Based on the 100-year earthquake source from the USGS in the study area, the Ulu Manna area has a maximum ground acceleration value of 0.18 to 0.77 g (Figure 7).

The soil shear strain can be estimated from the value of the seismic susceptibility index and maximum ground acceleration. The seismic susceptibility index value, the maximum ground acceleration value, and the velocity of seismic waves on rocks (Cb) affect the GSS value. The higher the GSS, the greater the risk that the ground structure or rock in the area will experience deformation, which can be in the form of a change in the texture of the rock or ground stucture to become plastic, liquefaction, or landslides during an earthquake.

The GSS microzonation map is shown in Figure 8. Two range classifications represent the γ ranges 10-3 and 10-4. This area is related to the land degradation phenomena listed in Table 1 (Ishihara, 1982). It can be seen that the western part of Bengkulu can feel the potential danger of wave vibrations during the Bengkulu-Enggano earthquake. It is possible that several areas in the central part of Bengkulu experienced cracks and subsidence during the Bengkulu-Enggano earthquake.

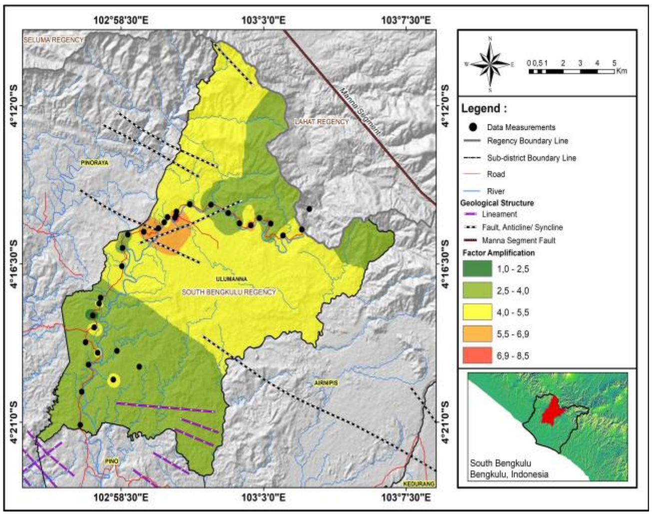

Figure 5. The Microzonation map of Ulu Manna Factor Amplification (A_0).

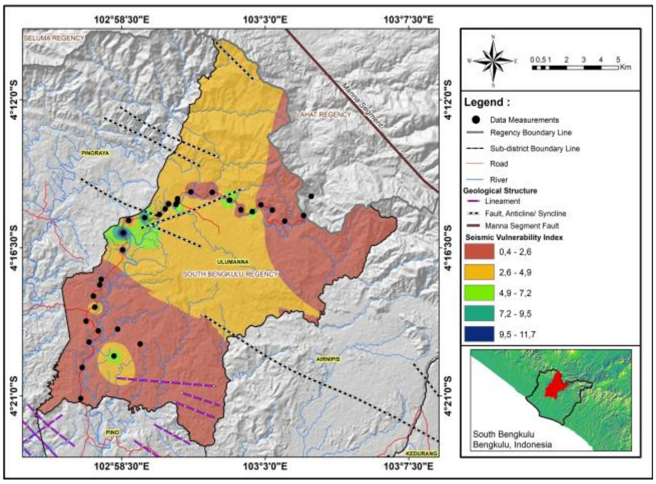

Figure 6. The Microzonation map of Ulu Manna seismic vulnerability index (K_g).

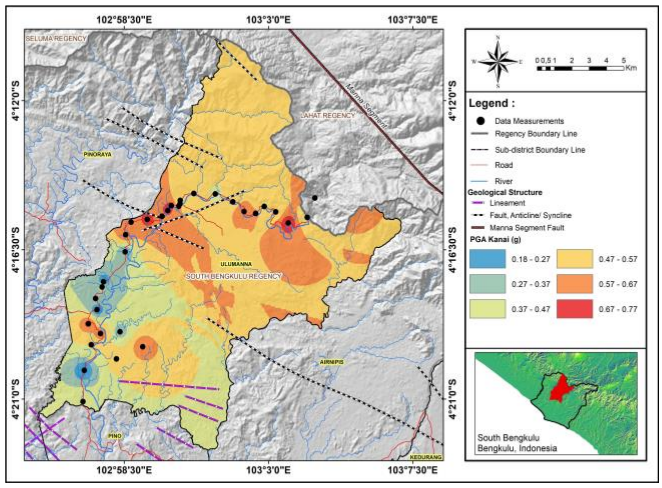

Figure 7. Microzonation map of Ulu Manna PGA Kanai map.

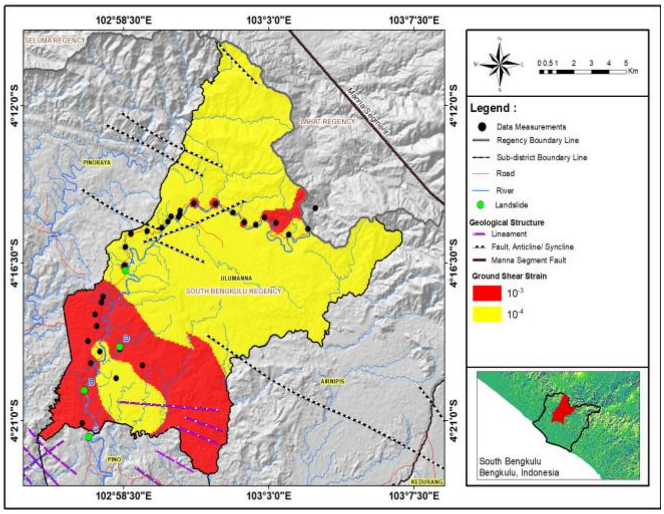

Figure 8. Microzonation map of Ulu Manna Ground Shear Strain (γ) map.

When the GSS value reaches ≅ 10^{-3}, the soil shows nonlinear or plastic properties, while GSS > 10^{-2} the soil shows significant deformation changes. Subsidence, liquefaction, and landslides are examples of deformation changes. According to the study's findings, elastic-plastic structures can be found in places with high ground shear strain values. The region is characterized as being prone to landslides by this elastic-plastic nature.

This study presents four microzonation maps: the A_0 microzonation map, the f_0 microzonation map, the K_g microzonation map, the PGA Kanai microzonation map, and the GSS microzonation map. These results are related to the geological conditions of the study area and previous studies. In general, the results of this study can provide recommendations for earthquake disaster mitigation in Ulu Manna District. In addition, the results can be used as information for the local community about the earthquake hazard zone

Microzonation interpretation based on the Ulu Manna geophysical survey shows that areas prone to seismic damage (landslides) tend to be concentrated in socio-economic centers such as the Bengkulu-South Sumatra provincial highway. Moreover, the result shows that people prefer to live in strategic areas rather than relatively empty areas, even though the empty areas are relatively safe from disasters, such as along the Bengkulu-South Sumatra Province highway. However, the community needs to learn complete information about the impact of natural disasters. Therefore, the regional government must gradually educate the people who live in these vulnerable areas. The results of this study can be a first step in disaster preparedness in South Bengkulu Regency, especially Ulu Manna District.

Table 2. The landslide potential area based on the value of Ground Shear Strain.

GSS value	Area (km²)	Percentage (%)	Potential
10^{-4}	143.19	73.43	Modarate
10^{-3}	51.81	26.57	High

Figure 9. The Landslides in Ulu Manna. The picture is taken in field observation on July, 3rd-9th 2022.

Conclusion

This paper presents the implementation of earthquake hazard mitigation based on indicators of ground shear strain to see the potential for landslides in Ulu Manna District. Thirty-two sites in the Ulu Manna District were studied. The geophysical characteristics, such as amplification (A_0), dominant frequency (f_0), and seismic susceptibility index (K_g) are presented. The ground shear strain (γ) was also analyzed to measure the possibility of seismic impact when a strong earthquake occurs in Ulu Manna District.

Understanding the value of site effects in all areas surveyed through the dominant frequency and amplification factor can reflect the nature and characteristics of soil deposits near the surface. Therefore, in addition to the seismic susceptibility index and ground shear strain, these parameters are essential for reducing the risk of earthquakes in the Ulu Manna sub-district.

The ground shear strain (GSS) measurements can be used to produce a potential landslide map. The measurements can also estimate rock slide potentials, beach erosion potentials, and sediment thickness. According to these results, the potential for landslides is very high for microtremor measurements with a GSS value greater than 10^{-3}. We discover that the value of the susceptibility index (K_g) grows proportionally with the expected GSS (γ). Therefore, GSS approximate analysis indicates that all sites are susceptible to high shear strain. These results can help to increase the input parameters of the Indonesian building code, especially for the Ulu Manna District, Bengkulu Province.

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