Songklanakarin J. Sci. Technol.
47 (3), 207–213, May – Jun. 2025

http://www.sjst.psu.ac.th

Original Article

Micro-zonation of landslide potential based on seismic wave velocities on Bengkulu-Kepahiang alternative road, central Bengkulu, Bengkulu province, Indonesia

Arif Ismul Hadi[1*], Refrizon[1], Budi Harlianto[1], Suharsono[2], and Darmawan Ikhlas Fadli[1]

[1] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, University of Bengkulu, Bengkulu, 38371 Indonesia*

[2] *Department of Geophysics Engineering, Faculty of Mineral Technology, Universitas Pembangunan Nasional Veteran, Condongcatur, Yogyakarta, 55283 Indonesia*

Received: 5 March 2024; Revised: 20 February 2025; Accepted: 21 April 2025

Abstract

Rural roads in Central Bengkulu, Bengkulu Province, Indonesia, are on a sloping morphology with moderate to steep slopes and are adjacent to an earthquake source. This investigation aimed to identify and map the vulnerability to landslides in the Bengkulu-Kepahiang alternative road area, in Central Bengkulu, based on the the velocities of compression wave (*Vp*) and shear wave (*Vs*), and Poisson’s ratio, by microzonation. Multichannel Analysis of Surface Wave (MASW) method was used for field data in this study. The seismic equipment tool used in this study has a set of 24 geophone channels. To obtain a 1-dimensional model, field data were analyzed using Win-MASW 5.0 Professional. Areas with high landslide potential are areas that have low *Vp* and *Vs*, but a high Poisson's ratio. Conversely, areas with low landslide potential are those that have high *Vp* and *Vs*, but a low Poisson's ratio. These low-potential areas are related to high rock density and compactness. In this study, it was found that areas with high landslide potential that need to be watched out for are at the locations labeled 1, 3, 11, 12, and 14. It is very significant to know the locations that have a high risk potential, so that the community will be more alert and the local government can anticipate landslides in these locations.

Keywords: alternative roads, Bengkulu-Kepahiang, landslide, MASW, seismic wave

1. Introduction

The subduction zone between the tectonic plates of Indo-Australia and Eurasia is very close to Central Bengkulu regency, Bengkulu province, Indonesia (Petersen *et al.*, 2004). This area is also near the Sumatran Great Fault movement. In addition, around this area, the movement of tectonic plates has the highest cumulative energy and strain rate in the Sumatra Island region. These conditions trigger the occurrence of faults and cause a high seismicity in the Central Bengkulu area and its surroundings (Murjaya, 2011).

Central Bengkulu is an area that has an undulating and hilly topography with a gentle to steep slope. Central Bengkulu also has high rainfall throughout the year, namely above 2,500 mm/year (Badan Meteorologi, Klimatologi, dan Geofisika, 2020). Areas with rainfall above 2,500 mm/year have a great potential to experience landslides, especially on steep slopes (Kirmanto, 2007; Zuidam, 1983). The combination of a subduction zone, the great Sumatran fault, high rainfall, undulating, and hilly topography, makes this area landslide-prone. Earthquakes and high rainfall are triggers for landslides (Hadi *et al*, 2021a; Nepop & Agatova, 2008; Zhang, Zhang & Glade, 2014).

One area that has an undulating and hilly topography with steep slopes is the Bengkulu-Kepahiang alternative road. This alternative road is used by the surrounding community for access to Bengkulu and Kepahiang city and to other cities in the neighboring

*Corresponding author
Email address: ismulhadi@unib.ac.id

provinces. The results of the study using rock physical parameters in the form of ground shear strain (GSS), slope, slope height, Vs_{30}, fault distance to the measurement point, rock conditions, rainfall, and peak ground acceleration (PGA) indicate that this area has moderate to high landslide potential (Hadi *et al.*, 2021a) (Figure 1). However, this prior study has not examined in detail at which points the potential is highest for landslides to occur. For this reason, this study examines the potential for landslides by micro-zonation using different parameters, namely the compression wave (*Vp*) and shear wave (*Vs*) velocities, and Poisson's ratio, as geophysical parameters. The use of geophysical parameters is more effective than geotechnical parameters (Sujitapan, Kendall, Chambers & Yordkayhun, 2023). In addition, geophysical measurements of *Vp* and *Vs* have a good resolution, namely below 0.5 m/s (Whiteley *et al.*, 2021).

The mechanism of landslide movement can take place through the sliding of rock mass blocks with the orientation of the fracture plane and the rock layer plane, as well as by differences in the level of weathering of rocks that have a slope gradient > 40° (Karnawati, 2007). Gafoer, Amin and Pardede (2012) created a regional geological map including the faults in the study area, which shows that the Bengkulu-Kepahiang alternative road, Central Bengkulu regency, is an area traversed by faults.

Meanwhile, based on the peak ground acceleration (PGA) map using the Probabilistic Seismic Hazard Analysis (PSHA) approach, it is stated that in Central Bengkulu Regency, the PGA is in the fairly high category, namely between 0.40 g and 0.55 g (Hadi & Brotopuspito, 2015; Petersen *et al.*, 2004). Furthermore Hadi, Brotopuspito, Pramumijoyo, and Hardiyatmo, (2021b), conducted a landslide study using the catastrophe theory that is associated with slope stability via the factor of safety (FS). At greater FS values, the slope is stable. Changes in state from stable to unstable indicate a catastrophic phenomenon at the study site.

Investigations of potential ground motion using GSS parameters have been carried out by several researchers, for example by Farid (2014) and Hadi & Brotopuspito (2016). The results of their studies stated that the ground motion occurs due to a large GSS in that place. In general, this high GSS is related to the lithology of the material that is not solid, so that the material is easily moved. Ground motion research can also be linked to landslides based on geophysical parameters in the form of *Vp*, *Vs*, and Poisson's ratio (Akpan, Ilori & Essie, 2015; Uhlemann *et al.*, 2016). Low *Vp* and *Vs* with a high Poisson's ratio are related to a weathered layer that is not compact, and therefore are associated with landslides caused by lithology of sand, while the lithology of very dense clay is interpreted as a slip plane (Capizzi & Martorana, 2014; Mahandani, 2017; Uhlemann *et al.*, 2016).

In general, the studies described above are still widely assessed and there are several studies that have been assessed locally but that have not been mapped by micro-zonation, so this current research has a high urgency because it is performs the mapping of potential for landslides in microzonation, using *Vp*, *Vs*, and Poisson's ratio. The results of this current study also provide some important information as a basis for detailed study materials. This investigation aims to identify and map the vulnerability to landslides in the Bengkulu-Kepahiang alternative road area based on the velocity of seismic waves by microzonation.

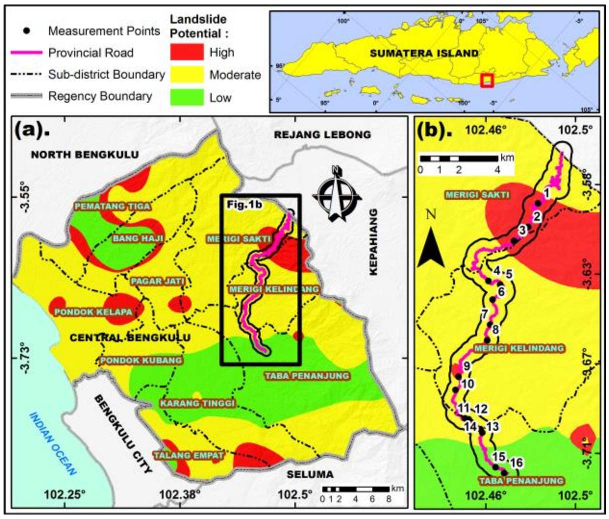

Figure 1. (a) The landslide potential map created from GSS, slope, slope height, Vs_{30}, fault proximity to measuring points, soil condition, PGA, and rainfall (Hadi *et al.*, 2021a), and (b) overlaps with MASW measurement points.

2. Materials and Methods

The study locations are spread over several different rock units, including the Andesite-Basalt Volcano (Qv), Bal Formation (Tmba), Simpangaur Formation (Tmps), and Hulu Simpang Formation (Tomh) (Gafoer, Amin & Pardede, 2012; Gafoer, Amin & Pardede, 2007). Different rock units have different lithologies as well. This can influence rock conditions as regards their density and the propagation of seismic waves passing through (Figure 2).

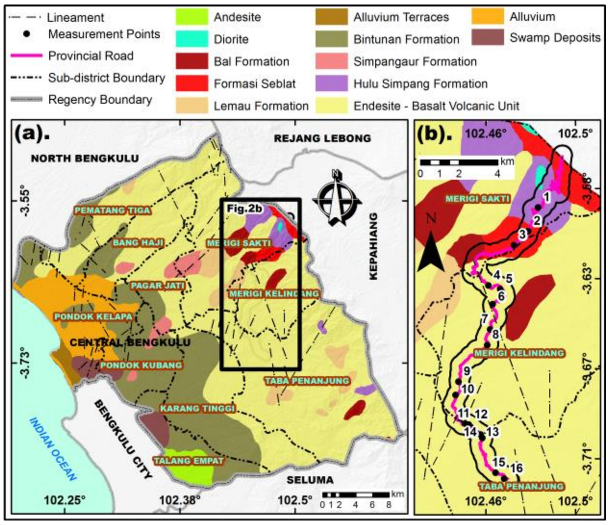

Figure 2. (a) The map of geological setting in Central Bengkulu regency (Gafoer *et al.*, 2007), and (b) overlaps with MASW measurement points.

The Multichannel Analysis of Surface Wave (MASW) technique was used to acquire the data. A 16S24-P digital seismograph equipment with 24 geophone channels is utilized for this purpose. The sampling interval is 1.25 ms and the recording time is 512 ms, both of which are calibrated to field circumstances by adjusting the spacing of geophones and the offset. In this study, the distance between geophones was 2 m and the offset was 4 m for all research locations (Figure 3). Data acquisition is carried out by utilizing Rayleigh waves originating from an artificial source in the form of a hammer connected to a trigger cable. Through the relation between Rayleigh waves and shear waves, we can get the output in the form of *Vs* profile for each sediment layer thickness including the rock density. The relationship between Rayleigh waves (V_R) and shear waves (*Vs*) is expressed by (Milsom & Eriksen, 2011).

$$V_R = (0.91 \text{ to } 0.955)V_S. \quad (1)$$

The Rayleigh wave velocity is always less than the shear wave velocity.

In MASW method, only one artificial source is used, which is placed outside the stretch adjacent to the first geophone. In field measurements, a set of seismic data records that record the time and amplitude of the wave energy against the geophone distance is then obtained from a single field configuration. Furthermore, in one measurement trajectory, seismic data is recorded. Seismic data recordings are then processed and analyzed to obtain a *Vs* profile and density by depth (Ariestianty, Taha, Nayan & Chik, 2009).

Seismic data were processed utilizing Win-MASW 5.0 Professional (PASI, 2021). In this software, the best value is obtained from matching the dispersion curve of the field data with the model data until the lowest misfit is obtained. These data are still in the Society Exploration Geophysics (SEG-2) format, so the processed seismic data must first be converted into the Sesame ASCII Format. Distance between geophones, source offset, track length, and other field factors are not included in the raw data from the field. That is why it is important to establish the field's geometry initially. The next process is to minimize noise by filtering using frequencies between 0 - 50 Hz, so that the dispersion curve is quite clear. The resulting dispersion curve can be in the form of fundamental mode (M_0) or a higher mode. The selection of different modes aims to describe the true heterogeneity of the earth. Waves that are converted in the form of a phase velocity spectrum are used to describe the distribution of energy based on frequency and velocity.

From the phase velocity spectrum, Rayleigh wave dispersion is produced to form a dispersion curve. The inversion procedure continues with the development of a preliminary model following the formation of the dispersion curve. The inversion procedure requires taking the model's parameters into consideration, such as the number of layers and the depth. To get the smallest possible margin of error, an inversion procedure is used. If a small error has not been obtained, then the initial model parameters are changed and the inversion process is repeated. The inversion process uses a genetic algorithm, namely by matching the curve between the dispersion curve from the field data and the dispersion curve of the initial model that has been determined. The initial model determined in the iteration process is the expected depths and the number of layers. This iteration process will stop after several consecutive generations where the highest fitness value does not change or stops after *n* generations where no higher fitness value is obtained (misfit evolution).

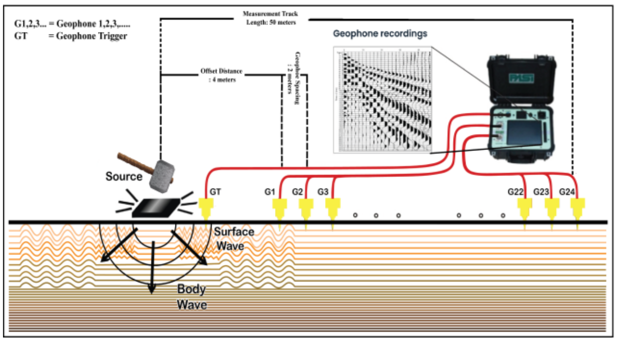

Figure 3. The data acquisition process using the MASW method by digital seismograph with 24 geophone channels (Rusydy *et al.*, 2016).

This is indicated by the overlap between the theoretical dispersion curve and the observed dispersion curve, which is indicated by a small best misfit or root mean square error (RMSE) (Hadi *et al.*, 2024). The RMSE can be determined as follows (EPM, 2024):

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}, \quad (2)$$

Where $\hat{y}_i$ are the model outputs, y_i are the field data, and *n* is the number of observations. The final model obtained reveals the *Vs* profile, sediment layer thickness, and rock density to a certain depth whose position is in the middle of the stretch of track. In addition, from the MASW method, the *Vp* and Poisson's ratio are also obtained.

Data interpretation is carried out on subsurface structures associated with the values of *Vs*, density, *Vp*, Poisson's ratio, and the thickness of each layer. Lithology can be known based on the wave propagation of *Vs*, density, *Vp*, and Poisson's ratio through the rock (Schon, 2015). Values of *Vs*, *Vp*, and high density with a low Poisson's ratio indicate that the rock layer has a low level of deformation or the rock is compact. Based on this, the potential for landslides at each study location is microzoned.

3. Results and Discussion

This study was conducted on the Bengkulu-Kepahiang alternative road, Central Bengkulu, at 16 measurement locations (Figure 2). *Vs* profile is the result of applying the MASW method to different sediment layer thicknesses and rock densities. In the inversion process, the model parameters for the number of layers are entered for as many as four layers. The variety of layers was determined based on the findings of landslide investigations (Hadi, 2019). Based on the results of this study, the use of four layers in the inversion approach produces the smallest RMSE and misfit values. This shows that the estimates obtained in the inversion process match the data well compared to the use of some other choice of model parameters. An example of the results from the inversion process is shown in Figure 4.

The final model in the form of *Vs*, *Vp*, density, and thickness profiles is shown in Figure 5. In Figure 5, the seismic wave velocities (*Vs* and *Vp*) and density have different values at each layer thickness. This depends on the rock

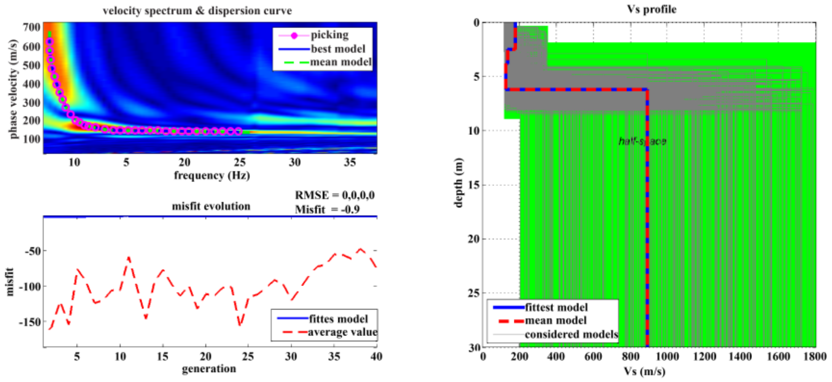

Figure 4. The results of MASW data processing at location 11

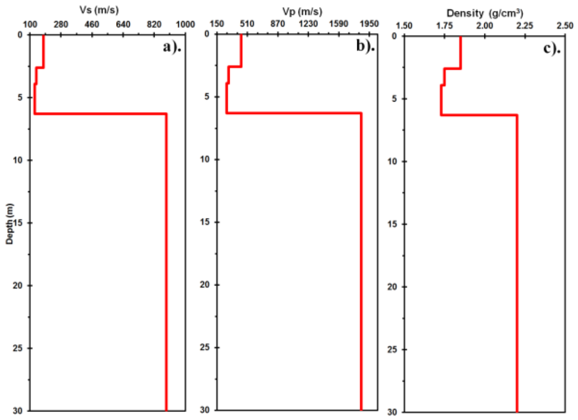

Figure 5. At location 11, (a) the 1-D profiles of *Vs*, (b) *Vp*, and (c) density

density level. At a certain depth, there is a decrease in parameter values due to the rock density level decreasing and will increase again in denser rock types. The decrease in Vs and Vp is thought to be the boundary between the weathered layer and bedrock.

Vs and *Vp* with densities are estimated for four layers. *Vs* ranges from 96 to 1680 m/s, *Vp* from 225 to 3497 m/s, and density from 1.69 to 2.36 g/cm^3. The average *Vs* in the first layer is 241.63 m/s; in the second layer 238.50 m/s; in the third layer 282 m/s; and in the fourth layer 841.56 m/s. *Vp* averages 591.81 m/s in the first layer, 496.5 m/s in the second, 586.88 m/s in the third, and 1751.9 m/s in the fourth. While the average density (ρ) in the first layer is 1.91 g/cm^3, in the second layer it is 1.87 g/cm^3, in the third layer 1.90 g/cm^3, and in the fourth layer 2.17 g/cm^3. At several measurement locations, it appears that there is a decrease in seismic wave velocity in the layer below. This phenomenon indicates the presence of softer soil between denser soil layers (Capizzi & Martorana, 2014; Foti, Lancellota, Sambuelli & Socco, 2000).

The estimates obtained from field data are then classified for analysis of the potential for landslides. The classification of *Vs* values refers to the Indonesian National Standard/ SNI 1726:2019 (Badan Standardisasi Nasional, 2019). According to Badan Standardisasi Nasional [BSN] (2019), the value of *Vs* < 175 m/s is soil, 175 m/s < *Vs* ≤ 350 m/s is stiff soil, 350 < *Vs* ≤ 750 m/s is very dense soil and soft rock, 750 m/s < *Vs* ≤ 1500 m/s is rock, and *Vs* > 1500 m/s is hard rock. The distribution of *Vs* values at each measurement location is shown in Figure 6.

Figure 6 shows that the study locations along the Bengkulu-Kepahiang alternative road are dominated by stiff soil. The stiff soil dominates in the first layer/surface to the third layer. The types of soil on the surface are at location 11, location 12, location 7, location 3, and location 1, while others are stiff soil except at location 6 and location 11 which are very dense soil and soft rock. Very dense soil and soft rock then began to be found again in the third layer, especially at location 15, location 8, and location 2. The fourth layer is assumed to be bedrock consisting of very dense soil and soft rock, rock, and hard rock.

Regarding the *Vp*, it is classified based on the level of weathering of a rock and the lithology that affects the occurrence of landslides (Capizzi & Martorana., 2014). The results of related studies state that the more weathered a rock, the smaller the *Vp* and vice versa. Lithology with a coarse grain size and a large porosity gives a low compression wave velocity. Figure 7 shows the *Vp* distribution.

Based on Figure 7, at the study location the soil surface to third layer is dominated by weathered layers and sub-consolidated clay. The weathered stratum has a *Vp* of 300 as well as 900 m/s (Burger, 1992), while the sub-consolidated clay layer has a *Vp* of 500 as well as 1,000 m/s (Mahandani, 2017). According to Sujitapan, Kendall, Chambers and Yordkayhun, (2024), *Vp* < 600 m/s indicates a very dry and poorly consolidated sediment layer with minimal signs of silty clay that can be associated with weathered layers. A highly weathered layer at the soil surface and a second layer were found at location 3 and location 14. This highly weathered layer belongs to the unsaturated sand lithology (Burger, 1992), while the sub-consolidated clay layer consists of sand and clay (Mahandani, 2017). It has been hypothesized (Hadi, Brotopuspito, Pramumijoyo & Hardiyatmo, 2021b; Tokimatsu, Tamura and Kojima, 1992) that water penetrating the gap between sand and clay generates a slip plane that can impair the bonding between rocks, increase the driving force, and decrease the holding force. Rock pores filled with water will also induce a low *Vp*. Regarding bedrock found in the fourth layer, the lithology consists of very dense clay. Very dense clays and denser materials have *Vp* above 1,000 m/s (Schon, 2015).

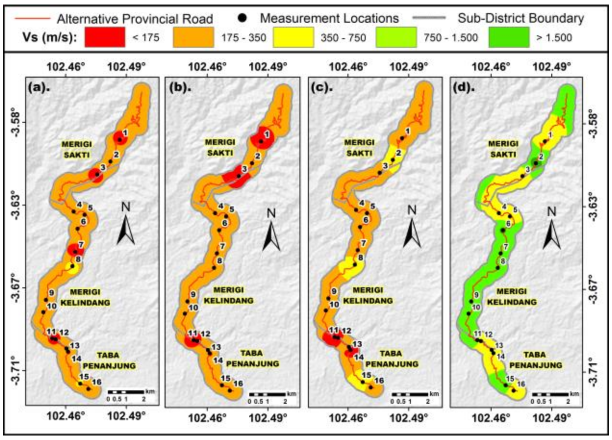

Figure 6. Distribution of *Vs*, (a) the first layer, (b) second layer, (c) third layer, and (d) fourth layer

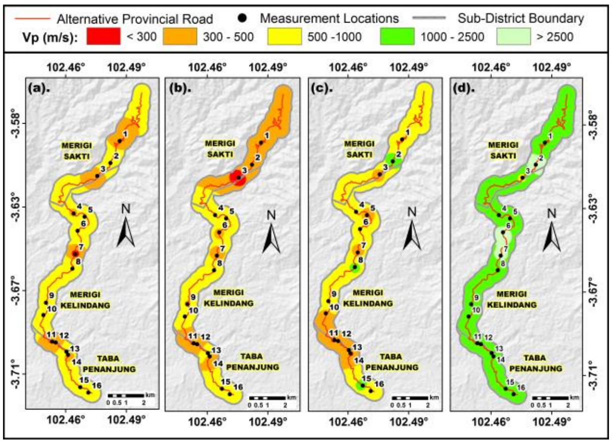

Figure 7. Distribution of *Vp*, (a) the first layer, (b) second layer, (c) third layer, and (d) fourth layer

In addition to the *Vs* and *Vp*, the identification of potential landslides can be strengthened by the rock density. The quicker the *Vs* and *Vp* travel inside a rock, the denser it needs to get. In the landslide area, a small density is related to the weathered layer that is not compact (Tokimatsu, Tamura, & Kojima, 1992). In weathered rock that is not compact, also *Vs* and *Vp* speeds are low. The distribution of density in the Bengkulu-Kepahiang alternative road is shown in Figure 8.

In Figure 8, low (< 1.86 g/cm^3) and moderate (1.86 – 1.96 g/cm^3) densities dominate from the surface to the third layer, except for some locations, for example location 6, location 11, and location 15. At these locations the density at the soil surface to the third layer density is quite large, namely between 1.96 to 2.08 g/cm^3. The low-densities obtained at the study site are associated with weathered layers whose lithology is loose sand. For moderate density, it is associated with stiff soil layer consisting of sandstone lithology. Densities within 1.96 - 2.08 g/cm^3 are for very hard soils with clay lithology, while densities of 2.08 - 2.30 g/cm^3 are for rocks with shale lithology (Schon., 2015). The fourth layer is very hard soil which is interpreted as bedrock layer. The density in the bedrock layer indicates lithology in the form of clay and shale. According to Akpan, Ilori and Essie (2015), the slip plane in the landslide area is a layer of clay and shale.

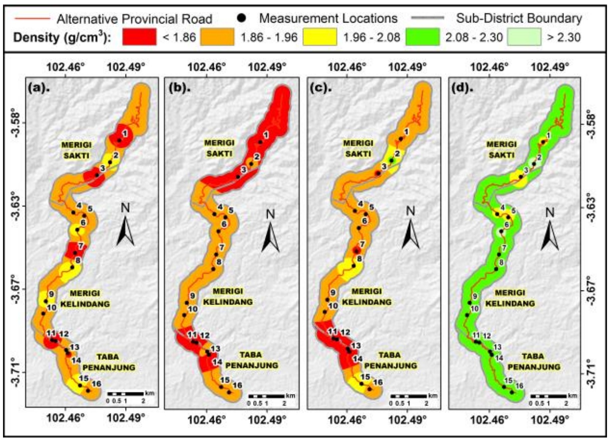

Figure 8. Distribution of density, (a) the first layer, (b) second layer, (c) third layer, and (d) fourth layer

The Poisson's ratios obtained in the field are in 0.35 – 0.4 (Figure 9). In geo-mechanical work, Poisson's ratio values range from 0.2 to 0.4. A value of 0.5 is usually used for saturated soils and 0 is often used for dry soils and other soils (Bowles, 1984). Poisson's ratio is a measure of the compressibility of a material. When a force is applied to a material, the material will deform in the direction of the applied force or in a direction perpendicular to the force. The greater the Poisson's ratio, the easier the material will be to deform and vice versa (Hadi *et al.*, 2024). The results of the study by Nakamura *et al.* (2014) on landslides caused by the 2011 Tohoku earthquake in Kuragasaki District, Sakura City, Japan, showed that the Poisson's ratio in the surface soil that is a weathered layer was around 0.40, and in the layer below consisting of sand and gravel it was around 0.30. Poisson's ratio of 0.4 can also be classified as saturated clay or sand material (Uhlemann *et al.*, 2016). In weathered layers with a larger Poisson's ratio, the soil is easily deformed when exposed to external forces. This study shows that the underlying layer with a lower Poisson's ratio (0.35) is rock as the slip plane. The slip field depth is calculated from the measured values of *Vs*, *Vp*, density, and Poisson's ratio at each measurement site. The values of *Vs*, *Vp*, Poisson's ratio, and density in the slip plane indicate very hard soils, rocks, and hard rocks. The depth of the slip field at each measurement location is shown in Figure 10.

Areas with high landslide potential are shown in Figure 10 at locations 1, 3, 11, 12, and 13. Locations 4, 5, 6, 7, 9, 10, 14, and 15 all have moderate potential, while locations 8 and 16 both have low potential. Location 2 has the lowest level of potential. The results of this study are almost in agreement with the results of studies conducted by Hadi *et al.* (2021a) who used microtremor data and the Analytical Hierarchy Process (AHP) method. The results of the study indicate that areas with high and moderate potential are located on the mapped area. In areas with high and moderate landslide potential, the presence of deeper bedrock layers needs to be watched out for because it has a higher risk of landslides. A deep bedrock layer shows a thicker weathered layer and will be more dangerous if it is in a location that has a steep slope. Slopes above 40° will have a high potential to cause landslides (Hadi *et al.*, 2021a; Karnawati, 2007; Hadi, Brotopuspito, Pramumijoyo, & Hardiyatmo, 2018). This will

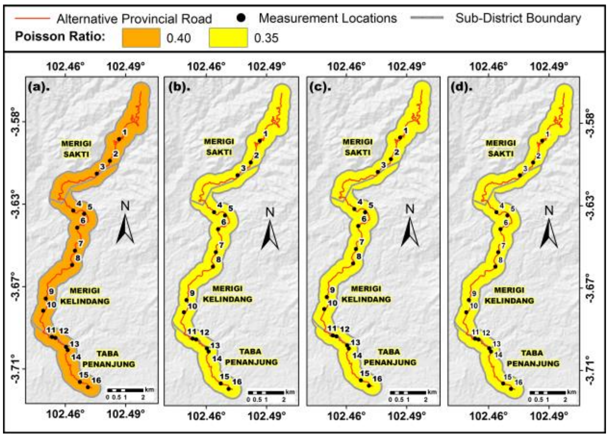

Figure 9. Distribution of Poisson's ratio, (a) the first layer, (b) second layer, (c) third layer, and (d) fourth layer

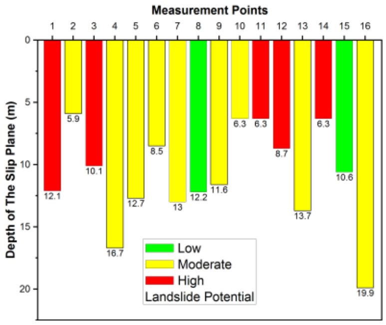

Figure 10. The slip plane depth at each MASW measurement point

be at higher risk if it is triggered by earthquake shaking, both from subduction earthquakes and Sumatran Great Fault movements, which are located close the study area. This study region receives a lot of rain, 2,500 – 3,300 mm/year to be exact, and is an area that has potential for landslides.

The geophysical approach in this study can identify landslide potential and the depth of the slip plane well. However, in this study, the slope stability parameters could not be obtained based on the slope safety factor. To obtain the slope safety factor, this research needs to be combined with other methods, for example geotechnical research to measure the angle of internal friction, soil cohesion, and others. The combination of other geophysical methods, namely the seismic refraction and resistivity methods, is also very important to study in more depth, so that the parameters obtained strengthen each other. (Sujitapan, Kendall, Chambers, & Yordkayhun, 2023, 2024; Uhlemann *et al.*, 2016; Whiteley *et al.*, 2021).

4. Conclusions

Areas with high landslide potential need to be watched out for especially. In this study, five areas with high landslide potential were found, namely: location 11 is Rena Lebar, locations 12 and 14 are Penum, and locations 1 and 3 are Talang Ambung. These locations need to be more vigilant against landslides. In addition, it is necessary to provide a marker that the area has a high potential for landslides. High potential areas have the *Vs*, *Vp*, and density lowest while Poisson's ratio is the highest. The high potential area consists of very weathered soil with a lithology of loose sand and weathered stiff soil with a lithology of sandstone. Clay and shale contribute to the bedrock's lithology, they are very dense, as are soft rock, rock, and hard rock. This research has determined regions with high, moderate, and low landslide risks. The *Vs*, *Vp*, density, and Poisson's ratio can also be used to determine the lithology at each measurement location.

Acknowledgements

Through the "Penelitian Unggulan FMIPA UNIB Fiscal Year 2021" program, we would like to privately convey our sincere thanks to the University of Bengkulu's Faculty of Mathematics and Natural Sciences.

References

Akpan, A. E., Ilori, A. O., & Essie, N. U. (2015). Geophysical investigation of obot ekpo landslide site, Cross River state, Nigeria. *Journal of African Earth Sciences*, *109*, 154-67. doi:10.1016/j.jafrearsci.2015.05.015.

Ariestianty, S. K., Taha, M., Nayan, M. A. M., & Chik, Z. (2009). Determination of ground shear modulus using multichannel analysis surface wave method. *Semesta Teknika*, *12*(2), 185-98. doi:10.18196/st.v12i2.742.

Badan Meteorologi, Klimatologi, dan Geofisika [BMKG]. (2020). *Laporan curah hujan Kabupaten Bengkulu Tengah 2015-2020*. Bengkulu, Indonesia: Author.

Bowles, J. E. (1984). *Physical and geotechnical properties of soil*. New York, NY: McGraw-Hill Inc.

Badan Standardisasi Nasional [BSN]. (2019). *Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung, Badan Standardisasi Nasional (SNI 1726:2019)*. Jakarta, Indonesia: Author.

Burger, H. B. (1992). *Exploration geophysics of the shallow subsurface*. New Jersey, NJ: Prentice Hall, Englewood Cliffs.

Capizzi, P., & Martorana, R. (2014). Integration of constrained electrical and seismic tomographies to study the landslide affecting the cathedral of Agrigento. *Journal of Geophysics and Engineering*, *11*, 1-16, 045009. doi:10.1088/1742-2132/11/4/045009.

EPM (2024). Oracle fusion cloud EPM working with planning. Austin, TX: Oracle Corporation.

Farid, M. (2014). *Studi mikroseismik untuk mendeteksi laju perubahan garis pantai dengan indikator indeks kerentanan seismik, peak ground acceleration dan ground shear strain di Provinsi Bengkulu* (Doctoral thesis, Universitas Gadjah Mada, Yogyakarta, Indonesia).

Foti, S., Lancellotta, R., Sambuelli, L., & Socco, L.V. (2000). Notes on fk analysis of surface waves. *Annali Di Geofisica*, *43*(6),1199-1209.

Gafoer, S., Amin, T. C., & Pardede. (2007). *Geological map of Bengkulu quadrangle, Sumatra*. Bandung, Indonesia: Directorate General of Geology and

Mineral Resources, Geological Research and Development Centre.

Gafoer, S., Amin, T. C., & Pardede. (2012). *Geology of the Bengkulu Quadrangle, Sumatra*. Bandung, Indonesia: Directorate General of Geology and Mineral Resources, Geological Research and Development Centre.

Hadi, A. I. & Brotopuspito, K. S. (2015). Peak ground acceleration mapping using probabilistic seismic hazard analysis (PSHA) approach in Kepahiang regency, Bengkulu Province. *Berkala Fisika*, *18*(3), 101-12.

Hadi, A. I. (2019). Studi potensi longsor daerah Kabupaten Kepahiang, Provinsi Bengkulu terutama akibat gempabumi menggunakan pendekatan parameter elastis (Doctoral thesis, Universitas Gadjah Mada, Yogyakarta, Indonesia).

Hadi, A. I. & Brotopuspito, K. S. (2016). Estimation of fault boundary depth of field from gravity data in ground movement prone areas (a case study: Sumatran fault Bengkulu Musi segment. *Simetri*, *2*(2): 37-42.

Hadi, A. I, Brotopuspito, K. S., Pramumijoyo, S., & Hardiyatmo, H. C. (2018). Regional landslide potential mapping in earthquake-prone areas of Kepahiang regency, Bengkulu Province, Indonesia. *Geosciences (Switzerland)*, *8*(6), 1-16. doi:10.3390/ geosciences8060219.

Hadi, A. I., Brotopuspito, K. S., Pramumijoyo, S., & Hardiyatmo, H. C. (2021b). Application of catastrophe theory in landslide case, and its relationship with the slope stability. *AIP Conference Proceedings*, *2320*, 040017. doi:10.1063/5.0037644.

Hadi, A. I, Refrizon, Farid, M., Harlianto, B., & Sari, J. I. (2021a). Landslide potential investigation for disaster risk reduction in Central Bengkulu regency, Bengkulu Province, Indonesia. *Indonesian Journal on Geoscience*, *8*(3), 313–28. doi:10.17014/ijog. 8.3.313-328.

Hadi, A. I., Sunaryo, Farid, M., Refrizon, Harlianto, B., Fadli, D. I., & Putriani, E. (2024). Analysis of earthquake-prone areas based on the seismic wave velocity, Young's modulus, shear modulus, and Poisson's ratio for disaster risk reduction in Bengkulu city, Indonesia. *Natural Hazards,*. doi:10.1007/s11069-024-06827-3.

Karnawati, D. (2007). The mechanism of rock mass movements as the impact of earthquake; Geology engineering review and analysis. *Dinamika Teknik Sipil*, *7*(2): 179-90.

Kirmanto, D. (2007). *Pedoman penataan ruang kawasan rawan bencana longsor*. Jakarta, Indonesia: Departemen Pekerjaan Umum.

Mahandani, H. S. (2017). *Identifikasi kerawanan tanah longsor dengan menggunakan metode seismik refraksi dan MASW di desa Purwosari Kabupaten Kulonprogo* (Master's thesis, Universitas Gadjah Mada, Yogyakarta, Indonesia).

Milsom, J. & Eriksen, A. (2011). *Field geophysics* (4th ed.). Chichester, WSX: John Wiley and Sons.

Murjaya, J. (2011). *Zonasi energi tektonik daerah subduksi berdasarkan bentuk kerutan (buckling) searah busur (studi kasus: wilayah Sumatra)* (Doctoral thesis, Universitas Gadjah Mada, Yogyakarta, Indonesia).

Nakamura, S., Wakai, A., Umemura, J., Sugimoto, H., & Takeshi, T. (2014). Earthquake-induced landslides: Distribution, motion, and mechanisms. *Soils and Foundations*, *54*(4), 544-559, doi:10.1016/j.sandf. 2014.06.001.

Nepop, R. K. & Agatova, A. R. (2008). Estimating magnitudes of prehistoric earthquakes from landslide data: First experience in Southeastern Altai. *Russian Geology and Geophysics*, *49*, 144-51. doi:10.1016/j.rgg.2007.06.013.

PASI. (2021). *WinMASW 2021.1 User Manual*. Retrieved from http://download.winmasw.com/documents/ manual_winMASW_eng.

Petersen, M. D., Dewey, J., Hartzell, S., Mueller, C., Harmsen, S., Frankel, A. D., & Rukstales, K. (2004). Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the southern Malaysian Peninsula. *Tectonophysics*, *390*, 141-58. doi:10.1016/j.tecto.2004.03.026.

Schon, J. H. (2015). *Physical properties of rock: A workbook*. Oxford, England: Elsevier Science.

Sujitapan, C., Kendall, J. M., Chambers, J. E., & Yordkayhun, S. (2023). Landslide ground development through integrated geoelectrical and seismic imaging in Thungsong district, Nakhon Si Thammarat, Thailand. *Journal of Asia Sciences: X*, *10*, 1-13. doi:https://doi.org/10.1016/j.jaesx.2023.100168.

Sujitapan, C., Kendall, J. M., Chambers, J. E., & Yordkayhun, S. (2024). Landslide assessment through integrated geoelectrical and seismic methods: A case study in Thungsong site, southern Thailand. *Heliyon, 10*, 1-17. doi:10.1016/j.heliyon.2024.e24660.

Tokimatsu, K., Tamura, S., & Kojima, H. (1992). Effects of multiple modes on Rayleigh wave dispersion characteristics. *Journal of Geotechnical Engineering*, *118*(10), 1529–43. doi:10.1061/ (ASCE)0733-9410(1992)118:10(1529.

Uhlemann, S., Hagedorn, S., Dashwood, B., Maurer, H., Gunn, D., Djikstra, T., & Chambers, J. (2016). Landslide characterization using P- and S-wave seismic refraction tomography – The importance of elastic moduli. *Journal of Applied Geophysics, 134*, 64-76. doi:10.1016/j.jappgeo.2016.08.014.

Whiteley, J. S., Watlet, A., Uhlemann, S., Wilkinson, P., Boyd, J. P., Jordan, C., . . . Chambers, J. E. (2021). Rapid characterisation of landslide heterogeneity using unsupervised classification of electrical resistivity and seismic refraction surveys. *Engineering Geology, 290*, 1-15, doi:10.1016/ j.enggeo.2021.106189.

Zhang, S., Zhang, L. M., & Glade, T. (2014). Characteristics of earthquake and rain induced landslides near the epicenter of Wenchuan earthquake. *Engineering Geology*, *175*, 58–73. doi:10.1016/j.enggeo.2014. 03.012.

Zuidam, R. A. (1983). *Guide to geomorphological aerial photographic interpretation and mapping*. Enschede, Netherlands: ITC, Eschede.