SUBSURFACE MODELING FOR IDENTIFYING SLIP SURFACE: USING THE 2D RESISTIVITY METHOD IN PESAWARAN REGENCY

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Abstract. *Way Ratai Road in Pesawaran Regency, Lampung Province, is characterized by hilly morphology with steep slopes, rendering the area susceptible to mass movement. To date, no geophysical studies have specifically identified the slip surface zone along this road corridor, making this research essential as a basis for landslide disaster mitigation. This study aims to identify the slip surface with criteria encompassing subsurface layer structure and weak zone depth estimation. Data acquisition was conducted using the dipole-dipole configuration resistivity geoelectrical method with a traverse length of 128 m, employing 33 electrodes at 4 m spacing. Resistivity data inversion modeling was performed using Res2Dinv software. The interpretation results indicate that the subsurface structure of the study area comprises five lithological units, namely clay, gravel, tuff, basite, and quartzite. The slip surface was identified at a depth of 6–21 m, located at the contact zone between the tuff and basalt units, which exhibits significant resistivity contrast. The estimated volume of potential landslide material reaches 34,560 m³. The findings of this research can serve as a reference for structural and non-structural mitigation planning to minimize landslide risk in the Way Ratai Road area.*
Keywords: *dipole-dipole configuration; geoelectrical; landslides; resistivity; slip fields.*

INTRODUCTION

Lampung Province is one of the provinces with high landslide potential due to its geographical conditions comprising hilly and mountainous terrains (Prawiradisastra, 2013). Landslide occurrence data compiled by the National Disaster Management Authority (BNPB) indicates that from 2015 to 2023, a total of 56 landslide events were recorded in Lampung Province. Within Lampung Province, Pesawaran Regency has been identified as one of the areas with significant landslide susceptibility. According to data from the Regional Disaster Management Agency (BPBD) of Pesawaran, 33 landslide events were reported between 2020 and 2023, primarily triggered by high rainfall intensity (BNPB, 2024).

Pesawaran Regency encompasses a variety of topographic features, ranging from lowlands and highlands to mountainous and hilly areas, with elevations between 0 and 1,682 meters above sea level. In addition, the region's topography is classified into two slope categories: 0–8% and over 40%. Slopes greater than 40% significantly increase the risk of landslides due to the stronger gravitational force acting on soil or rock materials. This force may exceed the shear strength of the material, potentially resulting in mass movement and triggering landslides (Robbi et al., 2022).

While Pesawaran Regency is well-known for its landslide susceptibility, it is also recognized for its coastal tourism attractions. Tourist destinations such as Mutun Beach, Tegal Mas, Pahawang Beach, Klara Beach, and Sari Ringgung Beach have increased the area's popularity among visitors. However, access to these coastal attractions is primarily dependent on the Way Ratai Road (Sardio, 2022). This road traverses hilly terrain with steep slopes, further exacerbating the landslide risk. Landslide events in this area could potentially cut off access to several coastal tourism sites. Therefore, this study was conducted to help minimize the potential for landslides in the region.

Geologically, Pesawaran Regency comprises rock formations ranging from the Pre-Tertiary and Tertiary to the Quaternary periods. The Pre-Tertiary rocks consist of metamorphic formations such as gneiss, schist, and quartzite. The Tertiary formations are characterized by tuff, tuffaceous sandstone, tuff breccia, and andesitic-basaltic lava. Meanwhile, the Quaternary deposits include gravel, sand, clay, and classical volcanic tuff deposits. The geological characteristics of the study area include the Qa formation (alluvium), which consists of gravel, sand, and clay; the QTI (Lampung) formation, composed of pumiceous tuff, rhyolitic tuff, massive tuffite, tuffaceous claystone, and tuffaceous sandstone; the Tomh (Hulusimpang) formation, comprising andesitic-basaltic lava, tuff, and altered volcanic breccia with limestone lenses; the Qhv-r formation (young volcanic deposits) resulting from Mount Ratai eruptions; and finally, the Tpot (Tarahan) formation, which includes massive tuff and breccia with intercalated chert layers (Rustadi dan Rananda, 2020).

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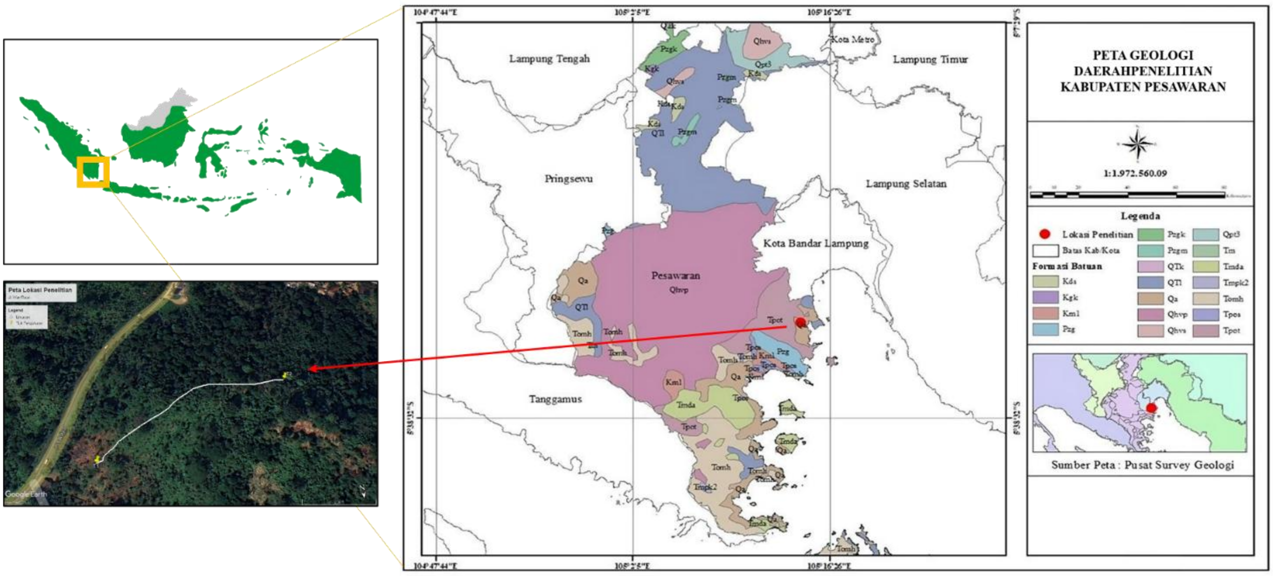

Figure 1. Geological Map of the Tanjung Karang Sheet (modified from Mangga, 1993)

To address the identified issues, this research was conducted to analyze slip surfaces on landslide-prone slopes along the Way Ratai road corridor in Pesawaran Regency. A previous study conducted in Padang Cermin, located along the Way Ratai Road, employed the Horizontal-to-Vertical Spectral Ratio (HVSR) microtremor method to assess site vulnerability. The objective was to determine seismic vulnerability indices and dynamic soil properties (Meilinda et al., 2023). Although the HVSR technique provides valuable information regarding dominant frequency, amplification factor, and overall site response characteristics, it does not enable precise imaging of subsurface lithological boundaries or the specific geometry of potential failure planes, which are critical for understanding landslide mechanisms.

To bridge this gap, the present study employs two-dimensional (2D) resistivity surveying with a dipole-dipole electrode configuration to obtain detailed subsurface information. Unlike passive seismic methods such as microtremor analysis, this resistivity-based approach enables direct mapping of subsurface geological structures, thereby facilitating the identification and delineation of shear surface geometry within landslide-prone zones. A 2D resistivity model depicting subsurface lithological conditions will be developed to accurately characterize the geometry of potential landslide failure surfaces in the study area. This research aims to complement previous geophysical investigations and provide more precise subsurface data to support local communities and stakeholders in mitigating landslide hazards and reducing potential losses in the region.

METHODOLOGY

Landslide analysis can be conducted using various geophysical methods, such as electrical resistivity, self-potential (SP), microtremor, seismic, electromagnetic, and Ground Penetrating Radar (GPR). In this study, the electrical resistivity method was chosen due to its environmentally friendly nature, relatively low cost, and ability to detect subsurface soil layers several meters below the surface based on the resistivity values of soil or rock at the study site (Pambudi, 2022). Exploration using this method can be carried out with various array configurations, including Wenner, Schlumberger, dipole-dipole, and Wenner-Schlumberger. The dipole-dipole configuration was selected for this research because of its high sensitivity to horizontal variations at shallow depths, high lateral resolution, greater penetration depth compared to other configurations, improved imaging resolution especially for vertical structures and inclined layers, as well as its slightly deeper penetration capability. Moreover, this configuration can reduce electromagnetic effects that arise between the current and potential circuits (Rahma, 2018; Loke, 1999; Effendy, 2012).

Electrical resistivity is an essential physical characteristic that describes a material's tendency to oppose the flow of electrical current (Griffiths, 2017). Unlike resistance, which is related to the shape of the conductor, resistivity (ρ) is a characteristic specific to the material, defined as the quotient of the electric field E divided by the current density J:

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$$\rho = \frac{E}{J} \tag{1}$$

ρ as resistivity (Ω·m) → intrinsic property of the material, E as electric field (V/m) and J as current density (A/m²). This relationship, known as the microscopic form of Ohm's law, illustrates the local behavior of current in a conductive material. For an isotropic and homogeneous substance with a cross-sectional area A (in m²) and a length L (in meters), the relationship between resistivity ρ (in Ω·m) and resistance R (in Ω) is given by the following equation:

$$R = \rho \frac{L}{A} \tag{2}$$

In geological rocks, electrical resistivity can vary considerably depending on mineral composition, porosity, water content, and weathering level (Telford et al., 1990). In general, resistivity values range from less than 1 Ω·m for water-saturated clays and saline groundwater to more than 10^4 Ω·m for dense crystalline rocks such as granite and quartzite. This wide variation makes electrical resistivity a useful indicator for differentiating underground lithologies and delineating geological boundaries, including possible slip surfaces in areas at risk of landslides (Reynolds, 2011).

Resistive geoelectric techniques take advantage of this disparity by introducing a current into the ground and evaluating the resulting potential variation. The electrode configuration used in the electrical resistivity survey is the dipole-dipole configuration, in which pairs of current and potential electrodes are placed on the ground surface (Blasio, 2011). The current electrodes are installed on the surface at a predetermined distance (denoted as A and B), while the potential electrodes (M and N) are placed either between or near the current electrodes at equal spacing. Electrical current is injected through the current electrodes (A and B), while the resulting potential difference is measured using the potential electrodes (M and N) (Loke & Barker, 1995).

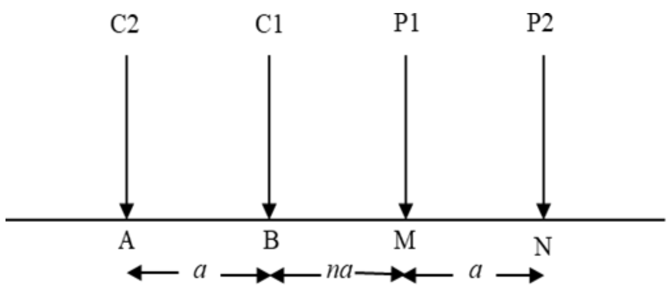

Figure 3. Electrode Arrangement of the Dipole-Dipole Configuration (Reynolds, 1997).

The main advantage of the dipole-dipole configuration is its high sensitivity to lateral changes in resistivity, making it well-suited for detecting subsurface structures with horizontal variations**.** However, this configuration is less effective in detecting vertical resistivity changes and requires a larger spatial area for electrode deployment compared to other configurations (Kearey et al., 2022).

The geometric factor in the dipole-dipole configuration:

$$K = \pi a(n(n+1)(n+2)) \tag{3}$$

This research was conducted at the landslide-prone cliff on Jalan Way Ratai in Pesawaran Regency. The starting point of the electrode was located at coordinates 05°31.006' S and 105°14.340' E, and the end point of the electrode was located at coordinates 05°31.030' S and 105°14.289' E. The cliff has a height of 94 meters above sea level with a length of 128 meters and a lowest point of 60 meters above sea level. Primary data was obtained through direct field measurements using resistivity measuring instruments with a dipole-dipole configuration using 33 electrodes with a spacing of 4 m.

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Figure 4. Research location map.

One measurement path was selected based on preliminary analysis results showing that the anomaly zone was concentrated in a certain area, making it representative enough to characterize the aquifer structure at the research site. The tools and materials used in this study included hardware and software components. The hardware consisted of: one set of IRES Geophysical Instrument, electrodes, cables, battery, measuring tape, hammer, GPS, radio communication devices (HT), and a laptop. The software included: Res2Dinv, ArcGIS, Google Earth, Global Mapper, Microsoft Excel, and Notepad.

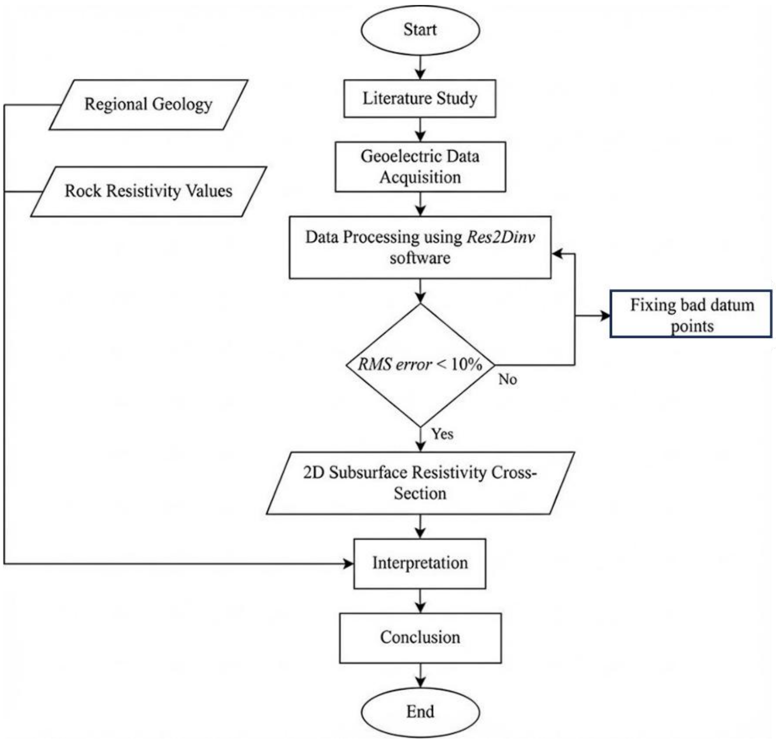

Figure 5. Research Flowchart.

This research was conducted through several methodological phases. The initial phase involved a literature review encompassing regional geological analysis and rock resistivity reference values for

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interpretation purposes. Subsequently, geoelectrical data were acquired at the study site and analyzed using Res2Dinv software. Data processing was performed iteratively, employing a Root Mean Square (RMS) error threshold of less than 10%. When this threshold was exceeded, erroneous data points (bad datum points) were corrected until satisfactory results were achieved. Upon completion of the inversion process with an acceptable RMS error, a two-dimensional (2D) subsurface resistivity model was generated and subsequently analyzed to determine lithological structures and potential slip planes. The conclusions of this research were derived from the results obtained through this interpretation.

Inversion modeling is a method used in data interpretation to construct subsurface models. The target model or values are obtained through an automated modeling process. In inversion modeling, a 2D representation of the rock layer formations and their respective resistivity values is generated based on apparent resistivity data collected from field measurements (Parwatiningtyas, 2021). In this study, geoelectrical data processing was carried out using the least-squares inversion method. This process is designed to produce an optimal model by minimizing the sum of squared errors, thereby reducing the discrepancy between the calculated model and the field data. For field data, a generally acceptable RMS error threshold is below 10%, which indicates a satisfactory correspondence between the information obtained by measurement and that predicted by the model. When the RMS error exceeds the tolerable limit, the incorrect data points are studied to identify and remove any outliers that could compromise the accuracy of the model (Loke, 2018). Subsequently, data interpretation is conducted to identify the slip surface on the landslide-prone slope along Way Ratai Road, Pesawaran Regency.

RESULTS AND DISCUSSION

The Way Ratai road, with a total length of approximately 113.755 km, is a strategic route for the region's tourism, transportation, and economy (Pemerintah Kabupaten Pesawaran, 2024). Throughout the study, topographic surveys were conducted, generating coordinate information (longitude and latitude) as well as altitude values. The information collected was processed using Global Mapper software, producing a topographic profile as shown in Figure 4.

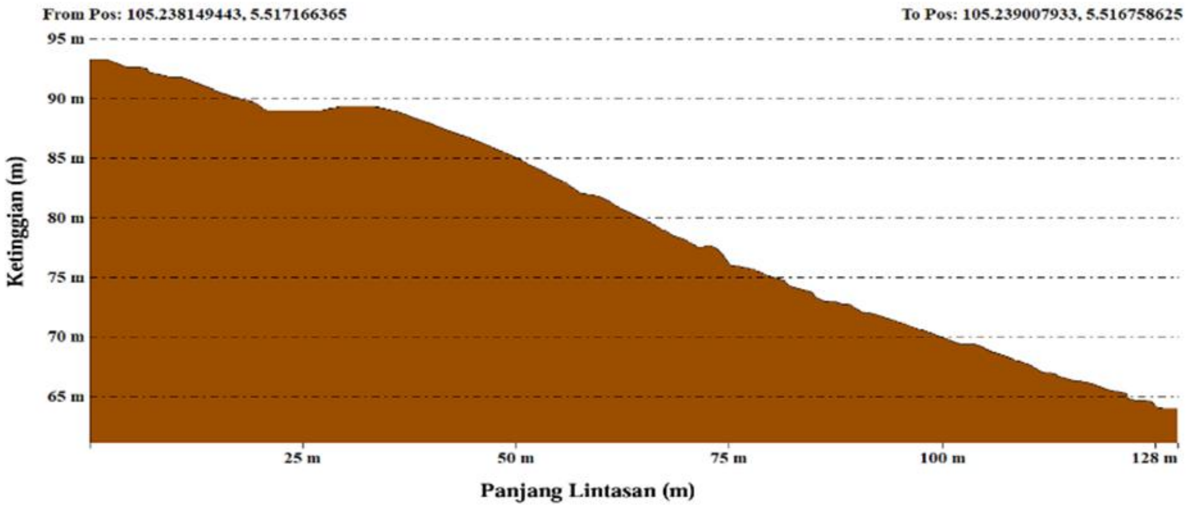

Figure 6. Topographic Cross-Section of the Study Area.

Based on this topographic profile, the survey route varies from 94 m to 64 m over a horizontal distance of 128 m, resulting in an angle of inclination of 14° (corresponding to a slope of 23.4%). According to Van Zuidam's slope categorization, this type of gradient is classified as a "steep slope" (15-30%), which is characterized by a high sensitivity to mass movement or landslide phenomena (Van Zuidam, 1985).

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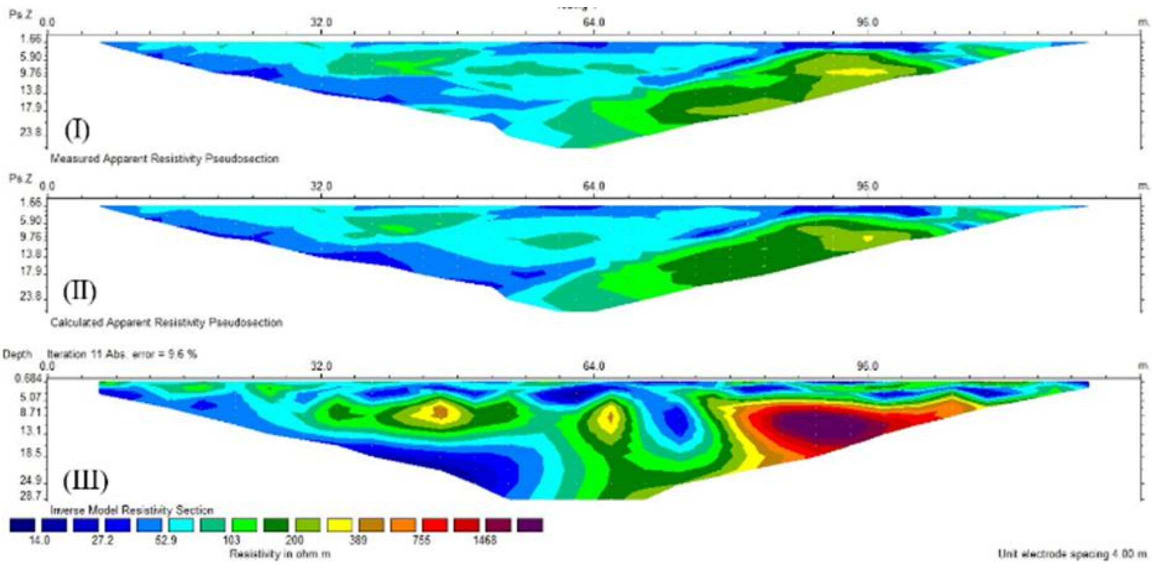

Figure 7. Subsurface Cross-Section of the Study Area.

Based on Figure 5, the subsurface profile consists of three sections: the measured apparent resistivity pseudosection, the calculated apparent resistivity pseudosection, and the inverse model resistivity section. The first section (I), the measured apparent resistivity pseudosection, represents the apparent resistivity values obtained directly from field measurements. Apparent resistivity refers to resistivity values that have not yet been corrected for subsurface heterogeneities. Lower resistivity values (indicated by blue to green colors) are observed in several areas, particularly at greater depths. This suggests the possible presence of weaker or more water-saturated materials in the subsurface layers. Conversely, zones with higher resistivity values (indicated by yellow to red colors) may represent denser or more compact materials. The second section (II), the calculated apparent resistivity pseudosection, is the result of a computational model that attempts to match the measured resistivity data with a modeled subsurface resistivity distribution. The resistivity distribution patterns in this section resemble those of the first section, but have been adjusted through forward modeling, illustrating how the model approximates the geological conditions beneath the surface. The third section (III), the inverse model resistivity section, presents the final result in the form of a true resistivity distribution after inversion of the apparent resistivity data. This section provides a more accurate and detailed subsurface resistivity profile (Telford et al., 1990).

The measurements were conducted using the electrical resistivity method with a dipole-dipole configuration, with the survey line oriented from east to northwest. A total of 33 electrodes were used, spaced 4 meters apart, resulting in a total survey line length of 128 meters. A Root Mean Square Error (RMSE) value of 9.6% was obtained after 11 iterations, producing the subsurface profile shown in Figure 6.

In Figure 6, the subsurface cross-section consists of several rock layers, distinguished by different colors. Resistivity is measured in ohm-meters (Ω·m), with a color scale ranging from low (blue) to high (purple) values. The profile is predominantly characterized by the distribution of blue and green colors, indicating zones of low resistivity.

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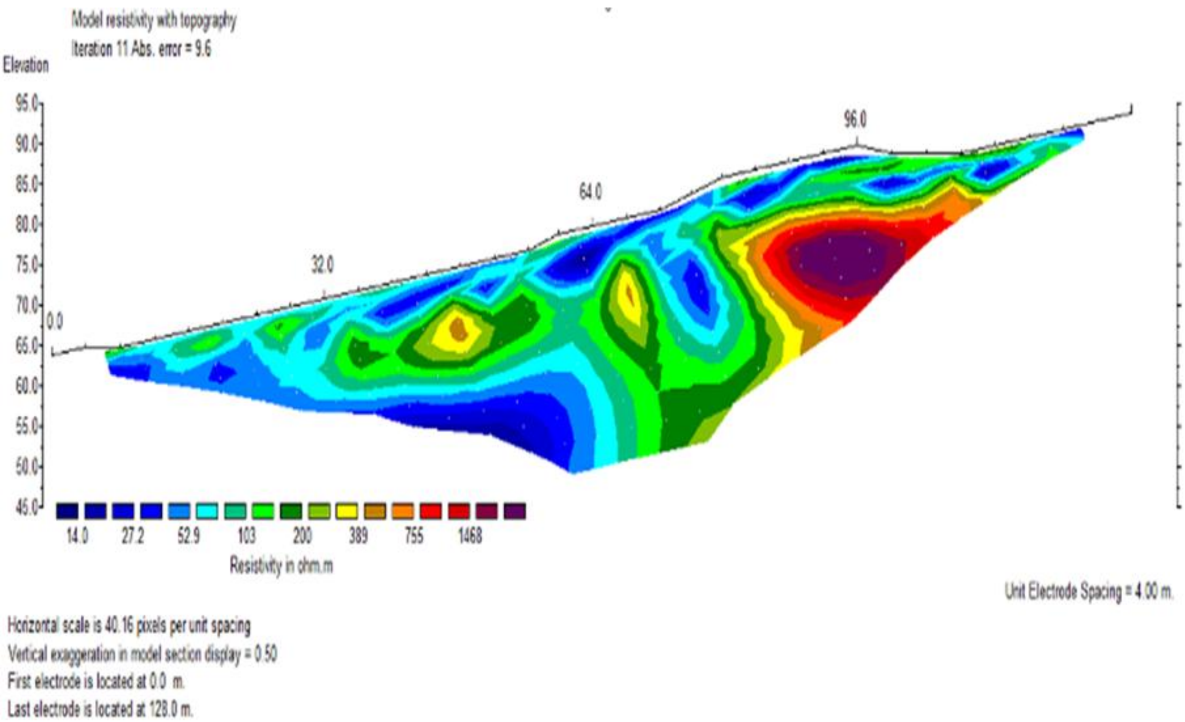

Figure 8. Subsurface Cross-Section of the Study Area with Topographic Profile.

Based on the resistivity cross-section, five types of soil/rock layers were identified, each with a different range of resistivity values. The identification of subsurface layers was carried out by referring to resistivity values as classified by Telford (1990), as shown in Table 1.

Table 1. Resistivity Values of Rock Types.

No	Color Range in Layer	Resistivity Range (Ω·m)	Depth (m)	Soil/Rock Type
1.		14 – 52,9	0,6 – 2,8	Clay
2.		10 – 200	5 – 28	Gravel
3.		300 - 800	6 – 21	Tuff
4.		200 – 10^5	6 – 21	Basalt
5.		1000 - 10^4	6 – 15	Quartzite

The first layer, with a resistivity value ranging from 14 to 52.9 Ωm at a depth of 0.6 to 28 meters, is presumed to be clay, characterized by dark blue to light blue colors. This interpretation aligns with typical clay resistivity values, which generally range from 1 to 100 Ωm. The second layer, exhibiting resistivity values between 103 and 200 Ωm at depths of 5 to 28 meters, is interpreted as gravel, which typically has resistivity values ranging from 100 to 600 Ωm. This layer is represented by light green to dark green colors in the resistivity section. The third layer is interpreted as tuff, with a resistivity value of 389 Ωm at a depth of 6 to 21 meters, and is characterized by yellow to brown color gradients. Tuff generally exhibits resistivity values within the range of 300 to 800 Ωm. The fourth layer, found at 6 to 21 meters depth and depicted in orange to dark red hues, shows a resistivity value of 755 Ωm. This layer is presumed to consist of basalt, whose resistivity typically ranges from 200 to 1050 Ωm, depending on its porosity and degree of weathering. The fifth layer,

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located at 6 to 15 meters depth and marked by plum to dark purple colors, displays a high resistivity value of 1468 Ωm. This layer is interpreted as quartzite, which commonly has resistivity values ranging from 10^3 to 10^4 Ωm, indicative of a compact and highly resistive rock type.

Based on the geological map of the Tanjungkarang sheet, Sumatra, the study area is regionally covered by the Qa formation (alluvium), which consists of gravel, sand, and clay. The QTI (Lampung) formation comprises pumiceous tuff, rhyolitic tuff, massive tuffite, tuffaceous claystone, and tuffaceous sandstone. The Tomh (Hulusimpang) formation includes andesitic basalt lava, tuff, and altered volcanic breccia with limestone lenses. The Qhv-r formation (young volcanic deposits) was formed by the eruption of Mount Ratai. Meanwhile, the Tpot (Tarahan) formation consists of massive tuff and breccia interbedded with chert. Subsurface inversion imaging results indicate the presence of clay, gravel, tuff, basalt, and quartzite.

The subsurface lithological interpretation derived from the resistivity inversion model is consistent with the regional geology of the Tanjungkarang Sheet. The shallow low-resistivity layer interpreted as clay and gravel (14–200 Ωm) likely corresponds to Quaternary alluvial deposits (Qa), which consist of unconsolidated clay, sand, and gravel materials. These surface sediments commonly exhibit relatively low resistivity due to high moisture content and fine-grained composition.

The intermediate resistivity zone interpreted as tuff (300–800 Ωm) is considered to correlate with volcanic pyroclastic units of the Lampung Formation (QTl) and partly the Tarahan Formation (Tpot), which regionally consist of pumiceous tuff, rhyolitic tuff, tuffaceous sandstone, and volcanic breccia. Tuff generally shows moderate resistivity because its porosity is relatively high and it can store infiltrated groundwater within pore spaces and fractures.

The high-resistivity unit interpreted as basalt (755 Ωm) is associated with the Hulusimpang Formation (Tomh), which regionally contains andesitic-basaltic lava flows and volcanic breccia. Basaltic lava commonly exhibits higher resistivity values because of its massive texture, lower porosity, and lower water saturation compared to overlying tuffaceous materials.

Meanwhile, the very high resistivity anomaly interpreted as quartzite (1468 Ωm) may represent older metamorphic basement rocks underlying the younger volcanic sequence. Quartzite commonly has very high resistivity due to its dense crystalline structure and limited pore connectivity.

This stratigraphic relationship indicates that permeable tuffaceous deposits overlie relatively impermeable basaltic units. Such lithological contrast may promote groundwater accumulation along the contact boundary, reduce shear strength, and create a preferential slip surface. Therefore, the interpreted slip plane at depths of 6–21 m is geologically reasonable and consistent with the regional volcanic stratigraphy of Pesawaran Regency.

The lithological diversity in the research area reflects various geological processes that have occurred in the region. Based on field observations and geophysical analysis, the identified rocks consist of igneous, sedimentary, and metamorphic types. Each rock type possesses distinct physical and mechanical properties, which influence the subsurface structure and slope stability in this area. Therefore, geological potential, including the presence of mineral resources, vulnerability to geohazards, and subsurface aquifer conditions, can be understood through lithological analysis. The subsurface lithology of the study area is shown in Figure 7.

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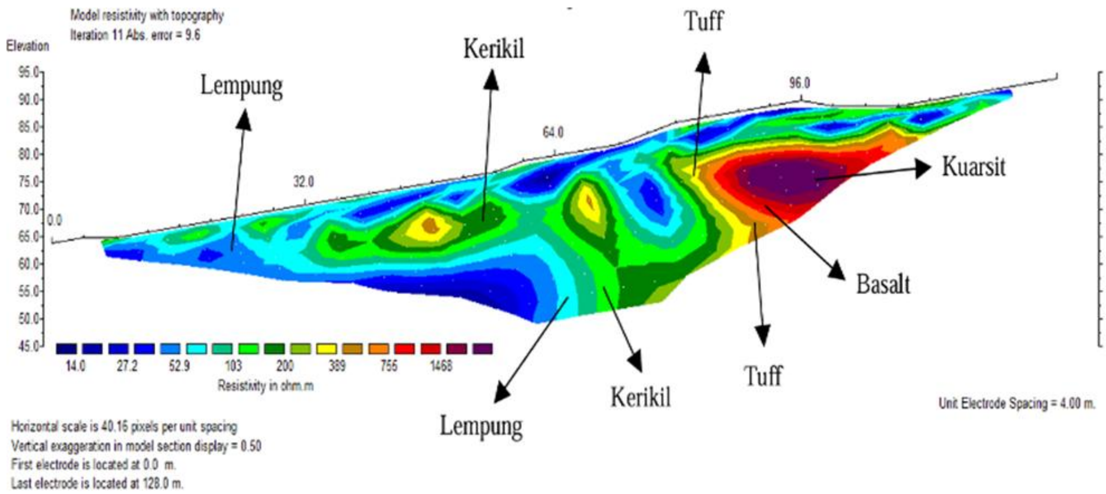

Figure 7. Subsurface Rock Lithology.

Based on the interpretation of geoelectrical data, the slip surface is characterized by a zone with lower resistivity compared to the overlying layers. This condition indicates the presence of water-saturated materials that have the potential to trigger ground movement.

In Figure 8, a low-resistivity zone (14–389 Ωm) is observed. This zone most likely consists of soft, water-saturated soil materials with low permeability and weak bearing capacity. In contrast, high-resistivity zones (755–1468 Ωm) likely comprise impermeable (hard) materials. These layers act as support for the soil mass and can restrict movement from the overlying layers. The layers assumed to be impermeable (hard) are predicted to be quartzite rock with a resistivity of 1468 Ωm and basalt with a resistivity of 755 Ωm. Meanwhile, the layers estimated to be saturated (soft) consist of clay with resistivity values of 14–389 Ωm, gravel with resistivity values of 103–200 Ωm, and tuff rock with a resistivity of 389 Ωm.

Based on the structural analysis of subsurface rock layers in the landslide-prone slope area along Way Ratai Road, Pesawaran Regency, the slip surface is marked by a dashed line in Figure 8.

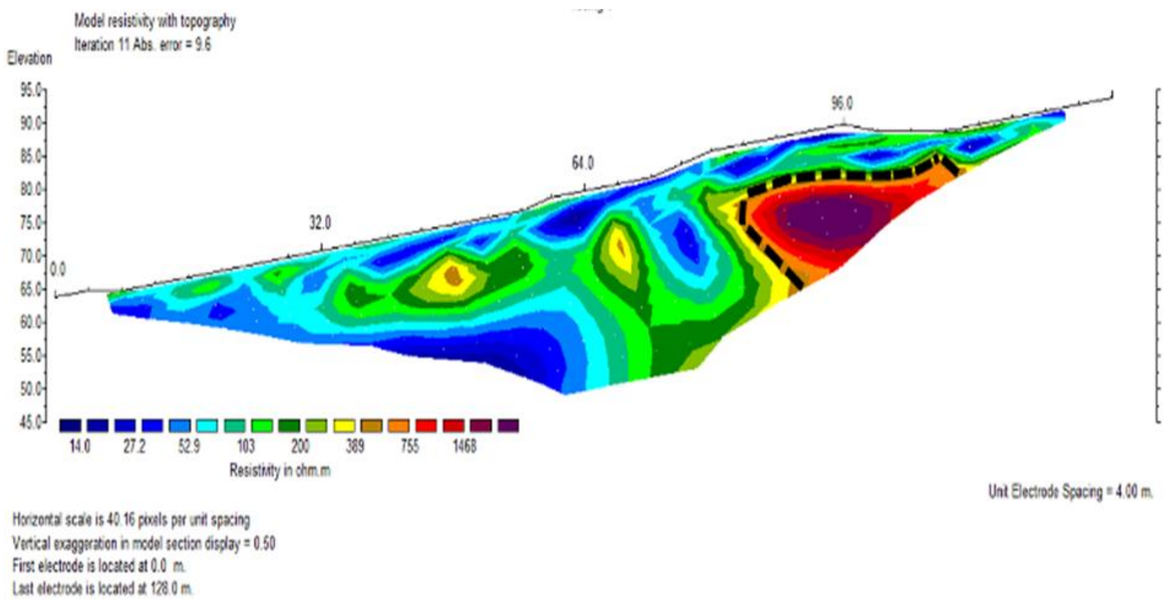

Figure 8. Slip Surface in the Study Area.

Based on the subsurface rock structure in the study area, it is suspected that the slip surface lies at the boundary between tuff and basalt rocks, at depths ranging from 6 to 21 meters, with an estimated slip surface length of approximately 27 meters. This analysis is confirmed by regional geological characteristics. According to the geological map of Tanjungkarang, the study area is dominated by the Quaternary Lampung

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Formation (QTl), which consists of volcanic materials resting on Tertiary basaltic rocks (Syahrir, A. M., & Amiruddin, 1994). This interpretation is consistent with geotechnical data, which highlights that lithological contacts, particularly between permeable tuff and impermeable basalt, often tend to serve as preferred slip surfaces due to hydrogeological contrasts and mechanical discontinuities. Such conditions have been documented in volcanic sequences located in tropical areas, thus attesting to the possibility of the existence of slip surfaces at the tuff-basalt boundary (González de Vallejo & Ferrer, 2011). Basalt, due to its high hardness, is more resistant to erosion and ground movement, and better able to withstand pressure and load, thereby reducing the risk of landslides along the slip surface. Its resistance to deformation and cracking also contributes to the stability of the surrounding soil, helping to maintain the integrity of the slip zone.

In addition, basalt is characterized by low porosity and permeability. Porosity is defined as the measure of void space within rocks that can be filled with water or gas. In basalt, porosity is considered low, generally ranging between 0.1% and 2% (Vallejo & Ferrer, 2011). This limited void volume restricts water accumulation within the rock, thereby maintaining low pore water pressure and supporting the stability of the slip surface. Conversely, rocks with high porosity tend to retain more water, potentially increasing pore pressure and triggering landslides. Permeability refers to a rock's ability to allow fluids to pass through its pores or fractures. Basalt typically has low permeability, which limits water infiltration. This reduced permeability slows down water movement into the subsurface, thereby decreasing the potential for landslides caused by surface water accumulation. In contrast, high-permeability rocks allow faster water infiltration, which can increase the risk of ground movement (Swan & Hurst, 2000).

When rainfall occurs, water infiltrates the soil and is stored within soft layers such as clay, gravel, and tuff. If infiltration continues over time, these soft layers may reach a state of saturation. Once saturated, water can percolate further down until it reaches impermeable rock layers such as basalt and quartzite. As a result, water accumulates above the surface of these impermeable layers. The increase in water content leads to a rise in pore water pressure and a reduction in the shear strength of the soil layers, thereby decreasing the cohesive forces that maintain slope stability. This condition compromises slope stability. The accumulation of water above the quartzite and basalt layers also creates a slippery interface, which causes weathered materials above to slide along these layers, eventually triggering landslides.

Slope angle is another critical factor influencing landslide occurrence, as it directly relates to gravitational forces acting on slope materials. On steep slopes, the gravitational shear component pulling materials downward becomes more dominant than the normal force that stabilizes the slope. This condition significantly reduces slope stability, especially in soils with low cohesion or saturated conditions. Slope steepness is closely linked to topography, as topography reflects variations in elevation, shape, and surface inclination. Areas with varied topography, such as hilly or mountainous regions, tend to have steeper slopes and, thus, a higher potential for landslides. In contrast, flatlands with gentle slopes generally have lower landslide risks, except when influenced by external factors such as flooding or erosion (Terzaghi et al., 1996).

To calculate the slope angle, the following equation can be used:

$$\beta = \tan^{-1}\frac{a}{b} \tag{4}$$

Based on the calculation results provided in the appendix, the slope angle is determined to be 14°, thus the slope in the study area is classified as moderately steep (Sitanala, 2010).

Based on resistivity inversion interpretation, the potential landslide volume can be calculated using the following equation. This approach is in line with the method discussed by Jaboyedoff (Jaboyedoff et al, 2010) particularly in the section on balanced cross sections and surface velocity-based volume estimation.

$$V = \frac{1}{2}\cdot a\cdot t\cdot L \tag{5}$$

Where V is the estimated landslide volume (m^3), a is the length of the potential sliding mass along the survey line (m), t is the average thickness of the unstable material above the slip surface (m), and L is the estimated width of the landslide body perpendicular to the survey line (m).

The coefficient 1/2 assumes that the landslide body approximates a triangular prism geometry, which is commonly used for preliminary slope-failure volume estimation. Based on the resistivity interpretation, the unstable zone extends approximately 128 m along the slope, with an average thickness of 9 m, while the estimated lateral width of the potentially unstable mass is 60 m.

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Based on calculations using equation (5), the predicted landslide volume is 34,560 m³. Due to the RMS error of the resistivity inversion model (9.6%), the depth of the slip plane is estimated with an uncertainty that affects the volume calculation. This leads to an estimated volume ranging from 31,240 to 37,880 m³ (±9.6%). Given the scale of the situation, it is very likely that the Way Ratai road in the Pesawaran district will be blocked by landslide debris, which would hinder access to coastal tourist sites and have an impact on the local economy. It is therefore necessary to implement preventive measures based on the characteristics of the identified landslides. According to Abramson et al. (2002), for shallow landslides (with a depth of 6 to 10 m), it is possible to erect retaining walls with deep foundations or pile walls anchored at the bottom of slopes to hold back the earth masses that could slide. As the landslide zone is located at a depth of 6 to 21 m, major technical interventions such as soil nailing, ground anchors, or a deep drainage system may be necessary to ensure effective slope stabilization (Turner & Schuster, 1996).

CONCLUSION AND RECOMMENDATIONS

Based on the analysis carried out, it can be deduced that the study area is home to an estimated underground structure composed of five lithological units that show variable lateral and vertical distribution. The upper horizon is composed of clay at a depth ranging from 0.6 to 2.8 m, which gradually changes to gravel between 5 and 28 m deep. Digging deeper, three types of rock were detected: tuff (from 6 to 21 meters), basalt (from 6 to 21 meters), and quartzite (from 6 to 15 meters). The alternating depths between tuff, basalt, and quartzite suggest lateral variation in facies along the study route, rather than vertical superposition at the same location. This lateral diversity illustrates the complex volcanic stratification typical of the Lampung Formation, where pyroclastic accumulations (tuff) alternate with lava flows (basalt) and metamorphic rocks (quartzite) visible at various locations along the flank. The slip surface is predicted to be located at the boundary between the tuff and basalt layers, at a depth ranging from 6 to 21 m. The use of the tuff-basalt boundary as a shear plane is explained by the significant lithological and hydrogeological differences between these two units. Basalt acts as an impermeable barrier, directing groundwater flow when it encounters tuff, which is more permeable. The accumulation of interstitial water reduces shear strength and establishes a mechanical discontinuity that functions as a preferred slip plane. Additionally, the volume of soil mass with potential for landslides is estimated to be approximately 34,560 m³.

This study suggests several directions for future research. First, the addition of survey lines is recommended, particularly to the west and east of the existing lines, where the contact zone between the tuff and basalt (defined as a potential slip plane between 6 and 21 m) could spread laterally. The introduction of parallel lines spaced 20 to 30 m apart will facilitate three-dimensional characterization of the slip plane and more accurate interpretation of the spatial distribution of areas vulnerable to landslides along the Way Ratai road corridor. It is also essential to take soil samples in order to carry out an in-depth analysis of landslide susceptibility. This is particularly relevant for undisturbed samples from the clay layer (depth varying between 0.6 and 2.8 m) and the weathered tuff layer (depth ranging from 6 to 21 m). These samples will be used to perform direct shear tests and determine the actual shear strength parameters (cohesion and internal friction angle) of the soil likely to be displaced. Third, it would be wise to use additional geophysical techniques such as seismic refraction or HVSR microtremor to corroborate and confirm the analysis of slip planes based on resistivity. It is also advisable to install inclinometers or extensometers to monitor long-term slope movements in identified sensitive areas.

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