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LANDSLIDE CHARACTERISTICS FROM CONCEPTUAL MODELLING OF WEATHERED LAYERS USING SUBSURFACE RESISTIVITY IN SANGON, DIY

KARAKTERISTIK LONGSOR DARI PEMODELAN KONSEPTUAL LAPISAN LAPUK MENGGUNAKAN RESISTIVITAS BAWAH PERMUKAAN DI SANGON, DIY

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Abstract. The Sangon area is located in Kulonprogo Regency, which physiographically has landforms in the form of hills and mountains. Steep slope angles of the hills and weathered surface rock conditions increase the potential for landslides hazard in the Sangon area. This study aims to identify unstable layers that are prone to landslides in the Sangon, Kokap, and Kulonprogo areas. Information regarding the potential characteristics of landslides can significantly impact reducing losses caused by landslides hazard. Conceptual modelling of weathered layers that have the potential to trigger landslides has been carried out in the research area using resistivity distribution data of subsurface rocks using the geoelectrical method. Geoelectrical data from five measurement lines with a length of 290 m each line with a southeast-northwest orientation can delineate an image of the distribution of weathered layers in the subsurface. Based on the results of two-dimensional (2D) subsurface resistivity inversion modelling, it is known that the weathered layer as soil form andesite rock has a low resistivity value with a range of 7 m – 246 m with a depth of 0 - 12 meters in the subsurface. The distribution of resistivity value of the weathered layer is depicted in the 3D model to determine the distribution of the weathered layer, which is then made into a conceptual model that can describe the characteristics of landslides. The description of the 3D resistivity model of subsurface rocks produces a conceptual model of landslides in the research area, where the potential for landslides that may occur has characteristics in the form of debris flow or translational. The unstable layer volume was 947,000 m^3, with a slope gradient ranging from 19% to 35%, with a moderate to steep slope.

Abstrak. *Daerah Sangon terletak di Kabupaten Kulonprogo yang secara fisiografis memiliki bentuk lahan berupa perbukitan dan pegunungan. Sudut lereng perbukitan yang curam dan kondisi batuan permukaan yang lapuk meningkatkan potensi bahaya longsor di daerah Sangon. Penelitian ini bertujuan untuk mengidentifikasi lapisan-lapisan labil yang rawan longsor di daerah Sangon, Kokap, dan Kulonprogo. Informasi mengenai karakteristik potensi longsor dapat berdampak signifikan dalam mengurangi kerugian akibat bahaya longsor. Pemodelan konseptual lapisan lapuk yang berpotensi memicu longsor telah dilakukan di daerah penelitian menggunakan data sebaran resistivitas batuan bawah permukaan dengan metode geolistrik. Data geolistrik dari lima jalur pengukuran dengan panjang masing-masing jalur 290 m dengan orientasi tenggara-barat laut dapat menggambarkan gambaran sebaran lapisan lapuk di bawah permukaan. Berdasarkan hasil pemodelan inversi resistivitas bawah permukaan dua dimensi (2D) diketahui bahwa lapisan lapuk berupa batuan andesit pembentuk tanah memiliki nilai resistivitas rendah dengan rentang 7 m – 246 m dengan kedalaman 0 – 12 meter di bawah permukaan. Sebaran nilai resistivitas lapisan lapuk tersebut digambarkan dalam model 3D untuk mengetahui sebaran lapisan lapuk tersebut, yang selanjutnya dibuat menjadi model konseptual yang dapat menggambarkan karakteristik longsoran. Gambaran model resistivitas 3D batuan bawah permukaan tersebut menghasilkan model konseptual longsoran di daerah penelitian, dimana potensi longsoran yang mungkin terjadi memiliki karakteristik berupa aliran debris maupun translasi. Volume lapisan yang tidak stabil sebesar 947.000 m³, dengan kemiringan lereng berkisar antara 19% sampai dengan 35%, dengan kemiringan lereng sedang sampai curam.*

1. INTRODUCTION

Landslides are a physiographically potential in the southern mountains of Java Island, particularly in Kulonprogo Regency, Special Region of Yogyakarta. The Kulonprogo Regency had a landslide on October 2nd 2022, which injured several people, and several residences damaged due to the landslide materials. Landslides usually have an impact on surrounding residents' safety as well as material losses. Based on data from the Yogyakarta Special Region Disaster Management Institute (BPBD DIY) in 2017 there were 162 landslides in Kulonprogo Regency which resulted in 156 people being killed and more than 7,000 houses damaged and material losses estimated at 10.788 billion rupiah. Identifying out about the possibility of landslides is one of the strategies to reduce the impact of damages from landslides. According to Zakaria and Maisarah (2020), landslide susceptibility in this region is influenced by the steep gradients of the slopes and the underlying geological conditions, particularly the characteristics of slip surfaces.

Scientific study on various types of landslide causes is essential to understanding more about a potential area's landslide risk (Samyn et al., 2012). One of the numerous scientific studies on the potential for landslides can be conducted by measuring the properties of subsurface rocks using geophysical technologies. (Giamboro et al., 2020). The physical properties of the subsurface rock are measured by the geophysical technique, which provides a broader view of the physical properties of the rocks (Telford et al., 1990). Landslide investigations using geophysical methods have been commonly used as carried out by McCann and Forster (1990); Hack (2000); Jongmans and Garambois (2007); and Giamboro et al., (2020). One of the relevant geophysical methods used in landslide investigations is the geoelectrical method. The geoelectrical method is a geophysical technique that uses surface data to determine the electrical characteristics of subsurface rocks (Lowrie & Fichtner, 2020). Contrasting electrical properties of rocks will produce different responses. The geoelectric resistivity method can be used because it is highly sensitive to electrical anomalies, allowing it to identify unstable rock layers that could potentially cause landslides]. The weathered rocks that have the potential to become landslide material are identified by measuring the resistivity values of the subsurface rocks using the Geoelectrical method.

The geoelectrical resistivity method, particularly the 2D resistivity technique, has been extensively utilized to identify slip surfaces and assess landslide potential in various regions. This method leverages the contrast in electrical resistivity between different subsurface materials to delineate geological structures and detect zones of weakness that may predispose an area to landslides (Mulyasari et al., 2020). Knowledge of the probable features of landslides is crucial for determining the impact that produced by landslides. For instance, debris flow characteristics in landslides have a wider radius than block slide and lateral spread characteristics in landslides (Highland, 2004). In particular, in the Sangon area, Kulonprogo district, DIY, Indonesia, this research was carried out to estimate the resistivity of subsurface rocks that provide information about the features of landslides.

This research aims to provide a general overview of the potential landslide characteristics in the study area, serving as an indicator of the effects these landslides may have on the surrounding environment. The analysis begins by examining rock resistivity data to identify subsurface layers that may be unstable, providing insight into areas that could be prone to landslides. Next, the study focuses on determining the specific regions within the subsurface that could be impacted by such disasters, highlighting areas vulnerable to landslides. Finally, the research seeks to construct a conceptual model of landslides, helping to better understand their potential characteristics and behaviour in the study region. This model will offer valuable insights into the dynamics of landslides, aiding in disaster preparedness and mitigation efforts.

2. LITERATURE REVIEW

Geoelectrical techniques—especially Electrical Resistivity Tomography (ERT)—are now widely regarded as reliable tools for assessing slope stability and landslide hazards. Perrone et al., (2014) provided a comprehensive review of ERT applications in landslide studies, highlighting its value in identifying subsurface moisture zones and shear surfaces.

In Malaysia, Sulaiman et al. (2023) conducted an ERI survey in Kelantan, revealing resistivity ranges from 1–1500 .m (loose residual soils) up to >1500 .m (weathered volcanic rock), thereby successfully mapping fracture zones and slip planes. Additionally, bolstering these findings, time-lapse field ERT surveys demonstrate that temporal resistivity changes correlate strongly with fluctuations in soil water content during rainfall-triggered slope instabilities, as increased water content reduces resistivity and weakens soil cohesion, thereby increasing the risk of slope failure.

From a perspective modelling, there has been a methodological shift toward coupling ERT with high-resolution geospatial and statistical techniques. For example, Swiss studies employed logistic regression driven by soil moisture data, showing strong predictive power for landslide occurrence based on antecedent wetness (Wicki et al., 2020). Similarly, 2023 hydrophysical–geophysical coupling models utilized resistivity–moisture relationships to simulate subsurface fluid dynamics, refining vulnerability maps. In the study in Batu Koneng, Ambon, utilized the dipole-dipole geoelectric configuration to identify potential slip planes. The interpretation of resistivity data revealed clay layers with resistivity values between 8.77 and 24.9 Ω·m, while limestone layers exhibited higher resistivity values ranging from 23.0 to 70.1 Ω·m. The slip plane was identified within the clay layers, detected across all measurement sections at varying depths, indicating the method's reliability in mapping subsurface structures associated with landslide susceptibility (Multi et al., 2024).

2.1. Geological Setting

During the early Pleistocene (0.01-0.7 million years ago), the Southern Mountains and the Kulonprogo Mountains were removed, resulting in the formation of Yogyakarta, according to Bemmelen Van (1949). According to Rahardjo et al., (1995), There formerly was a lake that spread to Ganwarno and Baturetno from the slopes of the Southern Mountains. This has to do with allowing surface water to collect in a smaller basin by halting its flow along the base of the mountains (**Figure 1**).

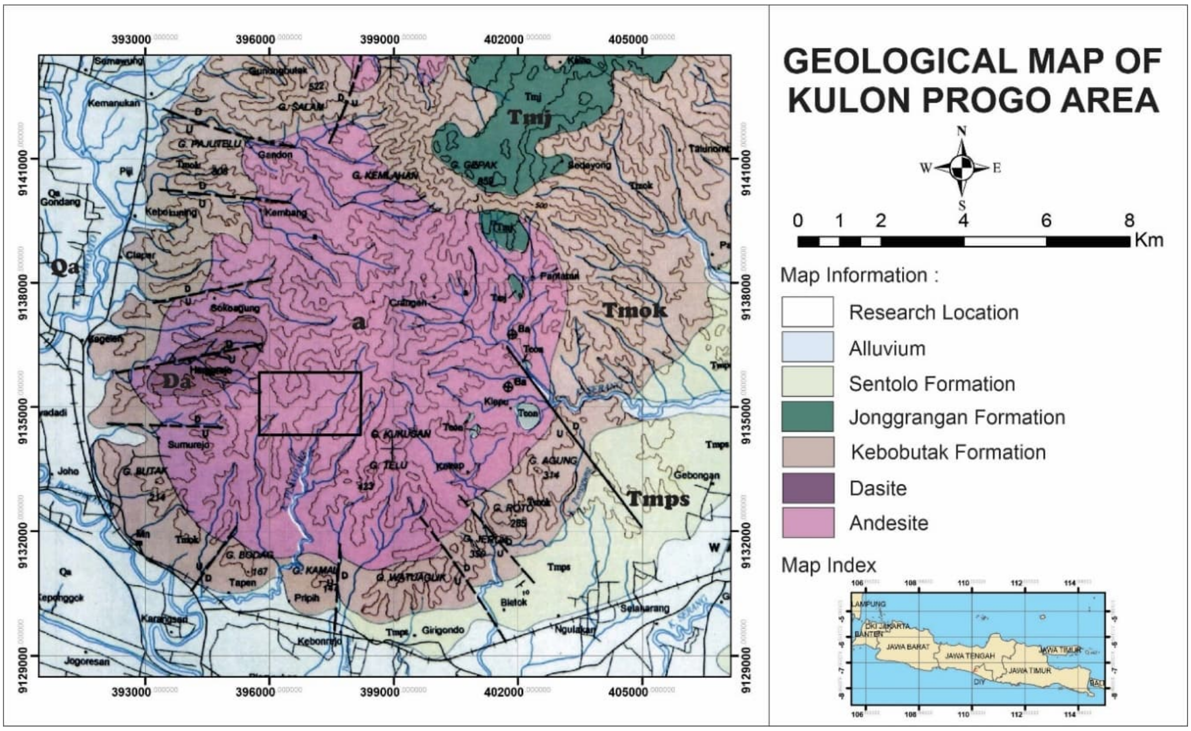

Figure 1. Geological Map of Yogyakarta (Rahardjo et al., 1995).

Physiographically, the Yogyakarta Region is a basin area bounded by several highlands, volcanic mountains and fault structures, where the north is bounded by Mount Merapi, in the east it is bounded by the Wonosari Mountains and the Opak Fault, and in the west, it is bounded by the Menoreh Hills. According to Bemmelen (1949), it is part of the Kulon Progo Mountains and is arranged in chronological order from oldest to youngest based on local strata. The low to medium wavy hills that make up the Nanggulan Formation are uniformly spaced throughout the region (eastern part of the Kulon Progo mountains). Locally, this formation is also present as lenses or xenolith blocks in andesitic igneous rocks in the Sermo, Gandul, and Kokap regions.

In the Kalisongo region, there is a site type called Nanggulan for the Nanggulan Formation. According to Bemmelen (1949), this formation, which had a littoral depositional environment during the sea flood epoch, is the oldest rock in the Kulon Progo Mountains. With an estimated thickness of 350 m, its constituent lithology comprises sandstone with lignite inserts, sandy marl, claystone with limonite concretion, marl and limestone inserts, sandstones, and tuff rich in

Foraminifera and molluscs. This formation-type area is made up of alternating marls and lignite, sandstones, shales, and shallow marine deposits. The Nanggulan Formation has an age range between the Middle Eocene and the Oligocene based on research on planktonic Foraminifera.

The Kebo Butak Formation which is exposed in the northern and southeastern parts of Kulonprogo is a younger formation than the underlying Nanggulan Formation which consists of rock units of lapilli, breccia, lapilli breccia, volcanic lava, agglomerate, and volcanic sandstone (Rahardjo et al., 1995). Based on the planktonic Foraminifera fossils found in marl, and the Oligocene Old Andesite Formation. In the Kulon Progo mountain complex, several eruption centres were found consisting of alternating lava and andesitic breccias (Soeria-Atmadja et al., 1994).

On top of the Old Andesite Formation, the unconformably deposited Jonggrangan Formation. The morphology formed from the rocks making up this formation is in the form of mountains and conical hills and is spread in the northern part of the Kulon Progo mountains. The thickness of the rocks making up this formation is 250 - 400 meters and is of Lower Miocene - Middle Miocene age. This formation is Lower Miocene in age and at the bottom, it is radiused with the lower part of the Sentolo Formation (Pringgoprawiro & Riyanto, 1987).

3. RESEARCH METHODS

The earth's surface is measured using the geoelectric method to determine the subsurface conditions based on resistivity measurements. These readings can be used to determine the subsurface layer's resistivity value. Different geological factors, such as mineral and water content, porosity, and the degree of water saturation in the rock, impact each layer's resistivity value (Loke, 1999). Ohm's law states that the potential difference (voltage) across a conductor is directly proportional to the current flowing through it and inversely proportional to its resistance (R). The resistance value can be expressed as follows:

$$R=\frac{V}{I} \quad (1)$$

The geoelectrical method assumes that the earth is considered a homogeneous medium or, in other words, has the same physical composition. Even though, in reality, the earth is not homogeneous, but heterogeneous, consisting of different layers. The apparent resistivity value can be formulated in the following equation:

$$\rho_a = K\frac{\Delta V}{I} \quad (2)$$

The value of K is a geometric factor that depends on the electrodes configuration, a current is introduced into the subsurface in a homogeneous isotropic medium, and a single current source will result in the propagation of a spherical electric current with a potential distribution forming an equipotential surface (Telford et al., 1990). Electric current is injected into the subsurface using two electrodes at a predetermined spacing. The potential value acquired represents the potential value impacted by the current flowing between the two electrodes. The potential electrodes P1 and P2 are used to monitor the potential difference after injecting electric current through electrodes C1 and C2. Therefore, the following equation can be used to determine the potential difference at P1 caused by the current injected at C1 and C2:

$$\Delta V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{r_1}-\frac{1}{r_2}\right)-\left(\frac{1}{r_3}-\frac{1}{r_4}\right)\right] \quad (3)$$

The current and potential electrodes must be parallel and symmetrical in the dipole-dipole design. The dipole-dipole configuration (**Figure 2**) offers better lateral resolution than the Wenner or Schlumberger configurations, making it especially useful for detecting vertical or steeply dipping structures like faults or fractures. It is more flexible in rough terrain and well-suited for detailed 2D or 3D imaging. Although it has weaker signal strength and shallower depth penetration compared to Schlumberger, its ability to clearly image lateral resistivity variations makes it a preferred choice for complex geological investigations. In this situation, a high impedance, high precision voltage measurement device is needed. Because there is no capability to make inhomogeneous rocks appear to be homogeneous in a dipole-dipole configuration, the term "apparent resistivity" used here instead of "actual resistivity" overlooks the geoelectrical measurement requirements, namely rock homogeneity (Loke, 2004).

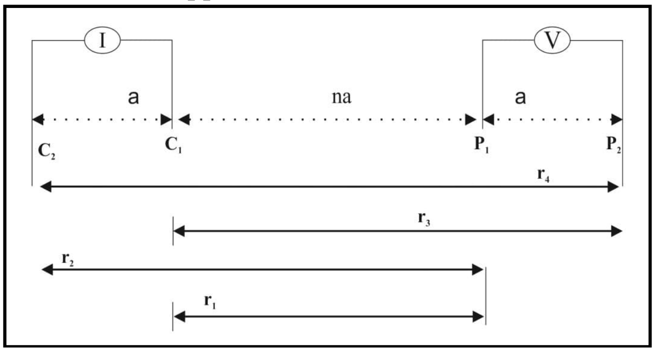

Figure 2. Dipole–dipole configuration (Loke, 2004).

In conducting this research, there are several stages carried out. The following is a research flowchart showing several stages in the research (**Figure 3**).

The initial stage of the investigation was to perform a literature review by learning about the local geological conditions. The following step involves utilizing Excel to process the initial data in *V* and *I* value to determine the apparent resistivity value. Then the data is processed using the Res2dinV program, which in the processing process will produce a 2D cross-section based on the results of 5 iterations. The 2D cross-section is subjected to interpretation and correlation to determine whether the geological conditions are met. Utilizing Rockworks15 software, the next step is to perform 3D modelling. This research also incorporates topographic data to enhance the accuracy of the 3D geological model and reflect surface elevation variations.

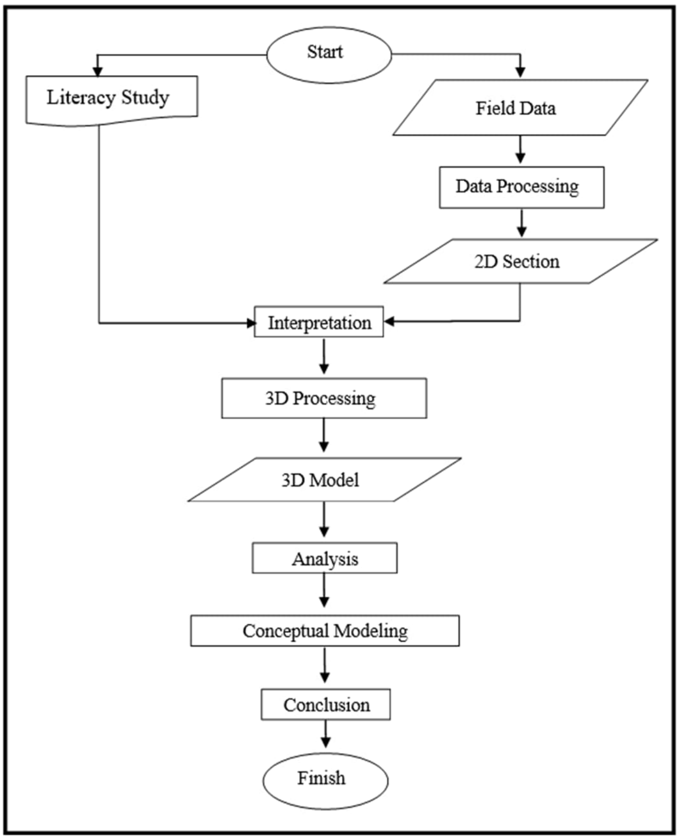

Figure 3. Research flowchart stage.

4. RESULTS AND DISCUSSION

4.1. 2D Resistivity Modelling and Interpretation

From the survey design that has been made, it is known that this research uses the dipole-dipole configuration geoelectric method which consists of 5 lines where each track has a track length of 290 m (**Figure 4**). Each track uses 14 electrodes and the distance between electrodes is 20 m.

Based on the measured resistivity values, the research region is divided into three categories, as seen from the resulting 2D resistivity cross-section. The first layer, which is demarcated from dark blue to light blue, has a low resistivity value between 36.9 Ω.m and 246 Ω.m, likely a response from the soil at the surface. The resistivity values in the second layer, which range from 246 Ω.m to 500 Ω.m, are coloured light green to dark green to indicate the weathering of andesitic rocks. There are several depths at which this layer is accessible on the surface. In the meantime, fresh andesite is considered to have high resistivity values >500 Ω.m, denoted by yellow to purple colors (**Figure 5**).

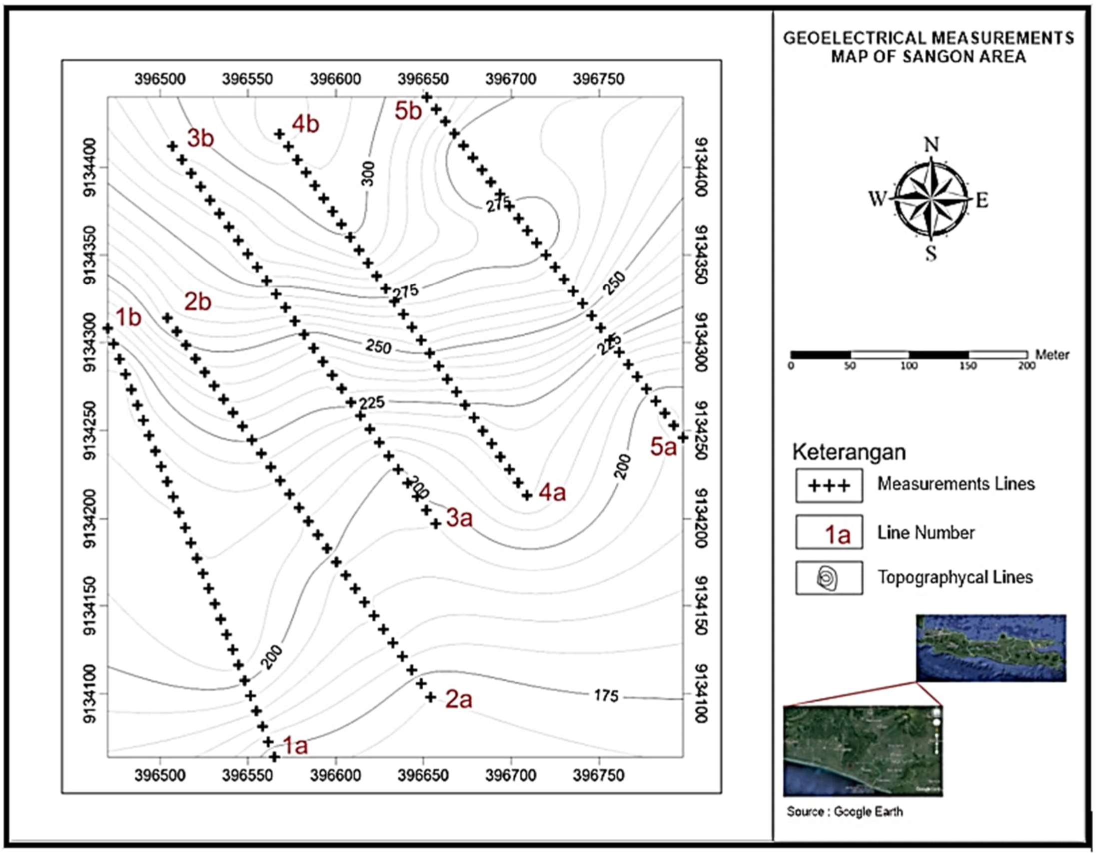

Figure 1. Acquisition survey design map using a dipole-dipole configuration in the Sangon Kulonprogo area.

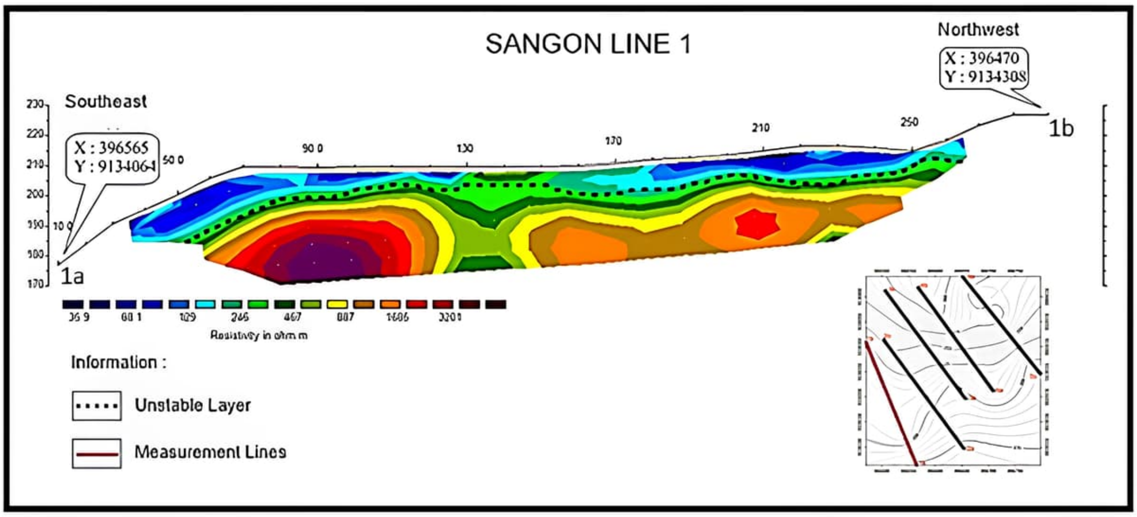

Figure 5. 2D Resistivity section line 1 Sangon.

According to **Figure 6**, the research area has a low resistivity value between 7.49 Ω.m to 101 .m, which is possibly a response from the soil on the surface and is indicated by the dark blue to light blue shading. The second layer's moderate resistivity value, which ranges from 102 Ω.m to 500 Ω.m, is indicative of the weathering of andesite rocks and is indicated by the presence of light to dark green tints. At a distance of 40–60 meters, this layer is visible on the surface. High resistivity values >500 m, meanwhile, is represented by yellow to purple tints and are thought to represent fresh andesite. A high resistivity value may be observed on the surface at a distance of 90 to 130 meters when viewed from this 2D section.

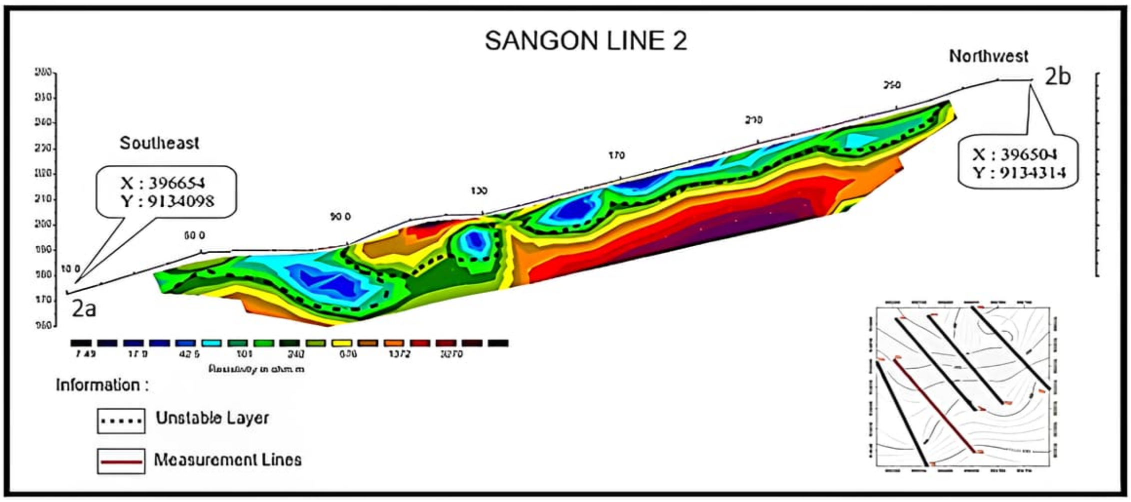

Figure 6. 2D Resistivity section line 2 Sangon.

If seen from the cross-section results (**Figure 7**), the variations in resistivity values obtained are almost the same as the previous cross-sections, namely low, medium and high. The low resistivity value is between 28 Ω.m – 121 Ω.m which is probably a response from the soil on the surface and is marked in dark blue to light blue. In the second layer, the resistivity value is moderate, which is between 122 Ω.m – 500 Ω.m, which is interpreted as weathering of andesite rocks and marked with light green to dark green colours. Meanwhile, high resistivity values > 500 Ω.m are interpreted as fresh andesite and marked with yellow to purple colours. When viewed from this 2D cross-section, moderate to high resistivity values are found at the measurement point 250 – 265, which are interpreted as chunks of andesite that have experienced weathering, which, if a landslide occurs, will cause the chunks to most likely be carried along avalanche material.

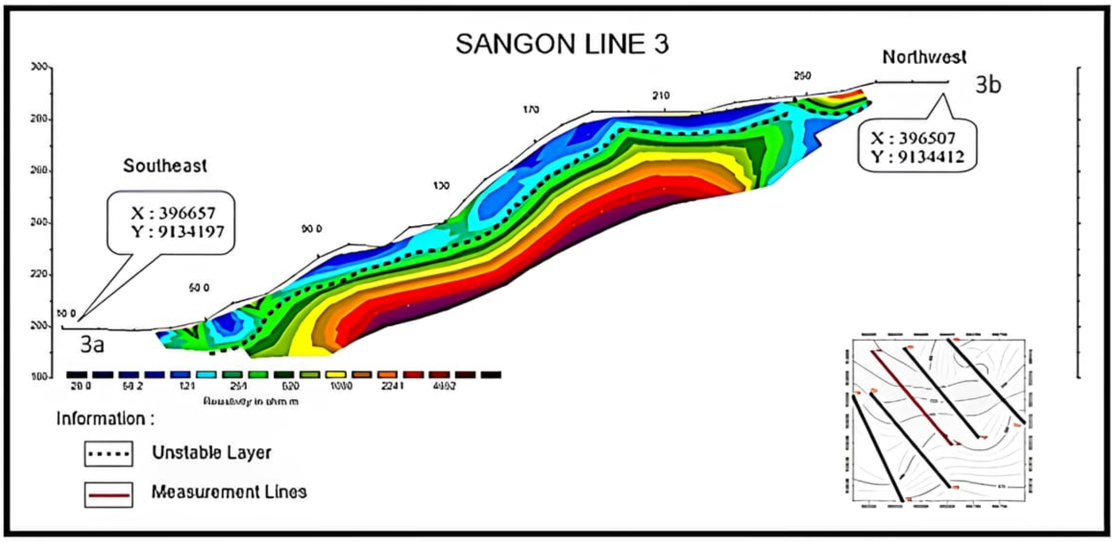

Figure 7. 2D Resistivity section line 3 Sangon.

The cross section of line 4 has a topography that tends to be the same as the third track (**Figure 8**). Interpretation of the cross section of line 4 is based on the table of resistivity values and geological information of the research area. The resistivity values obtained on the fourth track can be categorized into three, namely low, medium and high. The low resistivity value is between 33.1 Ω.m – 129 Ω.m which is probably a response from the soil on the surface and is marked in dark blue to blue. In the second layer, the resistivity value is moderate, which is between 129 Ω.m – 500 Ω.m, which is interpreted as weathering of andesite rocks and marked with light blue to green colours. Meanwhile, high resistivity values > 500 Ω.m are interpreted as fresh andesite and marked with dark green to purple colours. When viewed from the resistivity value obtained, the fresh andesite layer has a high resistivity value, which indicates that the layer is more compact and watertight than the other layers. This layer is suspected as a landslide slip plane.

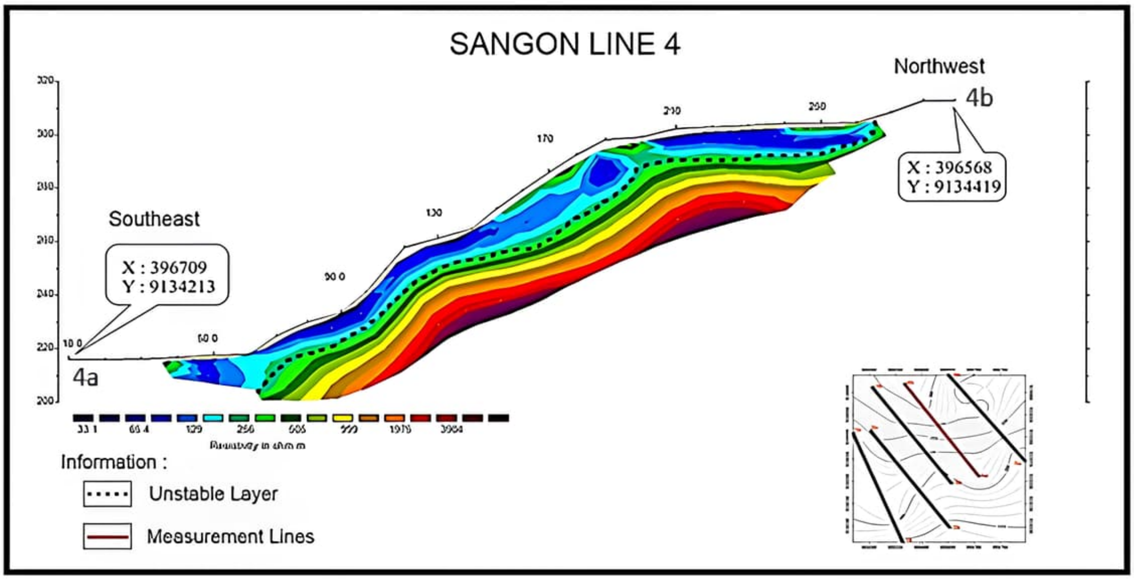

Figure 8. 2D Resistivity section line 4 Sangon.

In this 2D cross-section of line 5, interpretation is carried out based on the table of resistivity values and geological information of the research area. If seen from the cross-section results (**Figure 9**), the variations in resistivity values obtained are almost the same as the previous cross-sections, namely low, medium and high. The low resistivity value is between 21.3 Ω.m – 90.2 Ω.m which is probably a response from the soil on the surface and is marked in dark blue to blue. In the second layer, the resistivity value is moderate, which is between 90.2 Ω.m – 500 Ω.m, which is interpreted as weathering of andesite rocks and marked with light green to dark green colours. Meanwhile, high resistivity values >500 Ω.m are interpreted as fresh andesite and marked with dark green to purple colours. When viewed from the overall cross-sectional results, it is found that the fresh andesite layer is a layer that is suspected to be the slip plane of the landslide.

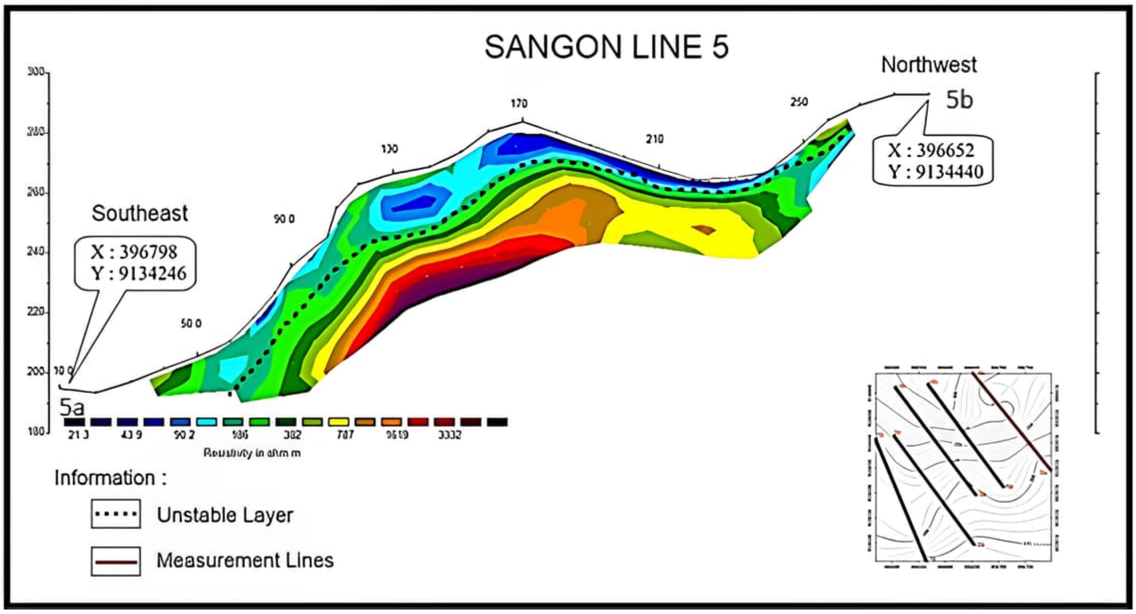

Figure 2. 2D Resistivity section line 5 Sangon.

From the results of the 2D modelling that has been done, it can be seen that line 5 has a height of 195 m at the starting point of the measurement and 293 m at the end of the measurement. The slope obtained from the Wenworth method calculation results is 36.53% with a steep slope classification. Meanwhile, the thickness of the unstable layer on line 5 varies between 5 – 12 meters. From the overall results of the 2D cross-section and the slope calculation, then on line 2, 3, 4, and 5, there is a high potential for landslides. The higher landslide is on line 4. Considering that the slope of the four measurement lines has a steep slope level. Therefore, it is necessary to watch out for the potential for landslides, especially in months with high levels of rainfall.

4.2. 3D Modelling and Conceptual Model Landslide

From the 2D modelling results that have undergone a resistivity cut-off process, the unstable layer's volume is 947,000 m^3 based on 3D modeling shown in **Figure 10**. 3D modeling was created using Rockworks15 software based on topographic data obtained from GPS in the field and topographic maps.

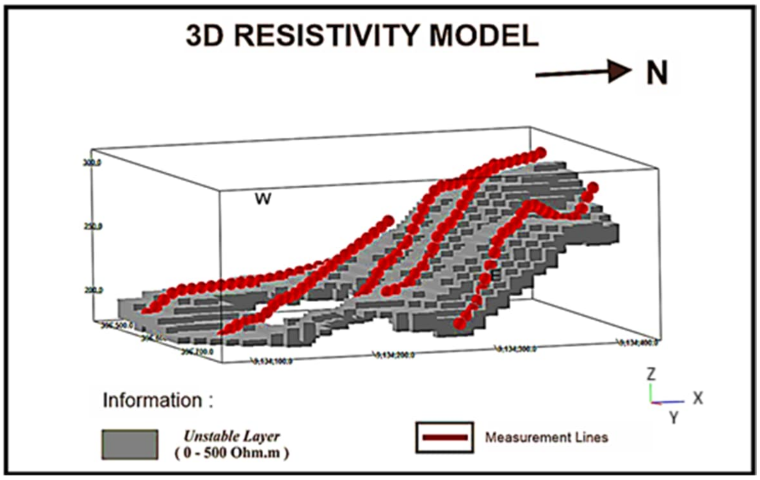

Figure 3. 3D Resistivity Model.

In contrast, the distribution of the unstable layer is found in the entire research area from the first to the last measurement path with a thickness between 3 – 12 meters. In the 3D model, it can be seen that on the surface, there are several empty areas. This is because, in that area, there is fresh andesite on the surface (**Figure 11**).

Figure 4. Andesite outcrop found in Line 2.

Following the findings of field investigations and 3D resistivity modelling (**Figure 10**), the conceptual model of a landslide presented in **Figure 12** was developed. This conceptual model of a landslide depicts the kind and motion of the landslide in the research area, indicating that a mixed type of landslide between a translational landslide and a debris flow is the sort that could occur in the research location. Debris flow is the movement of loose dirt, rock, organic materials, and water in a viscous fluid while flowing down a slope. Heavy rains that erode and mobilize loose soil or rock on steep slopes can result in debris flows. Meanwhile, transitional landslides are the movement of soil and rock masses on relatively flat slip planes.

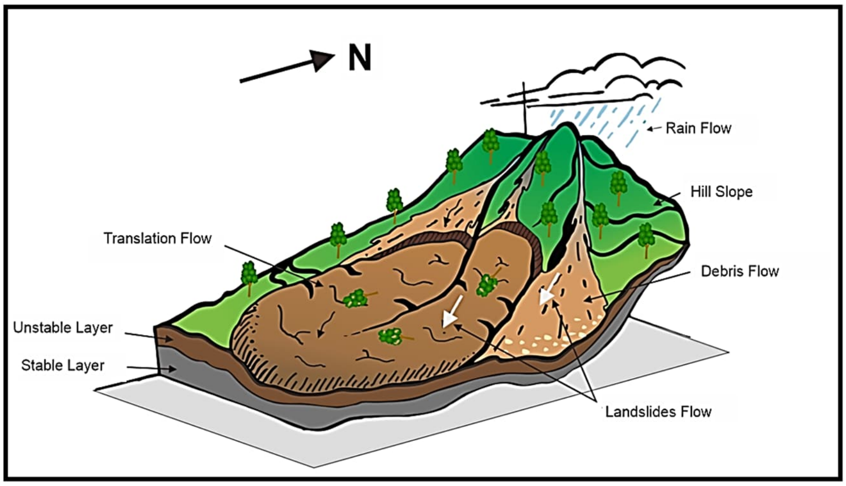

Figure 5. Conceptual model of Sangon landslides.

5. CONCLUSION

The data processing and analysis have led to several key conclusions. First, the 2D resistivity section reveals that the unstable layer in the research area exhibits resistivity values ranging from 7 to 246 Ω.m, with depths extending from

0 to 12 meters. Additionally, both weathered and unstable layers are found to be widely distributed across almost the entire study area. Finally, the potential landslide events in the region are characterized by debris flow and translational landslides, indicating the types of movements that could occur in the event of a landslide. These findings offer valuable insights into the subsurface conditions and potential landslide risks in the area.

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