

Analysis of Landslide Potential Based on Subsurface Lithology using Geoelectrical Method in Jatirejo, Wukirsari, Imogiri, Bantul, DIY

Hilma Lutfiana^{1*}, Rial Dwi Martasari¹, Rahmawati Fitrianingtyas¹, Uli Ulfa¹, Mafrida Fayza Putri Hidayat², and Khafidh Nur Aziz²

¹Geophysical Engineering Department, Faculty of Mineral Technology and Energy, UPN "Veteran" Yogyakarta, Yogyakarta, Indonesia

²Physics Education Department, Faculty of Mathematics and Science, Yogyakarta State University, Yogyakarta, Indonesia

*Corresponding author: hilmalutfiana@upnyk.ac.id

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ABSTRACT

Landslides are among the most recurrent natural hazards in Indonesia, particularly within the Special Region of Yogyakarta, where Bantul Regency is classified as a high-risk zone. Jatirejo Hamlet, situated in Wukirsari Village, Imogiri Subdistrict, is characterized by steep slope morphology, complex geological conditions, and high rainfall intensity, all of which contribute to its high landslide susceptibility. This research aimed to characterize the subsurface lithology and identify potential slip surfaces in this area using the electrical resistivity method with Wenner array array. Geoelectrical surveys were conducted along four lines, each 225 meters in length, utilizing a Naniura NRD 300 HF resistivity meter. The inversion result indicated the presence of a low-resistivity layer (0.05-8.4 Ωm), interpreted as water-saturated clay, underlying more permeable layers and likely functioning as a slip plane. These conditions suggest a high potential for mass movement driven by gravitational forces and local geological structures, including the Opak Fault. The findings demonstrate that the Wenner array effectively delineates subsurface slip surfaces and can serve as a valuable tool for informing hazard assessment and the development of mitigation strategies in landslide-prone regions such as Jatirejo.

1. Introduction

Landslides are among the most frequently occurring natural disasters in Indonesia and have the potential to cause significant damage to the environment, infrastructure, and human safety. According to data from the Badan Nasional Penanggulangan Bencana (BNPB), a total of 4,246 landslide events were recorded across various regions of Indonesia between 2019 and 2023 [1]. The Special Region of Yogyakarta, particularly Bantul Regency, is one of the areas with a high level of landslide susceptibility. Based on data from the Badan Penanggulangan Bencana Daerah (BPBD) of Yogyakarta, there were 707 landslide incidents in 2022, making it the most dominant type of disaster in the past five years [2]. One of the most affected areas is Imogiri District, especially Jatirejo Hamlet in Wukirsari Village. This region is located within a hilly zone with slopes exceeding 25% and is traversed by an active geological structure, the Opak Fault, which may further increase slope instability during seismic activity [3], [4].

These geological and geomorphological conditions increase the likelihood of landslides, particularly during periods of high rainfall that trigger a rise in pore water pressure and a reduction in slope stability [5]. Therefore, geophysical investigations are required to identify subsurface structures and detect the presence of slip surfaces as part of disaster mitigation efforts. One effective method is the resistivity geoelectrical method using

the Wenner array, as it offers high vertical resolution and is sensitive to lateral lithological variations [6], [7].

Several landslide susceptibility assessments have been conducted in the Imogiri District; however, investigations explicitly targeting subsurface conditions in Jatirejo Hamlet remain scarce. Geoelectrical resistivity methods have been extensively employed to delineate subsurface lithology and identify slip surfaces in landslide-prone terrains. [6] Demonstrated the capability of the Wenner array in detecting water-saturated clay layers acting as potential slip planes in Padang City. Similarly, [7] highlighted the array's advantages in terms of high vertical resolution and enhanced sensitivity to lateral resistivity contrasts, which critical for slope stability analysis. Despite these findings, no study to date has focused on subsurface characterization and slip surface detection in Jatirejo Hamlet using the Wenner array. This research, therefore, seeks to address this gap by providing detailed subsurface information to support landslide mitigation efforts in the area.

Landslides are among the most extensively studied natural hazards, particularly in relation to their triggering factors and the identification of susceptible zones. The geoelectrical resistivity method has been widely recognized as an effective technique for delineating subsurface lithology and detecting slip surfaces that act as primary failure planes. For instance, [8] employed the Wenner-

Schlumberger and Wenner-Alpha arrays to assess the potential of landslides along the Suban Highway in Bandar Lampung. Their findings revealed that variations in subsurface resistivity correspond to differences in permeability, which indicate the presence of potential slip planes. Consequently, they recommended the geoelectrical method as a non-destructive and efficient tool to support landslide mitigation efforts.

In the Imogiri district of Bantul Regency, several studies have been conducted with similar objectives. [9] utilized the Wenner array in Selopamiro Village and successfully delineated weak layers that may function as failure zones. Another research by [10] integrated the Dipole-Dipole resistivity array with Geographic Information Systems (GIS) to assess landslide susceptibility in Sangon Village, providing a more comprehensive spatial understanding of vulnerable areas. Furthermore, [11] applied the Dipole-Dipole array in Sriharjo Village and the broader Imogiri Region, confirming the presence of low-resistivity layers indicative of potential slip surfaces. This research collectively highlights the crucial role of geoelectrical methods in identifying subsurface instability, thereby offering valuable insights for developing a more targeted and preventive landslide mitigation strategy in the Imogiri area.

Several recent research have demonstrated the effectiveness of electrical resistivity tomography (ERT) for characterizing landslide-prone subsurface conditions, particularly where low resistivity values correlate with clay-rich and water-saturated zones that act as potential slip surfaces. For example, integrated ERT and seismic refraction tomography have been successfully applied to delineate weak subsurface zones linked to slope failure in southern Thailand [12] while combined ERT and VES approaches reveal similar low-resistivity clay and saturated layers controlling landslide instability [13]. Researchers have also developed improved geophysical and geotechnical models to better understand slope materials and failure mechanisms in diverse geological settings [14].

2. Method

This research was conducted from November 2023 to April 2024 in Jatirejo Hamlet, Wukirsari Village, Imogiri District, Bantul Regency, Special Region of Yogyakarta. The research area is geographically situated between -7.911065° to -7.913475° S and -110.415854° to 110.418364° E. The site was chosen based on geomorphological and geological characteristics indicating a high susceptibility to mass movement. The following is a research flowchart showing several stages in the research (Figure 1).

The geoelectrical resistivity survey employed the Wenner array, which was selected for its capability to provide excellent vertical resolution and high sensitivity to lateral variations in subsurface lithology. This approach aimed to characterize subsurface geological conditions and to delineate potential slip surfaces and weak zones that may serve as initiation planes for landslides.

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[15]:

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

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 array, 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[16].

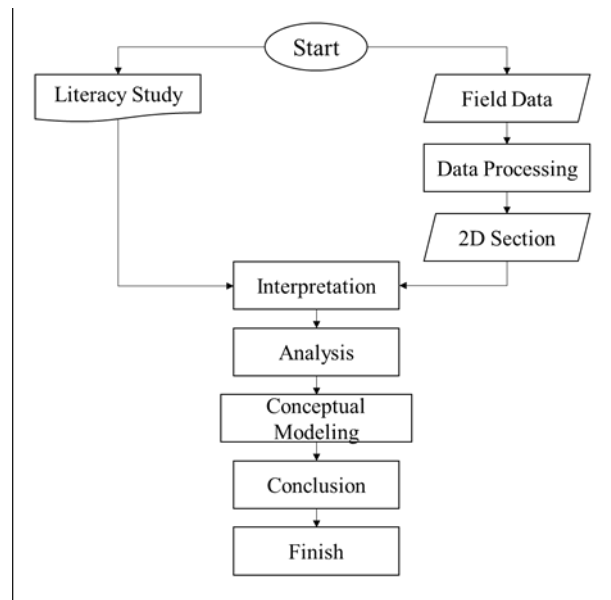


Fig. 1: Research flowchart

The Wenner array was commonly employed in lateral or mapping-type geoelectrical surveys [17]. In lateral measurements, higher vertical resolution was achieved with this array compared to other array types [18]. Various electrode arrays in geoelectrical surveys exhibit different sensitivities and resolutions depending on the target geometry and investigation objectives. Although arrays such as Schlumberger and Gradient arrays generally provide better resolution for steeply dipping structures and higher sensitivity to surface inhomogeneity, the Wenner array offers superior vertical resolution and a higher signal-to-noise ratio, particularly in environments characterized by strong lateral resistivity contrasts and highly conductive near-surface materials.

In landslide-prone volcanic terrains dominated by water-saturated clay layers, the Wenner array is effective in delineating laterally continuous weak horizons that function as slip surfaces. Therefore, despite its limitations in resolving steep structures, the Wenner array was selected in this study to

emphasize accurate imaging of shallow subsurface layering and clay-rich zones that primarily control landslide initiation [15]. In the Wenner array, the electrodes were arranged linearly and symmetrically with respect to the sounding point, with equal spacing where $r_1 = r_4 = a$ and $r_2 = r_3 = 2a$ [16], as shown in Figure 2. The distance between the current electrodes (C_1 and C_2) was set to three times the spacing between the potential electrodes (P_1 and P_2).

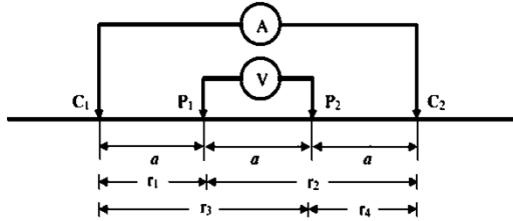


Fig. 2: Wenner array [12]

Data acquisitions in this research involved both hardware and software components. The hardware setup comprised a Naniura NRD 300 HF resistivity meter, batteries as a power source, stainless steel current electrodes, copper potential electrodes, connecting cables, measuring tape, geological hammer, Garmin 78S GPS, handy talkie (HT), compass, alligator clips, field recording sheets, and a laptop for data processing.

The software tools included Google Earth and QGIS for site localization and geological mapping, Microsoft Excel for computing resistance and apparent resistivity values, Notepad and Res2DinV for two-dimensional inversion and modelling, and RockWorks for three-dimensional visualization of subsurface lithology. These integrated tools ensured accurate data collection, processing, and visualization of resistivity variations across the research area. Four survey lines were established in total—two oriented vertically and two horizontally—each extending 225 meters in length. Electrode spacing was maintained at 15 meters, determined based on field accessibility and the desired data resolution. The survey layout and electrode array are illustrated in Figure 3. The locations of the geoelectrical measurement lines were determined by integrating slope morphology, surface geological features, and historical landslide records. The survey lines were arranged to maximize sensitivity to lateral resistivity contrasts across suspected slip zones, enabling the Wenner configuration to effectively delineate weak clay-rich horizons beneath the slope.

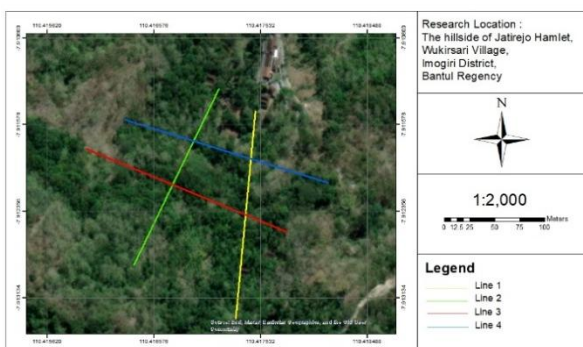


Fig. 3: Acquisition survey design map using a Wenner array in the Jatirejo, Wukirsari, Imogiri, Bantul.

The acquired data included measurement of current strength (I), potential differences (V), as well as coordinates positions and elevation. These datasets were processed using Microsoft Excel to calculate apparent resistivity (ρ_a) values based on fundamental resistivity equation. The resulting data were subsequently converted into *.dat format and analyzed using Res2DnV software. Through an inversion process, two-dimensional subsurface resistivity sections were generated, providing a detailed representation of subsurface variations. Furthermore, RockWorks software was employed to construct three-dimensional visualizations, enabling a more comprehensive spatial interpretation of the lithological structures.

3. Geological Setting

Regionally, the study area is located within the Southern Mountains Zone of Java, which developed as a result of Paleogene–Neogene volcanic activity related to the subduction of the Indo-Australian Plate beneath the Eurasian Plate. The regional stratigraphy is dominated by volcanic and volcanoclastic sequences that have undergone tectonic deformation and intensive weathering. Geological structures such as faults and fractures are widely developed and play an important role in controlling slope morphology and stability.

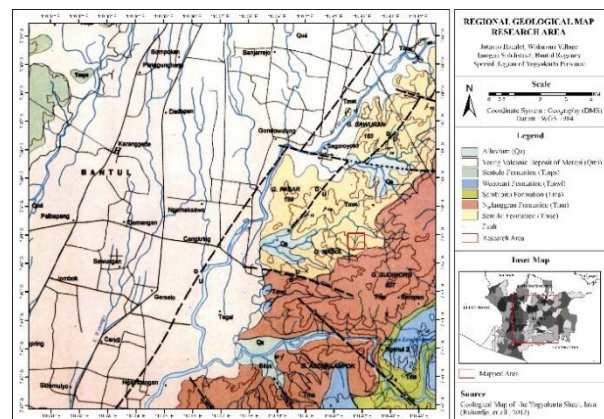


Fig. 4: Regional Geological map of location. Modified from [19]

Based on Regional Geological map [19], the lithological framework of the study area is primarily composed of the Semilir Formation, which is widely exposed in the eastern part of Bantul Regency, including the Imogiri area is presented in Figure 4. The Semilir Formation mainly consists of tuff, lapilli tuff, volcanic breccia, and tuffaceous sandstone, which were deposited by explosive volcanic activity during the Early to Middle Miocene. These volcanoclastics are generally weakly consolidated and highly susceptible to weathering, resulting in the development of thick residual soil and clay-rich layers.

In the study area, weathering of tuffaceous materials from the Semilir Formation produces clayey layers with low permeability, which commonly act as mechanically weak horizons. These layers tend to function as potential slip surfaces, particularly under saturated conditions. Overlying volcanic breccia units contribute additional loading to the slope, increasing shear stress along the clay-rich horizons. The presence of joints and fractures further enhances rainwater infiltration, leading to

increased pore water pressure and a reduction in shear strength [20].

Such geological conditions generate significant contrasts in the physical properties of subsurface layers, which are reflected in variations in electrical resistivity values. Therefore, the geoelectrical method provides an effective means to delineate subsurface lithology and identify weak zones associated with landslide initiation in the study area [21].

Data interpretation was carried out by correlating the modeled resistivity values with local geological and lithological data obtained from previous surveys and field observations. Subsurface rock classification was determined based on standard resistivity ranges that correspond to specific physical properties and lithological compositions. This process facilitated the identification of weak zones and potential slip surface associated with landslide initiation. The resulting 2D and 3D models served as the scientific basis for developing targeted recommendations for ground movement mitigation in the research area.

4. Result and Discussions

Line 1

The 2D resistivity cross-section obtained from an Electrical Resistivity Tomography (ERT) survey along Line 1, with an electrode spacing of 15 m and topographic correction, shows resistivity values ranging from approximately 0.05 to 3624.4 Ωm . The two-dimensional cross section of Line 1 is presented in Figure 5.

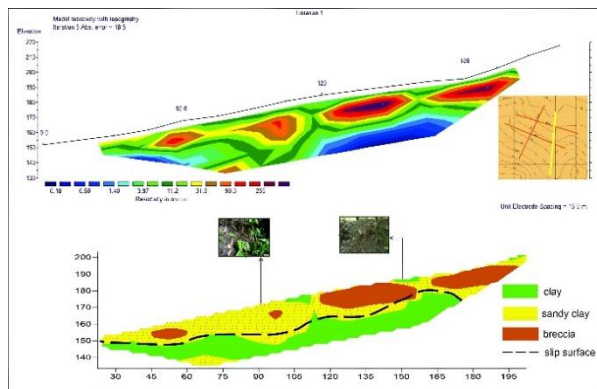


Fig 5. 2D cross-section model of resistivity distribution of line 1

The inversion result, achieved at the fifth iteration with an absolute error of 18.5%, reflects the lithological heterogeneity characteristic of the Semilir Formation, which is composed of volcanic pyroclastic materials. Low resistivity zones ($\approx 0.05\text{--}8.4 \Omega\text{m}$) are interpreted as water-saturated clay layers with low permeability, moderate resistivity zones ($\approx 8.4\text{--}186 \Omega\text{m}$) represent sandy clay or sandy tuff, while high resistivity zones ($\approx 186\text{--}3624.4 \Omega\text{m}$) are interpreted as volcanic breccia or coarse pyroclastic deposits that are relatively compact and dry. Very low resistivity values in water-saturated clay materials have been widely reported in the geophysical literature. Clay with a high degree of water saturation, conductive clay mineral content, and ion-rich pore fluids can exhibit resistivity values of less than 1 Ωm .

Reynolds [18] explains that wet clay materials with high surface conductivity associated with clay minerals may produce extremely low resistivity values, even approaching 0.5 Ωm . In this context, the

resistivity range of approximately 0.05–0.8 Ωm identified in this study is interpreted as highly water-saturated clay and remains physically plausible, particularly under conditions of intense rainfall infiltration and elevated pore water pressure in landslide-prone slopes. The integration of ERT results with field observations yields a conceptual subsurface model indicating the presence of a slip surface at the boundary between the sandy clay and clay layers.

Line 2

This line extends 225 meters vertically from south to north, with a slope gradient of 35%. The two-dimensional cross-section of Line 2 is presented in Figure 6.

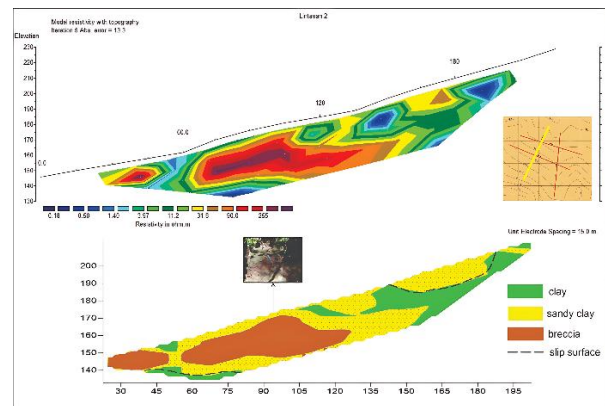


Fig. 6: 2D cross-section model of resistivity distribution of line 2

The 2D resistivity cross-section derived from an Electrical Resistivity Tomography (ERT) survey along Line 2, using an electrode spacing of 15 m and applying topographic correction, reveals resistivity values ranging from approximately 0.05 to 3624.4 Ωm , with the inversion carried out up to the fifth iteration and yielding an absolute error of 13.3%. The maximum depth of investigation along this line reaches approximately 30–35 m below the ground surface, which is sufficient to characterize subsurface conditions within a landslide-prone zone. The observed resistivity distribution reflects the lithological heterogeneity typical of the Semilir Formation, which is composed of volcanic pyroclastic deposits such as tuff, volcanic breccia, and interbedded clay to sandy clay layers with varying degrees of weathering.

Low resistivity zones ($\approx 0.05\text{--}8.4 \Omega\text{m}$) are interpreted as water-saturated clay layers, predominantly occurring at depths of approximately 10–30 m and showing lateral continuity along the line. Overlying these units, moderate resistivity zones ($\approx 8.4\text{--}186 \Omega\text{m}$) correspond to sandy clay or sandy tuff, with variable thicknesses and dominant depths ranging from about 5 to 15 m below the surface. In contrast, high resistivity zones ($\approx 186\text{--}3624.4 \Omega\text{m}$) are interpreted as volcanic breccia or coarse pyroclastic deposits that are relatively compact and dry, generally appearing at shallow to intermediate depths of approximately 0–10 m and occurring as discontinuous lenses. The integration of ERT results with field observations indicates that a slip surface is developed at the interface between the sandy clay and the underlying clay layer, where contrasts in

physical properties and water saturation create a mechanically weak zone that controls the landslide mechanism within the Semilir Formation.

Based on the resistivity cross-section along Line 2, the zone with the highest landslide potential is identified at distances of approximately 60–120 m along the profile. In this segment, a laterally continuous low-resistivity layer ($\approx 0.05\text{--}8.4 \Omega\text{m}$), interpreted as water-saturated clay, underlies a moderately resistive sandy clay unit and is overlain by relatively high-resistivity volcanic breccia. This lithological arrangement creates a mechanically unfavorable condition, where the saturated clay layer acts as a weak horizon, while the overlying breccia imposes additional loading that increases shear stress along the interface. The slip surface is inferred to develop along the boundary between the sandy clay and the underlying clay layer, as indicated by the contrast in resistivity values and the geometry of the resistivity contours.

Toward the left side of the profile (approximately 0–45 m), the continuity of breccia, sandy clay, and clay layers is less clearly defined. This ambiguity is attributed to the presence of discontinuous breccia lenses, lateral lithological heterogeneity, and possible near-surface inhomogeneities that reduce resistivity contrast resolution in this segment. Consequently, although breccia appears at the lower part of the section, the lack of a well-developed, laterally continuous clay horizon in this area suggests a relatively lower landslide potential compared to the central part of the profile.

Line 3

This line extends 225 meters vertically from west to east, and cross with first line and second line. The two-dimensional cross-section of Line 3 is presented in Figure 7.

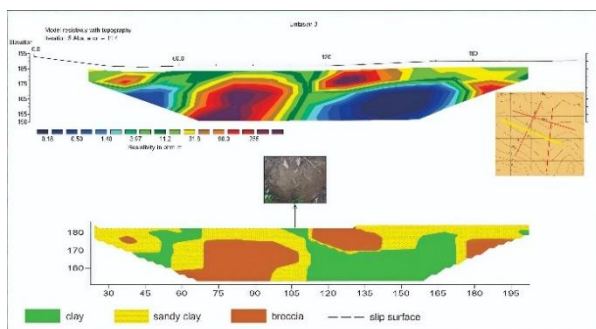


Fig. 7: 2D cross-section model of resistivity distribution of line 3

The 2D resistivity cross-section obtained from an Electrical Resistivity Tomography (ERT) survey along Line 3, using an electrode spacing of 15 m and applying topographic correction, reveals resistivity values ranging from approximately 0.05 to 3624.4 Ωm . The inversion was performed up to the fifth iteration, resulting in an absolute error of 11.4%. The maximum depth of investigation along this line reaches approximately 25–30 m below the ground surface, which is sufficient to characterize shallow to intermediate subsurface conditions relevant to slope stability analysis. The observed resistivity distribution reflects the lithological heterogeneity typical of the Semilir Formation, which is composed

of volcanic pyroclastic deposits such as tuff, volcanic breccia, and interbedded clay to sandy clay layers with varying degrees of weathering.

Low resistivity zones ($\approx 0.05\text{--}8.4 \Omega\text{m}$) are interpreted as water-saturated clay layers, generally occurring at depths of approximately 12–30 m and exhibiting lateral continuity along the line. Overlying these units, moderate resistivity zones ($\approx 8.4\text{--}186 \Omega\text{m}$) correspond to sandy clay or sandy tuff, with variable thicknesses and dominant depths ranging from about 5 to 15 m below the surface. In contrast, high resistivity zones ($\approx 186\text{--}3624.4 \Omega\text{m}$) are interpreted as volcanic breccia or coarse pyroclastic deposits that are relatively compact and dry, typically developed at shallow to intermediate depths of approximately 0–10 m and occurring as discontinuous lenses. The integration of ERT results with field observations indicates that a slip surface is developed at the interface between the sandy clay and the underlying clay layer, where contrasts in physical properties and water saturation form a mechanically weak zone that controls the landslide mechanism within the Semilir Formation.

Line 4

The last survey profile, referred to as Line 4, extends in an east–west direction, running parallel to Line 3 and perpendicular to Lines 1 and 2. The corresponding two-dimensional resistivity cross-section is presented in Figure 8.

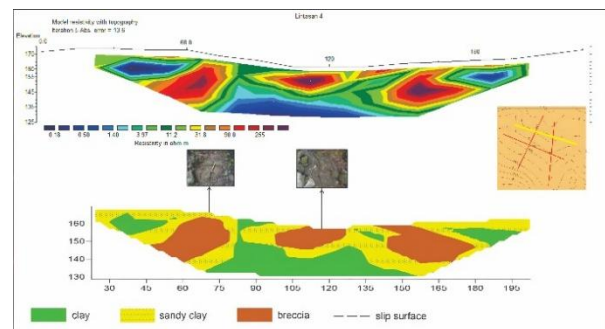


Fig. 8: 2D cross-section model of resistivity distribution of line 4

The two-dimensional resistivity cross-section obtained from an Electrical Resistivity Tomography (ERT) survey along Line 4, using an electrode spacing of 15 m and applying topographic correction, reveals resistivity values ranging from approximately 0.05 to 3624.4 Ωm . The inversion was performed up to the fifth iteration, resulting in an absolute error of 15.8%. The maximum depth of investigation along this line reaches approximately 25–30 m below the ground surface, which is sufficient to characterize shallow to intermediate subsurface conditions within a landslide-prone area. The recorded resistivity distribution reflects the lithological heterogeneity characteristic of the Semilir Formation, which is composed of volcanic pyroclastic deposits, including tuff, volcanic breccia, and interbedded clay to sandy clay layers with varying degrees of weathering.

Low resistivity zones ($\approx 0.05\text{--}8.4 \Omega\text{m}$) are interpreted as water-saturated clay layers, generally occurring at depths of approximately 12–30 m and exhibiting relatively good lateral continuity along the line. Moderate resistivity zones ($\approx 8.4\text{--}186 \Omega\text{m}$) correspond to sandy clay or sandy tuff, with variable thicknesses and dominant depths ranging from about

5 to 15 m below the surface. In contrast, high resistivity zones ($\approx 186\text{--}3624.4 \Omega\text{m}$) are interpreted as volcanic breccia or coarse pyroclastic deposits that are relatively compact and dry, typically developed at shallow to intermediate depths of approximately 0–10 m and occurring as discontinuous lenses. The direction of landslide movement is toward the north. The integration of ERT results with field observations indicates that a slip surface is developed at the interface between the sandy clay and the underlying clay layer, which acts as a mechanically weak zone due to contrasts in physical properties and water saturation and serves as the primary controlling factor of the landslide mechanism within the Semilir Formation.

5. Conclusions

The subsurface structure of the landslide area in Jatirejo Hamlet, Wukirsari Village, Imogiri District, Bantul Regency, as interpreted from resistivity values, consists of four main layers: clay, freshwater-bearing layer, sandstone, and breccia. The clay layer exhibits resistivity values ranging from 0.05 to 8.4 Ωm , the freshwater layer from 8.4 to 13.3 Ωm , the sandstone layer from 13.3 to 186 Ωm , and the breccia layer from 186 to 3624.2 Ωm . The water-saturated clay layer acts as a mechanically weak horizon, while the overlying breccia and sandstone units impose additional loading that increases shear stress. This condition is further intensified by rainfall infiltration, which reduces shear strength and increases pore water pressure, thereby controlling the initiation and development of slope failure. Consequently, landslide susceptibility in the study area is strongly governed by the lithological array of the Semilir Formation, particularly by the presence of a laterally continuous clay layer underlying more competent pyroclastic materials. Based on the geometric characteristics of the inferred failure surface, the landslide mechanism in the study area is classified as a rotational slip.

This research provides a site-specific contribution by demonstrating the effectiveness of the Wenner resistivity array in delineating laterally continuous water-saturated clay layers that control rotational landslide mechanisms within the volcanics of the Semilir Formation. The integration of two-dimensional and three-dimensional resistivity models offers a practical subsurface framework that can be directly applied to landslide hazard assessment and mitigation planning in similar geological settings. Future research should focus on integrating time-lapse resistivity monitoring with geotechnical and rainfall data to better quantify temporal changes in pore water pressure and to improve landslide prediction and early-warning strategies.

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