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Recent developments in the use of geoelectric resistivity for landslide surveys: an overview

Selly Feranie[1*], Adinda Pramesti Wahyuning Putri[1], Amata Kara Perdani Handiman[1], Adrin Tohari[2]

[1]*Department of Physics, Universitas Pendidikan Indonesia, Indonesia*

[2]*Badan Riset dan Inovasi Nasional, Indonesia*

**E-mail: feranie@upi.edu*

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ABSTRACT

The peak of the rainy season in 2022/2023 has caused many disasters, especially landslides in Indonesia, which have claimed many victims and caused damage to settlements and infrastructure. Various geophysical methods have been widely applied to identify slip fields. In addition, geophysical methods are used to determine the type and characteristics of landslides. The slip field has a lithology of 2 subsurface layers of soil or contrasting rocks, namely soft and hard soil layers. Therefore, one of the geophysical methods that is effective in identifying slip planes is the geoelectric method because of the stark contrast in resistivity in the two soil layers. This article will review research that uses geoelectric data to survey landslide potential in the last ten years. In addition, this article also reviews the latest research related to geoelectricity, namely *Time-Lapse Electrical Resistivity Tomography* (TL-ERT), starting from studies that have used this method and the potential and direction of using this method in the future.

Keywords: Avalanche, geoelectric resistivity, slip field, TL-ERT

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INTRODUCTION

The territory of Indonesia is included in the tropics, resulting in frequent rainy seasons. According to BMKG, in 2022/2023, the Indonesian region experienced high-category rainfall of 21.71% (BMKG, 2023). Due to frequent rain, this can result in avalanches. Sitepu (2017) said that every rainwater that falls to the bottom of the soil has great kinetic energy, thus causing damage to soil particles and making the ground unstable. This avalanche can be followed up its potential by using environmentally friendly geophysical methods. Geophysics is a branch of science that focuses on investigating structures under the earth's surface using physical equipment. In geophysics, the parameters of the physical properties of the earth have a significant role in the study of its structure and physical properties. Geophysical methods are known to consist of two types, namely active geophysical methods and passive geophysical methods. Active geophysical methods inject signals or fields affected by the earth's structure. If the geophysical method is inactive, it works by receiving natural calls, in other words, it does not inject something against the earth (Zuhdi et al., 2021).

One geophysical method that is often used to analyze avalanches is resistivity geoelectricity, such as research conducted by Aryanto and Indriastuty (2020) in the Central Java area, Tejakusuma et al. (2020) in West Java, and Utiya (2015) in Manado City. These studies show that this resistivity geoelectric method is suitable for describing the subsurface structure of avalanche areas. This article will review previous studies related to the development of geoelectric applications for avalanches over the past ten years and will also check the latest method, *Time-Lapsed Electrical Resistivity Tomography* (TL-ERT), and how the potential of the TL-ERT method in the future.

RESEARCH METHODS

The method used in writing this article is a review of national and international literature obtained through Google Scholar searches. The literature used was previously ascertained whether it had been indexed by Scopus or Sinta, at least Sinta 4. The articles sought are also identified and analyzed in advance to determine whether they are relevant to the writing of this article review, namely the application of resistivity geoelectricity for slope movement. Through this search stage, approximately 30 articles were obtained from 2000 to 2022 with search keywords, namely "geophysics," "geoelectricity," "slope," "avalanche," and "TL-ERT."

RESULTS & DISCUSSION

Geophysical Methods: Geoelectric Resistivity

Geophysical methods have branches of methods related to electricity on Earth. It is known that this earth has several layers of soil that have different physical properties from other soil layers. Such differences can occur due to different atomic structures with rocks in layers. Atoms have their electrical conductivity, form matter in nature, and cause the emergence of various natural sciences that study the electrical properties caused by these materials, such as geoelectricity. Geoelectric methods study the state of the earth's subsurface with the characteristics of electric flow (Vebrianto, 2016).

This method works by injecting an electric current into the ground surface using a current electrode. The potential difference will be measured by using a potential electrode. The results indicate prisoners of various soil layers (Nengah Simpen, 2015). As depicted can be seen in Figure 1.

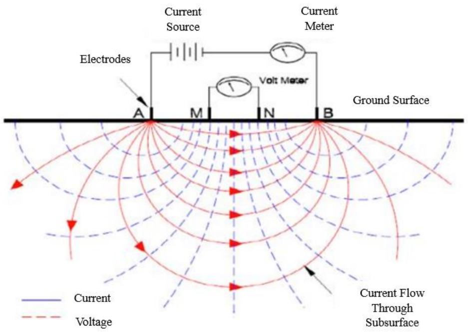

Figure 1. Geoelectric method working system (Rizky, 2015)

Geoelectric methods can be found in 2 types: active geoelectric methods and passive geoelectric methods. Passive Geoelectric methods, such as self-potential, can be known by obtaining values derived from rocks. Active geoelectric methods such as resistivity and *Induced Polarization* (IP), where this active geoelectric method works by injecting electrodes or electric current into the earth. Because this Active Geoelectric Method uses electric current, a configuration is needed to understand a resistant layer. The structure of the geoelectric method has various variations, namely:

1. Wenner Alpha Configuration

   This configuration is used for research that requires spaced with long distances. Vebrianto (2016), in his book Exploration of Geoelectric Methods, said that this Wenner Configuration has three types: wennerr alpha, wenner beta, and wenner gamma configurations. Compared to other configurations, the Wenner Alpha configuration is sensitive to changes in lateral and shallow resistivity. The configuration of Wenner Alpha can be seen in Figure 2.

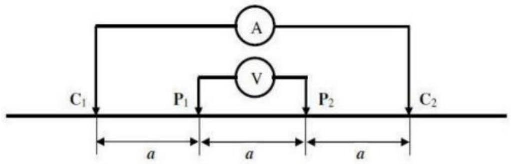

Figure 2. Wenner-Alpha configuration form (Pazha, 2019)

According to Figure 2, the formula for the configuration is obtained. So, the formula, namely:

$$r_1 = P_1 - C_1 \quad (1)$$

$$r_1 = a$$

$$r_2 = P_1 - C_2 \quad (2)$$

$$r_2 = a + a$$

$$r_2 = 2a$$

$$r_3 = P_2 - C_1 \quad (3)$$

$$r_3 = a + a$$

$$r_3 = 2a$$

$$r_4 = P_2 - C_2 \quad (4)$$

$$r_4 = a$$

After obtaining each value of r, the Wenner alpha geometry correction factor, namely :

$$K = 2\pi\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right]^{-1} \quad (5)$$

To complete the formula, it is necessary to produce equations from (1), (2), (3), and (4). From these results that have been combined into equation (5), it will produce the following:

$$K = 2\pi\left[\left(\frac{2-1}{2a}\right) - \left(\frac{1-2}{2a}\right)\right]^{-1}$$

$$K = 2\pi\left[\left(\frac{1}{2a}\right) + \left(\frac{1}{2a}\right)\right]^{-1}$$

$K = 2\pi\frac{2a}{2}$, or it can be

$$K = 2\pi a \quad (6)$$

The information is the distance between the electrodes, while 2 is a constant (Vebrianto, 2016). When using the wenner alpha configuration, the reading will be more accurate if P1 and P2 have large numbers because the P1 and P2 electrodes are close to the C1 and C2 electrodes.

2. Schlumberger

The Schlumberger configuration is often used in subsurface exploration to estimate rocks' geological structure and characteristics below the Earth's surface. An overview of the Schlumberger configuration can be seen as shown in Figure 3.

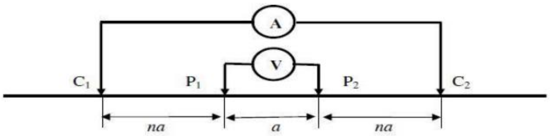

Figure 3. Schlumberger configuration form (Utiya, 2015)

The following is the value of r in Figure 3, namely:

$$r_1 = na \quad (7)$$

$$r_2 = na + a \quad (8)$$

$$r_3 = na + a \quad (9)$$

$$r_4 = na \quad (10)$$

After obtaining each value of r, the Schlumberger geometry correction factor, namely:

$$K = 2\pi\left[\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)\right]^{-1} \quad (5)$$

To complete the formula, it is necessary to produce equations of (7), (8), (9), and (10). From these results that have been combined into equation (1.5), it will produce the following:

$$K = \pi an(n+1) \quad (11)$$

This Schlumberger configuration has the advantage of being easy to use for beginners and, in addition to being able to detect non-homogeneous rock layers on the surface. It can be the reason why this configuration is often used for geophysical exploration, however, this configuration requires a multimeter with high impedance characteristics and high accuracy. In addition, high DC voltages are needed to read relatively small P1 and P2 voltages (Suyanto, 2017).

3. Dipole-dipole

The dipole-dipole configuration is a configuration in which the positions of the current electrodes are separated from each other according to the need to obtain depth interpretation (Suntoko, 2018). The advantage of this configuration is that the dipole-dipole configuration has high sensitivity so that it can detect structures on vertical and horizontal surfaces (Putra, 2021). The following is an overview of the dipole-dipole configuration in Figure 4.

Figure 4. Dipole-dipole configuration form (Suyanto, 2017)

From Figure 4. The following equation can be generated:

$$K = \pi n(n+1)(n+2)a \quad (12)$$

4. Pole-pole

Pole-pole configuration is a configuration used for measuring rock resistivity. This configuration ignores the C2 current electrode and P2 potential electrode and is positioned far apart from C1 and P1. The following is an overview of the pole-pole configuration in Figure 5.

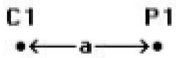

Figure 5. Pole-pole configuration form (Suyanto, 2017)

Figure 5 can be obtained from the following equation:

$$K = 2\pi a \quad (13)$$

5. Wenner – Schlumberger

This configuration merges the two geoelectric configurations, namely the Wenner configuration and the Schlumberger configuration. It is known that the Schlumberger configuration is the configuration used for sounding. In this configuration, the distance between electrodes P1-P2 is a, and the spacing between C1-P1=P2-C2 is na, so the spacing between the electrodes is constant. The advantages of this configuration are good horizontal coverage and optimal depth penetration. The following is an overview of the Wenner-Schlumberger configuration in Figure 6.

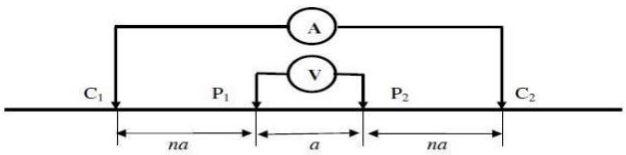

Figure 6. Wenner-Schlumberger configuration form (Adhe, 2022)

$$K = 2\pi n(n + 1)a \quad (14)$$

Application of Geoelectricity for Slope Movement

As one of the geophysical methods often used by researchers, the resistivity geoelectric method has many uses in various surveys and natural explorations, which are used to analyze slope movements. What underlies many slope movement surveys using resistivity geoelectricity is that this method is not environmentally damaging and has a sufficient range to detect soil layers about 50 to 100 meters below the ground surface. With these properties and ranges, this resistivity geoelectric method is very suitable and easy to do because it will not interfere too much with the research area and will get quite good interpretation results. Geoelectricity is applied in slope analysis based on the range of resistivity values to produce interpretations of subsurface rock structures.

The use of resistivity geoelectricity for landslide disaster investigation has been carried out by Jufriadi and Ayu (2014) where the research was conducted in the hilly areas of Mount Sriti and Mount Bagong Purwohaj Village, Ampelgading District, Malang Regency. In this study, Akhmad and Hena first physiographically examined the study area to predict slope slope in the 30° to 50°. Geoelectric surveys were carried out on two trajectories in the Northwest-Southeast direction, each with a length of 240 meters, using the Wenner configuration with a space of 10 meters. The results obtained from this study are in the form of a cross-section of subsurface resistivity where the slip plane layer is characterized by the presence of an impermeable layer (clay layer), which for the first pass is in the range of resistivity values of less than 29.8 Ωm, while for the second pass, it is in the range of 23.9 Ωm. The geological conditions of this track show that the study area is a landslide-prone area, especially the second track, which has a higher potential than the first track due to less cover vegetation and a steep slope. The high rainfall factor also strengthens the interpretation of landslide predictions in the study area. Overall, this study explains the methods used in detail, from data acquisition to data processing. Not only that, but the results of the interpretation are also presented in detail, accompanied by several conjectures such as the first trajectory, which has the possibility of landslides accompanied by *boulders* of andesite rock, and also the suspicion of rainfall, which is an important factor. However, the literature review for the range of resistivity values used as a reference is poorly presented, making it difficult to know whether or not the range used is valid.

A similar study was conducted by Akmam et al. (2018), who succeeded in identifying the slip planes of the four geoelectric trajectories used, each of which has a stretch of 64 meters with 32 electrodes at a space of 2 meters (Tunena et al., 2018). Using the Wenner-Alpha configuration, Akmam et al. obtained a cross-sectional profile of subsurface resistivity and used the resistivity value (1 - 100) Ωm as a benchmark for identifying the slip plane. The results obtained from research conducted by Akmam et al. showed that the research area, namely

Tinoor Village, has a huge landslide potential where the slip fields in the four tracks tested on average have a length of (8 - 10) meters with a depth of about (0 - 5) meters below ground level. The slip plane and this study also managed to get the slope angle to see how steep the research area was. This article clearly explains the research purpose so that research results can be structured. However, the presentation of research results and conclusions only races on the subsurface cross-sectional interpretation analysis results without considering the possibility of other factors, such as high rainfall.

Unlike previous studies that used specific resistivity ranges in interpreting subsurface cross-sections, the analysis conducted by Akmam et al. (2018) was based on the contrast of resistivity values between two layers seen in the subsurface cross-section indicating that the part is a slip plane. A similar analysis was also carried out by Hendri et al. (2019), who identified slip planes based on the presence of contrasting resistivity values between the two layers and identified the type of landslide in the area as a translational type.

Studies on slip field investigations show developments, one of which is carried out by Iwan et al. (2020) in their research to determine the potential for landslides in the Mount Geger Pulus area, Cililin District, West Bandung Regency. To examine in detail, this study combines resistivity geoelectric geophysical methods with testing soil physical properties parameters obtained through undisturbed soil sample drilling surveys (Tejakusuma et al., 2020). This research also makes observations and measurements of fairly specific conditions by considering essential things such as geological conditions, slopes, and local land use to identify what external factors can increase the potential for landslides in the study area. This study's laboratory testing of soil drilling was conducted to obtain index properties data such as fill weight, Atterberg boundaries, grain size, and hydrometer analysis. This geoelectric measurement is accompanied by electrode positioning and elevation using GPS topography to obtain slope slopes. The use of geotechnical methods to get lithology of the research area with geophysical methods that only race against the range of resistivity values in this study is proven to be able to validate further the interpretation results obtained in the resulting subsurface cross-section. This article successfully explains in detail and structures the methods and results accepted based on a supporting literature review.

Reza et al. (2020) conducted a similar study by combining resistivity data with drill data in the same year. However, not only to determine the size of grains and soil types at the research site but *index properties data* from research conducted by Reza et al. were also used to calculate the value of slope safety factors of the research location. The values obtained from the results of the calculation of safety factors can be classified in Table 1. The analysis of the safety factor in the research of Reza et al. used the Janbu method and obtained a result of 1.942, which means that the slope is stable. The factor that affects the calculation is the height of the groundwater table that cuts through the slip field. This safety factor calculation is suitable for avalanche investigations because it can calculate and predict the stability condition of a slope and whether an avalanche will occur.

The research on the characteristics of slopes that have the potential for landslides and mitigation efforts was carried out by Angga et al. (2016). It is explained that the FK value will be affected if the landslide mass decreases, and if the retaining wall is added, the FK value will increase less noticeably. In addition, FK~1, which indicates critical soil in the event of a landslide, will fill the road.

Table 1. Classification of safety factor values (Aryanto et al., 2020)

Safety Factor Value	Intensity Avalanche
F < 1	The slope will landslide
F = 1	Critical condition slopes
F > 1	The slope is considered stable

The latest is a similar study conducted by Moch Syahril et al. (2022) by interpreting the subsurface of geoelectric methods and calculating safety factors. However, this study does not explain the geoelectric method but focuses more on the limit *equilibrium method*.

The application of geoelectricity can also be combined with a center-of-mass approach to determine the speed and distance of landslide coverage, such as research conducted by Firmansyah et al. (2015). These methods were incorporated to predict soil movement, with the approach being a soil mass and carrying out calculations with Coulomb friction.

In other studies on slope stability using the resistivity geoelectric method, some studies also consider other parameters or factors, such as rainfall and earthquakes. Khoiriyah et al. (2016) have conducted a study to examine rainfall as an essential factor triggering landslides. This research uses engineering geological methods in the form of soil engineering characteristics tests to see changes in rainfall patterns and their effect on slope safety factors' value. From the research of Khoiriyah et al., it can be concluded that the value of slope stability will be smaller if the rainfall is higher. In another study, Rizkianti et al. (2019) conducted a study on the effect of earthquakes on slope stability during heavy rain using various slope angles. The study of Rizkianti et al. shows that the combination of rain and earthquakes can make the slope stability value smaller than just because of rain alone.

Time Lapse-Electrical Resistivity Tomography for Slope Observation

Geoelectric resistivity, a consolidated method, can produce surface resistivity images in two-dimensional and three-dimensional forms for various geological, engineering, and scientific applications. The development of technology and tomography algorithms for data inversion makes resistivity geoelectric one of the popular geophysical methods coupled with varying resistivity parameters so that it can be used in various geological environments (Lapenna & Perrone, 2022).

Geoelectric methods can be applied to studying changes in soil resistivity patterns that depend on time. Research related to time-dependent geoelectric methods was carried out in 1995 - 2005, where in this research, data acquisition was carried out, as well as for 2D and 3D geoelectric surveys in general. However, this data collection is repeated to produce a 4D cross-sectional image. One such study was conducted by Binley et al. (1996), who applied ERT (*Electrical Resistance Tomography*) to detect solute transport pathways in the soil core and experimented to exploit this new data acquisition technique to understand groundwater transport characteristics. Assuming the resistivity distribution is determined over time, the ERT pictorial of this study acts as a breakthrough of several tracer samples through the investigation area. Undisturbed soil samples will first be saturated with a fixed flow until equilibrium. The sample will then be injected with 0.025 M NaCl until the condition stabilizes and then added back about one pore volume of 0.06 *M* NaCl for 97 hours. As for measuring ERT, it is done at 5-minute intervals for each electrode plane. This study's results suggest that ERT's time-to-time application has a high potential to improve solute transport modeling in soils. However, the resolution obtained from imaging is much lower when compared to X-ray or magnetic resonance. However, increasing the number of electrodes used will also increase the resolution of the area. Although it has potential, similar research must be carried out in a more controlled and detailed environment to apply this method on a much larger scale (Binley et al., 1996).

In addition to research conducted by Binley et al. (1996), a study was conducted by Slater et al. (2002) on ERT (*Electrical Resistivity Tomography*) 3D, which was carried out on solute transportation commonly called solutes in a sizeable experimental tank. The study used the ERT voxel method, consisting of a series of electrical images in time sequences converted into a 3D array showing the translucent curve of liquid conductivity estimated by ERT. Next, the results are compared with direct measurements of the breakdown point of fluid conductivity carried out in the wells. The results showed that the voxel response of ERT adequately matched the *fluid conductivity breakthrough* curve observed in six wells measured directly. However, there was a discrepancy at the beginning of time, caused by differences in the voxel scale of the image and the measurement of fluid conductivity, measurement errors reflected in the electrical inversion, and the roughness of the image resulting from the inversion.

The TL-ERT method has been used for various research, ranging from hydrogeology, agriculture, engineering geology, and geohazards to the effects of climate change on the soil and subsurface. Research has been conducted in the field of hydrogeology by Paz et al. (2020) using MASW (*Multichannel Analysis Of Surface Waves*) and ERT (*Electrical Resistivity Tomography)* aimed at determining aquifer geometry and transient groundwater features of the Holocene alluvial *aquifer Cascalheira Stream Basin* (aquifer H) which contributes to *Lagoa Santo André*, part of a coastal groundwater-dependent ecosystem (GDE) in southwestern Portugal. In addition, there is also research on testing and comparing various characterization and monitoring methods, a new experimental site has been built in a coastal alluvial aquifer north of Barcelona (Catalonia, Spain), conducted by Folch et al. (2020). It is understanding underwater groundwater disposal and groundwater source management and making characterization of saltwater and hydrodynamics intrusion the beginning of the problem. Then, there is research conducted by Palacios et al. (2020) regarding testing the use of CHERT (*cross-hole ERT) in* imaging and monitoring the dynamics of seawater intrusion in Argentona. By comparing the CHERT results with electrical conductivity measurements from water samples and total electrical conductivity from the induction log

In agriculture using TL-ERT, research has been conducted by Fishkis et al. (2020) on the importance of preferential flow in non-sorbing solute transportation in sandy agricultural fields that have nitrate-contaminated groundwater, using 3D ERT data with time intervals during irrigation experiments. The research on the impact of using salt wastewater for corn irrigation by Carlo et al. (2020). In the irrigation process, the distribution of groundwater content uses ERT with *time-lapse.* The resistivity value of the soil has a high sensitivity to soil moisture and salt content in irrigation water. In addition, there is research on agricultural practices on soil moisture dynamics using *time-lapse* by Blanchy et al. (2020). This study discusses using ERT and *time-lapse* through three studies describing standard agricultural practices.

For the field of engineering geology, TL-ERT is useful as a mapping of old mines that are not reused by Srivastava et al. (2020) this research is about the exploration of the depth, expansion, and condition of old mines by monitoring time-lapse using a combined study of self-potential techniques and ERT (Srivastava et al., 2020). In addition, TL-ERT can also be used to monitor the seasonal behavior of soil moisture on river embankments, as done by Jodry et al. (2019). This research resulted in a model of seasonal resistivity change that proved effective for monitoring design and could provide a detailed understanding of the seasonal behavior of soil moisture.

Di Giuseppe & Troiano (2019) has implemented TL-ERT to monitor active areas in volcanic areas to investigate disaster phenomena in the field of geohazards. TL-ERT can detect gas accumulation zones, and in this study, tomogram results will be compared with geochemical time series where changes in electrical resistivity can be associated with depth-related effects. Chak-Hau et al. (2020) have also carried out other applications to detect leaks and monitor the development of contamination pipelines. This study tested each proposed hydrological modeling of TL-ET measurements, showing that this approach was possible for identification and reduced uncertainty values across the study site. The latest study was conducted by Christophe et al. (2021) to study subsurface hydrological infiltration and processes during heavy rains and flash floods by combining TL-ERT with physical/chemical *tracing* and groundwater content measurements.

The last is applying TL-ERT to assess climate change's effects on soil and subsurface. Some related studies include research conducted by Coline et al. (2019) to investigate *permafrost* due to different resistivity of ice and water several orders of magnitude to allow a clear separation between frozen and non-theoretical soils. In this study, resistivity measurements were carried out regularly for 20 years, and the results showed that the resistivity dataset provided a bright spot regarding melting point. Another study related to permafrost was also conducted by Christopher et al. (2020), who characterized the distribution of permafrost at wetland sites in Alaska carried out over four months and showed the results of how vegetation reflects the shallow distribution of permafrost, which is at a depth of 0 - 10 meters. Recent research on permafrost by Scandroglio et al. (2021) for a study on the effect of heating permafrost on mechanical stability and hydrocryostatic pressure on rock walls.

Of the various disciplines that can be used with the TL-ET method, other fields can use TL-ERT, namely in slope observation. The TL-ERT method is optimal for investigating factors affecting mass movement, such as water infiltration and soil moisture. TL-ERT's ability to provide quantitative information on water content and map water infiltration paths makes it very useful for evacuating water saturation effects for rainfall threshold estimation in landslide disaster mitigation systems. However, applying the TL-ERT method requires appropriate and correct geological models to be more effective. Most studies that have used this method are mostly conducted in areas with minimal sources of *noise* or interference, such as rural areas. Another drawback of this method is that it is difficult to investigate deep subsoil because its shallow range covers as deep as (0 - 20) m and its deep range (> 50) m. However, there has been no research that can produce information related to resistivity patterns in deep layers, so deeper geophysical research is recommended for research.

CONCLUSION

Based on data and the results of previous research related to the use of resistivity geoelectric methods for slope stability analysis, this method is still a fairly accurate method to be applied in detecting the slip field of an area because it is not environmentally damaging and can adjust to the geological conditions of the research area, and the cost is relatively cheap. In addition, geoelectric methods can be used when studying the earth's surface vertically or horizontally. The development of geoelectricity for slope analysis that shows changes starting from the analysis method, integration with other fields such as geotechnics for more validated results, calculation of safety factors to determine the potential slope for landslides or not, as well as consideration of other external factors such as rainfall and earthquakes shows that the application of geoelectricity in slope stability still has the opportunity and room to be developed in a way that More effective and can produce more accurate analysis than before. Some researchers have successfully combined resistivity cross-sectional profiles with a center of mass approach, a *simple* Coulomb model, and *limit equilibrium* to predict avalanche velocity and range. This is also evidenced by the many recent studies on *Time-Lapsed Electrical Resistivity Tomography* for landslide analysis based on time, where the application of TL-ERT also still has room to be developed so that slope observations can produce more accurate predictions from time to time.

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