Geotechnical profiling of a surface mine waste dump using 2D Wenner–Schlumberger configuration

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Open Geosciences 2021; 13: 335–344

Research Article

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https://doi.org/10.1515/geo-2020-0234
received May 30, 2020; accepted February 09, 2021

Abstract: Mapping the subsurface in slope stability analysis of disposal areas is difficult, especially the disposal layering materials that are assumed to be homogeneous instead of their real conditions. Moreover, the hoarding activities on high slope form layers based on the nature of the rock mechanics with large materials or boulders rolling down to the toe of the slope, while small ones are held at the top. Each layer formed, however, has certain geotechnical characteristics. The aim of this study is to determine the profiling of disposal material using a geoelectrical method known as Wenner–Schlumberger configuration with a line length of 450 m and also to find the resistivity value for mine waste materials based on an empirical number, which is a number that is obtained from the result reading compared to the actual condition in the field. The study was conducted on an in-pit dump with an estimated height of 150 m and a thickness of 50 m, and the data obtained were processed using RES2DINV software. The results showed that the subsurface cross-section has three layers consisting of bedrock with a resistivity of 50–70 Ωm, contact zone with 30–50 Ωm, and disposal material layer with 1–30 Ωm, which can be used for the slope stability analysis. This concept is very helpful for the geotechnical analysis on high mine waste dumps or sloping basement zone. This study focuses on the resistivity value for waste dump materials, which has not been clearly mentioned in the previous studies.

Keywords: geoelectric, resistivity, disposal, high dump

1 Introduction

Mapping subsurface supports the slope stability analysis. In the analysis of disposal area, the disposal layering materials are usually assumed to be homogeneous, whereas they are not. This becomes a problem because each location has their own characteristics, so generalizing the condition is not relevant. Therefore, an adequate method is required.

Mapping subsurface conditions precisely and comprehensively requires an adequate method, for example, through the use of 2D geoelectrical resistivity. This method involves using the resistivity characteristics of rock layers as a tool to study the subsurface geological condition. Meanwhile, the electric current inside rocks or minerals are classified into three types, and these include electronic conduction, which is a normal type of electric current inside rocks/minerals; electrolytic conduction, which occurs in many porous rocks with the pores filled with an electrolyte solution; and dielectric conduction, which occurs in dielectric rocks having fewer or no free electron [1].

The basic principle of the resistivity method involves measuring the potential difference of a pair of electrodes injecting current into the ground, and the deviations from the expected pattern from the homogenous ground provide information on the form and electrical properties of subsurface inhomogeneities [2]. Every material on the earth has a specific resistivity value, which is used in displaying the subsurface rock layers, and several ranges of these values are usually produced by different compositions of rocks [3]. The resistivity values of materials on the earth are presented in Figure 1.

Conductors are defined as materials with the resistivity value less than 10^{-5} Ωm, insulators have more than 10^{7} Ωm, and semiconductors have values between the two ranges. A conductor has many free electrons with very high mobility, while a semiconductor has lesser free electrons, but an insulator is characterized by ionic bonding, and this means its valence electrons are not free to move [4].

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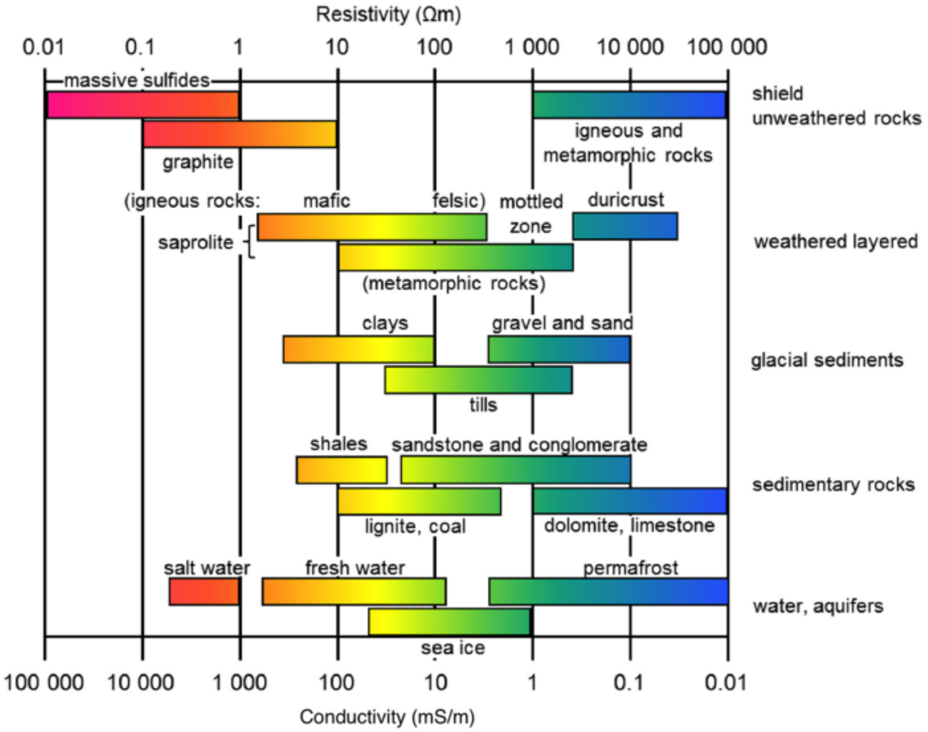

Figure 1: The resistivity and conductivity range of some common geological materials [4,8].

A geophysical method is used in identifying slip surfaces and weak fields. Meanwhile, a slip surface usually consists of two solid soil layers, hard and soft, which act as a water-retaining field with low permeability, thereby causing weathered soil to move above the surface [5]. Resistivity value is highly influenced by pore fluid and grain matrix of geomaterials [6], while electric resistivity value (ERV) is strongly affected by the variations in the basic physical properties (BPP) of soil, especially the particle size fraction, moisture content, and soil density [7].

Resistivity is closely related to the subsurface water pattern and is also considered important due to its relation to the pore pressure. Moreover, its relationship with rock types is influenced by the following factors:

1. An unconsolidated sedimentary rock with lower resistivity value than a solid sedimentary rock.
2. The porosity of the rock. A porous rock has a lower resistivity than a nonporous rock.
3. The pH of water inside rock pores. Low pH indicates acid rock with low resistivity.
4. The resistivity of rocks varies depending on the depositional environment.
5. Resistivity is very different between rock layers and in one-layer rock.
6. A high temperature or hot water has lower resistivity compared to a low temperature or freshwater.
7. Permeability or the ability of rocks to drain the fluids.
8. The porosity of rock, which is a comparison between the volume of the cavity with the volume of a rock. High porosity indicates a higher volume of water is stored.

The conductance of the pore fluid in sedimentary rocks is important. The relationship between the electrical conductivity of groundwater and the formation resistivity of porous clay free water-bearing rocks can be described by an empirical formula derived by Archie in 1942 [9]. By knowing the porosity of a rock, water content, and the resistivity of the pore fluid, its formation resistivity can be calculated using equation 1:

$$\rho = a \cdot \varnothing^{-m} \cdot s^{-n} \cdot \rho_{\mathrm{w}}, \qquad (1)$$

where ρ is the formation resistivity of rocks, ρ_{w} is the resistivity of the pore fluid, and ρ/ρ_{w} is the ratio between the two variables, which is the formation factor (F); $\varnothing$ is porosity and s is the volume fraction of pores filled with water; a, m, and n are constants that range from 0.5 to 2.5, 1.3 to 2.5, and approximately 2, respectively.

Subsurface can be investigated using electrical resistivity surveying by passing a current (I), in controlled amount, between two grounded electrodes. Between the second pair of grounded electrodes, the difference of voltage (ΔV) is measured using a high-impedance voltmeter. By applying Ohm's Law, the resistance (R) can then be calculated as follows:

$$R = \frac{\Delta V}{I}. \tag{2}$$

Apparent resistivity values for the subsurface are obtained by equation 3 [9]:

$$\rho = R \times K, \tag{3}$$

where ρ is the resistivity in Ωm, R is the resistance, and K is the geometrical factor that is specific for two pairs of electrodes.

Several factors such as slope-forming material and groundwater condition affect slope stability of the mine waste dump. Moreover, the slope of mine waste dump that has been reported in many studies is unstable due to a decrease in the physical and mechanical properties of the material as a result of increased pore pressure [10]. The material layer lying above the groundwater table is called the vadose zone, while the almost saturated zone between the vadose zone and the groundwater table with 1–10 m thickness as shown in Figure 2 is known as the capillary fringe [11]. The groundwater table that touches the slip surface of the slope forms a deep-seated landscape even though the other part of the slope is dry. The slope failure due to the increase of the groundwater table requires time for the water to infiltrate from the ground landslide and developed perched water tables; therefore, it requires 1 day or more to trigger landslide [12].

The layering material used during the slope stability analysis on mine waste material and the detailed profiling applied is very important, but the determination of the stratigraphic profile is very difficult due to mine waste dump. More effort is required in determining the stratigraphic profile, such as using a geophysical method. Moreover, it is possible to determine the stratigraphic profile using different methods, but the use of resistivity covers several areas, is very fast, and covers a wider area compared to the drilling method, which is specific on one point. However, the resistivity method requires an empirical analysis to determine each layering, which is carried out by comparing the resistivity value with the actual value based on the field condition.

The disposal of overburden or waste rocks produced from coal mining activities has become an issue of concern due to the quantity of land required and the stability of dumps needed for the materials [13]. The higher the slope stability, the land requirement will increase, which means that the area needed for the material placement increases. Moreover, the deformation of the waste disposal field needs to be continuously monitored to prevent drainage penetration, while the arrangement of buildings or construction sites at the downstream of the waste disposal field channel or the ditch mouth is strictly forbidden. A stratigraphy for geotechnical analysis has been conducted using homogeneous material without detailing

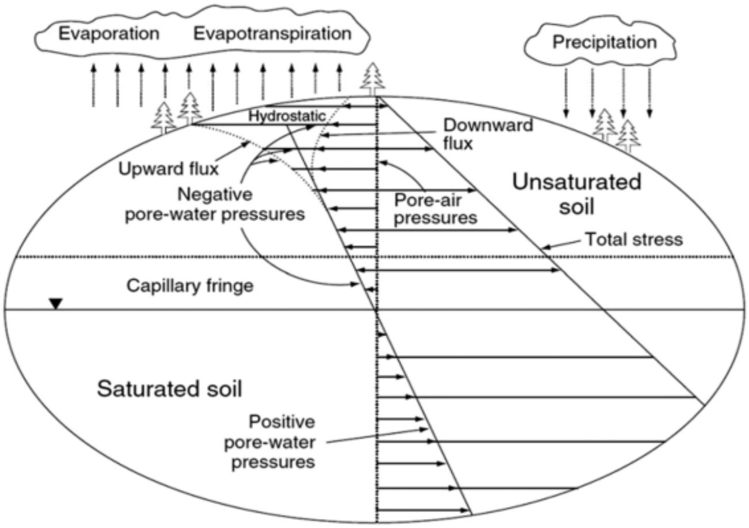

Figure 2: Saturated/unsaturated soil mechanics based on the nature of the fluid phases [12].

the layering stratigraphy on waste material [14]. This is critical for the development of impoundments, which requires considering the typical water-impounding dams and additional requirements of coal waste disposal impoundments [15].

The regional geology in the Banjarmasin sheet [16] shows the research area located in the Tanjung Pudak (Kap) that consists of quartz sandstone intercalated by claystone and coal, which is shown in Figure 3. The quartz sandstone [17] has a fine-to-coarse grain with a 50–150 cm layer thickness as well as parallel lamination and cross-bedding sedimentary structures. Moreover, the gray claystone, which usually in some places occurs as intercalation in the upper part of formation with the 30–150 cm bed thickness, while the coal seam is black, lustrous, and massive and found as intercalation in the lower part of formation with 50–150 cm thickness. Meanwhile, the lenses of limestone in some places are brownish gray. This study was conducted in one of the overburden mine waste dumps located at the low wall of active mines in the South Kalimantan, Indonesia, as shown in Figure 4. The geometry of the mine waste dump was found to have a height of 150 m, layer tilt of 14°, and thickness of 50 m and contains sand-to-boulder size or 50 cm to 100 m materials found at the toe of the slope with a little of sandy materials at the top.

Similar studies have been performed using the same method, but the range differs from one location to another. This is due to the condition of the material at each site based on its geological and hydrogeological conditions as well as the fragmentation. The range obtained from the previous studies cannot be applied to this location, so an empirical approach is required to obtain the optimum range.

2 Materials and method

The site studied is one of the overburden mine waste dumps located at the low wall of active mines in the South Kalimantan, Indonesia, as shown in Figure 5, and the tools used include resistivity meter, two electrodes, four cable reels, two dry batteries, GPS, and measuring tape, while field data were acquired using the Wenner–Schlumberger configuration method and the standard operational procedure of American Society for Testing and Material (ASTM) D7852 – 13 and processed using RES2DINV software.

Experimental design combines theory and actual condition of the field in which each location has its own characteristic. By conducting experiment on the

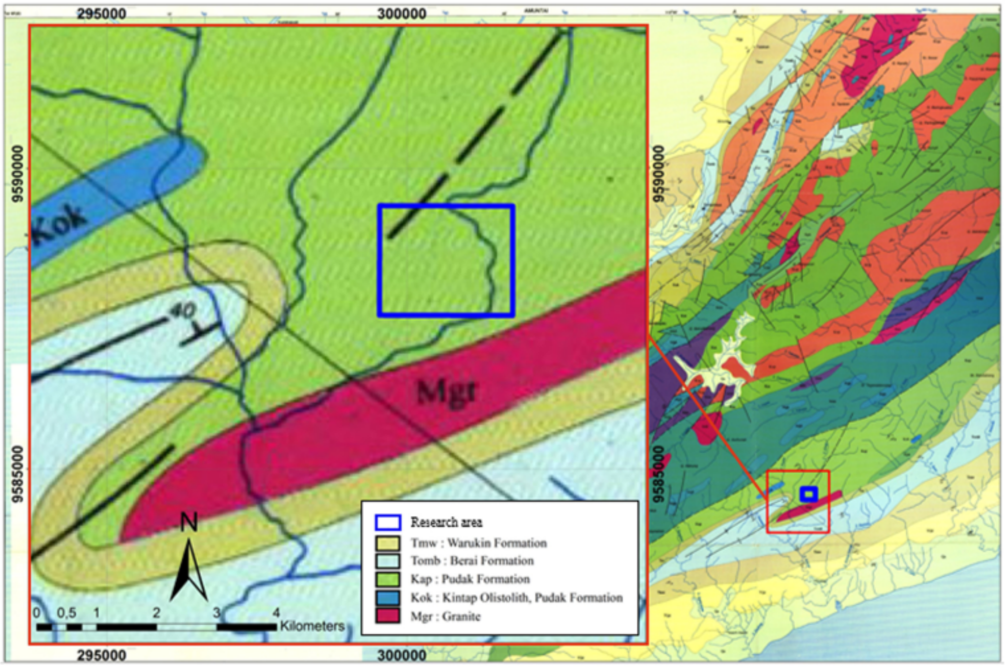

Figure 3: Regional geology of the research area [16].

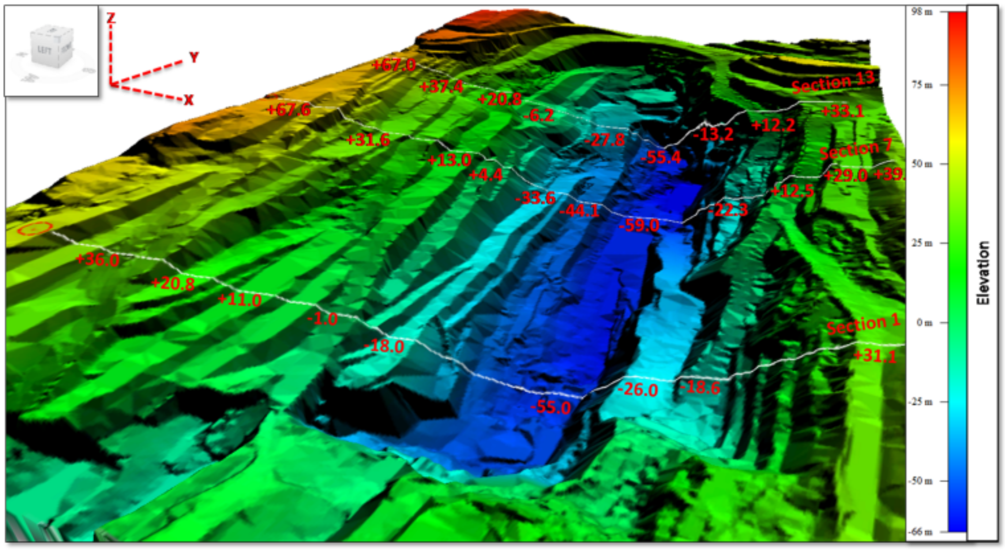

Figure 4: Research area at the low-wall part of coal open pit mine.

resistivity of mine waste dump combined with observation of the outcrop, the layer of material on the body of the pile can be interpreted. Determination of the layer in waste dump material was carried out by comparing the

Figure 5: Location of the site studied.

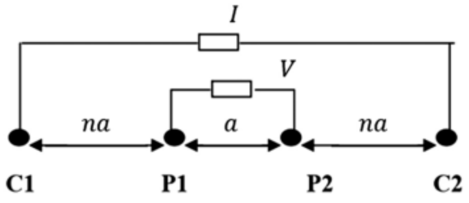

Figure 6: Electrodes setting of the Wenner–Schlumberger configuration.

resistivity value, which is the result reading, with the real condition of the material exposed derived from visual description of several outcrops. By comparing this, criterion for each layer was determined based on the resistivity value.

Wenner–Schlumberger configuration is a constant spacing system, which shows that factor “n” is a spacing comparison between electrode C1–P1 and C2–P2 with P1–P2 space as shown in Figure 6. Moreover, provided that the distance between the potential electrodes, P1 and P2, is a, the distance between current electrodes, C1 and C2, is $2na + a$. The resistivity value is, therefore, determined using the four electrodes placed in a straight line [18].

When a direct current is delivered through a medium, the ratio of potential difference (ΔV) and current (I) is constant, depending on the medium, and expressed as resistance (R) in Ω, using the relationship given in equation 2.

The data were obtained from the field by making a 500 m straight line with a targeted depth reaching up to 70 m, while the distance between measurement points was 15 m with 10 pseudo layers as indicated in the 2D configuration shown in Figure 7.

The data processed were the resistivity input using RES2DINV software, which involves a mathematical calculation that processes the raw data resulted from the measurement in the field into informative analysis results from which interpretation can be made, including several inversions to show the geoelectric cross-sections between the original data from field measurement before processing and the data obtained after processing. The results from the cross-sections were inverted to obtain the actual resistivity data. The inversion process ensures the discovery of data error related to the values observed to be the outside range from the field and sort the data to eliminate the errors to produce better map quality. Moreover, the 2D data processing result was a cross-section of subsurface resistivity distribution.

3 Results and discussion

A comprehensive geotechnical analysis is necessary to maintain mine waste dump stability, especially due to the possible constraints presented by the mine waste dump layers that are assumed to have homogeneous materials. Dumping sequences have also been observed to have the ability to cause natural segregation with boulder materials rolling down, while fine materials are retained at the crest. The advancement of the dump usually starts from the bottom and move to the upper part leaving the layering material on the mine waste dump.

This study illustrates the distribution of water in the mine waste dump materials to determine the saturation material, while the position of mud formed was evaluated using the resistivity measurement. Moreover, high rainfall intensity also has the ability to trigger the accumulation of fine materials in a certain place to form a mud zone.

Resistivity was measured with three straight line tracks, which are perpendicular to the slope, separated

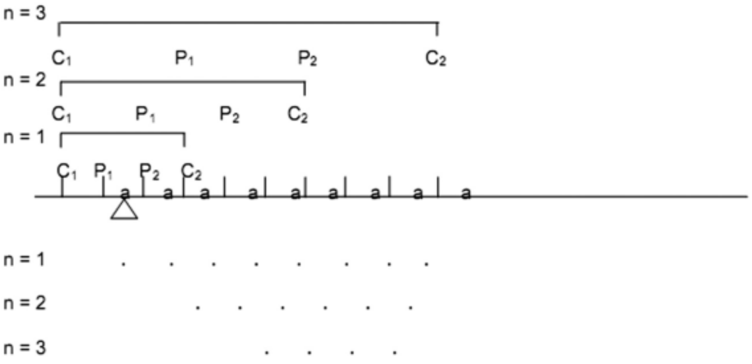

Figure 7: Data acquisition design using 2D Wenner–Schlumberger configuration.

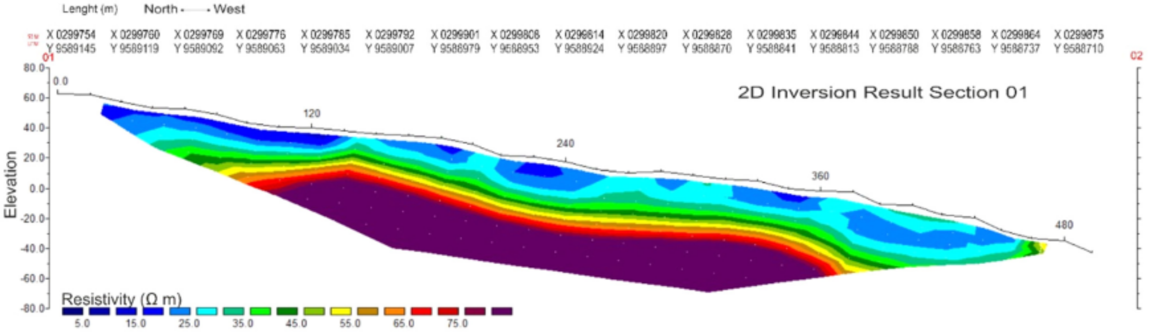

Figure 8: Cross-section of 2D inversion results in section 1.

500 m apart having a line length of 450–540 m and reaching 80 m depth. The topography of the resistivity measurement tracks was perpendicular to the slope of the mine waste dump at approximately 25°, while the bedrock had a slope of 14° in the south dip direction. The dump was backfilling up on bedrock at a tilt difference estimated to be 10°, while the slope height was 150 m with mine waste dump up thickness approximately 50 m. The toe disposal was retained on the slope, while mining activities were conducted at the bottom pit. These conditions, however, require stable mine waste dumps to ensure safe operation and mining sustainability.

Multiple iterations in the inversion process were required to improve the quality of the analysis result and, in this case, iteration was conducted seven times using RES2DINV software in 1, 7, and 13 tracks to provide 2D subsurface cross-section with 15.5% error value, which was accepted because it is less than 30% [19]. The subsurface cross-sections 1, 7, and 13 are presented in Figures 8–10, respectively, which shows eight layers with resistivity values of 5, 15, 25, 35, 45, 55, 65, and 75 Ωm, which are visualized using different colors. The layers with 5–30 Ωm resistivity value were assumed to be the same unconsolidated gravel, which is formed on a new mine waste dump that has not experienced maximum consolidation, thereby having the tendency to be loose. Moreover, it is made of gravel, and this means water continuously seeps in due to the inability of the zone to hold the water, thereby showing its very low resistivity value.

The next layer has 30–50 Ωm resistivity value and consists of cobble and gravel. It also has contact with bedrock and better compactness compared to the previous layer. Moreover, the cobble-to-boulder sized materials are composed of sandstone and claystone with a little sandy material, and this shows that groundwater is not restrained in this zone; therefore, the resistivity value is not high. The last layer is a base layer with 50–75 Ωm resistivity, which is made up of mudstone and observed to be rigid with a hardness of 6 MPa, while the groundwater condition was found not to be visible using resistivity measurement.

The mine waste dump material was profiled based on an empirical approach using the resistivity value of geoelectric measurement and the results of the observation made on a material outcrop on the field. The stratigraphic

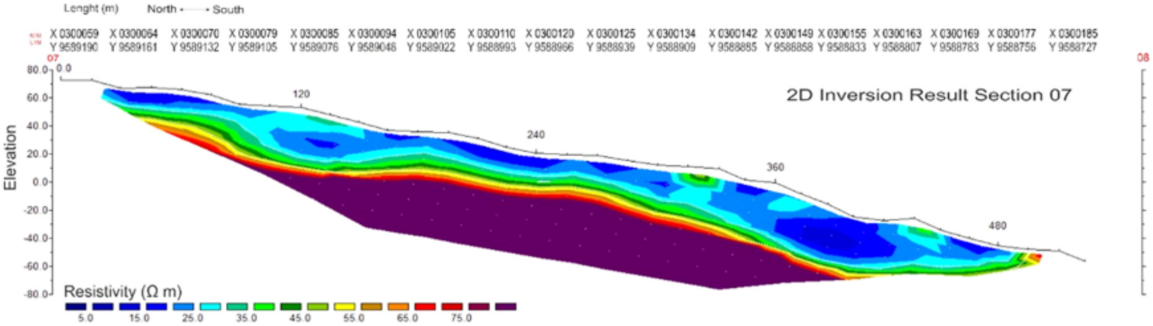

Figure 9: Cross-section of 2D inversion results in section 7.

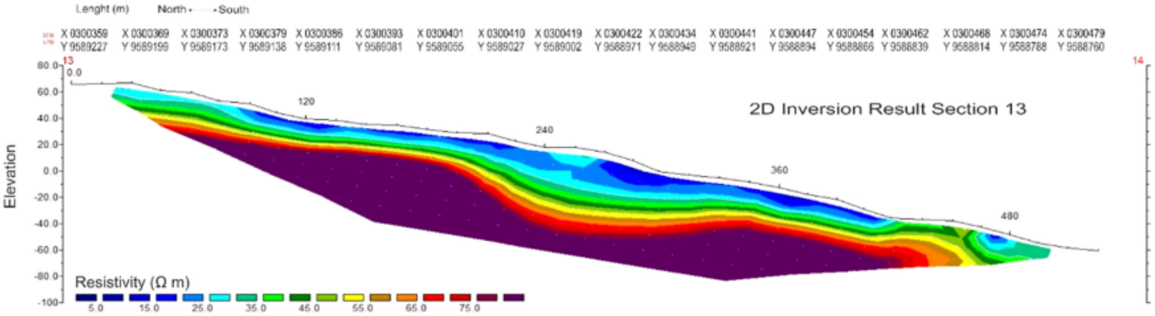

Figure 10: Cross-section of 2D inversion results in section 13.

profile was determined by linking the resistivity value in a certain range. Each range will be assumed to have the same characteristics, so it will be the same layer. Every change in the resistivity value will be shown in a resistivity contour where each change shows different color as shown in Figures 8–10.

All the cross-sections are observed to have layers with different thicknesses and are in accordance with the field condition with in situ rocks found at the toe of the slope, while the shape of the bedrock is slightly bumpy and not flat, thereby showing a hilly zone topography. In situ rock is visible at the toe of the slope, so the waste dump material appears to be hanging on the slope. This is due to hoarding carried out not on a flat plane but on a sloping topography. The hoarding sequence starts from the west side, and this makes section 1 to be thicker than sections 7 and 13. The detailed interpretation of the results of the rocks is represented as follows:

3.1 Bedrock

This very bottom layer has a resistivity of 50–300 Ωm, which is intercalated by claystone and siltstone with a depth estimated at 75 m. It does not show potential as a confined aquifer due to its availability at a depth of 10–40 m.

3.2 Contact zone (dense material)

This layer has a resistivity of 30–50 Ωm and is dominated by coarse materials such as gravel and sand. It is interpreted as a waterway during the raining period, and this makes some of the areas a temporary groundwater level. Moreover, this layer is designed as a drain or a filter due to its estimated thickness of 10 m and availability in 20–30 or 30–40 m depth in some areas.

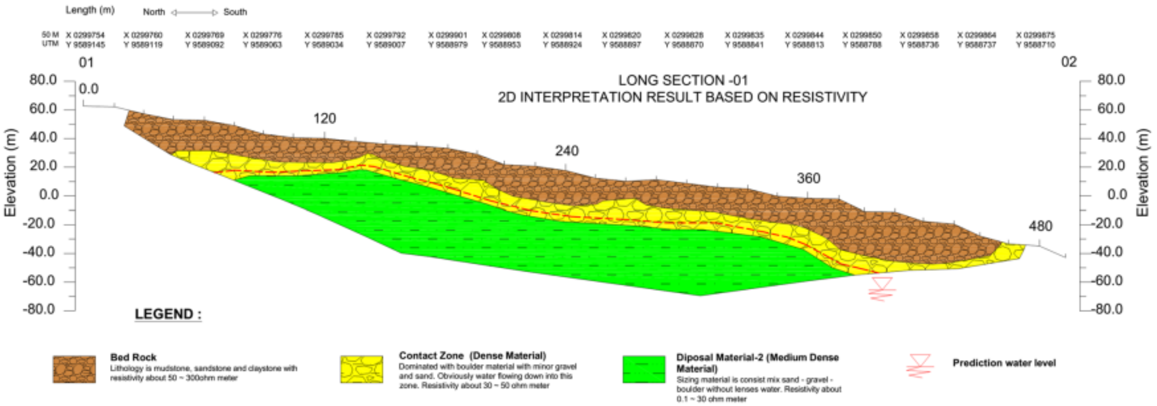

Figure 11: Stratigraphy profile of section 1.

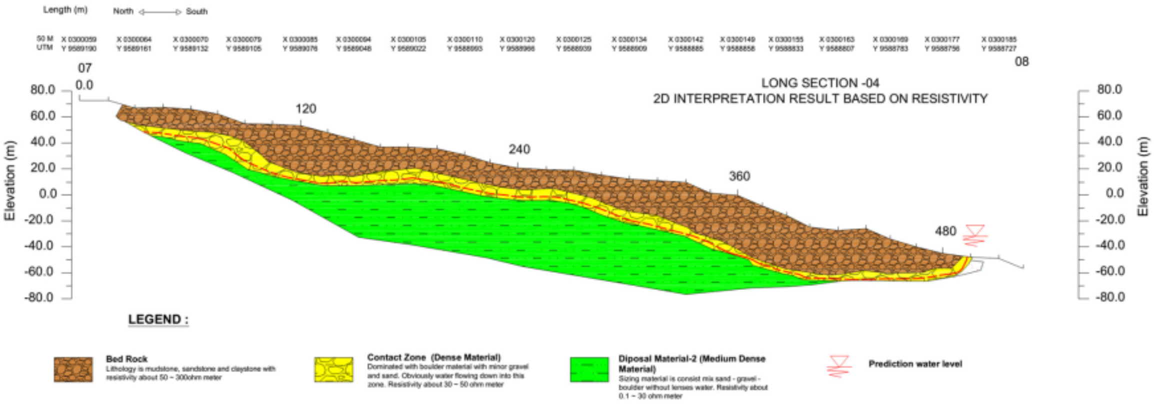

Figure 12: Stratigraphy profile of section 7.

3.3 Disposal material (medium-dense material)

This layer has a resistivity of 0.1–30 Ωm and consists of a mixture of sand, gravel and boulder with little fine materials such as clay and silt. The distribution and the pattern of resistivity value cross-section in this layer do not show an indication of mud weak zone or stacked water lenses with the potential to create pore water pressure. Its thickness was 10–30 m.

The cross-section profile based on resistivity results used in geotechnical analysis modeling is shown in Figures 11–13 for sections 1, 7, and 13, respectively, with the strata presented to be upside down. Moreover, the original topography was inclined at approximately 14°, while the thickness of the construction mine waste dump was estimated at 60 m. The dumping was started from the bottom and observed to be moving toward the upper part.

The interpretation of the results showed that the disposal construction is in accordance with the plan as observed in the contact zone, which is made up of large materials with high porosity and found to be acting as a rock drain zone. Rainwater enters the mine waste dump and flows down to the contact zone. Moreover, the bedrock is a mudstone with low permeability, which allows the flow of water along the slope in the contact zone to form seepages at the toe of the slope. This cycle makes the water entering the mine waste dump not to be trapped, thereby avoiding pore pressure. Meanwhile, seepages are widely found at the toe of the slope in the contact zone, and the 2D interpretation result showed the absence of mud or water in the mine waste dump.

The advantages of implementing this method include easiness, fastness, and the ability to cover a wide area to ensure subsurface conditions compared to other methods such as drilling, which is more expensive and observed to

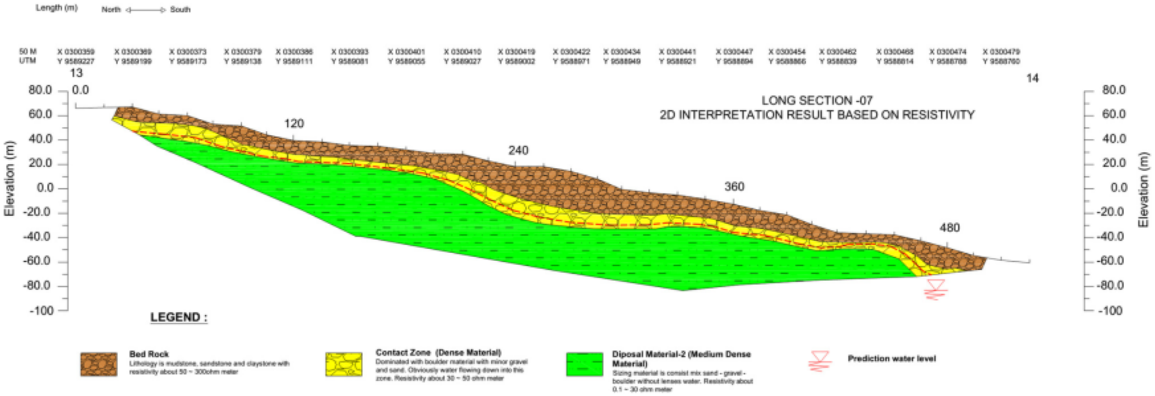

Figure 13: Stratigraphy profile of section 13.

be covering a limited area. This method is bad to reach stratigraphy with thickness less than 1 m, it can be implemented instead of not having any data on profiling.

4 Conclusion

The 2D Wenner–Schlumberger configuration and RES2DINV software showed that the research area has three layers, which are the bedrock, contact zone, and disposal material layer. The bedrock layer has a resistivity value of 50–70 Ωm and consists of claystone, sandstone, and mudstone with surface tilt estimated to be 14°. The contact zone layer has a resistivity of 30–70 Ωm and consists of a big rock with an estimated thickness of 10 m found approximately 40 m from the surface. Moreover, the disposal material layer (medium-dense material) has a resistivity of 1–30 Ωm, which consists of unconsolidated mine waste materials and found at the surface with thickness of 10–30 m. This shows the disposal construction is in accordance with the plan, and no water or mud was found to be trapped in the mine waste dump. Therefore, it is possible to use the results of this study in the geotechnical analysis to arrange a stratigraphy model.

This method is universal due to its applicability in other areas with the determination of the resistivity value depending on the condition of each material. Moreover, the mine waste dump material was not assumed to be homogeneous when the method is used in the geotechnical analysis, and this allows for a more detailed layer profile. This is very useful for mine waste dumps with significantly high difference and those with high risks such as near habitation or other infrastructure. It is, therefore, recommended that the future research make a more detailed isopach map for comprehensive interpretation of mine waste dump material profiling.

This study helps in profiling waste dump material, and hence, when conducting slope stability analysis, the analysis will be very detailed and it is very useful in hydrological modeling. The research wasn't conducted slope stability analysis and geohydrology, but based on a theory with this method, geotechnical profiling will better and geotechnical analysis can be improved. Further research to make clear the impact of geotechnical profiling using this method is recommended.

Acknowledgments: The authors appreciate the AB Omah Geo team for supporting this research and allowing the publication of the results and to PT AOG for supporting the paper management to ensure it is published.

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