Analysis of Rock Structures Based on Geoelectrical Resistivity Data of Wenner-Alpha Configuration Using Marquardt’s Inversion Method

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Abstract. Information about subsurface structures is crucial to support work related to civil construction, one of which is the identification of basement rock for a preliminary research of laying the foundation of a building. Hard layers play an important role in maintaining the stability of the foundation from the effects of natural disasters (earthquakes) and land shifts caused by the exploitation of soil carrying capacity. One of the methods that can be used for identifying hard layers is geoelectrical resistivity method. This method processing uses Marquardt’s inversion and damping factor functioning to stabilize the inversion process. The inversion process will be carried out when the value of RMSE between the synthetic resistivity data correlation of the initial estimation (starting model) and the field resistivity measurement data is over 10%. The error values of each line (L.1, L.2, and L.3) are 9.3%, 7.2%, and 6.1%. Hard layers are identified as layers with resistivity values above 100 Ωm, namely tuffaceous sandstone, tuffaceous gravel, inserted breccia and limestone.

1. Introduction

Information about the condition of rock structures below the earth’s surface is required in the construction planning of a foundation. It is important to know the depth of the basement rock and the types of rock that can serve as suitable layers to support the weight of the foundation to be built [1] [2]. The characteristics of rock layers in the place that will be used for installing a foundation of a building must be in accordance with the support capacity for the load and force generated by both the foundation and the building in order to minimize the risk of earthquake damage and land subsidence due to the exploitation of soil carrying capacity [3] [4].

One of the methods that can be used for estimating the structure of the subsurface rock constituents is geoelectrical resistivity method [5]. This method has been widely used for various purposes related to the estimation of subsurface structures such as, groundwater investigation [6], coal exploration [7], and identification of basement rock as a preliminary research of large-scale construction planning such as bridges, dams, or high-rise buildings [8].

Basement rock usually comes from both igneous and metamorphic rocks with high density and low porosity, causing it to have a higher range of resistivity value than sedimentary rock. Another typical characteristic of basement rock is the low level of permeability caused by the brittle rock structure which has matrix porosity, which is the reason why the presence of basement rock is crucial in the field of civil engineering [5].
The resistivity of rocks below the earth’s surface is studied by injecting electric current into the earth through two current electrodes [9]. The electric current flowing in a rock layer depends on the type of rock it passes through. Potential differences due to the response of the current injected to the physical condition of the rock are measured through two other electrodes [10].

The type of electrode configuration used in this research is Wenner-Alpha configuration using four electrodes including two current electrodes and two potential electrodes arranged in a straight line. In general, this configuration is more sensitive to changes in lateral and shallow resistivity than other electrode configurations. Wenner-Alpha configuration can be seen in Figure 1 below.

![Figure 1. Wenner-Alpha Configuration (Telford, 1976)](image)

Geo-electrical method assumes that the earth is an isotropic homogeneous medium. The current flowing down the earth’s surface will flow to all directions because the air has a vast resistivity causing the current not to flow into the air. It causes the distribution of the current flow to only flow down the earth’s surface with a half-ball pattern shown in Figure 2 [11].

![Figure 2. Current Flow Distribution (Telford, 1976)](image)

The resistivity measured in the geoelectrical method is not the real resistivity, but apparent resistivity \( \rho \) which can be determined by the following equation,

\[
\rho = k \frac{\Delta V}{I}
\]

where

\[
k = \frac{2\pi}{\left(\frac{1}{r_1} - \frac{1}{r_2}\right) - \left(\frac{1}{r_3} - \frac{1}{r_4}\right)}
\]

\( \rho \) is apparent resistivity (\( \Omega \cdot \text{m} \)); \( \Delta V \) is potential (mV); \( I \) is the current injected into the earth (I); and \( k \) is the geometric factor, meanwhile, the geometric factor of Wenner-Alpha configuration is \( k = 2\pi a \) where \( a \) is electrode spacing (m).

The resistivity measured during measurement is the apparent resistivity. To estimate the distribution of the apparent resistivity to depth can be done through inversion method. Inversion optimization is done by minimizing the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the block model as the starting model [12].
Furthermore, the resistivity value of the starting model is considered as synthetic data. The reference commonly used is the value of the Root Mean-Square Error (RMSE) which is the difference between the resistivity value of the starting model and the resistivity value of the data obtained in the field. The following equation can be used for determining RMSE value [13]

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_{\text{obs}} - X_{\text{model}})^2}{n}} \]

Where \( X_{\text{obs}} \) is resistivity data of the observation and \( X_{\text{model}} \) is synthetic resistivity data of the starting model. Data of modelling and field observation results can be said to be fit for the subsurface conditions if the value of RMSE is below 10% [12].

If the error value is still above 10%, the data from this research will be analyzed using the Marquardt’s inversion method through the following equation [14]

\[ (J^T J + \mu I)\Delta m_k = J^T d \]

where \( J \) is current density \( I \) is identity matrix, \( \mu \) is damping factor \( d = [\rho^T_I] \) namely apparent resistivity with \( I = 1, 2, \ldots, N \) and \( N \) is the number of data. Meanwhile, the model of resistivity and thickness of subsurface rocks is \( \Delta m_k = [\rho_k, h_k], k = 1, 2, \ldots, n \) and \( n \) is the number of layers.

Marquardt’s inversion method applies the Gauss-Newton iteration method with the addition of scalar multiplication of damping factor \( \mu \) and identity matrix. The term ‘damping’ relates to the process of reducing instability that might arise due to limited data on inversion. If the damping factor used in the inversion process is very small or close to zero, the prediction error will be minimized. The following is the equation of damping factor [15]

\[ m = (G^T G + \epsilon^2 I)^{-1} G^T d \]

The concept of the minimization of linear inversion errors can be expanded to the minimization of data prediction errors and solution errors. In other words, the addition of damping factor to an inversion process can stabilize the inversion process.

2. Research Method

This research is conducted in the construction area of Campus II of UIN Sunan Gunung Djati, located on Cimencrang street, Bandung. The research site is shown in Figure 4a. The number of measurement lines is 3 lines (L.1, L.2, and L.3) using Masagi Multichannel Resistivity Meter with 32 electrodes and 6-meter space between electrodes so that each measurement line has a length of ± 192 meters.

The geoelectrical measurement method applied in this research is geoelectrical imaging of Wenner configuration to determine subsurface hard zones which then will be interpreted into 2D cross sections of the subsurface hard zones at the research site.
3. Results and Discussion

Based on the data of the research results, it is found that rock layers predicted to be subsurface hard layers are identified as tuffaceous sandstone layer (100-250 $\mu$m) at a depth of 11.9-16.1 m, tuffaceous gravel layer containing a little tuffaceous sand (250-400 $\Omega$m) at a depth of 16.1 - 20.7 m, tuffaceous gravel layer with inserted breccia (400 - 600 $\Omega$m) at a depth of 20.7 - 25.8 m, and basic constituent layer predicted to be dominated by limestone (> 600 $\Omega$m) at a depth above 25.8 m. According to these data, on average, the position of hard layers is at a distance of 96 - 144 m from the starting measurement point of each linear geoelectrical line presented in the following 2D cross sections of each line.

![2D Geological Cross Sections](a)

![2D Geological Cross Sections](b)

![2D Geological Cross Sections](c)

**Figure 5.** 2D Geological Cross Sections  
(a) Line 1 (L.1), (b) Line 2 (L.2), (c) Line 3 (L.3)

**Table 1.** Rock Types Based on Resistivity Value

| No | Depth (m) | Resistivity Value ($\Omega$m) | Type of Soil Layers / Rock | Color Index |
|----|-----------|-----------------------------|---------------------------|------------|
| 1  | 0.00 – 11.9 | < 100                       | This layer is dominated by grave and tuffaceous clay | [Blue]     |
| 2  | 11.9 – 16.1 | 100 – 250                   | Sedimentary rocks composed of tuffaceous sandstone | [Light Blue, Green] |
| 3  | 16.1 – 20.7 | 250 – 400                   | Sedimentary rocks composed of tuffaceous gravel and containing a little | [Green, Yellow, Orange] |
4. Conclusion

Based on the results of the research conducted in the construction area of Campus II of UIN Sunan Gunung Djati Bandung and according to the measurement results of 3 lines (L.1, L.2, and L.3), it is found that hard layers are found from a depth of 11.9-16.1 m identified as tuffaceous sandstone layer (100-250 μm) followed by tuffaceous gravel layer containing a little tuffaceous sand (250-400 Ωm) at a depth of 16.1 - 20.7 m, tuffaceous gravel layer with inserted breccia (400 - 600 Ωm) at a depth of 20.7 - 25.8 m, to basic constituent layer predicted to be dominated by limestone (> 600 Ωm) at a depth above 25.8 m. Therefore, it can be concluded that on average the position of hard layers is at a distance of 96 - 144 m from the starting measurement point of each linear geoelectrical line with error percentages of each line of 9.3 %, 7.2 %, and 6.1 %.

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