Laboratory-scaled Azimuthal Resistivity Survey for Fracture Detection

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Abstract. We conducted azimuthal resistivity survey (ARS) at laboratory scale to study apparent resistivity patterns due to fracture existing in subsurface through physical modeling using test objects buried in a sandbox as well as in a test location outside laboratory building. This survey was divided into 2 experiments, i.e. experiment A and experiment B. In experiment A the survey is implemented on 2.50 m x 1.5 m x 0.81 m sandbox, made of 10mm thick glass plates. Sandstone was used as medium representing quasi homogenous medium. Clay roof tiles as well as steel plates as test objects were buried in the sandbox with three different deep angles: 90°, 45° and 0°. In experiment B this survey was conducted outside laboratory building on the grass field and implemented on 2.50 m x 2.5 m x 1.0 m soil body. Vertical single glass plate as well as vertical double glass plates at 30 cm distance were buried in the soil body. Azimuthal resistivity measurements at 15° angular step using Wenner and dipole-dipole configuration were carried out in both experiments located at 1 point just above anomalous object for experiment A and at 3 points at 15 cm distance from anomalous object for experiment B. As a compliment to ARS we acquired profiling data from two lines parallel and perpendicular to horizontal axis of anomalous object. Our results show that the apparent resistivity pattern can show the direction of anomalous object for both configurations and experiments with a little deviation.

1. Introduction
Fractures are defined as mechanical breaks in rocks originating from strain arising from stress concentrations around the crack, heterogeneity and physical discontinuity [1]. They are formed as a result of tectonic, lithostatic as well as thermal stresses and high fluid pressures. Fractures occur at a wide variety of scales, from microscopic to continental [1]. They form gaps filled with liquid fluid, gas, solid material or their combination. Fracture systems are of great interests for engineer, geotechnical engineer and hydrogeologists. A lot of significant geothermal, water supply as well as petroleum reservoirs form in fractured rocks. They acts as pathways for fluid flow. The existence of fractures is also influence the stability of engineered structures, which are built on surface as well as in subsurface. Studying fracture system are of great importance for many researchers and practitioners. One of geophysical methods suitable for studying fractures is the so-called azimuthal resistivity survey (ARS), a technique belongs to DC resistivity method. The application of ARS technique to fracture problem are widely studied, ranging from practical application in identifying fracture [2, 3, 4, 5] over theoretical development to separate its effect [6] until determining its orientation and characteristics [7, 8, 9, 10].
The existence of fracture system, homogeneous rock layering, oblique layer interface, heterogeneous rock layering as well as their combination in subsurface results in anisotropic effect in the DC resistivity data, that is hard to differentiate. Using only measurement from single azimuth often in inadequate to identify, locate and characterize fracture systems in subsurface [7]. Applying ARS technique based on measurement from multi azimuth is therefore required. ARS method deploys resistivity equipment similar to the equipment used in conventional measurement. This is carried out by measuring the apparent resistivity at various azimuths at a fixed point using a specific electrode configuration. The depth of investigation of this technique can reach 40m – 50 m depending on the electrode spacing used.

Fractures occurred in base rocks cause road and other infrastructures and substructures sitting on weak rocks to collapse. Bumpy road and tilted wall of houses exist. This phenomenon is visibly observed in karstic region in West Java. Since such phenomena are found commonly in Indonesia, investigation of the fracture system in subsurface using ARS technique is extremely needed to be carried out.

This research is aimed at identifying and studying apparent resistivity patterns due to fracture existing in subsurface through physical modeling in laboratory using test objects buried in a sandbox as well as buried in a test location outside laboratory building.

2. Theory

2.1. 1D and 2D electrode configurations

The DC resistivity method studies the variation of rock resistivity beneath the ground by injecting direct current \( I \) into the ground through a pair of current electrodes \( C_1 \) and \( C_2 \) and recording the potential difference \( \Delta V \) through a pair of potential electrodes \( P_1 \) and \( P_2 \), resulting an apparent resistivity \( \rho_a \). The apparent resistivity \( \rho_a \) is calculated through [3]:

\[
\rho_a = K \frac{\Delta V}{I}
\]

where \( K \) is geometrical factor, depending on electrode position.

Among many electrode configurations available for DC resistivity survey, Wenner and dipole-dipole are two of most used electrode configuration for 1-dimensional (1D) and 2-dimensional (2D) earth model (Figure 1). For Wenner and dipole-dipole, electrode configuration \( K = 2\pi a \) and \( K = \pi an(n+1)(n+2) \), respectively. \( a \) is electrode spacing and \( n \) is integer. These \( K \) values are valid for 1D and 2D measurements. In the Wenner array the electrodes are uniformly spaced in a line and all electrodes are moved about a fixed center, increasing the spacing \( a \) in steps. In the Dipole-dipole configuration, the potential electrodes are closely spaced and remote from the current electrodes, which are also close together and moved about a fixed center between potential electrodes pair and current electrodes pair, increasing the spacing between them.

![Figure 1. Wenner (a) and dipole-dipole electrode configurations (b) used for 1D and 2D measurements](image)

2.2. Azimuthal Resistivity Survey

Azimuthal resistivity survey (ARS) belongs to a technique in 1D resistivity measurement. The azimuthal Wenner, dipole-dipole as well as square configurations are illustrated in figure 2 where azimuthal data is collected at different azimuths.
Figure 2. Common electrode configurations used for azimuthal resistivity survey: Wenner (a), dipole-dipole (b) and square arrays (c)

2.3. Azimuthal apparent resistivity plot
The result of azimuthal resistivity measurement is plotted in polar coordinate form as shown in figure 3. An isotropic medium shows a circular geometry whilst an anisotropic medium is elliptical [7], [11]. Best fitted circle and ellipse geometry of the data are shown. To evaluate whether the medium is isotropic or not, the quantity $R^2$ is used. $R^2$ is defined as the percentage of the variance $\sigma$ from the circular model which has been removed by the elliptical model [7]:

$$R^2 = \frac{\sigma^2(\text{circle}) - \sigma^2(\text{ellipse})}{\sigma^2(\text{circle})} \tag{2}$$

$R^2$ values lie between 0 and 1. $R^2$ values close to 1 indicate very strong anisotropic properties of the rock, while it close to 0 indicate that the medium is isotropic.

Figure 3. Polar plot of apparent resistivity value versus azimuth. Circles and ellipses of data that fit best are plots on the figure. The orientation of the arrow denotes the strike direction of the fracture-like object.

3. Method

3.1. Experimental setup
We planned and implemented physical modeling through two experiments in this research, i.e. experiment A which was carried out in the laboratory and experiment B which was conducted outside laboratory building.
Experiment A
This survey was conducted in laboratory and implemented on 2.50 m x 1.5 m x 0.81 m sandbox, made of 10mm thick glass plates. Sandstone from a river was used as medium representing quasi homogenous medium. Clay roof tiles as well as steel plates as test objects were buried in the sandbox (figure 4). Clay roof tiles with moderate resistivity values were used that represent a moderately conductive fracture zone in a resistive rocks whereas steel plate was used simulating a highly conductive value in a resistive rocks. The anomalous object was placed with three different dip angles: 90°, 45° and 0°.

Figure 4. Sketch of physical model of sandbox in broad side (links) and long side views (right). Clay roof tiles (top) and steel plate (bottom) are used as test objects. Θ are varied: 0°, 45° and 90°. The external dimensions of sandbox are 2.00 m x 1.50 m x 0.81 m. Dimensions are in mm.

Experiment B
This survey was conducted outside laboratory building on the grass field and implemented on 2.50 m x 2.5 m x 1.0 m soil body. To make the soil act as a homogeneous medium, the soil dug first dug and crushed in such a way that the soil conditions are close to homogeneous. The soil was then returned to the excavation hole. Glass plates with resistivity values far below that of soil, acting as test objects were buried in the soil body (figure 5). Vertical single glass plate as well as vertical double glass plates at 30 cm distance were buried in the soil body, simulating vertical single fracture as well as vertical double fractures.

Figure 5. Sketch of physical model of a vertical single glass plate (a) as well as vertical double plates buried in soil environment (b) and their resistivity measurements (c) with Mc OYO resistivity meter (d). The dimensions of physical model are 2.50 m x 2.50 m x 1.00 m. Glass plates are used as test objects representing fracture at small scale.
3.2. Azimuthal resistivity measurement

Azimuthal resistivity measurements were carried out on soil surface above the anomalous objects (figure 6). For experiment A and experiment B with single glass plate, 1 measurement point (point 1) just above a test object is chosen as the location for azimuthal resistivity measurement. For model with vertical double glass plate, azimuthal resistivity measurements was carried out at 3 points locating at 15 cm distance from glass plate as shown in figure 6. For all measurement points in experiment A and B, collinear Wenner as well as collinear dipole-dipole electrode configurations were used and data were acquired at 15° angular step. As a compliment to Azimuthal resistivity measurement, 2D profiling data from two lines parallel and perpendicular to horizontal axis of anomalous object were acquired.

Figure 6. Sketch of measurement point location for experiment A (a), for experiment B with a vertical single glass plate (b) and for experiment B with vertical double glass plates (c).

4. Results and discussion

Figure 7 shows polar apparent resistivity plot at point 1 from model in experiment A using clay roof tiles and steel plate as anomalous objects at 3 different angles: 0°, 45° and 90°. Average calculated orientation of the anomalous objects is shown with grey arrow and the real anomalous object direction is shown with white arrow. All results show consistent anomalous object direction with a slightly average deviation of 12.6° from the real direction. Orientation trend from all data using Wenner and dipole-dipole configuration looks similar. This orientation deviation from the real one is probably due to the sand condition which is not a homogeneous medium and other error occurred during measurement.

Results from azimuthal resistivity measurement from model in experiment B show better results as seen in figure 8. All results showing the direction of anomalous objects approximating 45° that is the direction of both vertical anomalous objects as illustrated in figure 6. Those results are valid for point 1, 2 and 3. Slightly deviation shown in the dipole-dipole data from measurement at point 3. Similar to the results from model in experiment A is most likely caused by the soil condition which is not a homogeneous medium. This condition are obvious from the 2D resistivity profile as seen in figure 9. It seems that azimuthal resistivity measurement using dipole-dipole configuration is more sensitive than that of Wenner configuration in determining the anomalous object orientation. Nevertheless, it is obviously seen that the correct position of anomalous objects in experiment B is visible in the data.
Figure 7. Polar apparent resistivity plot at point 1 from model in experiment A: (a) clay roof tiles and steel plate. Results using Wenner (left) as well as dipole-dipole configurations (right) are shown. Results at different dip angle are shown from top (0°), middle (45°) to bottom (90°). Grey arrow shows the direction of anomalous body in the sandbox and white arrow pinned at the plot is average direction determined from data.

Figure 8. Polar apparent resistivity plot at point 1 to 3 from model in experiment B with vertical double glass plates at point 1 (a), point 2 (b), and point 3 (c).

Figure 9. Two-dimensional resistivity profile of model in experiment B with vertical single glass plate (top) and vertical double glass plates (bottom). The position of anomalous objects is shown.
5. Conclusions
We conducted azimuthal resistivity survey (ARS) on physical model using test objects buried in a sandbox in our laboratory for experiment A as well as in a test location outside laboratory building for experiment B. Azimuthal resistivity measurements at 15° angular step using Wenner and dipole-dipole configuration were carried out in both experiments located at 1 point just above anomalous object for experiment A and at 3 points at 15 cm distance from anomalous object for experiment B. As a compliment to ARS we acquired profiling data from two lines parallel and perpendicular to horizontal axis of anomalous object. Our results show that the apparent resistivity pattern can show the direction of anomalous object for both configurations and experiments with a little deviation.

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