

A NON-DESTRUCTIVE METHOD FOR INVESTIGATING SOIL LAYERS OF AN INDIVIDUAL VULNERABLE SLOPE

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ABSTRACT: Soil stability analysis becomes main concern in the preliminary design of new construction project. In a critical soil slope, the stability can be affected by the additional load and water infiltration significantly. This is due to additional overturning moment and decreasing of shear strength of the slope material. In such scenario, the non-destructive soil investigation method is needed to analyze the stability. This paper examines the use of Electrical Resistivity Tomography (ERT) to investigate soil layers in a critical slope and to measure parameters of soil shear strength indirectly. Two ERT methods used in this research were dipole-dipole array and square array resistivity (SAR). The results of ERT were verified using geotechnical testing (Bore-hole and Standard Penetration Test) results by investigating the presence of high porosity and water content with soil resistivity. The results of Dipole-dipole array and SAR at selected locations are consistent and suggest a possible crack at the location was reflected by the low soil resistivity value. Furthermore, the results of the SAR confirmed the existence of the deep crack as a continuance of visible cracks on the surface. The results of ERT can be used to detect deep cracks in the subsoil if ERT is conducted in the wet seasons, due to the existence of infiltrated rainwater. Due to the limitations of this technique, the ERT result should be interpreted cautiously. The study demonstrated the benefits of the use of electrical resistivity for the detection of soil layers in residual soil slope.

Keywords: Soil layers detection, Electrical resistivity tomography, Geotechnical investigation, Soil crack

1. INTRODUCTION

Analyses in stability of slope can be well undertaken by knowing the soil layers underground. Including cracks in soil slopes that has a significant effect on rain-induced slope instability. The stability of slopes associated with surface cracks and rain-water infiltration, has been widely investigated [1], [2], [3], [4], [5]. Surface cracks in soils can be easily seen. In contrast, it is difficult to detect deep cracks unless special equipment for subsoil investigations, such as geophysical tools, is used. The application of geophysical methods may be useful for subsoil investigations, especially at the reconnaissance stage. Based on different physical principles, several geophysical techniques can be used as non-destructive test methods for in-ground investigations. Three of the techniques that can be used to identify soil cracks are based on seismic refraction, electromagnetic wave refraction, and electrical resistivity.

Ground investigations using Electrical Resistivity Tomography (ERT), have been used by [6], [7], [8], [9], [10], [11]. The electrical resistivity method determines the soil type by using electrical resistances differences in different soil types. The flow of an electrical current can move through a soil due to electrolytic action. Water content and the

concentration of salts will then measure the resistivity of soil. For example, a saturated soil with a high void ratio would be detected as having low resistivity, due to the significant quantity of pore water and free ions in the water.

Samouëlian et al. [6] have reviewed the application of ERT for characterization of soils, including the early detection of soil layers. Colangelo et al. [12] have used ERT to obtain information on the deep characteristics of landslide bodies, such as sliding surface location and thickness of the slide materials, by comparing information with previous geological maps. Some researchers have attempted to verify the results of geophysical application by using in-situ geotechnical tests such as Standard Penetration Test (SPT) and Dynamic Cone Penetrometers test (DCPT) by [11], [13], [14].

Although attempts at soil characterization have been made, to integrate the results of geophysical application testing and geotechnical data, there is still a lack of investigations of soil slopes associated with deep cracks using ERT, field and laboratory geotechnical testing. This paper discusses the results of soil investigations to detect soil layers with deep cracks on unsaturated residual soil slopes using an electrical resistivity tomography (ERT). The results then being verified using data from field and laboratory geotechnical testing.

2. SITE CHARACTERISTICS

A residual soil slope in the hilly terrain of East Java Province in Indonesia was selected for this study as shown in Fig. 1. This slope is located at a high seismically active zone [15] and experience a high average annual rainfall of about 2,700 mm [16], [17]. Figure 2 shows the distribution of slope angle in the study area. The result of a land survey conducted on the slope was used to generate the geometry of slope along AA' with the average slope angle being measured at 20°.

There is evidence of past rainfall-induced residual soil slope failures in the study area [18, [19]. Local authorities had reported that areas downstream of the targeted slope had experienced a sliding one year before this research was conducted by [20]. Some surface cracks subsequently emerged on the upper side of the soil slope.

There were three profile lines (see Fig. 1), each 150 m long and separated by a distance of 5 m (from A to A'), with one profile line (line 4) of 100 m crossing the other profile lines (from C to C'). To obtain a sub-soil resistivity profile for the slope, an ERT survey using the Dipole-Dipole array method was conducted along profile lines 1, 2, 3, and 4 with 15 electrode points at a spacing of 10 m. The total length of each profile line, from A to A', was 150 m.

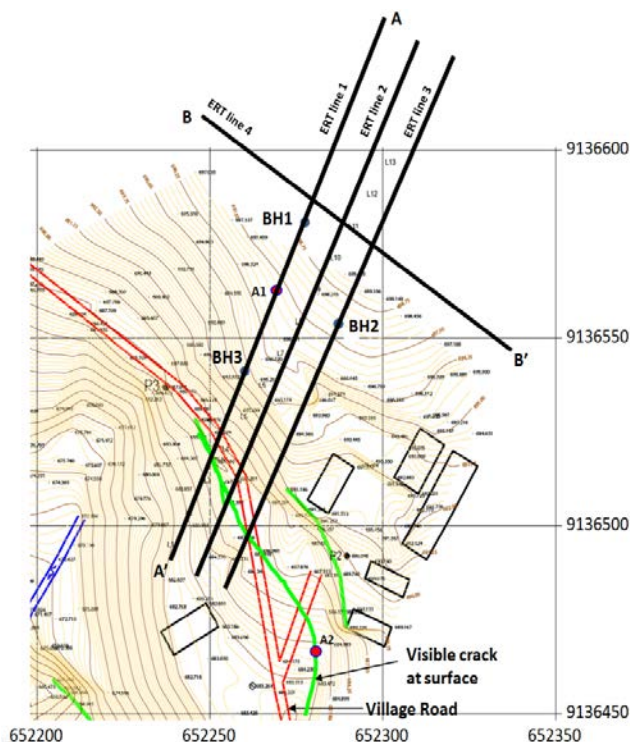


Fig. 1 Map of the study area showing ERT and borehole locations (BH)

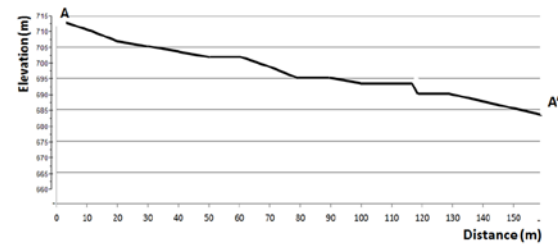


Fig. 2 Cross section long A-A' of the selected slope

3. METHODOLOGY

To provide electrical resistivity and soil parameters, two soil investigation methods were used in the study: field and laboratory geotechnical testing; and Electrical Resistivity Tomography (ERT).

From the field and laboratory geotechnical testing, selected relevant soil parameters were measured such as water content, porosity and clay content. The electrical resistivity of the subsoil identified the location and provided geometrical information relating to subsoil cracks [6], [7], [8], [9], [10], [11]. Soil resistivity can be affected by soil water content, porosity, and clay content. Sub-surface cracks or deep cracks can be associated with high porosity and high water-content in wet seasons, providing low resistivity. The location of deep cracks was confirmed when a low resistivity value was found in the subsoil, in association with high porosity, high water content, and low clay content. The results of SPT test and other laboratory tests conducted on soil samples obtained from the bore-holes were used to verify the location of the deep cracks detected by ERT

3.1 Geotechnical Test Method

In this study, geotechnical investigations (SPT and soil sampling) were carried out in the selected slope in order to characterize the sub-surface soils. Three borehole tests were conducted at BH1, BH2 and BH3, as shown at Fig. 1. At every 2 m depth interval in each borehole, an SPT test was performed following the procedure of the American Society for Testing and Material (ASTM) Standard. Soil samples collected at every 1 m depth in each borehole were used to determine water content, specific gravity, Atterberg limits, dry unit weight, grain size distribution, and shear strength using direct shear test in the laboratory following ASTM testing procedures.

3.2 Geophysical Application Method

Electrical resistivity tomography (ERT) was used for subsurface exploration along four profile lines at observed slope locations, as illustrated in Fig 1. The objective of the ERT was to detect deep cracks in the upper side of the soil slope. Two ERT methods used in this research were Dipole-dipole array and Square

array.

Dipole-dipole array provides the highest resolution, when compared with other arrays such as Wenner arrays and Schlumberger arrays. In addition, dipole-dipole array is most sensitive to vertical resistivity boundaries as is needed for deep-crack detection [21], [22], [23]. Santos et al. [23] stated that this array is more efficient for delineating the direction of faults when compared with other arrays. Hack [24] also reported that Dipole-dipole array is suitable for vertical structures, vertical discontinuities, and cavities. After comparing the Wenner and Dipole-dipole arrays, Neyamadpour et al. [25] concluded that the Dipole-dipole array produced a better lateral extension of the subsurface features. Therefore, in this research, the ERT survey was carried out using the Dipole-dipole array method along the profile lines (shown in Fig. 1) at an acceptable inter electrode spacing of 10 m, as applied by [12]. To gain comprehensive results, there were three profile lines, each 150 m long, with a 5 m spacing.

An ERT survey using the Dipole-Dipole array can be conducted on the profile lines on the slope. A direct current (D.C.) is driven into the ground through particular electrode position as shown in Fig. 3 to initiate electrical responses. A set of current input electrodes (labelled C1 and C2) and a set of voltage measurement electrodes (labelled P1 and P2) are put in place. The spacing between the C1 and C2 electrodes is denoted as "a". The P1 and P2 electrode pair with equal spacing is placed collinearly at distance "n.a" away from C1 and C2, where "n.a" is a distance equal to an integer multiple of "a". The 45-degree angle is used to plot the pseudo section data point. The electrical current is activated to measure soil resistivity which is recorded using the resistivity meter device.

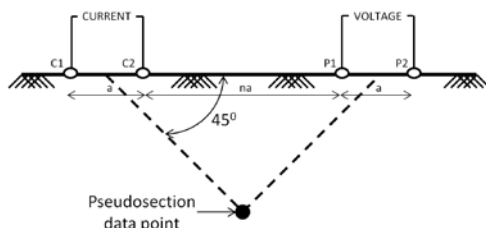


Fig. 3 Basic Dipole-dipole array method configuration

The next step requires that the electrodes are moved across the surface, following marked locations to measure all subsurface data points. For example, Fig. 4 illustrates the 3rd step of taking measurements to get data at selected locations; whereas C1 and C2 are inserted in the same poles, the P1 and P2 electrodes are moved to pole numbers 5 and 6.

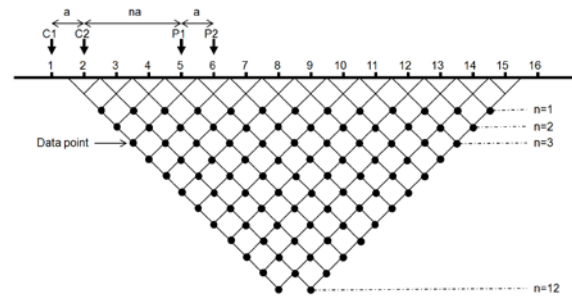


Fig. 4 Third measurement step using the Dipole-Dipole array method

The measurement process using the Dipole-Dipole array along a selected profile line is continued for all data points. Subsequently, data from the resistivity meter is processed using the Res2Div software to generate the inverted resistivity depth image for the selected profile line.

Possible location of deep crack can be interpreted from the ERT result by detecting the zone with lower resistivities. The low resistivity value can be an indication of increased water content due to higher porosity in that zone. However, clay content of the soil matrix also affects soil resistivity. A mobile cloud of additional ions can be formed around each clay particle by the ion exchange properties of clay. As these ions will facilitate easy flow of electrical current, the electrical resistivity in fine-grained soils, such as clay, is always lower than expected [26]. Therefore, the results from ERT need to be verified using a geotechnical test, to ensure that the deep crack has shown a low resistivity value due to high porosity.

To obtain detailed identification of deep cracks in subsoils, ERT application using Square array Resistivity (SAR) technique was used in the potential soil cracks zone detected from Dipole-Dipole array method. Basically, the principle of SAR is similar to Dipole-Dipole array, but in SAR the configuration is modified into a square and rotated measurement [27]. As shown in Fig. 1, there were two locations for the SAR: at the middle of Profile Line 1 (location A1) and on the nearby visible surface crack (location A2).

In general, the nature of anisotropy can be interpreted as cracks in a soil layer. SAR techniques can be used to determine the direction of vertical cracks in the soil [27], [28], [29]. The SAR technique was selected for use in this study to support the result of Dipole-dipole array method by indicates the existence of anisotropy in the soil with low resistivity value.

The SAR technique characterizes the soil crack by using minor resistivity, which indicates the angle direction of the soil crack and the influential depth of the crack zones. The measurement is obtained by inserting four electrodes into the ground following the square array illustrated in Fig. 5. Two current electrodes are placed on pole A (C1) and B (C2). Two

potential electrodes are then inserted on M (P1) and N (P2). In this square array, the measurement point is located at the centre of the square. The azimuth of the measurement is represented by the line connecting the current electrodes (A and B).

The observation depth that can be achieved using this method is related to the length of “a” being used. An incremental array size (a) from 2 m to 12 m was used. The plot of pseudosection data points is located at a 45-degree angle from the horizontal line between the electrode pole and the centre. Therefore, the depth of the measured data point (D) will be determined by:

$$D = \frac{1}{2} a \sqrt{2} \quad (1)$$

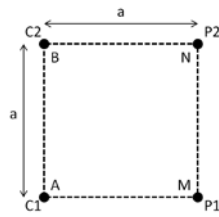


Fig. 5 Azimuthal square array configuration

In accordance with the electrode configuration of the square array as shown in Fig. 5, the value of apparent resistivity ρ_a is calculated as:

$$\rho_a = 2\pi \left\{ \left(\frac{1}{C_1P_1} - \frac{1}{C_2P_1} \right) - \left(\frac{1}{C_1P_2} - \frac{1}{C_2P_2} \right) \right\}^{-1} \frac{\Delta V}{I} \quad (2)$$

$$\text{If, } K = 2\pi \left\{ \left(\frac{1}{C_1P_1} - \frac{1}{C_2P_1} \right) - \left(\frac{1}{C_1P_2} - \frac{1}{C_2P_2} \right) \right\}^{-1}$$

Then, the value of apparent resistivity becomes:

$$\rho_a = \frac{K \Delta V}{I} \quad (3)$$

Where:

ρ_a = resistivity (Ω m)

K = geometric factor

ΔV = potential difference between P1 and P2 (volts)

I = electric current (amps)

Furthermore, the geometric factor, K, can be substituted with the side length of square (a):

$$K = 2\pi \frac{1}{\left\{ \left(\frac{1}{C_1P_1} - \frac{1}{C_2P_1} \right) - \left(\frac{1}{C_1P_2} - \frac{1}{C_2P_2} \right) \right\}}$$

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

$$K = \frac{2\pi a}{2 - \sqrt{2}} \quad (4)$$

Changes in the rotation angle (azimuth) can be made in 15° increments to 360°, in accordance with the rules of the British National Grid (BNG). Therefore, 24 parts with different resistivity values

can be obtained at every depth.

This SAR method will produce decreasing resistivity values if there is a crack inside the subsurface layer. Such a medium is called anisotropic and will produce an ellipse resistivity value plotted in polar coordinates, as shown in Fig. 6a. If the observed ground has an isotropy medium, the relationship will be seen as rounder as illustrated in Fig. 6b. The direction of the observed crack can be determined by viewing the results of a polar graph at each point of measurement, with the direction of the crack coinciding with the minor axis. If the polar graph is an ellipse-shape, then a crack can be found.

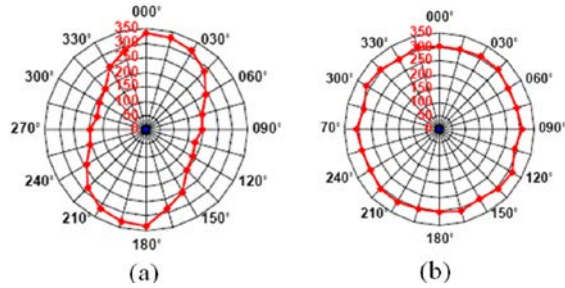


Fig. 6 Polar graphics of azimuthal square array result

However, Busby and Jackson [28] have stated that to be assumed as anisotropy, an ellipse polar graph has to have a coefficient of anisotropy of more than 1.16, based on the ratio of minor and major axis:

$$\lambda = \sqrt{\frac{p_l}{p_t}} \quad (5)$$

The results of geotechnical investigation and ERT can be used to develop useful correlations that can predict soil parameters from the soil resistivity data. As the measurement of soil resistivity using the ERT method is non-destructive, fast, and economical, it gives advantages in the prediction of soil parameters such as shear strength. Sudha et al. [11] presented a linear correlation between SPT N-values and the transverse resistance (T) that is expressed by Equation 6.

$$T = \sum_{i=1}^m \rho_i h_i \quad (6)$$

where ρ_i and h_i are the resistivity and thickness, respectively, of the i^{th} layer.

4. RESULTS AND DISCUSSION

4.1 Detection of Possible Crack Location Based On Soil Resistivity

Figure 7 presents the ERT Dipole-dipole array results, showing the soil resistivity distribution of the subsurface soil in the study area. A significant

variation in soil resistivity at different depths along the profile lines can be observed. The soil resistivity in the area ranges from 1 to 2000 Ωm , indicating a wide variation in soil type, clay content, porosity, and water content. In general, low soil resistivity was measured for the surface soil layers (5 – 10 m depth). This would be due to high water content in the surface soil, as this test was conducted in the rainy season.

Local zones with very low resistivity (3 – 30 Ωm) could be potential locations for cracks. Soil crack zones have very high porosity and high water content in the rainy season, as rain water can easily seep into the cracks. This hypothesis was justified in profile line 1 (Fig. 7.a), as the visible surface crack coincided with the very low resistivity zone in the subsoil.

However, it was not possible to perform a resistivity test in the vicinity of the surface crack in profile line 2 (Fig. 7.b) and profile line 3 (Fig. 7.c), due to the accessibility issues in the area.

The low resistivity zones at the horizontal distance (from A) between 60 m to 130 m and at depth 2 to 12 m, were consistent in all profiles. This suggests possible transverse cracks in this area, as shown in profile line 4 (Fig. 7.d) that crosses over the three other profile lines. This possible transverse crack can also be observed in Fig. 7.d, whereas a local zone with very low soil resistivity was found at the horizontal distance (from B) between 35 m to 55 m and at depth 2 to 12 m.

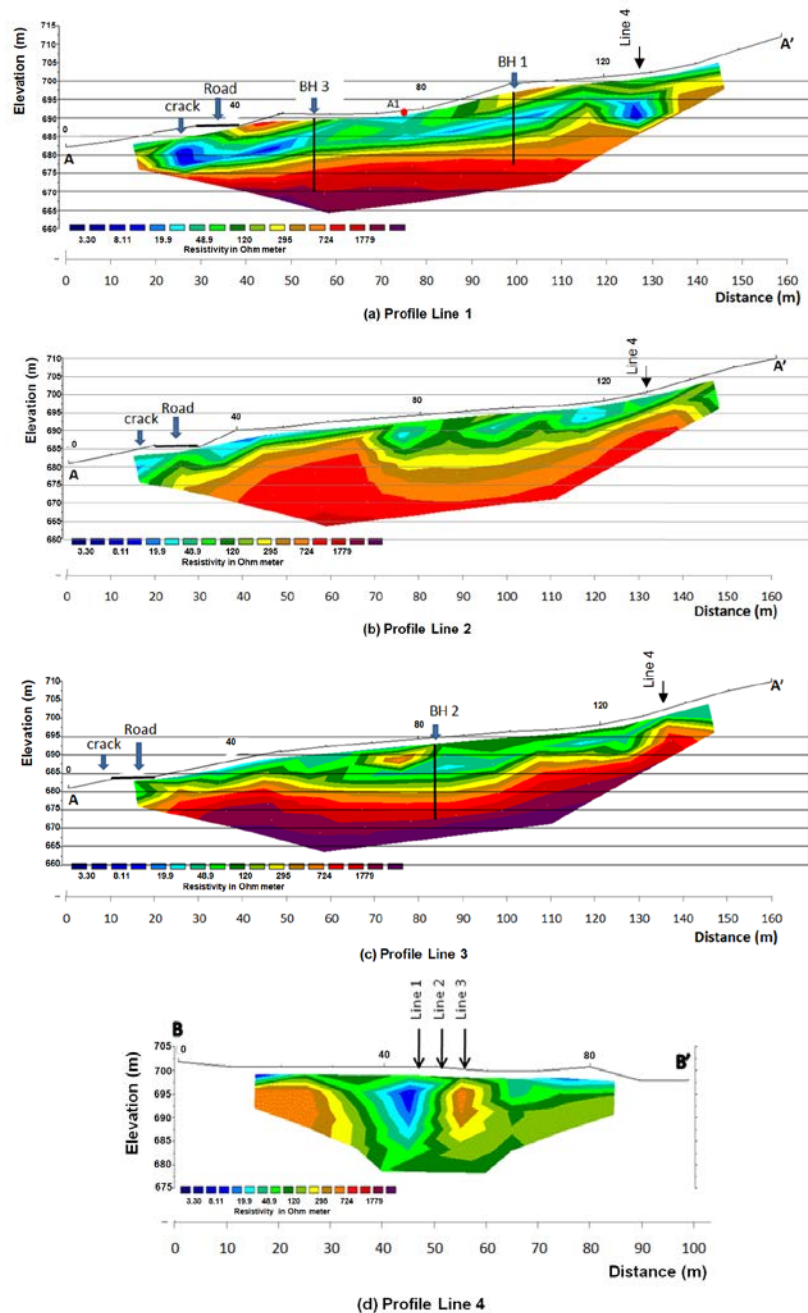


Fig. 7 The visual results of ERT along four profile line

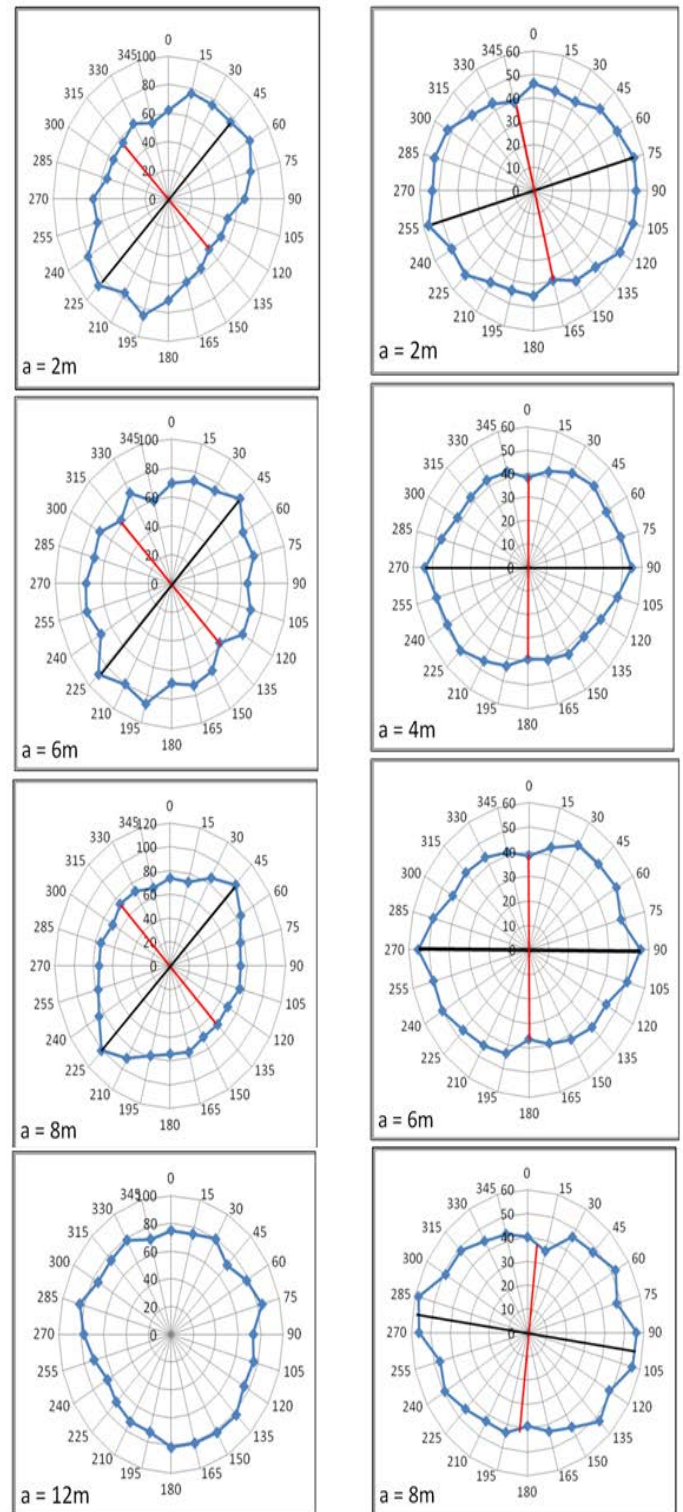
Possible cracks could be investigated by using the results of SAR technique in the selected locations, as shown in Fig. 8. It was found that: at location A1, cracks in the soil were detected in a direction of 135° from the north, 0 to 5.65 m deep; at location A2, a non linear crack direction was found. From the surface to a depth of 1.41 m, the crack began at an angle of 165° from the north (N 165° E). From the depth of 1.41 m to 4.24 m, the direction of the crack changed to an angle of 180° from the north (N 180° E). Then from a depth of 4.24 m to 5.65 m, the crack direction was found to lie between an angle of 180° - 195° from the north (N 180 - 195° E).

The results of Dipole-dipole array and SAR at A1 are consistent and suggest a possible crack at this location was reflected by the low soil resistivity value. The results of the SAR conducted at A2 confirmed the existence of the deep crack as a continuance of visible cracks on the surface (see Fig. 1).

4.2 Verification of Possible Crack Location Using Geotechnical Data

Since soil resistivity is affected by clay content and soil density, in addition to soil water content, it is important to use the measured soil parameters such as density, grain-size distribution and water content of the soil in the site, to verify the size and location of the cracks detected by ERT. The existence of cracks can be determined by the presence of high porosity and water content in the wet season. Verification was undertaken to all Bore Hole (BH-1, BH-2 and BH-3).

At bore hole location 1 (BH-1), it can be seen that a low soil resistivity zone was found at a depth of 6 m to 10 m (less than $50 \Omega\text{m}$), as illustrated in Fig. 9. At this depth, there was an average volumetric water content of 65%, and an average clay content of 20%. Therefore, the low resistivity at the depth 6 m to 10 m could have been mainly due to the high-water content, rather than an effect of the clay content. Based on the above information, it might be concluded that a deep crack could be located at the depth of 6 m to 10 m. It was further confirmed that the soil at 6 m to 10 m depth has a high porosity and low unit weight of around 68% and 14 kN/m^3 , respectively. Similar analyses were undertaken for BH-2 and BH-3 whereas possible crack location at a depth of 7 m to 9 m in BH-2 and at 2 m to 5 m depth in BH-3.



(a) A1 location results (b) A2 location results
Fig. 8 Results of SAR Technique

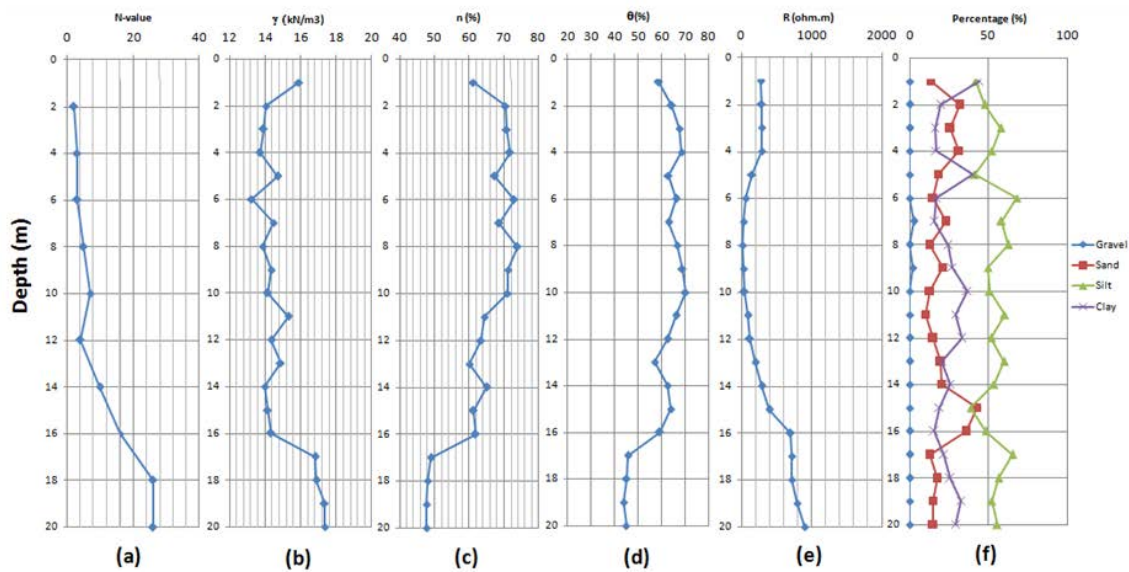


Fig. 9 Soil parameters at BH-1: (a) N-value, (b) Unit weight, (c) Porosity, (d) Volumetric water content, (e) Resistivity, (f) Grain-size distribution

5. CONCLUSIONS

The following conclusions can be drawn from this study that the results of ERT can be used to detect deep cracks in the subsoil if ERT is conducted in the wet seasons, due to the existence of infiltrated rainwater. However, the ERT result should be interpreted cautiously due to its limitations.

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7. ACKNOWLEDGMENTS

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