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Application of 2D Electrical Resistivity Imaging Technique for Detecting Soil Cracks: Laboratory Study

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Abstract

Cracking of soils affects their geotechnical properties and behavior such as soil strength and stability. In this paper, 2D Electrical Resistivity Imaging Method, as a non-invasive technique, was adopted to investigate the effect of soil cracks of a centemetric scale on resistivity of sandy soil. The electrical resistivity measurements were carried out using ABEM SAS 300C Terrameter system at a laboratory scale using Wenner array. The measurements were interpreted using horizontal profiles, forward modeling and 2D inverse resistivity sections. The results showed that soil cracks cause significant changes in soil resistivity. These changes can be attributed to the high resistivity contrast between the highly resistive air-filled cracks and the surrounding intact soil. The results indicate the visibility of the method to detect cracking of soils which is of high importance in the geological and geotechnical investigations.

Keywords: 2D Resistivity Imaging, Soil Cracks, Wenner array

تطبيق طريقة المقاومة النوعية الكهربائية التصويرية ثنائية البعد في تحديد تشققات التربة: دراسة مختبرية

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الخلاصة

تؤثر تشققات التربة على خصائصها و سلوكها الجيوتكنيكي كقوة تحملها واستقراريتها. في هذا البحث، اعتمدت طريقة المقاومة النوعية الكهربائية التصويرية ثنائية البعد لدراسة اثر تشققات التربة على المقاومة النوعية لنموذج مختبري من تربة رملية. اخذت قياسات المقاومة النوعية الكهربائية باستخدام جهاز (ABEM SAS 300C) باستخدام ترتيب فنر للاقطاب. تم تفسير المعطيات المقاسة باستخدام المقاطع الافقية، النمذجة الرياضية ومقاطع المقاومة النوعية الكهربائية ثنائية البعد. لقد بينت نتائج الدراسة بان تشققات التربة تسبب تغيرات شديدة في مقاومتها النوعية الكهربائية. ان هذه التغيرات يمكن ان تعزى الى فارق المقاومة النوعية الكبير بين التشققات الحاوية على الهواء ذي المقاومة العالية والتربة المحيطة. لقد بينت الدراسة امكانية استخدام طريقة المقاومة النوعية الكهربائية في الكشف عن تشققات التربة التي لها اهمية بالغة في الدراسات الجيولوجية والجيوتكنيكية.

الكلمات المفتاحية: المقاومة النوعية الكهربائية التصويرية ثنائية البعد، تشققات التربة، ترتيب فنر

Introduction

Unsaturated soils are subjected to wetting, drying and cracking cycles that significantly affect their geotechnical properties and behavior. In particular, soil cracks alter the macro porosity, infiltration, run off and create pathways for water that reduce soil strength and stability [1].

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However, soil cracks have complex patterns that are difficult to characterize, and measurement of cracking patterns has largely been limited to measuring crack geometries at the soil surface. Although surface crack networks can directly be described by measuring crack geometries [2] or imaging crack morphology using surface imaging analysis [3], these methods are largely based on visual inspections. 2D laser scanning technique [4] can be used only for small scale samples under laboratory conditions. Field measurements of cracking dynamics are difficult and have largely been limited to soil pits [5] or pushing a probe wire or measuring tape into the crack [6] and [7]. Obviously, these techniques are destructive and prohibit repetitive measurements. Recently, in a review paper, Dinka and Lascano [8] concluded that, none of the available techniques can provide sufficient information on cracking dynamics continuously, non-destructively and with a reasonable certainty. Clearly, an accurate understanding of cracking dynamics requires a non-invasive technique that can offer continuous monitoring of cracking dynamics below the soil surface.

2D resistivity imaging method offers non-invasive measurements that can be used at laboratory and field scales. Early studies have focused on detecting joints and fractures in rocks to: determine strike of jointed bedrock [9]; map fractures pattern [10]; locate flow pathways in conductive fracture zones [11] and monitor migration of a saline tracer [12] However, application of ERT method for characterizing small scale soil cracks is challenging. A number of authors have focused on using ERT to map cracks forming in soils. In the first reported 2D laboratory experiment, Samouëlian et al. (2003) [13] demonstrated the efficiency of the method to detect an artificial manually introduced crack of 2mm wide on a compacted soil. However, 2D resistivity sections were not considered. Other studies e.g. [14], [15] and [16] demonstrated that changing cracking parameters, such as depth, length, width and angle of manually created cracks in 1D laboratory experiments produces significant changes in the electrical resistivity of the soils. They concluded that the resistivity method can be used to identify the formation of soil cracks as cracks formation cause directional dependence of the electrical current flow. Recently, the method has proven successful to map a cracking network forming in soil at laboratory [17] and field [18] scales.

In current work, 2D resistivity imaging method was adopted to investigate the effect of cracking depth of sandy soil at a laboratory scale. The results were discussed using horizontal profiling, forward modeling and 2D inverse resistivity sections.

Methodology

2D resistivity imaging technique

Electrical resistivity is an intrinsic physical property of a material that describes its ability to resist the flow of electricity [19]. The traditional four-electrode resistivity method is, therefore, based on the principle that the potential drop across a pair of electrode associated with DC or low frequency current injected into the soil using another pair, is proportional to the soil resistivity, that is:

$$\rho = K\frac{\Delta V}{I} \qquad (1)$$

Where, ρ is the soil resistivity (Ohm.m), ΔV is the voltage difference (Volts), I is the current (Amps), and K is a geometric factor (m) that accounts for the electrode arrangement.

Modern 2D resistivity imaging technique, however, is based on using the principle of traditional four-electrode method and the adoption of multiplexing of a number of electrodes. The measurements can be acquired for different electrode arrays. For Wenner array shown in Figure-1, the measurements are collected for different electrode spacing (a) and acquisition level (n) [20]. In this array, the four electrodes (C1 and C2 for the injected current and P1 and P2 for the resulted voltage drop) are equally spaced with an electrode spacing (a) between the electrodes. In the first acquisition level (n=1), the measurements are started with the electrode spacing (1a). For the first reading, the electrodes 1, 2, 3, and 4 are used as C1, P1, P2, and C2, respectively. The array is then moved by (a) to collect the second reading. This process is repeated to end of the profile. The measurements of the second level (n=2) are collected with electrode spacing of (2a) moving the array by (a) to the end of the profile. The same procedure is repeated to acquire the data for the rest of the acquisition levels. 2D inverse resistivity sections can be constructed using appropriate inversion software [21].

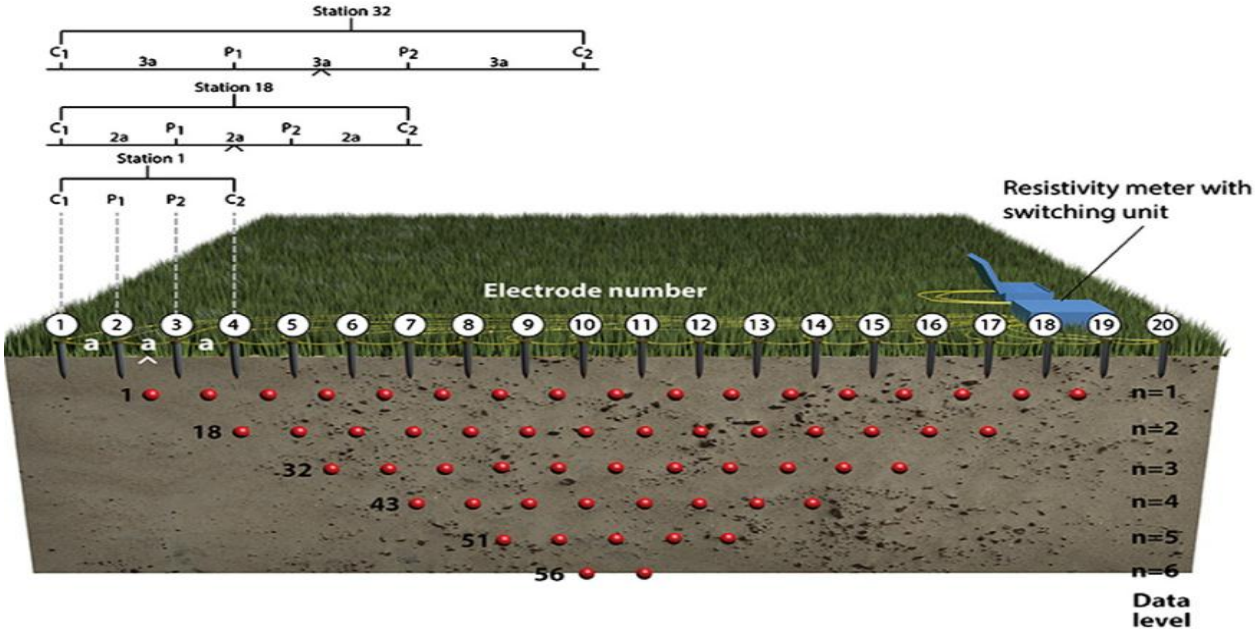

Figure 1- 2D resistivity data acquisition sequence of Wenner array (Loke et al., 2013)

Data Acquisition

The resistivity measurements were carried out using ABEM SAS 300 Terrameter using custom stainless steel electrodes (0.07m length), locally manufactured and installed on the top of sandy soil. The soil was compacted in a plastic container of (80X60X40cm) dimensions, as shown in Figure-2. The current injected through the current electrodes (C1 and C2) is varied from 0.2 to 2 mA. Apparent resistivity measurements were collected along 65cm profile using a minimum electrode spacing a= 5cm for four acquisition levels (n=4) using Wenner array. With this array 11, 8,5 and 2 measurements (26 measurements) were performed as the acquisition level n increased from 1to 4 ,as shown in Figure-3. The measurements were collected in four stages. In stage 1, resistivity measurements were collected along the profile (base model- without a crack). A crack between electrode No. 7 and No. 8 (i.e. X distance= 0.325m) with 1, 4, and 6 cm depth was then introduced manually using sheet of glass (0.5cm width, 7cm length) in stages 2, 3, and 4, respectively. This method was previously adopted to simulate an air filled crack in 1D electrical resistivity studies at a laboratory scale [14-16].

Figure 2- The acquisition system (a- side view to electrode arrangement and container, b- top view to instrument used SAS300)

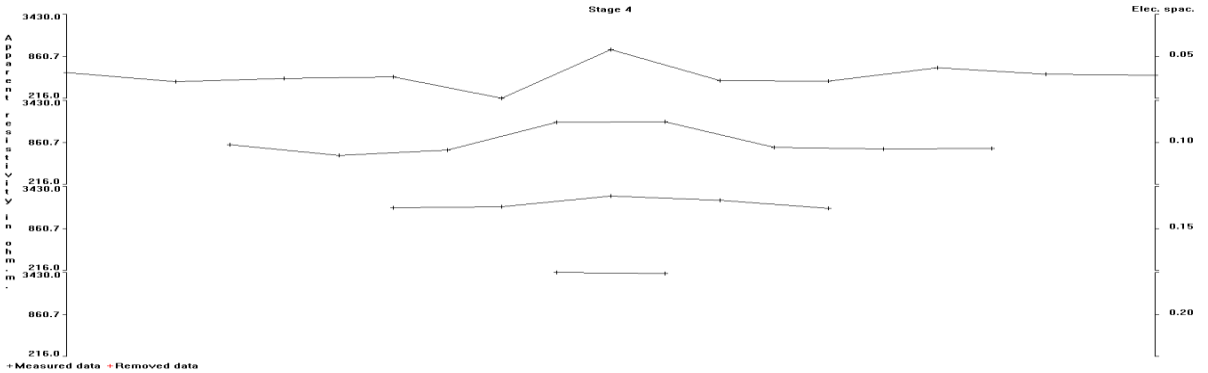

Figure 3- Apparent resistivity measurements for stage 4

Data Interpretation

The results were analyzed qualitatively using the resistivity horizontal profiling, 2D resistivity forward modeling and quantitatively using 2D inverse resistivity sections. Horizontal profiles can be performed by moving an array of electrodes with fixed electrode spacing along a profile to detect the lateral resistivity variations. Res2dmod ver. 3.02.04 and Res2dinv ver. 3.71.115 software were used for forward modeling and to create the 2D inverse sections, respectively.

Results and Discussion

Horizontal Profiling

Figure-4 shows the horizontal profiles of stage 1, 2, 3, and 4 (a=5cm, n=1). It can be seen that relative to stage 1, the apparent resistivity increases significantly at the position (X=0.325m), where the crack was introduced, particularly in stage 3 and 4, the more the cracking depth, the more the soil resistivity. To better emphasize this effect reference to the non-cracked model [14], the measured resistivities in stage 2, 3 and 4 were normalized referenced to the measured resistivities in stage 1, see Figure-5. No significant resistivity changes were noticed in stage 2, as the crack depth was relatively small (i.e. 1cm). However, the apparent resistivity increases at x=0.325m position by 44% and 90% in stage 3 and 4, respectively, relative to the non-cracked stage. Increasing cracking depth causes more deviation to the electrical current paths (high voltage drop) hence increases soil resistivity [13-16]. It also can be seen that the apparent resistivity decreases at the position X distance= 0.255m and 0.355cm, where the electrical current paths tend to concentrate (low voltage drop) hence decreases soil resistivity. Away from the crack position, the soil resistivity is relatively constant. The apparent resistivity variation will be discussed further using the forward modeling.

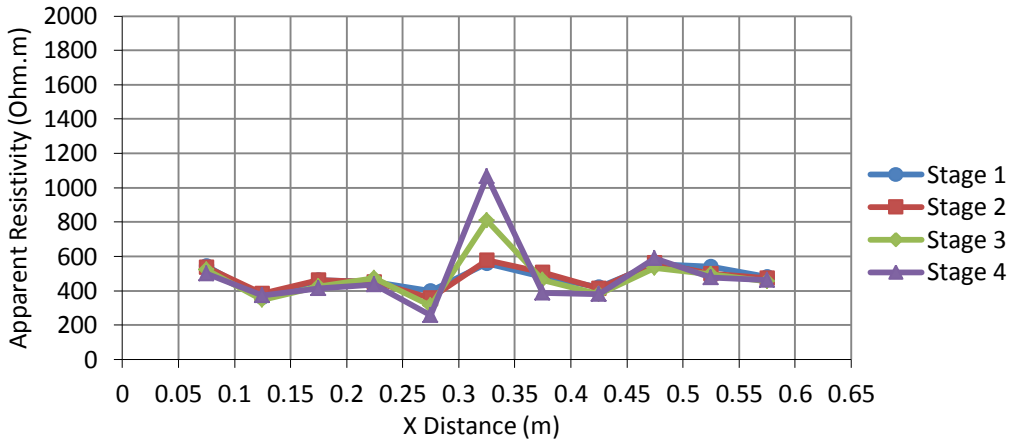

Figure 4- Horizontal resistivity profiles of stages 1,2,3 and 4 (a=5cm, n=1)

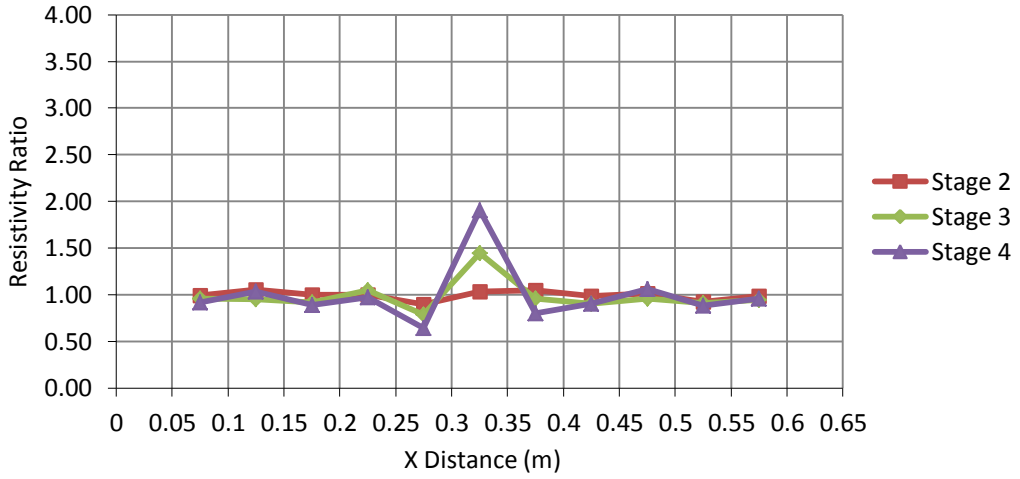

Figure 5- Horizontal resistivity profiles (a=5cm, (n=1)) of stages 2, 3 and 4 normalized referenced to the non-cracked stage (i.e. stage1)

Forward Modeling

To support the above discussion, a forward model using Res2dmod ver. 3.02.04 software was produced. The aim of the forward modeling is to calculate the apparent resistivity for a user defined synthetic model. Using this method complex geological structures can be modeled such as fractures [10], faults [22] and landslides [23]. As the crack is filled with air, that is infinitely resistive, model blocks containing the crack were simulated by setting their resistivity to 10000 Ohm.m [24]. A 4 cm depth crack model in 400 Ohm.m soil (close to the measured soil resistivity in the lab) using Wenner array was tested as an example, see Figure-6.

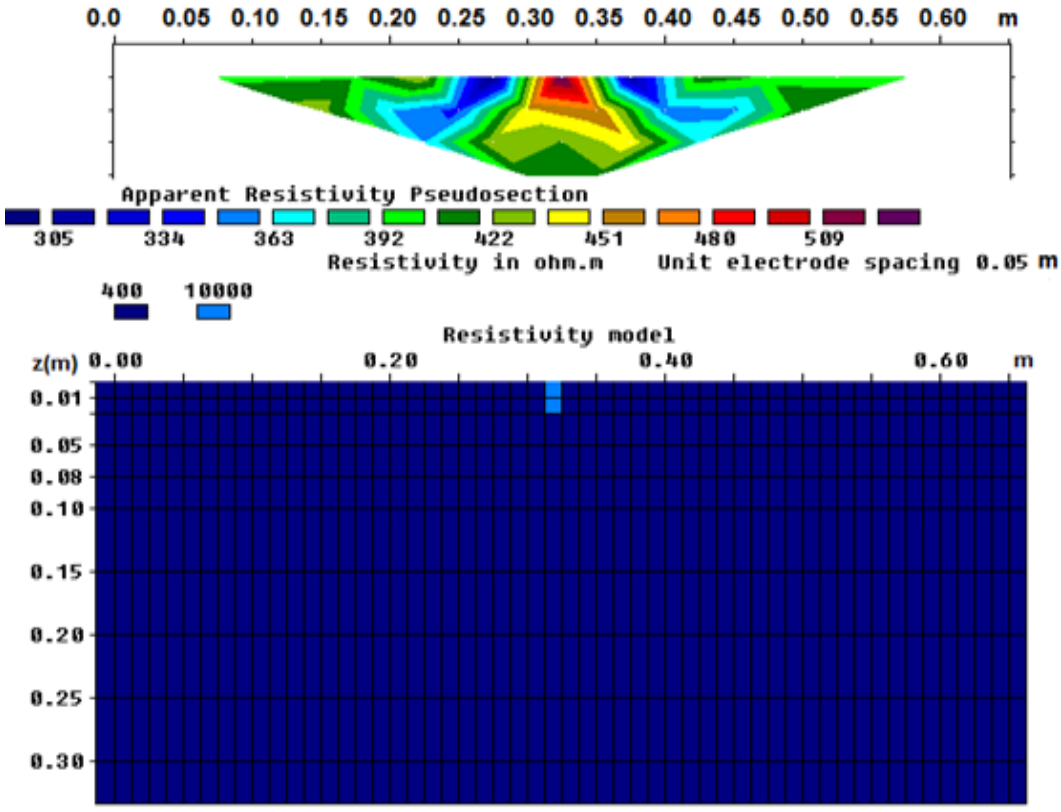

Figure 6- 2D apparent resistivity pseudosection section with a 4cm crack model

The forward model in Figure-6 supports the finding of Figure-5. High resistivity value (indicated in dark purple color) was noticed in the middle of the model at X distance= 0.325m (i.e. the crack position). A way from this position, the resistivity changes homogenously. However, a relatively low resistivity (Blue color) was noticed at X distance= 0.255m and 0.355cm, as also noticed in Figure-5. Again, this can be attributed to the deviation of the electrical current due to the presence of the crack. By theory, the resistivity method is based on the assumption that the subsurface is continuous, and measuring the voltage drop associated with the current injected into the soil provides information about the subsurface resistivity distribution. In a medium with conductive anomalies, the current flow lines tend to concentrate, hence low resistivity, while in a medium with resistive anomalies (e.g. air-filled crack), the current lines tend to deviate around them, hence high resistivity [25, 26] . As the soil cracks are normally filled with air that is electrically resistive, cracks form barriers that deviate the flow of current, resulting in a greater voltage drop relative to that measured for the surrounding intact soil, and hence high resistivity, while at the positions very close to the crack the current lines concentrate, resulting in a lower voltage drop, hence low resistivity. This fact is clearly evident in Figure-5.

2D Inverse Resistivity Sections

Figures-7, 8, 9, and 10 show, respectively, the 2D inverse resistivity sections of stage1, 2, 3, and 4. In stage 1, relatively homogenous resistivity variations were noticed. High resistivity values at the bottom reflects the effect of the plastic container [17]. In stage 2 (1 cm-depth crack), the inverse section showed no visible resistivity effect as the depth of the crack is relatively small. However, high resistivity values can clearly be noticed in the area between electrodes 7 and 8, where the crack was introduced (see Figures-9, 10), and the depth of the crack is reasonably indicated. The 2D inverse sections support the findings of the horizontal profiles and the forward model, discussed above. The sections showed that air-filled cracks cause significant changes in the soil resistivity, and the resistivity contrast between the crack and the intact soil is highly enough to be detected [17,18, 27], and the more the cracking depth, the more the effect as confirmed in 1D resistivity investigations [14-16]. The results indicated the visibility of the 2D resistivity imaging method, as a non invasive technique to characterize cracking of soils.

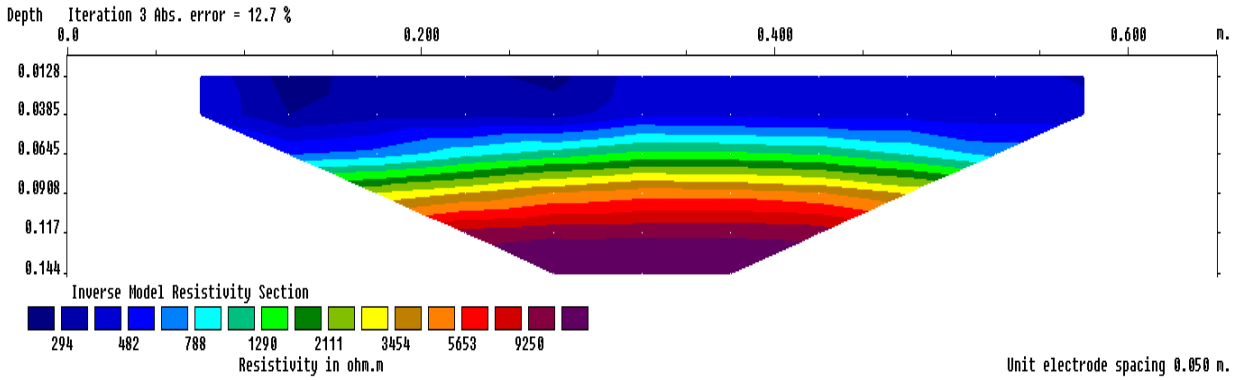

Figure 7- The 2D inverse resistivity section of stage 1.

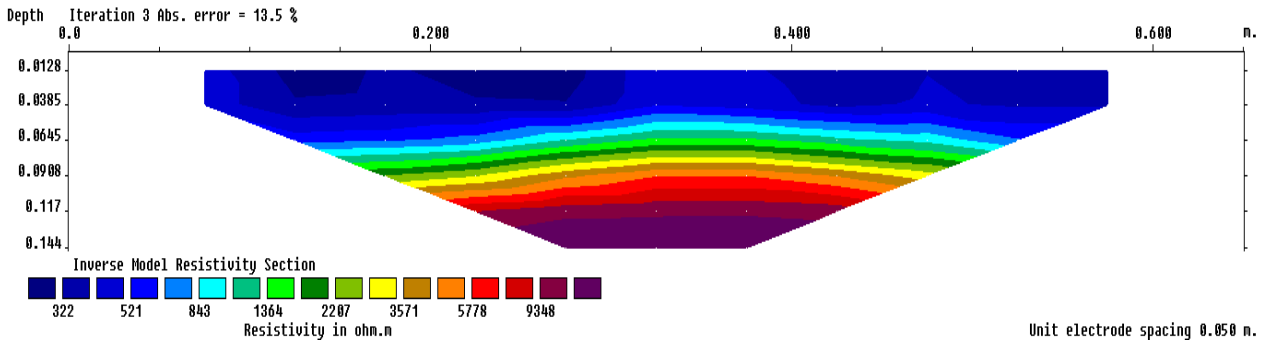

Figure 8- The 2D inverse resistivity section of stage 2.

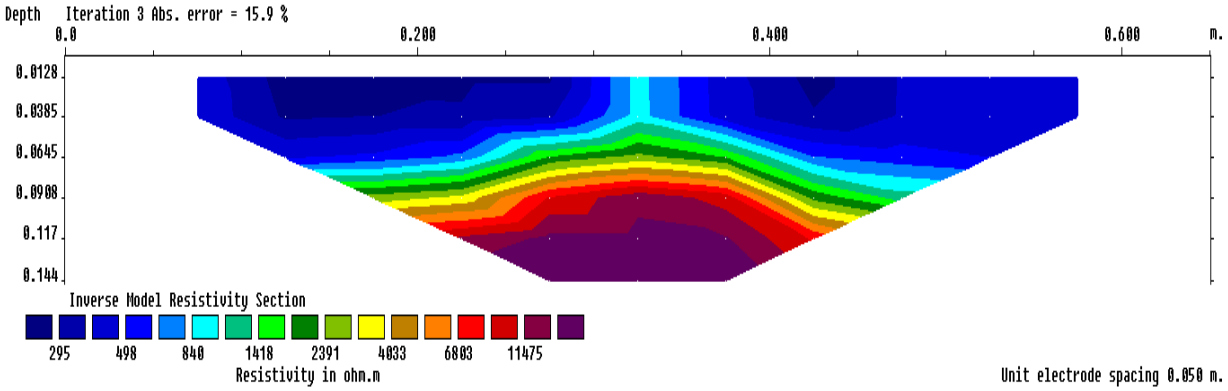

Figure 9- The 2D inverse resistivity section of stage 3.

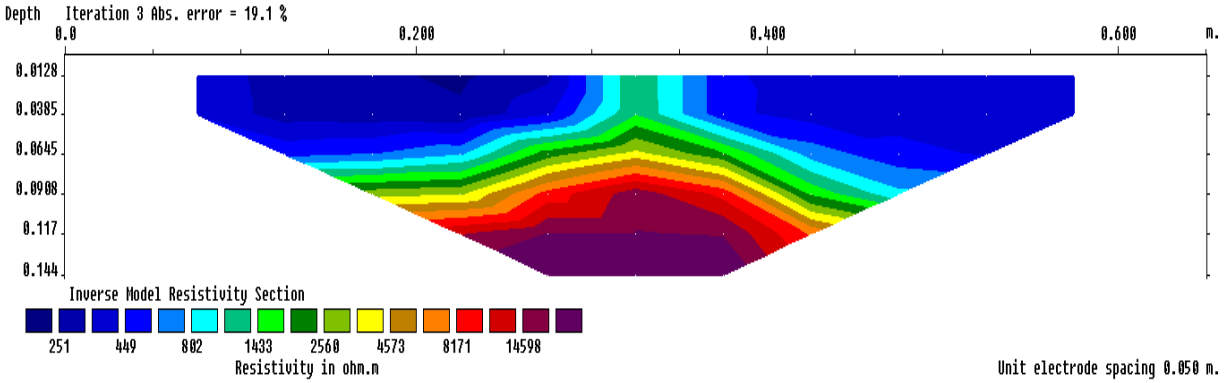

Figure 10- The 2D inverse resistivity section for stage 4.

Conclusion

In this paper, 2D Electrical Resistivity Imaging Technique was used to characterize the effect of soil cracks on soil resistivity at a laboratory scale. The results showed that the resistivity distribution of the soil was significantly affected by resistive air-filled cracks. The results indicate the visibility of the method to characterize cracking of soils which is of great importance in the geological and engineering applications. Future work is scheduled to investigate of the effect of natural soil cracks on soil resistivity distribution using different electrode arrays.

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