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3D Electrical Resistivity Tomography Method for Simulating of Polygonal Soil Cracks

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Abstract— Continuous wetting and drying of soils cause a cyclic process of swelling, shrinkage and cracking that adversely impacts the geotechnical properties and behaviour of these soils. In particular, continuous drying and shrinkage of soil might lead to the development of interconnected cracks to form polygonal blocks that significantly reduce the soil strength and stability. In this paper, 3D numerical modelling using Electrical Resistivity Tomography method is adopted for simulating polygonal cracks, commonly found in soils. The cracks are simuated in dry and wet soils at different scenarios. The results showed that the method is sensitive to soil cracking due to the high resistivity contrast between the cracked soil and the intact surrounding soil. As the air-filled cracks are infinitely resistive, soil cracks are reflected in the models as anomalous high resistivity spots that can be distinguished from the background. The geometry and cracking depth can be identified particularly in cases where the crack intersects the soil at the surface due to the departure of the electrical current.

Index Terms— resistivity, tomography, simulation, cracks, polygonal, soil cracks

1 INTRODUCTION

Soils tend to shrink when they lose moisture. Shrinkage of soils commonly often causes cracking. In addition to the moisture content, the cracking process is governed by a large number of factors (e.g. soil heterogeneity, mineral composition, temperature, evaporation, layer thickness, land cover, etc.). However, the development of tensile stresses due to shrinkage of the soil has widely been accepted as the common cause of the cracks [1]. As the water evaporates from the surface of the soil, the matric suction develops and progressively increases. Consequently, the soil consolidates and shrinks.
Increasing matric suction induces tensile stress at the soil surface and, once the tensile stress exceeds the tensile strength, the soil cracks. Howeverr, continuous drying and shrinkage of soils might lead to the development of interconnected cracks (see Fig. (1)) to form polygonal blocks. This might lead to the development of shear zones beneath the soil and, hence, slope failure [2], [3].
However, soil cracks have complex patterns that are difficult to charachterize. Although surface crack networks can directly be described by measuring crack geometries [4], or imaging crack morphology using surface imaging analysis [5], these methods are largely based on visual inspections. Field measurements of cracking dynamics are difficult and have largely been limited to soil pits [6], or pushing a probe wire or measuring tape into the crack [7], [8]. Obviously, these techniques are destructive and prohibit repetitive measurements [9].
The Electrical Resistivity Tomography ERT method offers non-invasive measurements at laboratory and field scales that can be used to identify the formation of soil cracks, as crack formation causes directional dependence of the electrical current flow [10], [11], [12]. The method has recently proven successful to map a cracking network forming in soil at lab scale [13] and field scale [14].
Numerical modelling using ERT method has been used for simulating different geologic situations in the literature, for example, to simulate simple soil cracks [11], [12], fractures in crystalline rocks [15], landslides [16] and faults [17].
In the current work, complicated polygonal (e.g. hexagonal) cracks, commonly found in soils, are simulated using 3D Electrical Resistivity Tomography method at different dry and wet soil situations.

Fig. 1. Development of polygonal cracks

2 3D NUMERICAL MODELLING USING ELECTRICAL RESISTIVITY TOMOGRAPHY METHOD

Electrical resistivity is a physical property that describes how a material resists the flow of electricity. The electrical resistivity method is, therefore, based on the principle that the

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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 distribution [18]. The numerical modelling using ERT method is useful to simulate real scenarios and to exam the effectiveness of the method applied before carrying out costly actual laboratory and field measurements. It is an effective and an inexpensive tool to plan and design the field surveys , and to test the success and limitations of the method [19].

Numerical modelling using ERT method is a two-step procedure [19], [20]; (i) a synthetic resistivity model is created based on the user prior information and assumptions (i.e. forward modelling), and (ii) the model is inverted to reconstruct the subsurface resistivity distribution (i.e. inverse modelling), see Fig. (2).

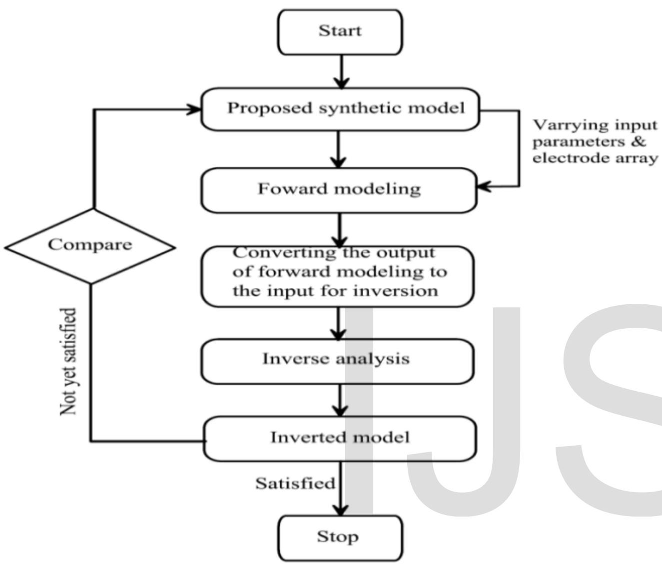

Fig. 2. Numerical modelling steps using ERT method [20]

In this work, to simulate polygonal cracks of a centimetric scale, 3D forward modelling (RES3DMOD) and 3D inversion (RES3DINV) packages [21] are used. RES3DMOD is a finite difference forward modelling software that determines the apparent resistivity values for a synthetic survey carried out with a user defined electrode arrangement and resistivity distribution using a rectangular grid of electrodes. The software solves the 3D potential distribution due to point current source in a half space subsurface. A 3D subsurface model is created using rectangular blocks with a number of electrodes at the nodes. RES3DINV uses the smoothness constrained least squares method to produce a 3D model of the subsurface resistivity distribution from the apparent resistivity data. The software attempts to determine the resistivity of the cells in the inversion model that will closely reproduce the observed apparent resistivity data.

To explore the effectiveness of the method to identify small-scale polygonal cracks, a model consisting of six layers was generated. The minimum electrode spacing was set to be 5cm. As the crack is filled with the air, that is highly resistant, model blocks containing a crack were simulated by setting their resistivity to 3000 Ohm.m. A model of 7cm depth polygonal crack in a relatively dry (1000 Ohm.m) and wet (10 Ohm.m) soils was tested. Once the model file is prepared, RES3DMOD is used to calculate the apparent resistivity at each node, and the results were saved to be used for input in RES3DINV software to produce subsurface resistivity distribution [20]. To simulate real situations, adding 5% resistivity noise is a common practice in the literature [22], Therefore, a scattered 5% resistivity noise was added to the simulated models.

3 Results and Discussion

Fig. (3) shows the inverted resistivity sections of the 7 cm-depth polygonal (e.g.hexagonal) crack in 1000 Ohm.m dry soil. Figure (4) shows the 3Dvisualization of the model created using a 3D visualization program [23]. It can be seen that the geometry of the crack is clearly indicated. As the crack is filled with air of high resistivity, the crack can be identified as an anomalous high resistivity spot comparing to the intact soil [13]. It can also be seen that the depth of the crack (7cm) can be detected in the model, as no high resistivity values were noticed below this depth.

However, to simulate real situations, a scattered 5% resistivity noise was added to the model, see Figure (5). Obviously, the crack geometry and depth can still be identified.

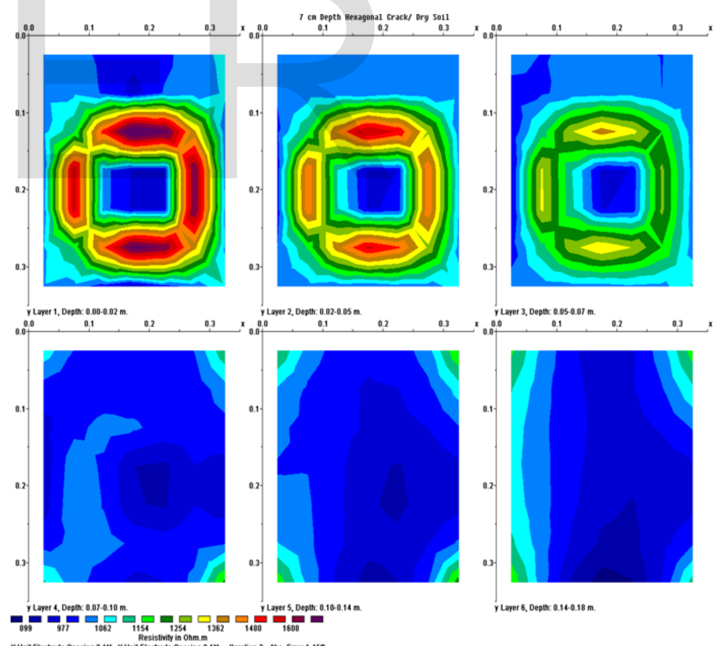

Fig. 3. The inverted resistivity sections of the 7 cm- depth hexagonal crack in dry soil

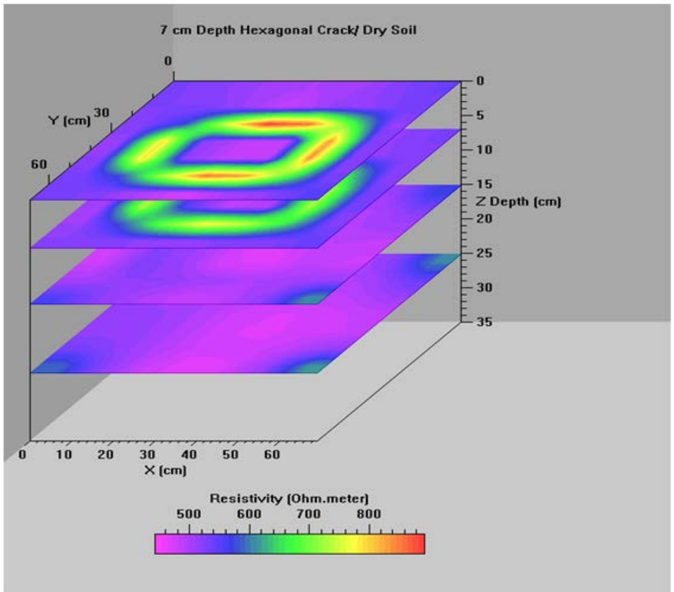

Fig. 4. 3D visualization of the7cm- depth hexagonal crack model in dry soil

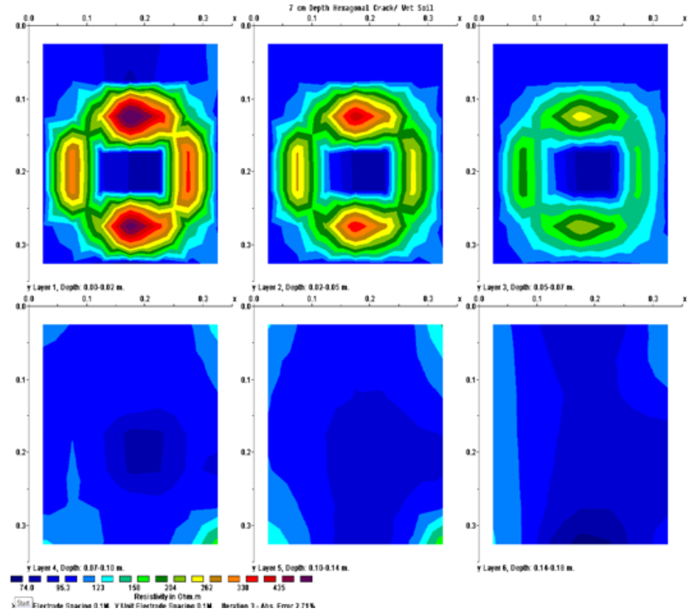

Fig. 6. The inverted resistivity sections of the 7 cm- depth hexagonal crack in wet soil

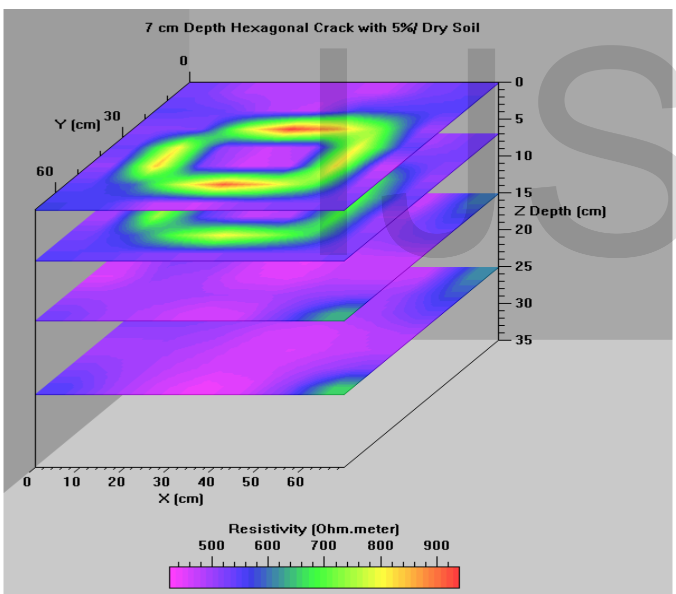

Fig. 5. 3D visualization of the 7cm- depth hexagonal crack in dry soil with a 5% resistivity noise

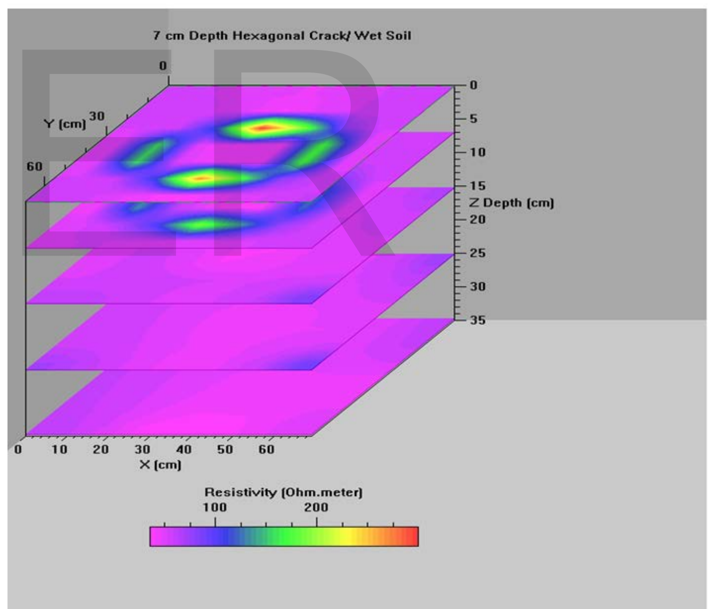

Fig. 7. 3D visualization of the7cm- depth hexagonal crack model in wet soil

To examine different situations, a model of a 7cm depth crack was tested in a 10 Ohm.m wet soil. Fig. (6), (7), (8) show, respectively, the inverted sections, the 3D visualization of the model and the model with a scattered 5% noise. As the resistivity contrast between the air-filled crack and the surrounding soil is still high, the crack geometry and depth can still be characterized.

In 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.

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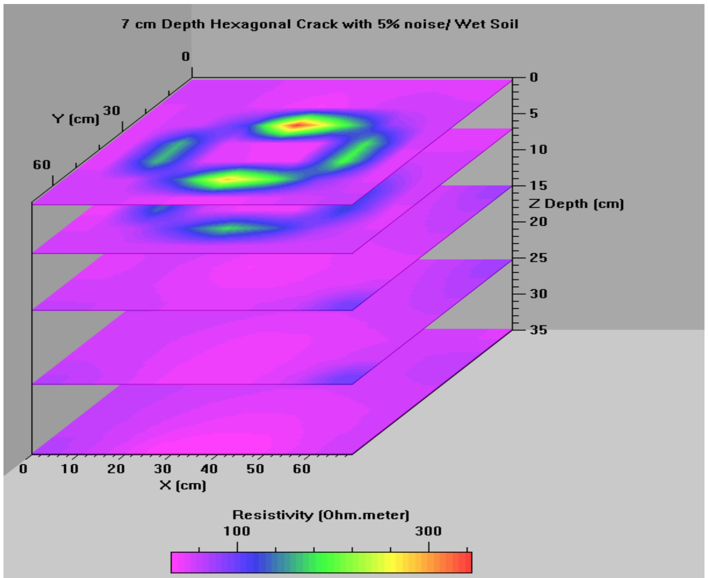

Fig. 8. 3D visualization of the 7cm- depth hexagonal crack with 5% noise in wet soil

In a medium with resistive bodies (e.g. soil cracks), the current lines tend to deviate around them, and hence high voltage drop (i.e. high resistivity). Soil cracks form barriers that disturb the flow of current, resulting in greater voltage drop relative to that measured for the surrounding intact soil. Therefore, cracks are expected to alter soil resistivity distribution significantly [24].

In the above tested models, the crack has an anomalous high resistivity that can be distinguished from the background [11], [14], [25], and the cracking depth can reasonably be identified. Moreover, the tested models indicate that the higher resistivity values were noticed at the surface, where the formation of the crack deviates the electrical current paths significantly. This finding was also reported by [11], [12], [24].

To examine these findings, the same model was tested in a situation where the crack is covered by 5cm thickness soil. Fig. (9), (10) and (11) show,respectively, the inverted sections, the 3D visualization and the model with a scattered 5% noise of the 7 cm- depth hexagonal crack in 1000 Ohm.m dry soil covered by 5cm thickness sediments. Although the high resistivity value of crack can still be noticed (see Figures 9 and 10), the geometry of the crack is poorly indicated, particularly when a 5% resistivity noise was added (see Figure 11). This can be attributed to the fact that the calculated resistivities represent the measured values for the whole section including the added layer.

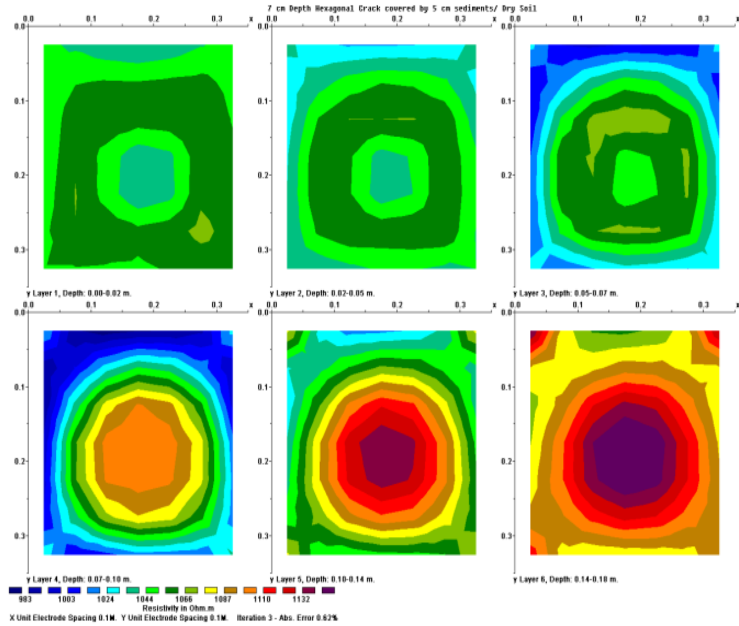

Fig. 9. The inverted resistivity sections of the 7 cm- depth hexagonal crack in dry soil covered by 5cm thickness sediments

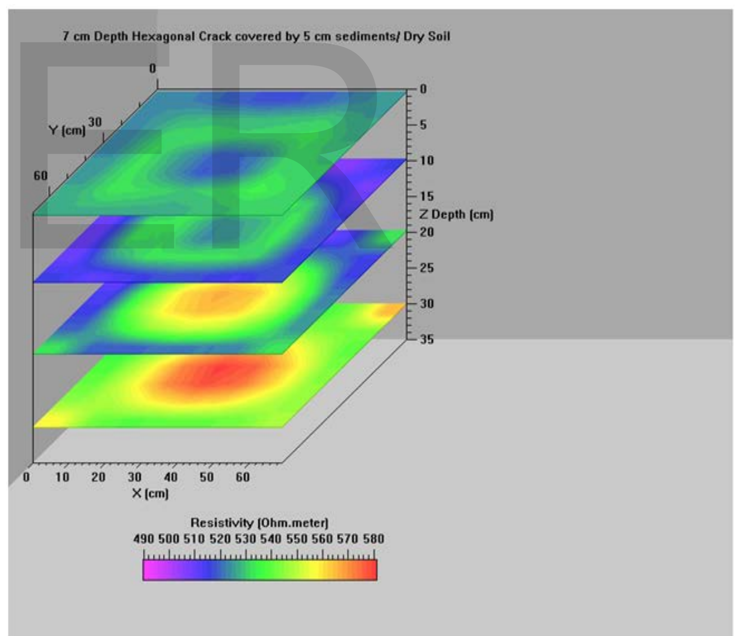

Fig. 10. 3D visualization of the 7cm depth hexagonal crack model in dry soil covered by 5cm thickness sediments

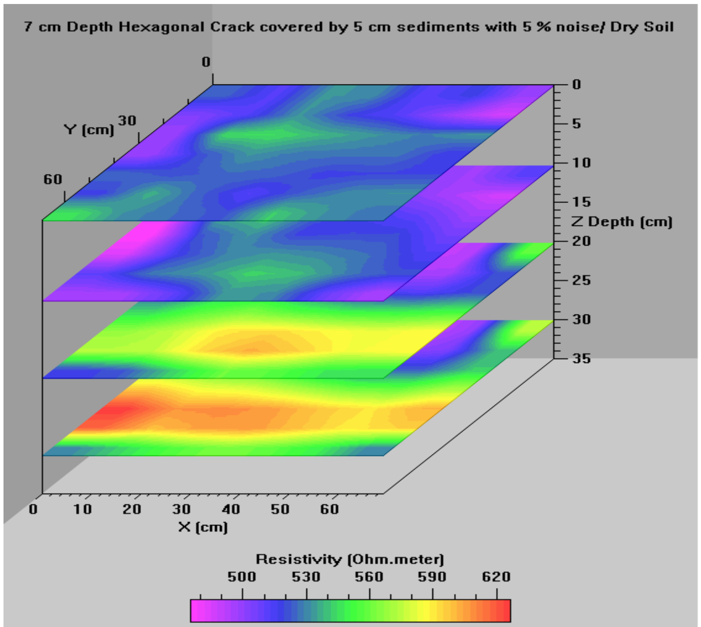

Fig. 11. 3D visualization of the 7cm- depth hexagonal crack with 5% noise in dry soil covered by 5cm thickness sediments

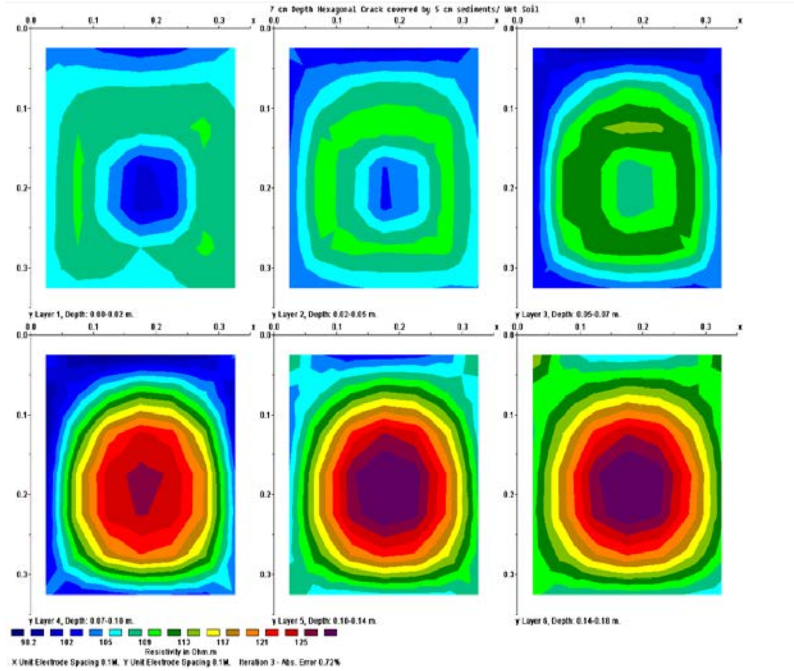

Fig. 12. The inverted resistivity sections of the 7 cm- depth hexagonal crack in wet soil covered by 5cm thickness sediments

Similarly, Fig. (12), (13) and (14) show, respectively, the inverted sections, the 3D visualization and the model with a scattered 5% resistivity noise of the 7 cm- depth hexagonal crack in 10 Ohm.m wet soil covered by 5cm thickness sediments.

In this case, as the resistivity contrast between the crack and the intact soil is relatively higher, the crack can better be distinguished although the geometry of the crack is still poorly indicated. In the literature, a high resistivity anomaly is detected at the surface of cracked soil and this anomaly is reduced with depth. The high resistivity anomaly indicates that the current is more blocked at the surface due to the presence of the crack, and hence increases the soil resistivity [11], [12], [24].

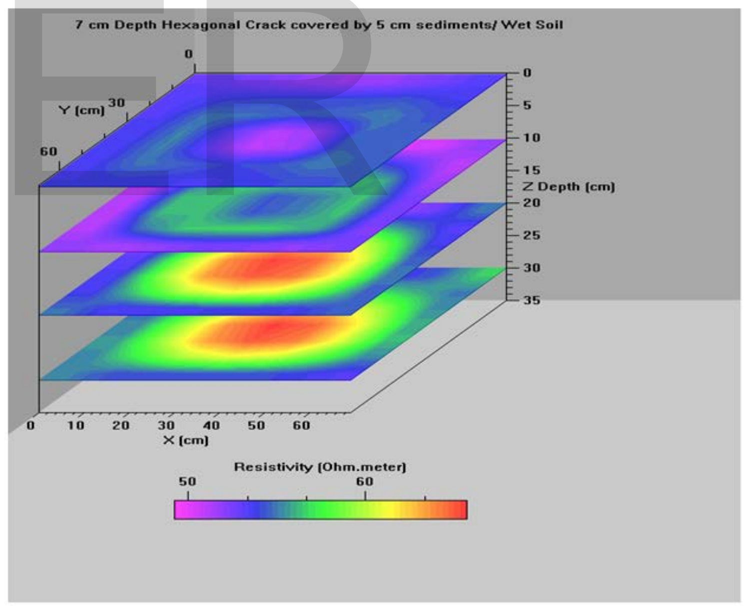

Fig. 13. 3D visualization of the 7cm depth hexagonal crack model in wet soil covered by 5cm thickness sediments

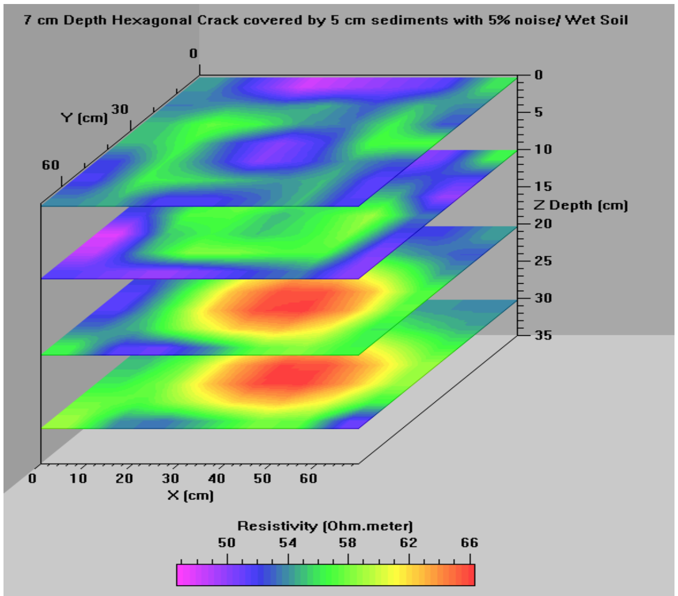

Fig. 14. 3D visualization of the 7cm- depth hexagonal crack with 5% noise in wet soil covered by 5cm thickness sediments

4 Conclusions:

In this paper, numerical simulation using 3D Electrical Resistivity Tomography Method was used to simulate polygonal soil cracks commonly found in the field. Cracks were simulated in different dry and wet soils scenarios. The results showed that the method is sensitive to soil cracking due to the high resistivity contrast between the cracked soil and the intact surrounding soil. As the air-filled cracks are highly resistive, soil cracks were reflected in the models in anomalous high resistivity spots. The geometry and cracking depth can be distinguished particularly in the cases where the crack intersects the soil at the surface due to the departure of the electrical current. Laboratory and field experiment are scheduled to examine the results.

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