Detection of Cracks in Clay Soil Using Quasi-3D Electrical Resistivity Tomography Method: Numerical and Experimental Study

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Abstract. Soil cracks affect the geotechnical characteristics of clay soils frequently used in engineered earth structures. In this work, numerical simulation and laboratory tests using Wenner- Schlumberger array of Electrical Resistivity Tomography (ERT) method are adopted to detect soil cracks in compacted clay soil. 3D numerical simulation showed that air-filled cracks have an anomalous high resistivity signature that can be differentiated from the background due to the high resistivity contrast between cracks and the surrounding soil. Depth, geometry, and extension of the simulated cracks are reasonably indicated. At the laboratory scale, quasi-3D ERT experiment was conducted. The results showed that soil resistivity is significantly affected by an artificially introduced crack as the crack forms a barrier that disturbs the flow of electricity in the soil. Similarly, depth, geometry, and extension of the crack are detected. Both numerical and experimental findings demonstrated that ERT method can effectively be used to identify cracking in clay soils. It is suggested that ERT, as a non invasive method, can be adopted with other traditional geotechnical methods for detecting cracks in clay soils.

Keywords: Cracks; Clay Soil; Quasi-3D ERT

1. Introduction

Soil cracks alter the geotechnical properties of clay soils and cause serious geotechnical and environmental problems for engineered earth structures. However, cracking dynamics of clay soils are difficult to monitor. Surface cracking patterns can be described using visual imaging analysis [1], laser scanning method [2], and direct measurements of cracking dimensions [3]. Destructive methods such as soil pits [4] are frequently implemented for in situ measurements. Obviously, none of these techniques offer sufficient information on cracking dynamics accurately and non-destructively [5].

On the other hand, Electrical Resistivity Tomography (ERT) method has increasingly been recognized for several geotechnical applications. It provides non-invasive 2D/3D resistivity sections, at laboratory and field scales, that have been used at the early stages to map fractures and faults [6, 7, 8]. For detecting small scale cracks, electrical resistivity method has proven successful in identifying cracks in metals [9], and concrete [10]. In soil science, laboratory experiments were conducted to characterize cracking of clay soils. In this regard, Samouëlian et al. (2003) [11] utilized 2D ERT to detect an artificial crake introduced in compacted clay soil. Electrical Anisotropy Index AI of a square resistivity configuration was adopted to provide information on presence, position, and extension of cracks [12], and cracking dynamics [13] in clay soils. In addition, cracks in clays cause a directional dependence of
the electrical current injected in soils. Therefore, Kong et al., 2012 [14] found that changing cracking depth, length, width and angle cause severe changes in soil resistivity. At the laboratory scale, ERT method has been implemented to identify soil cracks. Sentenac and Zielinski (2009) [15] mapped fine fissures formed in compacted clay soil. Hassan and Toll (2013) [16] imaged an artificial small scale cracks of different depths. Lee (2020) monitored propagation of desiccation cracks network [17]. At the field scale, the method has proven successful to detect cracking patterns formed in soil [18]. In the current study, ERT method was adopted to detect cracks in compacted clay soil using Wenner-Schlumberger array. 3D numerical resistivity model and quasi-3D ERT experiments were conducted to map cracking geometry in the soil.

2. Methods

2.1. ERT Technique

ERT is a technique of construction subsurface electrical resistivity image. A number of current (C1 and C2) and voltage (P1 and P2) electrodes are attached to a computer controlled multi-electrode resistivity system to collect subsurface apparent resistivity data using a particular electrode configuration. True subsurface resistivity distribution can be obtained in 2D/3D inverse models using appropriate inversion software [19], [20]. In 2D mode figure 1, the electrodes are installed at regular electrode spacing (a) along a profile, and resistivity measurements are progressively acquired for particular electrodes spacing and acquisition (n) levels [21]. A 3D resistivity mode offers more acceptable results especially in geotechnical engineering investigations where the subsurface is highly complex [22]. However, 3D ERT surveys are time consuming using single channel resistivity system as it requires a large number of measurements. Therefore, in practice, 3D ERT models can be generated by combining parallel 2D sections [20], [21]. In the current work, Wenner-Schlumberger array figure 2 was adopted. This array has good signal strength and moderate characteristics that compromise between the ability to resolve horizontal and vertical structures [23].

![Figure 1. Data acquisition of 2D ERT survey [21].](image1)

![Figure 2. Wenner-Schlumberger array.](image2)

2.2. Numerical Simulation

Numerical simulation using ERT technique is a useful tool to simulate actual laboratory and field resistivity measurements. First, a proposed synthetic model of known resistivity values is created based on the user knowledge. This step is called forward modelling. Second, the model is inverted to obtain the subsurface resistivity distribution. This step is called inverse modelling [24]. A 3D resistivity model of 4cm depth, 2.5cm width, 15 cm length, air-filled crack introduced in dry clay soil is designed. Clay has a resistivity range of (2-100) Ohm.m [19, 21]. Therefore, 100 Ohm.m resistivity value was used for dry clay soil, and 100000 Ohm.m value was chosen for air-filled crack, as air is ultimately resistive [25]. RES3DMOD and RES3DINV software [21] were used for forward and inverse modelling, respectively.
2.3. Experimental Setup
ERT experiment was conducted to identify cracks in clay soil sample collected from the campus site of College of Science, University of Diyala, northeast of Iraq figure 3. The soil in the area is composed of dark brown low plasticity clay (CL) layer above dark gray silty sand (SM) layer [26].

Soil sample is manually compacted in plastic container and stainless steel electrodes were installed in four L1, L2, L3 and L4 profiles. Electrode spacing (a) of 0.03m was chosen and 0.03m distance between the lines was maintained. The apparent resistivity measurements were gathered in two stages. Stage one represents a base model with no crack figure 4. In stage two, a crack of 4cm depth, 2.5 cm width and 6 cm length was manually introduced to intersect L2 and L3 at the center as showed in figure 5. 2D inverse sections were produced for the resistivity profiles of stage one and two using smoothness constrained method of ZONDRES2D software [27]. Finally quasi-3D ERT section was plotted for each stage.
3. Results and Discussion

Figure 6 presents XY layers of the modelled crack at different Z depth intervals. The high resistivity trace of the crack is clearly distinguished in Layer 1 and 2 at Z depths up to 4cm (i.e. depth of the crack) and below this depth no high resistivity effect is seen. The crack is reflected in the model as a high resistivity isolated object due to the high resistivity contrast between air and the intact soil [12, 18, 28]. Figure 7 shows XZ planes of the model at different Y distance intervals. The plane 4 clearly indicates the crack geometry and position. In addition, length and depth extent of the crack are fairly resolved. Figure 8 depicts YZ planes of the model at different X distance intervals. The planes 3, 4 and 5 reflect the extent of the crack. Again, depth of the crack is clearly detected in the model.

![Figure 6. XY layers of the simulated crack model at different Z depth intervals](image1)

![Figure 7. XZ planes of the simulated crack model at different Y distance intervals](image2)
Figure 8. YZ planes of the simulated crack model at different X distance intervals

3D visualization of the crack is useful to improve the interpretation of ERT model. Figure 9 presents 3D visualization of the simulated crack model. It clearly indicates position and geometry of the simulated crack shown in dark red colour. Moreover, the horizontal slices showed that cracking depth is resolved in and no high resistivity trace below 4cm is seen.

Figure 9. 3D visualization of the crack model
Quasi-3D ERT section of the laboratory experiment-stage one is illustrated in figure 10. In general, resistivity values across L1, L2, L3, and L4 profiles are within the range of the clay soil reported in the literature. It reflects the homogenous background of the intact clay soil in this stage (no crack introduced). However, some resistivity variations are expected due to the differences in the soil water moisture content and compaction efforts used.

Figure 11 depicts stage two of the experiment which obviously reflects the effect of crack on soil resistivity distribution. As the introduced crack intersects L2 and L3, high resistivity values (beyond the normal range of the clay) are noticed at the position of the crack, and the crack depth (i.e. 4cm) is fairly evident. Air-filled crack is ultimately resistive because of the infinite resistivity of the air. Therefore, the crack acts as a strong barrier that disturbs the electrical current injected into the soil causing a high voltage drop, therefore, reflected in ERT section as an anomalous and isolated high resistivity object [11, 12, 15, 28]. However, resistivity of air-filled crack is far away lower due to the effect of the surrounding intact soil. As expected, L1 and L2 are less affected by the introduced crack.

Both numerical and laboratory results showed that ERT method can effectively be utilized to capture resistivity changes introduced by small scale cracks.
4. Conclusions
Numerical and laboratory experiments using ERT method are used to detect cracking in clay soils. The results showed that cracks are reflected in the simulated model as isolated objects of high resistivity due to the high resistivity contrast between air and the intact soil. Geometry and cracking dimensions are fairly resolved. The experimental results confirmed the numerical simulation findings. Quasi-3D section is produced for air-filled crack introduced in compacted clay soil. As crack forms barrier that obstacle the injected current, it can be identified as a high resistivity zone beyond the normal range of the intact soil. Therefore, the high resistivity signature of the air filled crack is clearly evident and can be distinguished from the background. Numerical and laboratory results demonstrated that ERT method can effectively be adopted to detect high resistivity changes introduced by small scale cracks in clay soil. The current findings of this work are being examined through scheduled field resistivity surveys.

5. References

[1] Vogel H J, Hoffmann H and Roth K 2005 Geoderma 125 203-211
[2] Sánchez M, Atiue A, Kim S, Romero E and Zielinski M 2013 Geo-Congress 804-807
[3] Ringrose-Voase A, and Sanidad W 1996 Geoderma 71 245-261
[4] Kishne A, Morgan C and Miller W 2009 Soil Sci. Soc. of Am. J. 73 1221–1230
[5] Dinka R and Lascano R J 2012 Open J. of Soil Sci. 2 (2) 82-90
[6] Taylor S B and Barker R D 2002 Geoph. Pros. 50 603-613
[7] Adagunodo T A, Sunmonu L A, Erinle AV, Adabanija M A, Oyeyemi K D, and Kayode O T 2018 IOP Conf. Series: Earth and Environmental Science 173 (2018) 012030
[8] Cassiani G, Godio A, Stocco S, Villa A, Deiana R, Frattini P and Rossi M 2009 Near Surf. Geophysics 7 475-486
[9] Farrell D M, Robbins B J, Stallings J, Cardoso S and Bakker W 2008 Insight 50 (12) 690-694
[10] Mathew J and Vishnudas S 2021 IOP Conf. Series: Materials Science and Engineering 1114 (2021) 012003
[11] Samouëlian A, Cousin I, Richard G, Tabbagh A and Bruand A 2003 Soil Sci. Soc. J. Am. 67 1319–1326
[12] Samouëlian A, Richard G, Cousin I, Guérin R, Bruand A and Tabbagh A 2004 Eur. J. Soil Sci. 55 751–762
[13] Greve A, Acworth R J and Kelly B F J 2010 Geophysics 75 WA85-93
[14] Kong L W, Bai W and Guo A G 2012 Geotech. Test. J. 35 (6) 1-9
[15] Sentenac P and Zielinski M 2009 Environ. Geo. 59 205-214
[16] Hassan A and Toll D G 2013 Proc. Int. Conf. on Stability and performance of Slopes and Embankments Mechan C, Pradel D, Pando M and Labuz F (ed) California American Society of Civil Engineers ASCE 818-827
[17] Lee S 2020 Drying cracks network in soils: Remedial solutions and 3-D ERT monitoring PhD Thesis Texas A&M University
[18] Jones G, Sentenac P and Zielinski M 2014 J. of App. Geophysics 106 196-211
[19] Telford W M, Geldert L P and Sheriff R E 1990 Applied Geophysics Cambridge University Press Cambridge UK p 770
[20] Loke M H, Chambers J E and Kuras O 2011 Instrumentation, electrical resistivity Solid Earth Geophysics Encyclopedia (2nd ed) Electrical & Electromagnetic Gupta H (ed) Springer Berlin 599-604701
[21] Loke M H 2016 Tutorial: 2-D and 3-D electrical imaging surveys Geotomo Software Malaysia p 207
[22] Loke M H and Barker R D 1996 Geoph. Pros. 44 499-524
[23] Dahlin T and Zhou B 2004 Geoph. Pros. 52 379–398
[24] Giao P, Nguyen Cuong Q and Loke M H 2011 Monitoring the chemical grouting in sandy soil by electrical resistivity tomography (ERT) Berichte Geol. B.-A. 93 International Workshop on Geoelectric Monitoring 168-178
[25] Greve A K 2009 Detection of subsurface cracking depth through electrical resistivity anisotropy
PhD Thesis The University of New South Wales Sydney Australia

[26] Al-Ebdaa Company 2015 Soil Investigation Report for the New Buildings of Diyala University Part II Report No ESR-015-08. P 210

[27] Kaminsky A 2018 Zondres2D: Software for 2D resistivity and IP imaging http://zondgeo.ru/english/zond-software/ert-and-ves/zondres2d

[28] Amidu S A and Dunbar J A 2007 Vadose Zone J. 6 511-523.

[29] S. Jeyalakshmi et al 2021 J. Phys.: Conf. Ser. 1963 012145.