Real-time detection of soil crack depth by apparent electrical resistivity method

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Abstract. Soil cracks are caused by many factors, which are harmful to the mechanical and hydraulic properties of the soil. At present, most previous studies have focused on the crack morphology of soil surface, and there are few studies on the depth of soil cracks. The traditional methods for detecting the depth of soil cracks are mostly destructive, so the non-destructive measurement of crack depth needs to be further studied. The electrical resistivity method has been widely used in the measurement of soil surface cracks, but its applications in depth measurements are still poorly studied. In this paper, a three-dimensional desiccation crack experiment of soil was carried out in the laboratory. The variation of the anisotropy index (AI) with the crack depth propagation was studied by a multi-layer electrode array. A new method to detect the crack depth was proposed by theoretical and experimental analyses. The validity of this new method in the detection of crack depth is demonstrated by using the method of crack-tip opening angle (CTOA).

1. Introduction

Soil cracks are generally produced in both cases, one is the external force and the other is the condition of the drying-wetting cycle[1]. Water is lost through evaporation in the soil due to the change of temperature, wind speed and other external factors[2]. The porosity of the soil decreases with the evaporation of water, and soil cracks also form. The existence of cracks will destroy the integrity of the soil and reduce the strength of the soil. Cracks provide a fast-track for rainwater infiltration, which enhances the permeability of the soil and intensifies the deformation of the soil structure. The cracks will in turn accelerate water evaporation in the soil and further propagate the cracks[3]. In geotechnical engineering, cracks will reduce the stability of foundation pits and embankments, and then lead to landslides[4]. In environmental engineering, cracks provide a fast migration channel for heavy metal ions to rapidly infiltrate into groundwater[5]. In agricultural engineering, the direction and depth of cracks will change the runoff of surface water, nutrients and microorganisms in the soil. This will affect the absorption of useful substances by crop roots and the yield of agricultural crops[6]. Therefore, it is important to understand the basic parameters and propagation process of cracks.

The basic geometric parameters of a crack typically include crack length, width and depth. Most of the current studies on the characteristics of crack soil are based on the geometrical characteristics of soil surface cracks, but there is still a lack of visual and effective analysis methods for the research of crack
depth[7]. Soil surface cracks can be easily observed, while the geometry of soil internal cracks is difficult to be expressed quantitatively. Among many geometric parameters of cracks in soil, we are most concerned about the crack depth. It is worth pointing out that the establishment of indicators is significant to the evaluation of crack geometry. In a previous study by Samouëlian et al.[8], the anisotropy index (AI) of apparent electrical resistivity was used as the detection index when the electrical resistivity method (ERM) was used to detect the cracks. As for the relationship between AI and crack propagation, Greve et al.[9] combined electrical resistivity tomography (ERT) technology to further explain AI data. However, the measurement of crack depth using ERT is complicated, and it is important to propose a simpler and faster method. As an index, whether AI can detect the crack depth or crack propagation area is worthy of being studied. The objective of this study is to find a characterization method to detect the propagation process of crack depth using apparent electrical resistivity method. This paper proposes a method of detecting the crack depth with the anisotropy index of apparent resistivity. Compared with other methods of detecting crack depth, this method is relatively simple and more conducive to practical operation.

2. Materials and methods

2.1. Soil
In this study, we aim to test the ability of ERM to characterize the crack depth in the soil. Therefore, the soil used in the experiment should have an excellent cracking capacity under desiccation conditions. Because pure kaolin is easy to form cracks during the desiccation process, kaolin is used in this experiment. Its specific gravity, liquid limit, plastic limit and maximum dry density are 2.69, 53.2%, 30.1% and 1.28 Mg/m³, respectively. The particle size distribution curve of kaolin used in this experiment reveals that the silt content is 23% and the clay content is 77%. According to the unified soil classification system (USCS), the soil is classified as highly plastic clay (CH).

2.2. Electrical resistivity method
The apparent electrical resistivity is a physical parameter of soil, and its unit is Ω·m. It is the resistance in the direction of the current when the current passes vertically through a cubic soil with a length of 1m. The ERM is non-destructive, fast and continuous. A four-electrode measurement system was used in the laboratory detection of soil cracks. In a measurement procedure, current $I$ (A) is injected into the soil through two electrodes. The resulting potential difference $ΔU$ (V) is recorded through the other two electrodes. Anisotropy index (AI) was proposed by Samouëlian et al.[8], based on square arrays, to characterize the influence of soil cracks on soil anisotropy. Resistivity $ρ$ and AI are calculated by the following equations:

$$\rho = K \frac{ΔU}{I} \quad (1)$$

$$AI = \frac{ρ_\alpha}{ρ_\beta} \quad (2)$$

Where $K$ is the geometric coefficient, representing the dependence of the current on the arrangement of the four electrodes. In homogeneous soils, the electrical resistivity obtained according to Equation (1) is considered to be true electrical resistivity. For heterogeneous soils, the current paths and equipotential planes are obviously distorted due to the inhomogeneity. The measured electrical resistivity is location-dependent and is called the apparent electrical resistivity. The measured values in this study are also apparent resistivity, where $ρ_α$ and $ρ_β$ indicate the apparent electrical resistivity of $α$ array and $β$ array[9].

2.3. Experimental procedure
The soil was dried and crushed to ensure the uniformity of the soil sample. The volume moisture content was set to 34% and using a mixer to stir evenly. The chamber size is 400 mm long, 400 mm wide, and 400 mm deep. The kaolin is evenly filled into the chamber with a dry density of 1.1 Mg/m3. The volume
moisture content is 47.8% after compaction. Twelve copper sheet electrodes are fixed to a cylindrical plexiglass tube with a diameter of 10 mm at 30 mm intervals. The electrode string consists of wires and a tube with electrodes. It is worth noting that the model needs to be saturated with water during the experiment. In order to prevent water from flowing into the electrode tube through the holes on the electrode, and then conducting copper electrodes on it. Therefore, the wire should be tied outside the plexiglass tube. A square area with a side length of 200 mm is determined on the surface of the chamber, and then it is divided into four small squares with a side length of 100 mm. Nine electrode strings are inserted into nine vertices of four-square regions to form an electrode string array, which forms four cells (I, II, III, IV) in Figure 1. During the experiment, the anisotropy of four cells with 12 layers of electrodes was measured.

![Figure 1. Top view of chamber and the arrangement of electrode strings.](image)

Studies have shown that crack-tip opening angle (CTOA) can be considered as a special property of material disruption, and it is assumed that CTOA remains unchanged during crack propagation[10]. When the width of a soil surface crack is known, the crack depth can be estimated by the CTOA. At the end of the experiment, the model is excavated at the same time. For each cell, the vernier caliper is used to measure the maximum width of the crack. At the same time, the crack is excavated where the crack is widest to measure the maximum depth of the crack. According to the experimental results, the CTOA of kaolin used in the study is about 2.8°.

3. Results and discussions

3.1. The variation of anisotropy index of apparent electrical resistivity

This paper focuses on the variation of the anisotropy index (AI) of soil with the crack depth in the process of soil desiccation and proposes a method to infer the crack depth according to the variation of AI. Therefore, the AI of apparent electrical resistivity of soil was measured in the desiccation experiment. We use AI data, which are measured in the cell with the largest surface crack width, and the surface crack width of cell III is the largest. Therefore, the AI data of cell III is shown in Figure 2.
According to the analysis of AI data in Figure 2, there are some irregular points in the test data, which could be caused by manual test errors. The AI in the upper soil layer decreases as the desiccation time increases, which indicates that the anisotropy of the upper soil is increasing. The anisotropy of soil apparent resistivity is related to electric field and conductor properties. According to the distribution of the electric field and the conductivity of soil, when the crack crosses through the electrode plane array, it has the largest effect on the electric field and conductor properties of the electrode plane array. For a multi-layer electrode array, when the leading edge of the crack passes through an electrode plane array, the change of AI (ΔAI) measured by it is the largest among all electrode plane arrays. In the process of using a multi-layer electrode array to detect soil crack depth, if the ΔAI of a certain electrode plane array is the largest, indicating that the crack has crossed through this electrode plane array. Taking the AI measured by III cell as an example, each cell can get four groups of ΔAI after subtraction of two adjacent measurements of AI. The results are shown in Figure 3.

In Figure 3, there are peaks in each set of ΔAI data. According to the above analysis, the electrode burial depth corresponding to the peak value is the depth of the crack at this time. If there are multiple peaks in a set of AI data, it may be affected by surface cracks. Considering that the depth of the main crack is generally deeper than that of the secondary crack, the burial depth of the electrode corresponding to the maximum depth is the crack depth. According to the arrangement of the electrode array in this
experiment, if the directions of secondary cracks are perpendicular to the main crack, the AI will increase during the propagation of the secondary crack. As shown in Figure 3, AI at the electrode burial depth of 30 mm also increases as the desiccation progresses.

3.2. Prediction of crack depth by anisotropy index

Taking AI data measured in 3.0 and 6.0 days of the cell III as an example (Figure 2), the AI data measured in two adjacent measurements are subtracted to get the ΔAI (Figure 3). Based on the above analysis, we think the crack depth on the 6th day is 60 mm corresponding to the ΔAI peak. At this time, it is necessary to measure the widest surface crack width on the 6th day and to get the crack depth according to CTOA of 2.8 °. The crack depth predicted by the ΔAI peak in cell III at different times and the crack depth obtained by CTOA are plotted in Figure 4 to verify the effectiveness of using ΔAI to predict soil crack depth. It can be seen that the depth obtained by the two methods is almost the same, and the allowable error is 0.5 times the electrode spacing (15mm). Because the error of data points is mostly less than the allowable error, it can be considered that the method of predicting crack depth by ΔAI peak is feasible.

![Figure 4. Depth comparison of AI peak prediction and CTOA prediction.](image)

4. Conclusions

In this study, laboratory experiments were carried out to monitor soil crack propagation. Anisotropy index (AI) of apparent electrical resistivity in crack propagation are studied. The method of detecting crack depth by using the crack-tip opening angle (CTOA) verified the applicability of measuring the crack depth by using AI. The ΔAI data obtained by subtracting the AI data of two adjacent measurements along the depth can be used to predict the depth of soil cracks. The main conclusions are as follows:

(1) For the multi-layer electrode array, when the crack passes through an electrode plane array, it has the greatest influence on the soil anisotropy measured by this electrode plane array. Using this conclusion, the crack depth can be predicted by using the AI measured by the multi-layer electrode array. In the laboratory desiccation experiment, this method is compared with the CTOA method, which proves the effectiveness of this method in crack depth measurement. Using this method, the approximate crack depth can be obtained without inverting the measured apparent electrical resistivity. It is simpler than the electrical resistivity tomography method.

(2) In this paper, we only use AI to study the crack depth in laboratory experiments, and the experimental conditions are ideal and controllable. The actual soil crack measurement is more complex, which is manifested in the heterogeneity of soil, complex crack development, and so on. The applicability of this method for outdoor soil crack measurement needs to be further studied. Meanwhile, the possibility of applying this method to other materials, such as concrete and steel, needs to be further investigated.
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