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Can electrical resistivity tomography describe soil structure evolution?

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ABSTRACT

Variations of soil structure is significant for the understanding of water and gas transfer in soil profiles. In the context of arable land, soil structure can be compacted due to either agriculture operation (wheel tracks), or hardsetting and crusting processes. As a consequence, soil porosity is reduced which may lead to decrease water infiltration and to anoxic conditions. Porosity can be increased by cracks formation due to swelling and shrinking phenomenon.

We present here a laboratory experiment based on soil electrical characteristics. Electrical resistivity allows a non destructive three dimensional and dynamical analysis of the soil structure. Our main objective is to detect cracks in the soil. Cracks form an electrical resistant object and the contrast of resistivity between air and soil is large enough to be detected.

Our sample is an undisturbed soil block 240mm*170mm*160mm with an initial structure compacted by wheel traffic. Successive artificial cracks are generated. Electrodes built with 2 mm ceramic cups permit a good electrical contact at the soil surface whatever its water content. They are installed 15 mm apart and the electrical resistivity is monitored using a dipole-dipole and wenner multi-electrodes 2D imaging method which gives a picture of the subsurface resistivity.

The interpreted resistivity sections show the major soil structure. The electrical response changes with the cracks formation. The structure information extracted from the electrical map is in good agreement with the artificially man-made cracks. These first results demonstrate the relevance of high resolution electrical imaging of the soil profile. Further experiments need to be carried out in order to monitor natural soil structure evolution during wetting-drying cycles.

INTRODUCTION

In the context of arable land, soil can be compacted by traffic, hardsetting and crusting processes. With new agricultural practices such as reduced tillage or no-tillage, soil structure mostly regenerates via natural processes: such as swelling and shrinking or freezing and thawing phenomenon or biological process. We are focusing the study on the soil structure evolution due to climate effects, and more especially the ability for soil to recover porosity by crack formation due to desiccation period.

Up to now, a soil cracking patterns was commonly characterized either by measuring manually in the field the crack geometry that forms at the soil surface (Blackwell et al., 1985; Ringrose-Voase and Sanidad, 1996), or automatically by using two-dimensional image analysis (Bullock and Murphy, 1980; Hallaire, 1984; Hartge and Bachmann, 2000).

The assumption was usually made that the soil consists in simple structures which justified the use of either a one- or a two- dimensional analysis. However the tensile and shearing stresses vary in a soil with depth. Therefore, the cracks network analysis requires a non-destructive tool. Electrical resistivity tomography is a geophysical investigation tool which permitted a temporal and spatial monitoring of the subsurface. This technique is already useful in geological survey (Griffiths and Barker, 1993), in environmental works (Chambers et al., 1999; Guérin et al., 2002), in hydrological context (Dannowski and Yaramanci, 1999; Göbel et al., 1993; Hagey and Michaelsen, 1999; Kemna et al., 2002). Electrical resistivity depends on the electrical resistivity of : the solid constituent, the fluid content, the porosity and the degree of saturation. Common electrical resistivity surveys are used to detect object larger than decimetric.

The aim of this study is to adapt this method to detect small heterogeneities related to the soil structure and especially to cracks developing. Since a crack is air-filled, it should be easy to detectable due to infinite electrical resistivity of air. We presented here a first experiment to test the feasibility of electrical resistivity tomography to detect resistivity anomalies at the centimeter scale.

MATERIEL AND METHOD

SOIL

The experiments were conducted in the laboratory on an air-dried loess soil block ($24 \times 17 \times 16 \text{ cm}^3$) (19.2% clay, 73.9% silt 3.8% sand 1.7 organic substances). It exhibited a massive structure resulting from severe compaction by wheels traffic in wet condition. We used intentionally a simplistic physical crack model because this experiment consists in a feasibility test. The initial stage A, was without crack. Then artificially cracks were made by sawing the soil block. A 2-mm crack width with respectively varying depths, 1 to 4 cm deep, constitute four cracking stage (B to E). The experiment lasted 4 hours and the volumetric water content remained stable $0.09 \text{ cm}^3\text{cm}^{-3}$, the variation of resistivity was then related to the structure evolution.

PRINCIPLE OF 2D ELECTRICAL PROFILE ACQUISITION

The electrical resistivity methods allow a current to circulate through the ground between a pair of electrodes (A and B), and the potential difference is measured with another pair of electrodes (M and N), providing a measure of the electrical resistance of the soil system. The depth of penetration increases with the distance between the AB electrodes. Apparent electrical resistivity is calculated as the product of the electrical resistance (measured between the M and N electrodes), with the geometrical factor (specific to the electrode array configuration AMNB). When the soil is not electrically homogeneous, the current lines and equipotential surfaces are distorted.

In order to detect the crack presence, position, and extension, electrical resistivity measurement were done by a 2D vertical pseudo-section. As shown figure 1, we disposed in-line 15 electrodes separated by a constant distance "a" equal to 1.5 cm. The first four electrodes 1-2-3-4 were connected as AMNB (station1). A second measurement was performed by disconnecting and moving the array by a single electrode spacing "a" along the in-line measurement. Then a second profile was recorded by connecting the electrodes in a way that AMNB occupied electrode position 1-3-5-7 (station2). The array was then moved by a 2a spacing. The process was repeated by increasing the electrode spacing each time by a multiple N of the initial electrode spacing. The resistivity values were attributed to the geometric centre point of the experimental array.

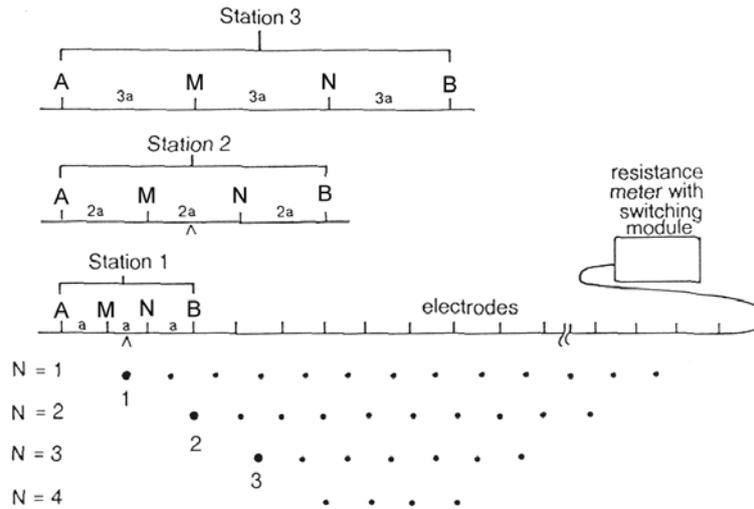


Figure 1. The measurement sequence for building up a pseudo-section.

MICRO-ELECTRODES DEVELOPMENT

The low quality contact between the drying soil and classical electrodes and the unusually close electrode spacing imposed to build up new small electrode (2 mm diameter). The Cu/CuSO₄ electrode permitted a wet punctual electrical contact with the soil surface.

RESISTIVITY INVERSION

The apparent resistivity measurement corresponds to a volumetric measurement and provides qualitative information. Quantitative information requires a mathematical inversion of the apparent resistivity into interpreted resistivity. We used an automated inversion software Res2Dinv (Loke and Barker, 1996) for the numerical inversion. Res2dinv is the software the widely used in electrical survey (Acworth, 1999; Andrews et al., 1995; Olayinka and Yaramanci, 2000)

RESULTS

APPARENT RESISTIVITY PSEUDO-SECTION

For a better demonstration of the expected increased in resistivity caused by the crack formation between the electrode 8 and 9, the apparent resistivity anomaly [1] was calculated.

$$\Delta\rho_a = \frac{(\rho_{a,X} - \rho_{a,A})}{\rho_{a,A}} \quad [1]$$

$\rho_{a,A}$ and $\rho_{a,X}$ were respectively the apparent resistivity of the initial stage A and the apparent resistivity of the different cracking growing stages (X = B, C, D or E). Figure 2 displayed the resulting maps for the 4 pseudo-section. All the pseudo-sections showed a similar distribution. The positive anomaly varied from 38 to 104 % directly above the crack respectively for the stages B and E. Not only the amplitude of the apparent resistivity anomalies increased when the crack grew but also its downward extension. The classical reversed V-shape corresponded to a vertical discontinuity. Outside the crack area the electrical current was not disturb.

RESISTIVITY INVERSION: QUANTITATIVE INTERPRETATION

The inversion was conducted in order to obtain the interpreted resistivity section. Five iterations were enough to derive a model distribution with a root mean square error lower than 5%. The initial stage A was relatively homogeneous with a soil resistivity equal to 37 Ω m. The stages B to E clearly show an area of higher electrical resistivity between the electrode 8 and 9 from 168 up to 2185 Ω m. As the crack grew, the electrical resistivity increased too. As shown on the figure 3 the highest heterogeneity amplitude was located at 0-0.8cm depth. The second layer (0.8-1.5cm) increased by 10% between the stage B and E. Beyond the 1.5cm depth layer, the resistivity remained stable. The first layer was the most sensitive to the crack growing up. The lateral variation was negligible. For the initial stage, the

resistivity remained stable between electrode 8 to electrode 13. Then directly above the crack, between the electrode 8 and 9, the electrical resistivity increased as the cracks depth increased. The electrical resistivity from electrode 10 to 13 decreased and reaches the mean values corresponding to the initial stage. The electrical resistivity contrast between the soil and the crack was abrupt.

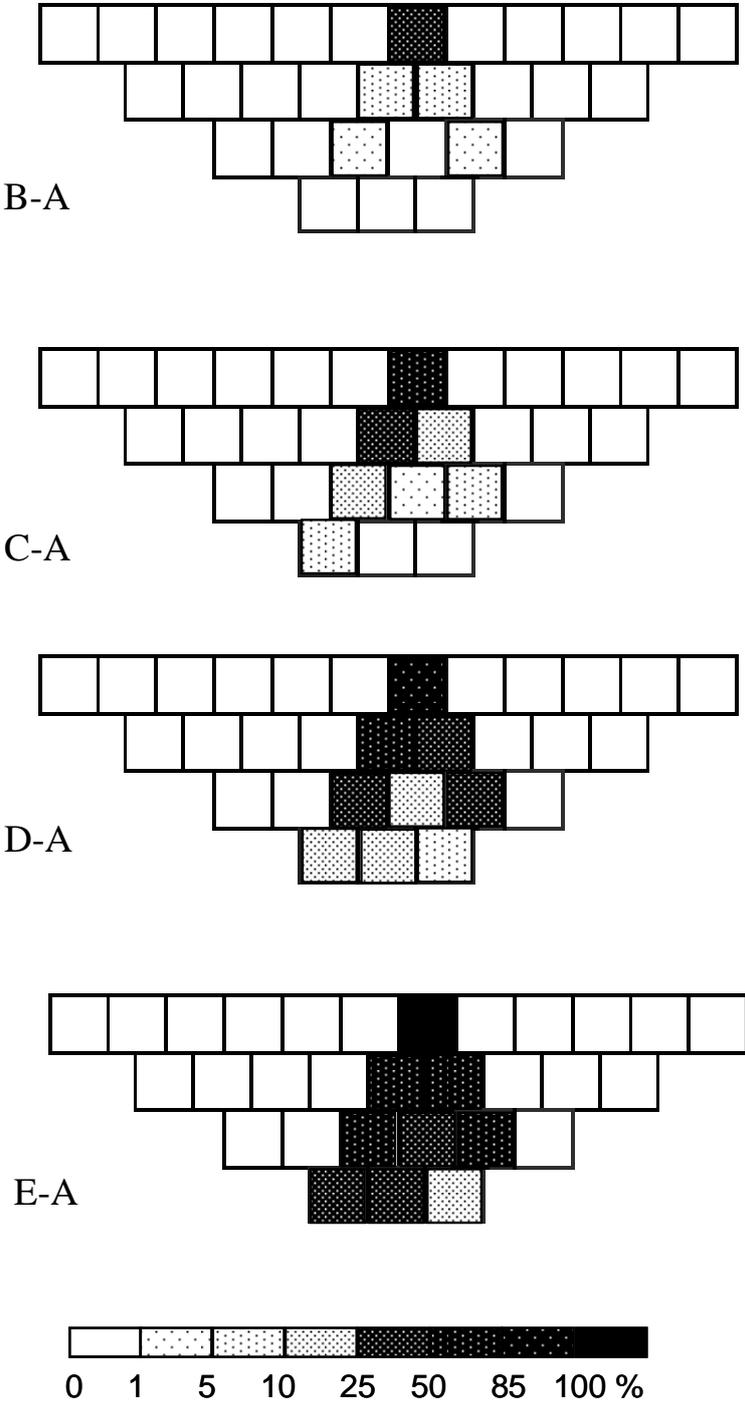


Figure 2 : Apparent resistivity pseudo-section for the stage A, B, C, D and E; crack location is between the electrode 8 and 9.

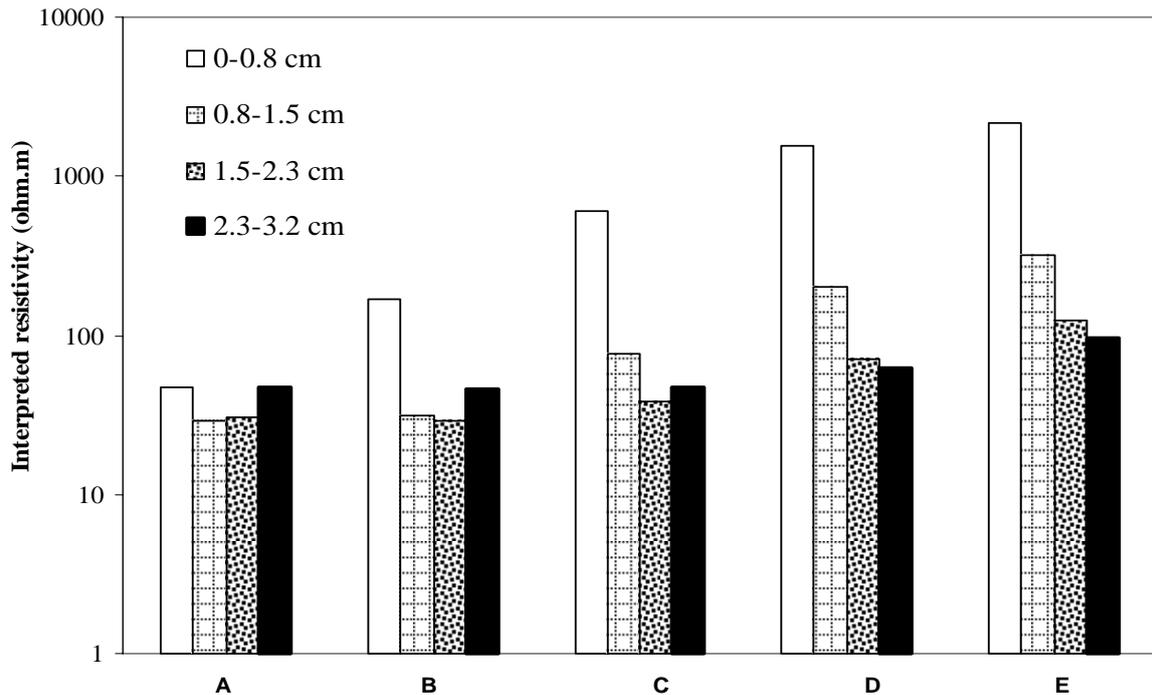


Figure 3: Interpreted resistivity variation between the electrodes 8 and 9 during the following cracking stages.

DISCUSSION

The range of interpreted resistivity measurement varied from 48 to 2185 Ωm and was attributed to the artificial crack. The crack is filled with air and represented a resistant structure in terms of electrical prospecting. Compared to electrical survey of water infiltration (Göbel et al., 1993; Michot et al., 2000; Zhou et al., 2001), the range of interpreted resistivity varied from low resistivity 10 Ωm , corresponding to wet condition, to 200 Ωm for dry condition.

The electrodes enable efficient electrical monitoring in dry soil. Although the shortest inter-electrodes spacing, the principle of point source electrical measurement was respected owing to the wet punctual contact.

The interpreted resistivity sections revealed the presence of high resistivity contrast in a vertical zone located at the position of the crack. The highest resistivity was recorded in the top 1.5cm depth. Both position and orientation were well done by the inversion. Nevertheless the downward extension was not obtained. These results lead us to reconsider the inversion model: abrupt and strong resistivity gradients combined with elongated and small structure can not be resolved. Indeed the numerical resolution of the mathematical algorithms is based on a regular mesh and smoothness condition.

CONCLUSION

This first experimentation confirms the interest of the use of electrical resistivity imaging in order to detect heterogeneities in the soil structure. At this scale of experiment, the resistivity contrast is enough sensitive for monitoring a crack system. The electrical signature of the cracks is well recognized in the profile. The new electrodes with ceramic cup enable correct electrical measurements at this scale.

During the four cracking stages B, C, D and E the change of interpreted electrical signature of the crack has significant effect on the first 1.5 cm depth. The actual interpreted data did not allow predicting the depth of the crack.

The actual model RES2DINV does not totally succeed in detecting abrupt structure geometry variations and strong electrical resistivity gradients. The result confirms the need of future works concerning the inversion of the apparent resistivity data.

Moreover a detailed analysis of a natural crack network requires a three-dimensional electrical resistivity set-up.

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