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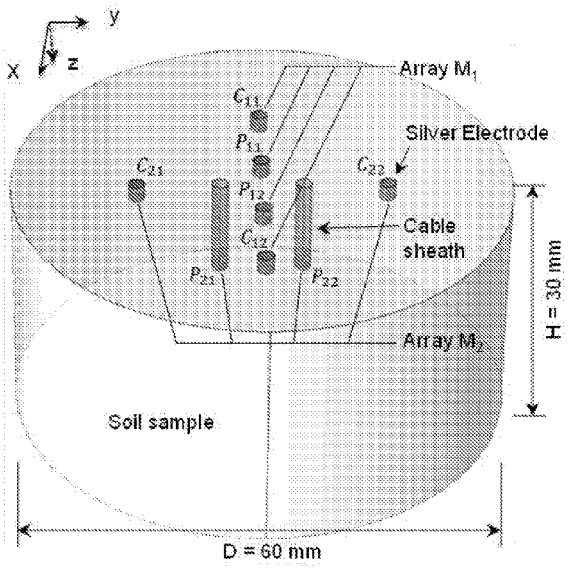


Figure 2

(57) Abstract: A resistivity measurement cell includes a first four-probe array (M_1) including a first array first point current source (C_{11}), a first array second point current source (C_{12}), a first array first point potential electrode (P_{11}), and a first array second point potential electrode (P_{12}) in a first direction; and a second four-probe array (M_2) including a second array first point current source (C_{21}), a second array second point current source (C_{22}), a second array first point potential electrode (P_{21}), and a second array second point potential electrode (P_{22}) in a second direction, wherein each distal end of the first array first point potential electrode (P_{11}) and the first array second point potential electrode (P_{12}) is placed at a different plane from each distal end of the second array first point potential electrode (P_{21}) and the second array second point potential electrode (P_{22}) in a third direction.

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DESCRIPTION

RESISTIVITY MEASUREMENT CELL MEASURING ELECTRICAL RESISTIVITY ANISOTROPY OF UNSATURATED SOIL

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application Serial No. 62/497,046, filed November 8, 2016, the disclosure of which is hereby incorporated by reference in its entirety, including any figures, tables, or drawings.

BACKGROUND

During the sedimentation or compaction process of soil, the fabric anisotropy is gradually formed mainly due to the preferential alignment of non-spherical particles. The fabric anisotropy in turn gives rise to anisotropic responses of the flow-related soil properties, such as electrical resistivity (conductivity) anisotropy, thermal conductivity anisotropy, and permeability (hydraulic conductivity) anisotropy. Since all of these flow phenomena are analogous processes and the electrical resistivity is relatively easy to measure among these flow-related properties of unsaturated soils, the electrical resistivity of the soils is often used as an aid to predict other flow properties, such as hydraulic conductivity and even the associated anisotropic responses. The existing methods to measure anisotropy electrical resistivity are costly or difficult for unsaturated soils' measurement. Traditional four-probe method can only measure the apparent electrical resistivity of soil and is unable to measure the anisotropy of electrical resistivity.

BRIEF SUMMARY

Embodiments of the subject invention provide novel and advantageous resistivity measurement cells that comprise two probes to be inserted into a soil sample, thereby measuring the anisotropy of electrical resistivity and soil water characteristic curve of unsaturated soils at the same time.

In an embodiment, a resistivity measurement cell can comprise a first measurement array arranged in a first direction; and a second measurement array arranged in a second direction; wherein the second measurement array comprises a first point current source, a second point current source, a first point potential electrode, and a second point potential electrode; and wherein each of the first and second point potential electrodes is placed lower

than each of the first and second point current sources in a third direction.

In another embodiment, a resistivity measurement cell can comprise a first four-probe array including a first array first point current source, a first array second point current source, a first array first point potential electrode, and a first array second point potential electrode in a first direction; and a second four-probe array including a second array first point current source, a second array second point current source, a second array first point potential electrode, and a second array second point potential electrode in a second direction; wherein each distal end of the first array first point potential electrode and the first array second point potential electrode is placed at a different plane from each distal end of the second array first point potential electrode and the second array second point potential electrode in a third direction.

In yet another embodiment, a resistivity measurement cell can comprise a first array first point current source and a first array second point current source disposed in a first direction; a first array first point potential electrode and a first array second point potential electrode disposed between the first array first point current source and the first array second point current source in the first direction; a second array first point current source and a second array second point current source disposed in a second direction; a second array first point potential electrode and a second array second point potential electrode disposed between the second array first point current source and the second array second point current source in the second direction; wherein each distal end of the second array first point potential electrode and the second array second point potential electrode is located lower than each distal end of the second array first point current source and the second array second point current source in a third direction; and wherein the first and second direction are a horizontal direction and the third direction is a vertical direction.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1(a) shows a schematic of an electrical potential on a half infinite space with respect to a single point current source.

Figure 1(b) shows a schematic of an electrical potential on a half infinite space with respect to a first four-probe array M_1.

Figure 1(c) shows a schematic of an electrical potential on a half infinite space with respect to a second four-probe array M_2.

Figure 2 shows a schematic of a resistivity measurement cell according to an embodiment of the subject invention.

Figure 3 shows correction factors, α_1 and α_2, for the first and second four-probe arrays, as a function of R_1/R_2.

Figure 4(a) shows a cross sectional view of a first four-probe array M_1 according to an embodiment of the subject invention.

Figure 4(b) shows a cross sectional view of a second four-probe array M_2 according to an embodiment of the subject invention.

Figure 4(c) shows a perspective view of a resistivity measurement cell according to an embodiment of the subject invention with a photo inset.

Figure 5 shows a Soil Water Characteristic Cell (SWCC) device combined with a resistivity measurement cell according to an embodiment of the subject invention.

DETAILED DESCRIOPTION

Embodiments of the subject invention provide novel and advantageous resistivity measurement cells that comprise two probes to be inserted into a soil sample, thereby measuring the anisotropy of electrical resistivity and soil water characteristic curve of unsaturated soils at the same time.

Figure 1(a) shows a schematic of an electrical potential on a half infinite space with respect to a single point current source. Referring to Figure 1(a), the electrical potential ψ at point P induced by a point current source C on the surface of a half infinite space, has the same electrical resistivity along the x and y directions (i.e., the horizontal direction, ρ_H) but differs in the z direction (i.e., the vertical direction, ρ_V). In addition, the electrical potential ψ at point P is given as following Eq. (1),

$$\psi = \frac{I\rho_M}{2\pi r} \tag{1}$$

where I is the magnitude of the applied current, ρ_M is the average electrical resistivity ($\rho_M = \sqrt{\rho_V \cdot \rho_H}$ where ρ_V is greater than ρ_H in general), λ is the anisotropic factor ($\lambda = \sqrt{\rho_V/\rho_H}$), and r is the equivalent distance to the current source, $r = \sqrt{x^2 + y^2 + (\lambda z)^2}$.

Figure 1(b) shows a schematic of an electrical potential on a half infinite space with respect to a first four-probe array M_1. Referring to Figure 1(b), the first four-probe array M_1 (or the first measurement array) includes four electrodes for probing, in particular, comprises a first array first point current source C_{11}, a first array second point current source C_{12}, a first array first point potential electrode P_{11}, and a first array second point potential electrode P_{12}.

The first P_{11} and second P_{12} point potential electrodes are located between the first C_{11} and second C_{12} point current sources in a first direction (i.e., x direction). All electrodes are located on the same plane of the ground surface in a third direction (i.e., z direction), and each electrode is spaced apart from adjacent electrode at a horizontal spacing a, wherein the ground surface can be a soil sample surface to be measured.

The first array first point current source C_{11} provides a current and the first array second point current source C_{12} receives the current, thereby forming a current streamline as shown in Figure 1(b). When the current flows from the first array first point current source C_{11} to the first array second point current source C_{12}, the first array first point potential electrode P_{11} and the first array second point potential electrode P_{12} measure the potential.

When Eq. (1) is applied to the first type of arrangement of the four-probe measurement, as illustrated in Figure 1(b) and herein called a first four-probe array M_1, the electrical potential difference V_1 measured between the potential electrodes P_{11} and P_{12} is given as following Eq. (2),

$$V_1 = \psi_{11} - \psi_{12} = \frac{I_1 \rho_M}{2\pi a} \tag{2}$$

where ψ_{11} and ψ_{12} are the electrical potentials at P_{11} and P_{12}, respectively; I_1 is the magnitude of the applied current; and a is the spacing between the electrodes, as also indicated in Figure 1(b). To facilitate the following discussion, Eq. (2) can be written as following Eq. (3),

$$\frac{V_1}{I_1} = R_1 = \frac{\rho_M}{2\pi a} \tag{3}$$

Figure 1(c) shows a schematic of an electrical potential on a half infinite space with respect to a second four-probe array M_2. Referring to Figure 1(c), the second four-probe array M_2 is similar to the first four-probe array M_1 except for the position of point potential electrodes. In particular, the second four-probe array M_2 (or the second measurement array) comprises four electrodes including a second array first point current source C_{21}, a second array second point current source C_{22}, a second array first point potential electrode P_{21}, and a second array second point potential electrode P_{22}. The first P_{21} and second P_{22} point potential electrodes are located between the first C_{21} and second C_{22} point current sources in a second direction (i.e., y direction) and each electrode is spaced apart from adjacent electrode at the horizontal spacing a. The first P_{21} and second P_{22} point potential electrodes are placed lower than the first C_{21} and second C_{22} point current sources in the third direction (i.e., z direction)

such that the first P_{21} and second P_{22} point potential electrodes are inserted into a soil sample and placed at a vertical spacing b lower than the soil sample surface.

Similar to the point current sources C_{11} and C_{12} of the first four-probe array M_1, the second array first point current source C_{21} supplies a current and the second array second point current source C_{22} receives the current. However, the second array first point potential electrode P_{21} and the second array second point potential electrode P_{22} measure the potential at a position below the current streamline formed by the point current sources C_{21} and C_{22}.

Similarly, for the second type of arrangement of the four-probe measurement, called as the second four-prove array M_2 as illustrated in Figure 1(c), the electrical potential difference V_2 measured between the potential electrodes P_{21} and P_{22} is expressed as following Eq. (4)

$$V_2 = \psi_{21} - \psi_{22} = \frac{I_2 \rho_M}{\pi}\left(\frac{1}{\sqrt{a^2 + \lambda^2 b^2}} - \frac{1}{\sqrt{4a^2 + \lambda^2 b^2}}\right) \tag{4}$$

which can also be expressed as following Eq. (5)

$$\frac{V_2}{I_2} = R_2 = \frac{\rho_M}{\pi}\left(\frac{1}{\sqrt{a^2 + \lambda^2 b^2}} - \frac{1}{\sqrt{4a^2 + \lambda^2 b^2}}\right) \tag{5}$$

where ψ_{21} and ψ_{22} are the potentials at electrodes P_{21} and P_{22}, respectively; I_2 is the magnitude of the applied current; a is the horizontal spacing between the electrodes; and b is the vertical spacing between the potential electrodes and the current electrodes.

With respect to the schematics of Figures 1(a), 1(b), and 1(c), the assumptions of the half infinite space, the point current sources, and the point potential electrodes used to theoretically derive Eqs. (3) and (5) cannot remain valid for the laboratory testing conditions, where the sample and the electrodes have a certain size and geometry, especially the boundary effects arising from the finite-sized sample. Therefore, Eqs. (3) and (5) have to be corrected to compensate for the deviations from the ideal assumptions, and correction factors are introduced into the following two equations as

$$R_1 = (1 + \alpha_1)\frac{\rho_M}{2\pi a} \tag{6}$$

$$R_2 = (1 + \alpha_2)\frac{\rho_M}{\pi}\left(\frac{1}{\sqrt{a^2 + \lambda^2 b^2}} - \frac{1}{\sqrt{4a^2 + \lambda^2 b^2}}\right) \tag{7}$$

where $\alpha_1 = \frac{R_{1,reality}}{R_{1,theory}} - 1$ and $\alpha_2 = \frac{R_{2,reality}}{R_{2,theory}} - 1$ are the associated correction factors for the measurement arrays M_1 and M_2, respectively. Based on Eqs. (6) and (7), the anisotropic resistivity of soils, i.e., ρ_M and λ (or ρ_H and ρ_V), can be accurately obtained from the two independent measurements using arrays M_1 and M_2 after the two correction coefficients, α_1 and α_2, are determined as described below.

In Eqs. (6) and (7), R_1 and R_2 can be determined experimentally from the applied current I and the measured voltage V, while λ and ρ_M are the unknown parameters that need to be determined. Therefore, establishing the relationship between R_1/R_2 and the correction factors to facilitate the measurement corrections is an intuitive approach. In addition, based on Eqs. (6) and (7), the ratio R_1/R_2, is independent of the average electrical resistivity ρ_M when the other parameters are kept unchanged, suggesting that the effect of ρ_M can be ignored while exploring the relationship between R_1/R_2 and the correction factors.

Considering that an electrode with a small contact area has a high interface impedance between the soil and electrode and the high impedance affects the measurement accuracy, an electrode of 2 mm in diameter can be selected in the designed device, and the method and designed device of the subject invention can be simulated using FEM (finite element method), as shown in Figure 2. Figure 2 shows a schematic of a resistivity measurement cell according to an embodiment of the subject invention, and the schematic is used for simulation using FEM. Referring to Figure 2, the first measurement array M_1 is placed in the first direction x and the second measurement array M_2 is placed in the second direction y. The soil sample configured to be measured is disposed in a cell that has a cylindrical shape of which diameter is 60 mm and height is 30 mm. While all electrodes of the first measurement array M_1, and the point current sources C_{21} and C_{22} of the second measurement array M_2 are placed on a top surface of the soil sample, the point potential electrodes P_{21} and P_{22} of the second measurement array M_2 are inserted into the soil sample. All electrodes of the first M_1 and second M_2 measurement arrays include a silver electrode at each distal end thereof so as to be in contact with the soil sample. Since the point potential electrodes P_{21} and P_{22} of the second measurement array M_2 are located in the soil sample, the point potential electrodes P_{21} and P_{22} further comprise a cable sheath located in the soil sample.

Based on a model configuration for the FEM simulation of Figure 2, the corrections factors, α_1 and α_2, then can be obtained by using FEM according to their definitions and Eqs. (6) and (7), i.e., from the difference between the theoretical prediction based on the point electrode and infinite half space and the FEM simulation results where the effects from the

boundary and electrode size are considered. The values of α_1 and α_2 as a function of R_1/R_2 can be derived and are presented in Figure 3 that shows correction factors, α_1 and α_2, for the first and second four-probe arrays, as a function of R_1/R_2. Hence, in the measurements, α_1 and α_2 can be identified by using Figure 3 to correct the measurement bias after R_1 and R_2 are determined from the two measurement arrays.

Figure 4(a) shows a cross sectional view of a first four-probe array M_1 according to an embodiment of the subject invention, and Figure 4(b) shows a cross sectional view of a second four-probe array M_2 according to an embodiment of the subject invention. In addition, Figure 4(c) shows a perspective view of a resistivity measurement cell according to an embodiment of the subject invention. Referring to Figures 4(a), 4(b), and 4(c), a resistivity measurement cell device of the subject invention comprises a first array M_1 and a second array M_2, wherein the first array M_1 is aligned in a first direction x and the second array M_2 is aligned in a second direction y, and wherein each of the first array M_1 and the second array M_2 comprises four electrodes of which two electrodes function as current sources and two electrodes function as potential electrodes.

Referring to Figure 4(a), the first array M_1 includes a first array first point current source C_{11}, a first array second point current source C_{12}, a first array first point potential electrode P_{11}, and a first array second point potential electrode P_{12}. The first P_{11} and second P_{12} point potential electrodes are located between the first C_{11} and second C_{12} point current sources in the first direction x. All electrodes are located on the same plane in a third direction z. That is, distal ends of the four electrodes C_{11}, C_{12}, P_{11}, and P_{12} are aligned in the same position in the third direction z.

Referring to Figure 4(b), the second array M_2 includes a second array first point current source C_{21}, a second array second point current source C_{22}, a second array first point potential electrode P_{21}, and a second array second point potential electrode P_{22}. The first P_{21} and second P_{22} point potential electrodes are located between the first C_{21} and second C_{22} point current sources in the second direction y. Distal ends of the first P_{21} and second P_{22} point potential electrodes are located lower than distal ends of the first C_{21} and second C_{22} point current sources in the third direction z. That is, the distal ends of the first P_{21} and second P_{22} point potential electrodes are spaced apart from the cross frame.

Referring to Figures 4(a), 4(b), and 4(c), the first array M_1 and the second array M_2 are supported by the cross frame so as to be fixed at predetermined position and the cross frame is attached to a cell. The cell has a cylindrical shape of which an outer diameter D_1 is 70 mm, an inner diameter D_2 is 60 mm, and an outer height H is 40 mm. The cross frame is

fixed at a top portion of the cell such that an inner space of the cell has an inner height h of 30 mm. Thus, a soil sample to be measured can be disposed in the inner space having a volume defined by a diameter of 60 mm and a height of 30 mm. The cell and the cross frame can be made by 3D printing.

Each electrode of the first array M_1 and the second array M_2 comprises a silver electrode at a distal end of each electrode, a cable sheath passing through the cross frame, and a copper rod connected to the silver electrode. The silver electrode has a diameter of 2 mm and a height of 2 mm, and is made of Silver-Silver Chloride (Ag-AgCl). While the cable sheaths of the first P_{21} and second P_{22} point potential electrodes further extend into the inner space of the cell to the silver electrodes of the first P_{21} and second P_{22} point potential electrodes, the cable sheaths for other six electrodes do not extend into the inner space.

The first direction x of the first array M_1 and the second direction y of the second array M_2 are different from each other and can be perpendicular to each other in the same horizontal plane. In addition, the first array M_1 and the second array M_2 can be placed in different planes in order to avoid mutual interference.

The measurement of R_1 and R_2, and the calculation of ρ_M and λ based on Eqs. (6) and (7) can be carried out by two independent electrical resistivity measurements by using the two different four-probe arrays M_1 and M_2 as illustrated in Figures 4(a) and 4(b). In addition, it is better to put the two arrays in different planes to avoid mutual interference. Figures 4(a), 4(b), and 4(c) present the sample cell, which has an outer diameter D_1 of 70 mm, an inner diameter D_2 of 60 mm, an outer height H of 40 mm and an inner height h of 30 mm; and the whole cell can be put into the SWCC device (to be shown later). In addition, there is a cross frame to install the electrode arrays. A multiple materials 3D printer can be used to print out the sample cell and the frame. Silver-Silver Chloride (Ag-AgCl) electrodes, 2 mm in diameter and 2 mm in height, can be used to inhibit corrosion during the prolonged testing period. Copper rods of diameter 2 mm and various lengths serve as bridges to connect the electrodes and the resistivity meter.

The subject invention includes, but is not limited to, the following exemplified embodiments.

Embodiment 1. A resistivity measurement cell, comprising:

a first measurement array arranged in a first direction; and

a second measurement array arranged in a second direction,

wherein the second measurement array comprises a first point current source, a second point current source, a first point potential electrode, and a second point potential electrode; and

wherein each of the first and second point potential electrodes is placed at a measurement depth different from that of each of the first and second point current sources in a third direction (e.g., the measurement depth of the first and second point potential electrodes can be lower than that of the first and second point current sources in the third direction).

Embodiment 2. The resistivity measurement cell according to embodiment 1, wherein the first point current source, the first point potential electrode, the second point potential electrode, and the second point current source are arranged in any types of arrays (e.g., in series).

Embodiment 3. The resistivity measurement cell according to any of embodiments 1-2, wherein a horizontal spacing between the first point current source and the first point potential electrode in the second direction is the same as a vertical spacing between the first point current source and the first point potential electrode in the third direction.

Embodiment 4. The resistivity measurement cell according to any of embodiments 1-3, wherein the first direction and the second direction are different from each other and the third direction is perpendicular to the first and second directions.

Embodiment 5. The resistivity measurement cell according to any of embodiments 1-4, wherein each of the first point current source, the second point current source, the first point potential electrode, and the second point potential electrode comprises a silver electrode, a copper rod electrically connected to the silver electrode, and a cable sheath surrounding the copper rod.

Embodiment 6. The resistivity measurement cell according to any of embodiments 1-5, wherein the first measurement array comprises two first array point current sources and two first array point potential electrodes; and the two first array point current sources and the two first array point potential electrodes are located in the same plane in the

third direction.

Embodiment 7. The resistivity measurement cell according to any of embodiments 1-6, further comprising a cross frame supporting the first measurement array and the second measurement array.

Embodiment 8. A Soil Water Characteristic Cell (SWCC) device, comprising:

the resistivity measurement cell according to any of embodiments 1-7; and

a chamber surrounding the resistivity measurement cell,

wherein the chamber comprises a plurality of holes through which a plurality of wires connected to the first and second measurement arrays pass.

Embodiment 9. A resistivity measurement cell, comprising:

a first four-probe array including a first array first point current source, a first array second point current source, a first array first point potential electrode, and a first array second point potential electrode in a first direction; and

a second four-probe array including a second array first point current source, a second array second point current source, a second array first point potential electrode, and a second array second point potential electrode in a second direction;

wherein each distal end of the first array first point potential electrode and the first array second point potential electrode is placed at a different plane from each distal end of the second array first point potential electrode and the second array second point potential electrode in a third direction.

Embodiment 10. The resistivity measurement cell according to embodiment 9, wherein the distal ends of the second array first point potential electrode and the second array second point potential electrode are located lower than the distal ends of the first array first point potential electrode and the first array second point potential electrode in the third direction.

Embodiment 11. The resistivity measurement cell according to any of embodiments 9-10, wherein the distal ends of the first array first point potential electrode and the first array second point potential electrode are located in the same plane as distal ends of the first array first point current source, the first array second point current source, the second

array first point current source, and the second array second point current source.

Embodiment 12. The resistivity measurement cell according to any of embodiments 9-11, wherein the first array first point current source, the first array first point potential electrode, the first array second point potential electrode, and the first array second point current source are arranged in series and spaced apart at a horizontal spacing; and the second array first point current source, the second array first point potential electrode, the second array second point potential electrode, and the second array second point current source are arranged in series and spaced apart at the horizontal spacing.

Embodiment 13. The resistivity measurement cell according to any of embodiments 9-12, further comprising a cross frame supporting the first and second four-probe arrays, and a cell connected to the cross frame and surrounding the cross frame and the first and second four-probe arrays.

Embodiment 14. The resistivity measurement cell according to any of embodiments 9-13, wherein each of the first array first point current source, the first array second point current source, the first array first point potential electrode, the first array second point potential electrode, the second array first point current source, the second array second point current source, the second array first point potential electrode, and the second array second point potential electrode comprises a cable sheath passing through the cross frame.

Embodiment 15. The resistivity measurement cell according to any of embodiments 9-14, wherein each of the first array first point current source, the first array second point current source, the first array first point potential electrode, the first array second point potential electrode, the second array first point current source, the second array second point current source, the second array first point potential electrode, and the second array second point potential electrode further comprises an electrode disposed inside the cell.

Embodiment 16. The resistivity measurement cell according to any of embodiments 9-15, wherein each cable sheath of the second array first point potential electrode and the second array second point potential electrode extends to each electrode of the second array first point potential electrode and the second array second point potential

electrode inside the cell.

Embodiment 17. A Soil Water Characteristic Cell (SWCC) device, comprising:

a plate;

the resistivity measurement cell according to any of embodiments 9-16 disposed on the plate;

a chamber surrounding the resistivity measurement cell and the plate; and

a plurality of wire passing through the chamber and connected to the first and second four-probe arrays.

Embodiment 18. A resistivity measurement cell, comprising:

a first array first point current source and a first array second point current source disposed in a first direction;

a first array first point potential electrode and a first array second point potential electrode disposed between the first array first point current source and the first array second point current source in the first direction;

a second array first point current source and a second array second point current source disposed in a second direction;

a second array first point potential electrode and a second array second point potential electrode disposed between the second array first point current source and the second array second point current source in the second direction,

wherein each distal end of the second array first point potential electrode and the second array second point potential electrode is located lower than each distal end of the second array first point current source and the second array second point current source in a third direction, and

wherein the first and second direction are a horizontal direction and the third direction is a vertical direction.

Embodiment 19. A Soil Water Characteristic Cell (SWCC) device, comprising:

the resistivity measurement cell according to embodiment 18; and

a chamber surrounding the resistivity measurement cell.

A greater understanding of the present invention and it many advantages may be had from the following example, given by way illustration. The following example shows some

of the methods, applications, embodiments and variants of the present invention. They are, of course, not to be considered as limiting the invention. Numerous changes and modifications can be made with respect to the invention.

EXAMPLE

Figure 5 shows a Soil Water Characteristic Cell (SWCC) device combined with a resistivity measurement cell according to an embodiment of the subject invention. Referring to Figure 5, the whole sample cell together with the electrode arrays is put into a chamber of the Fredlund SWCC device (GCTS testing system, Arizona, USA). The resistivity measurement cell is disposed on a ceramic plate and surrounded by a chamber. Eight extra holes are the drilled holes formed by drilling the top wall of the chamber to allow the wires to pass through in order to connect the electrodes to the resistivity meter; each hole is well sealed to ensure no air and vapor leaked in or out. The resistivity meter used in this measurement is SYSCAL JUNIOR SWITCH 48.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

All patents, patent applications, provisional applications, and publications referred to or cited herein (including those in the "References" section) are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

REFERENCES

1. Amidu, S. A., and Dunbar, J. A., 2007, "Geoelectric studies of seasonal wetting and drying of a Texas Vertisol," Vadose Zone Journal, 6(3), 511-523.

2. Telford, W., Geldart, L., and Sheri, R., 1990, "Resistivity methods," Cambridge University Press, England.

CLAIMS

What is claimed is:

1. A resistivity measurement cell, comprising:

a first measurement array arranged in a first direction; and

a second measurement array arranged in a second direction,

wherein the second measurement array comprises a first point current source, a second point current source, a first point potential electrode, and a second point potential electrode; and

wherein each of the first and second point potential electrodes is placed at a measurement depth different from that of each of the first and second point current sources in a third direction.

2. The resistivity measurement cell according to claim 1, wherein the first point current source, the first point potential electrode, the second point potential electrode, and the second point current source are arranged in any types of arrays.

3. The resistivity measurement cell according to claim 2, wherein a horizontal spacing between the first point current source and the first point potential electrode in the second direction is the same as a vertical spacing between the first point current source and the first point potential electrode in the third direction.

4. The resistivity measurement cell according to claim 2, wherein the first direction and the second direction are different from each other and the third direction is perpendicular to the first and second directions.

5. The resistivity measurement cell according to claim 2, wherein each of the first point current source, the second point current source, the first point potential electrode, and the second point potential electrode comprises a silver electrode, a copper rod electrically connected to the silver electrode, and a cable sheath surrounding the copper rod.

6. The resistivity measurement cell according to claim 2, wherein the first

measurement array comprises two first array point current sources and two first array point potential electrodes; and the two first array point current sources and the two first array point potential electrodes are located in the same plane in the third direction.

7. The resistivity measurement cell according to claim 2, further comprising a cross frame supporting the first measurement array and the second measurement array.

8. A Soil Water Characteristic Cell (SWCC) device, comprising:

the resistivity measurement cell according to claim 7; and

a chamber surrounding the resistivity measurement cell,

wherein the chamber comprises a plurality of holes through which a plurality of wires connected to the first and second measurement arrays pass.

9. A resistivity measurement cell, comprising:

a first four-probe array including a first array first point current source, a first array second point current source, a first array first point potential electrode, and a first array second point potential electrode in a first direction; and

a second four-probe array including a second array first point current source, a second array second point current source, a second array first point potential electrode, and a second array second point potential electrode in a second direction;

wherein each distal end of the first array first point potential electrode and the first array second point potential electrode is placed at a different plane from each distal end of the second array first point potential electrode and the second array second point potential electrode in a third direction.

10. The resistivity measurement cell according to claim 9, wherein the distal ends of the second array first point potential electrode and the second array second point potential electrode are located lower than the distal ends of the first array first point potential electrode and the first array second point potential electrode in the third direction.

11. The resistivity measurement cell according to claim 9, wherein the distal ends of the first array first point potential electrode and the first array second point potential electrode are located in the same plane as distal ends of the first array first point current source, the first array second point current source, the second array first point current source,

and the second array second point current source.

12. The resistivity measurement cell according to claim 11, wherein the first array first point current source, the first array first point potential electrode, the first array second point potential electrode, and the first array second point current source are arranged in series and spaced apart at a horizontal spacing; and the second array first point current source, the second array first point potential electrode, the second array second point potential electrode, and the second array second point current source are arranged in series and spaced apart at the horizontal spacing.

13. The resistivity measurement cell according to claim 9, further comprising a cross frame supporting the first and second four-probe arrays, and a cell connected to the cross frame and surrounding the cross frame and the first and second four-probe arrays.

14. The resistivity measurement cell according to claim 13, wherein each of the first array first point current source, the first array second point current source, the first array first point potential electrode, the first array second point potential electrode, the second array first point current source, the second array second point current source, the second array first point potential electrode, and the second array second point potential electrode comprises a cable sheath passing through the cross frame.

15. The resistivity measurement cell according to claim 14, wherein each of the first array first point current source, the first array second point current source, the first array first point potential electrode, the first array second point potential electrode, the second array first point current source, the second array second point current source, the second array first point potential electrode, and the second array second point potential electrode further comprises an electrode disposed inside the cell.

16. The resistivity measurement cell according to claim 15, wherein each cable sheath of the second array first point potential electrode and the second array second point potential electrode extends to each electrode of the second array first point potential electrode and the second array second point potential electrode inside the cell.

17. A Soil Water Characteristic Cell (SWCC) device, comprising:

a plate;

the resistivity measurement cell according to claim 16 disposed on the plate;

a chamber surrounding the resistivity measurement cell and the plate; and

a plurality of wire passing through the chamber and connected to the first and second four-probe arrays.

18. A resistivity measurement cell, comprising:

a first array first point current source and a first array second point current source disposed in a first direction;

a first array first point potential electrode and a first array second point potential electrode disposed between the first array first point current source and the first array second point current source in the first direction;

a second array first point current source and a second array second point current source disposed in a second direction;

a second array first point potential electrode and a second array second point potential electrode disposed between the second array first point current source and the second array second point current source in the second direction,

wherein each distal end of the second array first point potential electrode and the second array second point potential electrode is located lower than each distal end of the second array first point current source and the second array second point current source in a third direction, and

wherein the first and second direction are a horizontal direction and the third direction is a vertical direction.

19. A Soil Water Characteristic Cell (SWCC) device, comprising:

the resistivity measurement cell according to claim 20; and

a chamber surrounding the resistivity measurement cell.

20. The SWCC device according to claim 19, further comprising a ceramic plate on which the resistivity measurement cell is disposed.

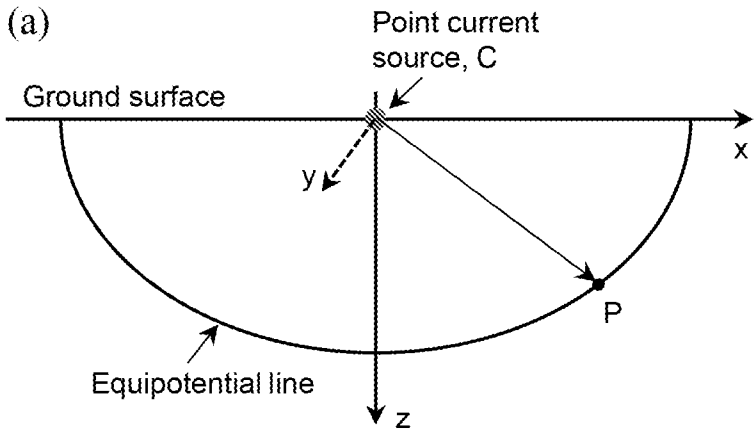


Figure 1(a)

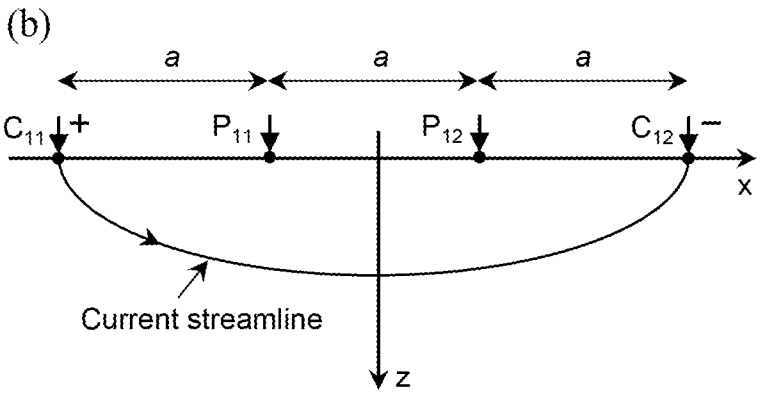


Figure 1(b)

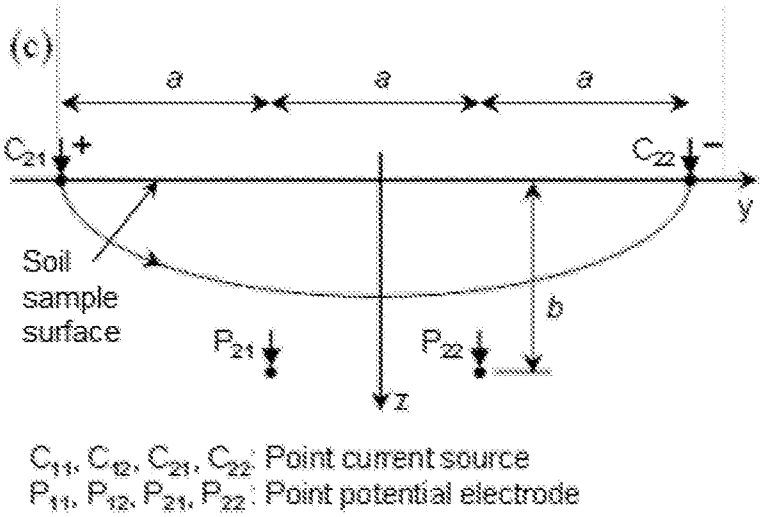


Figure 1(c)

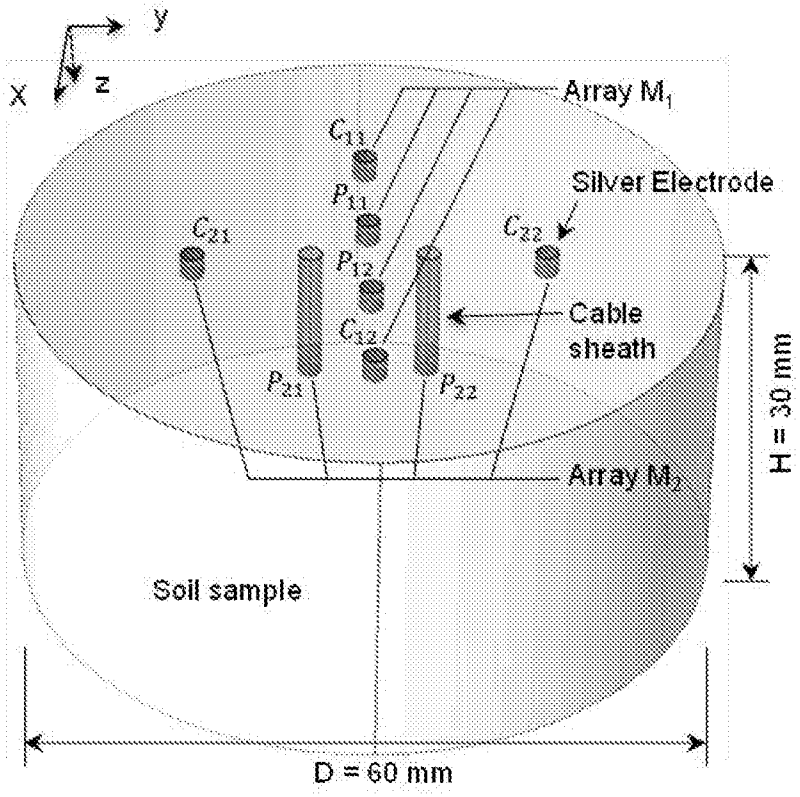

y
X
z
Array M_1
C_{11}
P_{11}
Silver Electrode
C_{21}
C_{22}
P_{12}
Cable sheath
C_{12}
P_{21}
P_{22}
H = 30 mm
Array M_2
Soil sample
D = 60 mm

Figure 2

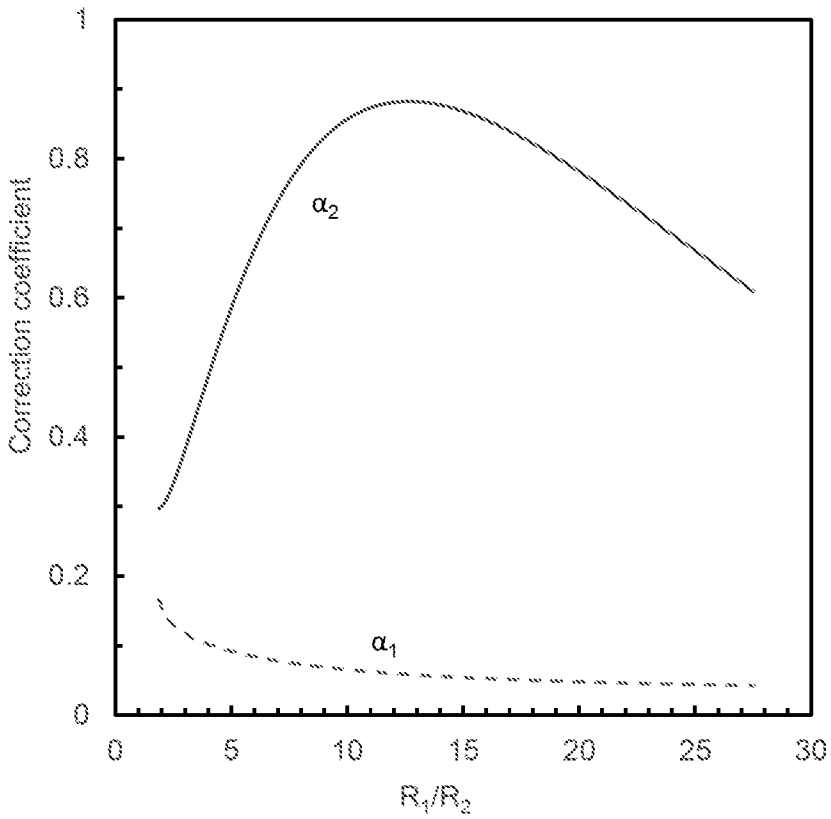

Correction coefficient
1
0.8
0.6
0.4
0.2
0
α_2
α_1
0
5
10
15
20
25
30
R_1/R_2

Figure 3

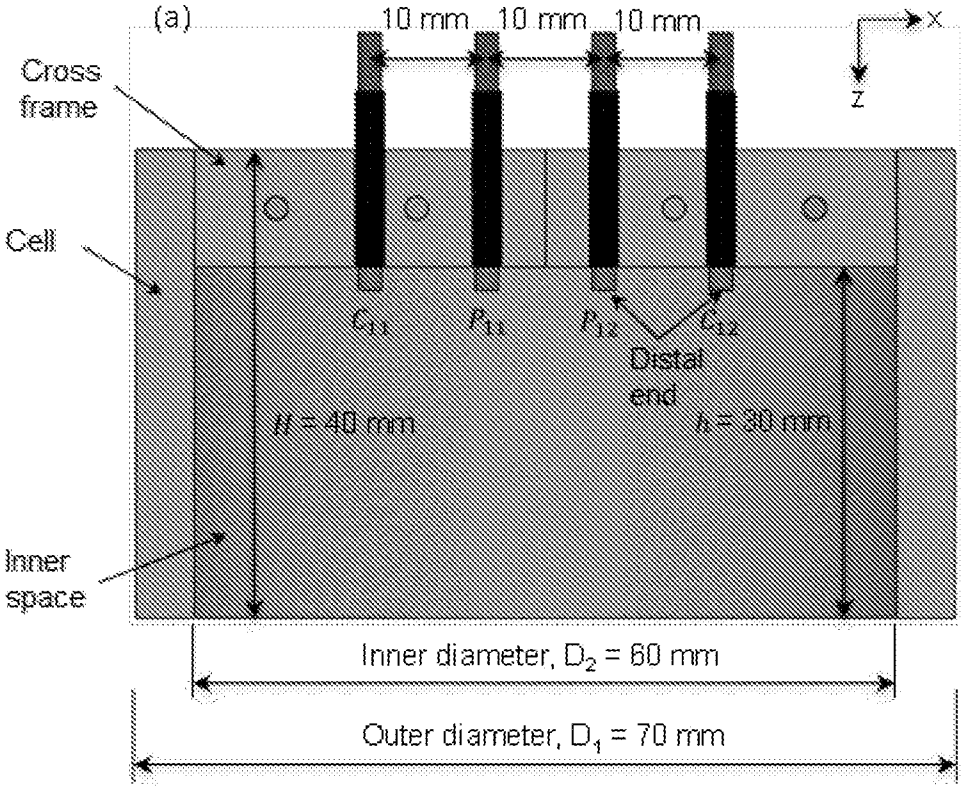


Figure 4(a)

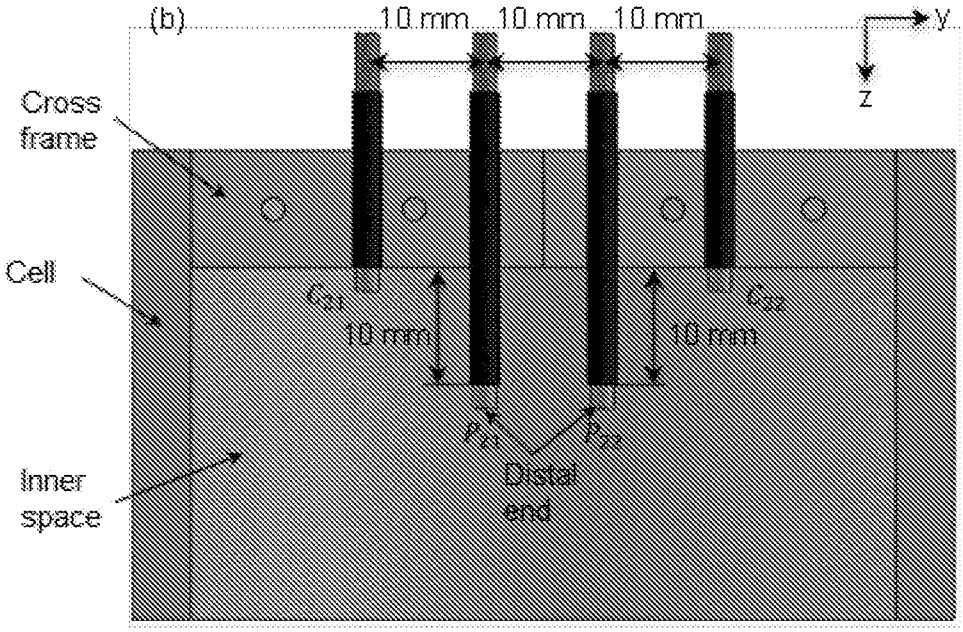


Figure 4(b)

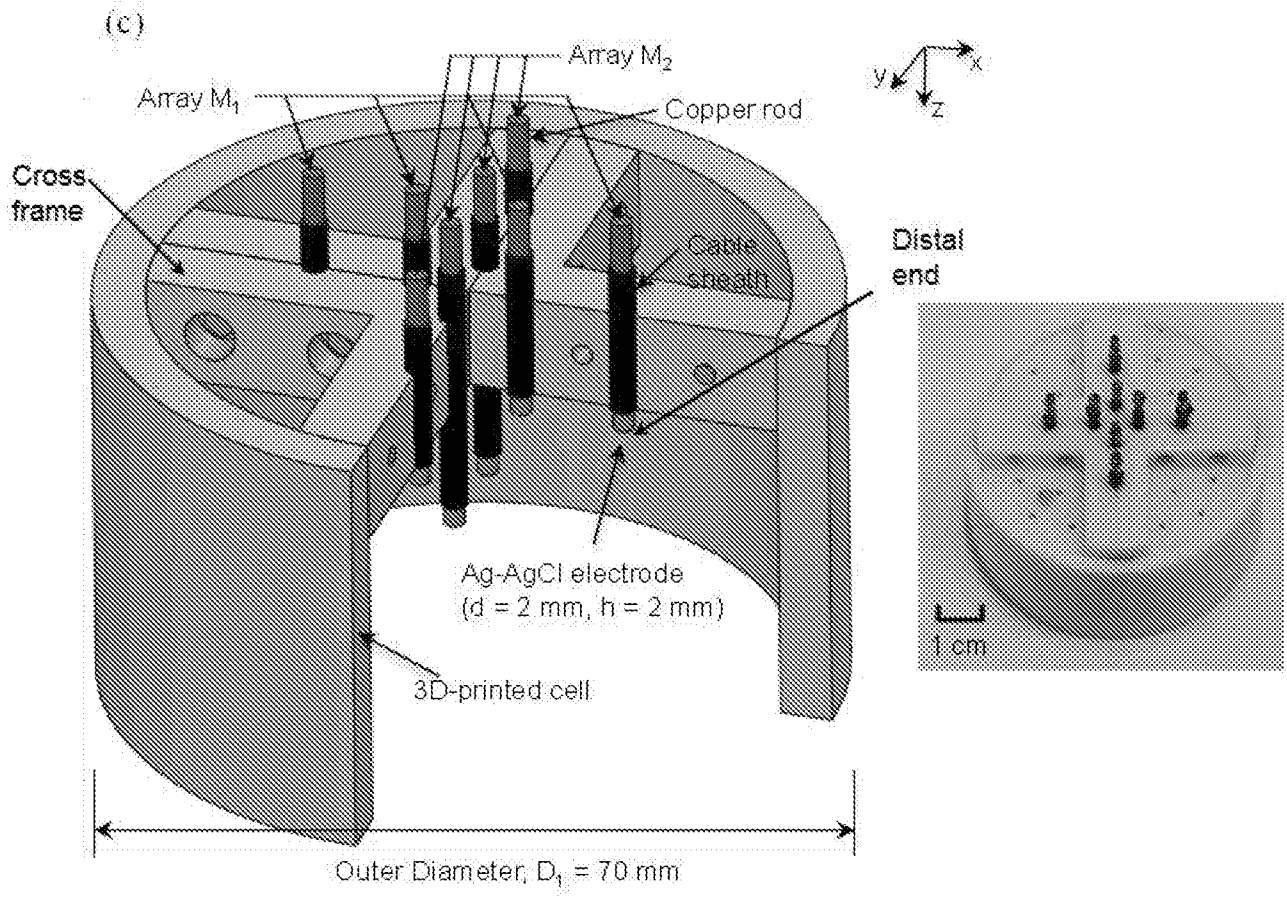

(c)
Array M_2
Array M_1
Copper rod
y
x
z
Cross frame
Distal end
Cable sheath
Ag-AgCl electrode
(d = 2 mm, h = 2 mm)
3D-printed cell
Outer Diameter, D_1 = 70 mm
1 cm

Figure 4(c)

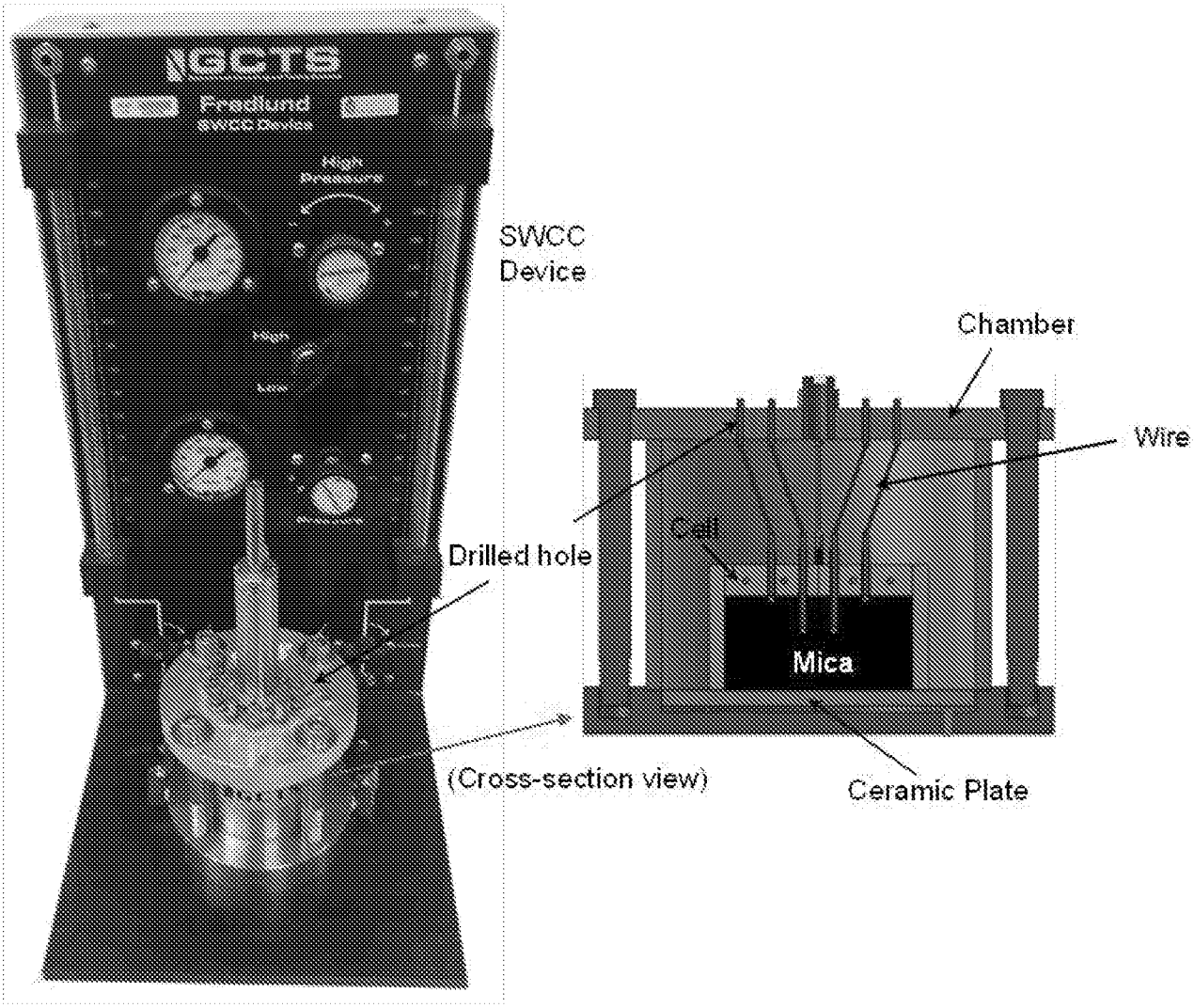

NGCTS
Fredlund
SWCC Device
SWCC
Device
Chamber
Wire
Cell
Drilled hole
Mica
(Cross-section view)
Ceramic Plate

Figure 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2017/001473

A. CLASSIFICATION OF SUBJECT MATTER

G01R 27/14(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNPAT, EPODOC, WPI, CNKI: resistivity, electrical, measure+, soil, moisture, water, SWCC, direction, array, Wenner, electrode?, plane?, multi+, perpendicular, cross, diagonal, point s current, current, horizontal, vertical

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 102027366 A (COTTON CATCHMENT COMMUNITIES) 20 April 2011 (2011-04-20) description, paragraphs [0048]-[0093], Annexure A, figures 1-9	1-20
A	CN 102854392 A (CHINA ENERGY ENGINEERING GROUP GUANGDONG ELECTRIC POWER DESIGN INSTITUTE) 02 January 2013 (2013-01-02) the whole document	1-20
A	CN 103869173 A (STATE GRID CORP. CHINA ET AL.) 18 June 2014 (2014-06-18) the whole document	1-20
A	CN 102426297 A (UNIV. SHAANXI TECHNOLOGY) 25 April 2012 (2012-04-25) the whole document	1-20
A	US 2003071604 A1 (LEE, KI HA ET AL.) 17 April 2003 (2003-04-17) the whole document	1-20
A	WO 9621872 A1 (ANDERSON, DENNIS MICHAEL ET AL.) 18 July 1996 (1996-07-18) the whole document	1-20

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 March 2018	**03 April 2018**

Name and mailing address of the ISA/CN	Authorized officer
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IB2017/001473

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
CN	102027366	A	20 April 2011	AU	2009227997	A1	01 October 2009
				WO	2009117784	A1	01 October 2009
CN	102854392	A	02 January 2013		None		
CN	103869173	A	18 June 2014	CN	103869173	B	30 March 2016
CN	102426297	A	25 April 2012	CN	102426297	B	19 March 2014
US	2003071604	A1	17 April 2003	US	6636046	B2	21 October 2003
WO	9621872	A1	18 July 1996	CA	2209132	A1	18 July 1996
				US	5861750	A	19 January 1999