Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-182

Effect of the contact resistivity and AC frequency on the resistivity of clays under different contamination states

Qi Yanmin[1], Zhang dingwen[2], and Lin Wenli[3]

[1]Prostgraduate, Institute of Geotechnical Engineering, Southeast University, Nanjing, China, email: 220203217@seu.edu.cn

[2]Professor, Institute of Geotechnical Engineering, Southeast University, Nanjing, China, email: Zhang@seu.edu.cn

[3]Associate professor, Institute of Geotechnical Engineering, Southeast University, Nanjing, China, email: linwenli@seu.edu.cn

ABSTRACT

Resistivity surveys have been widely used to study the transport behavior of contaminants in soil, while its accuracy is stated will be influenced by the testing methods including the two-electrode and the four-electrode method. In this paper, the Miller soil box test was performed to investigate this subject on clays with different contamination states. Firstly, two factors of the contact resistivity and AC frequency, which may affect the accuracy of the two-electrode method on the soil resistivity were studied and quantified. The results show that the presence of the contact resistivity causes the tested soil resistivity to be larger than its true value, and the contact resistivity itself decreases as a power function with the increase of soil volumetric water content, due to the increase of the contact degree between the electrode and the soil specimen. The increase of AC frequency decreases the soil resistivity in a linear form, which is related to the electrode polarization and double layer relaxation effect of clay. The resistivity results of uncontaminated clay and Non-aqueous Phase Liquids（NAPLs) contaminated clay show that the difference in soil resistivity derived from two methods gradually decreases or even disappears with the increase of the soil volumetric water content, this difference is more obvious when the volumetric water content is low. After the resistivity correction of two-electrode method based on the quantitative analysis expressions of the contact resistivity and AC frequency, the difference in the soil resistivity between these two testing methods becomes smaller, indicating that the contact resistivity and AC frequency are the main factors that control the accuracy of the two-electrode method.

Keywords: two-electrode method, four-electrode method, miller soil box test, the contact resistivity, AC frequency, soil resistivity

1 INTRODUCTION

Resistivity is one of the inherent physical parameters of soils, which can reflect the overall structural characteristics of soils and has important application value. Besides, technologies associating the monitoring of soil resistivity have some prominent advantages such as low cost, high efficiency, rich information and convenient interpretation in the application process (Bai, 2008). Therefore, these technologies become increasingly popular in the application of various fields, including foundation survey (Wang, 2001), dam foundation safety (Song, 2008), urban engineering and environmental geological survey (Guo, 2001), etc.

At present, the indoor soil resistivity unit testing methods include two-electrode and four-electrode methods (Liu, 2010), their measurement principles are shown in Figure 1. Numerous experimental studies have shown that the influence of two-electrode method on the resistivity testing results is mainly reflected in the contact resistivity, while that of four-electrode method is mainly reflected in the type, insertion depth and electrode spacing of voltage pole. For the two-electrode method, Wang (2017) studied the effect of contact area between electrode and soil, and found that the smaller the contact area, the greater the contact resistivity, which resulted in a corresponding increase in the resistivity of the specimen. Shen (2019) discussed the effect of the degree of contact between electrode and specimen on the soil resistance, and found that an increase in the degree of contact would result in a gradual decrease in soil resistivity. For the four-electrode method, Wu (2015) studied the influence of three types of voltage poles (i.e. copper sheet, copper rod, and copper wire mesh) on the soil resistivity, and concluded that priority should be given to copper sheet electrodes. Zhou (2011) analyzed the effect of the insertion depth of voltage electrodes on the resistivity of five soil specimens, results showed that the insertion depth did not affect the measurement results, but it should not be too large in order to reduce the disturbance to the specimen.

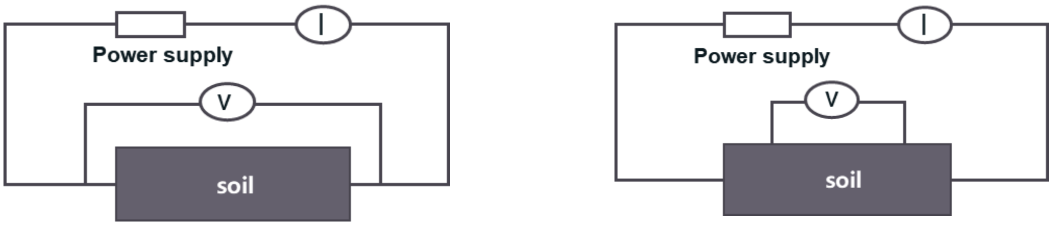


Figure 1. *The principles of two-electrode method (left) and four-electrode method (right)*

In addition to unit testing methods, factors such as the AC or DC type, AC frequency, current density, etc. will also affect the testing results of soil resistivity. Mitchell (1968) proposed that there would be electric and electrochemical effects when DC method was used, which can lead to irreversible changes in water content, soil structure and pore fluid chemical properties, therefore, AC is mostly used in engineering to test the soil resistivity. Liu (2018) summarised the performance characteristics of commonly used resistivity testing methods, as shown in Table 1, the results show that different AC test methods all have high sensitivity, but the level of AC frequency affects the accuracy of the test results. Shan and Singh (2004)'s research pointed out that the increase of AC frequency increases the soil conductivity, which is related to the electrode polarization and double layer relaxation effects, the conduction of current is only in accordance with Ohm's law when it is within a certain frequency range, as shown in Figure 2. In addition to the type of power supply and AC frequency, Fukue (2001) et al. further investigated the effect of current density on soil resistivity, noting that there is a critical value of current density allowed to pass in the soil, when this critical value is exceeded to reach the thermal capacity of the soil, the soil resistivity will show an unstable decrease.

Table 1. *Performance characteristics of commonly used indoor resistivity testing methods*

Testing method	Main advantages and disadvantages
DC method	The existence of electric phenomena, electrochemical effects, etc. can lead to inaccurate test results
Four-electrode low frequency AC method	High sensitivity, large test range, high accuracy, but difficult to continuously measure, causing disturbance to surrounding soil
Two-electrode low frequency AC method	High sensitivity, large test range, simple and safe operation, simultaneous and continuous measurement, low disturbance to the surrounding soil, slightly less accurate than four-electrode method
High frequency AC method	High sensitivity, large test range, poor accuracy, existence of polarisation, dangerous handling

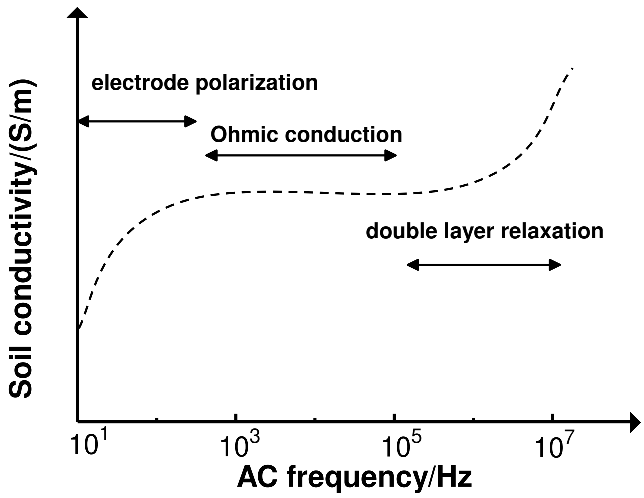


Figure 2. *The variation law of soil conductivity with AC frequency*

From the above study, it can be found that the resistivity unit testing method and power supply conditions can affect the measurement accuracy of soil resistivity. However, rare quantitative analysis has been performed to study the degree of these influencing factors on the soil resistivity. A further investigation on this subject is of necessary as to conduct resistivity measurements more accurately under the condition of controlling the variables as much as possible.

In this paper, the difference in the testing results of soil resistivity between two-electrode method and four-electrode method is analyzed for both uncontaminated and Non-aqueous phase liquids (NAPLs) contaminated soils. Furthermore, a special interest is also given to study the effects of the contact resistivity and AC frequency on the soil resistivity.

2 METHODS AND APPARATUS

The soil used in the test is uncontaminated clay, which is taken from a testing site in Fengxian District, Shanghai City, Table2 is the basic mechanical properties of used soil.

Table 2. *Basic mechanical properties of soil from Shanghai*

Density (g/cm^3)	Specific gravity	Liquid limit (%)	Plastic limit (%)	Maximum dry density (g/cm^3)
1.97	2.71	46.9	21.8	1.92

The NAPLs contaminant used in the test is Methyl Tertiary Butyl Ether (MTBE) with a density of 0.65 g/cm^3, which belongs to Light Non-aqueous Phase Liquid (LNAPL). As an additive of gasoline, MTBE is more likely to transport to the ground and cause soil pollution than other components.

A plexiglass homemade Miller Soil Box with an internal size of 12cm×3cm×2.5cm was used as the measuring device. Copper electrode sheets, with the area the same to the cross section of the box, were set at both ends as current measuring electrodes. Two removable copper rods were set on the cover of the Miller Soil Box as voltage measuring electrodes.

The LCR-817 type resistivity tester produced by GWINSTEK was used as the two-electrode method measuring instrument, as shown in Figure 3. The frequency can be changed when AC power is used to detect the resistivity, and the resistivity can be calculated by equation (1)

$$\rho = RA / L \quad (1)$$

where, R is the resistance of the whole specimen; A is the cross-sectional area of the specimen; L is the length of the specimen.

The student power supply and multimeter were used as the measuring instruments of four-electrode method, as shown in Figure 3. The test frequency of the circuit is the national grid frequency of 50Hz. The voltage and current were measured by two copper rod electrodes (spacing 7.5cm) and two end copper sheet electrodes respectively, the resistivity is calculated by equation (2).

$$\rho = UA / (I L') \quad (2)$$

where, U is the measured voltage of copper rod electrode; I is the current value; A is the cross-sectional area of the specimen; L' is the distance between two copper rod electrodes, A/L'=1.0.

To prepare the soil specimen properly, the soil was firstly air-dried, crushed and sieved through 2 mm sieve. Then distilled water at a designed weight ratio was added into the soil and mixed well. The specimen was then cured for 1 day in the standard curing room for uniform water distribution. Thereafter, MTBE with a designed weight ratio was added to the specimen, followed by a 7-day curing in the standard curing room to make MTBE distribute evenly. After curing, the mass of the mixture at a designed density was calculated from the dry density of the soil and the content of water and MTBE. Then the mixture was pressed into the Miller Soil Box in layers. Finally, electrical resistivity was tested and recorded. Noted that three parallel tests were performed for each testing condition, and the averaging value was calculated to represent the soil resistivity.

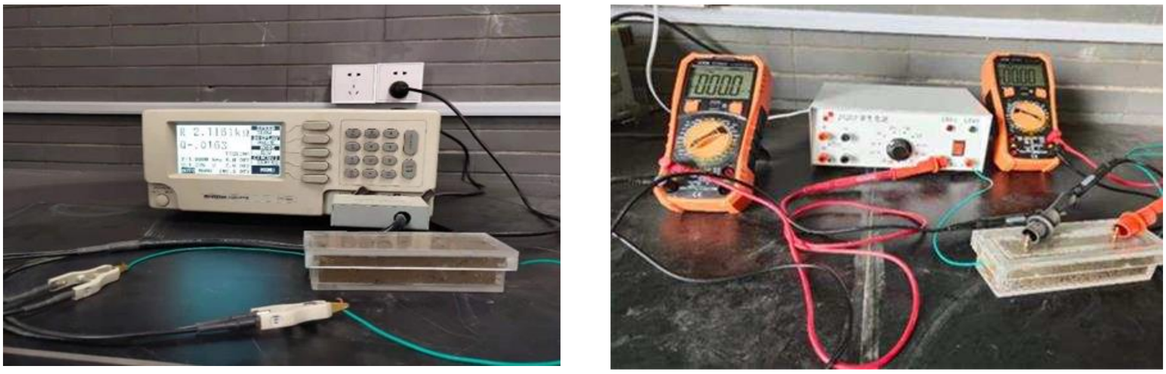


Figure 3. *Two-electrode method measurement circuit (left). Four-electrode method measurement circuit (right)*

3 TESTING RESULTS AND DISCUSSION

3.1 Effect of the contact resistivity on the soil resistivity

The degree of contact between the electrode and the specimen affects the resistivity test results, therefore, the correction of the contact resistivity needs to be considered when testing the resistivity of the specimen using two-electrode method. The contact resistivity can be obtained from the intercept of the specimen resistivity versus specimen length curve (Liu, 2006), and the variation curve of the contact resistivity with water content can be obtained by changing the water content of the specimen.

The new parameter of volumetric water content R_w is defined as the ratio of the volume of water in the soil to the volume of soil particles, and the contact resistivity of specimen was measured under the conditions of 1.4, 1.5 and 1.6 g/cm³ dry density respectively. The testing result is shown in Figure 4. It shows that for a certain dry density, the contact resistivity decreases as a power function with the increase of R_w, and is small or even negligible when it is close to saturation. The difference in the contact resistivity between different dry densities is small and can be expressed by equation (3):

$$\rho_c = 0.2181\ R_w^{-1.2778} \quad (3)$$

where, ρ_c is the contact resistivity; R_w is the volumetric water content.

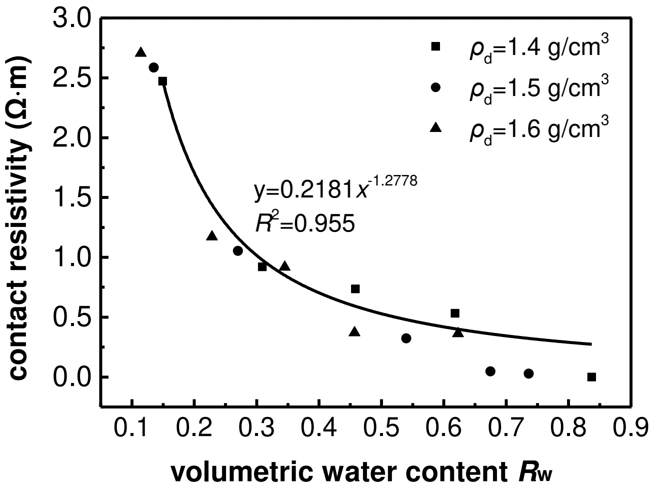


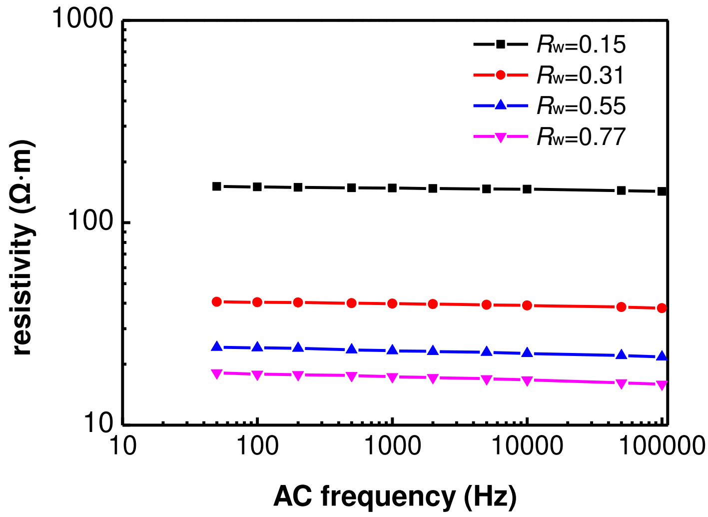
Figure 4. *Relationship between the contact resistivity and volumetric water content*

The variation of the contact resistivity is related to the volumetric water content R_w of the specimen. When R_w is low, the interface between the specimen and the electrode sheet is mainly in contact with soil particles, which will cause significant resistance to the conduction of current, resulting in a higher contact resistivity. when R_w is high, the specimen is in contact with the electrode sheet through pore water and soil particles, which is more conducive to the passage of currents, therefore, the contact resistivity decreases with the increase of R_w. As R_w continues to rise, the improvement in interfacial contact conditions gradually decreases, so there is little change in contact resistivity.

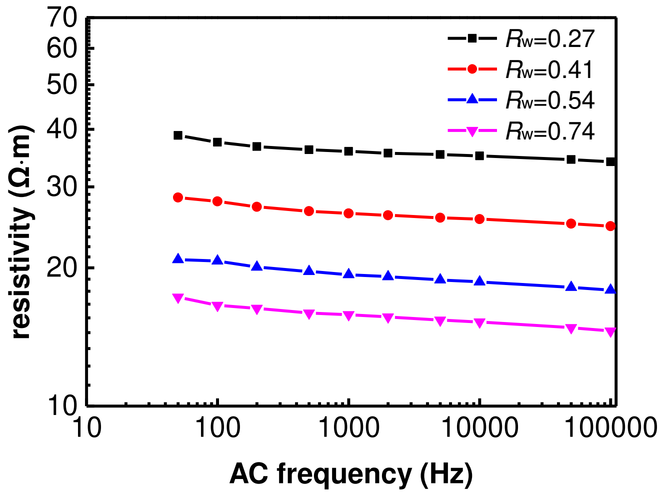
3.2 Effect of AC frequency on the soil resistivity

The resistivity change laws of uncontaminated soil with AC frequency under the dry density of 1.4, 1.5, and 1.6 g/cm^3 were measured, and the result is shown in Figure 5. It shows that the resistivity of the soil gradually decreases with the increase of AC frequency, and the change laws of resistivity under different dry density conditions are the same, which is consistent with the research results of Zhou (2011) and Son (2009).

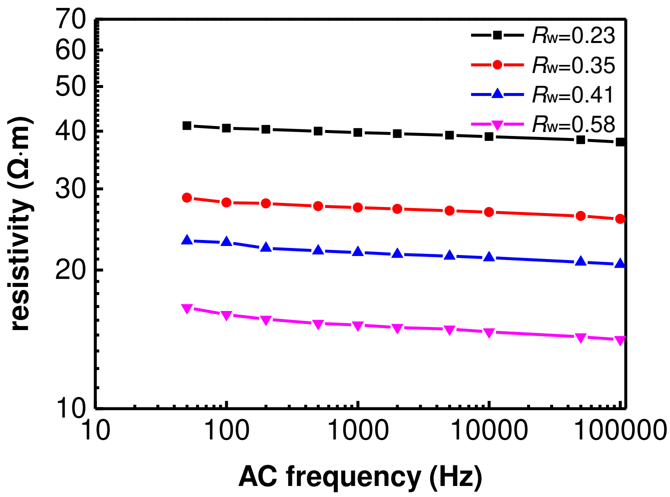
In terms of the selection of AC frequency, for clay, the phenomenon of electrode polarization exists when the AC frequency is low. Ions will accumulate near the electrode to form a layer of poor conductivity film, which leads to poor conductivity of the soil. When the AC frequency is high, there is a double layer relaxation effect, and the ions in the double layer on the surface of the clay particles will be released to improve the conductivity of the soil. Only in a certain frequency range the current can be conducted stably. According to the study of Shah and Singh (2004), the AC frequency range in which the current can be stably transmitted is about 1 k ~ 1 MHz. Therefore, 10kHz is chosen as the test frequency of two-electrode method in this work.



(a) 1.4 g/cm^3



(b) 1.5 g/cm^3



(c) 1.6 g/cm^3

Figure 5. *Relationship curve between specimen resistivity and AC frequency*

Four-electrode method circuit uses an AC frequency of 50 Hz, while two-electrode method circuit uses 10 kHz that allows for stable current conduction. A quantitative analysis of the difference in resistivity values caused by changes in AC frequency is required. Eqution (4) defines the resistivity difference ratio.

$$\Delta = (\rho_{50Hz} - \rho_{10kHz}) / \rho_{50Hz} \qquad (4)$$

Where, Δ is resistivity difference ratio (%) ; ρ_{50Hz} is the resistivity of the specimen at 50 Hz frequency; ρ_{10kHz} is the resistivity of the specimen at 10kHz frequency.

The resistivity difference ratio calculated from the experimental results in Figure 3 is plotted in Figure 6. Corresponding to the dry density of 1.4, 1.5, and 1.6 g/cm³, the resistivity difference ratio can be approximately expressed by equation (5), equation (6) and equation (7), respectively.

$$\Delta = 8.9739\ R_w^{0.5861} \quad R^2=0.943 \qquad (5)$$

$$\Delta = 11.9901\ R_w^{0.1613} \quad R^2=0.910 \qquad (6)$$

$$\Delta = 817.8884\ R_w^{0.5861} \quad R^2=0.984 \qquad (7)$$

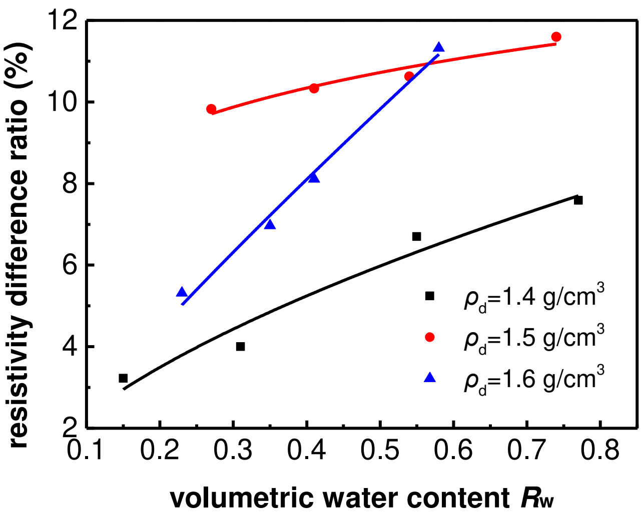


Figure 6. *Relationship curve between resistivity difference ratio and volumetric water content*

3.3 Correction of resistivity results

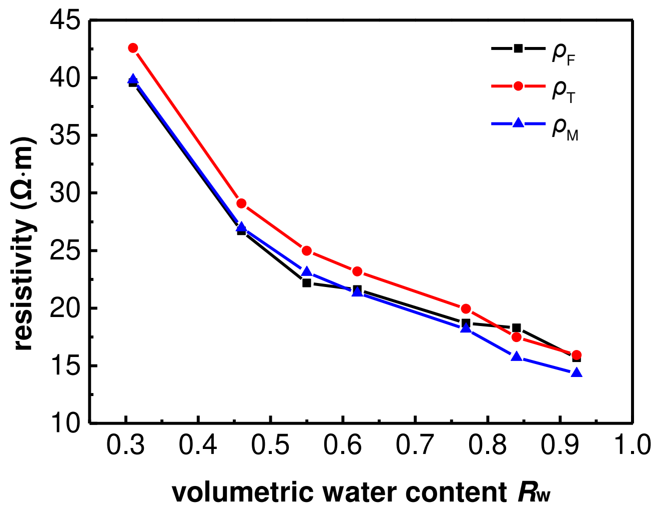
The resistivity of uncontaminated soil and NAPLs contaminated soil were tested by two-electrode and four-electrode method, and the results of two methods are compared with modified two-electrode method to study the main reasons for the differences between different testing methods.

Modified two-electrode method resistivity is calculated by subtracting the two-electrode resistivity testing results from the contact resistivity and the difference caused by the AC frequency under the corresponding volumetric water content R_w. The modification can be calculated according to equation (8):

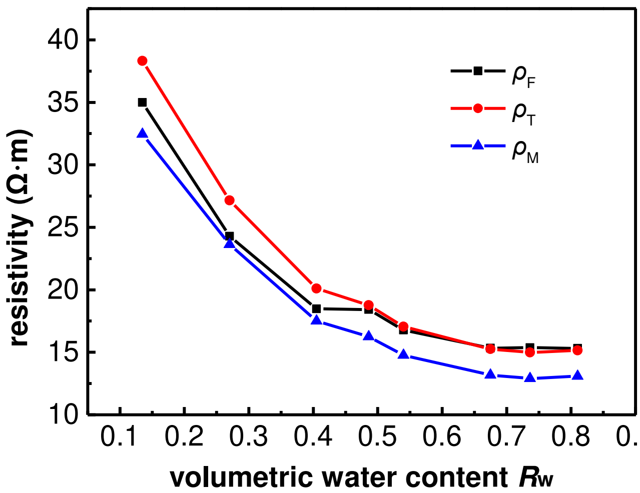
$$\rho_M = \rho_T - \rho_C - \Delta\ \rho_F \qquad (8)$$

where, ρ_M、ρ_T 、ρ_F are the resistivity results of modified two-electrode method, two-electrode method and four-electrode method respectively, ρ_C is the contact resistivity.

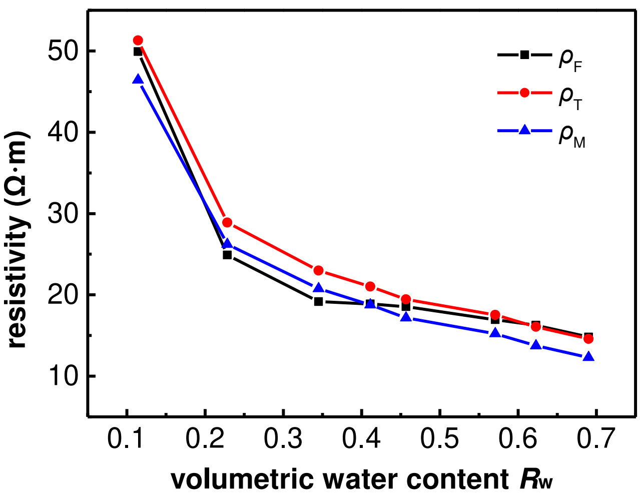
Figure 7 and Figure 8 compare the soil resistivity derived from the two-electrode method, four-electrode method, modified two-electrode method for uncontaminated soil and NAPLs contaminated soil, respectively.



(a) 1.4 g/cm³

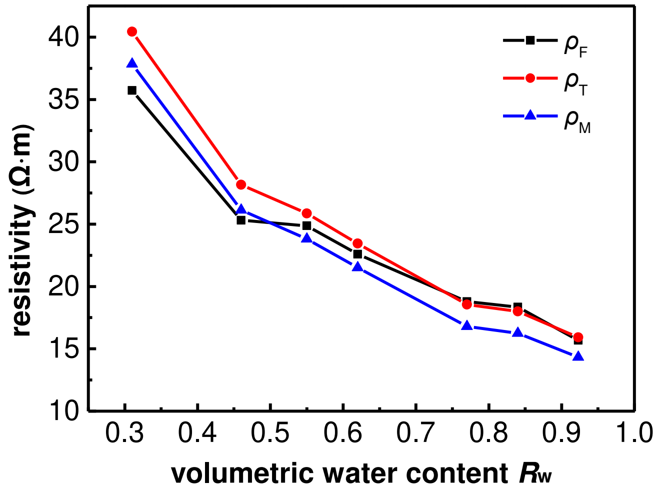


(b) 1.5 g/cm³

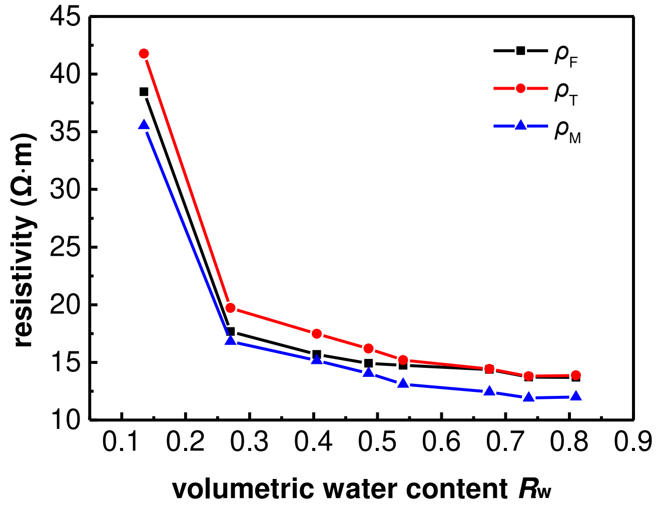


(c) 1.6 g/cm³

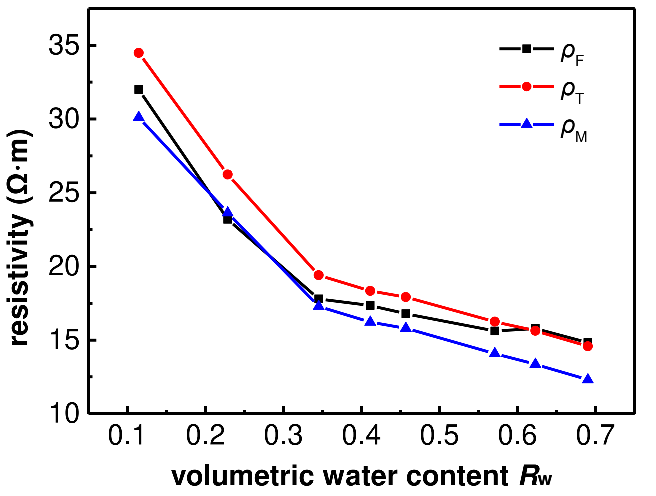
Figure 7. *Comparison of resistivity test results of uncontaminated soil*



(a) 1.4 g/cm³



(b) 1.5 g/cm³



(c) 1.6 g/cm³

Figure 8. *Comparison of resistivity test results of NAPLs contaminated soil*

From Figure 7 and Figure 8, it can be seen that when the volumetric water content R_w is low, the difference between the resistivity test results of two-electrode method and four-electrode method is relatively obvious. With the increase of R_w, the difference gradually decreases or even becomes neglected. After the correction of the resistivity by considering the contact resistivity and AC frequency, the resistivity of modified two-electrode method is closer to that of four-electrode method. However, when R_w is high, there are still some deviations between the results of two methods, and the AC frequency correction is the main reason for the difference.

From the above testing results, it is understood that the contact resistivity and AC frequency are the main reasons for the difference in resistivity between two-electrode method and four-electrode method. In addition, the comparison of modified two-electrode method with the four-electrode method reveals that there are still small differences between the two testing methods, which may be caused by operating issues such as the difficulty in ensuring the uniformity of compaction, small fluctuations in environmental temperature, and testing duration, etc. The above test results can provide reference for the selection of resistivity testing method for contaminated soil.

4 CONCLUSIONS

In this work, a series of Miller soil box unit tests were performed to investigate the influence of different testing methods on the resistivity of clays with different contamination states. Particularly, two factors of the contact resistivity and AC frequency, which may affect the accuracy of the two-electrode method on the soil resistivity were studied and quantified. The following conclusions are drawn.

(1) The contact resistivity decreases as a power function with the increase of volumetric water content for a certain dry density, and the difference in the contact resistivity between different dry densities is small.

(2) Soil resistivity decreases linearly with the increase of AC frequency from 50 Hz to 10 kHz. The higher the volumetric water content of the specimen, the larger the difference caused by the change of test frequency.

(3) The resistivity results of uncontaminated soil and NAPLs contaminated soil show that with the increase of volumetric water content, the difference between the resistivity of two-electrode method and four-electrode method gradually decreases; the results of modified two-electrode method are closer to the results of four-electrode method, but there are still differences when the volumetric water content is high, which mainly caused by the correction of the AC frequency.

5 ACKNOWLEDGEMENTS

The authors appreciate the support of National Key R&D Program of China under Grant No. 2020YFC1808101.

REFERENCES

Bai, L. (2008). Research on the application of physical exploration methods in contaminated sites [Masters Thesis D]. Lanzhou University, Lanzhou, China.

Wang, Y.Q., Zhang, X.Q., Ma, D.H., Wei, W.X. (2001). The application of comprehensive physical propecting in selecting address on high building. HeNan Geology, 19(3): 208—211.

Song, X.D., Wang, H., Wang, S.J., Ma, W.M. (2008). Application of the high density resistivity method in the safe appraisement of dam. Journal of ShanDong agricultural university(natural science edition), 39(2): 295-297.

Guo, X.J., Wang, X.T. (2001). Some problems in the application of high density resistivity method to cavity exploration. Geophysical & Geochemical exploration, 25(4):306～311.

Liu, Z.B., Xu, C. (2010). Several basic problems in electrical resistivity measurement of soils. Highway, (9): 187-192.

Wang, B.H., Wang, Z.H., Jiang, P.M., Zhou, A.Z. (2017). Resistivity characteristics of saturated sandy soils with different porosity. Chinese Journal of Geotechnical Engineering, 39(9): 1739-1745.

Shen, J.W., Mao, H.T., Wang, Z.C., Yan, L., Tang, X. (2019). Influence of electrode contact and distance on soil resistivity measurement. Acta Pedologica Sinica, 56(5):1247-1258.

Shen, J.W., Mao, H.T., Huang, Q.H., Wang Z.C., Yan L. (2019). Experimental and simulation analysis on influences of electrode arrangement on resistivity accuracy. 41(6):61-70.

Wu, D. (2015). Research of method based on the resistivity test of determining the sandy soil porosity and its application [Masters Thesis D]. Jiangsu University of Science and Technology, Jiangsu, China.

Zhou, M., Wang, J.G., Huang, S.B., Dou, P., Zhang, L.Q., Yao, W. (2011). Experimental investigation on influencing factors in soil resistivity measurement. Rock and Soil Mechanics, 32(11):3269-3275.

Mitchell J K, Arulanandan K. Electrical dispersion in relation to soil structure[J]. Journal of Geotechnical Engineering Division, ASCE, 1968, 94: 447-471.

Liu, S.Y., Du, Y.J., Liu, Z.B. (2018). Principles and methods of contaminated site treatment. Nan Jing: Southeast University Press.

Shah, P. H., Singh, D. N. (2004). A simple methodology for determining electrical conductivity of soils. Journal of ASTM International, 1(5), 1-11.

Fukue, M., Minato, T., Matsumoto, M. A., Horibe, H., and Taya, N. (2001). Use of a resistivity cone for detecting contaminated soil layers. Engineering Geology, 60(1-4), 361-369.

Liu, S.Y., Zha, F.S., Yu, X.J. (2006). Laboratory measurement techniques of the electrical resistivity of soils. Journal of engineering geology, 14(2):216-222.

Son, Y., Oh, M., and Lee, S. (2009). Influence of diesel fuel contamination on the electrical properties of unsaturated soil at a low frequency range of 100 Hz–10 MHz. Environmental Geology, 58(6), 1341-1348.