Comparison of Different Electrical Resistivity Measurement Methods of Soft Marine Clays

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Abstract. The electrical resistivity of soil is one of the comprehensive indexes of the inherent property of soil, which has important theoretical signification and application value. The measured methods of soil electrical resistivity mainly can be divided into two groups: laboratory tests and in-situ tests. The in situ testing has been widely used in geotechnical site characterization due to its high accuracy and repeatability. Especially the emergence and development of resistivity piezocone penetration test (RCPTU), the RCPTU becomes the main tool of in situ measurement of the electrical resistivity of soil due to its not only include a conventional piezocone penetration test, but also provides a continuous profile of electrical resistivity. The objective of this paper was to compare the different methods for measuring the electrical resistivity of soil. First, the principle of the electrical resistivity of soil was briefly presented. Then, the comparison of different electrical resistivity measurement methods of soft marine clays was made based on the Ningbo marine clay and the advantages and disadvantages of various measured methods were also analyzed and summarized. The results of comparative analysis was verified the reliability of soil electrical resistivity measured by RCPTU.

Keywords: Electrical resistivity · Piezocone penetration test
Site characterization · Soft marine clay

1 Introduction

Electrical resistivity is the basic parameter to describe the conductivity of soil. It is closely linked to other soil physical and mechanical parameters. Soil resistivity can reflect the composition and structure characteristics of soil [1]. It can quickly and accurately obtain the soil structure index, quantitative analysis of soil structure characteristics, and finally establish a reasonable model to determine the soil engineering mechanics characteristic parameters. The value of electrical resistivity depends on soil

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porosity, pore shape, pore fluid resistivity, saturation, water content, particle composition, shape, orientation and cementation [2]. With development of a practical application of electrical resistivity theory, resistivity measurement methods have been increasingly and widely used to solve engineering and environmental problems, including soil micromorphology [1, 3], pollution characteristics [4], and soil liquefaction [5], and geotechnical parameters evaluation [6]. Particularly, the advanced resistivity piezocone penetration test (RCPTU) has been widely used in geotechnical site characterization due to its high accuracy and repeatability.

Due to the difficulties in obtaining high quality undisturbed samples in laboratory testing, the in situ measurement methods of electrical resistivity have been became a primary choice. Electrical logging, symmetrical quadrupole vertical electrical method and RCPTU test are the primary and common in situ measurement methods of electrical resistivity and are therefore considered in this study. In the face of many testing methods, different literatures do not unify the method of soil resistivity measurement. The different factors affecting the measurement of soil resistivity are compared with the quadrupole method and the dipole method by Zhou et al. [7]. The two electrical resistivity inversion techniques has been applied for geotechnical site investigation by Wisén et al. [8]. However, the different of electrical resistivity measurement techniques will result in different testing results. In practice, there are many different kinds of electrode arrays or configuration that one could use in the field. The typical electrode arrays are including Wenner, Schlumberger, Pole-pole and Dipole-dipole. Whether the method of electrical resistivity test is correct or not and the accuracy of the test results is very important to the analysis of soil properties.

The purpose of this study was to compare different electrical resistivity measurement methods of soft marine clays. The four kinds of measurement methods of electric logging, symmetrical vertical electrical measurement method, RCPTU, laboratory test were compared and analyzed based on engineering site of Ningbo Metro Line 5 station road. The results can not only provide reference and guidance of the test methods and equipment of soil resistivity, but also eventually provide reliable parameters for the engineering design and construction.

2 Soil Resistivity Theory

Archie (1942) firstly studied the relationship between soil resistivity and its structure, and established the relationship model between resistivity and pore water resistivity [9]. The model is suitable for saturated cohesionless soil and pure sand. Specific equations are as follows:

$$\rho = a\rho_w n^{-m} \tag{1}$$

where ρ is soil resistivity; a is soil parameters; ρ_w is pore water fluid resistivity; n is soil porosity; m is cementation coefficient.

Electrical resistivity of soils is not measured directly, but can be inferred from the measured voltage across an electrode, pair at a constant supplied current (I). The soil resistance, R, can be computed by Ohm's law, as follows [10]:

$$R = \frac{V}{I} \tag{2}$$

where R = resistance, I = electric current, and V = electric potential difference.

However, the measured resistance is not an intrinsic property and it depends on the area of the cross section (A) and of the current path length (L). The electrical resistivity, ρ is then a fundamental soil property which can be defined as:

$$\rho = \frac{A}{L} R \tag{3}$$

3 Geological Conditions and Basic Soil Parameters

The site is located in Ningbo Metro Line 5 station road. The Ningbo City is located in the coastal plain and is widely distributed marine sedimentary soft soil. There is a weathered hard crust layer of 1 to 1.5 m. The soft soil layer below the hard crust is mainly composed of clay, muck, mucky clay and mucky silty clay. The mucky soil has typical characteristics of soft soil with high water content, large pore ratio and high compressibility. Table 1 summaries the main physical properties of cohesive soils in investigated sites.

Table 1. Main physical properties of cohesive soils.

Soil layer	γ (kN/m^3)	w (%)	w_L (%)	w_P (%)	I_L
Clay	19.2	30.7	40.4	22.6	0.46
Mucky clay	17.2	50.1	42.4	19.1	1.41
Mucky silty clay	16.9	49.2	36.5	15.2	1.76
Clay	18.9	34.4	40.0	20.8	0.64
Silty sand	19.4	27.5			

4 Testing Method

4.1 Electrical Logging

The test equipment is adopted JDC-1 type resistivity logging instrument and its supporting device of JDX-1 soft electrode. The instrument connecting underground ground electrode system, and supporting the use of PC, can measure the apparent resistivity and natural potential parameters. The field test is shown in Fig. 1.

Fig. 1. Field test of electric logging method

4.2 Quadrupole Vertical Electrical Method

This study adopts the type of WDDS-1 digital resistivity instrument. The way it works: the electrical resistivity can be calculated by the measurement of the potential difference (V) of each electrode and supply current (I) using the formula (2). The method provides underground the artificial electric field and changes the power supply electrode pitch based on the electrical difference of stratum. Thus it can be obtained the apparent resistivity curve of each measuring depth. The ρ values of different depths can be calculated using the weighted average method based on the values of thickness and resistivity values of each electrical layer.

$$\rho = \frac{\rho_1 \cdot h_1 + \rho_2 \cdot h_2 + \cdots + \rho_i \cdot h_i}{h_1 + h_2 + \cdots h_i} \ (\Omega \cdot \mathrm{m}) \tag{4}$$

Where ρ_i = soil resistivity of ith layer ($\Omega \cdot$ m); h_i = thickness of ith layer (m).

4.3 RCPTU Testing

RCPTU field tests were conducted using g a lightweight truck with a 20 ton capacity hydraulic system, as per American Society for Testing and Materials ASTM D5778 (ASTM 2012). The RCPTU system was consist of a hydraulic pushing and leveling system, 1-m length segmental rods, cone penetrometers and a data acquisition system. The dimensions of the probe are: diameter 35.7 mm, conical tip area 10 cm^2, and friction sleeve area 150 cm^2, and the data was collected every 5 cm. The cone tip resistance (q_c), sleeve friction (f_s), penetration pore pressures (u_2) behind the tip at the shoulder, and ρ were be simultaneously measured in the process of penetration. The field RCPTU test with the resistivity piezocone probe with a four-electrode array are shown in the Fig. 2.

4.4 Soil Sampling and Laboratory Testing

High quality soil samples were taken at different depths for laboratory testing. The soil samples were collected by averages of a stationary piston sampler 76 mm in diameter at 1.0 m interval from ground level to the penetration depth, When the Shelby tube sampler was withdrawn from the borehole, the soil sample at the end of the tube was excavated with waxing sealing at both ends.

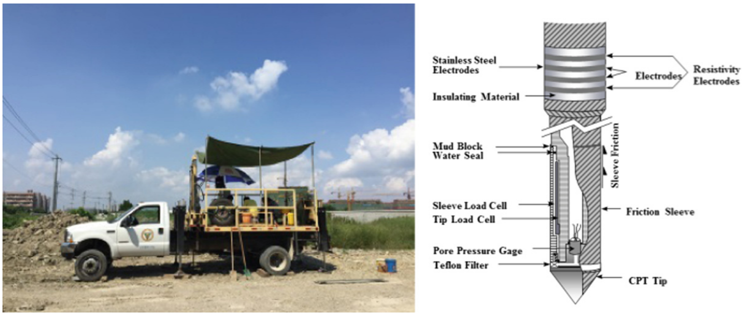

Fig. 2. Schematic diagram of field RCPTU test

Laboratory test was tested by Wenner equidistant quadrupole method (Fig. 3). The small electrodes are buried in the four small holes arranged on the measured surface soil. The current I flows into the outer two electrode, while the potential difference V between the two inner electrodes can be measured by a potential difference meter or a high resistance voltmeter. Soil resistivity is calculated as follows:

$$\rho = \frac{4\pi aR}{\left(1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}\right)} \tag{5}$$

where R = measured resistance; a = straight line spacing; b = buried depth of electrode.

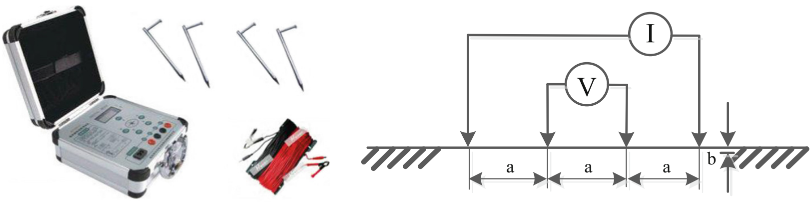

Fig. 3. Schematic diagram of resistivity test device

5 Analysis of Test Results and Discussion

5.1 Test Results of Electrical Logging

According to the test results of electrical logging, the variation curves of electrical resistivity with depth are obtained. The test results are shown in Fig. 4.

It can be seen from Fig. 4 that there is a 1.5 m weathered crust layer, commonly referred to plain fill; underlain by silt clay of 5.5 m, the average value of ρ is 5.02 $\Omega \cdot$ m; Mucky silty clay, clay and silt sand are also distributed in the lower part. The ρ of soil changes obviously with the changing of soil layer. The ρ value is

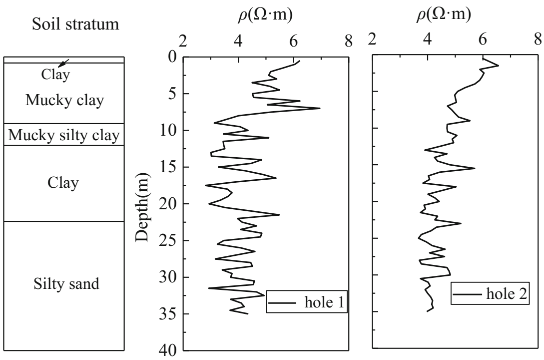

Fig. 4. Resistivity curve of electrical logging

larger in surface clay and mucky silty clay, and decreases with the depth. The ρ value of surface clay is very high, the average value can reach 5.62 $\Omega \cdot$ m. The ρ value of silty sand layer is the lowest with average value of 4.09 $\Omega \cdot$ m. The results indicate that the soil electrical resistivity decreases with the increase of porosity.

5.2 Test Results of Symmetrical Quadrupole Vertical Electrical Method

The test result of resistivity profile is shown in Fig. 5. Taking the thickness of each electrical layer as the weight to weight average and obtaining the soil electrical resistivity values of 1 m, 2 m, 5 m and 10 m in each electrical sounding (Table 2).

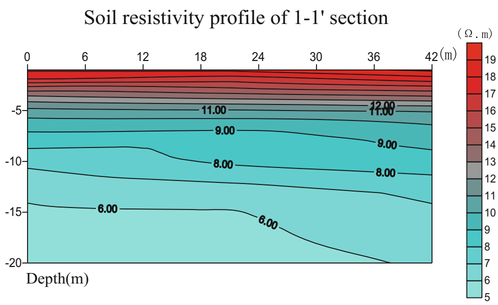

Fig. 5. Test results of soil electrical resistivity

Table 2. Test results of soil resistivity in shallow soil

Physical point	Soil resistivity (Ω · m)			
	1 m	2 m	5 m	10 m
D1	23.9	16.2	10.6	7.1
D4	19.6	20.8	13.0	8.0

It can be seen from the Table 2 that the range of ρ value in 1 m is 4.7 to 23.9 $\Omega \cdot$ m with an average value of 11.7 $\Omega \cdot$ m; the range of ρ value in 2 m is 6.4 to 20.8 $\Omega \cdot$ m with an average value of 10.9 $\Omega \cdot$ m; the range of ρ value in 5 m is 6.4 to 13.0 $\Omega \cdot$ m with an average value of 8.7 $\Omega \cdot$ m; the range of ρ value in 10 m is 4.6 to 8.0 $\Omega \cdot$ m with an average value of 5.7 $\Omega \cdot$ m. The maximum test depth is 10 m and the electrical resistivity decreases with the increasing of depth, which is closely related to soil layering and soil properties. But compared with electrical logging method, its soil electrical resistivity values are greater.

5.3 Test Results of Resistivity Piezocone Penetration Test

According to RCPTU test results, the curves of electrical resistivity along depth are shown in Fig. 6. As can be seen from Fig. 6, the ρ changes obviously with the change of soil layer. The ρ values are larger in mucky clay and decreases with the increasing depth. In silty sand, the varied range of are great and the range of ρ values are 7.05 to 12.55 $\Omega \cdot$ m. The ρ values of surface clay are very high and the average value is up to 10.55 $\Omega \cdot$ m. The electrical resistivity of mucky clay below surface clay is the highest. The ρ values of silty sand are low with average value of 7.05 $\Omega \cdot$ m. The electrical resistivity is closely related to properties of soil layer.

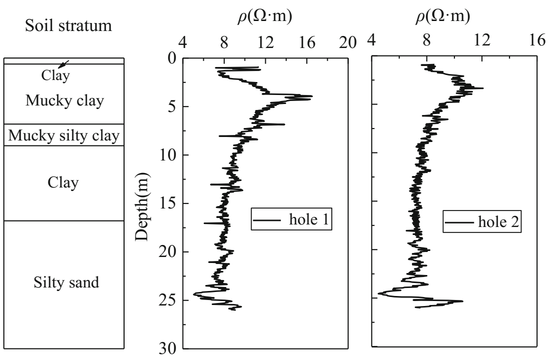

Fig. 6. Resistivity curve of RCPTU

5.4 Comparison and Discussion

Combined with laboratory test, the results are plotted in Fig. 7. It can be noted that the trends of ρ along the depth between schlumberger vertical electrical test and electric logging method is basically the same. The trend of RCPTU results and laboratory test results are high consistency. By contrast, the deviation of electrical logging method from laboratory test results is large, and the vertical electric method deviates from laboratory test results with small amplitude. The results show that the RCPTU is closer to the laboratory tests and verify the RCPTU is a promising in situ method to measure ρ of soil.

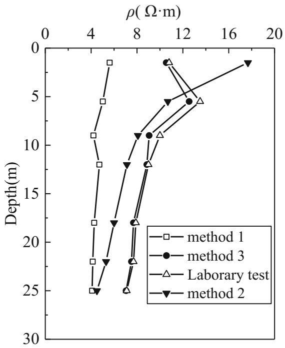

Fig. 7. Comparison of different methods of soil electrical resistivity

6 Conclusion

The three kinds of in-situ test of electric logging, schlumberger vertical electrical measurement method and resistivity piezocone penetration test were performed in the site of the Ningbo City Metro Line 5 project. The in situ results were compared with laboratory tests and the following conclusions are obtained:

(1) The electrical resistivity changes with the change of soil properties, and the soil resistivity decreases gradually from ground surface to bottom. It can be seen that the electrical resistivity reflects the change of soil structure and strength to a certain extent. The change of soil electrical resistivity can be used as a reference parameter for soil classification and soil layer stratification.

(2) The soil electrical resistivity is closely related to the structure and strength. It can reflect the basic physical and mechanical properties, such as soil water content, saturation, porosity, compaction, consolidation and permeability characteristics. The electrical resistivity is an important parameter in the analysis of geotechnical testing.

(3) The electrical resistivity measured by RCPTU test is between the other in situ methods and is basically close to laboratory test. Therefore, the RCPTU can be used for predicting geotechnical parameters. With the development of theoretical study on soil electrical resistivity, RCPTU test technology will be widely used in geotechnical situ investigation due to its rapid, in-situ and high accuracy.

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