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Research Article

Contact Resistance between Calcareous Sand and Electrodes Based on the Two-Electrode Method

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In the process of measuring the resistivity of calcareous sand by the two-electrode method, the contact resistance between calcareous sand and electrodes is an unavoidable problem. In this paper, the effects of the particle size, relative density, current frequency, and saturation on the contact resistance of calcareous sand samples with different electrode spacings were studied. The results show that the larger the particle size and relative density are, the greater the contact resistance. The contact resistance decreases with an increasing current frequency, and the decreasing amplitude decreases with an increasing saturation. The contact resistance decreases with an increasing saturation. The relationship between the contact resistance and current frequency and saturation is established in this paper. When the two-electrode method is used to study the resistivity of calcareous sand, the influence of contact resistance should be considered, especially for samples with low saturation.

1. Introduction

Calcareous sand is mainly distributed in shallow water areas within latitude 30 degrees north and south. Due to the excessive development of siliceous sand, calcareous sand may become the main material to replace siliceous sand in the future. However, because of its numerous pores and irregular shape, its mechanical properties and electrical resistance are significantly different from those of siliceous sand. Therefore, studying the related properties of calcareous sand is of great significance [1, 2].

Resistivity is an important parameter of soil, and it is important to characterize the conductivity of soil [3]. Due to the differences in structure, mineral composition, water content, and temperature, the resistivity of different soils is also different [4].

It has attracted increasing attention because it is nondestructive and economical and has a rapid response [5]. Using the relationship between artificially applied currents and voltages formed by medium properties, electrical resistivity can be determined.

Generally, there are two main methods that can be used to measure the electrical resistance of soil: the two-electrode method [6, 7] and four-electrode method [8–11]. Both are detected via voltametric means. The four-electrode method can avoid the influence of the electrode polarization effect on the resistance, and the test results are relatively accurate. However, in the four-electrode method, the electrode needs to be inserted into the soil sample, which will cause great disturbance to the soil sample [12]. The depth of the electrode insertion and the contact degree with the soil will also affect the accuracy of the measurement results [13]. The two-electrode method is simple to operate, but the contact conditions between the electrode and the soil sample will greatly affect the accuracy of the test results; that is, the contact resistance between the soil and the electrode (hereinafter referred to as the contact resistance) will affect the test results.

In the two-electrode method, electrode polarization and disturbance caused by voltage electrodes are reduced; thus, these advantages have attracted the attention of some scholars [14, 15]. Regarding the two-electrode method, the contact resistance between the soil sample and the electrode is caused by the shrinkage resistance between the electrode and the soil sample and the oxide film resistance on the electrode surface [16, 17]. López-Sánchez et al. believed that, in the two-electrode method, it is impossible to separate the resistance from the contact resistance [18].

Bai et al. considered the influence of the contact resistance on the conductivity of samples in the process of studying the conductivity of compacted red clay with the two-electrode method [4]. When studying the resistivity characteristics of sand, Bing-hui et al. [19] studied the contact resistance of sand samples with different densities and water contents by using the two-electrode method and considered that the contact resistance and saturation were power functions. The results showed that the pore ratio had little influence on the contact resistance of saturated sand. Mi et al. [20] studied the resistivity characteristics of different soils by using the four-electrode and two-electrode methods. They believed that there was contact resistance between the electrodes and the soil in the two-electrode method. The study showed that the soil resistivity measured with the two-electrode method included the contact resistance, which led to the measurement results being too large. Xiao-qiang et al. [21] considered the influence of the contact resistance in the process of studying the change in cement soil resistivity under NaOH pollution and corrected the cement soil resistivity. The above scholars only considered the influence of the contact resistance in the research process and did not systematically study the influencing factors of the contact resistance.

The resistance of soil can be measured by either direct current (DC) or alternating current (AC) [22]. When using AC to test the soil resistance, the frequency of the AC signal had an impact on the test results. Different scholars chose different frequencies. Abu-Hassanein et al. [23] selected a frequency of 60 Hz, which is the frequency of the United States power grid and considered that this frequency could avoid the influence of the excitation on the electrical characteristics of the soil. Arulanandan [24] noted that the dielectric constant of soil at a high frequency is only a function of porosity, orientation, and particle shape; thus, the high frequency of 50 MHz can be used to analyse the soil resistivity and porosity of saturated soil.

Fukue et al. chose a frequency of 1000 Hz to measure the resistivity of clay and to study its microstructure [5]. However, most scholars in China adopt a power grid frequency of 50 Hz [8, 19, 21, 25]. There are differences in the resistance measurement results of soil samples with different test frequencies. At present, there are relatively few studies with regard to the influence of test frequencies on soil resistance and contact resistance.

To explore the effects of the particle size, saturation, relative density, and current frequency of calcareous sand on the electrical resistance and contact resistance of calcareous sand samples, a series of electrical resistance tests was carried out on calcareous sand samples taken from an island and reef in the South China Sea. The effects of the particle size, relative density, saturation, and current frequency on the electrical resistance and contact resistance of calcareous sand samples were expounded, and the relationship curve between the current frequency, saturation, and contact resistance was established.

2. Test Process

2.1. Calcareous Sand for Test. The calcareous sand used in this test is taken from an island and reef in the South China Sea. The calcareous sand sample was dried, and a vibrator sieve shaker was used to sieve the dried calcareous sand. The follow-up tests are carried out using the obtained particle sizes of 1-1.5 mm, 1.5-2 mm, and 2-2.5 mm, as shown in Figure 1. Table 1 shows the basic physical characteristic parameters of calcareous sands with three particle sizes. Electron microscope scanning tests were carried out on calcareous sand particles with three particle sizes. The scanning results are shown in Figure 2.

2.2. Test Principle and Instrument. Through the resistance test of the same sample with the same section and different electrode spacing, the test resistance is linearly fitted, and the intercept of the fitting line is the contact resistance. The test electrode is an inert copper sheet, which does not easily corrode [26]. The test principle is shown in Figure 3(a). The resistance $R\,(\Omega)$ of the sample can be calculated with Ohm's law:

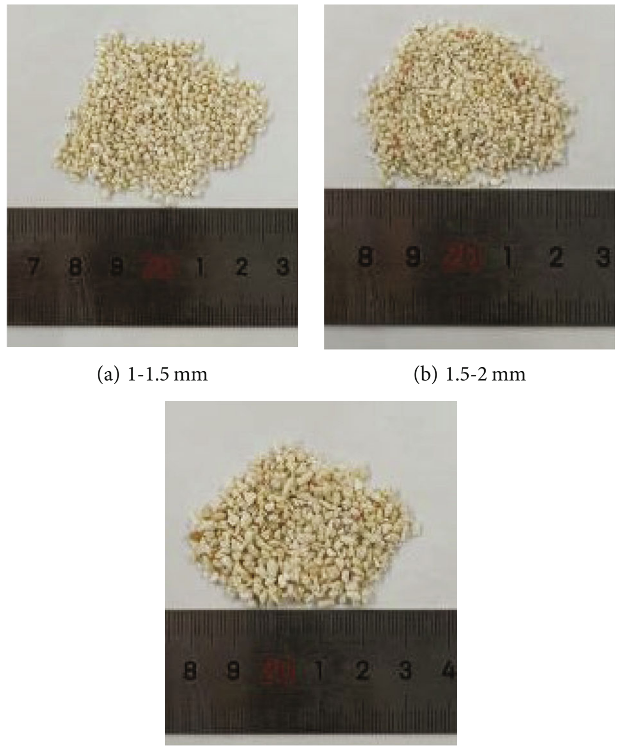
$$R = \frac{U}{I}, \tag{1}$$

where U is the voltage (V) and I is the current (A).

In this paper, an Anbai LCR (capacitance inductance resistance) digital bridge, which is a two-electrode AC testing instrument, is used to test the resistance of calcareous sand to study the contact resistance of calcareous sand samples. The equipment adopts a high-performance 32-bit ARM microprocessor controlled micro desktop instrument for full-automatic real-time monitoring. The instrument can select any test frequency between 10 Hz and 300 kHz and can select a test signal level between 0.01 V and 2 V in steps of 0.01 V. The resistance test accuracy reaches 0.05%. Moreover, the test instrument is shown in Figure 3(b).

2.3. Test Scheme. To study the influence of the particle size, relative density, saturation, and current frequency of calcareous sand on the contact resistance of calcareous sand and explore the law, a series of resistance tests of calcareous sand was carried out in this paper. To calculate the contact resistance, sample boxes with different electrode spacings need to be made, and calcareous sand under different conditions needs to be place into the sample boxes for the resistance test. The cross section of the sample box is the same, 6 cm (high) × 5 cm (width), and the electrode spacing L is 5 cm, 10 cm, 15 cm, and 20 cm, as shown in Figure 4.

In this paper, samples of calcareous sand with particle sizes of 1-1.5 mm, 1.5-2 mm, and 2-2.5 mm are selected as the soil to be tested. The relative densities are $D_r = 0.3$, 0.6, and 0.9, and the saturations are $S_r = 20\%$, 40%, 60%, 80%, and 100%, respectively. According to formulas (2)-(4), the



(a) 1-1.5 mm (b) 1.5-2 mm

(c) 2-2.5 mm

Figure 1: Calcareous sand with three particle sizes.

Table 1: Physical properties of calcareous sand.

Particle size (mm)	Specific gravity G_s	Maximum dry density (g·cm^{-3})	Minimum dry density (g·cm^{-3})
1-1.5	2.74	1.35	1.15
1.5-2	2.73	1.33	1.13
2-2.5	2.71	1.30	1.11

water contents of the calcareous sand samples with three particle sizes at different saturations are calculated.

$$S_r = \frac{G_s \cdot w}{e}, \tag{2}$$

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}}, \tag{3}$$

$$w = \frac{S_r \cdot e_{\max} \cdot D_r \cdot (e_{\max} - e_{\min})}{G_s}, \tag{4}$$

where S_r is the saturation of the sample, G_s is the specific gravity of the calcareous sand particles, ρ_d is the dry density of the sample, e is the void ratio of the sample, $e_{\max}$ is the maximum porosity ratio of the sample, $e_{\min}$ is the minimum porosity ratio of the sample, D_r is the relative density, and w is the water content (%).These parameters are dimensionless numbers.

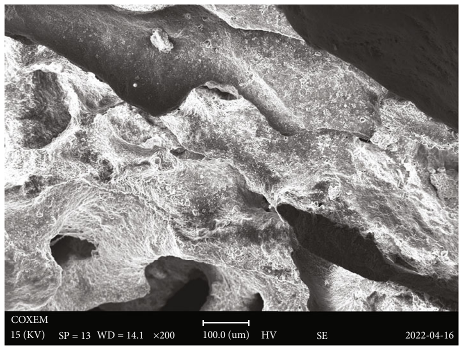
To study the influence of the current frequency on the contact resistance of calcareous sand, the current frequency f is selected to be 50 Hz, 100 Hz, 200 Hz, 400 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Regarding the frequency influence, samples with different particle sizes and different saturations are first made with a relative density of $D_r = 0.6$. Then, the resistance of the sample is tested when the current frequency is $f = 50$ Hz, the frequency is gradually increased, and the resistance of the sample is tested at different frequencies. According to the test conditions, a total of 60 groups of test conditions are carried out, and three parallel tests are carried out for each group of tests at the same time. The test results are taken as the average value of the three groups of tests. The specific test scheme is shown in Table 2 (only the test scheme with an electrode spacing of 5 cm and particle size of 1-1.5 mm is given).

2.4. Test Method

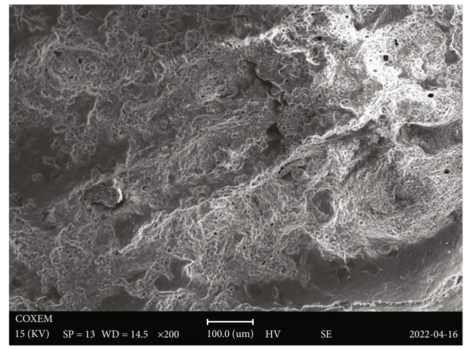
(1) To wash away the surface salt, tap water is used to repeatedly clean the samples of calcareous sand with three particle sizes

(2) Then, the samples were placed into an oven at 105°C and dried for at least 8 hours. After the samples were dried, they were removed to a bag for standby cooling

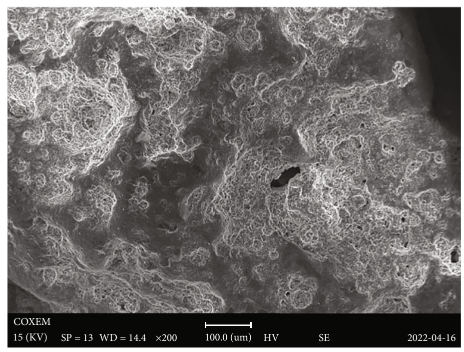
(3) A sieve shaker was used to vibrate the samples for 10 min to obtain three kinds of calcareous sands with particle sizes of 1-1.5 mm, 1.5-2 mm, and 2-2.5 mm. Then, the samples were packed for standby



(a) 2-2.5 mm

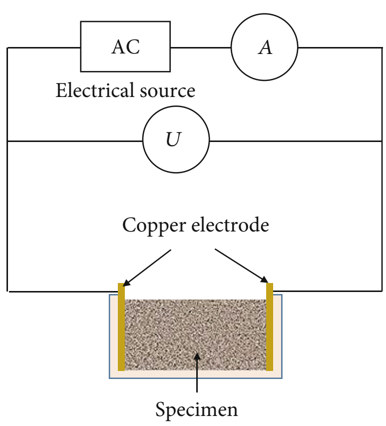


(b) 1.5-2 mm



(c) 1-1.5 mm

Figure 2: Scanning test results of three kinds of calcareous sands by electron microscopy (200 times).



(a) Test principle

(b) Instrument

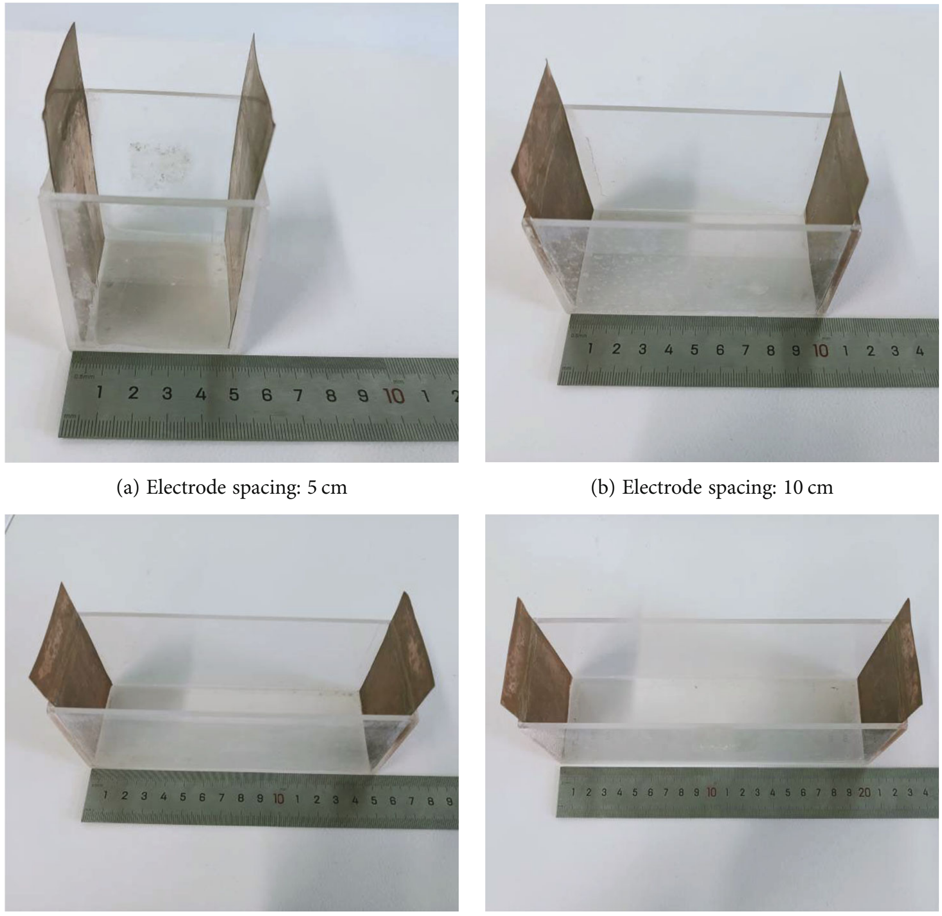
Figure 3: Test principle and instrument.

(4) The calcareous sand and water of a certain quality are measured according to the test scheme. Then, the samples were evenly mixed, placed into sealed bags, and left to standby for 24 h

(5) The sample was placed into the sample box, the electrodes were connected at both ends of the sample to the digital bridge, and the resistance value was obtained. The data reading is completed within seconds. According to the research results of Bing-hui et al. [19], the influence of the early electrification of the sample is negligible. At the same time, the indoor temperature is controlled within $20 \pm 2^{\circ}C$ to prevent the influence of temperature on the test results [4, 27]

3. Results and Discussion

3.1. Calculation Method of the Contact Resistance of Calcareous Sand. Regarding the two-electrode method, the contact resistance between the sand sample and the electrode is caused by the shrinkage resistance between the



(a) Electrode spacing: 5 cm

(b) Electrode spacing: 10 cm

(c) Electrode spacing: 15 cm

(d) Electrode spacing: 20 cm

Figure 4: Sample boxes with different electrode spacings.

Table 2: Contact resistance test scheme with an electrode spacing of 5 cm (1-1.5 mm).

Particle size (mm)	Relative density D_r	Saturation S_r (%)	Mass of calcareous sand m (g)	Water content w (%)
		20		9.3
		40		18.6
	0.3	60	180.52	28.0
		80		37.3
		100		46.6
		20		8.5
		40		17.1
1-1.5	0.6	60	189.33	25.6
		80		34.2
		100		42.7
		20		7.8
		40		15.5
	0.9	60	199.04	23.3
		80		31.1
		100		38.9

electrode and the soil sample and the resistance of the oxide film on the electrode surface. By testing the resistances of the samples with the same section and different lengths, the test results are linearly fitted, and the intercept of the fitting line is the contact resistance. Figure 5 shows the relationship between the sample resistance and the electrode spacing

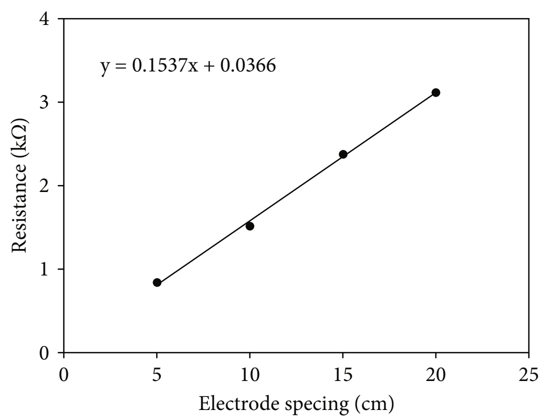


Figure 5: Contact resistance test results of calcareous sand ($D_r = 0.6$, $S_r = 100\%$, and 1-1.5 mm).

when the relative density is $D_r = 0.6$, the saturation is $S_r = 100\%$, and the particle size is 1-1.5 mm. According to the fitting result shown in the figure, the contact resistance under this condition can be obtained to be 0.0366 kΩ. The contact resistance calculation method under other conditions is the same as above.

3.2. Influence of the Particle Size on the Contact Resistance of Calcareous Sand. To study the influence of the particle size of calcareous sand on the contact resistance, a series of tests was carried out in this paper. The test conditions were as follows: the saturation was 20%~100%, the current frequency was 1000 Hz, the relative density was 0.6, the electrode spacing was 5 cm~20 cm, and the particle sizes were 1-1.5 mm, 1.5-2 mm, and 2-2.5 mm. The above test conditions were used to test the resistance of the calcareous sand sample.

To study the effect of the particle sizes on the contact resistance between calcareous sand and the electrodes, the curves between the contact resistance with different particle sizes under different saturation conditions are drawn, as shown in Figure 6. Taking the sample with a saturation of 0.4 as an example, the resistance under different particle sizes is shown in Table 3. With increasing particle sizes, the contact resistance of calcareous sand increases gradually.

Compared with the contact resistance of calcareous sand with particle sizes of 1-1.5 mm, the contact resistance of calcareous sand with particle sizes of 1-1.5 mm increases by 17.9%. Compared with the contact resistance of calcareous sand with particle sizes of 1.5-2 mm, the contact resistance of calcareous sand with particle sizes of 2-2.5 mm increases by 35.3%, and the contact resistance of calcareous sand with particle sizes of 2-2.5 mm further increases. This is because the larger the particle size is, the less the contact between the calcareous sand and the electrode, resulting in an increase in the contact resistance.

3.3. Influence of the Relative Density on the Contact Resistance of Calcareous Sand. To study the influence of the relative density of the calcareous sand sample on the contact resistance, a series of tests was carried out in this paper. The test conditions were as follows: the saturation was 20%~100%; the AC frequency was 1000 Hz; the relative density was 0.3, 0.6, and 0.9; the electrode spacing was 5 cm~20 cm; and the particle size was 1.5-2 mm. The above test conditions were used to test the resistance of the calcareous sand sample.

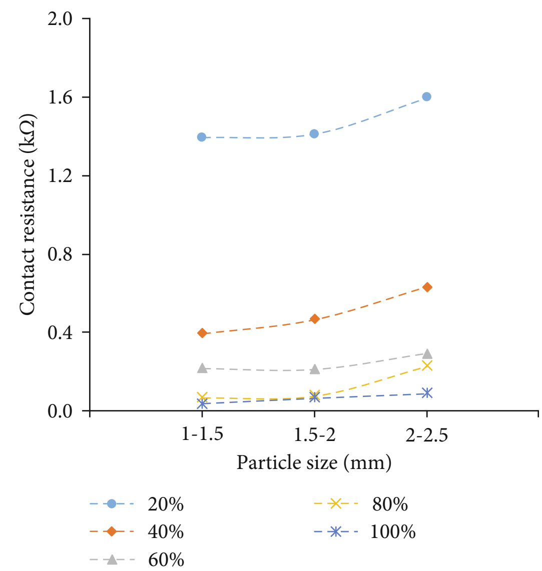


Figure 6: Relationship between the particle size of calcareous sand and the contact resistance.

Table 3: Particle size and resistivity data with saturation of 0.4.

Particle size (mm)	The contact resistances (kΩ)
1-1.5	0.3962
1.5-2	0.4673
2-2.5	0.6324

To study the influence of the relative density on the contact resistance of the sample, the relationship curve between relative density and contact resistance under different saturation conditions is drawn, as shown in Figure 7. Regarding the sample with a saturation of $S_r = 20\%$, the contact resistances corresponding to the relative densities of $D_r = 0.3$, 0.6, and 0.9 are 1.39 kΩ, 1.41 kΩ, and 2.00 kΩ, respectively. The contact resistance gradually increases with an increasing relative density. The initial resistances of the samples under other saturation conditions also increase with an increasing relative density, but the increase decreases with an increasing saturation. The specific reasons are explained as follows: regarding samples of the same gradation, the void ratio gradually decreases with an increasing relative density. Under the same saturation (i.e., the same water content), the proportion of the particles in the sample of the electrode contact part is larger, and the contact resistance is larger.

3.4. Influence of the Current Frequency on the Contact Resistance of Calcareous Sand. To study the influence of the saturation of the calcareous sand sample on the contact resistance, a series of tests was carried out in this paper.

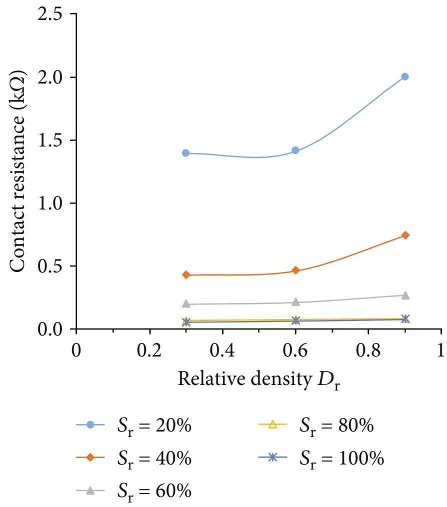


FIGURE 7: Relationship between the relative density and contact resistance.

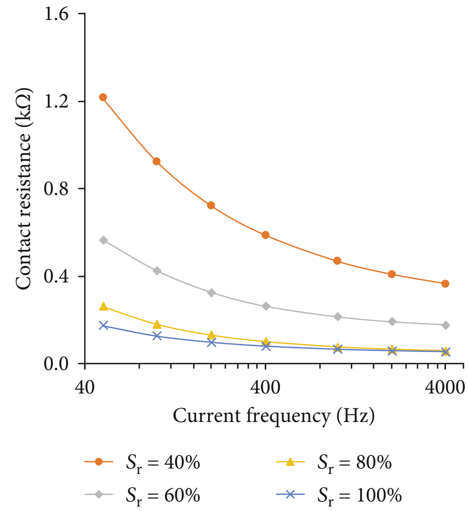


FIGURE 8: Relationship between the contact resistance of calcareous sand with different saturations and current frequencies.

The test conditions were as follows: the saturation was 40%~100%, the current frequency was 50~4000 Hz, the relative density was 0.6, the electrode spacing was 5 cm-20 cm, and the particle size was 1.5-2 mm. The above test conditions were used to test the resistance of the calcareous sand sample.

Figure 8 shows the relationship between the contact resistance and current frequency of calcareous sands with different saturations. It can be seen from the figure that when the saturation is 40%, the contact resistance decreases from 1.21 kΩ to 0.36 kΩ in the process of increasing the current frequency from 50 Hz to 4000 Hz. When the saturation is 100%, the contact resistance decreases from 0.18 kΩ to 0.054 kΩ when the current frequency increases from 50 Hz to 4000 Hz. Under the same saturation conditions, the contact resistance decreases with an increasing current frequency. With an increasing saturation, the influence of the current frequency on the contact resistance decreases. In the process of the soil resistance test with two electrodes, a higher current frequency should be selected to reduce the influence of the contact resistance.

According to the relationship shown in Figure 8, the relationship between the contact resistance and the current frequency can be approximately expressed as a power function relationship:

$$R^* = m\left(\frac{f}{f_{\max}}\right)^{-n}, \quad (5)$$

where R^* is the contact resistance, f is the current frequency, $f_{\max}$ is the maximum current frequency of 4000 Hz, and m and n are the fitting coefficients. Moreover, the fitting results are shown in Table 4.

TABLE 4: Fitting coefficient in formula (5).

Saturation S_r (%)	m	n	R^2
40	0.3359	0.273	0.9789
60	0.1584	0.264	0.9582
80	0.0521	0.335	0.9650
100	0.0486	0.262	0.9524

3.5. Influence of the Saturation on the Contact Resistance of Calcareous Sand. To study the influence of the saturation of the calcareous sand sample on the contact resistance, a series of tests was carried out in this paper. The test

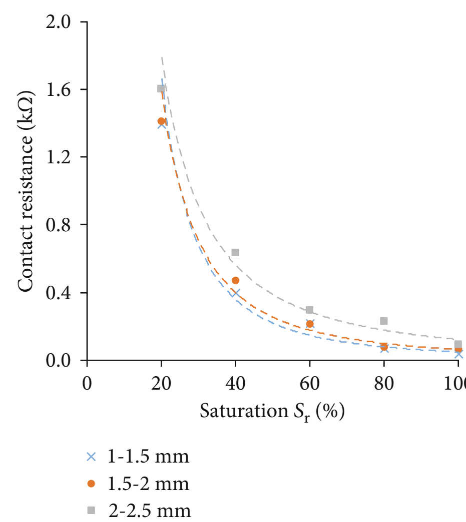


FIGURE 9: Relationship between the saturation of calcareous sand and the contact resistance (D_r = 0.6).

TABLE 5: Fitting coefficient in formula (6).

Particle size (mm)	a	b	R^2
1-1.5	1317.3	2.228	0.966
1.5-2	624.7	1.995	0.9781
2-2.5	267.6	1.672	0.9612

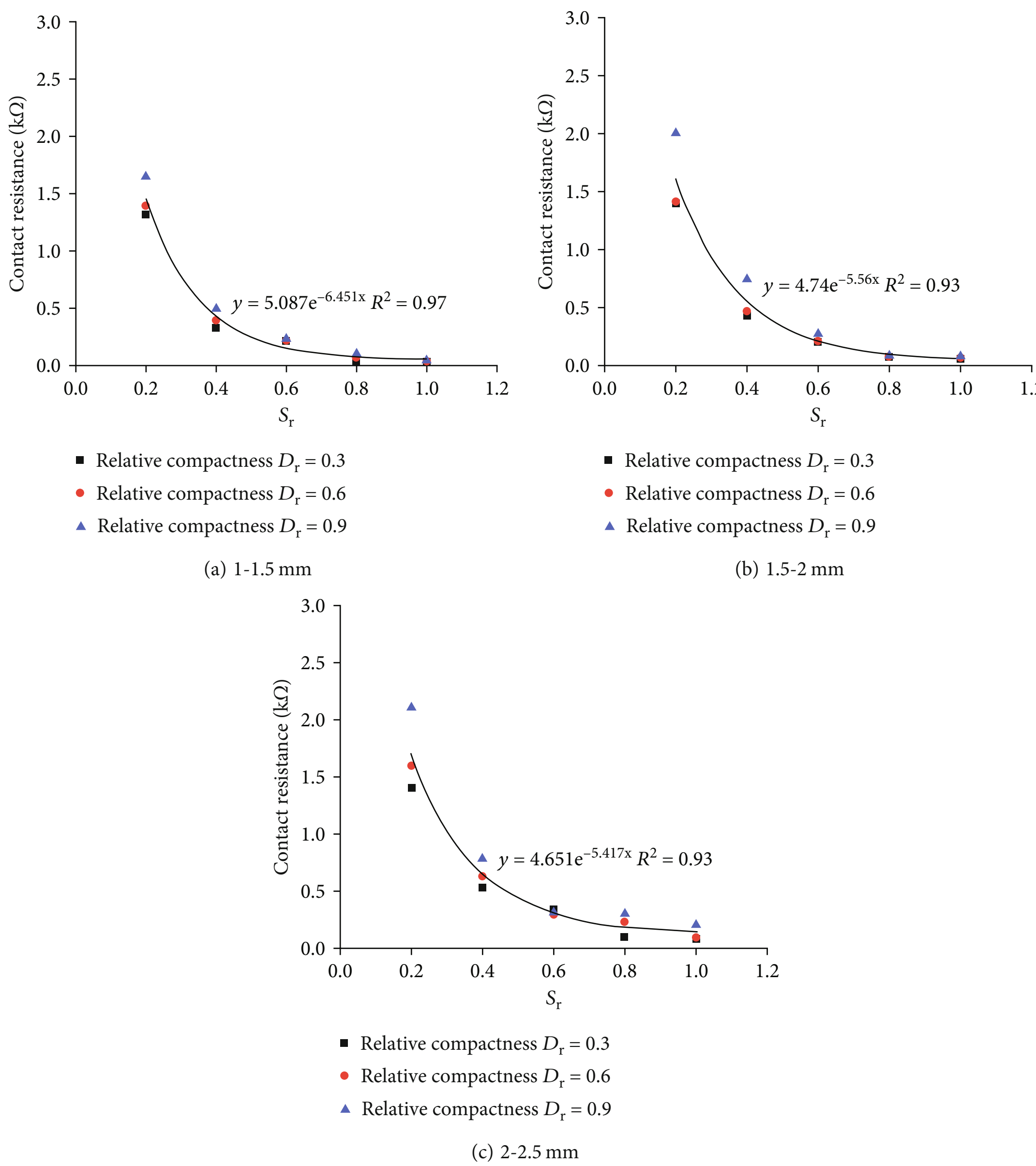


Figure 10: Relationship between the contact resistance and saturation of calcareous sand with a single particle size.

conditions were as follows: the saturation was 20%~100%, the current frequency was 1000 Hz, the relative density was 0.6, the electrode spacing was 5 cm-20 cm, and the particle sizes were 1-1.5 mm, 1.5-2 mm, and 2-2.5 mm. The above test conditions were used to test the resistance of the calcareous sand sample.

Figure 9 shows the relationship between the saturation and contact resistance of calcareous sands with different particle sizes when the relative density is 0.6. According to the test results, the contact resistance of calcareous sand decreases gradually with an increasing saturation and finally tends to stability. When the water content is small (i.e., the saturation is low), there is pore water and pore gas between the calcareous sand particles, and the pore gas accounts for a large proportion. At this time, the contact degree between the calcareous sand sample and the copper electrode is poor, and the contact resistance is large. With an increasing water content (i.e., saturation), the proportion of pore gas between calcareous sand particles decreases greatly. At this time, the contact degree between the calcareous sand sample and copper electrode increases, and the contact resistance of calcareous sand decreases. When the soil sample is close to saturation, the influence of the pore gas on the contact degree between the calcareous sand sample and the copper electrode can be almost ignored, and the contact resistance tends to stability.

According to the above analysis, the power function can be used to fit the relationship between the contact resistance and saturation. Table 5 provides the fitting results.

$$R^* = ae^{-bS_r}, \tag{6}$$

Table 6: Fitting relationship between the contact resistance and saturation of calcareous sand with a single particle size.

Particle size (mm)	The contact resistance	R^2
1-1.5	$R^* = 5.087e^{-6.451S_r}$	0.97
1.5-2	$R^* = 4.74e^{-5.56S_r}$	0.93
2-2.5	$R^* = 4.651e^{-5.417S_r}$	0.93

where R^* is the contact resistance, S_r is the saturation, and a and b are the fitting coefficients.

The coefficient a reflects the soil composition and determines the type and quantity of charged ions; moreover, the coefficient b reflects the sensitivity of the contact resistance to the saturation change [28]. The larger the value of b is, the stronger the contact resistance change and the steeper the relationship. The notable disparity in the value of a highlights that particle size plays a significant role in the electrical resistance of sand samples, even when comparing samples of the same sand. As the value of a increases and the curve shifts upwards, the contact resistance at each saturation level will correspondingly increase. The difference in the b value is small, which indicates that the change in the contact resistance is similar and the relationship curve is gentler. The contact resistances of other relative density samples also display similar characteristics.

The relationship between the contact resistance and saturation of samples with the same particle size and different relative densities is plotted on the same coordinate axis, as shown in Figure 10.

It can be seen from Figure 10 that there is a certain correlation between the contact resistance between the electrodes in calcareous sand with a single particle size and the saturation, which decreases with an increasing saturation in general. Moreover, a power function attenuation trend is shown. The fitting coefficients are all greater than 0.93, but the dispersion degree is also significantly reduced. Table 6 provides the fitting results.

According to the above analysis, in the process of measuring the resistivity of calcareous sand with the two-electrode method, the contact resistance needs to be measured first, and then, the contact resistance is used to correct the test results to improve the accuracy of the test results, especially for samples with low saturations.

4. Conclusion

In this paper, the particle size, relative density, current frequency, and saturation are studied with the two-electrode method, and the contact resistance between the calcareous sand sample and electrode is systematically studied. The main conclusions are as follows:

(1) Since the contact degree between the calcareous sand and the electrode decreases with an increasing particle size, the contact resistance of the calcareous sand gradually increases with an increasing particle size

(2) The contact resistance of calcareous sand samples increases with an increasing relative density, but the rate of increase gradually decreases as the saturation level increases

(3) Under the same saturation conditions, the contact resistance decreases with an increasing current frequency. Regarding the soil resistance test with two electrodes, a higher current frequency should be selected to reduce the influence of the contact resistance. The relationship between the contact resistance and current frequency is established with a power function

(4) The contact resistance of calcareous sand decreases gradually with an increasing saturation and finally tends to stability. When the sand sample approaches saturation, the influence of the contact resistance on the sample resistance can be ignored. The power function is used to fit the relationship between the contact resistance and saturation

Data Availability

The data are generated from experiments and can be available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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