Experimental Study on Resistivity Characteristics of Compacted Loess

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Abstract. In order to study the resistivity characteristics of compacted loess, the resistivity values of 36 groups of samples were measured under six different dry densities. It was found that there was a good exponential relationship between resistivity \( \rho \) and water content \( w \). At the same time, the SWCC and Fredlund curve equation of soil water in the process of soil moisture increasing are obtained by using the self-designed loess moisture increasing and decreasing device. The results show that, for compacted loess, the resistivity and suction \( \psi \) of soil are closely related to its water content. By comparing the \( \rho-w \) curve and SWCC, it is found that the relationship between soil resistivity and suction satisfies the expression \( \psi = u \cdot \rho^\lambda \), \( u, \lambda \) are fitting coefficients. The formula shows that the suction value can be obtained indirectly by measuring the soil resistivity, which avoids the difficulty of suction test and has good applicability.

Keywords. Compacted Loess, Resistivity, Moisture Content, Matric Suction.

1. Introduction

Soil resistivity is the basic parameter to characterize its conductivity, which belongs to the inherent physical properties of soil [1]. It is mainly related to the water content, saturation, porosity, material composition, and pore water solution of soil. Changing any of these factors will make the resistivity change greatly. At present, it is a relatively continuous, fast and economical geophysical testing method to study the soil properties by measuring the resistivity.

Many scholars have carried out a lot of relevant research. Zha [2] tested the compacted loess in Xi’an by the development of ESEU-1 resistivity tester, systematically studied the relationship between water content, pore fluid chemical composition, saturation and temperature, and resistivity. Feng et al. [3] introduced VDP method into the test of unsaturated soil, verified the sensitivity factors in the test of soil resistivity. Cai [4] used static cone penetration method to test the resistivity of Jiangsu marine clay, analyzed the correlation between the resistivity of marine clay and basic soil parameters and mechanical indexes. Among them, the moisture content of the soil is one of the most important indexes [5].

For the typical unsaturated soil, such as loess, its properties are very complex, so it is of great significance to study its suction. The curve of characteristic of soil and water (SWCC) is an important link in this study, which represents the relationship between matric suction and volume water content [6]. Chen et al. [7] take the residual sandy cohesive soil in Xiamen area, China, as the research object, finally get the SWCC correction model applicable to the residual soil. Lu Jing et al. [8] tested the soil-water characteristics of loess under different temperatures and density conditions by using a high-speed centrifuge method and obtained that the soil-water characteristic curve conforms to the power
function expression. Based on this, a fitting formula of soil water characteristics considering these two factors is proposed. For example, Qi [9] summarized the soil water characteristic models of different soils into four main types and obtained that all soil water characteristic models can be expressed by power function polynomial form of mathematical model.

It can be seen that, for the soil mass, whether it is the inherent physical property parameter resistivity or the important factor affecting the unsaturated characteristic matric suction, there is a close relationship with the water content of the soil mass itself [10]. The relationship between the resistivity of the soil mass and the soil-water characteristic curve can be obtained by testing the resistivity of the soil mass and the soil-water characteristic curve, in order to obtain a more concise and rapid method to study the unsaturated characteristics of the soil. Based on this, in this paper, we use the compacted loess in Yan'an to remodel the soil sample, test the resistivity, moisture content and matric suction value of the soil, and discuss the method of using the resistivity to predict the suction of the soil, so as to avoid the drawback of the difficulty of suction measurement.

2. Text Methods

2.1. Test Soil
The compacted loess used in the test is mainly Q2 loess from Yan'an new area. The natural water content is about 26%, the maximum dry density of light compaction is 1.69 g/cm³, the optimum water content is 14.11%, the plastic limit w_p is 16.1, the liquid limit w_L is 28.9, and the plastic index I_p is 12.8. The particle size accumulation curve of the soil sample is shown in figure 1.

![Figure 1. Cumulative curve of soil sample size.](image)

3. Test Plan and Steps

3.1. Resistivity Test
The cylinder samples with the dry density of 1.35, 1.45, 1.50, 1.55, 1.60 and 1.65 g/cm³, the height of 20 mm and the diameter of 61.8 mm were prepared. Under the same dry density, five samples with its water content of 10%, 13%, 16%, 19%, 22%, and saturated state were prepared respectively. During the preparation of samples, soil samples with the moisture content of 10% are prepared first, and other moisture contents are prepared by the water film transfer method. Use T2810D LCR digital bridge V2.0 (as shown in figure 2) to test the impedance value of each sample. During the test, connect the test fixture with the wire connected with the copper electrode piece. And ensure that the copper electrode piece is in close contact with the surface of the soil sample, then read the stable data. This test was carried out in the laboratory for a short time with little temperature change, so no temperature correction was made during the test. Soil resistivity \( \rho \) is:
$$\rho = \frac{RS}{L}$$

(1)

Figure 2. TH2810D LCR digital bridge V2.0.

R-impedance value (Ω); S-cross section area of the sample (m$^2$); L-length of sample (m) (it’s 0.02 m in this paper).

Figure 3. Schematic diagram of resistivity test [11].

3.2. Soil Water Characteristic Curve Test

The self-designed loess moisture increasing and decreasing device (figure 4) is used for the test. The specific structure is similar to that of reference [12], the difference is that the device in this paper has only one layer of the cylinder body, with a height of 25 cm and a diameter of 30 cm. There are two relative holes 3 cm away from the copper-based on the cylinder wall, with a diameter of 1.2 cm. During the test, first, weigh the prepared soil sample with a certain quality, the initial moisture content is 10%, put it into the loess humidification device, and use the loess compression collapsible device, which applies pressure through the air pump, as shown in figure 4. The soil is compacted layer by layer, and the dry density of the soil column is 1.55 g / cm$^3$ and 1.65 g / cm$^3$ respectively, with a height of 6 cm. A pair of soil moisture and water potential sensors are placed in the hole position of the device to monitor the change of soil moisture and suction in real-time.

After the soil column is pressed, the device is sealed, and the reading of the sensor is stable, about 3D. Then put a layer of geotextile on the surface of the soil column, keep a certain head of water in the device and slowly soak it until the bottom of the device stops flowing water, at this time, the soil has reached the saturation state. Through the monitoring data of sensors, the change of soil water characteristics is analyzed.
4. Results, Analysis and Discussion

4.1. Analysis of the Relationship Between Resistivity and Water Content

According to the data measured during the test (table 1), the relationship curve between soil resistivity and water content under different dry density is obtained (figure 5).

Table 1. Soil resistivity test data.

| w/%  | ρ/ρd (g·cm⁻³) | 1.35  | 1.45  | 1.50  | 1.55  | 1.60  | 1.65  |
|------|---------------|-------|-------|-------|-------|-------|-------|
| 10   | 2619.422      | 3163.854 | 2039.594 | 2842.249 | 1559.355 | 1855.567 |
| 13   | 943.922       | 1092.568 | 1584.551 | 1276.715 | 752.021  | 1041.215 |
| 16   | 797.225       | 604.169  | 866.996  | 747.746  | 571.068  | 499.257  |
| 19   | 703.082       | 696.378  | 753.251  | 910.431  | 246.434  | 412.463  |
| 22   | 585.107       | 450.199  | 524.634  | 633.506  | 298.043  | 93.336   |
| Saturation | 45.513 | 43.709  | 39.121  | 43.283  | 38.016  | 43.853   |

It can be seen that under the same dry density, with the increase of water content, in turn, the soil resistivity shows a decreasing trend. In the process of resistivity decreasing, the water content is small, and the resistivity decreases rapidly. When the water content reaches a certain value, the decreasing rate becomes slow. The reasons for the above phenomena are as follows: 1) the surface of soil particles has a diffusion double electric layer formed by the absorbed charge. In the process of increasing water content, the absorbed charge will be released continuously, resulting in the thickness of the double electric layer on the surface of soil particles, so that the conductivity of the soil surface increases, and the resistivity decreases [13]; 2) when the water content in soil increases, the connectivity of pore water increases rapidly. The electrical conductivity becomes stronger, so the resistivity decreases rapidly. When the water content increases to a certain extent, the connectivity of pore water has reached a relatively ideal state, so the resistivity changes slowly [14].
Figure 5. The relation curve between soil resistivity and water content.

As can be seen from the figure, $\rho - w$ curve can be fitted to get the following expression:

$$\rho = k \cdot w^m$$  \hspace{1cm} (2)

$\rho$ - soil resistivity (Ω·m); $k$, $m$ - fitting parameters; $w$ - soil moisture content.

The fitting results show that the above expression can better characterize the functional relationship between soil resistivity and water content.

4.2. Analysis of Soil-Water Characteristic Curve

The soil-water characteristic curve is the relation curve between the soil volume moisture content ($\theta$) and the matrix suction ($\psi$). In this paper, the soil column with the dry density of 1.55 g/cm$^3$ and 1.65 g/cm$^3$ is pressed by the self-designed loess moisture increasing and decreasing device to test the matrix suction and volume moisture content of the soil. The final soil water characteristic test results of each dry density soil column are shown in figure 6.

Figure 6. SWCC.

At present, there are many fitting functions of SWCC curves, such as van Genuchten [15], Fredlund [16], etc. in this paper, Fredlund curve equation is used, and the fitting coefficients are all above 0.98, which can achieve good results.

$$\theta = C(\psi) \cdot \frac{\theta_s}{\ln[\epsilon + (\psi / a)^{n}]}$$  \hspace{1cm} (3)

$m$, $n$-fitting parameters; $a$-parameters related to intake value; $\theta_s$-saturated volume moisture content; $\psi$ - matrix suction (kPa); $\psi_r$-residual matrix suction (kPa), generally 1500 - 3000 kPa, taken as 3000 kPa; $\theta$ - Volume moisture content.

4.3. Relationship Between Matrix Suction and Resistivity

According to the above discussion, there is a relationship between soil moisture content, resistivity, and matrix suction, so there must be a certain relationship between suction and resistivity. According to the relationship between resistivity $\rho$ and water content $w$, we can get the relationship between
resistivity $\rho$ and volume water content $\theta$ under the dry density of 1.55 g/cm$^3$ and 1.65 g/cm$^3$. Because:

$$\theta = \frac{w \cdot \rho_d}{\rho_w}$$  \hspace{1cm} (4)

$\rho_d$-dry density (g/cm$^3$); $\rho_w$-pore water density, generally 1.0 g/cm$^3$.

Then the relationship of $\rho - \theta$ is shown in figure 7.

![Figure 7. $\rho - \theta$ relation curve.](image)

It can be seen that the resistivity of the soil decreases with the increase of the volume moisture content, which is consistent with the law of the change of the moisture content and the resistivity, and meets the expression:

$$\rho = A \cdot \theta^B$$  \hspace{1cm} (5)

A and B are fitting coefficients.

For the same dry density soil, the increasing process of its water content is realized by the water film transfer method, which is the same as the test method of suction. The water content changes, and the suction changes with the wetting. According to the above test results, select the soil moisture content from the SWCC curve to obtain the suction value of the soil under the determined moisture content (table 2).

| $\rho_d$(g·cm$^{-3}$) | w/% | $\theta$ | $\psi$/kPa | $\rho_d$/((g·cm$^{-3}$) | w/% | $\theta$ | $\psi$/kPa |
|----------------------|-----|---------|-------------|------------------|-----|---------|-------------|
| 1.55                 | 10  | 0.1550  | 286.8       | 10               | 0.1650 | 415.2 |
|                      | 13  | 0.2015  | 71.9        | 13               | 0.2145 | 241.5 |
|                      | 16  | 0.2480  | 17.8        | 1.65             | 16   | 0.2640  | 71.6       |
|                      | 19  | 0.2945  | 11.7        | 19               | 0.3135 | 36.1 |
|                      | 22  | 0.3410  | 11.6        | 22               | 0.3630 | 20.6 |
|                      | Saturation | 0.4259 | 11.6        | Saturation       | 0.3887 | 14.5 |

Combined with the test data in table 1, the corresponding relationship between the soil suction and its resistivity under the determined water content can be obtained, as shown in figure 12.
It can be seen that the change rule of suction and resistivity is different with different dry density. For 1.55 g/cm³ soil sample, when the suction is 11.6 - 17.8 kPa, the change rate of suction with resistivity is slow; when the suction is greater than 17.8 kPa, the suction changes rapidly with resistivity. The suction of 1.65 g/cm³ soil sample increases with the increase of resistivity, and the increasing trend of 1.65 dry density soil sample is stronger. The reason is that when the dry density is small, the pores in the soil sample are large, and the saturation time is longer, so the change of resistivity is the same. When the dry density is small, the change of volume moisture content is relatively small, and its influence on resistivity is also small, so the change trend of \( \psi - \rho \) relation curve of 1.55 g/cm³ tends to be weaker than that of 1.65 g/cm³. It can be seen from the figure that \( \psi - \rho \) obeys the following relation:

\[
\psi = u \cdot \rho^\lambda
\]

(6)

\( u \) and \( \lambda \) are fitting coefficients.

In order to verify the applicability of the expression, the suction value calculated by the formula is compared with the data obtained by the test, and the result is shown in figure 13.

It can be seen that the formula has good applicability for different dry densities of soil, and can well verify the relationship between suction and resistivity. In the research field of unsaturated soil, the measurement of matric suction is usually difficult, and different test methods often get different results, which affects the accuracy of the research results. Using the above expression, the soil suction value can be obtained indirectly through the method of measuring the soil resistivity, which avoids the related test problems and is simple and easy.

5. Conclusion
The SWCC curve of compacted loess is tested by using the self-designed device for increasing and decreasing the moisture content of loess, and the resistivity of soil samples with moisture content increasing from 10% to saturated state under six different dry densities is tested by using TH2810D LCR digital bridge V2.0. It is found that for the soil, whether the matric suction or resistivity is large or small, it is closely related to the moisture content of the soil itself. Through the experimental study, the function expression of soil resistivity and water content is obtained, and then the suction value under specific water content is obtained from the SWCC curve. The relationship between soil resistivity and suction is compared, which can provide a simple and easy indirect method to measure suction and avoid the difficulty of suction measurement in the study.

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