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Effect of Water Content and Dry Density on Electrical Resistivity of Granite Residual Soils of Taishan Section, Guangdong, China

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Abstract

Electrical resistivity method is rapid, non-destructive and a very attractive tool for describing the geotechnical properties of soil. The main objective of this research is to evaluate the influence of water content and dry density on the electrical resistivity for different densities compacted granite residual soils collected from Taishan section, Guangdong, China based on laboratory experiments. The results show that the resistivity value decreases with increasing dry density and water content, and tends to constant at higher values. The variations of electrical resistivity due to dry density are more pronounced at low water content but negligible for higher water contents. The water content is found to have more significant effect on electrical resistivity than dry density. Based on regression analysis, a mathematical model is also proposed to show the combined influence of water content and dry density i.e., volumetric water content on the electrical resistivity of the studied soils. The proposed model is well agreement with the experimental data and capable of capturing some intrinsic hydraulic behavior of fine grained soils and might be used for practical purposes.

Keywords: Electrical resistivity, dry density, water content, granite residual soil, RWCC.

1. Introduction

Electrical resistivity is an intrinsic physical property of a material and the measure of it's resistance to the passage of current through it. It can be considered as a proxy for the spatial and temporal variability of soil physical properties and it offers a very attractive tool for describing the

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subsurface properties without soil disturbance that cannot be provided by more traditional techniques [1-2]. In recent years, electrical resistivity method has increasingly practiced in geotechnical engineering site characterization as being non-destructive, rapid and cost-effective.

The electrical resistivity of soils is influenced by external conditions (temperature, stress state, etc) as well as the internal parameters of soils (water content, density, soil composition, void ratio, porosity etc). A number of attempts have been made by researchers to explore the phenomenon of electrical resistivity in soils and its relationship with other soil properties. The resistivity of soils decreased with the increase of temperature [3]. Moisture content is identified as one of the major factors that causes change in soil resistivity. Electrical resistivity decreased with increasing moisture content in soils and found a non-linear relationship [3-10]. The electrical resistivity of unsaturated soil is influenced by the cross- sectional area of conductive path, type and quantity charged ions, and the amount of pore water in soils as well as the particle size distributions [11]. The other factors that influenced the resistivity values include porosity, pore fluid composition, salinity, pore structure or grain matrix structure of soils, crack properties, etc are also examined by numerous researchers [12-19]. The soil composition could change the electrical resistivity appreciably and this knowledge applied successfully as an alternative index for determining hydraulic conductivity and weathering degree of a soil [20-21]. The correlations between electrical resistivity and geotechnical parameters of soil (such as plasticity index, unit weight, compaction, dry density, cohesion, friction angle, organic content) have also been carried out by numerous researchers [6, 22-23]. The soil electrical resistivity is influenced by the degree of saturation and microstructure changes during compaction [24].

The studied soils are granite residual soils which are the weathering product of their parent material and their engineering properties vary widely from place to place depending upon the rock of origin and the local climate during their formation and show significantly different characteristics in comparison to other natural clay soils [25-26]. These soils are found in many parts of the world (for example in Bangladesh, China, India, Malaysia, Singapore, Thailand etc) and are used extensively in construction, either to build upon, or as construction material of both geotechnical and geo-environmental structures such as embankments, pavements, earth fills and soil barriers. Many geo-engineering problems (subsidences, slope failures, landslides, collapse of buildings etc.) are also associated with these soils [27]. Therefore, these kinds of soil from a particular region need to be characterized individually for an appropriate assessment of its engineering behavior. The main objective of this study is to evaluate the variations of resistivity with respect to water content and dry density of compacted granite residual soils of Kaping, Guangdong, China. Based on the laboratory data, a mathematical model is also proposed to show the combined influence of water content and dry density on the electrical resistivity of the studied soils.

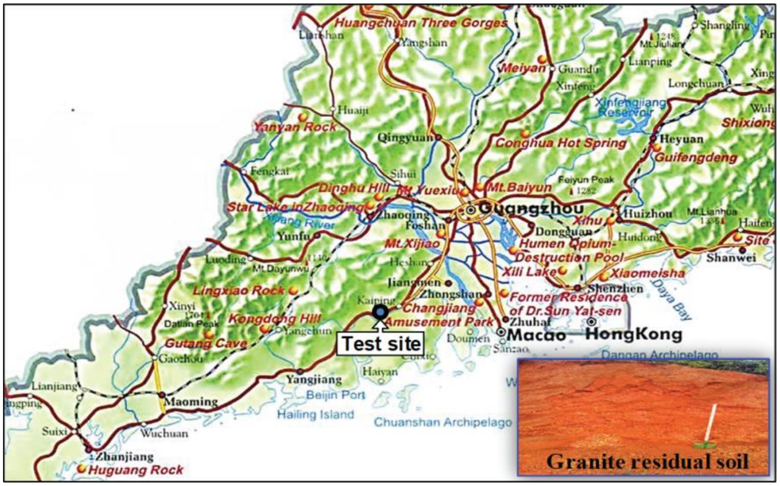

Figure 1. Location map of the study area [28].

2. Materials and Methods

2.1. Basic properties of the soil

For this research, the disturbed soil samples collected at areas around Taishan Section (Jiangmen city) of Guangdong province, China which belongs to the southwest part of Pearl River Delta and near the western edge of the Shenzhen-Mao high-speed railway (Figure 1). The studied soils are reddish brown in color and known as granite residual soil which are mainly composed of clay minerals and quartz with small amount of pyrite and gibbsite. Among the clay minerals, kaolinite content is around 95% and minor amount of illite also presents. The physical properties and grain size distribution of the soil samples are examined in the laboratory that is shown in Table 1 and Figure 2, respectively. The compaction curve is presented in Figure 3 which is determined by using the Standard Proctor energy. From the curve, the maximum dry density (ρ_{dmax}= 1.71 g/cm^3) and the optimum moisture content (W_{omc}= 19.5%) are obtained [28-29]. The compacted soil samples with four different dry densities (1.71 g/cm^3, 1.66 g/cm^3, 1.57 g/cm^3 and 1.49 g/cm^3) at water content of 19.5% are prepared to analyze the influences of water content and dry density on the electrical resistivity.

Table 1. Index properties of the studied granite residual soil [28].

G_s	Atterberg Limits (%)			Free Swell (%)	Grain size distribution (%)			
	W_L	W_p	I_P		Gravel	Sand	Silt	Clay
2.75	57.1	30.7	26.4	12.6	18.1	26.1	24.8	31

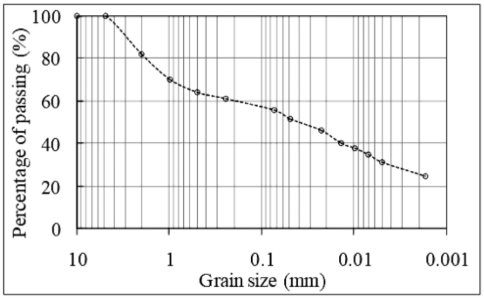

Figure 2. Grain size distribution curve of the studied granite residual soil [28].

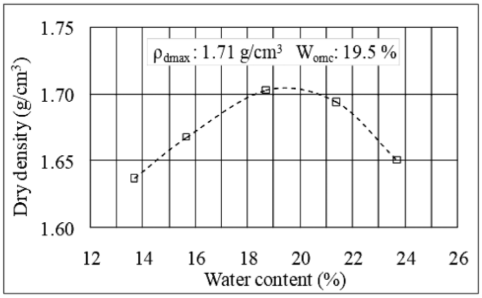

Figure 3. Compaction curve of the studied granite residual soil.

2.2. Experimental Procedures

Electrical resistivity of the compacted granite residual soil samples with different densities is measured using a self-developed testing device and a digital electrical system with 6 volts direct current (DC) where two-disc electrodes are connected to both ends of cylindrical soil samples and also attached to DC power source (Figure 4). The samples height and diameter are 80 mm and 39.1 mm, respectively, and are saturated using distilled water before the test. The samples are periodically turned upside down to obtain a uniform distribution of the water content during the testing period.

The resistivity measurements stopped when the water content is nearly at the residual state or needed more times to drain out. Laboratory temperature is kept constant at 25±1°C by air-conditioner during the test. The electrical resistivity (R) of samples is determined by the following equation:

$$R = \left(\frac{S}{L}\right) \times \frac{V}{I}$$

Where, R is the resistivity of ohms.meter, S is the cross-sectional area of the soil sample in meter squares, L is the length of soil sample in meters, *V* is voltage in volts and *I* is current in amperes.

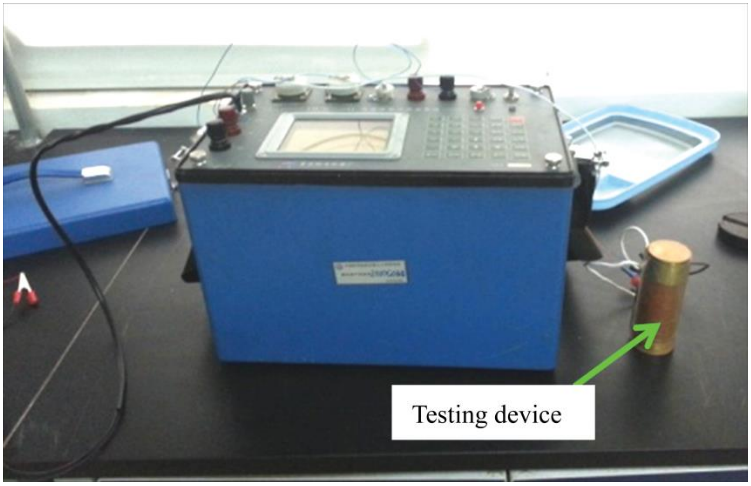

Figure 4. DZD-6A Multi-function DC Resistivity Meter [29].

3. Results and Discussions

3.1. Effect of Water Content on Electrical Resistivity

The variation of electrical resistivity with gravimetric water content is shown in Figure 5 and found that the electrical resistivity of soils decreases with increasing water content and the relationship is non-linear. For example, the resistivity values decreased about 27.34%, 57.01%, 77.55% and 87.29% with increasing the water content from 15.79% to 17.13%, 18.85%, 21.28% and 23.72%, respectively, for the soil sample with dry density of 1.57 g/cm^3. At lower water content, most pores are filled with air which decreases the effective sectional area of conductive path, so the electrical resistivity is very large. At higher water content, water forms a sort of fluid conduction channel, the sectional area of conductive path increases and reduces the solution viscosity as well as the electrical resistivity decreases. When the water content saturation increases further, the water is in continuous state and has little effect on the electrical resistivity due to it is a conductor, so the change of the electrical resistivity is very minor and tends to be stable. Therefore, the electrical resistivity is significantly influenced by water content, but minor influence is observed when the water content is above 23.5% or nearly at saturated condition.

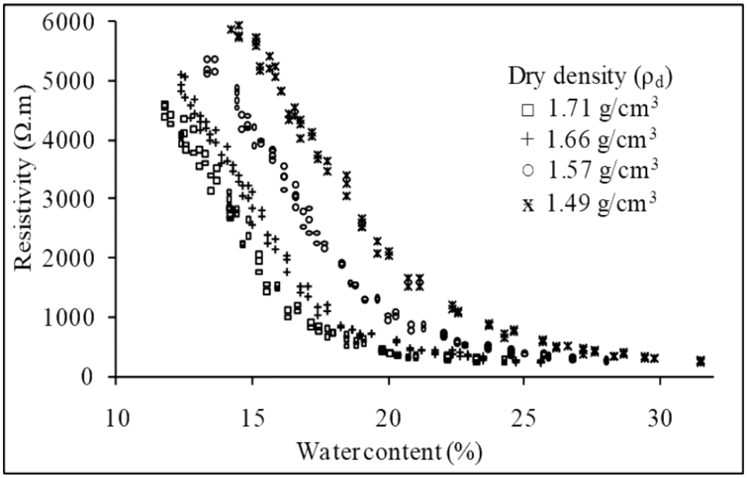

Figure 5. Relationship between resistivity and water content of compacted soils.

3.2. Effect of Dry Density on Electrical Resistivity

The relationship between electrical resistivity and dry density (at w=22.35%) is shown in Figure 6, which demonstrated that the electrical resistivity of compacted residual soil decreases with increasing dry density and tends to constant at higher dry density. For example, the electrical resistivity decreased about 46.7%, 69.5% and 75.7% with increasing dry density from 1.49 g/cm^3 to 1.57 g/cm^3, 1.66 g/cm^3 and 1.71 g/cm^3, respectively, at constant water content of 22.35%. It might be due to the reduction in the large pores or current flow path and breakdown in flocculated open fabric. This phenomenon is consistent with the contact conditions of the soil particles as reported by Rhoades et al. [30]. They pointed out that the dry density reflects the soil particle compactness to some degree and reduce pore volume i.e. the higher dry density soils show better connectivity of Rhoades' solid pathway consequently decrease the soil resistivity and when the soil approaches maximum dry density, soil particles are packed to the closest state, therefore, the electrical resistivity changes indistinctively or tends to be stable. That is, with increasing dry density, the particle contacts and pore continuity is improved and consequently the electrical resistivity decreased.

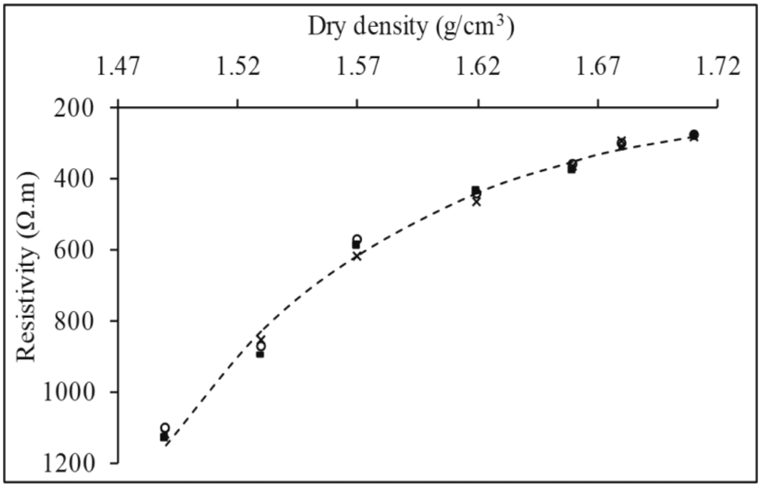

Figure 6. Relationship between resistivity and dry density of compacted soils.

3.3. Relationship between electrical resistivity and volumetric water content

To analyze the combined influence of water content and dry density on the electrical resistivity of the studied soils, the relationship between electrical resistivity and volumetric water content (θ=gravimetric water content x dry density) is drawn which is shown in Figure 7. It is also found that the electrical resistivity of soils decreases with increasing volumetric water content and the relationship is non-linear. For example, the resistivity value decreased about 16.30%, 44.02%, 69.53%, 85.31% and 90.68% with increasing the volumetric water content from 20.84% to 22.68%, 25.44%, 28.29%, 32.21% and 35.26%, respectively, for the soil sample with dry density of 1.66 g/cm^3. It reveals that for the same degree of soil water content, there is a noticeable decrease of soil resistivity with increasing dry density or vice-versa. The variations of electrical resistivity due to dry density are more pronounced at low water content but negligible for higher water contents. The water content is found to have more significant effect on electrical resistivity than dry density. Therefore, the water content alone cannot be used as a criterion on which to base the resistivity of soil because soil samples may have identical water contents but different dry density (i.e., different void ratio or porosity).

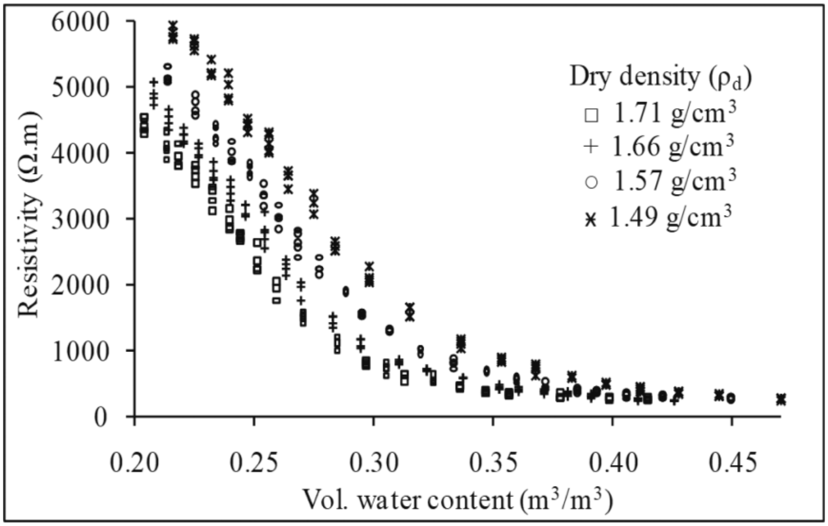

Figure 7. Relationship between resistivity and volumetric water content of compacted soils.

Based on regression analysis and taking Fukue et al. [16] micro-structural model of fine grained soils as consideration, it is found that the relationship between resistivity and volumetric water content for different densities compacted granite residual soil can be described by a sigmoid function and the model named as Resistivity-volumetric water content characteristic curve (RWCC). The proposed mathematical function of the model is-

$$R_{(\theta)} = R_r + \frac{R_S - R_r}{1 + \left(\frac{x_o}{\theta}\right)^b}$$

Where, $R_{(\theta)}$ is the resistivity with respect to volumetric water content, R_s and R_r are saturated and residual resistivity respectively, x_o is the x-value of the sigmoid's midpoint, b is the structural factor which depends on the compaction, porosity and particle distributions of the solid phase.

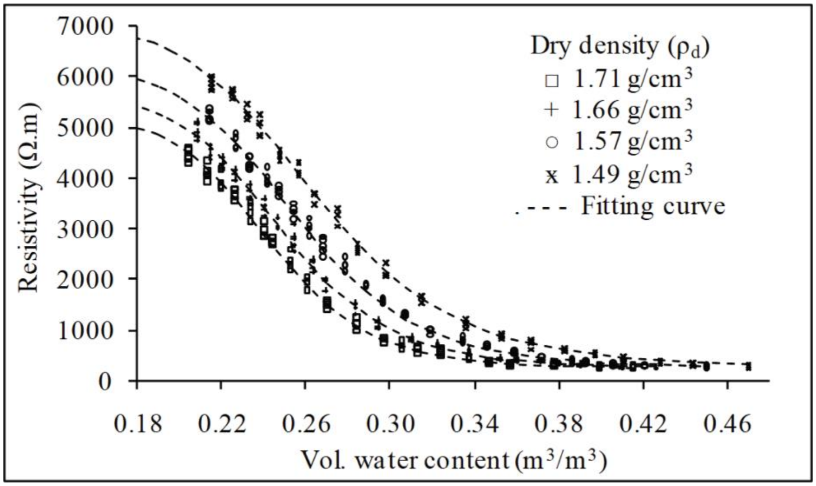

Figure 8. RWCC fitting curves of different densities granite residual soils.

Table 2. Fitting parameters of Resistivity-water characteristic curves.

Dry density, ρ_d (g/cm^3)	RWCC Fitting parameters				R^2
	R_s (Ω.m)	R_r (Ω.m)	x_o	b	
1.71	233.42	5225.04	0.2427	10.09	0.9962
1.66	242.36	5667.15	0.2485	9.53	0.9903
1.57	257.23	6214.25	0.2553	8.91	0.9891
1.49	274.37	7057.56	0.2646	8.03	0.9839

The obtained RWCCs and corresponding fitting parameters are shown in Figure 8 and Table 2, respectively, and found that the curves shift downwards with increasing dry density. It is important to note that when the soil is well saturated, the liquid phase consists mainly of free water which is almost all connected. Then the average resistivity of the soil is closely related to that of free water. At unsaturated condition, the liquid phase is largely depending on bound water. Though the studied soils have similar mineralogical and fluid composition, the saturated resistivity (R_s) values varied due to variations of water content and dry density. The other parameters are also varied due to the variations of de-saturation rate with time, porosity and dry density. With increasing dry density, the effective sectional area of the conductive path increased but the void ratio and porosity of the soils decreased consequently the value of R_s, R_r, and x_o also decreased. The value of b increased with increasing dry density which reflects the uniform pore size distributions at higher density soils and controls the resistivity increasing rate due to desaturation. It can also be seen that there is a decreased of resistivity increasing rate at a certain range of water content which is termed as adsorbed water content by Fukue et al. [16] and the corresponding resistivity values are termed as residual resistivity (R_r). The obtained results using proposed equation are also consistent with that of Kibushi clay and bentonite clay [16]. The validity of the proposed resistivity-suction model is preliminarily verified by the laboratory test data. This model may provide a new approach to solving the problem related to fine-grained unsaturated soils which will be time-saving and cost-effective.

4. Conclusions

This paper is aimed to evaluate the variations of electrical resistivity with respect to water content and dry density of compacted granite residual soils. From the test results, it is found that the resistivity of compacted residual soil decreases with increasing water content and tends to be constant at higher water content. A minor influence is observed when the water content is above 23.5% or nearly at saturated condition. Similarly, the values decrease with increasing dry density. There is a noticeable decrease of soil resistivity with the increase of dry density for the same degree of soil water content. The variations of electrical resistivity due to dry density are more pronounced at low water content but negligible for higher water contents. The results also revealed that the volumetric water content is a more reliable factor than the gravimetric water content to correlate with the resistivity of the soil. A non-linear sigmoid model named as Resistivity-water content curve (RWCC) is proposed to develop a relationship between resistivity and volumetric water content is this study. The proposed model is in good agreement with the experimental data as well as reflects the physical characteristics and hydraulic behavior of the compacted studied soils. However, resistivity test is conducted only for limited number of granite residual soil samples which is a special kind of regional residual soil, more laboratory tests with different kind of fine grained soils should be performed to verify the general formula further.

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