Quantitative Analysis of Generalized Suction on the Shear Strength of Unsaturated Soils

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Abstract. Taking the shear strength as the characteristic index to measure the strength of the soil, a characteristic parameter is established that can describe the contact distance between the surface of soil particles—the mean value of particle contact density. Using the indoor direct shear test of the preset scheme, the first-hand test data that three different factors such as moisture content, dry density and grain size quantitatively affect the shear strength of soil are obtained. Through the establishment of the quantitative relationship between the mean value of particle contact density and the shear strength, the theoretical description of the influence law that several key elements such as moisture content, void ratio, gradation, and particle size on the shear strength of unsaturated soil is realized, and the theoretical description and quantitative analysis of the influence of generalized suction on the shear strength of unsaturated soils are also completed.

1. Introduction

Geotechnical earthquake engineering belongs to the intersection of geotechnical engineering and earthquake engineering. It mainly studies geotechnical engineering problems under earthquake action, such as elastic waves in the rock and soil medium, soil dynamic characteristics and constitutive relations, site seismic responses, seismic technology of the foundations, soil-structure dynamic interaction, seismic resistance of underground engineering, seismic resistance of geotechnical structures, testing technology and application of soil dynamic characteristics, etc[1]. Taking into account these circumstances that frequent earthquakes at home and abroad have caused severe disasters in recent years and the rock-soil media has the characteristics of complex structure, strong time domain, and great regional differences, the research on geotechnical seismic engineering is extremely difficult and has practical significance.

In the previous half century, the theory of saturated soil mechanics has been developed rapidly, various constitutive theories, consolidation theories and strength theories that apply to saturated soils have been put forward by scholars. Some of these theories have been developed more maturely and have been applied in engineering[2]. However, most of the soil encountered in engineering is an unsaturated state, which is a three-phase composite medium of solid, water and gas, and its properties are much more complex than saturated soil[3]. After many years of development, well-known scholars
at home and abroad have derived many theoretical formulas\[4-9\] and empirical formulas\[10-14\] which lay a foundation for the development of modern unsaturated soil strength characteristics, and have studied the strength characteristics of unsaturated soil from multiple angles. People all know that shear strength is one of the important mechanical indicators of soil. Therefore, based on this key scientific issue, the thesis carried out research work combining soil mechanics experiments, theoretical analysis and mathematical calculations.

2. The concept of generalized suction

The shear strength of soil is usually the ability of soil to resist shear failure, that is, the maximum generalized shear force in a certain failure state\[15\]. Shen Zhujiang\[16\] believes that the existence of suction increases the anti-sliding resistance between soil particles, and the generalized suction is a natural extension of the concept of effective suction, that is, all factors that can effectively increase the anti-sliding resistance between particles are included, regardless of whether it comes from the matrix suction or the cementing force and bite force between particles\[16\]. That is to say, the generalized suction force between soil particles includes the effective cohesion between soil particles and the variable suction force related to capillary action, as well as the apparent cohesion related to the cementation force between particles and the frictional force to block shear. In short, the generalized suction refers to all inter-particle forces that can against sliding.

3. Theoretical construction of the mean value of particle contact density

The existence of the generalized suction makes different forms of force exist between soil particles. Factors such as particle size, particle shape, and distance between particles will affect the force between soil particles, which in turn affects the shear strength of soil.

The soil is a three-phase composite medium of solid, water and gas. The solid phase is a structural skeleton with soil particles as the main body, which has a specific arrangement structure inside the soil. Therefore, we consider constructing a theoretical parameter to express the average distance of the particles inside the soil. If the selected soil sample is divided into several smaller soil samples, it can be approximately considered that the particles inside the soil are spherical and uniformly distributed; according to the definition of soil void ratio: $e = V_v / V_s$, we use the theoretical average distance between particles in the soil (referred to as $d_s$) as the theoretical description parameter of the soil shear strength, the schematic diagram of the theoretical analysis of $d_s$ is shown in Figure 1.

![Figure 1. The schematic diagram of the theoretical parameter of the mean value of particle contact density.](image)

In Figure 1, $r$ is the radius (m), $H$ is the height of the sample (m), $e$ is the void ratio, $G_s$ is the specific gravity of the solid particles, $\rho_d$ is the dry density (kg/m$^3$), and $r_s$ is the radius of a single solid particle approximately as a sphere (m).

The total volume of the ideal sample is solved by the following formula

$$V_t = \pi r^2 H$$

(1)
The total volume of solid particles and the total volume of pores are solved as follows

\[ V_s = \frac{1}{1+e} \pi r^2 H \]  

\[ V_e = \frac{e}{1+e} \pi r^2 H \]  

The solid phase particle volume is solved by the following formula

\[ V_{sp} = \frac{4}{3} \pi r^3 \]  

The solid particle mass is solved by the following formula

\[ m_{sp} = \frac{4}{3} \pi r^3 \rho_d \]  

Assuming that the particle size of the solid particles of the soil in the sample is uniform and evenly distributed, then the number of solid particles is calculated by the following formula \((N_{sp} = m_{s}/m_{sp}, m_{s} = V_s \rho_d)\)

\[ N_{sp-s} = \frac{3}{4} \rho_d \frac{r^2}{r_s} H \]  

The total surface area of solid particles in the sample is solved by the following formula (the void ratio \( e = s \rho \omega / \rho_d - 1 \))

\[ S_{sp-s} = \frac{3 \pi r^2 H}{100} \sum_{i=1}^{n} g_{si} r_{si} \]  

For the soil samples sampled in the same place, the lithology of the soil is relatively stable. When considering the gradation and particle size of soil particles, assuming that there are solid particles with \( N \) kinds of different particle sizes in the sample, the particle size data can be recorded as \( r_{s1}, r_{s2}, ..., r_{sn} \), the corresponding particle masses are \( m_{s1}, m_{s2}, ..., m_{sn} \), the gradations are \( g_{s1}, g_{s2}, ..., g_{sn} \) (among them \( m_{si} = g_{si} V_{i} \rho_d / 100 \)).

The total surface area of solid particles in the sample is solved by the following formula

\[ S_{sp} = \frac{3 \pi r^2 H}{100} \sum_{i=1}^{n} g_{si} r_{si} \]  

The number of solid particles of any size in an ideal sample is calculated by the following formula

\[ N_{spi} = \frac{3}{400} \frac{\rho_d}{G_s \rho \omega} \frac{r^2 g_{si}}{r_{si}} H \]  

While considering the pore volume but not the water, the characteristic parameter that can reflect the cohesive force and the internal friction angle (shear strength) is constructed—the mean value of particle contact density, its value is the ratio of the total volume of the voids to the total surface area of the solid particles in the ideal sample.

The mean value of particle contact density is solved by the following formula.

\[ d_s = \frac{v_e}{s_{sp}} = \frac{100 e}{3 \sum_{i=1}^{n} g_{si} r_{si}^2} \]  

Considering the definition of void ratio, the formula can be changed as follows

\[ d_s = \frac{100(G_s \rho \omega - \rho_d)}{3 \rho_d \sum_{i=1}^{n} g_{si} r_{si}^2} \]  

In formula (11), \( d_s \): the average distance of the particle contact degree (m), \( G_s \): the specific gravity of soil solid particles, \( \rho_0 \): the density of water (kg/m\(^3\)), \( \rho_d \): the dry density of soil (kg/m\(^3\)), \( g_{si} \): the gradation of soil particles, \( r_{si} \): the solid particle radius of soil (m).
In order to consider the effect of water, on the basis of Equation 11, the corrected mean distance of soil particle contact degree is calculated by saturation, and the formula is as follows:

$$d_{s-\omega} = \frac{100e}{3\sum_{i=1}^{n}g_{si}r_{si}} \left[ 1 + \frac{\omega G_{s} \rho_{d}}{100(G_{s} \rho_{d} - \rho_{d})} \right]$$

(12)

Considering $e = \frac{s \rho_{ds}}{\rho_{d}} - 1$, then formula 12 can be changed as follows:

$$d_{s-\omega} = \frac{100e + \omega G_{s}}{3\sum_{i=1}^{n}g_{si}r_{si}}$$

(13)

In formula (13), $\omega$: the moisture content (%).

4. The direct shear test

The Mohr-Coulomb strength theory can accurately determine the shear strength of soil, which has been confirmed by experiments and engineering practices long ago [17]. In this paper, the direct shear test method is used to determine the shear strength of soil samples.

Loess: The test uses unsaturated loess and remolded loess. The test results of five unsaturated loess and remolded loess samples with different moisture content are shown in Table 1 (the initial moisture content of loess is 5.8%). The test results of eight remolded loess samples with different dry densities are shown in Table 2, and the moisture content of the remolded loess samples is 0% and 10% respectively. In Table 1 and 2, the basic physical parameters of the soil, the direct shear test results and the calculation results of the mean distance are shown.

Table 1. The direct shear test results of undisturbed loess and remolded loess with different moisture content.

| Moisture Content (%) | Dry Density (g/cm$^3$) | Void Ratio | Undisturbed Loess | Remolded Loess | Mean Distance (μm) |
|---------------------|------------------------|------------|-------------------|----------------|------------------|
|                     |                        |            | Internal Friction Angle (°) | Cohesion (kpa) | Internal Friction Angle (°) | Cohesion (kpa) |          |
| 0                   | 1.29                   | 1.11       | 35.95             | 30.6           | 32.2             | 23.05         | 3.36     |
| 5.8                 | 1.27                   | 1.14       | 29.31             | 25.2           | 25.8             | 20.15         | 3.94     |
| 10                  | 1.27                   | 1.14       | 26.24             | 21.92          | 22.97            | 17.6          | 4.28     |
| 15                  | 1.28                   | 1.125      | 24.81             | 18.7           | 20.89            | 15.12         | 4.65     |
| 35                  | 1.28                   | 1.125      | 18.83             | 13             | 15.77            | 10.95         | 6.3      |

Table 2. The direct shear test results of remolded loess with different dry density.

| Moisture Content (%) | Dry Density (g/cm$^3$) | Void Ratio | Internal Friction Angle (°) | Cohesion (kpa) | Mean Distance (μm) |
|---------------------|------------------------|------------|-----------------------------|----------------|------------------|
|                     |                        |            | Internal Friction Angle (°) | Cohesion (kpa) |                   |
| 0                   | 1.28                   | 1.125      | 32.2                         | 23.05          | 3.41             |
| 0                   | 1.37                   | 0.985      | 35.6                         | 28.0           | 2.99             |
| 0                   | 1.43                   | 0.902      | 36.7                         | 29.6           | 2.74             |
| 0                   | 1.51                   | 0.801      | 37.4                         | 31.1           | 2.43             |
| 10                  | 1.28                   | 1.125      | 22.97                        | 17.6           | 4.23             |
| 10                  | 1.37                   | 0.985      | 25.01                        | 20.6           | 3.81             |
| 10                  | 1.43                   | 0.902      | 25.7                         | 21.2           | 3.57             |
| 10                  | 1.51                   | 0.801      | 26.3                         | 22.1           | 3.26             |

Sand: In order to meet the actual needs of the project and accurately measure the shear strength of sand, a compaction test of sand was carried out in the research of the thesis [18], and the compaction test shows that the maximum dry density of sand is 1.82g/cm$^3$, and its corresponding optimal moisture content is 10.2%. Under the test conditions that the dry density of the sample is the maximum dry density, seven sand samples with different moisture content were subjected to direct shear test, and the test results
are shown in Table 3 (the initial moisture content of sand is 6.2%); under the test conditions that the moisture content of the sample is 0 and 10.2%, the test results of 8 sand samples with different dry densities are shown in Table 4.

**Table 3.** The direct shear test results of the sand with different moisture content.

| Moisture Content (%) | Dry Density (g/cm³) | Density (g/cm³) | Void Ratio | Internal Friction Angle (°) | Cohesion (kpa) | Mean Distance (μm) |
|----------------------|---------------------|-----------------|------------|----------------------------|----------------|-------------------|
| 0                    | 1.82                | 1.82            | 0.478      | 32.74                      | 7.45           | 1.56              |
| 6.2                  | 1.82                | 1.93            | 0.478      | 38.1                       | 9.8            | 2.1               |
| 8                    | 1.82                | 1.965           | 0.478      | 38.8                       | 11             | 2.26              |
| 10.2                 | 1.82                | 2.00            | 0.478      | 39.2                       | 12.4           | 2.45              |
| 15                   | 1.82                | 2.1             | 0.478      | 32.25                      | 10.8           | 2.87              |
| 18                   | 1.82                | 2.15            | 0.478      | 26.6                       | 8.5            | 3.14              |
| 20                   | 1.82                | 2.2             | 0.478      | 21.5                       | 6.4            | 3.31              |

**Quartz sand:** quartz sand with different particle sizes (40-70 mesh, 400 mesh) are used for direct shear test. Under the condition that the dry density of quartz sand samples is 1.5 g/cm³, the test results of five quartz sand samples with different moisture content are shown in Table 5. Under the test conditions that the quartz sand samples are all dried, the test results of three quartz sand samples with different dry densities are shown in Table 6.

**Table 4.** The direct shear test results of the sand with different dry density.

| Moisture Content (%) | Dry Density (g/cm³) | Compaction | Internal Friction Angle (°) | Cohesion (kpa) | Mean Distance (μm) |
|----------------------|---------------------|------------|-----------------------------|----------------|-------------------|
| 0                    | 1.638               | 90%        | 22.6                        | 3.8            | 2.09              |
| 0                    | 1.69                | 93%        | 27.2                        | 5.3            | 1.93              |
| 0                    | 1.75                | 96%        | 29.8                        | 6.47           | 1.75              |
| 0                    | 1.82                | 100%       | 32.74                       | 7.45           | 1.56              |
| 10.2                 | 1.638               | 90%        | 28.8                        | 7.5            | 2.99              |
| 10.2                 | 1.69                | 93%        | 33.5                        | 9.3            | 2.83              |
| 10.2                 | 1.75                | 96%        | 36                          | 11.2           | 2.65              |
| 10.2                 | 1.82                | 100%       | 39.2                        | 12.4           | 2.45              |

**Table 5.** The direct shear test results of quartz sand with different moisture content.

| Moisture Content (%) | Dry Density (g/cm³) | 40-70 Mesh | 400 Mesh |
|----------------------|---------------------|------------|----------|
|                      |                     | Internal Friction Angle (°) | Mean Distance (μm) | Internal Friction Angle (°) | Mean Distance (μm) |
| 0                    | 1.5                 | 37.45      | 93.59    | 39.83 | 1.24 |
| 5                    | 1.5                 | 35.24      | 109.79   | 38.73 | 1.45 |
| 10                   | 1.5                 | 33.38      | 125.97   | 37.76 | 1.66 |
| 15                   | 1.5                 | 31.2       | 142.14   | 36.72 | 1.87 |
| 20                   | 1.5                 | 29.0       | 158.32   | 35.69 | 2.08 |

**Table 6.** The direct shear test results of quartz sand with different dry density.

| Dry Density (g/cm³) | Moisture Content (%) | 40-70 Mesh | 400 Mesh |
|---------------------|---------------------|------------|----------|
|                     |                     | Internal Friction Angle (°) | Mean Distance (μm) | Internal Friction Angle (°) | Mean Distance (μm) |
| 1.4                 | 0                   | 34.87      | 109.02   | 39.83 | 1.24 |
| 1.5                 | 0                   | 37.45      | 93.59    | 39.83 | 1.24 |
| 1.6                 | 0                   | 40.58      | 73.99    | 42.09 | 1.06 |
5. The quantitative relationship between the mean value of particle contact density and shear strength

5.1. The quantitative relationship between the mean value and shear strength under the condition of controlling the moisture content.

The test found that there are many factors affecting the shear strength of the soil: such as effective stress, clay content, void ratio, stress path, strain rate, moisture content, natural density, dry density, gradation, particle size, etc. The special sensitivity of water to unsaturated soils and the law of influence of water on the deformation and strength of unsaturated soils have always been the center of research on the mechanical properties of loess. Based on the data obtained from the test, the author calculated the shear strength of undisturbed loess, remolded loess, sand and quartz sand with different moisture content under 100kpa normal stress, and used the least square method to fit the relationship between the shear strength and the mean distance. The purpose is to analyze the quantitative relationship between the mean distance and the shear strength of various soil samples under different moisture content, and then analyze the quantitative influence of the generalized suction on the shear strength inside the soil.

When the dry density of the sample is the same, as the change of moisture content, the fitting relationship between the mean distance and the shear strength of the undisturbed loess is shown in Figure 2(a). Because the structure of remolded loess is destroyed, the shear strength of remolded loess is smaller than that of undisturbed loess with the same physical parameters and external conditions; with the increase of the moisture content, that is, the mean distance increases, the internal friction angle and cohesive force of undisturbed loess and remolded loess are reduced, and the shear strength is also gradually reduced. The fitting relationship between the mean distance and the shear strength of the undisturbed is very good in accordance with the relationship of the power function.

When the dry density of the sample is the same, as the change of moisture content, the fitting relationship between the mean distance and the shear strength of the sand is shown in Figure 2(b). Because the compacted sand has an optimal moisture content, with the increase of the moisture content, that is, the mean distance increases, the internal friction angle and cohesive force of sand both increase first and then decrease. At the position of the sand with the optimal moisture content, its shear strength reaches its peak. The relationship between the mean distance and the shear strength of sand is very good in accordance with the relationship of the quadratic function.

![Figure 2](image-url)

Figure 2. The quantitative relationship between the mean value and shear strength of loess and sand.

When the dry density of the sample is the same, as the change of moisture content, the fitting relationship between the mean distance and the shear strength of quartz sand is shown in Figure 3. With the increase of the moisture content, that is, the mean distance increases, the shear strength of 40-70 mesh and 400 mesh quartz sand gradually decreases. Because the gradation, particle shape and distribution of quartz sand materials are very uniform, the increase in shear strength has good uniformity
with the increase in the mean distance, that is to say, the relationship between the mean distance and shear strength of quartz sand is very good in accordance with the relationship of the linear function.

![Figure 3](image_url) The quantitative relationship between the mean value and shear strength of quartz sand.

5.2. The Quantitative Relationship Between the Mean Value and Shear Strength Under the Condition of Controlling the Dry Density.

According to the basic knowledge of soil mechanics and foundation[19], the compactness of the soil is mainly evaluated by the void ratio of the soil, and the void ratio of the soil is only related to the dry density, and the compactness of the soil is closely related to the shear strength. As mentioned, to study the shear strength of soil, it is necessary to study the influence of dry density on it.

When the moisture content of the sample is the same, as the change of dry density, the fitting relationship between the mean distance and the shear strength of the remolded loess is shown in Figure 4(a). When the loess has the same moisture content, as the average distance increases, its shear strength gradually decreases. The fitting relationship between the mean distance and the shear strength of the remolded loess is very good in accordance with the relationship of the quadratic function. Under the condition that the remolded loess has the same moisture content, when the mean distance is smaller (that is, the dry density is larger), the shear strength decreases slowly; but with the gradual increase of the mean distance (that is, the dry density gradually decreases), the shear strength decreases faster.

When the moisture content of the sample is the same, as the change of dry density, the fitting relationship between the mean distance and the shear strength of sand is shown in Figure 4(b). When sand has the same moisture content, as the average distance increases, its shear strength gradually decreases. The fitting relationship between the mean distance and the shear strength of sand is very good in accordance with the relationship of the quadratic function. Because the cohesive force of sand is very small, its shear strength mainly depends on the friction strength, and the dry density has a great influence on the friction strength, so, the change in the shear strength of sand with the mean distance is more sensitive than that of loess. In other words, as the average distance increases, the shear strength of sand decreases faster than that of loess.
Figure 4. The quantitative relationship between the mean value and shear strength of remolded loess and sand.

When the moisture content of the sample is the same, as the change of dry density, the fitting relationship between the mean distance and the shear strength of quartz sand is shown in Figure 5. When quartz sand has the same moisture content, with the increase of the average distance, its shear strength gradually decreases. The fitting relationship between the mean distance and the shear strength of quartz sand is very good in accordance with the relationship of the linear function. Under the condition that quartz sand has the same moisture content and dry density, the shear strength of 400 mesh quartz sand is greater than that of 40-70 mesh quartz sand. The reason is that compared with 40-70 mesh quartz sand, 400 mesh quartz sand has a smaller particle size and a smaller average distance, so that the particles are tightly combined with each other, and the effective contact area between the particles increases. Therefore, when quartz sand is in the process of shear failure to resist external forces, the greater the frictional resistance of quartz sand, and the higher the corresponding shear strength. This conclusion is also applicable to the soil in nature.

Figure 5. The quantitative relationship between the mean value and shear strength of quartz sand.

6. The quantitative analysis of the generalized suction on the shear strength of unsaturated soil

According to the quantitative relationship between the mean value of particle contact density and the shear strength, it can be seen that: for loess, as the moisture content increases, the shear strength of the soil will decrease, that is, the increase in moisture content will increase the mean value of particle contact density, resulting in a decrease in the force between particles, in other words, the increase in the mean value of particle contact density effectively reduces the generalized suction between soil particles, which in turn reduces the shear strength of the soil. For compacted sand, when the moisture content does not reach its optimal moisture content, the shear strength of the sand is gradually increasing when the
moisture content increases. And the reason is that the sand is a non-cohesive soil. When its moisture content is low, its particles are loose and the force between the particles is small. Then when the moisture content increases, the cement content in the soil plays a role in increasing its general suction, which in turn increases the shear strength of the sand. After reaching the optimal moisture content, the continuous increase of moisture content makes the mean distance increase continuously, but the forces such as cementation and friction between particles are continuously reduced, so the shear strength is gradually reduced. For the ideal material, quartz sand, its shear strength gradually decreases with the increase of moisture content. This is because the increase of water increases the mean value of particle contact density, which effectively reduces the friction resistance between particles. Therefore, its shear strength is reduced.

As the dry density of the soil increases and the particle size of the soil decreases, the shear strength of loess, sand, and quartz sand all increase. This is because that the higher the dry density and the smaller the particle size, the tighter the inter-particle bonding. In that way, the smaller the mean distance, the greater the force between particles, and therefore the greater the generalized suction, and the higher the shear strength of the soil affected by the generalized suction.

From the direct shear test results and the quantitative relationship obtained, it can be seen that the quantitative relationship of the unsaturated soil shear strength established by the mean distance has a higher fitting index, even higher than the relationship of the shear strength established by the moisture content and dry density. The reason is that the characteristic parameter of the mean value of particle contact density constructed in the paper includes the characteristics of moisture content, void ratio, gradation and particle size, which can better reflect the mechanical properties of soil and also reflect the generalized suction between soil particles.

7. Conclusion and discussion
(1) The mean value of particle contact density constructed in the paper includes the characteristics of moisture content, void ratio, gradation and particle size, which can better reflect the mechanical properties of soil. The mean value of particle contact density can be used as a parameter to characterize the shear strength of soil, and it can also be used as an intermediate parameter in the quantitative study of generalized suction on soil shear strength.

(2) The paper studies the quantitative relationship between the mean distance and shear strength of loess, sand and quartz sand under the control of moisture content and dry density, and taking the change of the mean value of particle contact density as the starting point, the physical and mechanical mechanism of the influence of generalized suction on the change of soil shear strength is analyzed.

(3) The test data verifies that the relationship is good, that is to say, it is feasible to use the mean value of particle contact density to characterize the shear strength of soil, but whether the mean value of particle contact density can be used to characterize other dynamic characteristics of the soil (such as deformation characteristics) and whether it can reflect the microstructure of various soils well needs further verification.

(4) In the next research work, adopting different types of soil samples for dynamic triaxial tests and taking the physical and mechanism of plastic deformation of the soil as the starting point, we will use the mean value of particle contact density to characterize the deformation characteristics of the soil and carry out quantitative research.

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