Experimental study on the strength and deformation characteristics of sandy pebble soil foundation based on the equivalent density method

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Abstract: With the rapid development of urban construction, many bridges and subways are built on sandy pebble soil foundation. As a special kind of soil, sandy pebble soil has the characteristics of large particle size, low compressibility, low cohesion, poor self-stability, large permeability coefficient, large friction coefficient, etc. The strength and deformation characteristics of the sandy pebble soil are one of the key concerns in engineering field. Due to the size limitation of the laboratory test equipment, scaling is necessary for sandy pebble soil. The equivalent density of coarse-grained material could be obtained by equivalent density method; large-scale triaxial and interface shear tests were performed to study the comprehensive mechanical characteristics. Furthermore, appropriate models were investigated to describe the stress-strain relationships of sandy pebble soil, and the corresponding model parameters were summarized. The tests results reveal that the saturated sand pebble soil show shear shrinkage characteristics under low confining pressure, conversely unsaturated samples show shear dilatancy characteristics under low confining pressure. Under high confining pressure, obvious shear shrinkage characteristics could be observed. The shear strength parameters of unsaturated samples are obviously larger than those of saturated samples. It shows a good hyperbolic relationship between shear stress and displacement on the interface of sandy pebble soil and concrete slab, and the shear strength and normal stress are in a good linear relationship. The research could provide strong support for engineering design in sandy pebble soil.

Keywords: sandy pebble soil; equivalent density; pressuremeter tests; triaxial shear tests; interface shear tests.

1. Introduction

Sand pebble soil is distributed in many regions in China. With the rapid development of urban construction, greater number of bridges, subways, and other municipal traffic projects are built on the sandy pebble soil [1]. Compared with soft clay, sandy pebble soil has unique characteristics, such as large particle size, low compressibility, low cohesion, poor self-stability, large permeability coefficient, large friction coefficient, etc. [2]. When foundation pit excavation, tunnel construction, and structure building occur on sand pebble soil foundation, deformation control becomes difficult, resulting in various safety accidents. Therefore, it has been the major concern in geotechnical engineering.
At present, many studies have been performed on mechanical characteristics of coarse-grained soil, including unit shear characteristics [3-5] and interfacial shear characteristics [6-8]. However, previous studies mainly focused on dam rockfill materials. As a special coarse-grained soil, sand pebble soil has significantly different physical and mechanical characteristics as compared to the dam rockfill materials. The research results of the rockfill materials cannot be applied to sandy pebble soil directly. Unfortunately, the mechanical characteristics of the sandy pebble soil have not been fully exploited due to the lack of systematic experimental studies. Moreover, the deformation analysis based on numerical method for sandy pebble soil foundation relies on suitable mechanical model selection and accurate model parameters. Therefore, it is essential to study the mechanical properties of the sandy pebble soil systematically and thoroughly.

The maximum particle size of the sandy pebble soil could reach 100~200 mm in field, while the maximum allowable particle size given by the laboratory equipment is 60 mm. It is difficult to directly conduct model tests for prototype grading sand pebble soil, hence scaling is necessary. Various research works [9-10] have shown that the mechanical characteristics of the coarse-grain material are closely related to the particle size and density. According to “Standard for Geotechnical Test Methods” (GB/T50123-2019) [11], four gradation scaling methods are recommended, while there is no description on how to determine the density. Equivalent density method is proposed [12], which can consider both gradation and density to make the mechanical characteristics of the scaling material close to that of the prototype grading material, and the reasonability has already been proven by many studies [13].

For typical sandy pebble soil, the equivalent density of laboratory tests was obtained by pressuremeter tests, then triaxial and interface shear tests were conducted to examine the strength and deformation characteristics. Based on the test results, appropriate mechanical models were chosen to describe its stress-strain relationship, and the corresponding model parameters were summarized. The research provides a useful reference for the mechanical characteristics study and deformation prediction of the sandy pebble soil foundation.

2. Materials and equipment

The large-scale model pressuremeter test system is shown in Fig. 1. Mena G-AM(BX) pressuremeter gauge was used as the pressurizing and stabilizing device. The model test chamber was made of steel plate, 0.86 m in length, 0.88 m in width, and 1.05 m in height. Four 50 T jacks were arranged symmetrically to form the reflexive force system, which could provide the overburden pressure. Displacement sensors were symmetrically arranged at the four corners to measure the settlement of the sample.

![Fig. 1. Large-scale model pressuremeter test system](image-url)
The test materials were taken from the typical sandy pebble soil foundation under a suspension bridge, and the maximum particle size of sandy pebble soil in field reached 200 mm. Due to the size limitation of the instrument in the laboratory tests, scaling of gradation was carried out based on the equivalent substitution method, granule group with particle size larger than 60 mm was replaced by that with particle size between 5 mm~60 mm. The gradation curves are shown in Fig. 2.

Pressuremeter tests were conducted in the laboratory to establish the relationship between pressuremeter modulus and density. The overburden pressure in model pressuremeter tests was 350 kPa, equivalent to the overburden pressure at a depth of 30 m. Model tests were carried out with different initial densities of 1.79 g/cm³, 1.83 g/cm³, 1.87 g/cm³, and 1.91 g/cm³.

3. Determination of equivalent density based on pressuremeter tests

Equivalent density method was performed to obtain the equivalent density of coarse-grained materials in the laboratory tests. It is known that the mechanical characteristics of coarse-grained materials with different gradation and density are similar when their pressuremeter moduli are equal. Firstly, pressuremeter tests were conducted to obtain the pressuremeter modulus in the field, and the relationship between the pressuremeter modulus and density could be established through pressuremeter model tests in the laboratory, then the equivalent density was obtained by comparing the tests results in the laboratory with that in the field.

The pressuremeter curves with different densities are shown in Fig. 3. According to the relation curve of pressure and the measured volume, the pressuremeter modulus $E_m$ could be calculated by the following formula

$$E_m = 2(1 + \mu)(V_c + V_m) \frac{\Delta p}{\Delta V}$$  \hspace{1cm} (1)

where $\mu$ is the Poisson's ratio, $V_c$ is the natural cavity volume of the pressuremeter device, $V_0$ is the volume corresponding to $P_0$, $V_f$ is the volume corresponding to the plastic pressure, and $\Delta P/\Delta V$ is the slope of the linear elastic segment of the pressuremeter curve.
According to the tests results conducted in the field, the pressuremeter modulus of the sandy pebble soil foundation is about 29.8 MPa at a depth of 30m. As shown in Fig. 4, combining the pressuremeter tests results in the field and in laboratory, the equivalent density in scaled tests is 1.87 g/cm$^3$.

4. Triaxial shear tests of sandy pebble soil
Triaxial shear tests are conducted with YLSZ30-3 high pressure triaxial instrument. As shown in Fig. 5, the instrument is mainly composed of loading, stabilizing, and controlling systems for vertical and confining pressures, triaxial pressure chamber, reaction system, displacement, and volume measurement system, data acquisition system, etc. The test sample size is $\Phi 300 \times H 600$ mm, the maximum confining pressure is 3.0 MPa, and the maximum axial stress is 21 MPa, moreover the maximum axial stroke is 300 mm.
Triaxial shear tests for the saturated and unsaturated sandy pebble soil were carried out consecutively with the confining pressures of 0.1, 0.2, 0.3, 0.4 MPa, and the shear rate was 0.4 mm/min. Axial load, axial displacement, and water discharge were recorded. The tests would not end until the shearing strain reached 15% of the axial strain.

Fig. 6(a) and (b) represent the deviator stress-axial strain curves and volumetric strain-axial strain curves of the saturated sandy pebble soil, and Fig. 7(a) and (b) represent the deviator stress-axial strain curves and volumetric strain-axial strain curves of the unsaturated sample. For both saturated and unsaturated sandy pebble soil samples, the deviator stress was constant with the increase of the axial strain in the end. It indicated that the samples were destroyed after reaching a certain stress level. The relationship between deviator stress and axial strain was greatly affected by the confining pressure. The larger the confining pressure was, the larger the deviatoric stress was with constant axial strain. Furthermore, under the same confining pressure, the deviator stress of the saturated sample was smaller than that of the unsaturated sample with the same axial strain. As per the test results, the saturated sand pebble soil showed shear shrinkage characteristics under low confining pressure (e.g., 0.1 MPa), the unsaturated samples showed dilatancy characteristics under low confining pressure, while obvious shear shrinkage characteristics were observed under high confining pressure (e.g., 0.2, 0.3, 0.4 MPa).

![Triaxial shear test results of the saturated sandy pebble soil](image-url)
Duncan model is a nonlinear elastic model, which has been widely used in the numerical analyses of the coarse-grain material \cite{14}. It is assumed that hyperbolic stress-strain function could describe the deviatoric stress-axial strain curve obtained from triaxial shear tests well. As shown in Table 1, Duncan model parameters were obtained according to triaxial shear tests results. For the saturated sandy pebble soil, the cohesion value $C_s$ was 20 kPa, and the friction angle value $\phi_{sat}$ was $30.5^\circ$. While for the unsaturated sandy pebble soil, the cohesion value $C_{us}$ was 22 kPa, and the friction angle value $\phi_{us}$ was $35.0^\circ$. With the same dry density, the shear strength index of the saturated sample was significantly smaller than that of the unsaturated sample, indicating that the strength of the sandy pebble soil foundation in water-rich area is worthy of attention.

Table 1. Duncan model parameters for the saturated and unsaturated sandy pebble soil

| Shear strength parameters | E-$\mu$(B) model parameters |
|---------------------------|-----------------------------|
| $C_d$ $\phi_d$ $\phi_0$ $\triangle \phi$ | $k$ $n$ $R_i$ $G$ $F$ $D$ $K_s$ $M$ |
| Saturated | 20 30.5 35.3 6.2 | 290 0.25 0.82 0.26 0.11 4.52 114 0.26 |
| unsaturated | 22 35.0 39.8 6.3 | 370 0.25 0.89 0.32 0.31 4.18 153 0.23 |

5. Interface shear tests of sandy pebble soil

As shown in Fig. 8, large-scale stack ring shear apparatus is mainly used to study the mechanical characteristics of the coarse-grain soil, interface characteristics between structure and soil, etc. The test sample size was $600 \text{ mm} \times 600 \text{ mm} \times 600 \text{ mm}$, the bottom shear box was $240 \text{ mm}$ in height, and the top part was made of 7-layer stack rings, and each layer was $30 \text{ mm}$ in height. The maximum vertical and horizontal loads were $500 \text{ kN}$ and $1000 \text{ kN}$, respectively. The instrument could overcome the shortcoming of single shear plane with conventional direct shear instrument with the possibility that the sample could get damaged along the weakest shear plane.
The interface shear characteristics of the sandy pebble soil were studied with the large-scale stack ring shear apparatus. The concrete slab was filled in bottom shear box, which was cured to the specified requirements before the interface shear tests, and the sandy pebble soil was filled in the top shear box. The overburden pressure was set to 100, 200, 300, and 400 kPa. The relation curve of shear stress $\tau$ and displacement of bottom shear box $\omega_s$ is shown in Fig. 9. It could be seen that the shear stress $\tau$ gradually increased with the increase of shear displacement $\omega_s$, expressed by a hyperbolic relationship. As shown in Fig. 10, the interface shear strength $\tau'$ increased linearly with the increase of normal stress $\sigma_n$. The fitting analysis results establish that the cohesion of interface between the sandy pebble soil and the concrete slab $C_s$ was 77.3 kPa, while the friction angle $\Phi_s$ was 29.2°.
Fig. 10. Relation curve of interface shear strength and normal stress

Clough-Duncan model is a typical interface nonlinear elastic constitutive model, which could well reflect the stress-strain relationship between the coarse-grained soil and structure. It assumes that the shear stress \( \tau \) and shear displacement \( \omega \) are in a hyperbolic relationship, which could be expressed as

\[
\tau = \frac{\omega}{a + b \cdot \omega}
\]

where \( a \) is the reciprocal of the initial shear stiffness \( k_{ii} \), \( a = 1/k_{ii} \), \( b = R_f / \tau_f \), interface shear strength \( \tau_f = \sigma_n \tan \phi + c \), \( R_f \) is break ratio.

The initial shear stiffness \( k_{ii} \) is in power function relationship with the normal stress \( \sigma_n \), it can be expressed as

\[
k_{ii} = K_i \cdot \gamma_o \cdot \left( \frac{\sigma_n}{P_a} \right)^n
\]

(3)

The shear stiffness coefficient \( k_{ss} \) can be expressed as

\[
k_{ss} = \frac{\partial \tau}{\partial \omega} = k_i \cdot \gamma_o \cdot \left( \frac{\sigma_n}{P_a} \right)^n \left( 1 - \frac{R_f \cdot \tau}{\sigma_n \cdot \tan \phi + c} \right)^2
\]

where \( k_i \) is the dimensionless stiffness coefficient, \( n \) is the stiffness index, \( \phi \) is the interface friction angle, \( c \) is cohesion of interface, \( P_a \) is atmospheric pressure, \( \gamma_o \) is the bulk density of water, and \( \tau \) is the interface failure strength.

Clough-Duncan model consists of five basic parameters \( K_i \), \( n \), \( c \), \( \phi \), \( R_f \), representing stress-related interface characteristics. According to the test results, the five parameters of the Clough-Duncan interface model are shown in Table 2.

| \( \kappa_i \) | \( n \) | \( c \) | \( \phi \) | \( R_f \) |
|---|---|---|---|---|
| 8592 | 0.691 | 77.3 | 29.2 | 0.682 |

6. Conclusion

(1) Equivalent density method could be used to obtain the equivalent density of the sandy pebble soil in the laboratory tests. Firstly, the pressuremeter tests were conducted to obtain the pressuremeter modulus
in the field, then the relationship between pressuremeter modulus and density was established through pressuremeter tests in the laboratory, and finally the equivalent density was obtained by comparing the tests results obtained in the laboratory with those in the field.

(2) In the triaxial shear tests of the sandy pebble soil, the larger the confining pressure, the larger the deviatoric stress and the volumetric strain were with the same axial strain. Under the same confining pressure, the deviatoric stress of the saturated sample was smaller than that of the unsaturated sample with the same axial strain. Under low confining pressure, the saturated and unsaturated sandy pebble soil showed shear shrinkage and dilatancy, respectively while under high confining pressure, they all showed obvious shear shrinkage. According to the tests results, Duncan model parameters of sandy pebble soil were obtained. The shear strength indices of the unsaturated samples were significantly improved compared to those of the saturated samples, indicating that the sandy pebble soil foundation strength in the water-rich area was worthy of attention.

(3) The shear stress and shear displacement on the interface of sandy pebble soil and concrete slab could be expressed by a hyperbolic relationship, and the shear strength increased linearly with the normal stress.

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