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EXPERIMENTAL INVESTIGATIONS

EXPERIMENTAL STUDY ON THE APPROACH TO PREDICT THE SHEAR STRENGTH OF IN-SITU SANDY GRAVEL

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Large-size consolidated drained triaxial tests for a gravel and a rockfill were performed. Because of the limit of the apparatus size, test specimens with different maximum grain sizes ranging from 10 to 60 mm, and thus with different particle size distributions, were prepared using the replacement technique (gravel) and mixed method (rockfill) to reduce the particle size of the in-situ soil. The nonlinear or linear shear strength of sandy gravel considering stress state and maximum size was described and verified based on the test data. Furthermore, an approach to estimate the nonlinear shear strength of in-situ sandy soil was developed.

Introduction

Shear strength is an important mechanical parameter of soils for consideration when designing earthworks. Measurement of the shear strength of the sand-gravel mixtures is valuable for use in further studies to analyze the stability of such structures [1].

The shear strength of sandy gravel can be measured in the laboratory by various methods, of which the most widely adopted is the large-size triaxial apparatus [2-4] and the direct shear box [5-6]. Due to the large particle size of sandy gravel and the dimensional limitation of the triaxial device, the particle size of the in-situ sandy gravel usually needs to be reduced by a preparation technique. Therefore, the shear strength of sandy gravel in situ may not be accurately or entirely reflected by laboratory measurements [7-9]. The design of a method by which to obtain the real behavior of in-situ sandy gravel remains a difficult problem.

In this study, large-size consolidated drained (CD) triaxial tests were carried out for gravel and rockfill filling materials. The influence of particle size distribution (PSD) on the shear strength for sandy gravel was analyzed based on the data of the CD triaxial test, and an approach to predict the shear strength of in-situ sandy gravel was proposed and verified.

Testing Apparatus and Programme

According to American Society for Testing Materials Standard D7181-11[10], large-size CD triaxial tests for sandy gravel were carried out with confining pressures of 0.6, 1.2, 1.8, and 2.4 MPa. The CD triaxial tests were conducted by using large-size triaxial shear test apparatus developed by Hohai University. A labeled diagram of the test apparatus is given in Fig. 1.

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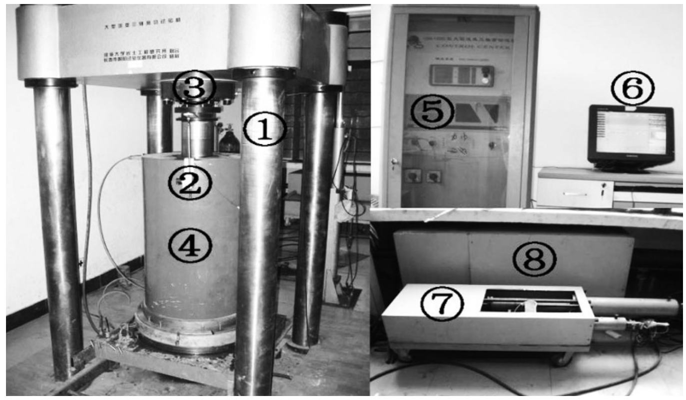

Fig. 1. Test equipment: 1) loading frame, 2) displacement sensor, 3) load sensor, 4) triaxial chamber, 5) main operating system, 6) data acquisition system, 7) confining pressure loading device, 8) normal force loading device.

TABLE 1

Soils	Density (g/cm^3)	Grain groups content (%)					
		100~60	60~40	40~20	20~10	10~5	< 5
Original		21.87	12.25	16.51	12.76	8.14	28.46
S60	2.010	-	17.64	23.79	18.38	11.73	28.46
S40	2.009	-	-	31.58	24.39	15.56	28.46
S20	1.942	-	-	-	43.68	27.86	28.46
S10	1.907	-	-	-	-	71.54	28.46

TABLE 2

Tested specimens	Effective internal friction angle $\sigma_3 = \phi'$(MPa)				Nonlinear shear strength			Linear shear strength	
	0.6	1.2	1.8	2.4	ϕ'_0 (°)	$\Delta\phi'$(°)	R^2	ϕ'(°)	c (kPa)
S10	41.48	37.91	36.57	34.64	49.99	4.77	0.99	32.8	221.3
S20	41.81	39.88	38.60	37.54	49.36	3.96	0.91	35.8	226.5
S40	44.66	42.04	40.22	40.03	49.10	2.90	0.96	37.9	230.2
S60	44.45	43.31	41.08	40.83	48.70	2.43	0.92	38.9	233.5
R10	44.11	40.33	38.18	37.74	57.01	4.46	0.98	34.7	298.8
R20	45.06	42.14	39.69	39.21	55.69	4.17	0.94	36.4	316.5
R40	47.79	45.08	41.05	42.27	52.98	4.43	0.92	38.4	345.7
R60	48.14	46.29	44.55	43.15	52.47	4.79	0.99	40.8	374.7

The test materials were the gravel used for a large face rockfill dam in Xingjiang, and a rockfill used as filling material for Rumei rockfill dam. Due to the limit of the apparatus size, the two kinds of sandy gravels with original PSD could not be directly used for the test. In this paper, the replacement technique [11] was used to reduce the particle size of the gravel, and the maximum particle size (d_M) of tested soils were 60, 40, 20, and 10 mm, which are referred to as S60, S40, S20, and S10, respectively. The mixed method [12] was used to reduce the particle size of the rockfill to the d_M of 60, 40, 20 and 10 mm, which are referred to as R60, R40, R20, and R10, respectively. The diameter and height of each test specimen were 300 and 600 mm, respectively, and initial relative density was 0.8. The initial dry densities and PSDs of the test specimens are listed in Table 1.

Interpretation of Experimental Results

According to triaxial test results, the effective internal friction angle ϕ' under different confining pressures (σ_3) was obtained. Table 2 shows that ϕ' for sand gravels with the same PSD decreased as the value of σ_3 increased, which is consistent with the test results reported by published works [8, 13]. Duncan et al. [13] has proposed nonlinear shear strength τ_f formula for coarse grained soil:

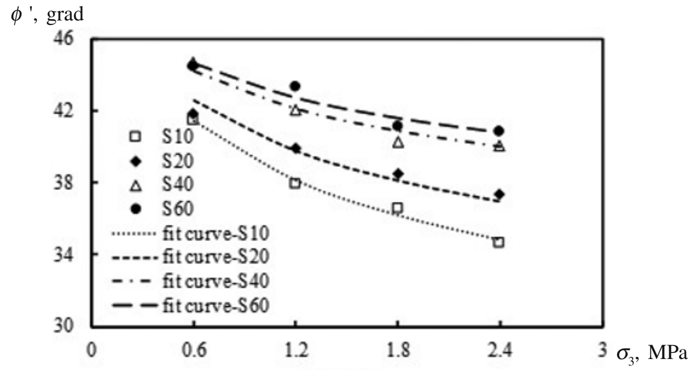

Fig.2. Test data and fitting ϕ'–σ_3 curves.

$$\begin{cases} \phi' = \phi_0' - \Delta\phi' \lg\left(\sigma_3 / P_a\right), \\ \tau_f = \sigma \tan(\phi'), \end{cases} \quad (1)$$

where ϕ_0' and $\Delta\phi'$ are material parameters; P_a is standard atmosphere pressure; σ is the normal stress on the failure surface; and σ_3 is the minimum principal stress, which is the confining pressure in the triaxial test.

To study the reliability of Eq. (1), the test data of S10-S60 (see Table 2) were plotted in Fig. 2. The fitting curves showed a good agreement with the test data. The errors of the predicted value, compared with the test data, were mostly less than 1%, and the maximum error value was only 1.8%. The correlation coefficient (R^2) supports this, with all the values larger than 0.91. Therefore, Eq. (1) can be used to describe the ϕ'–σ_3 relationship and determine the shear strength of sandy gravel.

Table 2 shows that ϕ' for sandy gravel increased with increasing d_M under the same σ_3, which is consistent with the test results reported in [7, 8]. According to [14], if a given original PSD soil is prepared by the same preparation technique with different d_M, each of its PSDs is then determined by d_M uniquely. Therefore, there may be a different relationship between ϕ' and d_M. Once this relationship has been established, it may be used to extrapolate the value of ϕ' for the in-situ soil. Theoretically speaking, the extrapolation may not be reliable, but the triaxial test cannot be conducted in the in-situ PSD specimen for sandy gravel because of the dimensional limitations of the apparatus. Extrapolation can be regarded as an acceptable method.

As shown in Table 2, ϕ_0' and $\Delta\phi'$ decrease with increasing of d_M for the test specimens prepared by the same preparation technique. The test data are plotted as scattered points in Fig. 5, and the relationship can be described by

$$\begin{cases} \phi_0' = a d_M^b \\ \Delta\phi' = c d_M^e, \end{cases} \quad (2)$$

where a, b, c, and e are fitting parameters, and $b < 0$ and $e < 0$. The values of a, b, c, and e for S10-S60 were 51.56, −0.014, 11.865, and −0.382, respectively.

Equation (2) was used to fit the test data of S60-S10 for verification purposes. The fitting curves are shown in Fig. 3 by dotted lines. The curves agreed well with the test data.

Combining Eqs. (1) and (2),

$$\phi' = a d_M^b - c d_M^e \lg\left[(\sigma_3 + P_a) / P_a\right]. \quad (3)$$

In order to study the reliability of Eq. (3), the fitting curves were plotted in Fig. 4, and the corresponding parameters a, b, c, and e were 68.689, −0.076, 5.298, and −0.078, respectively. The fitting

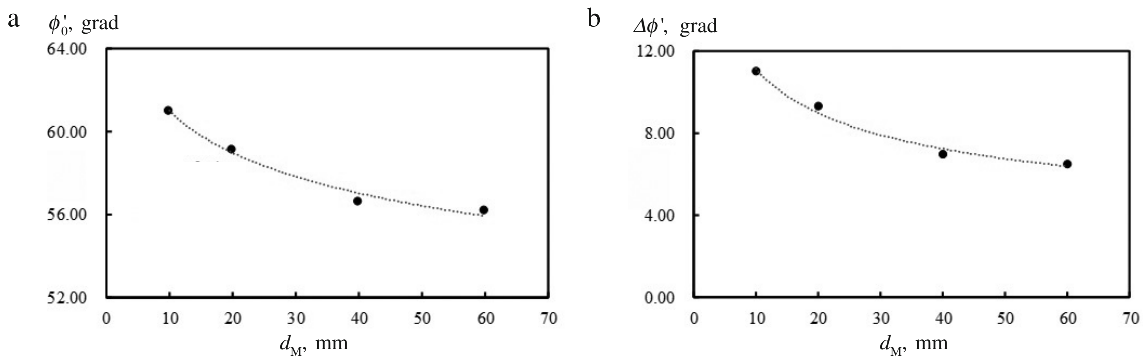

Fig. 3. Relationship of ϕ'_0 (a) and $\Delta\phi'$ (b) versus d_M: •) test results.

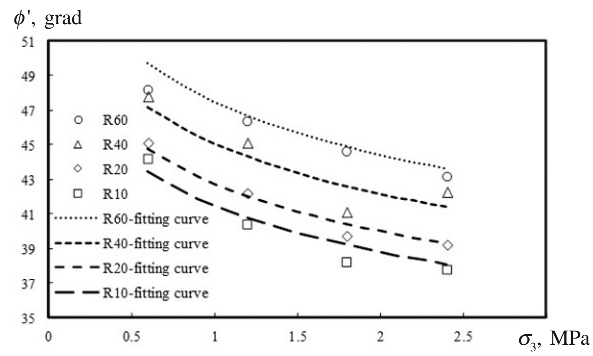

Fig. 4. Fitting ϕ'–σ_3 curves for the tested specimens prepared by replacement technique.

curves given by Eq. (3) showed good agreement with the test data. The errors of the predicted value, compared with the test data, were mostly less than 1%, and the maximum error value was only 3.7%. Combining Eqs. (1) and (3), an empirical equation, which can well describe the relationship between the nonlinear shear strength τ_f of sandy gravel and stress state as well as d_M is as follows:

$$\tau_f = \sigma \tan\left\{ a d_M^b - c d_M^e \lg\left[{(\sigma_3 + P_a)}/{P_a} \right] \right\}. \quad (4)$$

As a result, the approach to predict the nonlinear shear strength of in-situ sandy gravel may be summarized as follows: (1) select a preparation technique to reduce the original PSD of in-situ sandy gravel to PSDs with different d_M, and conduct the triaxial test of the soil with that d_M in the laboratory; (2) perform triaxial tests, then based on the triaxial test data of the specimens with different d_M, use Eqs. (1) and (2) to calculate the value of a, b, c, and e for the specimens prepared by the given preparation technique; and (3) put the d_M of the in-situ sandy gravel into Eq. (4) to predict the shear strength of in-situ sandy gravel under a different stress state.

The linear shear strength τ of sandy gravel is often calculated by Eq. (5) according to the Mohr-Coulomb strength theory:

$$\tau = c + \sigma \tan\phi', \quad (5)$$

where c and ϕ' are the cohesion and effective internal friction angle, respectively.

Equation (5) was fitted to the test data of S10-S60. As shown in Table 2, c and ϕ' increased with increasing d_M for the test specimens prepared by the same preparation technique. The test data are plotted in Fig. 5, and the relationship can be described by

$$\begin{cases} \phi' = m d_M^n \\ c = g d_M^h, \end{cases} \quad (6)$$

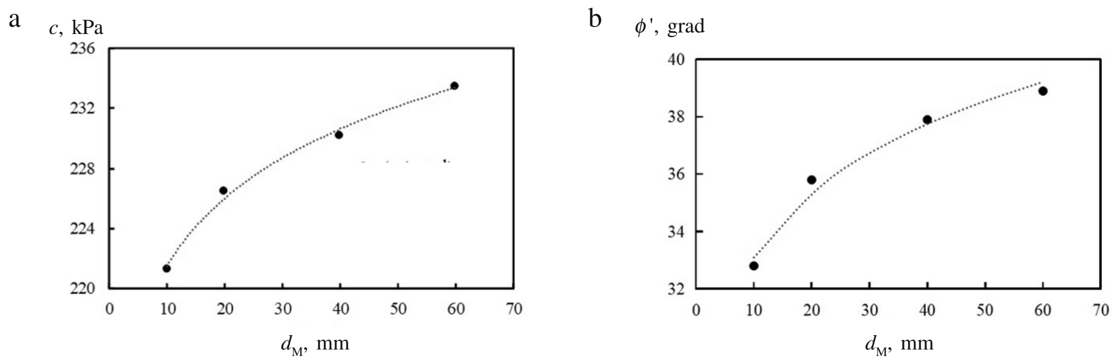

Fig. 5. Relationship of c(a) and ϕ'(b) versus d_M.

where m, n, g, and h are fitting parameters. The values of m, n, g, and h for S10-S60 are 26.6, 0.095, 207.14, and 0.029, respectively.

Equation (6) was used to fit the test data of S60-S10 for verification purposes. The fitting curves are shown in Fig. 5 by dotted lines. The curves showe high agreement with the test data, and Eq. (6) can describe the relationship of c and d_M as well as ϕ' and d_M.

Combining Eq. (5) and Eq. (6),

$$\tau = g d_M^h + \sigma \tan(m d_M^n). \tag{7}$$

Conclusions

In this study, the replacement technique and mixed method were used to reduce the particle size of a gravel and a rockfill, respectively, and a number of CD triaxial tests for the test specimens were carried out.

According to the results of the triaxial test, the nonlinear shear strength formula proposed by Duncan, and the linear shear strength formula according to Mohr-Coulomb strength theory, were shown to be applicable for sandy gravel. Based on the two formulas, an empirical equation of the nonlinear or linear shear strength versus stress state and maximum grain size of the sandy gravel was established and verified, and an approach to estimate the nonlinear shear strength of in-situ sandy gravel was proposed, which could be used to accurately analyze the stability of natural slopes and rockfill structures.

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