Research Article

Practical Approach to Predicting the K_0 Behavior of In Situ Sandy Gravel

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To investigate the scale effect on at-rest earth pressure coefficient K_0 for sandy gravel, a number of K_0 tests for sandy gravel were performed by using a new-developed large-size K_0 apparatus. The test samples with different maximum particle size d_M are prepared by different techniques, and the scale effect on K_0 behavior of sandy gravels is investigated. It is found that the vertical stress σ_v , preparation technique and d_M all have some influence on the value of K_0 for the tested sandy gravels. Since different d_M or preparation techniques all induce the scale effect, the scale effect on K_0 of sandy gravel can not be ignored. Based on the test data of sandy gravel, a description of K_0 considering scale effect as well as σ_v is proposed and an approach to predict the K_0 behavior of sandy gravel in situ is obtained. Furthermore, the accuracy and applicability of the approach is verified.

1. Introduction

The at-rest earth pressure coefficient K_0 is defined as the ratio of the effective horizontal stress versus vertical stress. It is a basic mechanic parameter of the soils in many practical engineering works such as slope [1] and tunnel [2] but is relatively difficult to determine.

The mechanical properties of soil essentially depend upon the stress state, and therefore, accurate measurement of the initial stress state plays an important role in analyzing and designing the earthworks. In general, the vertical stress, σ'_v , of a ground is calculated according to the bulk density of soil and the depth, and then the evaluation of initial stress state can be done by using the K_0 value. In fact, sandy gravels are usually adopted as filling materials in many earthworks such as heavily loaded railway and earth dam, and the evaluation of K_0 of sandy gravel is important in the analysis and design of the earthworks. Therefore, the investigation to

K_0 behavior of sandy gravels has great theoretical significance and practical value.

In the actual project, for example, earth rockfill dam, the maximum grain size d_M of sandy gravel can reach 800~1200 mm [3]. Due to the dimensional limitation of the laboratory instruments, preparation techniques, such as scalping technique [4], replacement technique [5], and parallel gradation technique [6], are used to reduce the grain size distribution (GSD) of in situ sandy gravel. In scalping technique, the oversize particles were removed from the soil in situ. In replacement technique, the oversize particles are replaced in proportion by the particles with the size less than d_M and more than 5 mm. In parallel gradation technique, the GSD of reduced particle size tested specimen is parallel to that of the soil in situ.

Due to the difference between GSD of test specimens and that of sandy gravel in situ, the mechanical properties of test specimen are always different from that of sandy gravel in situ, which is called scale effect [7].

Wide ranges of investigations to the scale effect on mechanical properties of soil have been published. Some researchers [8–11] have studied the scale effect on the shear strength of soil. Abu-Farsakh and Yu [12] and Wei et al. [13] have found that there is a big difference between the compression behavior of in situ soil and that measured in the laboratory. The published works [14, 15] point out that the scale effect on the particle crushing of sandstone particle mixtures is obvious. Chang et al. [16] have investigated the scale effect on the minimum void ratio of granular soil. Wang et al. [17] used PFC2D to analyze the scale effect on the key physical parameters of soil such as maximum dry density, initial elasticity modulus, and bulk modulus of coarse-grained soil. However, the relevant research about the scale effect on K_0 of sandy gravel is almost blank. Therefore, the investigation to scale effect on K_0 of sandy gravel still needs to make further studies.

In this study, K_0 tests for sandy gravel were conducted using a new-developed K_0 test apparatus. Based on the test results, the scale effect on K_0 of sandy gravel is investigated, and an approach to predict the K_0 behavior of sandy gravel is studied.

2. Testing Apparatus and Programme

2.1. Testing Apparatus. In this study, the K_0 test apparatus is newly developed by the authors and can be used for the most soils including sandy gravel. The apparatus, as shown in Figure 1, is similar to the oedometer, and its test principle will be introduced as follows.

In Figure 1, four force sensors (10) are adopted to fix the two rigid cylinders (6) and measure the total pressure N_h loaded on the test specimen, and the effective Horizontal stress σ'_h loaded on the test specimen can be expressed as

$$\sigma'_h = \frac{N_h}{(h - \Delta h)d}, \quad (1)$$

where d and h are the diameter and initial height of test specimen, respectively and Δh is the compression of test specimen during test, and obtained by the displacement sensor (11).

To diminish the influence of sidewall friction F between the rigid cylinders (6) and test specimen, according to Wang et al. [18], the arithmetic average of top and bottom effective vertical pressure is used as the vertical pressure applied to the test specimen, and the effective vertical stress σ'_v loaded on the test specimen can be calculated as

$$\sigma'_v = \frac{N_v + (N_v - F)}{2A} = \frac{4(N_v - F/2)}{\pi d^2}, \quad (2)$$

where N_v is the vertical pressure loaded on the top surface of test specimen and measured by load sensor (12). F is the sidewall friction and measured by four load sensor (3). $(N_v - F)$ is the vertical pressure loaded on the bottom surface of test specimen.

As a result, the K_0 value can be obtained according to Equation (3). For the detailed introduction and the calibration of this apparatus, it can be seen in the work [19].

$$K_0 = \frac{\sigma'_h}{\sigma'_v} = \frac{(N_h / (h - \Delta h)d)}{(4(N_v - F/2) / \pi d^2)}. \quad (3)$$

2.2. Programme and Testing Methods. The soil tested is a calcareous fluvial gravel with rounded grains, which is retrieved from Cihaxia rockfill dam, located in western China, as shown in Figure 2.

Due to the large particle size, the GSD of sandy gravel in situ is reduced to GSDs with different d_M ranging from 10 mm to 60 mm for lab test of this paper. The scalping technique [4], replacement technique [5], and parallel gradation technique [6] are used to reduce the GSD, and the test specimens are referred to as S1~S4 (series of test specimens prepared by scalping technique, called “S series”), P1~P4 (ones by parallel gradation technique, called “P series”) and R1~R4 (ones by replacement technique, called “R series”), respectively. The GSD and corresponding maximum grain size d_M of each test specimen are given in Table 1.

The height and diameter of test specimen is 30 cm and 40 cm, respectively, and all test specimens are air-dried and uncompacted. Since the difference, between the initial dry density of every test specimen and the test data of minimum dry density test, is less than 1%, the relative density of each test specimen can be seen as 0. The initial dry density of every test specimen is shown in Table 1 and Figure 3.

During test, with 10 kPa/min, σ'_v loaded on the test specimen from 100 kPa to 2000 kPa was applied step by step. When σ'_v reached the predetermined value, σ'_v was kept constant for 15 minutes and then the reading of each sensor was recorded. When σ'_v reached 2000 kPa, σ'_v was kept constant for 150 minutes, and then, the reading of each sensor was recorded. Afterward, σ'_v was reduced to zero with unloading stress rate of 10 kPa/min. When σ'_v reached the predetermined load during unloading, σ'_v was kept constant for 15 minutes and then reading of each sensor was recorded.

3. Interpretation of Experimental Results

Based on the K_0 test results of S1~S4 (S series), P1~P4 (P series), and R1~R4 (R series), the K_0 behavior of sandy gravel is investigated. The relationship between K_0 and σ'_v are plotted in Figures 4(a)–4(c), respectively. Figure 4 shows that the K_0 value of every test specimen tends to decrease with the increment of σ'_v , which is consistent with the published works [20–25]. Therefore, studying the relationship of K_0 and σ'_v has important theoretical significance. Based on the test data of sandy gravels, Zhu et al. [25] proposed a $K_0 - \sigma'_v$ correlation for sandy gravel:

$$K_0 = \frac{K_{0\max} + K_{0\min} \sqrt{\sigma'_v / p_a}}{\sqrt{\sigma'_v / p_a} + 1}, \quad (4)$$

where p_a is standard atmospheric pressure, $K_{0\max}$ and $K_{0\min}$ are fitting parameters. The physical meanings of $K_{0\max}$ and $K_{0\min}$ are the K_0 value when $\sigma'_v = 0$ and $\sigma'_v \rightarrow \infty$, respectively.

FIGURE 1: Sketch map of test equipment. (a) Sketch map of the apparatus. (b) Photo of the apparatus. (c) Top view of the apparatus (1, base; 2, baseplate; 3, load sensor; 4, steel ball; 5, the bottom force transmission plate; 6, semicircle rigid cylinders; 7, the top force transmission plate; 8, pressure plate; 9, compression plate; 10, pull pressure sensor; 11, displacement sensor; 12, load sensor; 13, loading frame; 14, load cylinder).

In order to verify Equation (4), the test data of S1~S4, R1~R4 and P1~P4 are fitted by Equation (4), and the fitting parameters and curves are shown in Table 2 and Figure 4, respectively. It can be seen from Figure 4 that the fitting curves agree well with the corresponding test data. Compared with the corresponding test data, the errors of the K_0 value predicted by Equation (4) are mostly below 2% and the maximum error is only 5.9%. Therefore, Equation (4) can describe well the relationship of K_0 and σ'_v .

To analyze the influence of d_M on K_0 of sandy gravel, the K_0 behaviours of test specimens in terms of d_M are investigated as plotted in Figures 4(a)–4(c). Figures 4(a)–4(c) show that increasing d_M tends to decrease the K_0 value with the same σ'_v loaded on test specimen, which means that d_M has a significant effect on the K_0 .

To investigate the influence of preparation technique on K_0 of sandy gravel. The $K_0 - \sigma'_v$ curves of the tested specimens modified by different preparation techniques with the

FIGURE 2: Photo of tested sample ($40 \text{ mm} < d_M < 60 \text{ mm}$).

same d_M are presented in Figure 5. Due to limited space, only the tested specimens with $d_M = 20 \text{ mm}$ are plotted in Figure 5, and the test results of test specimens with $d_M = 10 \text{ mm}$ and 40 mm indicate a consistent trend. It can be

TABLE 1: Basic property of tested soil and specimens.

Test specimen	d_M (mm)	Initial dry density (g/cm^3)	Grain groups content (%)					
			100~60	60~40	40~20	20~10	10~5	<5
Original GSD*	100	—	21.87	12.25	16.51	12.76	8.14	28.46
S1	60	2.05	—	15.68	21.13	16.33	10.42	36.43
S2	40	2.03	—	—	25.06	19.39	12.36	43.20
S3	20	1.96	—	—	—	25.85	16.49	57.66
S4	10	1.90	—	—	—	—	22.23	77.74
R1	60	2.01	—	17.64	23.79	18.38	11.73	28.46
R2	40	2.01	—	—	31.58	24.39	15.56	28.46
R3	20	1.94	—	—	—	43.68	27.86	28.46
R4	10	1.91	—	—	—	—	71.54	28.46
P1	60	2.01	—	18.30	21.00	14.20	12.30	34.20
P2	40	1.95	—	—	27.60	18.90	13.70	39.80
P3	20	1.89	—	—	—	27.60	18.50	53.90
P4	10	1.82	—	—	—	—	27.60	72.40

Note. Original GSD represents the GSD of the soil in situ.

FIGURE 3: Grain size distribution (PSD) curves of tested materials. (a) S1~S4, (b) P1~P4, and (c) R1~R4.

FIGURE 4: $K_0 - \sigma'_v$ curves. (a) S1~S4, (b) R1~R4, and (c) P1~P4.

seen from Figure 5 that there is a certain difference between the K_0 values of the test specimens prepared by different preparation techniques and the maximum difference can reach 22%. Therefore, preparation technique has some influence on the K_0 behavior of sandy gravel.

As discussed above, d_M and preparation technique all have some influence on K_0 of test specimen, and different d_M or preparation techniques all induce the scale effect. Therefore, the scale effect on K_0 of sandy gravel can not be ignored. This observation indicates that the laboratory test data can not reflect the accurate K_0 value of sandy gravel in situ, and therefore, the approach to accurately predict the K_0 behavior of in situ sandy gravel based on the laboratory test data is investigated in the next section.

4. The Approach to Predict K_0 Behavior of Sandy Gravel In Situ

As mentioned above, K_0 of each test specimen varies evidently with the variations of d_M or preparation technique. This means that there is some relationship between K_0 and

TABLE 2: $K_{0\max}$ and $K_{0\min}$ of the test specimens.

Preparation technique	d_M (mm)	10	20	40	60
Scalping technique	Test specimen	S4	S3	S2	S1
	$K_{0\max}$	1.042	1.006	0.972	0.953
	$K_{0\min}$	0.312	0.304	0.296	0.291
	R^2	0.998	0.997	0.997	0.975
Replacement technique	Test specimen	R4	R3	R2	R1
	$K_{0\max}$	0.935	0.914	0.892	0.880
	$K_{0\min}$	0.311	0.297	0.284	0.277
	R^2	0.997	0.997	0.994	0.997
Parallel gradation technique	Test specimen	P4	P3	P2	P1
	$K_{0\max}$	0.970	0.926	0.885	0.861
	$K_{0\min}$	0.324	0.313	0.302	0.296
	R^2	0.999	0.996	0.997	0.995

GSD of sandy gravel. On the other hand, for a given in situ sandy gravel, if the preparation technique is the same, the GSD of test specimen are principally determined by d_M [26],

FIGURE 5: $K_0 - \sigma'_v$ curves under different preparation techniques ($d_M = 20$ mm).

and therefore, there may be some relationship of K_0 and d_M for test specimens prepared by the same preparation technique. If the relationship of K_0 and d_M can be obtained, the K_0 behavior of the sandy gravel in situ can be extrapolated by using the $K_0 - d_M$ relation. In theory, extrapolating may not be reliable. However, due to the large particle size, the laboratory K_0 test for sandy gravel with original GSD can not be performed directly, and extrapolating is adopted by some scholars [27, 28] as an acceptable approach.

According to Equation (4), if $K_{0\max}$ and $K_{0\min}$ of in situ sandy gravel is determined, the K_0 behavior of in situ sandy gravel can then be predicted. Therefore, if the relationship of $K_{0\max}$ and $K_{0\min}$ versus d_M can be obtained, the $K_{0\max}$ and $K_{0\min}$ of the sandy gravel in situ can be extrapolated by using this relation from test data, and the K_0 behavior of the sandy gravel in situ can be predicted using Equation (4) with the corresponding $K_{0\max}$ and $K_{0\min}$.

To further study the relationship of $K_{0\max}$ and d_M , the test results of specimens prepared by scalping technique and replacement technique, i.e., the S series tests and R series tests, are illustrated in $(1 - (d_{M1}/d_{M2})) \sim \ln(K_{0\max 1}/K_{0\max 2})$ plane, as shown in Figure 6, where $K_{0\max 1}$ and $K_{0\max 2}$ are the $K_{0\max}$ value of test specimen with d_{M1} and d_{M2} , respectively. Figure 6 shows that the relationship between $(1 - (d_{M1}/d_{M2}))$ and $\ln(K_{0\max 1}/K_{0\max 2})$ is nonlinear and positive. Fitting with a power function curve to data points, the fitting curves are plotted in Figure 6. As shown in Figure 6, the fitting curves have a good agreement with the corresponding test data. Compared with the test data, the maximum errors of predicted value is less than 10%. Therefore, an equation, to describe the relationship of $K_{0\max}$ and d_M , is obtained:

$$\ln \frac{K_{0\max 1}}{K_{0\max 2}} = c_0 \left(1 - \frac{d_{M1}}{d_{M2}} \right)^{c_1}, \quad (5)$$

where d_{M1} and d_{M2} are the maximum particle size of test specimens with different GSD prepared by the same preparation technique, and $d_{M1} < d_{M2}$; $K_{0\max 1}$ and $K_{0\max 2}$ are

FIGURE 6: $(1 - (d_{M1}/d_{M2})) \sim \ln(K_{0\max 1}/K_{0\max 2})$ fitting curves for S1~S4 and R1~R4.

the $K_{0\max}$ value of test specimen with d_{M1} and d_{M2} ; and c_0 and c_1 are fitting parameters.

In a similar way, the relationship of $K_{0\min}$ in Equation (4) and d_M may be expressed as

$$\ln \frac{K_{0\min 1}}{K_{0\min 2}} = c_2 \left(1 - \frac{d_{M1}}{d_{M2}} \right)^{c_3}, \quad (6)$$

where d_{M1} and d_{M2} are the maximum particle size of test specimens with different GSD prepared by the same preparation technique, and $d_{M1} < d_{M2}$; $K_{0\min 1}$ and $K_{0\min 2}$ are the $K_{0\min}$ value of test specimen with d_{M1} and d_{M2} ; and c_2 and c_3 are fitting parameters.

To verify Equations (5) and (6), $K_{0\max}$ and $K_{0\min}$ and corresponding d_M of P1, P2, and P4 test specimens with $d_M = 10, 40$, and 60 mm prepared by parallel gradation technique are put into Equations (5) and (6), respectively, and the corresponding c_0, c_1, c_2 , and c_3 are determined. For example, for $d_{M1} = 10$ mm and $d_{M2} = 40$ mm, the corresponding $K_{0\max}$ are 0.97 and 0.885 (Table 2), and substituting in Equation (5), an equation with unknowns of c_0 and c_1 is established. Similarly, for $d_{M1} = 10$ mm and $d_{M2} = 60$ mm, another equation is established. Combining these two equations, c_0 and c_1 can be found, and they are 0.115 and 1.609. In a similar way, for Equation (6), c_2 and c_3 are determined, and they are 0.117 and 1.603.

Using Equations (5) and (6) with $K_{0\max}$, $K_{0\min}$, and corresponding d_M of P1, P2, and P4, when c_0, c_1, c_2 , and c_3 are determined, $K_{0\max}$ and $K_{0\min}$ of P3 can be listed in Table 3. It can be seen from Table 3 that based on the test results of P1, P2, and P4, the predicted $K_{0\max}$ and $K_{0\min}$ of P3 are almost the same. Compared with the fitting value given by Equation (4), the maximum error of predicted value is only 1%. Therefore, Equations (5) and (6) are applicable to describe the relationship of $K_{0\max}$ and $K_{0\min}$ versus d_M , respectively.

The arithmetic average of three groups of values predicted by Equations (5) and (6) is used as the predicted

TABLE 3: Predicted $K_{0\max}$ and $K_{0\min}$ of P3.

	P1	P2	P4	Eq. (4)	Maximum difference
$K_{0\max}$	0.924	0.932	0.933	0.926	1%
$K_{0\min}$	0.312	0.314	0.315	0.313	0.9%

$K_{0\max}$ and $K_{0\min}$ of P3. Using Equation (4) with predicted $K_{0\max}$ and $K_{0\min}$ of P3, the $K_0 - \sigma'_v$ fitting curve of P3 is obtained and plotted in Figure 7. It can be seen from Figure 7 that the predicted $K_0 - \sigma'_v$ curves have a good agreement with the corresponding test results. The difference between the K_0 value predicted by Equation (4) and the corresponding test result is less than 4.2%. This observation shows that based on the test data of test specimens with different d_M prepared by a given preparation technique, Equation (4) combined with Equations (5) and (6) can predict well the K_0 behavior of sandy gravels with another d_M prepared by the same preparation technique.

Therefore, based on the test data of test specimens prepared by a given preparation technique, $K_{0\max}$ and $K_{0\min}$ of sandy gravel in situ can be calculated using Equations (5) and (6), and then the K_0 behavior of sandy gravel in situ can be predicted using Equation (4) with corresponding $K_{0\max}$ and $K_{0\min}$ of sandy gravel in situ.

Based on the method discussed above, Equations (5) and (6) are used to fit the test data of test specimens prepared by three preparation technique, and the corresponding fitting parameters are obtained and given in Table 4. As shown in Table 4, the fitting parameters of test specimens prepared by three preparation techniques that are different, which indicates that parameters of Equations (5) and (6) can be only adopted for the same preparation technique.

Using Equation (4) with predicted $K_{0\max}$ and $K_{0\min}$ of sandy gravel in situ, $K_0 - \sigma'_v$ curves of sandy gravel in situ can be predicted as given in Figure 8. Figure 8 shows that the predicted K_0 behaviors of sandy gravel in situ for three preparation techniques are different; however, the maximum difference is below 8%, and thus, the difference may be almost ignored. Therefore, Equation (4) combined with Equations (5) and (6) can predict well the K_0 behavior of sandy gravel in situ.

As mentioned above, the approach to estimate the K_0 behavior of in situ sandy gravel can be summarized as (a) using the same preparation technique to reduce the original GSD of in situ sandy gravel to GSDs of test specimen with different d_M , (b) performing the laboratory K_0 test for those test specimens (c) using Equation (4) to fit the test data and obtain the $K_{0\max}$ and $K_{0\min}$ of test specimens, (d) using Equations (5) and (6) with $K_{0\max}$, $K_{0\min}$, and corresponding d_M of test specimens, $K_{0\max}$ and $K_{0\min}$ of sandy gravel in situ are calculated, and (5) using Equation (4) with $K_{0\max}$ and $K_{0\min}$ of sandy gravel in situ, the K_0 behavior of in situ sandy gravel can be predicted.

5. Conclusions

In this study, scalping technique, replacement technique, and parallel gradation technique are adopted to reduce the

FIGURE 7: Testing and predicting $K_0 - \sigma'_v$ curves for P3.

TABLE 4: Fitting parameters of the tested specimen.

Preparation technique	c_0	c_1	c_2	c_3	$K_{0\max IS}$	$K_{0\min IS}$
Scalping technique	0.109	1.594	0.081	1.483	0.934	0.287
Replacement technique	0.075	1.588	0.144	1.622	0.868	0.27
Parallel gradation technique	0.142	1.546	0.111	1.593	0.84	0.29

FIGURE 8: Prediction of $K_0 - \sigma'_v$ curves under different preparation method.

GSD of in situ sandy gravel to GSDs of test specimen with different d_M , and the K_0 tests for the test specimens were performed using a large-size K_0 test apparatus. According to the test result, the conclusions are drawn as follows:

- (1) K_0 of sandy gravel tends to decrease with the increasing σ'_v , and therefore the influence of σ'_v should be taken into consideration when investigating K_0 behavior of sandy gravel.

- (2) d_M and preparation technique all have some influence on K_0 of test specimen, and different d_M or preparation techniques all induce the scale effect. Therefore, the scale effect should be taken into consideration when using K_0 test results to study the K_0 behavior of sandy gravel in situ.
- (3) Based on K_0 test results, an approach to predict the K_0 behavior of sandy gravel in situ is proposed and verified.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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