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EDITED BY

Jiangyu Wu,
China University of Mining and
Technology, China

REVIEWED BY

Erlu Wu,
Shaoxing University, China
Shiyuan Huang,
Chongqing Jiaotong University, China

*CORRESPONDENCE

Yunfei Sun,
✉ 2210302072@st.gxu.edu.cn

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Triaxial compression test of shear strength parameters of rock-fill materials considering scale effect

Xia Li¹, Xinggong Shen¹, Jun Du¹, Yunfei Sun^{2,3,4*}, Haoran Jin^{2,3,4},
Jian Gong^{2,3,4} and Mingjie Jiang^{2,3,4}

¹College of Architecture and Civil Engineering, Kunming University, Kunming, Yunnan, China, ²College of Civil Engineering and Architecture, Guangxi University, Nanning, Guangxi, China, ³Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Guangxi University, Nanning, Guangxi, China, ⁴Key Laboratory of Disaster Prevention and Mitigation and Engineering Safety of Guangxi, Nanning, Guangxi, China

Soil mass stability refers to the ability of soil to resist deformation and failure under external loads, and it is a fundamental consideration in geotechnical engineering, particularly for large-scale infrastructure such as earth-rock dams and slopes. This stability is primarily determined by the soil's shear strength, which defines the internal resistance of the soil to sliding along potential failure planes. A major challenge in accurately predicting the shear strength of coarse-grained soils is the scale effect, where laboratory test results on small-scale specimens may not fully represent the behavior of large-scale soil masses encountered in real-world applications. To address this issue, this study investigates the influence of two key factors—the maximum particle diameter ($d_{\max}$) and the gradation structure, quantified by the gradation area (S)—on the shear strength of coarse-grained soils. We designed 21 distinct soil specimens with varying $d_{\max}$ and S values to simulate natural soil gradations, and conducted large-scale triaxial compression tests to explore the relationship between these parameters and shear strength indicators, namely, cohesion (c) and internal friction angle (ϕ). The results show that increasing $d_{\max}$ enhances both cohesion and internal friction due to stronger interlocking between particles, while a higher gradation area (S), reflecting a broader particle size distribution, reduces these parameters as uneven stress distribution weakens the soil structure. Based on these observations, we propose a shear strength prediction model that incorporates the scale effect, which has been validated using independent datasets from a range of coarse-grained soils.

KEYWORDS

coarse-grained soil, scale effect, shear strength parameter, particle gradation, triaxial compression test

1 Introduction

In large-scale engineering projects, such as high earth-rock dams, measuring the shear strength of coarse-grained soils poses significant challenges due to limitations in existing test instruments, which cannot replicate the real-life gradation of soil particles. Scaling down the gradation for laboratory tests results in discrepancies that hinder the accurate determination of shear strength parameters, which are crucial for designing safe and reliable geotechnical structures.

Contemporary progress in soil mechanics and geotechnical engineering has significantly enhanced our knowledge of coarse-grained soil's properties and behaviors. The wide application of coarse-grained soil in engineering, especially in high earth-rock dams, has made its shear strength a key research focus. In practical applications, particularly in high earth-rock dams, the maximum particle diameter of coarse-grained soil can range from 800 to 1,000 mm (Guo, 2003). However, the size limitations of existing test instruments render it impossible to directly measure the shear strength parameters of coarse-grained soil through tests, and the original gradation must be scaled down (Ministry of Housing and Urban-Rural Development of the People's Republic of China, State Administration for Market Regulation, 2019). According to the existing research, however, the test results after scaling cannot accurately reflect the strength with the original gradation regardless of the scaling method, i.e., the scale effect. Consequently, investigating the impact of the scale effect on the shear strength of coarse-grained soil is essential.

International scholars have been rigorously investigating the implications of the scale effect on the strength of coarse-grained materials. In experiments using specimens with consistent dry density, a trend emerges showing a decline in shear strength as the maximum particle diameter increases. For example, Marsal (1967), Marschi et al. (1972), Varadarajan et al. (2003), Kong et al. (2019), and Meng and Shi (1983) proved through experiments that the shear strength decreased with the increase of the particle $d_{\max}$.

Despite using specimens with equivalent relative density, there remains a lack of agreement on how the scale effect impacts shear strength (Weng et al., 2009). Opinions among researchers vary; Li et al. (2001) and Li et al. (2008), for instance, argue that the internal friction angle φ rises as the maximum particle diameter $d_{\max}$ increases. On the other hand, Lee (1992) and Hu et al. (2011) argue that the maximum particle diameter $d_{\max}$ has negligible impact on the peak internal friction angle φ . Meanwhile, Wei et al. (2008) discovered that φ increases with reduced fine particle content, and Li and Xing (2006) found that φ remains stable at low levels of fine particle content but decreases rapidly with an increase in this content.

In summary, to summarize, the complexities involved in scaling methods, gradation properties, and specimen preparation density make it challenging to quantitatively define the relationship between the mechanical properties of scaled specimens and their original gradation counterparts. This results in a gap in the quantitative understanding of shear strength variation in coarse-grained soil post-scaling (Marsal, 1967; Marschi et al., 1972; Li et al., 2008). Consequently, there is a significant need for quantitative experimental research to investigate the scale effect's impact on the shear strength of coarse-grained soil.

Zhu et al. (2018) collated the common soil gradation curve patterns observed in global engineering endeavors and introduced an equation to precisely characterize coarse-grained soil gradation, as shown in Equation 1.

$$P = \frac{1}{(1-b)(d_{\max}/d)^m + b} \times 100\% \quad (1)$$

In this context, P represents the proportion of soil particles smaller than a given diameter d (%), d signifies the diameter of the soil particles (mm), $d_{\max}$ is the maximum diameter within the soil mass

(mm), while b and m are parameters in the gradation equation, influencing the gradation curve's shape and slope.

As noted by Wu et al. (Wu et al., 2019; Shi et al., 2024; Shi et al., 2023; Wu et al., 2020a; Wu et al., 2020b), the key variances between scaled specimens and their original-gradation counterparts are evident in aspects such as maximum particle diameter and particle gradation structure, independent of the specified scaling methods (China Planning Press). Consequently, the scale effect is seen as a consequence of the interplay between changes in the specimen's maximum particle diameter and its gradation structure.

This study undertook a detailed exploration of the scale effect on coarse-grained soil's shear strength by designing 21 different groups of specimens, each varying in maximum particle diameter or gradation structure, yet maintaining consistent initial relative compaction. Triaxial shear tests were then executed on these specimens. The study applied a single-variable method to specifically assess the impacts of maximum particle diameter and gradation structure on the coarse-grained soil's shear strength, aiming to quantitatively determine the laws influencing the scale effect on this property. Additionally, the study extrapolated the shear strength of the original-gradation coarse-grained soil in actual field conditions from the results of these indoor tests. It is anticipated that the outcomes of this research will significantly reduce the scale effect on coarse-grained soil's shear strength, leading to improvements in the safety and reliability of geotechnical engineering designs.

The outcomes of this research are expected to offer valuable insights into reducing the scale effect on the shear strength of coarse-grained soil, which in turn could enhance the safety and reliability of geotechnical engineering designs, particularly in large-scale projects such as tunnels, embankments, and dams.

2 Coarse-grained soil triaxial test

2.1 Test equipment

The experimental trials were carried out on a DJSZ-150 large-scale triaxial testing machine, suitable for both dynamic and static analyses of coarse-grained soil, showcased in Figure 1, located at the Kunming Institute's Geotechnical Engineering Experiment Center. The testing machine can facilitate dynamic and static loading on soil specimens with a size of $\Phi 300 \text{ mm} \times 600 \text{ mm}$ and can achieve different stress path conditions. It includes axial loading systems, a confining pressure loading system, and a loading servo control system. The testing machine can provide a maximum confining pressure of 3.0 MPa and static loads of 0–1,500 kN, and the test data are automatically acquired by computer. According to the Standard for Geotechnical Testing Method (GB/T50123-2019) (China Planning Press), the particle size of the tested soil material should be less than 1/5 to 1/6 of the instrument size, that is, the testing machine can facilitate triaxial consolidation drained shear tests on specimens with a maximum particle diameter of 60 mm. Through preliminary tests, the confining pressure of this test was determined as 400, 800, and 1,200 kPa, and the loading rate was set to 1 mm/min.

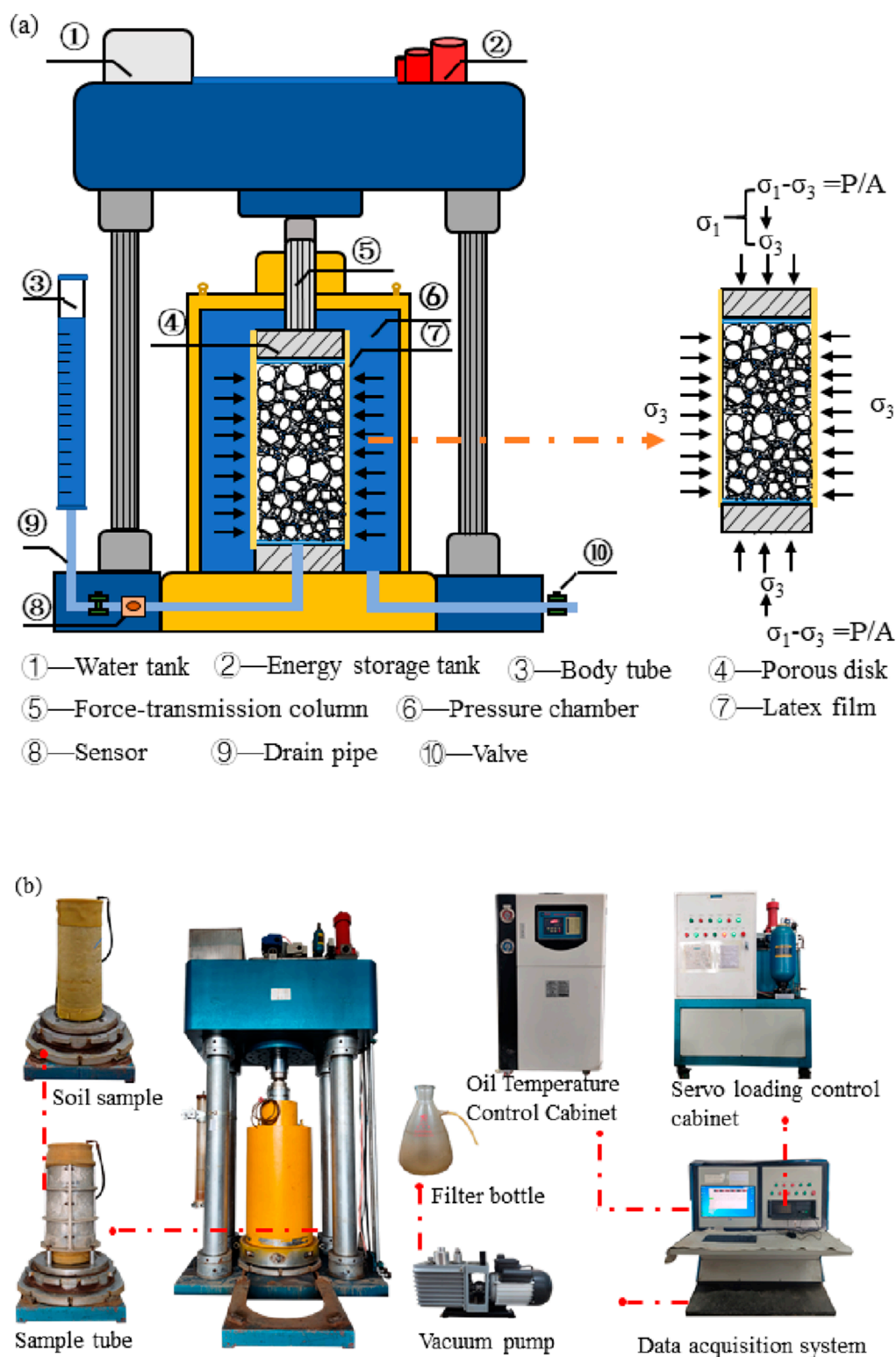


FIGURE 1
DJSZ-150 large coarse grained soil dynamic and static triaxial testing machine structure principle diagram (A) and physical diagram (B).

2.2 Test materials

The test material was selected from the rockfill material for the dam of the Lincang Daqiaopo Reservoir in Yunnan Province,

granular gravel obtained after blasting and processing. This sample originates from slightly weathered granite, exhibiting an average saturated uniaxial compressive strength of 50 MPa, along with a softening coefficient of 0.79, and a specific gravity of 2.70.



Particle screening tests were conducted on the obtained original-gradation specimens using a sieve shaker, and the particle fractions with particle diameters of 60~40 mm, 40~30 mm, 30~20 mm, 20~10 mm, 10~5 mm, 5~2 mm, and <2 mm were retained as soil material for specimen preparation (Figure 2).

2.3 Test protocol

Previous studies indicate that both the maximum particle diameter and gradation area significantly influence the strength of coarse-grained soil. In the earth-rock dam project, the commonly used value intervals of the grading parameters m and b of coarse-grained soil are: $0 < m < 2$ and $-2 < b < 1$. Therefore, this paper designs a total of 21 groups of grading samples by setting a series of parameters m and b . The maximum and minimum dry densities of these soil specimens were established through compaction testing. A relative compaction rate of 0.85 was maintained throughout the preparation of specimens for the triaxial compression tests. Gradation parameters and densities used in preparing the 21 groups of specimens are systematically listed in Table 1. Groups S1-40 through S9-40, encompassing nine specimen sets, share the same maximum particle diameter but differ in gradation areas. Their gradation curves are illustrated in Figure 3A. The specimen groups D1-40 to D1-10, D2-40 to D2-10, and D3-40 to D3-10, each comprising four specimens, are categorized by consistent gradation areas but varying maximum particle diameters, adding up to 12 specimens in these three groups. Their gradation curves can be viewed in Figure 3B. D1-60, D2-60, and D3-60 are three groups of specimens for validation experiments, and their corresponding gradation curves are shown in Figure 3C.

3 Scale effect research methods

The gradation area S is enclosed by the gradation equation curve, the horizontal axis of the coordinates, the maximum particle diameter line $d = d_{\max}$, and the $d = d_{\max 0}$ line (Wu et al., 2019; Wu et al., 2020a), as shown in Figure 4. It can be calculated as follows:

$$S = \frac{\ln(1 - kb) - \ln(1 - b)}{mb \ln 10} \quad (2)$$

where

$$k = \frac{1}{(1 - b)(d_{\max}/d_{\max 0})^m + b} \quad (3)$$

As per Equations 2, 3, the gradation area S is defined by the variables $d_{\max}$, m , and b . When $d/d_{\max 0}$ is set as a fixed value, S becomes exclusively dependent on the gradation parameters b and m . The gradation area S , being indicative of changes in gradation structure, which is governed by parameters b and m , acts as a key characteristic parameter in this context.

Parameters $d_{\max}$ and S , as outlined in Equations 2, 3, serve to quantitatively assess the impacts of maximum particle diameter $d_{\max}$ and gradation structure on the strength attributes of coarse-grained soil. Through correlating $d_{\max}$ and S with shear strength parameters like cohesion (c) and internal friction angle (φ), one can elucidate the governing principles of gradation structure on the strength of coarse-grained soil.

Guo (2003) proposed a boundary particle diameter of 5 mm to distinguish between sand and gravel. Based on this definition, this study established a maximum particle diameter $d_{\max}$ of 40 mm and a reference diameter $d_{\max 0}$ of 5 mm. This configuration enables the use of the single-variable method to investigate the effects of maximum particle diameter on the shear strength parameters of coarse-grained soil. The method requires that the gradation area S remains constant before and after scaling to ensure accurate comparisons.

To conclude, the application of the single-variable method, coupled with testing a range of specimens either having identical maximum particle diameters but varying gradation areas, or uniform gradation areas with differing maximum particle diameters, offers a viable approach to investigate how maximum particle diameter and gradation structure correlate with shear strength parameters.

4 Analysis of test results

Table 2 presents the values of soil C and f_{ai} obtained from 21 sets of large-scale triaxial tests.

4.1 The association between shear strength parameters and maximum particle diameter

The triaxial compression test results for specimens D1-40 to D3-10 allow for summarizing the relationship between the maximum particle diameter $d_{\max}$ and the shear strength parameters c and φ , which are presented as discrete data points in Figures 5A,B. As

TABLE 1 Summary of test soil sample gradation parameters and sample preparation density.

Test number	$d_{\max}/\text{mm}$	m	b	S	$\rho_{\min}/(\text{g}\cdot\text{cm}^{-3})$	$\rho_{\max}/(\text{g}\cdot\text{cm}^{-3})$	$\rho_0/(\text{g}\cdot\text{cm}^{-3})$
S1-40	40	1.2	−0.6	0.272	1.56	1.78	1.74
S2-40	40	1.2	0.2	0.381	1.67	1.85	1.82
S3-40	40	0.9	0.2	0.475	1.75	1.9	1.88
S4-40	40	0.9	0.4	0.533	1.78	1.95	1.92
S5-40	40	0.9	0.6	0.617	1.69	1.97	1.92
S6-40	40	1.2	0.8	0.645	1.66	1.95	1.92
S7-40	40	0.6	0.4	0.671	1.72	2.00	1.95
S8-40	40	0.6	0.6	0.754	1.80	2.00	1.97
S9-40	40	0.6	0.8	0.875	1.84	2.17	2.11
D1-40	40	0.9	0.6	0.617	1.69	1.97	1.92
D1-30	30	0.9	0.6	0.617	1.62	1.89	1.85
D1-20	20	0.9	0.6	0.617	1.73	2.05	2.00
D1-10	10	0.9	0.6	0.617	1.52	1.72	1.69
D2-40	40	1.2	0.8	0.645	1.66	1.95	1.90
D2-30	30	1.2	0.8	0.645	1.66	1.93	1.88
D2-20	20	1.2	0.8	0.645	1.68	2.00	1.94
D2-10	10	1.2	0.8	0.645	1.51	1.77	1.72
D3-40	40	0.6	0.4	0.671	1.72	2.0	1.95
D3-30	30	0.6	0.4	0.671	1.80	2.10	2.05
D3-20	20	0.6	0.4	0.671	1.73	2.04	1.99
D3-10	10	0.6	0.4	0.671	1.76	2.03	1.98
D1-60	60	0.9	0.6	0.617	1.70	2.00	1.95
D2-60	60	1.2	0.8	0.645	1.68	1.94	1.90
D3-60	60	0.6	0.4	0.671	1.72	2.02	1.97

evidenced by Figure 5, there is a notable influence of maximum particle diameter on the shear strength attributes of coarse-grained soil, with a discernible increase in cohesion c and internal friction angle φ accompanying the rise in maximum particle diameter, independent of changes in gradation structure. Jiang et al. (Wu et al., 2020b) conducted large-scale direct shear tests on rockfill materials, and their results mirrored the trends in c and φ changes in relation to $d_{\max}$ variations, corroborating the experimental findings of this study. In addition, through the use of DEM numerical simulations, Wang et al. (Jiang et al., 2023) investigated the scale effect on coarse-grained materials and concluded that increases in $d_{\max}$ correspond with rises in both c and φ .

Further analysis of the influence law of $d_{\max}$ on c and φ suggested that the relationships of $d_{\max}$ with c and φ were linear. Thus, the relationships of coarse-grained soil $d_{\max}$ with c and φ can be expressed as:

$$\left. \begin{aligned} c &= a_1(d_{\max} - d_{\max 0}) + c_0 \\ \varphi &= a_2(d_{\max} - d_{\max 0}) + \varphi_0 \end{aligned} \right\} \tag{4}$$

In this equation, $d_{\max 0} = 5\text{ mm}$ serves as the boundary diameter distinguishing sand from gravel. The parameters a_1 , a_2 , c_0 , and φ_0 are defined where c_0 (kPa) and φ_0 (°) signify the cohesion c and internal friction angle φ for a specimen with maximum particle diameter $d_{\max} = 5\text{ mm}$. Additionally, a_1 (kPa) and a_2 (°) indicate the rate of

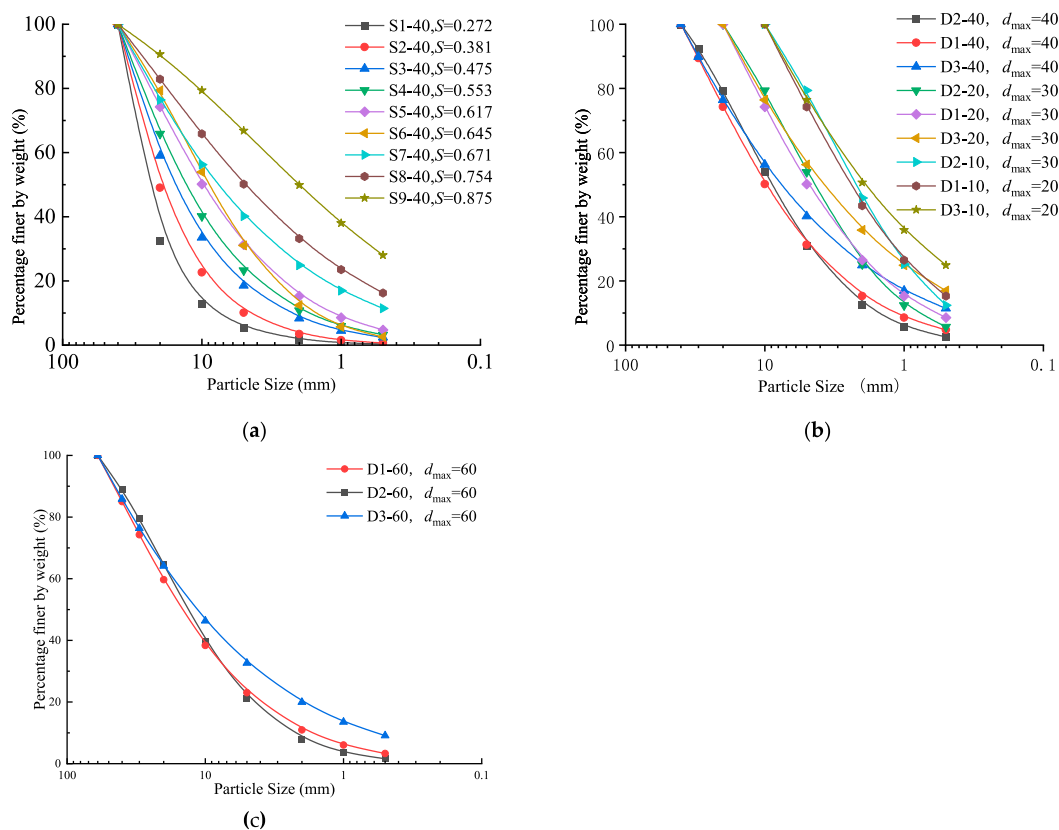


FIGURE 3

Particle gradation cumulative curve of rockfill material. (A), (B), and (C) correspond to S1-40~S9-40, D1-40~D1-10, D2-40~D2-10, D3-40~D3-10 and D1-60~D3-60, respectively.

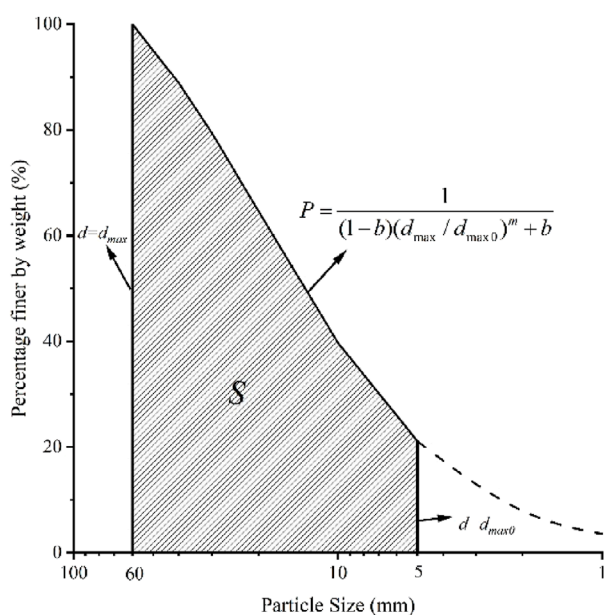


FIGURE 4

Schematic diagram of gradation curve area.

change in cohesion c and internal friction angle φ for specimens where d_{max} is 5 mm.

Equation 4 was employed to fit the test data from specimens D1-40 to D3-10. This fitting is visually represented in Figure 5, while the statistical outcomes of the fitting are detailed in Table 3. Examination of Figure 5 reveals that the fitting curves closely match the data points. The errors between the fitted values of c_0 and φ_0 and their respective test data points are below 4% and 2%, achieving determination coefficients greater than 0.963. Therefore, Equation 4 effectively quantifies the impact of d_{max} on the parameters c_0 and φ_0 , in relation to the scale effect.

4.2 The association between shear strength parameters and the gradation area

From the triaxial compression tests conducted on soil specimens S1-40 to S9-40, which possess an identical d_{max} , the trends showing how the cohesion c and internal friction angle φ of coarse-grained soil vary with the gradation area S are captured and illustrated as distinct points in Figures 6A,B. It can be observed from Figure 6 that c and φ decrease with the increase of the gradation area S , exhibiting linear relationships. Apparently, the gradation area S

TABLE 2 Detailed values of shear strength indicators for each group of styles.

Test number	c	φ	Test number	c	φ	Test number	c	φ
S1-40	125.3	36.3	S9-40	55.6	29.4	D2-10	46.7	30.6
S2-40	115.4	34.4	D1-40	85.8	33.6	D3-40	79.3	32.5
S3-40	102.2	35.1	D1-30	76.5	32.8	D3-30	71.1	31.9
S4-40	92.5	33.6	D1-20	62.9	32.0	D3-20	59.3	31.3
S5-40	85.8	33.4	D1-10	49.9	31.2	D3-10	44.7	30.1
S6-40	82.7	33.1	D2-40	82.7	33.1	D1-60	106.1	34.3
S7-40	79.3	32.3	D2-30	73.7	32.6	D2-60	93.9	34.0
S8-40	63.6	31.4	D2-20	61.9	31.8	D3-60	89.3	33.2

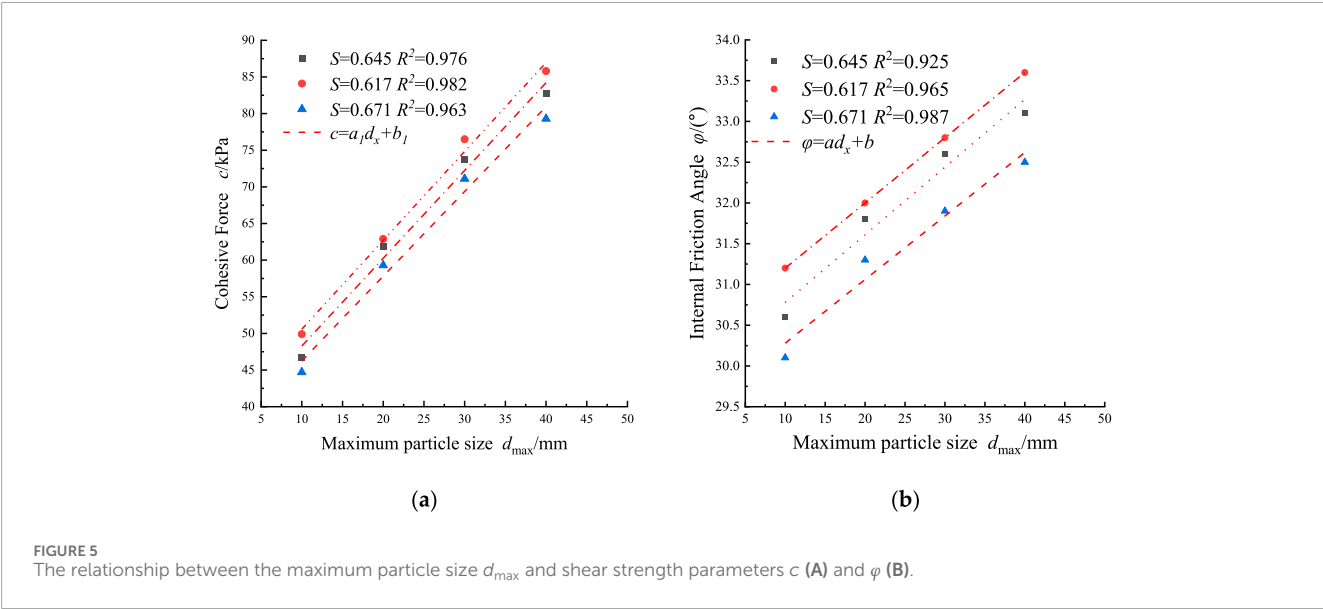


FIGURE 5 The relationship between the maximum particle size $d_{\max}$ and shear strength parameters c (A) and ϕ (B).

TABLE 3 Fitting results of Equation 4 for gravel soils.

S	Cohesion			Internal friction angle		
	a_1 /kPa	c_0 /kPa	R^2	a_2 /kPa	ϕ_0 /kPa	R^2
0.617	1.123	38.45	0.982	0.08	30.4	0.965
0.645	1.198	36.3	0.976	0.083	29.95	0.925
0.671	1.156	34.7	0.963	0.078	29.5	0.987

has significant effects on the coarse-grained soil shear strength parameters (cohesion c and internal friction angle ϕ).

By fitting the test data, the relationships of coarse-grained soil c and ϕ with soil gradation area S can be expressed as:

$$\left. \begin{aligned} c &= b_1S + d_1 \\ \phi &= b_2S + d_2 \end{aligned} \right\} \quad (5)$$

where b_1 , b_2 , d_1 , and d_2 are all parameters of the equation.

The test data from soil specimens S1-40 through S9-40 were analyzed using Equation 5. The fitting curves derived from this analysis are depicted in Figure 6, with detailed statistical outcomes presented in Table 4. As evidenced in Figure 6, there is a pronounced congruence between the fitting curves and the experimental data points. The deviations between the fitted and observed values for cohesion c and internal friction angle ϕ are less than 2% and 9%, respectively. Additionally, the coefficients of determination associated with these fits exceed 0.913. Consequently, the influence of gradation structure on the parameters of cohesion c and internal friction angle ϕ , particularly in relation to scale effects, can be quantitatively described using Equation 5.

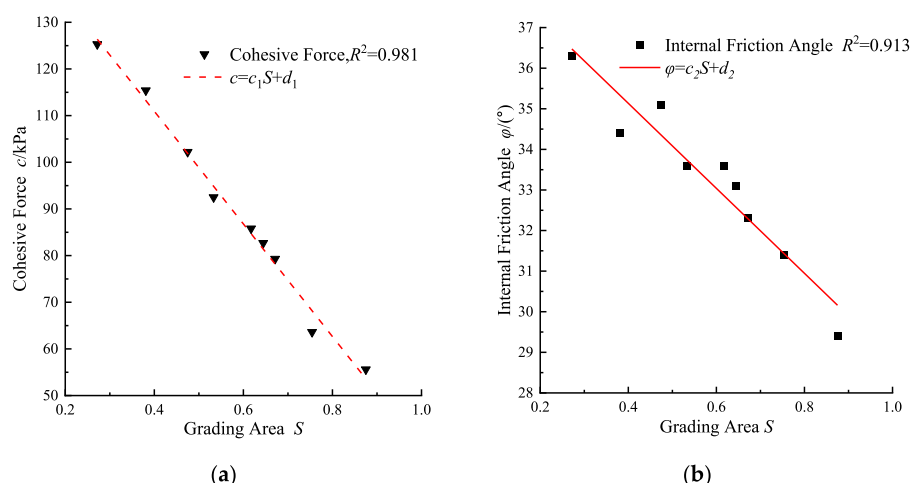


FIGURE 6
The relationship between gradation area S and shear strength parameters c (A) and φ (B).

TABLE 4 Fitting results of Equation 5 for gravel soils.

Cohesion fitting parameters			Internal friction angle fitting parameters		
b_1	d_1	R^2	b_2	d_2	R^2
-120.67	159.19	0.981	-10.47	39.31	0.913

4.3 Establishment of empirical formula for shear strength

To summarize, the relationships between the cohesion c and internal friction angle φ of coarse-grained soil, and the gradation area S , are consistent with Equation 5, provided the maximum particle diameter remains constant. In Equation 4, c_0 and φ_0 represent the baseline values of cohesion c and internal friction angle φ when the maximum particle diameter $d_{\max}$ is 5 mm. The dependency of these parameters on the gradation area S is thus effectively captured by Equation 5. Consequently, the combined effects of maximum particle diameter and gradation structure on the shear strength of coarse-grained soil can be quantitatively assessed using the following equation:

$$\left. \begin{aligned} c &= a_1(d_{\max} - d_{\max 0}) + b_1S + d_1 \\ \varphi &= a_2(d_{\max} - d_{\max 0}) + b_2S + d_2 \end{aligned} \right\} \quad (6)$$

Strength parameters for the 21 sets of coarse-grained soil specimens were analyzed and fitted using Equation 6, with the findings detailed in Table 5.

In Figure 7, there is a juxtaposition of the measured shear strength parameters from diverse gradations of coarse-grained soil and the soil specimens D1-60 to D3-60, against the outcomes calculated using the formula. It can be observed from Figure 7 that the fitted values of cohesion c and internal friction angle φ derived from Equation 6 have errors with the corresponding test

points below 3% and 8%, reaching determination coefficients above 0.924, which is in an acceptable range. Consequently, Equation 6 effectively quantifies the scale effect's impact on the shear strength of coarse-grained soil.

The utilization of Equation 6 to characterize the cumulative influence of the maximum particle diameter and gradation structure on the shear strength of soil masses is of substantial practical significance. By performing shear strength tests on scaled soil materials to ascertain their material parameters, it is feasible to infer the shear strength parameters of coarse-grained soil with original gradation *in situ* using Equation 6. This methodology effectively reduces the scale effect on the shear strength of soil masses, thereby augmenting the safety and reliability of geotechnical engineering endeavors.

5 Shear strength empirical formula verification

While this research focused solely on gravel material for shear strength testing, additional test data from various types of coarse-grained soil are needed to confirm the applicability of the proposed shear strength prediction formula. Jiang et al. (Shi et al., 2023) performed large-scale direct shear tests on sandy pebble materials, varying in maximum particle diameters and gradation structures. Shear strength tests of sandy pebble materials with $d_{\max}$ values of 40, 20, and 10 mm from Jiang et al. (Shi et al., 2023) were analyzed using Equation 6. The parameters derived from this fitting are listed in Table 6, and the corresponding fitting curves are illustrated in Figure 8.

To assess the validity and simplicity of our proposed formula, we compared it with the model presented by Jiang et al. (Shi et al., 2023). While Jiang's model provides a comprehensive approach, the formula proposed in this study offers a more straightforward and less complex method for predicting shear strength, without compromising accuracy. This makes our approach particularly

TABLE 5 Fitting results of Equation 6 for gravel soils.

Cohesion fitting parameters				Internal friction angle fitting parameters			
$a_1/(\text{kPa}\cdot\text{mm}^{-1})$	b_2/kPa	d_1/kPa	R^2	$a_2/((^\circ)\cdot\text{mm}^{-1})$	$b_2/(^{\circ})$	$d_2/(^{\circ})$	R^2
0.96	-124.05	121.5	0.970	0.06	-10.27	37.08	0.924

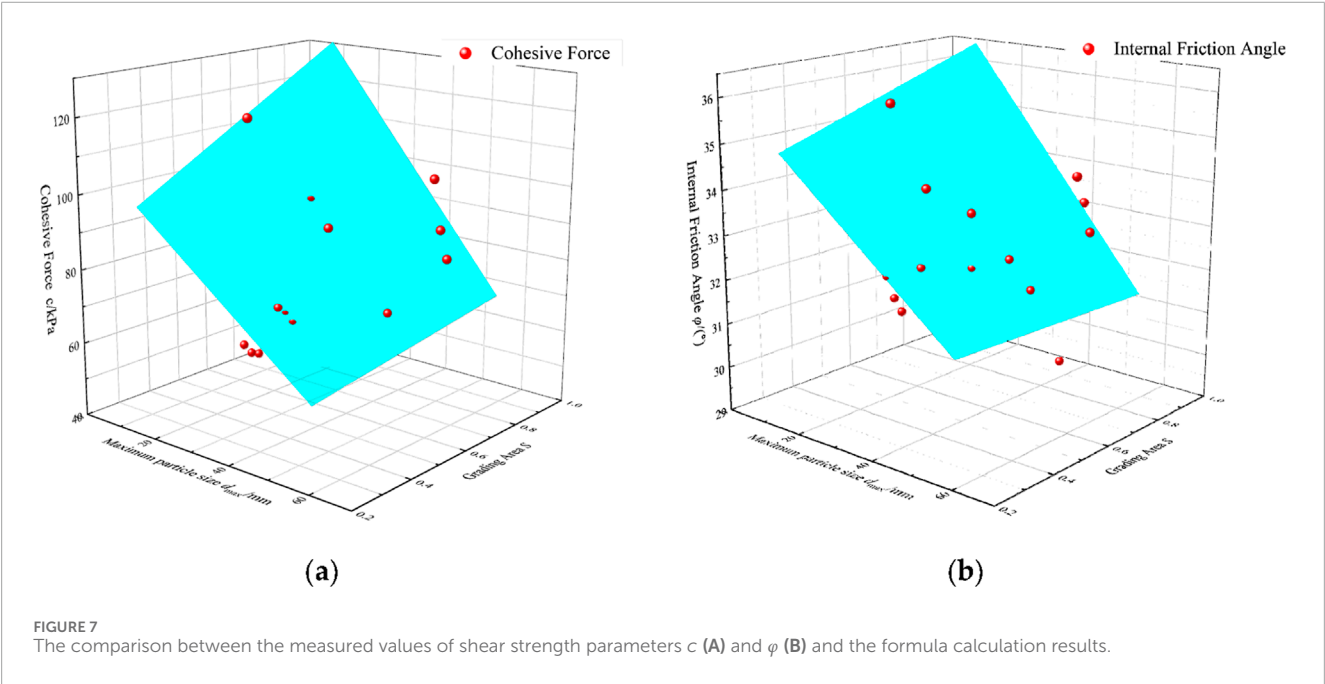


TABLE 6 Fitting results of Equation 6 for sand pebble soils.

Cohesion fitting parameters				Internal friction angle fitting parameters			
$a_1/(\text{kPa}\cdot\text{mm}^{-1})$	b_1/kPa	d_1/kPa	R^2	$a_2/((^\circ)\cdot\text{mm}^{-1})$	$b_2/(^{\circ})$	$d_2/(^{\circ})$	R^2
0.607	-34.841	15.807	0.862	0.179	-27.621	63.23	0.763

advantageous for practical applications where computational efficiency is critical.

It can be observed from Figure 8 that the errors between the fitted c and φ values derived from Equation 6 and the corresponding test values are basically below 14% and 24%, reaching determination coefficients above 0.763, with relatively good fitting effects. Apparently, Equation 6 can accurately describe the relationship between the shear strength and gradation of any type of coarse-grained soil.

An analysis of Figure 9 reveals a close alignment between the predicted and actual measured values, with the error margins for cohesion c and internal friction angle φ being 3.15% and 1.81%, respectively. The above comparative analysis demonstrated the high reliability of the established coarse-grained soil shear strength prediction model considering the scale effect and its applicability to different types of soil (Zheng et al., 2024a; Zheng et al., 2024b; Wu et al., 2024; Wu et al., 2022; Wu et al., 2020c). Therefore, the shear

strength parameters of coarse-grained soil with any gradation can be well predicted by Equation (6) after conducting shear strength tests on a series of scaled specimens of the same coarse-grained soil material to determine the various parameters of Equation 6.

6 Discussion

This study investigates the shear strength characteristics of coarse-grained soils and compares the findings with existing research. The results show that the shear strength of coarse-grained soils is influenced by various factors, including soil type, dry density, particle gradation, shear rate, coarse particle content, and moisture content. Consistent with the findings of Wang and Zhuang (2021), this study shows that sand and gravel soils exhibit significant differences in shear strength, with sand having a higher internal friction angle, while gravel soils demonstrate higher shear strength

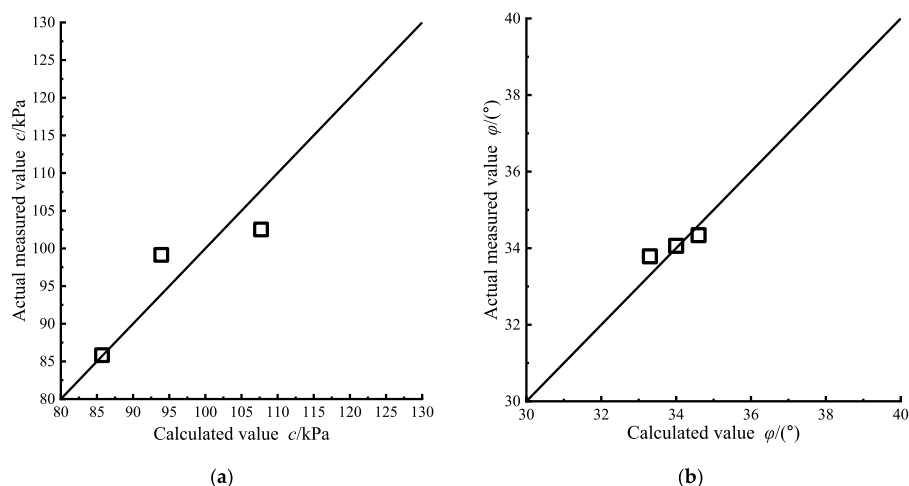


FIGURE 8
The measured and calculated values of shear strength parameters c (A) and ϕ (B) of sandy pebble soil.

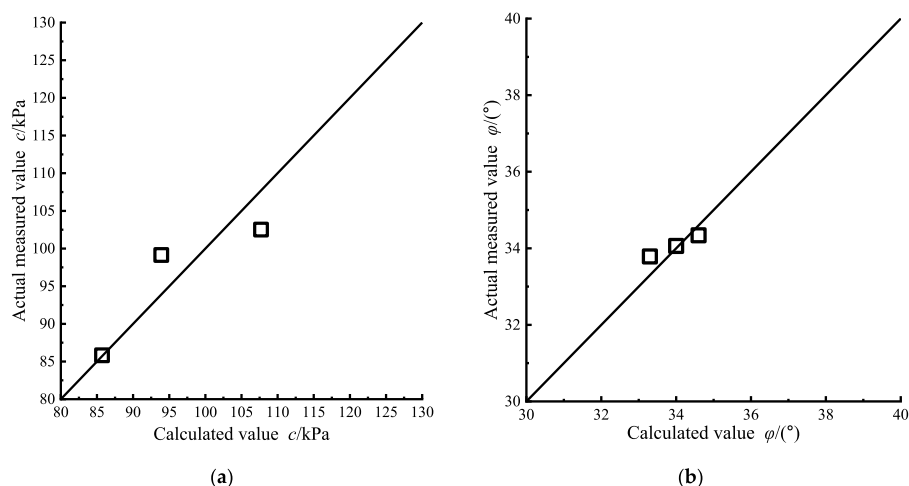


FIGURE 9
The predicted values of shear strength parameters c (A) and ϕ (B) are compared with the measured values when the test soil $d_{\max} = 60$ mm.

due to particle interlocking. Additionally, this study confirms that increased dry density significantly enhances both the internal friction angle and cohesion, which aligns with the conclusions of Gu et al. (2017) and Li and Selig (1996), highlighting the important role of dry density in shear strength. The study also verifies the scale effect, where larger sample sizes result in lower shear strength, which is consistent with the findings in Wang and Zhang (2020). Overall, the influence of particle gradation and compaction on shear strength is particularly significant in slope stability analysis, supporting the conclusions of Marsal (1967), Marschi et al. (1972), and Indraratna et al. (1998), which emphasize the importance of these factors in engineering applications.

However, there are some limitations in this study. First, the selection and scale of the experimental samples may affect the generalizability of the results, especially given the lack of consideration for larger-scale samples, which may impact the

representativeness of the data. Second, while this study focused on the impact of dry density and particle gradation, other geotechnical factors, such as pore water pressure and stress history, were not thoroughly considered. These factors could significantly influence shear strength under different environmental conditions. Finally, although the study provides laboratory data, it lacks field validation, which could introduce discrepancies between laboratory results and actual engineering conditions. Future research should incorporate field data or case studies to further validate the conclusions of this study.

7 Conclusion

Employing the continuous gradation formula for coarse-grained soil, the research crafted 21 distinct groups of specimens,

characterized by maximum particle diameters $d_{\max}$ of 40, 30, 20, and 10 mm. The shear strength of these coarse-grained soil specimens, varying in gradation structure and maximum particle diameter but unified in relative density, was quantitatively assessed using a large-scale triaxial testing machine for coarse-grained soil. The following four conclusions were reached:

- (1) Variations in the maximum particle diameter and the gradation structure substantially contribute to the scale effect observed in coarse-grained soil. Therefore, applying the single-variable approach to investigate the impacts of maximum particle diameter and gradation structure on coarse-grained soil's shear strength offers a quantitative insight into the scale effect's influence on this attribute.
- (2) With constant gradation areas S , implying no changes in gradation structure, there is a gradual increase in both cohesion c and internal friction angle φ with the rising maximum particle diameter $d_{\max}$, exhibiting a linear correlation with $d_{\max}$ with an error of less than 8%.
- (3) With fixed maximum particle diameters $d_{\max}$, an escalation in the gradation area S leads to a reduction in both cohesion c and internal friction angle φ , each maintaining a linear association with $d_{\max}$ with an error of less than 9%.
- (4) This research develops a model for predicting the shear strength of coarse-grained soil, incorporating the effects of maximum particle diameter and gradation structure. The model's effectiveness in predicting the shear strength of coarse-grained soil across all gradations was confirmed with related test data from existing literature, and its adaptability to diverse coarse-grained soil types was examined. Relative to prior research findings, this model offers more straightforward calculations and enhanced applicability in practical engineering scenarios.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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Author contributions

XL: Data curation, Formal Analysis, Funding acquisition, Validation, Writing–review and editing. XS: Data curation, Funding acquisition, Validation, Writing–review and editing. JD: Funding acquisition, Methodology, Writing–review and editing. YS: Project administration, Supervision, Writing–original draft. HJ: Investigation, Project administration, Writing–review and editing. JG: Data curation, Writing–review and editing. MJ: Data curation, Methodology, Writing–review and editing.

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