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Original Article

Experimental Study on Interface Characteristics of Sand-Steel Pipe Using Torsional Shear Method

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Abstract:
The interface between soil and structures has always been an important research topic in civil and geotechnical engineering. The interfacial shear tests of sand and steel structures were performed by modified motorized laboratory vane tester, factors influencing mechanical properties of sand - steel interface was studied, the effects of shear rate, relative density, stress state and roughness on mechanical properties of sand-steel interface were revealed. The results show that: (1) The shear stress-relative displacement relationship curves of the sand-steel interface have obvious peaks under different shear rates, relative densities, stress states and roughness, and the peak strength and residual strength of the sand-steel interface increase with the increase of relative density, vertical stress and roughness, and decrease with the increase of shear rate.(2) The peak strength and residual strength of the smooth sand-steel interface show a good linear decreasing relationship with the shear rate, which increases with the increase of relative density, and shows a good linear decreasing relationship with the vertical stress and normal stress. The relationship curve between the peak strength and roughness of the sand-steel interface can be fitted well by the exponential model, and there is a critical roughness that effectively affects the strength performance. (3) The shear dilatation and contraction of the smooth sand-steel interface at different shear rates is a dilatation phenomenon. For the smooth sand-steel interface at the three relative densities, the loose sand sample showed shear contraction, the medium dense sand sample first had a dilatation, and then turned into a shear contraction, and the dense sand sample showed a dilatation. Under the action of vertical stress from small to large, the shear dilatation and contraction of smooth sand-steel interface shows the transition from shear contraction to dilatation, and with the increase of vertical stress, the dilatation amount increases first and then decreases, and there is a trend of shear contraction. Under the action of low normal stress, with the increase of the surface roughness of the round steel bar, the shear dilatation and contraction of the sand-steel interface changes from no change in volume to dilatation, and then the dilatation increases first and then decreases, and gradually tends to have no change in volume. The results provide significant guidance to solving mechanical problems between soil and structures in practical engineering.
Key words sand-steel interface; mechanical properties; shear rate; relative density; stress state; roughness

1. Introduction

The interface between structures and soil has always been an important research topic in civil engineering and geotechnical engineering. The study of the mechanical properties of the surface between soil and structure involves all aspects of soil mechanics. Due to the difference in the physical and mechanical properties of structures and soil, the deformation of the two materials is also inconsistent when subjected to external loads, which will produce large shear stresses at the interface. It is necessary and crucial to correctly analyze the deformation mechanism and the development of shear failure on the contact surface and make reasonable calculations for the safety of the structure. Potyondy investigated the mechanical properties of different interfaces between soil and building materials using stress and strain-controlled direct shear apparatus (Potyondy,1961). Hu Liming et al. conducted interface shear tests on sand-steel interfaces using an improved strain-controlled direct shear apparatus, exploring the influence of different steel surface roughness on interface mechanical properties (Hu,2000; Hu and Pu,2001; Hu and Pu,2004). Clough et al. studied the mechanical properties of soil-concrete interfaces through direct shear tests, suggesting that the τ-δ curve of the interface exhibits a hyperbolic relationship (Clough and Duncan,1973). Feng Dakuo et al. conducted experimental research on the interface between coarse-grained soil and structures under constant stiffness normal boundary conditions and different shear paths using a large-scale three-dimensional geotechnical testing machine, and discussed the main mechanical properties and influencing factors of the interface under the above conditions (Feng et al,2009; Feng et al,2011). Pineda-Jaimes et al. achieved interfaces between soft clay and concrete with different roughness using a direct shear box and measured and studied the peak and residual shear strength of the interface through direct shear tests under consolidated drained conditions, analyzing the results based on roughness coefficient (R) (Pineda-Jaimes,2011). Evgin and Fakharian conducted multidimensional shear tests on soil-steel and steel-steel interfaces under normal boundary conditions of constant stress and constant stiffness using a cyclic three-dimensional contact single shear apparatus they developed, and investigated the influence of different stress paths on the interface τ-δ relationship and shear strength (Evgin and Fakharian,1996; Fakharian and Evgin,1997). Desai et al. conducted experimental research on the static and dynamic characteristics of soil-structure interfaces using a self-developed large-scale multi-degree-of-freedom cyclic shear apparatus (Desai and Rigby,1997).

Currently, both domestically and internationally, the experimental instruments used to study the mechanical properties of soil-structure interfaces mainly include direct shear apparatus, single shear apparatus, and ring shear apparatus. Direct shear and single shear both suffer from the issue of uneven stress distribution when there is excessive relative displacement at the interface. Meanwhile, the operation of the ring shear apparatus is relatively complex, especially in controlling the shear gap. In this paper, the laboratory vane tester is modified, and the function of interface shear test is simply realized by applying the normal stress of the interface through the spring, and the influencing factors and patterns of the mechanical properties of the sand-steel interface are comprehensively studied.

2 Experimental Equipment and Plan

This paper focuses on the interface between sand and steel structures. Interface shear tests were conducted using a modified laboratory vane tester, with standard sand and round steel bars as the test materials. The physical and mechanical properties of the standard sand are presented in Table 1.

Table 1 Physical and Mechanical Properties of Standard Sand

Soil Type	Average particle size (mm)	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	internal friction angleΦ (°)
Standard sand	0.375	1.755	1.50	30

In this study, four steel structures with different roughness were fabricated by creating grooves on the surface of round steel bars (D20mm×H40mm) with varying spacing and depth, as detailed in Table 2.

Table 2 Surface Characteristics of Round Steel Bars

Round steel rod	Square groove (length x width x depth)	Distance along the circumference	Roughnessy (mm)
1	0×0×0mm	0	0

2	40×1×1mm	30°	0.0356
3	40×2×2mm	60°	0.0730
4	40×2×2mm	30°	0.2918

Taking the No.4 round steel bar as an example, its structure and size are shown in Figure 1.

Main view Vertical view Schematic diagram

Figure 1. Structure and dimensions of No.4 round steel rod

Regarding roughness quantification, Kulhaway and Perterson defined the relative roughness of an interface as the ratio of the particle size of sand and concrete aggregate (Kulhaway and Peterson,1979). Uesugi and Kishida defined interface roughness as the maximum height difference of the material surface within a certain length range (Uesugi et al,1988). Li Jian used the sand filling method to evaluate the roughness of concrete structure surfaces (Li,2014) and proposed a modified formula for calculating the roughness of structure surfaces.

$$y = \frac{V_d}{V}\frac{S_c}{S}\frac{V}{S} \qquad (1)$$

In this study, the roughness index of the sand filling method was used to quantify the roughness of the surface of the round steel bars, and calculations were performed using the modified formula proposed by Li Jian(Li,2014). The construction and roughness of the round steel bars are shown in Table 2.

The modified laboratory vane tester, as shown in Figure 2, has modifications concentrated above the specimen container. Springs with stiffness coefficients of k=8.77N/mm and k=61.30N/mm were used to apply vertical stress to the specimen surface. Shear tests of the sand-steel interface under different stress conditions were conducted by replacing the vane with round steel bars of varying surface roughness. The specimen dimensions were ϕ99.4×H160mm, and according to the British Standard BS1377-7, the round steel bar should be inserted into the center of the specimen, with the center of the round steel bar 80mm from the bottom of the specimen. As the area of the interface between the specimen and the round steel bar remained constant throughout the test, changes in the vertical displacement of the specimen could represent changes in specimen volume. Vertical displacement of the specimen was measured by extending a dial gauge (100mm) through the top of the spring to contact the bottom plate of the spring base, which supported the round steel bar.

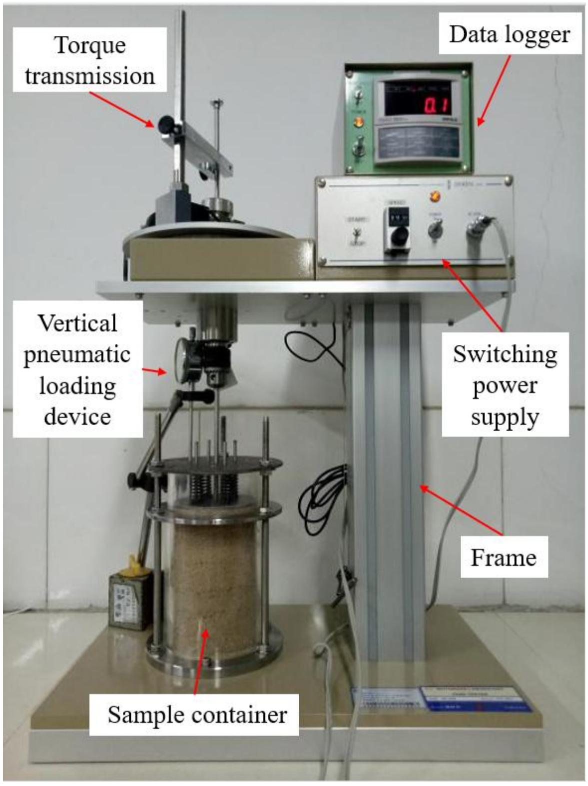

Figure 2 Modified laboratory vane tester

The summary of the design of the sand-steel interface shear test plan is shown in Table 3. During the experiment, torque was recorded every 10 seconds, and the test was stopped when the torque remained essentially unchanged or when the rotation angle reached 360°. Parallel tests were conducted for each group of experiments to verify the repeatability of the test results.

Table 3 Shear Test Scheme for Sand Steel Interface

Influence factor	Indicator value	Interface	Soil type	Vertical stress (kPa)	Number of tests
Shear rate	2°/min 0.349mm/min	No. 1 round steel rod	Standard sand	50	1
	4°/min 0.698mm/min	No. 1 round steel rod	Standard sand	50	1
	6°/min 1.047mm/min	No. 1 round steel rod	Standard sand	50	1
Relative density	27.4%	No. 1 round steel rod	Standard sand	50	1
	51.0%	No. 1 round steel rod	Standard sand	50	1
	72.2%	No. 1 round steel rod	Standard sand	50	1
Roughness	0mm	No.1 round steel rod	Standard sand	0/25/50/75/100	5
	0.0356mm	No.2 round steel rod	Standard sand	25	1
	0.073mm	No.3 round steel rod	Standard sand	25	1
	0.2918mm	No.4 round steel rod	Standard sand	25	1

3 Experimental Results and Analysis

3.1 Shear Stress-Relative Displacement Relationship Curve

After summarizing and organizing the experimental data, this paper presents the shear stress-relative displacement relationship curves of the sand-steel interface under different shear rates, relative densities, stress states, and roughness conditions, as shown in Figures 3.

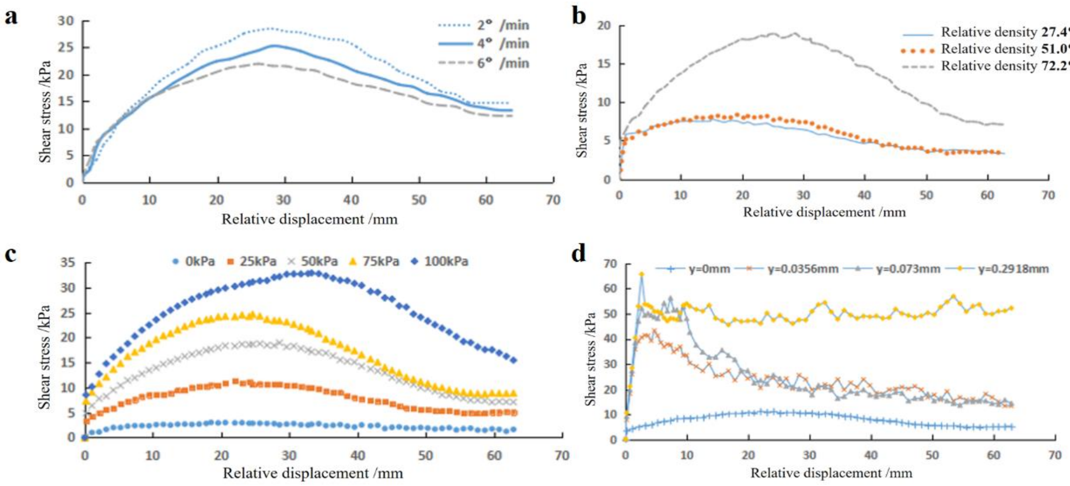

Figure3 Shear stress relative displacement relationship curve of sand steel interface under different conditions

A Shear stress relative displacement relationship curve of smooth sand steel interface under different shear rates(y=0mm, σ_N=50kPa, D_r=72.2%);b Shear stress relative displacement relationship curve of smooth sand steel interface under different relative densities(y=0mm, σ_N=50kPa, v=6°/min);c Shear stress relative displacement relationship curve of smooth sand steel interface under different vertical stress(y=0mm, D_r=72.2%, v=6°/min);d Shear stress relative displacement relationship curve of sand steel interface under different roughnesses（σ_N=25kPa, D_r=72.2%, v=6°/min)

The experimental results indicate that the shear stress-relative displacement relationship curves of the sand-steel interface under different shear rates, relative densities, stress states, and roughness conditions all exhibit distinct peaks, showing a peak-type behavior. The peak strength and residual strength of the sand-steel interface increase with increasing relative density, vertical stress, and roughness, while they decrease with increasing shear rate. The shear stress-relative displacement relationship curves under different conditions can be roughly divided into four stages: linear elastic growth stage, elastic-plastic growth stage, plastic softening stage, and residual friction stage. Taking the example of the shear stress-relative displacement relationship curve of the smooth sand-steel interface under a vertical stress of 50kPa, as shown in Figure 4:

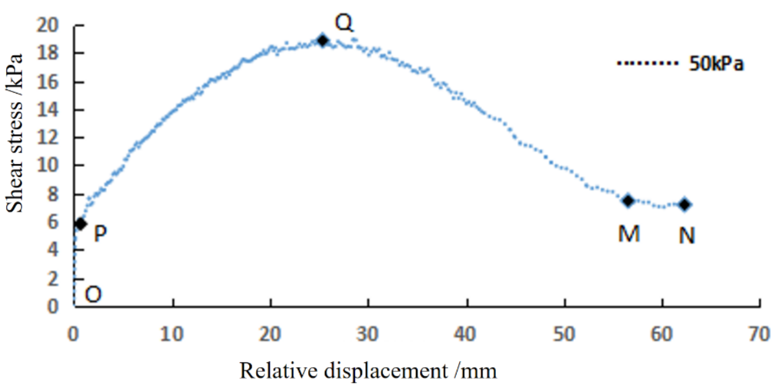

Figure 4 Shear stress relative displacement relationship curve of smooth sand steel interface under vertical stress of 50kPa (y=0mm, D_r=72.2%, v=6°/min)

Linear elastic growth stage OP: When there is a small relative displacement at the sand-steel interface, the interface shear stress rapidly increases linearly. This can be understood as the smooth round steel bar needing to overcome the static frictional force exerted by the surrounding sand sample to undergo relative displacement, hence exhibiting a rapid increase in shear stress within a short period.

Elastic-plastic growth stage PQ: The interface shear stress increases with increasing relative displacement, and the rate of increase gradually slows down, exhibiting significant elastic-plastic characteristics. The interface shear stress during this stage is mainly provided by the frictional force on the sand-steel interface, with some contribution from the interlocking force between them. As the relative displacement increases, standard sand particles continuously undergo translation and rolling, leading to an increase in frictional force between them and the smooth round steel bar, albeit at a decreasing rate.

Plastic softening stage QM: The interface shear stress decreases with increasing relative displacement, and the rate of decrease shows a trend of increasing first and then decreasing. Beyond point Q, as standard sand particles continue to translate and roll, exceeding the maximum value of the frictional force on the sand-steel interface, the original structure on the interface gradually breaks down, resulting in a decrease in the frictional force on the interface and hence a continuous decrease in interface shear stress, indicating the occurrence of stress softening phenomenon.

Residual friction stage MN: The interface shear stress gradually approaches a horizontal line with increasing relative displacement. At this point, the original structure of the sand-steel interface is completely destroyed, and the interface shear stress is entirely provided by the sliding friction between the standard sand and the smooth round steel bar surface. Meanwhile, as standard sand particles gradually align in the shear direction, there is a tendency for the interface shear stress to continue decreasing to a certain extent.

From Figure 3d, it can be observed that as the surface roughness of the round steel bars increases, the growth stage transitions from a combination of linear elasticity and elastic-plastic behavior to purely linear elastic growth. The softening stage gradually shifts from plastic softening to elastic softening, and the residual friction stage no longer approaches a horizontal line but instead forms a fluctuating waveform around a certain residual value. Moreover, the greater the roughness, the greater the degree of fluctuation. This also indicates that with increasing roughness, the surface irregularities of the round steel bars will influence the surrounding standard sand particles, resulting in the formation of shear bands at the interface. The soil particles will experience slipping, rolling, and vertical movement, leading to continuous fluctuations in the interface shear stress.

3.2 Interface Shear Failure Strength

There are two types of interface shear failure strength: peak strength and residual strength, and this study considers peak strength as the interface shear failure strength. To improve the accuracy of the experiments, the shear stress at the sand-steel interface needs to be corrected by deducting the shear stress generated by the vertical rod penetrating the sand sample. Based on the shear stress-relative displacement relationship curves of the sand-steel interface, this paper presents the relationship curves of interface shear failure strength with changes in shear rate, relative density, vertical stress, normal stress, and roughness.

Both the peak strength and residual strength of the sand-steel interface decrease with increasing shear rate. As shown in Figure 5a, the curve fitting similarities are R^2=1 and R^2=0.9988, both exceeding 0.99, indicating a good linear decrease relationship with shear rate.

Both the peak strength and residual strength of the sand-steel interface increase with increasing relative density. As shown in Figure 5b, when the sand transitions from loose to medium dense, the growth of interface shear failure strength is slow; however, when transitioning from medium dense to dense, the interface shear failure strength increases rapidly.

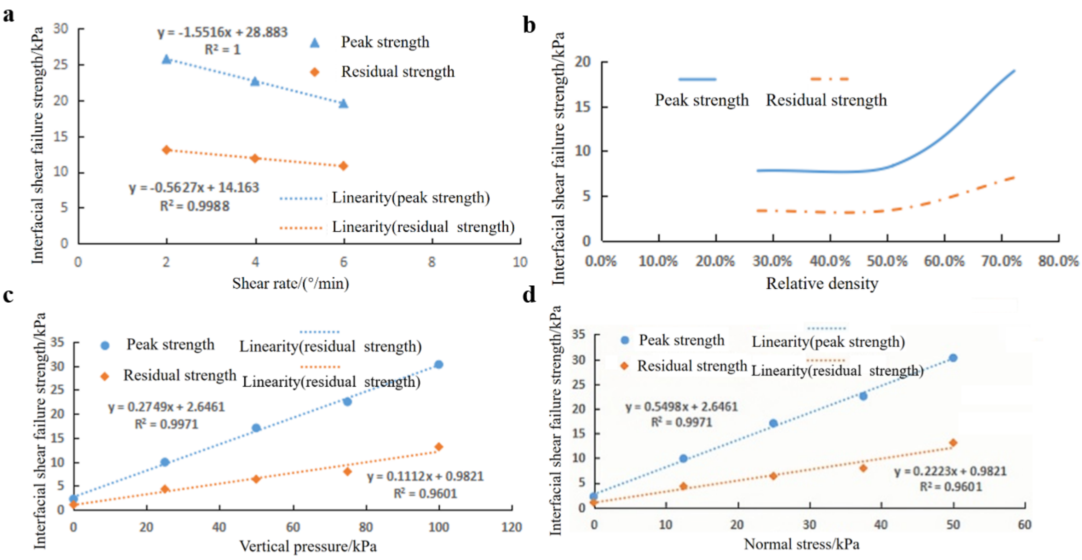

Figure 5 The variation curve of interface shear failure strength under different conditions

A Shear failure strength relative shear rate relationship curve at the sand steel interface (y=0mm, σ_N=50kPa, D_r=72.2%); b Shear failure strength relative density relationship curve at the sand steel interface(y=0mm, σ_N=50kPa, v=6°/min);c Shear failure strength relative vertical stress relationship curve at the sand steel interface(y=0mm, D_r=72.2%, v=6°/min);d Shear failure strength relative normal stress relationship curve at the sand steel interface(y=0mm, D_r=72.2%, v=6°/min)

Both the peak strength and residual strength of the sand-steel interface increase with increasing vertical stress. As shown in Figure 5c, the curve fitting similarities are R^2=0.9971 and R^2=0.9601, both exceeding 0.96, indicating a good linear increase relationship with vertical stress. In practical engineering, when the specific gravity of each layer of soil is obtained by drilling sampling, the vertical stress at a certain depth of the foundation can be directly calculated. The relationship formula of the fitted curve in Figure 5c can provide reference for practical engineering.

In the experiment, the pressure applied by the spring acts in the vertical direction of the sand sample, rather than directly on the normal direction of the sand-steel interface. Therefore, the pressure acting on the normal direction of the sand-steel interface is equivalent to the passive soil pressure. The formula for calculating the passive soil pressure is:

$$\sigma_0 = K_0 \sigma_n \qquad (2)$$

Where: K_0 is the passive soil pressure coefficient, σ_n is the vertical stress (kPa).

This paper uses the Jacky empirical formula to calculate the passive soil pressure coefficient, which is:

$$K_0 = 1 - \sin\varphi \qquad (3)$$

Where: ϕ is the effective internal friction angle of the standard sand (°).

The effective internal friction angle of the standard sand in this paper is 30°. Using the above formula, the passive soil pressure, i.e., the normal stress of the sand-steel interface, can be obtained. The relationship curve between the shear failure strength of the sand-steel interface and the normal stress can be derived accordingly, as shown in Figure 5d. Both the peak strength and residual strength of the sand-steel interface increase with increasing normal stress, and they approximately exhibit a linear growth relationship. This can be expressed using a similar form of Mohr-Coulomb criterion:

$$\tau = c + \sigma \tan\phi \qquad (4)$$

Where:τ is the interface shear stress (kPa),

c is the interface apparent cohesion, i.e., the interlocking force between the

standard sand and the smooth round steel bar (kPa),

σ is the interface normal stress (kPa),

ϕ is the interface internal friction angle (degrees).

The curve fitting similarities of the curves in Figure 5d are all above 0.96, indicating a good linear fitting effect, following the Mohr-Coulomb strength failure criterion. From the relationship formula of the curves in the figure, the apparent cohesion and internal friction angles of the smooth sand-steel interface obtained from the peak strength and residual strength are respectively: c=2.6461 kPa and ϕ=28.8°; c=0.9821 kPa and ϕ=12.6°. The interface internal friction angles are all less than 30°, indicating that the shear failure of the standard sand and smooth round steel bar interface occurs at the sand-steel interface. Additionally, the interface internal friction angle obtained from the residual strength is much smaller than the effective internal friction angle of the sand itself. Therefore, when the interface undergoes significant relative deformation (greater than 60 mm), the residual strength should be chosen as the interface shear failure strength.

The peak strength of the sand-steel interface increases with the increasing surface roughness of the round steel bar. However, the growth trend gradually slows down and approaches a horizontal line, indicating that the influence of roughness on the peak strength diminishes. This is shown in Figure 6.

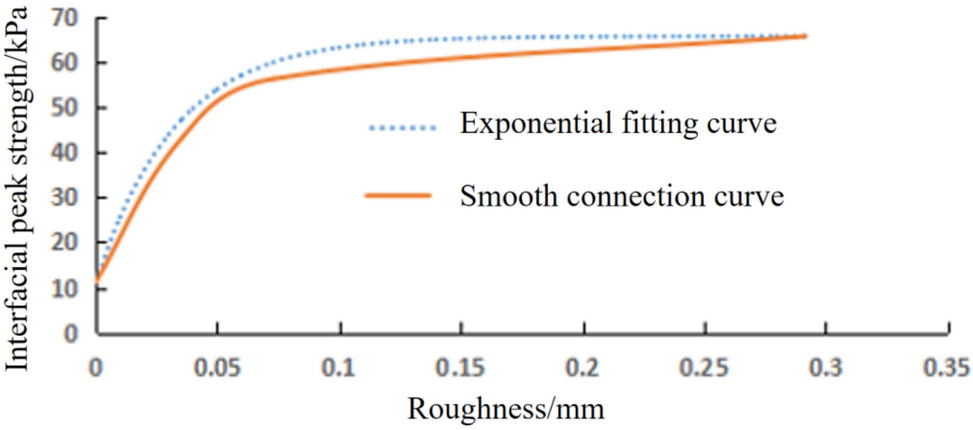

Figure 6 Peak strength relative roughness relationship curve of sand steel interface (σ_N=25kPa, D_r=72.2%, v=6°/min)

This curve also confirms the existence of the critical roughness y_{cr}. That is, when$0 \le y < y_{cr}$, the variation in the surface roughness of the round steel bar has a significant impact on the interface peak strength, and shear failure occurs at the sand-steel interface. When $y_{cr} \le y < d_{max}$, the variation in the surface roughness of the round steel bar has little effect on the interface peak strength, and shear failure occurs within the soil, exhibiting the shear characteristics of the sand itself. This paper also provides an exponential fitting curve for the relationship between the peak strength and roughness of the sand-steel interface. The functional relationship of this exponential fitting curve is:

$$\tau = 54.5(1\text{-}e^{-\frac{\delta}{0.0326}}) + 11.253 \tag{5}$$

Where:τ is the peak strength of the sand-steel interface for different roughness,δ is the surface roughness of the round steel bar.

The curve fitting similarity of this exponential fitting curve is R^2=0.9974, exceeding 0.99, indicating a good fitting effect. This suggests that an exponential model can be used to describe the relationship between the peak strength and roughness of the sand-steel interface.

3.3 Interface Shear Dilation (Contraction) Characteristics

During the sand-steel interface shear test, the vertical displacement of the sand sample can be obtained by regularly recording the readings of the dial gauge attached to the extensometer. This paper presents the vertical displacement-relative displacement curves of the sand sample under different shear rates, relative densities, stress states, and roughness conditions, with a decrease in sand sample volume represented as positive and an increase in sand sample volume represented as negative.

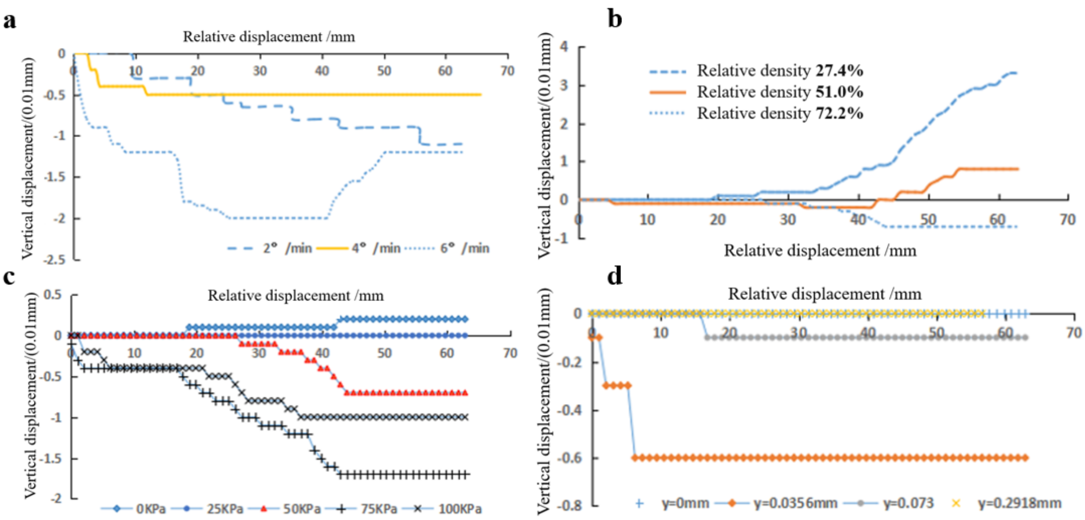

Figure 7 Vertical displacement relative displacement relationship curve of sand samples under different conditions

A Vertical displacement relative displacement relationship curve of sand samples under different shear rates(y=0mm, σ_N=50kPa, Dr=72.2%);b Vertical displacement relative displacement relationship curve of sand samples under different relative densities(y=0mm, σ N=50kPa, v=6°/min);c Vertical displacement relative displacement relationship curve of sand samples under different vertical stress(y=0mm, Dr=72.2%, v=6°/min);d Vertical displacement relative displacement relationship curve of sand samples under different roughness levels（σ_N=25kPa, Dr=72.2%, v=6°/min)

The dilation (contraction) of the smooth sand-steel interface under different shear rates all exhibit shear dilation phenomena, consistent with the shear characteristics of dense sand. Moreover, among the three shear rates, the vertical displacement is greatest at 6°/min and smallest at 4°/min. There is no apparent functional relationship between the vertical displacement of the sand sample and the shear rate, as shown in Figure 7a.

For the smooth sand-steel interface at three relative densities, the loose sand sample exhibits shear contraction phenomenon, the medium-density sand sample initially experiences shear dilation, then transitions to shear contraction, and the dense sand sample shows shear dilation phenomenon. This behavior aligns with the characteristic transition of sand from loose to dense, shifting from shear contraction to shear dilation. Before completing one full cycle of interface shear, the vertical displacement of medium-density and dense sand samples has stabilized, while the loose sand sample still shows a tendency for continued shear contraction by the time one full cycle of interface shear is completed, as depicted in Figure 7b.

Under increasing vertical stress from small to large, the smooth sand-steel interface exhibits a transition from shear contraction to shear dilation. Moreover, as the vertical stress increases, the amount of shear dilation initially increases and then decreases, with a tendency to develop towards shear contraction, as shown in Figure 7c. When the vertical stress is 25kPa, the vertical displacement of the sand sample is 0, indicating that there is no change in the volume of the sand sample. Therefore, it can be inferred that at a shear rate of 6°/min and a vertical stress of 25kPa, the critical relative density of the sand sample is approximately 72.2%.

Under low normal stress, with increasing roughness of the steel rod surface, the sand-steel interface exhibits a transition from no change in volume to shear dilation, followed by an increase and then decrease in shear dilation, gradually approaching no change in volume, as shown in Figure 7d. This is markedly different from the interface mechanical properties between cohesive soil and structures. Under low normal stress, the normal displacement of the cohesive soil-structure interface increases with the increase in surface roughness of the structure, exhibiting shear dilation, and the shear dilation becomes increasingly pronounced.

From the relationship curves of vertical displacement versus relative displacement under different shear rates, relative densities, stress states, and roughness conditions of the sand sample, it can be observed that the maximum vertical displacement of the sand sample does not exceed 0.035mm. Compared to the compression of the spring, this value is almost negligible, indicating that the volume change rate of the sand sample is very small (less than 0.022%). Therefore, it is considered in this study that the shear tests of the sand-steel interface under different conditions are conducted under constant normal stress boundary conditions.

4 Conclusion

This study conducted interface shear tests between sand and steel structures using a modified laboratory vane tester, investigating the influence of different factors on the mechanical properties of the sand-steel interface. The main conclusions are as follows:

(1) The shear stress-relative displacement relationship curves of the sand-steel interface under different test conditions exhibited a softening type, which can be divided into four stages: linear elastic growth stage, elastic-plastic growth stage, plastic softening stage, and residual friction stage.

(2) The peak strength and residual strength of the smooth sand-steel interface showed a good linear decrease relationship with shear rate, increased with relative density, decreased with vertical stress and showed a good linear increase relationship with normal stress, following the Mohr-Coulomb strength failure criterion. The relationship curve between the peak strength of the sand-steel interface and roughness could be well fitted by an exponential model. There exists a critical roughness, where the variation of steel surface roughness significantly affects the interface peak strength when the roughness is below the critical value, and shear failure occurs at the sand-steel interface. When the roughness is above the critical value, the steel surface roughness has little effect on the interface peak strength, and shear failure occurs within the soil, exhibiting the shear characteristics of the sand itself.

(3) The sand-steel interface under different shear rates showed shear dilatation. The loose, medium dense, and dense states showed shear contraction, first shear dilatation followed by shear contraction, and shear dilatation phenomena, respectively. With the increase of normal stress, it transitioned from shear contraction to shear dilatation. As the interface roughness increased, the shear dilatation trend did not always increase; instead, it decreased after the roughness exceeded the critical value. The volume change rate of the sand samples was very small, and the characteristics of the sand-steel interface under different conditions could be considered as normal constant stress.

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