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Experimental study on cyclic shear stiffness and damping ratio of carbonate sand-steel interface

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Abstract: The dynamic response of carbonate sand-steel interface is of great significance to the safety and stability of the structure foundations which are constructed under reef geotechnical conditions. To investigate the effects of normal stress, cyclic amplitude and particle size on the interface shear stiffness and damping ratio, a series of cyclic shear tests on the interface between carbonate sand and steel was carried out based on the interface ring shear apparatus, and further compare these properties of carbonate sand with quartz sand. The results indicate that normal stress and cyclic amplitude have significant effects on the interface shear stiffness and damping ratio. Specifically, the promotion of normal stress level increases the shear stiffness and meanwhile decreases the damping ratio; the enhancement of cyclic amplitude leads to an approximate inverse reduction of shear stiffness and an approximate logarithmic increase of damping ratio; for carbonate sand with a uniform particle size, there is a critical particle size which results in a significantly different interface shear behavior. When the particle size of quartz sands is large, the shear stiffness and damping ratio are significantly different from those of carbonate sands. However, if the particle size is small, the shear stiffness and damping ratio of these two sands are almost consistent with each other.

Keywords: carbonate sand; steel interface; cyclic shear; shear stiffness; damping ratio

1 Introduction

Carbonate sand, which is widely developed in low latitude regions, is a special geotechnical material formed by a variety of physical, chemical, and biological processes, which is mainly distributed in the Xisha, Zhongsha, and Nansha islands in China[1-3]. The typical characteristic of carbonate sand is that the particle breakage easily occurs under lower stress, which is mainly related to the features of low particle hardness, masses of internal pores, and irregular shapes[4-8]. The unique characteristic different from the quartz sand, which lead to great challenges to the construction of geotechnical engineering in coral reef islands.

The interaction between sands and structure interface has always been an important issue concerned by geotechnical engineers, which has a crucial impact on the safety and stability of foundation structures[9-10]. A lot of monotonic and cyclic shear tests have been implemented to study the interface shear behavior between sands and structure. In the small displacement monotonic shear area, the peak strength and volume change of the interface are mainly concerned. It was found that the peak strength and the ratio of the average roughness to the median particle size (R_a/D_{50}) had a satisfactory correspondence[11-12]. In terms of large displacement shear, it was detected that the shear breakage zone appears at the interface, and a large number of fine particles are formed during the shear process, which has an important impact on the strength of the interface[13]. In the aspect of cyclic shear, previous studies have focused on the variation of interfacial strength with the number of cycles, and found that the bulk shrinkage caused by the adjustment of sand particle position at the interface under cyclic action is the main reason for the weakening of interfacial strength[14-15].

As a matter of fact, the existing structures have been subjected to long term dynamic load in the complex and changeable marine environment. In geotechnical engineering shear stiffness and damping ratio are two important parameters reflecting the dynamic response of structures. In the current researches, researchers have mainly carried out some experiments on the interface shear stiffness and damping of geosynthetics and soil[16-22]. Among these studies, Vieira et al.[20] studied the dynamic characteristics of the interface between quartz sands and high-strength geotextile, and found that the shear stiffness of the interface remained almost unchanged after

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10 cycles; Liu et al. [21] conducted a series of cyclic shear tests with a large direct shear apparatus. They found that with the increasing of the relative density of sand samples, the shear stiffness corresponding to the same cycle times increases while the damping ratio decreases.

In summary, existing studies have mainly focused on the strength characteristics of the interface under monotonic and cyclic shear, but the research on the dynamic response of the interface between sand and structures is limited, especially for carbonate sand, a special geotechnical material. Therefore, this paper conducted a series of cyclic shear tests on the interface between carbonate sands and steel under constant normal stress. The effects of normal stress, cyclic amplitude and particle size on the interface shear stiffness and damping ratio were systematically investigated. Furthermore, compared with the quartz sand, this paper provides a certain reference for geotechnical engineering in reef cases.

2 Experimental procedure

2.1 Interface ring shear apparatus

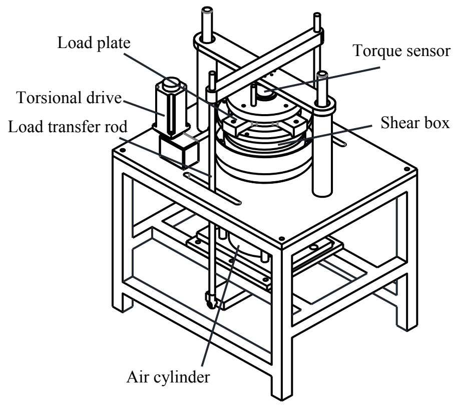
In recent years, interface ring shear apparatus has been used by many researchers to conduct large strain shear tests and interface shear tests. This instrument has two major advantages: 1) infinite displacement can be applied; 2) the stress unevenness existing in single shear or direct shear tests is avoided [23]. The structure of the interface ring shear apparatus used in this experiment is shown in Figs. 1(a) and 1(b), which mainly includes: interface shear ring, force transmission rod, motor, cylinder, axial force sensor, torque sensor, angle sensor and other components. The interface ring shear apparatus can apply 20−600 kPa normal stress with the shear speed among 0.01−15.70 mm/min. And the diameters of the outer ring and inner ring are 300 and 200 mm, respectively, the width of ring is 50 mm. The interface shear test adopts the lower interface configuration [Fig.1(b)], that is, the interface material is installed on the lower ring, and the soil sample is installed on the upper ring simultaneously.

2.2 Experimental materials

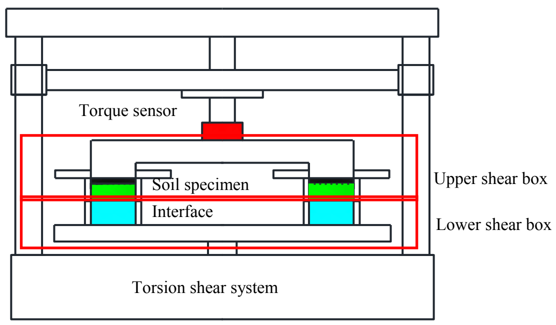
2.2.1 Sand sample

The carbonate sand sample used in this experiment was taken from a reef island in the South China Sea. There is no cementation between the particles, and the relative density of which is 2.81. According to X-ray diffraction analysis, the carbonate sand contains 80.3% aragonite, 17.9% calcite and 1.9% quartz, and its calcium carbonate content is 98.1%. In addition, Fujian Ping-tan standard quartz sand, the relative density of which is 2.65 was used for the control group.

The carbonate sand was immersed in airless water to remove the salt and then dried in an oven before the test. The sand was sieved into 5 groups: 0.10−0.25 mm, 0.25−0.50 mm, 0.50−1.0 mm, 1.0−2.0 mm, 2.0−5.0 mm. The maximum and minimum void ratios are shown in Table 1. Fig.2 are scanning electron microscope photographs (SEM) of carbonate sand and quartz sand at 200 times magnification. It can be found that there are many pores on the carbonate sand surface. Table 1 shows that the larger the calcareous sand particle size is, the larger the pore ratio is, whereas the quartz sand has an opposite trend. The main reason is that the particle irregularity of carbonate sand increases with the enlargement of particle size, while the relatively regular particle shape of quartz sand result in small pore ratio of large grains.



(a) Interface ring shear device



(b) Shear ring schematic

Fig.1 Schematic diagram of experimental apparatus

Table 1 Maximum and minimum void ratio of sand samples

Sand specimen	e_{max}	e_{min}
C0.10−0.25	1.210	0.948
C0.25−0.50	1.291	0.961
C0.5−1.0	1.321	0.970
C1−2	1.442	1.035
C2−5	1.533	1.148
Q0.1−0.25	0.949	0.650
Q0.5−1.0	0.836	0.600

Note: The letters “C” or “Q” stand for carbonate sand and quartz sand, respectively.

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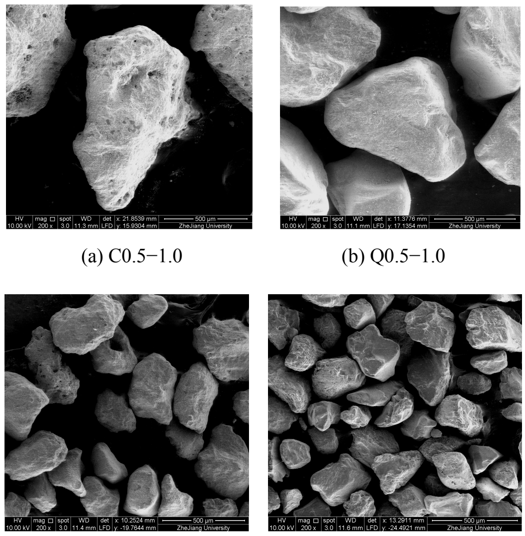


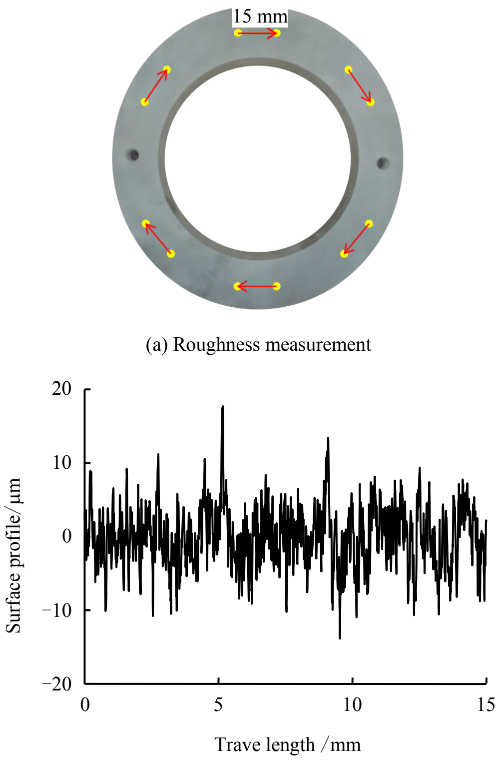
(a) C0.5−1.0 (b) Q0.5−1.0

(c) C0.10−0.25 (d) Q0.10−0.25

Fig.2 SEM images of sand samples

2.2.2 Steel interface

As shown in Fig.3 (a), the interface used in the test was a ring structure of No. 45 steel with an elastic modulus of 210 GPa and a tensile strength of 600 MPa. The surface roughness of the steel interface was adjusted by air blasting method, and six locations were selected in the circinal direction of the steel interface using a surface roughness tester. The interface contour line obtained by the test is shown in Fig.3(b), and the range of average roughness R_a is within 3.25 ±0.05 μm.



(a) Roughness measurement

(b) Typical surface roughness profile of steel.

Fig.3 Steel interface and roughness measurement

2.3 Experimental process

The air-pluviation method was used to prepare the samples in this study. The height of the samples is 20 mm and the relative density is about 72%. The top surface of the sand sample was gently smoothed to avoid uneven distribution of normal stress. After the vertical loading had been completed, interface shear started with the shear path shown in Fig. 4. The first cycle started from the equilibrium position and reached a set cycle amplitude at a certain shear speed, then sheared it reversely. In this test, the cycle amplitude of 2.5 mm was performed and a total of 200 cycles were carried out, mainly by referring the load period (60 s) of the 3 h storm surge, and made the cumulative shear displacement reached 2 m. A gap between the upper and lower rings should be kept to avoid the influence of friction during the test, but it may cause the leakage of sand. Therefore, this test only performed the test with a gap in the first 20 cycles (For the test group with a shear displacement amplitude of 5 mm, only 10 cycles were performed).

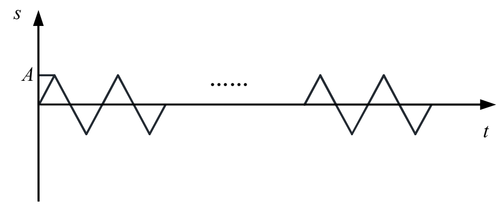


Fig.4 Shear displacement path applied during interface experiment

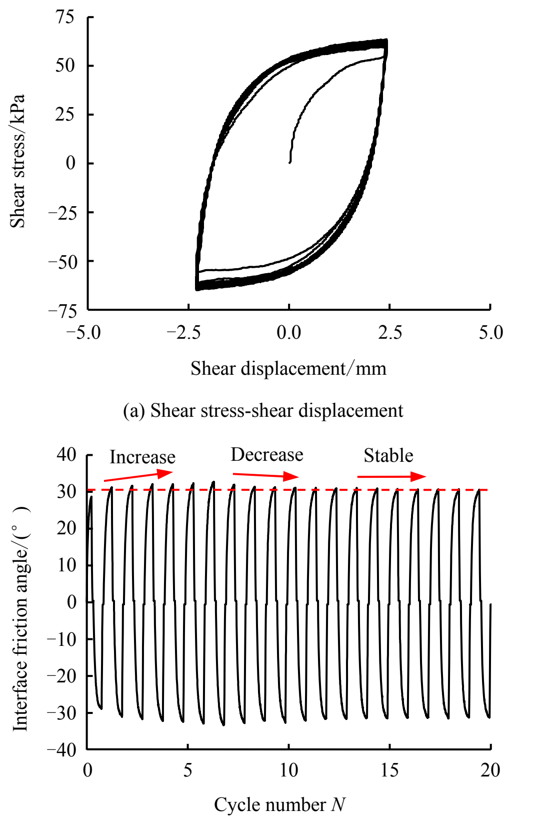
All the cyclic shear tests, a total of 22 groups, carried out in this paper are shown in Table 2. The shear rate is 5.45 mm/min and the normal stresses are 50, 100, 200 and 300 kPa, respectively, which covers the range of stresses often involved in geotechnical engineering. Among all the groups, the test groups T1 to T8 mainly investigated the effect of normal stress, the test groups T9 to T11 and T12 to T14 studied the effect of cyclic amplitude and particle size. Furthermore, the test conditions of the last eight groups (T15 to T22) are consistent with carbonate sands test for comparison with quartz sand.

3 Definition of stiffness and damping ratio

Take C0.5−1.0 group as example, the typical shear stress-shear displacement curve and the relationship between the interface friction angle and cycle number are shown in Fig.5. In the first cycle, the interface strength of the carbonate sand is the lowest in both forward and reverse shear (the interface friction angle in the first cycle is smaller than other subsequent cycles), and then shows a gradually upward trend with the increase of the cyclic number. The interface strength reaches the maximum value at the seventh cycle, and then gradually decreases and stabilizes.

Table 2 Details of interface cyclic shear tests

Test No.	Sand group	Normal stress /kPa	Cycle number	Cyclic amplitude /mm
T1	C0.5−1.0	50	200	2.50
T2	C0.5−1.0	100	200	2.50
T3	C0.5−1.0	200	200	2.50
T4	C0.5−1.0	300	200	2.50
T5	C0.10−0.25	50	200	2.50
T6	C0.10−0.25	100	200	2.50
T7	C0.10−0.25	200	200	2.50
T8	C0.10−0.25	300	200	2.50
T9	C0.5−1.0	100	500	1.00
T10	C0.5−1.0	100	400	1.25
T2	C0.5−1.0	100	200	2.50
T11	C0.5−1.0	100	100	5.00
T6	C0.10−0.25	100	200	2.50
T12	C0.25−0.50	100	200	2.50
T2	C0.5−1.0	100	200	2.50
T13	C1−2	100	200	2.50
T14	C2−5	100	200	2.50
T15	Q0.10−0.25	50	200	2.50
T16	Q0.10−0.25	100	200	2.50
T17	Q0.10−0.25	200	200	2.50
T18	Q0.10−0.25	300	200	2.50
T19	Q0.5−1.0	50	200	2.50
T20	Q0.5−1.0	100	200	2.50
T21	Q0.5−1.0	200	200	2.50
T22	Q0.5−1.0	300	200	2.50



(a) Shear stress-shear displacement

(b) Relationship between the interface friction angle and cycle number

Fig.5 Changes of interface strength under 100 kPa for C0.5−1.0 sand

Shear stiffness and damping ratio are often used for soil dynamic characteristics description and response analysis. For analyzing the interface cyclic shear test, Nye[18], Liu et al.[21-22] and other calculation methods are used in this paper. The schematic diagram is shown in Fig.6. After considering the asymmetry of the same hysteresis in two shear directions, the shear stiffness K in the hysteresis is defined as

$$K = \frac{K_1 + K_2}{2} = \frac{\tau_1 + \tau_2}{2A} \tag{1}$$

where K_1 and K_2 are the shear stiffnesses in the two shear directions; τ_1 and τ_2 are the peak shear stresses in the two shear directions. Similarly, the damping ratio D is calculated as

$$D = \frac{D_1 + D_2}{2} = \frac{1}{2}\left(\frac{S}{4\pi S_1} + \frac{S}{4\pi S_2}\right) = \frac{S}{4\pi A}\left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right) \tag{2}$$

D_1 and D_2 are the damping ratios in the two shear directions; S is the area of the entire hysteresis loop; S_1 and S_2 are the areas of the shaded parts in Fig.6, respectively.

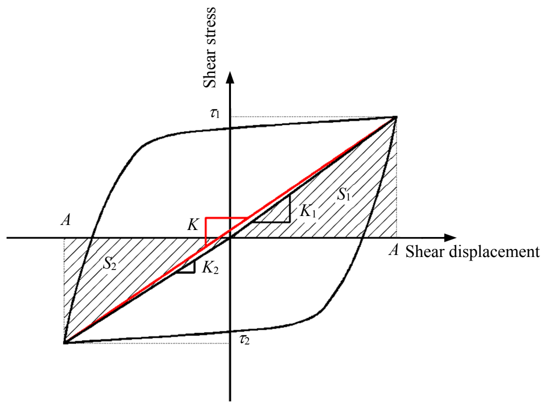


Fig.6 Schematic diagram of shear stiffness and damping ratio calculation

4 Results and analysis

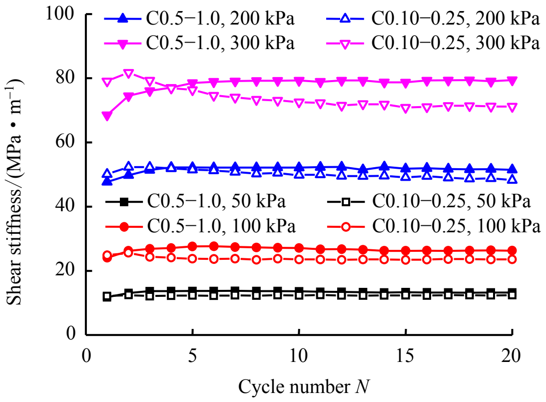
4.1 The effect of the normal stress

Related studies have indicated [24] that the shear stiffness and damping ratio of the interface are closely related to the normal stress. Fig.7 shows the shear stiffness and damping ratio of carbonate sands under different normal stress levels.

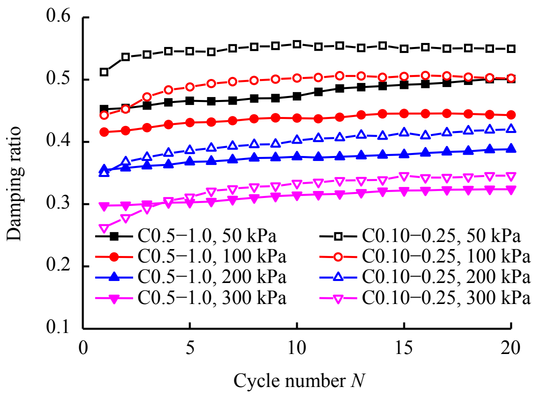
It can be revealed from Fig.7(a) that because interface shear is a frictional behavior, the value of interface shear stiffness of C0.5−1.0 and C0.10−0.25 sand samples increases approximately proportionally with the increase of normal stress. With the increase of the number of cycles, the interface stiffness of C0.5−1.0 presents a process of first increasing, then stabilizing or decreasing slightly and finally stabilizing. The stiffness after stabilization is greater than that of the first cycle. Moreover, this phenomenon becomes more pronounced as the normal stress increases. For the normal stress cases of 300 kPa, the interface stiffness of the first cycle of C0.5−1.0 samples is

68.49 MPa/m, and it increases to 79.43 MPa/m after 20 cycles, with a significant elevation of 15.9%. The peak shear stiffness of C0.10−0.25 at 300 kPa is 81.74 MPa/m, but it is only 71.15 MPa/m at the 20th cycle, with a decrease of 12.96%. After 15 cycles, sand samples C0.5−1.0 and C0.10−0.25 are basically stable with the change of the number of cycles, and the shear stiffness of C0.5−1.0 is slightly larger than C0.10−0.25 in the steady state. After more than dozens of cycles, the volume of sands with larger particle size is significantly compressed (Fig.8), which leads to denser contact between particles and stronger interfacial contact, result in a greater interface shear stiffness.

The variation law of the damping ratio of sand samples C0.5−1.0 and C0.10−0.25 under different normal stress with the number of cycles is shown in Fig.7(b). As seen in this figure, the experiment under larger normal stress shows the smaller damping ratio. The damping ratio of C0.5−1.0, which is slightly larger in particle size, increases approximately linearly in the first 20 cycles. However, the damping ratio of the C0.10−0.25 group increases rapidly in the first 6−10 cycles, and then shows a slight increasing or stabilized trend.

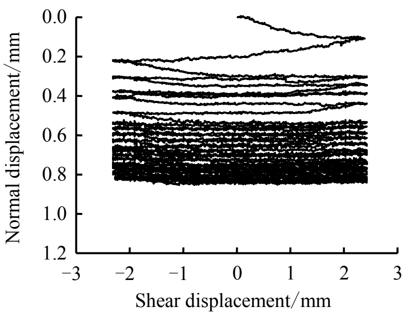


(a) Shear stiffness-cycle number

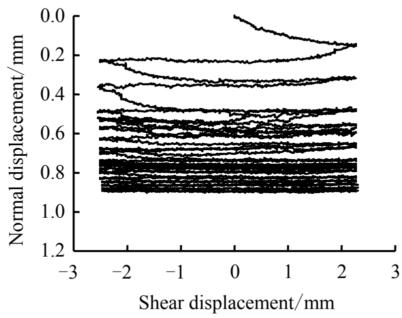


(b) Damping ratio-cycle number

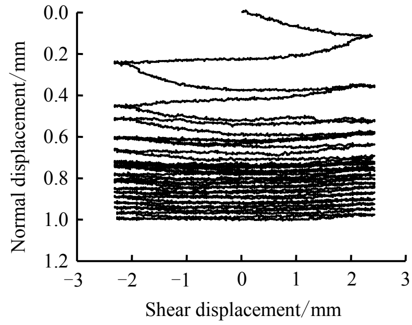
Fig.7 Stiffness and damping ratio of carbonate sand under different normal stresses



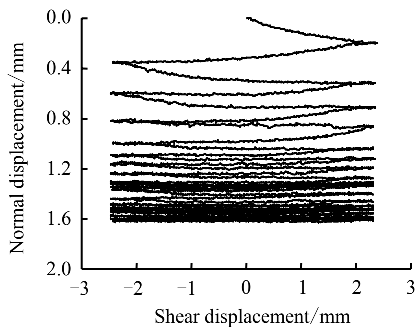
(a) C0.10−0.25



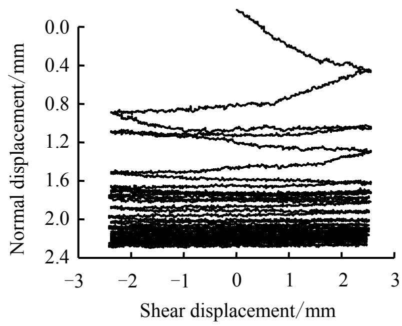
(b) C0.25−0.50



(c) C0.5−1.0



(d) C1−2

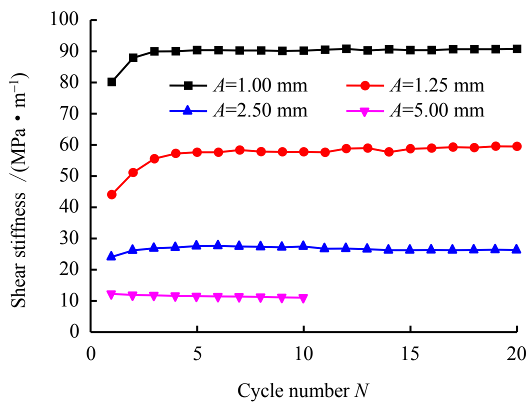


(e) C2−5

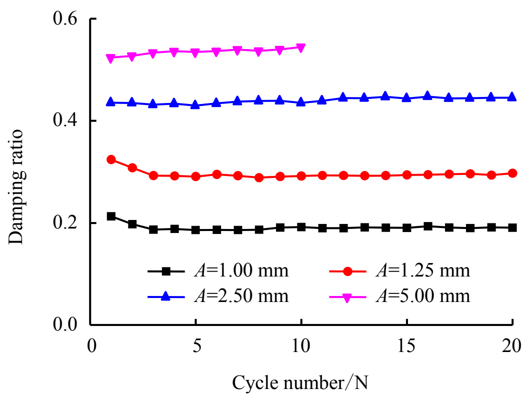
Fig.8 Changes of vertical displacement with shear displacement at 100 kPa

4.2 The effect of the cyclic amplitude

Fig.9(a) shows the interface shear stiffness at different shear displacement amplitudes under the 100 kPa normal stress. It can be found that the group with larger cyclic amplitude shows smaller shear stiffness, and when the cyclic amplitude is small, the shear stiffness appears to increase first and then becomes stable. At a cyclic amplitude of 5 mm, the shear stiffness reduces continuously. Fig.9(b) shows that the damping ratio has high sensitivity to the cyclic amplitude and will decreases with the increase of the cyclic amplitude. The damping ratios with 1.00 mm and 1.25 mm cyclic amplitude first decrease and then stabilize as the number of cycles increases, while the cyclic amplitudes of 2.50 mm and 5.00 mm both show a continuous increase in damping ratio. Further, the sand particles which are near the interface were photographed and observed after the cyclic shear test. Taking cyclic amplitudes of 1.00 mm and 5.00 mm as examples, the changes of particles at the interface after cyclic shear of the interface were shown in Fig.10. If the shear displacement is small, the particles will not be broken significantly. The compacted interface contact leads to continuous increase of stiffness due to the densification effect of the cyclic shear. On the contrary, when there is a large amplitude, accompanied by obvious particles breakage, a clear shear breakage zone appears at the interface, which causes continuous decrease trend of shear stiffness.



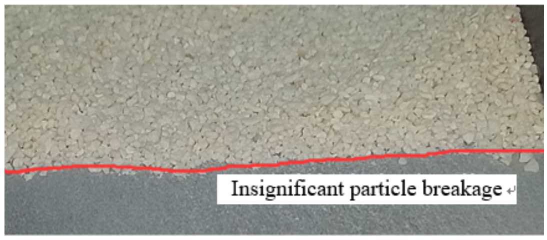
(a) Shear stiffness-cycle number



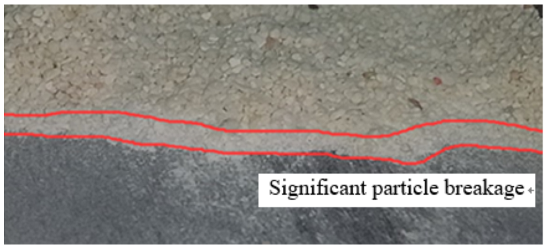
(b) Damping ratio-cycle number

Fig.9 Stiffness and damping ratios of different cyclic amplitudes

The relationship between the shear stiffness, damping ratio and the magnitude of the shear displacement at the 10th cycle is shown in Fig.11. From this figure, it is easy to find that the hyperbola curve has a better goodness of fitting shear stiffness, indicating that the shear stiffness and cyclic amplitude are approximately inversely proportional, and the damping ratio can be well described using a logarithmic equation in this research.

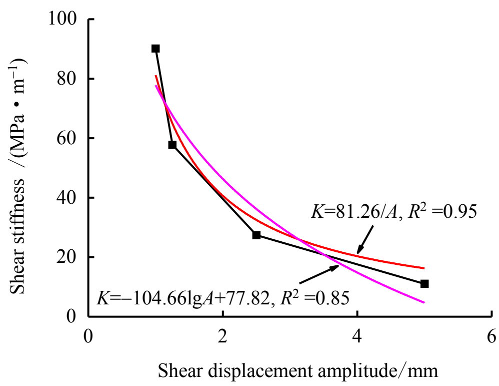


(a) A =1.00 mm

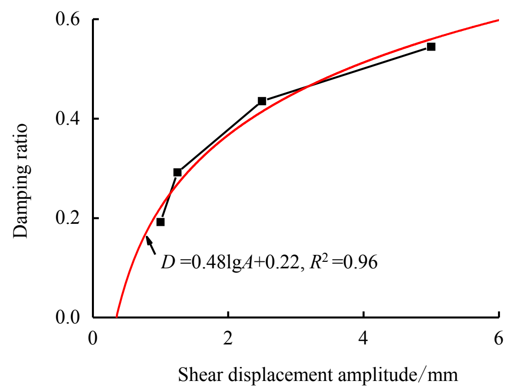


(b) A =5.00 mm

Fig.10 Particle breakage at interface after cyclic shear at 100 kPa



(a) Shear stiffness- shear displacement amplitudes

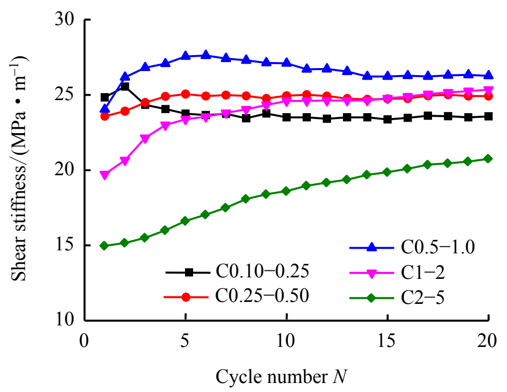


(b) Damping ration-shear displacement amplitudes

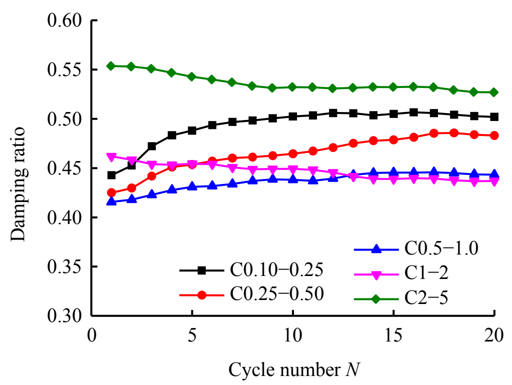
Fig.11 Relationships between shear stiffness and damping ratio and cyclic amplitude

4.3 The effect of the particle size

The variation of the shear stiffness of carbonate sands with the number of cycles under 100 kPa is shown in Fig.12(a). The initial shear stiffness of sand particles with a particle size less than 1 mm is relatively similar with each other, all of them are sequentially increase then decrease. Finally stable, and the stiffness after stabilization is positively correlated with the particle size. However, the sand particles whose size are larger than 1 mm have a lower initial shear stiffness, which gradually increases with the number of cycles, but without any stable trend in 20 cycles. This is mainly because the larger particles have less contact with the interface in the initial state, but as the number of cycle increases, the contact at the interface becomes larger due to the particle position adjustment and crushing, which lead to the increase of interface stiffness. The reason why the highest shear stiffness occurs in the C0.5−1.0 group is that as the particle size increases, the irregularity of the carbonate sand particles increases, result in the rise of interlocking between the particles and the interface. However, if the particle size improves further, the large particles lead to a larger void ratio of the material, and the contact points between the particles and the interface decrease, resulting in a lower shear stiffness.



(a) Shear stiffness-cycle number



(b) Damping ratio-cycle number

Fig.12 Stiffness and damping ratio of different particle sizes

The Fig.12(b) shows the damping ratio of sand samples with a size of smaller than 1 mm increases gradually with the repetition of cycle, conversely, the trend was completely reversed when the sand particle size is greater than 1mm. The reason for this phenomenon is: under the same cycle amplitude condition, if the particle size is smaller (C0.10−0.25), the particles will undergo a stronger position adjustment, which bring about a higher damping ratio; while the particle size is larger (C2−5), the large particle contains more pores, which makes it easier to be broken, thus increasing the damping ratio of the material

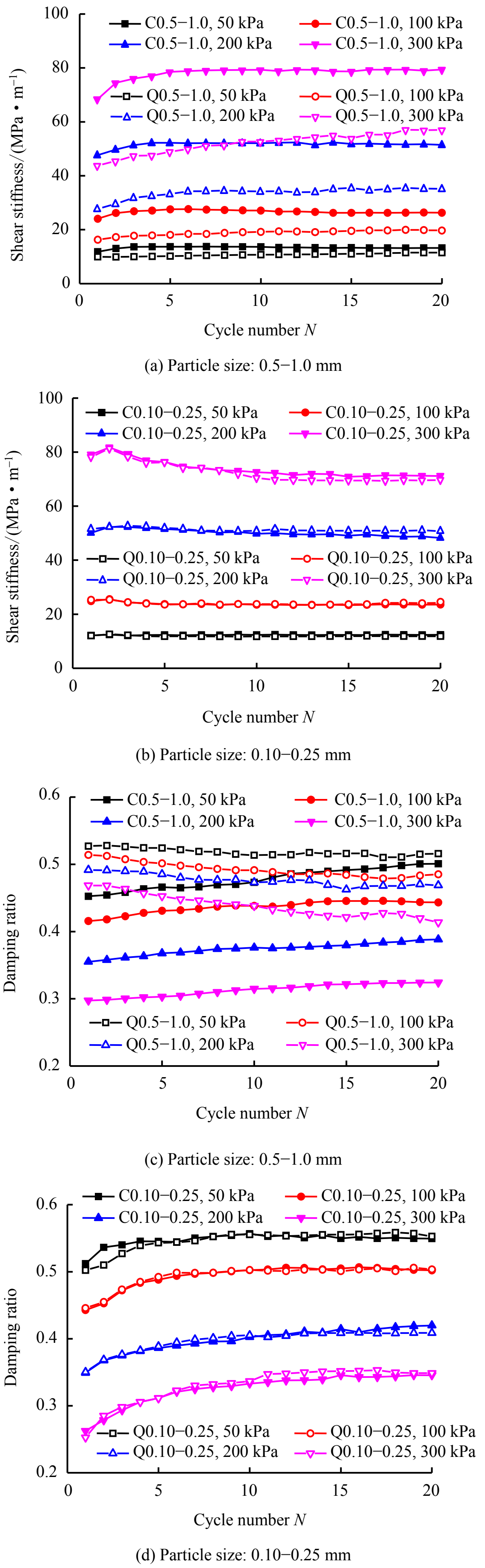
4.4 Comparison with quartz sand

In this experiment, the interface cyclic shear of Fujian Ping-tan standard sands with the same particle size as carbonate sands was selected as a comparative study. Fig.13 shows the variations of the shear stiffness and damping ratio of the two kinds of sands with the increase of cycle times. As shown in Figs.13(a) and 13(b), the shear stiffness of Q0.5−1.0 is significantly lower than that of group C0.5−1.0, and the difference between the two groups also increases with the rise of normal stress. As the number of cycles increase, the shear stiffness measured in group Q0.5−1.0 remains increasing during and after 20 experimental cycles. The change trend and value of the shear stiffness of Q0.10−0.25 are almost completely consistent with those of C0.10−0.25, indicating that when the particles are small, the two kinds of sand have similar interface shear stiffness. This is mainly because as the particle size increases, the carbonate sand particles become more irregular and therefore have greater shear stiffness. While the difference in particle shape declines as the particle size decreases, the shear stiffness tend to the same value in this procedure gradually.

The change of the damping ratio of the two sands with the number of cycles is shown in Figs.13(c) and 13(d). Significantly different from C0.5−1.0, the shear stiffness of Q0.5−1.0 group presents a trend of continuous decrease, furthermore, the larger the normal stress lead to more obvious drop of the damping ratio. The damping ratio of quartz fine sand and the carbonate sand are almost identical, showing a tendency which is increasing first and then stabilizing finally, indicating that the damping ratio of these two kinds of sand is very close when the particle size is diminutive.

5 Conclusions

A series of cyclic shear tests on the interface between carbonate sand and steel was carried out based on the interface ring shear apparatus, and further compared these properties of carbonate sand with quartz sand. It was found that the normal stress and the cyclic amplitude had a controlling effect on the interface shear stiffness and damping ratio. The particle size had a significant influence on the shear stiffness and damping ratio of carbonate sands. The specific conclusions are as follows:



(a) Particle size: 0.5−1.0 mm

(b) Particle size: 0.10−0.25 mm

(c) Particle size: 0.5−1.0 mm

(d) Particle size: 0.10−0.25 mm

Fig.13 Comparison of stiffness and damping ratio of quartz sand and carbonate sand

(1) The promotion of normal stress level at the interface increases the shear stiffness and decreases the damping ratio at the same time.

(2) The shear displacement amplitude have a significant influence on the stiffness and damping ratio. The increasing of cyclic amplitude approximately leads to a reduction of shear stiffness and a logarithmic increasing of damping ratio .

(3) For homogeneous carbonate sands, there is a boundary particle size, which makes the variation of shear stiffness and damping ratio conspicuously different.

(4) When the particle size of quartz sands is larger, the interface shear stiffness and damping ratio are obviously different from those of carbonate sands, while the two types of sands exhibit similar shear stiffness and damping ratio characteristics at small particle sizes.

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