Rock and Soil Mechanics

Volume 42 | Issue 6 Article 1

10-22-2021

Experimental study on cyclic shear softening characteristics of gravel–geogrid interface

Fei-yu LIU
Department of Civil Engineering, Shanghai University, Shanghai 200444, China

Huai JIANG
Department of Civil Engineering, Shanghai University, Shanghai 200444, China

Jun WANG
College of Architecture and Civil Engineering, Wenzhou University, Wenzhou, Zhejiang 325035, China, sunnystar1980@163.com

Custom Citation
LIU Fei-yu, JIANG Huai, WANG Jun, . Experimental study on cyclic shear softening characteristics of gravel–geogrid interface[J]. Rock and Soil Mechanics, 2021, 42(6): 1485-1492.

Rock and Soil Mechanics 2021 42(6): 1485−1492 ISSN 1000−7598
https: //doi.org/10.16285/j.rsm.2020.6692 rocksoilmech.researchcommons.org/journal

Experimental study on cyclic shear softening characteristics of gravel−geogrid interface

LIU Fei-yu[1], JIANG Huai[1], WANG Jun[2]

1. Department of Civil Engineering, Shanghai University, Shanghai 200444, China
2. College of Architecture and Civil Engineering, Wenzhou University, Wenzhou, Zhejiang 325035, China

Abstract: In order to study the softening characteristics of gravel−geogrid interface during and after cyclic shearing, a series of displacement controlled monotonic direct shear tests, cyclic direct shear tests with 2 000 cycles and post cyclic direct shear tests were carried out on the gravel−geogrid interface using dynamic direct shear apparatus. The shear strength characteristics, volume change behavior, shear stiffness and damping ratio of the gravel−geogrid interface under four groups of normal stresses of 20, 40, 60 and 80 kPa were studied. The direct shear characteristics of the gravel−geogrid interface before and after cyclic shear were compared and analyzed. The results show that: in the cyclic direct shear test, the average peak shear stress of gravel−geogrid interface first increases and then decreases, and finally tends to be stable with the increase of number of cycles, and the interface shows shear softening characteristics; the vertical displacement increment of gravel−geogrid interface decreases gradually with the increase of number of cycles; the shear stiffness first increases and then decreases with the increase of number of cycles, and finally tends to be stable; the damping ratio first decreases and then increases with the increase of number of cycles, and finally tends to be stable; under the same normal stress, the peak shear stress increases and the residual shear stress decreases in the cyclic direct shear test compared with the monotonic direct shear test; the cyclic shear makes the interface cohesion increase significantly and the internal friction angle decrease.

Keywords: direct shear test; shear stress; shear stiffness; damping ratio

1 Introduction

Reinforced soil structures can improve the bearing capacity and overall stability of soil, and has high economical and environmental benefits. This type of structures has been widely used in subgrade, slope, port, seawall and other civil engineering projects in recent decades[1]. The behavior of reinforcement−soil interface interaction is crucial to study the mechanical properties and stability of reinforced soil structures, and is important in the design of reinforced soil structures[2].

The direct shear behavior of reinforced soil interface under static conditions have been studied by various scholars. Liu et al.[3] conducted an experimental study on the shear behavior of geocell reinforced soil by using large-scale direct shear apparatus, and determined the nonlinear relationship between shear stress and shear strain of reinforced soil and the shear strength enhancement mechanism. Liu et al.[4] evaluated the effect of geogrid transverse ribs on the shear strength of reinforced soil interface through large-scale direct shear tests. Kamalzare et al.[5] conducted large-scale direct shear tests on two-layer soil samples reinforced with different geosynthetics, and studied the influence of geosynthetics on the shear strength parameters of road subbase. Liu et al.[6] studied the effects of particle size distribution, relative density, type of reinforcement and normal stress on the monotonic direct shear characteristics of reinforced soil interface through large-scale direct shear tests. Through a series of large-scale direct shear tests, Sweta et al.[7−8] examined the influence of different normal stresses and shear rates on the monotonic direct shear characteristics of geogrid−ballast interface, and found that the shear strength of interface decreased with the increase of shear rate and normal stress.

In practical engineering, reinforced soil structures are often affected by dynamic loads such as traffic loads, wave loads and seismic loads. Therefore, it is necessary to ascertain the cyclic shear characteristics of reinforcement−soil interface. Wang et al.[9] conducted a series of cyclic direct shear tests and post−cyclic direct shear tests to investigate the shear characteristics of the interface between geogrid and sand with different particle size distribution, and discussed the influence of cyclic shear stress history on the shear characteristics of the interface between reinforcement and soil. Wang et al.[10] conducted 10 cycles of cyclic shear test using a large-scale direct shear test device, and studied the cyclic shear characteristics of coarse-grained soil−geogrid interface under various particle sizes. The results show that the interface shows cyclic hardening, and the interfacial damping ratio decreases

Received: 16 November 2020 Revised: 5 March 2021
This work was supported by the National Natural Science Foundation of China(52078285, 51678352, 51878402).
First author: LIU Fei-yu, male, born in 1976, PhD, Professor, research interests: reinforced soil and soil dynamics. E-mail: lfyzju@shu.edu.cn
Corresponding author: WANG Jun, male, born in 1980, PhD, Professor, research interests: ground treatment. E-mail: sunnystar1980@163.com

with the increase of the number of cycle and the relative density of the filling, and the larger the particle size is, the greater the interfacial contraction value is. Liu et al.[11] studied the effects of normal stress, shear amplitude of shear displacement and number of cycles on the cyclic shear behavior of interface using cyclic shear tests of 10 cycles. Vieira et al.[12] carried out 40 cycles of strain controlled and stress controlled cycle shear tests with a large direct shear test device, and studied the characteristics of sand−geotextile interface under monotonic and cyclic shear. Liu et al.[13] studied the influence of shear rate, thickness of thin sand layer, amplitude of shear displacement and other factors on the cyclic shear characteristics of Sandwich reinforced soil interface through a series of cyclic shear tests with 10 cycles. Feng et al.[14−15] conducted 50 cycles of cyclic shear tests on soil−structure interface using a large-scale three-dimensional apparatus, and studied the three-dimensional cyclic mechanical properties of the interface under different shear paths. Based on the cyclic shear test of geomembrane−sand interface with 10 cycles, Cen et al.[16] established a theoretical dynamic model to describe the cyclic shear characteristics of reinforced soil interface.

In summary, due to the limitation of test instruments, the number of cycles is scanty in the study of cyclic shear behavior of reinforcement−soil interface, which cannot accurately reflect the cyclic shear behavior and post cyclic direct shear behavior of reinforcement−soil interface under the continuous action of dynamic loads such as traffic loads and wave loads. In this paper, the monotonic direct shear tests, cyclic direct shear tests and post-cyclic direct shear tests of gravel−geogrid interface are carried out by using dynamic direct shear apparatus. The variation of shear stress, vertical displacement, shear stiffness, damping ratio and interface softening behavior of gravel−geogrid interface under different normal stresses during continuous cyclic shear are studied, and the post cyclic direct shear behavior of interface after cyclic shearing are studied, which provides theoretical basis for the response analysis of reinforced soil−structures under dynamic loads.

2 Test materials and methods

2.1 Test materials and instruments

The soil is dry gravel with grain size of 2−8 mm, its effective grain size D_{10} = 3.32 mm, continuous grain size D_{30} = 4.28 mm, median particle size D_{50} = 4.96 mm, limited particle size D_{60} = 5.32 mm, coefficient of uniformity C_u = 1.61, and coefficient of curvature C_c = 1.04. Gravel particle gradation curve is shown in Fig.1. The reinforced material adopted in the test is biaxial polypropylene geogrid, and the technical indexes are shown in Table 1. RAW-60/2 microcomputer-controlled electro-hydraulic servo dynamic direct shear apparatus developed by Tongji University is used in the test. Its main functions and indexes are reported in reference [17].

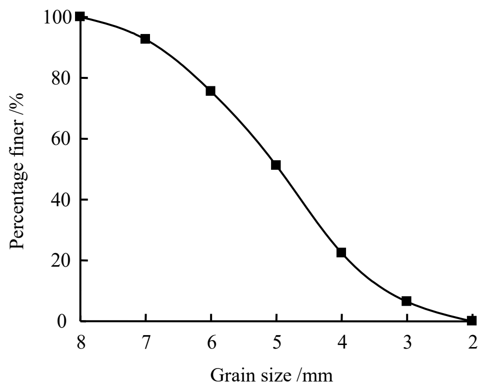


Fig. 1 Grain size distribution curve of gravel

Table 1 Main characteristics of geogrid

Geogrid	Mass per unit area /(g • m^{-2})	Aperture size /mm	LD and TD ribs width /mm		Maximum elongation /%		Ultimate tensile strength /(kN • m^{-1})	
			TD	LD	TD	LD	TD	LD
Polypropylene geogrid	280	30×30	5	5	13	15	20	20

2.2 Testing program

The relative density D_r of the sample is 80%, and mass of the sample is calculated according to the size of the shear box. The sample is compacted in layers to ensure the same relative density and reduce the influence of relative density on the test results. In the monotonic direct shear tests, the upper shear box is fixed, and the lower shear box moves from the equilibrium position along one direction until the specified shear displacement is reached. In the cyclic direct shear tests, sinusoidal wave is used as the loading waveform of cyclic shear horizontal displacement, and the lower shear box is subjected to cyclic shear, and finally returned to the equilibrium position. After the cyclic direct shear tests, the post−cyclic direct shear tests are continued.

In this experiment, the shear rate used in monotonic direct shear tests and post−cyclic direct shear tests is 1 mm/min. The frequency of cyclic direct shear tests is

Table 2 Testing Program

Test type	Normal stress /kPa	Shear rate /(mm • min^{-1})	Frequency /Hz	Amplitude /mm	Number of cycle N
Cyclic direct shear test	20, 40, 60, 80	—	0.2	2	2 000
Post cyclic monotonic direct shear test	20, 40, 60, 80	1	—	—	—
Monotonic shear test	20, 40, 60, 80	1	—	—	—

0.2 Hz, which is the common frequency of traffic loads. The normal stresses are 20 kPa, 40 kPa, 60 kPa and 80 kPa, and the amplitude of shear displacement is 2 mm. The testing program is shown in Table 2.

3 Cyclic direct shear test

3.1 Variation of shear stress

The cyclic direct shear tests of gravel–geogrid interface with a shear displacement amplitude of 2 mm, a frequency of 0.2 Hz, number of cycles of 2 000 and normal stresses of 20, 40, 60 and 80 kPa were carried out. The average absolute value of maximum and minimum shear stress in a hysteresis loop is defined as the average peak shear stress τ of the hysteresis loop[12]. The average peak shear stress in the first hysteresis loop is the initial interface shear stress τ_a. The maximum average peak shear stress in all hysteresis loops is the interface peak strength τ_p. The average peak shear stress at the stable residual stage is the interface residual strength τ_r. When the shear amplitude is 2 mm, the variation curve of the average peak shear stress with the number of cycles at the gravel–geogrid interface under different normal stresses is shown in Fig.2. It can be seen from the figure that the average peak shear stress at the gravel–geogrid interface under different normal stresses increases with the cyclic shear first, and then decreases to a stable residual strength after reaching the peak strength of the interface. The reinforcement–soil interface shows the characteristics of shear softening. The specific values of initial shear stress, interface peak strength and interface residual strength under different normal stresses and the number of cycles corresponding to the interface peak strength and residual strength are shown in Table 3.

It can also be seen from Fig.2 that the peak strength of the interface during cyclic shearing increases with the increase of normal stress, which can be explained by the Mohr-Coulomb shear strength criterion. That is, the greater the normal stress is, the greater the shear strength of the sample is. The larger the normal stress, the fewer the number of cycles required for the interface to reach the peak strength during cyclic shearing. This is can be explained that an increase in normal stress leads to an increase in the densification of soil particles in the initial stage of cyclic shearing, which also leads to an increase in the interlocking between soil and geogrid. It would be easier for the interface to reach the peak strength. The greater the normal stress, the more the number of cycles required to achieve the interface residual strength. This is because the increase of normal stress leads to the continuous crushing of soil particles and the continuous abrasion and deformation of the geogrid after the interface failure, which results in the weakening of the interlocking effect between the soil and the geogrid, and the cycle number corresponding to residual strength increases.

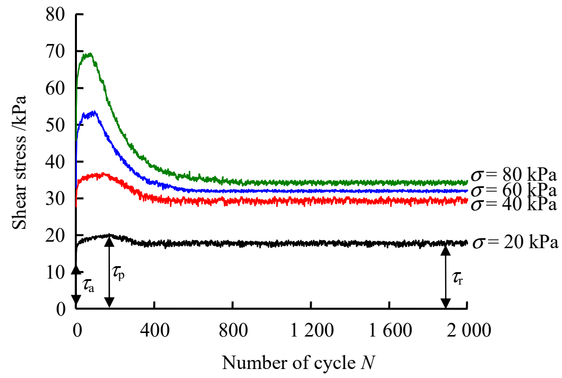


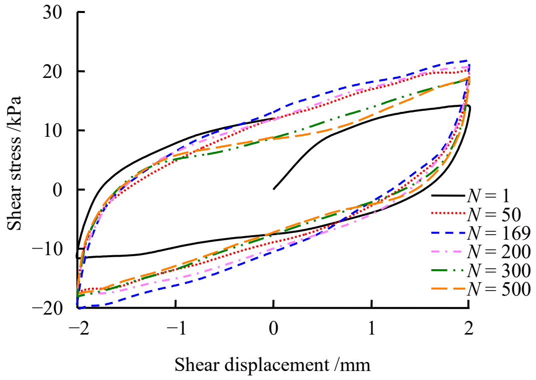
Fig. 2 Curve of average peak shear stress

Table 3 The values of τ_a, τ_p, τ_r and corresponding number of cyclic shear

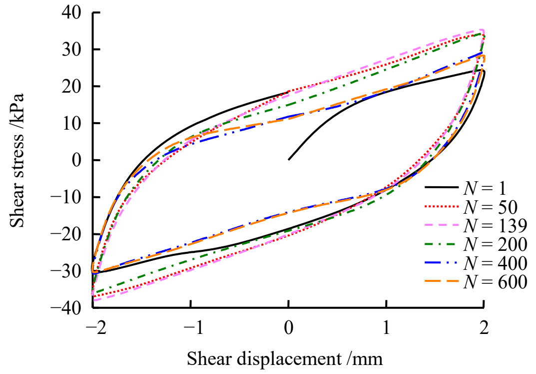
Normal stress /kPa	Initial shear stress τ_a /kPa	Interface peak strength τ_p /kPa	Number of cycle corresponding to τ_p N	Interfacial residual strength τ_r /kPa	Number of cycle corresponding to τ_r N
20	12.96	20.35	169	17.79	about 300
40	27.54	36.94	139	29.36	about 400
60	32.82	53.70	95	32.00	about 600
80	45.62	69.50	73	34.22	about 800

Since the average peak shear stress at the interface under each normal stress tends to be stable after the cycle number of cyclic shear directs reaches 1 000 cycles, this paper focuses on the variation of the shear characteristics of the gravel-geogrid interface in the first 1 000 cycles.

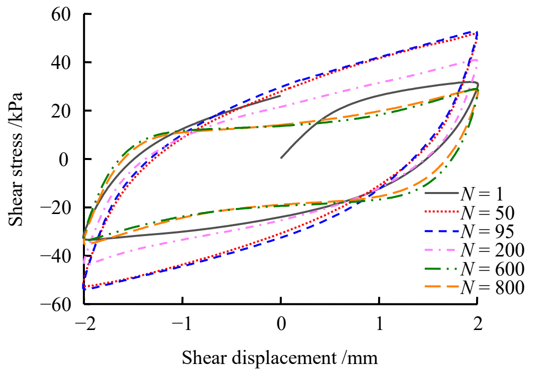
Figure 3 shows the shear stress–shear displacement hysteresis curves of gravel–geogrid interface with selected number of cycles under different normal stresses. It can be seen from the figure that under different normal stresses, the shear stress–shear displacement curve of gravel–geogrid interface shows an outward expansion trend in the number of cycles from the first cycle to the cycle corresponding to τ_p, and the interface shows shear hardening. After the number of cycles corresponding to τ_p is reached, the hysteresis curve gradually shrinks, and the interface shows shear softening. After reaching the number of cycles corresponding to τ_r, the hysteresis curve tends to overlap, and the shear stress gradually tends to be stable. The tendency of hysteresis loops corresponds to the variation of average peak shear stress with number of cycles in Fig.2. Referring to the definition of degradation coefficient[18], the ratio of the average peak shear stress τ to the peak interface strength τ_p in the N^{th} hysteresis loop is defined as the hardening coefficient H_τ. Figure 4 shows the development curve of interface hardening coefficient with cyclic shear under different normal stresses.



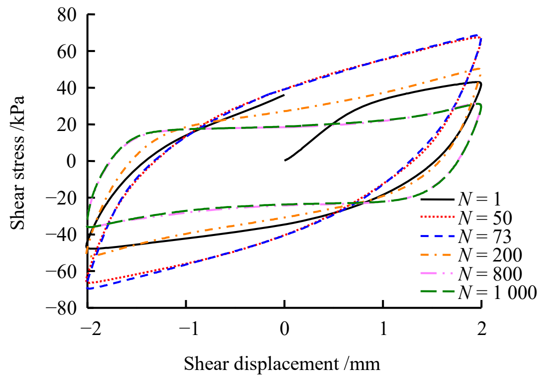
(a) σ = 20 kPa



(b) σ = 40 kPa



(c) σ = 60 kPa



(d) σ = 80 kPa

Fig. 3 Shear stress−shear displacement curves of gravel−geogrid interface

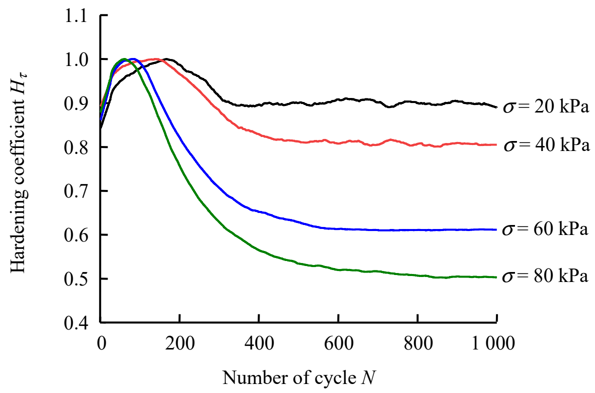


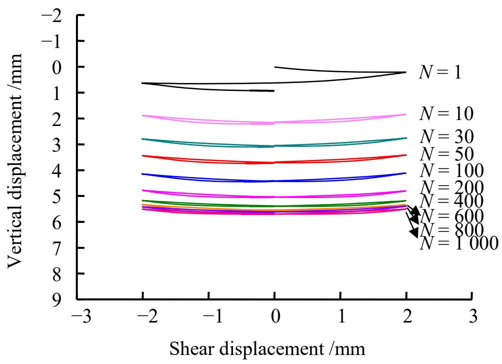
Fig. 4 Development curves of gravel−geogrid interface hardening factor

The hardening coefficient of each interface increases rapidly at the initial stage of cyclic shear. With the increase of cycle, the growth rate of hardening coefficient decreases continuously, and until the peak strength of interface is reached, the hardening coefficient decreases gradually and tends to be constant. Whether in the early growth stage or the late decline stage of the hardening coefficient, the change rate of the interface hardening coefficient under the normal stress of 80 kPa is the largest, followed by 60, 40 and 20 kPa, which shows that the greater the normal stress, the faster the hardening and softening of the interface. The higher the normal stress is, the smaller the final hardening coefficient of the interface is, which shows that under a high normal stress, the softening phenomenon of the shear stress of the gravel−geogrid interface after cyclic shearing is more obvious

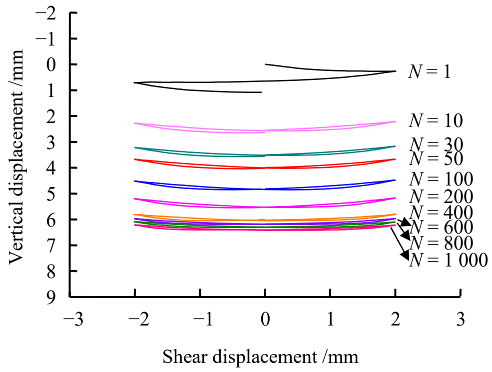
3.2 Variation of vertical displacement

Figure 5 illustrates the vertical displacement−shear displacement curves of gravel−geogrid interface with selected number of cycle under different normal stresses. Since the area of the shear surface remains constant in the shear process, the change of the vertical displacement can reflect the volume response of the soil. The positive vertical displacement indicates the shear contraction of the soil, and the negative vertical displacement indicates the dilatancy of the soil.

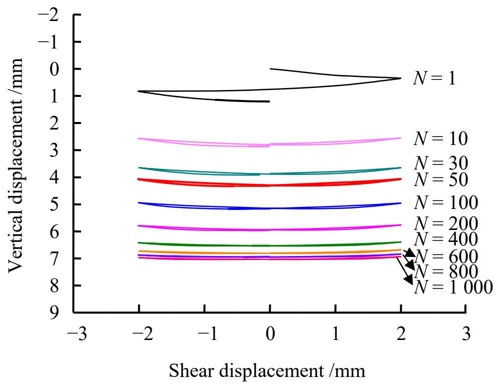
It can be observed from Fig.5 that at the initial stage of cyclic shear, the vertical displacement of the interface under each normal stress increases rapidly, but the subsequent vertical displacement increment decreases with the increase of the number of cycle. The shear contraction of soil is mainly concentrated in the first 100 cycles of shear. When the normal stresses are 20 kPa, 40 kPa, 60 kPa and 80 kPa, the ratios of the shear contraction of soil in the first 100 cycles of shear to the final shear contraction are 77.5%, 75.5%, 73.4% and 72.7%, respectively. Because in the initial stage of cyclic shear, sliding of soil particles occurred at the interface between



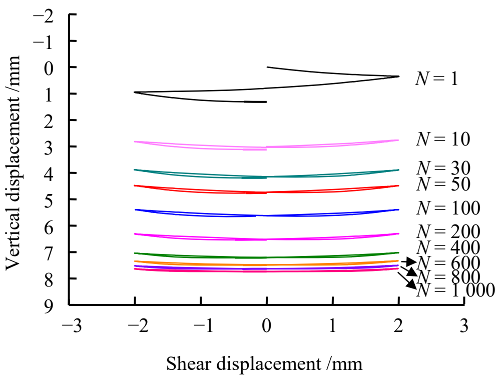
(a) σ = 20 kPa



(b) σ = 40 kPa



(c) σ = 60 kPa



(d) σ = 80 kPa

Fig. 5 Vertical displacement−shear displacement curves of gravel−geogrid interface

soil and reinforcement, that is position adjustment, so that the particles rearranged from the position in a relative disorder state into an organized state with certain orientation. It can also be seen from Fig.5 that the gravel−geogrid interface has undergone alternating changes of shear contraction and dilatancy after the initial shearing. With the continuous cyclic shearing, the phenomenon gradually weakens, and the vertical displacement of the interface tends to be stable.

The curves of vertical displacement versus number of cycles for gravel−geogrid interface under different normal stresses are plotted in Fig.6. During cyclic shearing, shear contraction generally occurs, and the increment in shear contraction increases with the increase of normal stress. The greater the normal stress is, the greater the vertical displacement is for the same number of cycles, and the greater the final shear contraction of the interface is. When the normal stresses are 20, 40, 60 and 80 kPa, the ultimate vertical displacements of the interface are 5.7, 6.4, 7.03 and 7.74 mm.

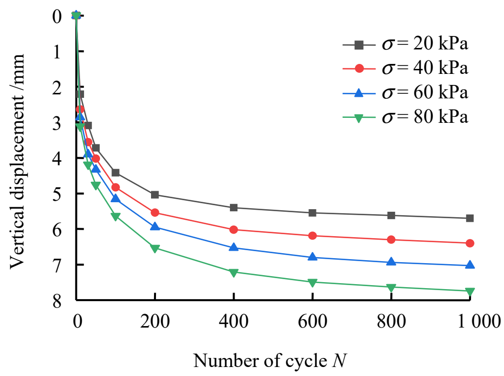


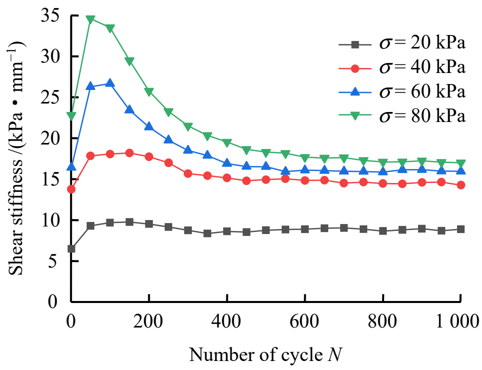
Fig. 6 Vertical displacement−number of cycle curve of gravel−geogrid interface

3.3 Shear stiffness and damping ratio

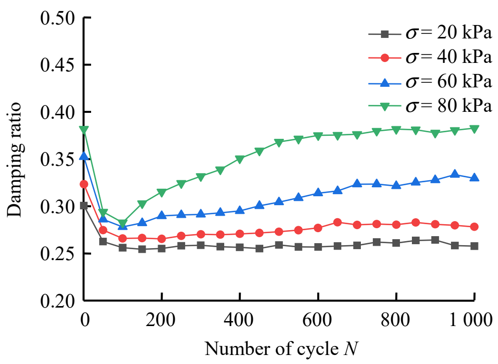
Shear stiffness and damping ratio are two important parameters for studying the dynamic shear characteristics of reinforcement−soil interface. Nye et al.[19] analyzed the dynamic response of geosynthetics−soil interface by shear stiffness and damping ratio. Using the same method, the cyclic shear characteristics of gravel−geogrid interface under normal stresses are analyzed using shear stiffness and damping ratio.

Figure 7(a) presents the variation of shear stiffness of gravel−geogrid interface under normal stresses. Under the same number of cycles, an increase in normal stress leads to an increase in stiffness, thus a stronger ability of the interface to resist deformation is achieved. Under the same normal stress, the shear stiffness increases first and then decreases, and finally tends to be stable. With the increase of normal stress, the change rate of shear stiffness increases.

Figure 7(b) displays the variation of interface damping ratio with number of cycles under normal stresses. As the number of cycles increases, the interface damping ratio under each normal stress decreases first and then increases, and finally tends to be stable. The number of cycles when the damping ratio decreases to a certain value and then increases corresponds to the number of cycles when the interface reaches the peak strength. Under the same number of cycles, a greater normal stress yields a greater damping ratio, which shows that the increase of normal stress will accelerate the energy dissipation of gravel−geogrid interface in the process of cyclic shear.



(a) Shear stiffness



(b) Damping ratio

Fig. 7 Development of shear stiffness and damping ratio with number of cycle

4 Comparison between post-cyclic direct shear tests and monotonic direct shear tests

4.1 Comparison of shear stress and vertical displacement

Figure 8 shows the shear stress−shear displacement curves of gravel−geogrid interface under varying normal stresses in monotonic direct shear tests and post−cyclic direct shear tests. In both monotonic shear tests and post−cyclic direct shear tests, the shear stress at the gravel−geogrid interface increases first and then decreases, and finally tends to be stable. When the normal stress increases, the shear stress of the interface increases. Under the same normal stress, the peak shear stress in the post−cyclic direct shear tests is greater than that in the monotonic direct shear tests, and the shear displacement corresponding to the peak shear stress is smaller. This is because, compared with the monotonic direct shear tests, when the gravel−geogrid interface is subjected to cyclic shearing, the soil particles and geogrid are closer, embedded effect is stronger, and the shear resistance of the interface plays a more important role.

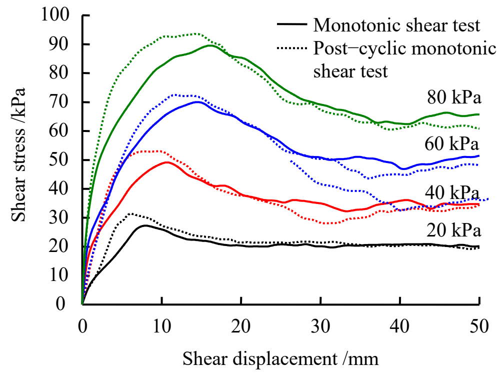


Fig. 8 Shear stress−shear displacement curves of direct shear tests

The ratio of residual shear stress to peak shear stress is defined as residual stress ratio[20] to describe the softening characteristics of gravel−geogrid interface after reaching peak shear stress. Table 4 gives the values of peak shear stress, residual shear stress and residual stress ratio obtained by monotonic and post−cyclic direct shear tests under different normal stresses. A reduction in the residual stress ratio of the interface between reinforcement and soil is observed after cyclic shearing, which may be due to the fact that the particles broken of the interface and the interaction between particles weaken in cyclic direct shear tests, resulting in a more obvious softening of the interface after reaching the peak shear stress.

Table 4 The values of peak shear stress, residual shear stress and residual stress ratio

Normal stress /kPa	Monotonic shear test			Post cyclic monotonic direct shear test		
	Peak shear stress /kPa	Residual shear stress /kPa	Residual stress ratio	Peak shear stress /kPa	Residual shear stress /kPa	Residual stress ratio
20	27.49	20.57	0.75	31.85	20.17	0.63
40	49.40	34.75	0.70	53.21	34.59	0.65
60	70.15	49.71	0.71	72.96	46.38	0.64
80	89.83	64.38	0.72	93.89	61.03	0.65

Figure 9 illustrates the curves of vertical displacement−shear displacement obtained by monotonic direct shear tests and post−cyclic direct shear test under different normal stresses. In the monotonic direct shear tests and the post−cyclic direct shear tests, the volume change of soil finally presents dilatancy. However, in the initial stage of the monotonic direct shear tests, the volume change shows a certain degree of contraction, and the volume change in the post−cyclic direct shear tests is dilatancy. Under the same normal stress, the dilatancy of soil in the post−cyclic direct shear tests is stronger than that in the monotonic shear test. A higher normal stress results in a smaller the dilatancy in monotonic direct shear tests and post−cyclic direct shear tests.

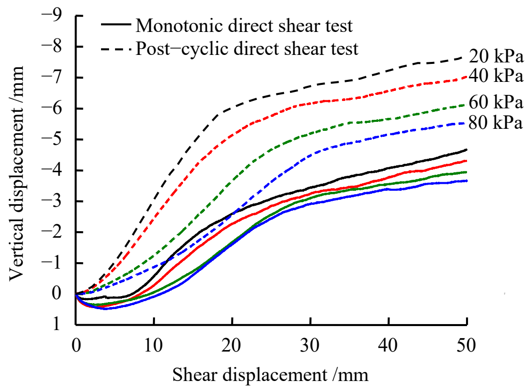
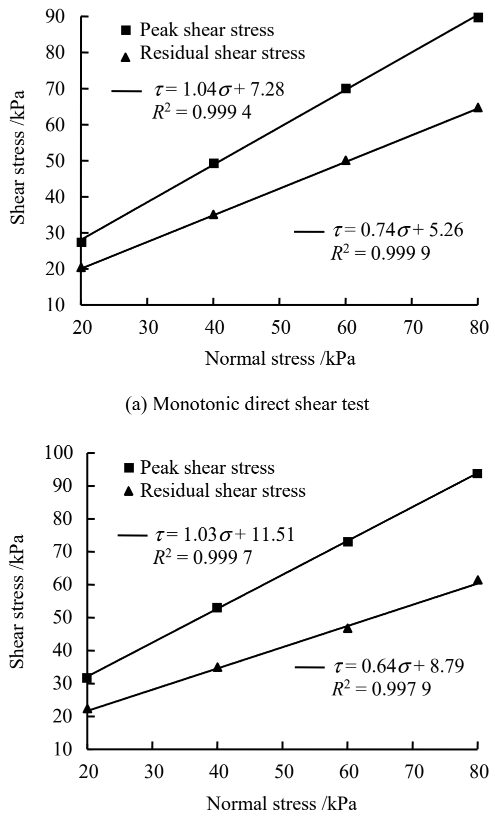


Fig. 9 Vertical displacement−shear displacement curves of direct shear tests

4.2 Comparison of shear strength parameters

Figure 10 shows the envelope curves of peak shear stress and residual shear stress at gravel−geogrid interface in monotonic direct shear test and post−cyclic direct shear test. It can be seen from the figure that the value of the correlation coefficient R^2 of the envelope curve is close to 1, which indicates that there are good linear relationships between the peak shear stress and the residual shear stress of the interface and the normal stress. The linear relationship is described by the Mohr-Coulomb criterion: $\tau = \sigma\tan\varphi + c$, where c, φ are the apparent cohesion and the internal friction angle of the interface. The apparent cohesions obtained by the envelope curves of peak shear stress and residual shear stress are denoted as peak apparent cohesion c_p and residual apparent cohesion c_r, respectively, and the obtained internal friction angles are denoted as peak internal friction angle φ_p and residual internal friction angle φ_r, respectively. The specific values of c_p, c_r, φ_p and φ_r obtained from monotonic direct shear test and post−cyclic direct shear test are shown in Table 5.

Table 5 shows that after cyclic shearing, the peak and residual apparent cohesions of the interface increase obviously. The peak apparent cohesion increases by 58% compared with that before cycle shearing, and the residual apparent cohesion increases by 67%. The apparent cohesion at the interface mainly reflects the constraint effect of reinforcement on soil[21], which indicates that after cyclic shearing, the constraint effect of reinforcement is enhanced at the interface of reinforcement and soil. The peak internal friction angle and residual internal friction angle of the interface decrease after cyclic shearing, which may be related to the reduction in interlocking effect between soil particles caused by particle breakage.



(a) Monotonic direct shear test

(b) Direct shear test after cyclic shearing

Fig. 10 Envelopes of peak shear stress and residual shear stress of gravel−geogrid interface in direct shear tests

Table 5 The values of c and φ in monotonic direct shear and post−cyclic direct shear tests

Test type	c_p /kPa	c_r /kPa	φ_p /(°)	φ_r /(°)
Monotone direct shear test	7.28	5.26	46.12	36.5
Post−cyclic direct shear test	11.51	8.79	45.85	32.62

5 Conclusion

(1) During cyclic shearing, the change of the average peak shear stress at the gravel−geogrid interface first increases and then decreases, and finally tends to be stable. The interface shows shear softening. The greater the normal stress is, the more obvious the softening phenomenon of the interface after cyclic shearing is.

(2) After initial shearing, the interface of gravel−geogrid changes alternately in shear contraction and dilatancy. The greater the normal stress, the greater the vertical

displacement for the same number of cycles, the greater the ultimate shear contraction of the interface.

(3) During cyclic shearing, the damping ratio first decreases and then increases with increasing number of cycles. Under the same number of cycles, the greater the normal stress is, the greater the shear stiffness is and the greater the damping ratio is.

(4) Under the same normal stress, the peak shear stress in the post−cyclic direct shear tests is greater than that in the monotonic direct shear tests, and the residual shear stress is lower than that in the monotonic direct shear tests. Cyclic shearing significantly raises the interfacial apparent cohesion and reduces the internal friction angle.

References

[1] CHEN Rong, LI Bo, HAO Dong-xue, et al. Simulation for interaction between geogrids and soil by cohesive zone model[J]. Chinese Journal of Geotechnical Engineering, 2020, 42(5): 934−940.

[2] LIU Fei-yu, LIN Xu, WANG Jun, et al. Effect of cyclic shear load on behavior of sand-geogrid interface[J]. China Journal of Highway and Transport, 2015, 28(2): 1−7.

[3] LIU Wei, WANG Yi-min, CHEN Ye-kai, et al. Research on large size direct shear test for geocell reinforced soil[J]. Rock and Soil Mechanics, 2008, 29(11): 3133−3138.

[4] LIU C N, ZORNBERG J G, CHEN T C, et al. Behavior of geogrid-sand interface in direct shear mode[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2009, 135(12): 1863−1871.

[5] KAMALZARE M, ZIAIE-MOAYED R. Influence of geosynthetic reinforcement on the shear strength characteristics of two-layer sub-grade[J]. Acta Geotechnica Slovenica, 2011, 8(1): 39−49.

[6] LIU Fei-yu, LIN Xu, WANG Jun. Influence of particle-size gradation on shear behavior of geosynthetics and sand interface[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(12): 2575−2582.

[7] SWETA K, HUSSAINI S K K. Effect of shearing rate on the behavior of geogrid-reinforced railroad ballast under direct shear conditions[J]. Geotextiles and Geomembranes, 2018, 46(3): 251−256.

[8] SWETA K, HUSSAINI S K K. Behavior evaluation of geogrid-reinforced ballast-subballast interface under shear condition[J]. Geotextiles and Geomembranes, 2019, 47(1): 23−31.

[9] WANG Jun, SHI Jing, LIU Fei-yu, et al. Influence of soil particle-size gradation on geogrid-sand interface static and dynamic shear behavior[J]. Rock and Soil Mechanics, 2019, 40(1): 109−117.

[10] WANG J, LIU F Y, WANG P, et al. Particle size effects on coarse soil-geogrid interface response in cyclic and post−cyclic direct shear tests[J]. Geotextiles and Geomembranes, 2016, 44(6): 854−861.

[11] LIU F Y, WANG P, GENG X, et al. Cyclic and post−cyclic behaviour from sand-geogrid interface large-scale direct shear tests[J]. Geosynthetics International, 2016, 23(2): 129−139.

[12] VIEIRA C S, LOPES M L, CALDEIRA L M. Sand-geotextile interface characterisation through monotonic and cyclic direct shear tests[J]. Geosynthetics International, 2013, 20(1): 26−38.

[13] LIU Fei-yu, ZHANG Tao, SHI Jing. Cyclic shear behavior on soil-geogrid interface of sandwich reinforced soil[J]. China Journal of Highway and Transport, 2017, 30(5): 38−43.

[14] FENG D K, ZHANG J M, DENG L. Three-dimensional monotonic and cyclic behavior of a gravel-steel interface from large-scale simple-shear tests[J]. Canadian Geotechnical Journal, 2018, 55(11): 1657−1667.

[15] FENG Da-kuo, ZHANG Jian-min. Influence of shear paths on 3D cyclic behaviors of the gravel-structure interface[J]. China Civil Engineering Journal, 2018, 51(9): 84−91, 101.

[16] CEN W J, BAUER E, WEN L S, et al. Experimental investigations and constitutive modeling of cyclic interface shearing between HDPE geomembrane and sandy gravel[J]. Geotextiles and Geomembranes, 2019, 47(2): 269−279.

[17] WANG J, LIU F Y, ZHENG Q T, et al. Effect of aperture ratio on the cyclic shear behavior of aggregate-geogrid interfaces[J]. Geosynthetics International, 2020. DOI: 10. 1680/jgein.20.00038.

[18] MORTARA G, MANGIOLA A, GHIONNA V N. Cyclic shear stress degradation and post−cyclic behaviour from sand-steel interface direct shear tests[J]. Canadian Geotechnical Journal, 2007, 44(7): 739−752.

[19] NYE C J, FOX P J. Dynamic shear behavior of a needle-punched geosynthetic clay liner[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2007, 133(8): 973−983.

[20] LI Hang-zhou, LIAO Hong-jian, KONG Ling-wei, et al. Experimental study of stress-strain relationship of expansive mud-stone[J]. Rock and Soil Mechanics, 2007, 28(1): 107−110.

[21] WANG Jun, WANG Pan, LIU Fei-yu, et al. Cyclic and post−cyclic direct shear behaviors of geogrid-sand interface with different soil densities[J]. Chinese Journal of Geotechnical Engineering, 2016, 38(2): 342−349.