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Quantitative research on morphological characteristics of hysteretic curves of remolded weak expansive soil under cyclic loading

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Abstract: A series of cyclic triaxial tests is conducted by GDS apparatus to investigate the effects of confining pressure, loading frequency, consolidation stress ratio on the hysteretic curves of the remolded weak expansive soil under multi-step loadings and single-step loadings respectively. Morphological characteristics of hysteretic curves are quantitatively described by three parameters, namely, the area S of the hysteretic curve, the slope of curve k, center offset distance d of adjacent hysteretic curves, and the degree of closure ε_p. The results show that the S, d and ε_p of the hysteretic curve of weak expansive soils increase nonlinearly with the increase of dynamic stress amplitude, while decrease with the increase of confining pressure, frequency and consolidation stress ratio. The k decreases logarithmically with the increase of dynamic stress amplitude, and increases with the increase of confining pressure, loading frequency and consolidation stress ratio. Hysteretic curves of weak expansive soil are approximately parallel under single-step loading. The parameters of ε_p, d and S decrease nonlinearly with the increase of loading cycle, which reflects the phenomenon of cyclic creep. The multi-step loading history has a slight influence on the hysteretic curve of weak expansive soil.
Keywords: expansive soil; cyclic loading; consolidation stress ratio; hysteretic curve; cyclic creep

1 Introduction

Expansive soil is a kind of clay with a high plastic limit, which is mainly composed of strong hydrophilic minerals. It has high strength and low compressibility. It is widely distributed in more than 20 provinces and cities in China. In practical engineering, the weak expansive soil can be used as subgrade filling material after water-proof and moisturizing treatment, which can not only make full use of local soil source, but also save time and effort. With the acceleration of urbanization in China, infrastructure such as expressways and railways is bound to span more weak expansive soil areas. It is of great significance to study the dynamic response characteristics of weak expansive soil under cyclic loadings.

The basic task of soil dynamics is to study the variation law of soil deformation and strength characteristics under dynamic load[1]. Hysteretic curve refers to the dynamic stress-strain relationship curve of soil in a period. Its morphological characteristics can represent the important dynamic characteristics of soil such as dynamic deformation, viscosity, stiffness change and energy loss. The hysteretic curve and backbone curve constitute the viscoelastic dynamic constitutive model of soil. In addition, the research on the dynamic modulus and damping ratio of soil is also based on the hysteresis curve. At present, scholars have more research on the evolution law of rock hysteretic curve[2−10], but less on soil. Luo et al.[11−12] analyzed the morphological characteristics of hysteresis curves of Qinghai-Tibet frozen clay and frozen Lanzhou loess by applying dynamic load step by step; and based on the basic characteristics of the hysteretic curves, they proposed a quantitative method to study the morphological characteristics of hysteresis curves. Guo et al.[13] studied the dynamic deformation characteristics of natural Wenzhou soft clay through undrained cyclic loading tests, and analyzed the influence law of confining pressure and cyclic vibration times on hysteretic curve and strength of structural soft clay. Zhang et al.[14] studied the dynamic performance and rheological characteristics of cement modified aeolian sand through dynamic cyclic loading and creep tests, analyzed the influence of frequency, temperature and vibration number on the evolution of hysteresis curve, and used the improved Nishihara model to describe the visco-elastic-plastic deformation characteristics of the hysteresis loop. Huang et al.[15−16] quantitatively studied Kunming peaty soil by exerting dynamic load by steps, and analyzed the influence of confining pressure, frequency and consolidation stress ratio on the morphological characteristics of hysteretic curve. Kumar et al.[17] carried out strain-controlled cyclic triaxial tests on Yarlung Zangbo River sand, investigated the dynamic characteristics of sand in a large range of

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shear strain, analyzed the evolution law of hysteretic curve of samples under different confining pressures and relative compactness, and estimated the damping ratio and shear modulus from the hysteresis curve. The above researches show that the macro hysteresis curve characteristics analysis of soil dynamic characteristics is better, and there are no research results on the characteristics of hysteresis curve of remolded weak expansive soil.

In view of the lack of studies on the hysteretic curve of weak expansive soil, in this study, a series of cyclic dynamic load tests was carried out on remolded weak expansive soil by using GDS dynamic and static true triaxial apparatus to examine the evolution law of hysteretic curve of weakly expansive soil under different confining pressures, frequencies and consolidation stress ratios. Based on the research method of Luo et al.[11−12], the quantitative parameters of characteristics of hysteresis curve of remolded weak expansive soil are determined (area S, slope k of long axis, center spacing d of adjacent hysteretic curves and unclosed degree ε_p), and the variation law of quantitative parameters with dynamic stress amplitude is analyzed. Based on the test data under the single-step loading, the attenuation model of quantitative parameters ε_p, d, S of weak expansive soil with cyclic vibration number is proposed, and the influence of graded loading history on the hysteresis curve of expansive soil is analyzed.

2 Sample preparation and test plan

2.1 Test apparatus

The test apparatus is GDS dynamic and static true triaxial apparatus as shown in Fig.1. The apparatus incorporates two modules, i.e., the dynamic loading module and three-dimensional stress loading module. The module switching can be realized by replacing accessories, and the axial pressure and unidirectional excitation can be accurately applied. The confining pressure and back pressure are provided by the servo system. The measurement system can accurately and real-time record the pore pressure, volumetric strain, axial strain and other data of soil samples, with an accuracy of 0.000 1 mm. In this test, the dynamic loading module is selected.

2.2 Tested soil

The soil samples were taken from a highway project in Hefei, and its physical property indexes are listed in Table 1. According to the classification of expansive soil-free expansion rate, it can be classified as weak expansive soil. Through the compaction test, the maximum dry density of the sample is 1.7 g/cm^3, and the optimum moisture content is 17%. The remolded soil sample is made according to the optimal moisture content and maximum dry density. The diameter of the sample is 50 mm and the height is 100 mm. The sample compaction is divided into 5 sub-layers with each roughened. The remolded weak expansive soil sample is shown in Fig.2.

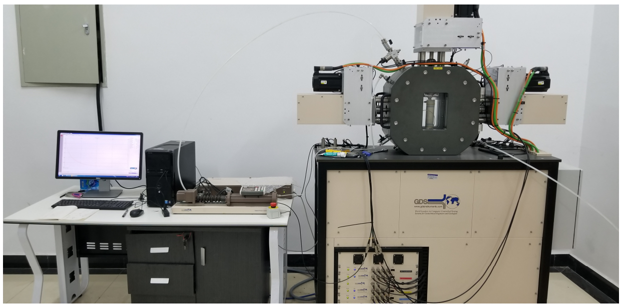


Fig. 1 GDS dynamic true triaxial apparatus

Table 1 Basic physical and mechanical properties of the tested expansive soil

Natural moisture content W/%	Liquid limit W_l/%	Plastic limit W_p/%	Specific gravity G_s	Free expansion rate/%
21.64	72	30	2.68	44

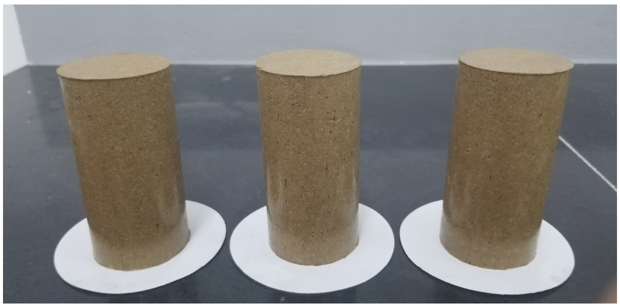


Fig. 2 Samples of the tested soil

2.3 Test plan

Before the test, the soil samples are saturated by saturator, and then put into GDS dynamic and static true triaxial apparatus, and saturated by a back pressure system again. When the saturation B value is greater than 0.98, the specified confining pressure and initial static stress are applied linearly for drainage consolidation. The test is undrained. The loading waveform is a sine wave, and the dynamic stress amplitude σ_d is initially 20 kPa in the multi-step loading test. It is divided into 15 vibration levels, and each step is increased by 15 kPa. The loading is terminated at 230 kPa. Each vibration level is vibrated 10 times. When the axial strain reaches 5%, it is regarded as a failure and the test is terminated[18].

Three influencing factors including confining pressure, frequency and consolidation stress ratio are considered in the multi-step loading test. According to results from Lu et al.[19], when the subgrade modulus is 20−200 MPa, the influence depth of traffic load on the subgrade working area is 1.28−2.45 m; considering vehicle overload, the actual impact depth will be deeper. Based on this depth range, the confining pressure σ_3 was selected as 100, 150 and 200 kPa, consolidation stress ratio k_c was 1.00, 1.25 and 1.50; and frequency f was 1, 2 and 3 Hz; as shown in Table 2(Categories 1−3).

In order to facilitate comparative analysis, σ_3 = 150 kPa, k_c = 1.25, f = 1 Hz were taken in the single-step loading test. The minimum value of dynamic stress amplitude σ_d was determined as 20 kPa, the maximum value was 230 kPa. The σ_d was divided into 8 levels (level difference was 30 kPa) corresponding to 8 samples, respectively. After each level of the dynamic load test was finished, the sample was replaced with new samples. A total of 8 single-step loading tests were carried out. The test scheme is given in Table 2 (Category 4).

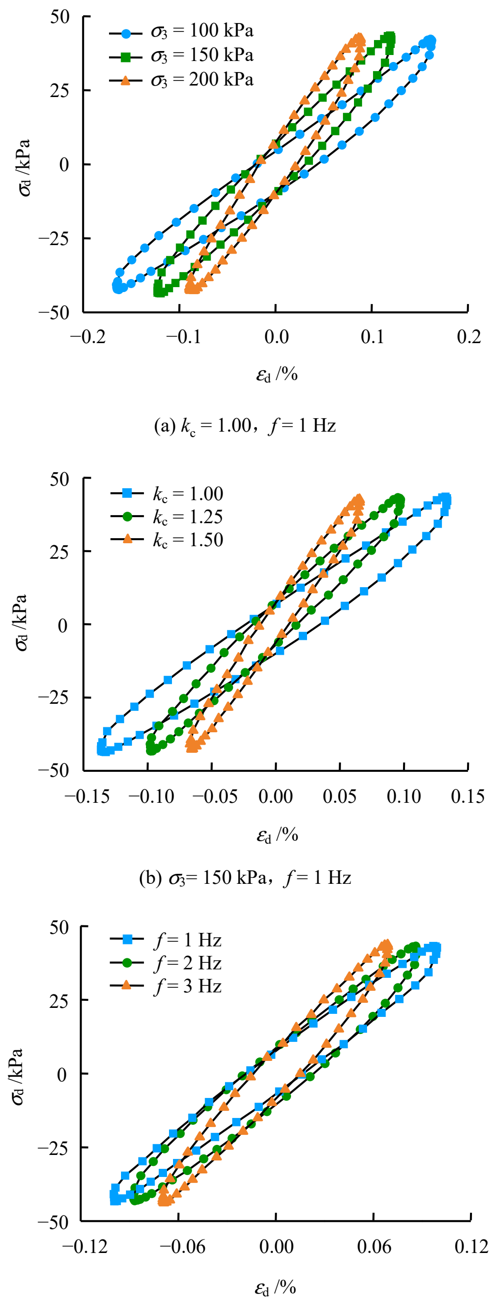
Table 2 Test plan

Category	k_c	σ_3/kPa	f/Hz	σ_d /kPa
	1.00	100	1	20−230
1	1.00	150	1	20−230
	1.00	200	1	20−230
	1.00	150	1	20−230
2	1.25	150	1	20−230
	1.50	150	1	20−230
	1.25	150	1	20−230
3	1.25	150	2	20−230
	1.25	150	3	20−230
4	1.25	150	1	20−230

3 Evolution law of hysteresis curve

The dynamic load is applied in steps. When the dynamic stress amplitude of each group of tests is 95 kPa, the curve of the second cyclic dynamic stress-strain relationship is shown in Fig.3. The characteristics of the hysteresis curve of expansive soil are analyzed.

Figure 3 shows that the hysteretic curve of expansive soil is approximately elliptic or willow leaf shape. With the increase of confining pressure, frequency and consolidation stress ratio, the area of hysteresis curve gradually decreases and the slope increases gradually. In Fig.3(b), the area of expansive soil hysteretic curve varies greatly under different consolidation stress ratios, while the slope of expansive soil hysteresis curve changes slightly at 1 Hz and 2 Hz frequency in Fig.3(c).



(a) k_c = 1.00, f = 1 Hz

(b) σ_3= 150 kPa, f = 1 Hz

(c) σ_3 = 150 kPa, k_c = 1.25

Fig. 3 Hysteretic curves under cyclic loading at the same level

Under the condition of step loading, the hysteretic curves obtained by the second cyclic loading with different dynamic stress amplitudes are plotted in Fig.4.

It can be seen from Fig.4 that with the increase of dynamic stress amplitude, the area of hysteresis curve of expansive soil gradually increases, and the slope of the long axis decreases gradually, and the phenomenon of non-closure appears in the later stage of loading.

4 Analysis of characteristics of hysteresis curve

In order to quantitatively study the characteristics of hysteresis curve, the soil hysteresis curve is analyzed by using the surrounding area *S*, the slope of long axis *k*, the center spacing *d* between the hysteresis curves under adjacent vibration levels and the degree of closure ε_p, as shown in Fig.5.

The distance d between the center point O_2 of the hysteretic curve under the current loading condition and the center O_1 of the previous loading hysteresis curve represents the offset of the hysteresis loop center:

$$d = \left| \overline{O_{n-1}O_n} \right| \tag{1}$$

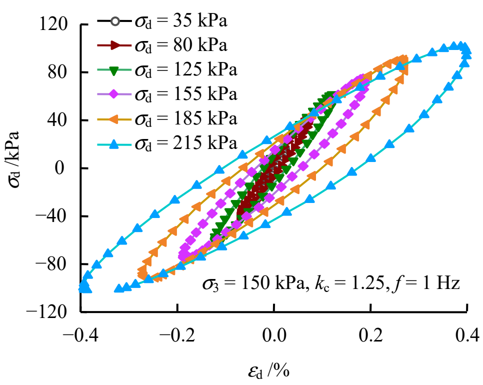


Fig. 4 Typical hysteretic curves under multi-step loading

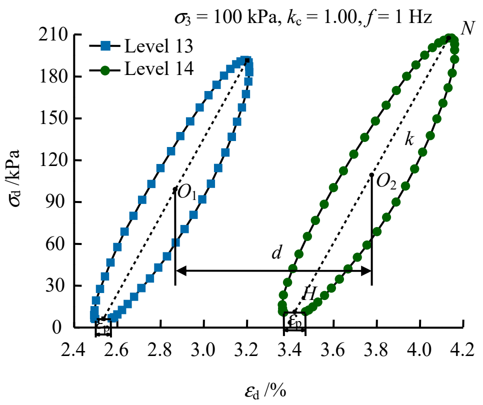


Fig. 5 Diagram for description of parameters

d represents the plastic deformation of soil. A larger *d* means a larger spacing between hysteresis loops, implying that the soil has a greater plastic deformation and a more serious damage at mesoscale of soil.

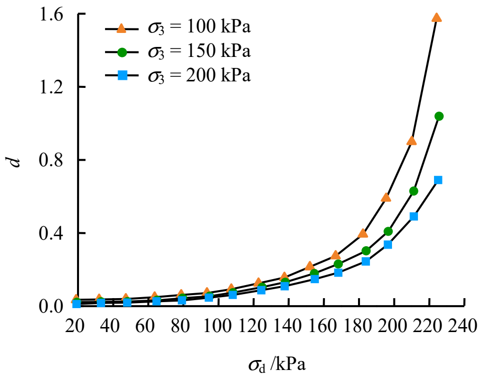
The slope *k* of the long axis is the slope of line *NH* connecting the two ends of the hysteresis curve (see Fig.5), which indicates the elastic properties of soil. The greater *k* is, the greater the stiffness and elastic modulus of soil are.

S denotes the area of hysteresis curve, represents the energy loss of soil. The larger *S* is, the greater the energy loss of soil in one cycle. In order to facilitate the calculation, the fitting ellipse is used to calculate when the closure degree of the expansive soil hysteretic curve is high in the early stage of multi-step loading. When the dynamic stress amplitude is large in the later stage of multi-step loading, the opening of the hysteresis curve is larger, and the hysteresis curve is connected from end to end to integrate the closed diagram.

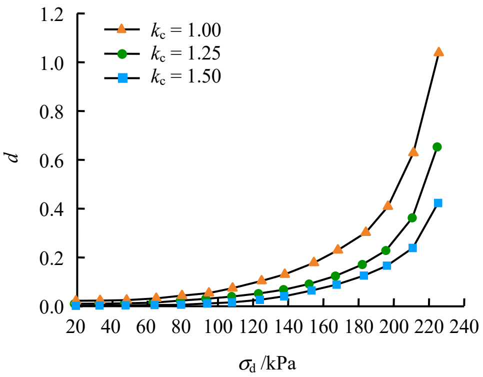
ε_p is the difference between the strain corresponding to the end of loading and the starting point in a cycle, that is, the unclosed degree or opening of hysteresis curve, which represents the residual strain of soil.

4.1 Evolution of *d*

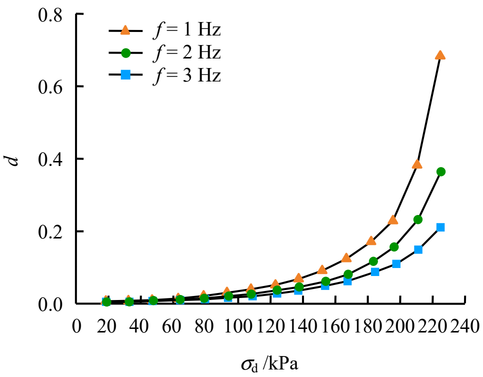
Under different confining pressure, frequency and consolidation stress ratio, the variations of center spacing *d* of expansive soil hysteretic curve with σ_d are shown in Fig.6. It can be found that *d* increases slowly with the amplitude of dynamic stress, and then increases rapidly in a nonlinear manner. In the early stage of step loading ($\sigma_d \leqslant 80$ kPa), the dynamic stress applied on soil is small, and the deformation is dominated by elastic deformation, and the meso damage of soil is small. Under different frequencies, the difference of *d* growth curve with σ_d is small or even overlapped, while the difference of *d* under different consolidation stress ratios is obvious. It shows that when the dynamic stress amplitude is small, the frequency has little influence on the development of soil plastic deformation, while the deviatoric stress has an more significant impact on the plastic deformation of soil. At the later stage of multi-step loading ($\sigma_d > 80$ kPa), the larger dynamic stress promotes the plastic deformation of soil, the plastic deformation of soil prevails, and the hysteresis curve of expansive soil gradually separates. Under the same stress amplitude, *d* decreases with the increase of confining pressure, frequency and consolidation stress ratio. It can be understood that with the increase of confining pressure and consolidation stress ratio, the soil becomes denser and the interaction between soil particles is enhanced, which inhibits the development of plastic deformation; with the increase of frequency, the plastic deformation of soil gradually decreases due to too late strain or delayed response. In Fig.6(b), there is a larger difference between the curve of *d* with σ_d under k_c = 1.25 and that under k_c = 1.0, while there exists a smaller gap between under k_c = 1.25 and k_c = 1.5, which indicates that the relationship between the attenuation of d with the increase of k_c is nonlinear under the same stress amplitude.



(a) k_c = 1.00, f = 1 Hz

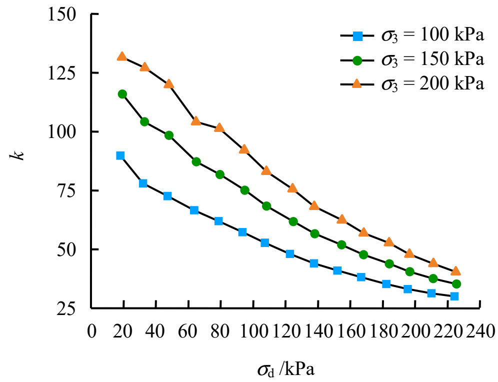


(b) σ_3 = 150 kPa, f = 1 Hz

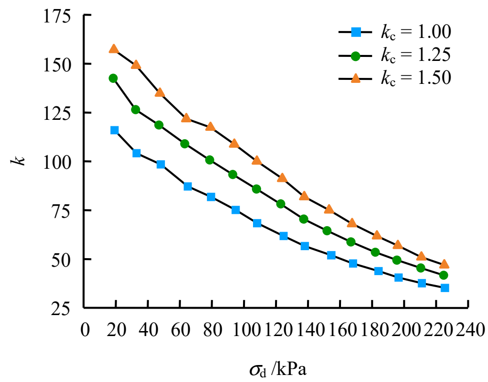


(c) σ_3 = 150 kPa, k_c = 1.25

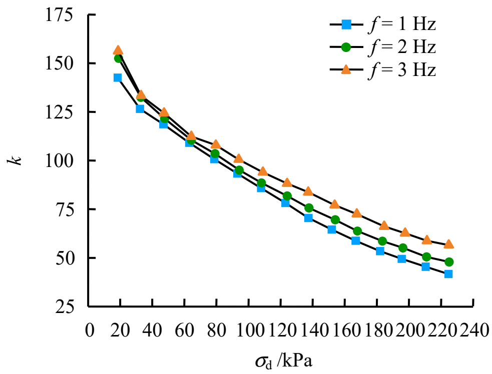
Fig. 6 Relationship between *d* and cyclic stress amplitude



(a) k_c = 1.00 kPa, f = 1 Hz



(b) σ_3 = 150 kPa, f = 1 Hz



(c) σ_3 = 150 kPa, k_c = 1.25

Fig. 7 Relationship between *k* and cyclic stress amplitude

4.2 Evolution of *k*

Under different confining pressures, frequencies and consolidation stress ratios, the relationships between the slope k of the long axis of the hysteresis curve of expansive soil and σ_d are illustrated in Fig.7. The plots shows that under different loading conditions, the variation of k with dynamic stress amplitude firstly decreases sharply and then tends to be gentle, which indicates that expansive soil has a strong resistance to deformation in the initial stage of multi-step loading, and with the increase of dynamic stress, the soil gradually loses the ability to resist deformation. Under the same dynamic stress amplitude, k increases with the increase of confining pressure, frequency and consolidation stress ratio. It can be understood that with the increase of confining pressure and consolidation stress ratio, the initial spherical stress of soil increases, the void ratio decreases, the cohesion c value and friction force between soil particles increase, and the relative slip becomes difficult, which improves the ability of soil sample to resist deformation. However, with the increase of frequency, the soil can not fully rebound, which is reflected in the enhancement of resistance to deformation. In Fig.7(c), in the early stage of loading ($\sigma_d \leqslant 80$ kPa), there is a small difference in the curve of k with σ_d. With the increase of dynamic stress amplitude, the k-σ_d curve gradually separates. This is because in the early stage of loading, the soil mainly presents elastic deformation, which is not sensitive to the loading frequency of 1−3 Hz, and can rebound fully. In the later stage of multi-step loading, with the increase of dynamic stress amplitude, the plastic deformation accumulated continuously, and the soil began to be sensitive to different loading frequencies.

4.3 Evolution of *S*

Under different confining pressures, frequencies and consolidation stress ratios, the relationship curves of the area S of the hysteresis curve of expansive soil with σ_d are shown in Fig.8.

It can be seen that S increases slowly first and then sharply with the increase of dynamic stress amplitude, and the overall relationship is hyperbolic. In the early stage of multi-step loading, S tends to 0, and the expansive soil can be regarded as a good viscoelastic body; with the increase of dynamic stress, S increases exponentially. Confining pressure, frequency and consolidation stress ratio have different degrees of inhibition on soil energy loss. It can be understood that with the increase of confining pressure, frequency and deviator stress, the stiffness of soil increases, the response to dynamic load is more timely, the transmission efficiency of the dynamic load is improved, as a result, S is reduced. In Fig.8(c), in the early stage of multi-step loading ($\sigma_d \leqslant 80$ kPa), the curve difference of S with σ_d is small or even overlapped. When the dynamic stress amplitude is more than 80 kPa, the S-σ_d curve gradually separates, indicating that the influence of frequency on the hysteresis curve S depends on the dynamic stress amplitude, or there is a critical dynamic stress amplitude. When the applied dynamic stress exceeds the critical value, the hysteresis curve S becomes sensitive to the change of frequency.

4.4 Evolution of ε_p

Under different confining pressures, frequencies and consolidation stress ratios, the relation curves of the unclosed degree of hysteresis curve of expansive soil ε_p with σ_d is shown in Fig.9.

Figure 9 illustrates that in the early stage of multi-step loading ($\sigma_d \leqslant 80$ kPa), under different confining pressures, frequencies and consolidation stress ratios, ε_p tends to 0. At this time, the hysteresis curve of expansive

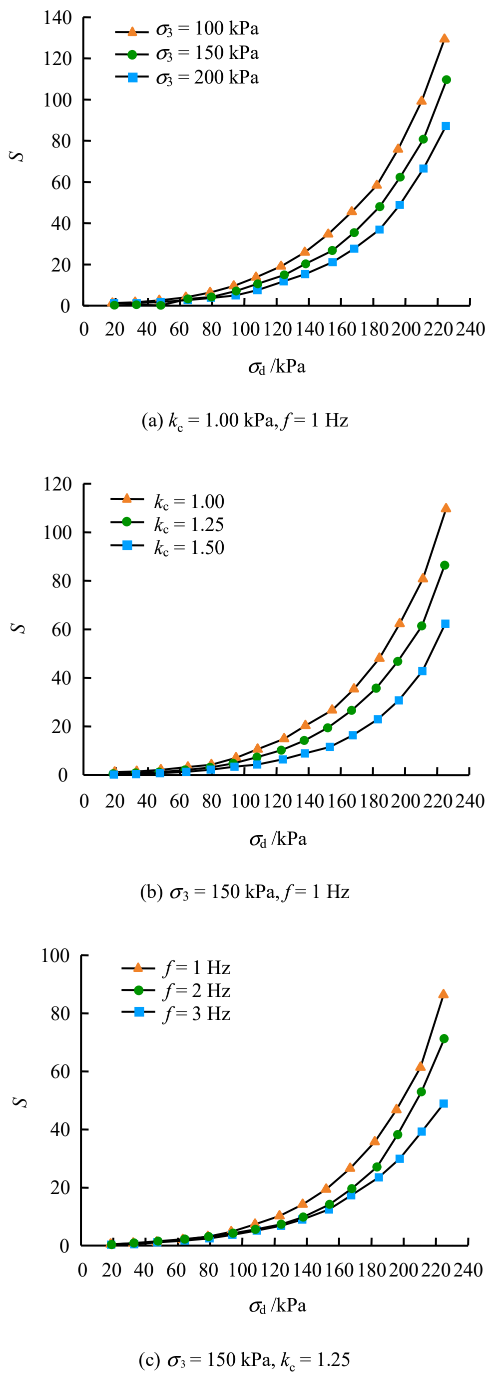
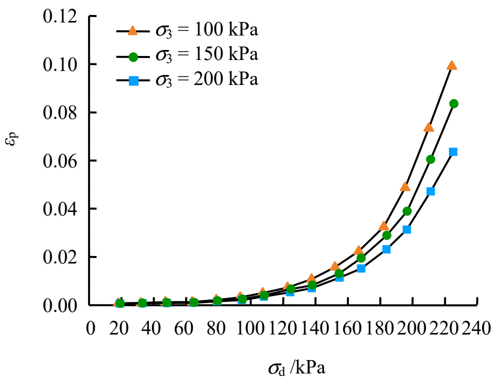
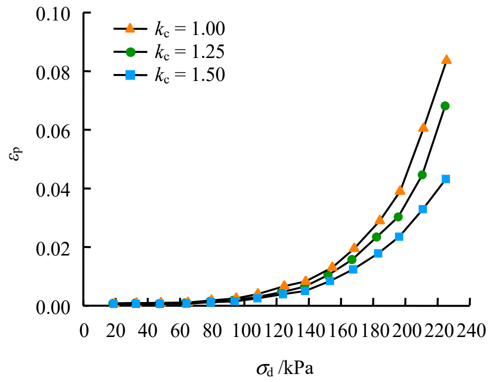


Fig. 8 Relationship between *S* and cyclic stress amplitude

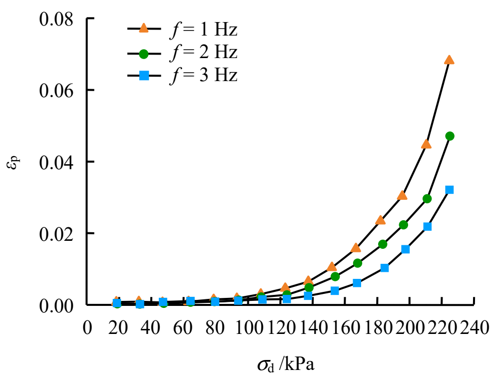
soil is basically closed, and the soil is in the stage of elastic deformation. In the later stage of multi-step loading, the elastic deformation of soil gradually transforms into the plastic deformation stage, and the loading endpoint can not return to the starting point, and ε_p increases exponentially with the increase of dynamic stress amplitude. Confining pressure, frequency and consolidation stress ratio all restrain the development of ε_p, which indicates that the compaction effect of confining pressure and consolidation stress ratio on soil body strengthens the biting force between internal soil particles, increases the



(a) k_c = 1.00 kPa，f = 1 Hz



(b) σ_3 = 150 kPa，f = 1 Hz



(c) σ_3 = 150 kPa，k_c = 1.25

Fig. 9 Relationship between ε_p and cyclic stress amplitude

cohesion and friction force, and makes the development of residual deformation difficult. However, with the increase of frequency, the rebound of soil reaction is not timely, and the deformation can not be fully developed, so ε_p decreases with the increase of frequency.

5 Analysis of hysteresis curve under monotonic loading

5.1 Evolution of shape of hysteresis curve

The typical hysteretic curve under single-step loading is illustrated in Fig.10. It can be seen that with the increase of vibration times, the hysteresis curve becomes denser and denser, and the opening of hysteresis curve becomes smaller and smaller. Finally, it will be repeated on a closed hysteresis curve and reach stability, showing cyclic hardening characteristics as a whole.

5.2 Analysis of characteristics of hysteresis curve

Similar to the quantitative research method under the condition of graded loading, the central spacing d of adjacent hysteretic curves, the unclosed degree of hysteretic curves ε_p and the area S of hysteretic curves under single-step loading are used to quantitatively analyze the shape of hysteretic curve of expansive soil.

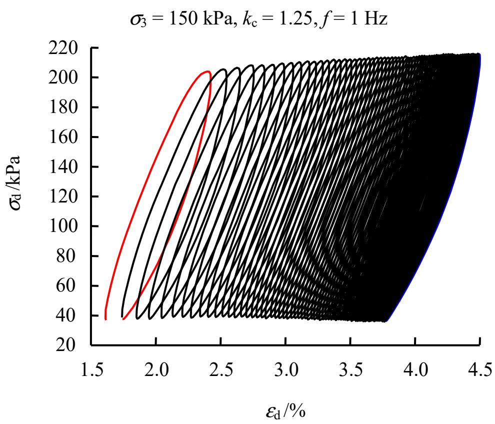


Fig. 10 Typical hysteretic curves under single-step loading

The relationship between quantitative parameters and vibration number is illustrated in Fig.11. The attenuation relations of ε_p and d with vibration number can be given as[1]

$$\varepsilon_p = \frac{\varepsilon_{p0}}{1 + aN_f} \tag{2}$$

$$d = \frac{d_0}{1 + bN_f} \tag{3}$$

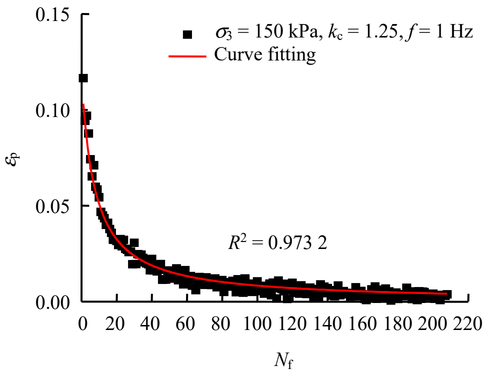
S conforms to the law of power function and can be expressed as

$$S = nN_f^m \tag{4}$$

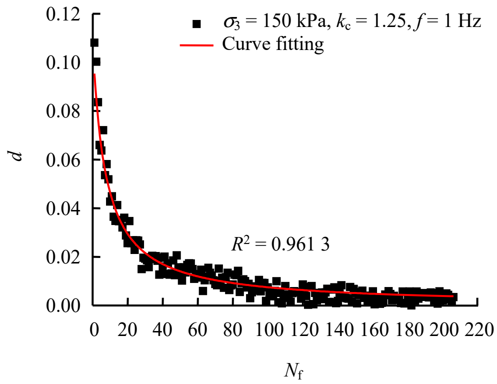
where ε_{p0} is the opening size of the first hysteresis curve; d_0 is the initial displacement of the hysteretic curve; N_f is the vibration number; and a, b, n, m are the fitting parameters.

The attenuation relationships of ε_p, d, S with vibration number are written as follows:

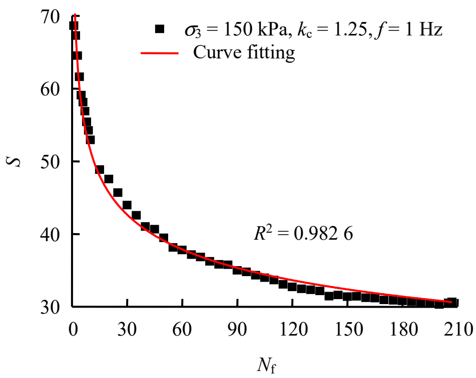
$$\varepsilon_p = \frac{0.116\,5}{1 + 0.129\,2N_f} \tag{5}$$



(a) ε_p versus N_f



(b) d versus N_f



(c) S versus N_f

Fig. 11 Quantitative analysis of hysteretic curves under single-step loading

$$d = \frac{0.108\,1}{1 + 0.133\,9 N_f} \tag{6}$$

$$S = 76.234\,4 N_f^{-0.171} \tag{7}$$

Figure 11 that the ε_p, d, S of expansive soil hysteretic curve decrease sharply at first and then tend to be stable with increasing N_f. It means that in the initial stage of loading ($N_f < 20$), the soil is in the stage of plastic deformation, and the compactness is small. At this stage, the overall plastic deformation and energy loss of the soil are large. Under the initial dynamic load, the soil is compacted rapidly, and the energy loss decreases rapidly with the increase of vibration times. At the later stage of loading ($N_f > 20$), after repeated compression and rebound, the compactness of soil is significantly improved, the interaction between soil particles is enhanced, and the soil mass transits from the plastic deformation stage to the elastic deformation stage. With the increase of vibration times, the plastic deformation and energy loss of soil decrease slowly and tend to be stable.

5.3 Influence of loading history on the characteristics of hysteresis curve

Under the conditions of multi-step and single-step loading, the hysteresis curves of the first three cycles are plotted in Fig.12 with σ_d = 170 kPa, σ_d = 185 kPa, and σ_d = 215 kPa. The dynamic stress-strain backbone curves under single-stage and multi-step loading are obtained by taking the top points of the hysteretic curve of each stage of cyclic loading, as shown in Fig.13.

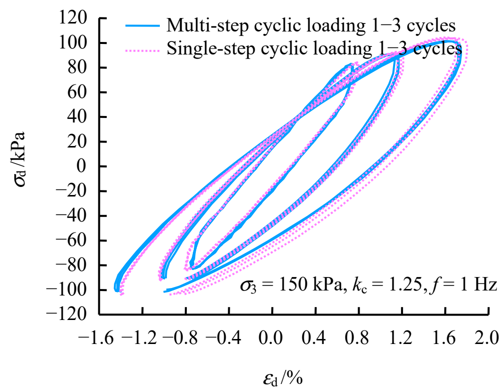


Fig. 12 Hysteretic curves under single-step cyclic loading and multi-step cyclic loading

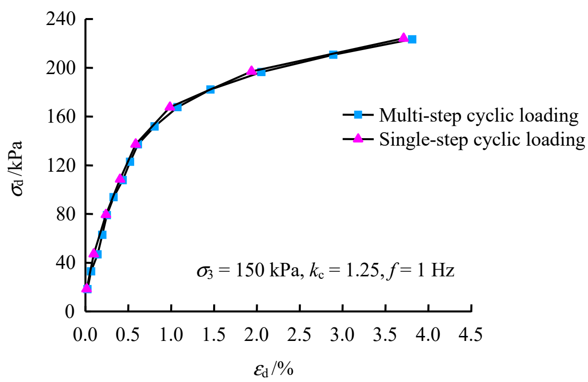


Fig. 13 Backbone curves under single-step cyclic loading and multi-step cyclic loading

It can be seen from Fig.12 that the hysteretic curve of graded loading is basically coincident with that of single-stage loading. Under the action of small dynamic stress, the expansive soil vibrates for 10 times, and then

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bears larger dynamic stress, which will eliminate the influence of previous smaller dynamic stress, that is, memory loss phenomenon[20]. It shows that the influence of multi-step loading history on the hysteresis curve of expansive soil is small.

Figure 13 shows that the dynamic stress-strain backbone curves of expansive soil under multi-step and single-step loading basically coincide, which suggesting that the cyclic creep of expansive soil occurs under single-step cyclic loading, but the peak of hysteresis curve will return to the initial backbone curve under a higher level of cyclic loading. Therefore, the influence of multi-step loading on the quantitative analysis of the expansive soil hysteresis curve is small.

6 Conclusions

The center distance d of the hysteresis curve of remolded weak expansive soil first increases gently and then increases in a nonlinear manner with the increase of σ_d, which shows a hyperbolic relationship as a whole. With the increase of confining pressure, frequency and consolidation stress ratio, the plastic deformation amplitude decreases, and the curve of d changing with σ_d moves downward as a whole. When $\sigma_d \leqslant 80$ kPa, the difference between curves of d with σ_d at different frequencies is small.

The overall slope k of the hysteresis curve of remolded weak expansive soil decreases logarithmically with the increase of σ_d. The larger the confining pressure, frequency and consolidation stress ratio are, the stronger the soil resistance to deformation is, and the greater the elastic modulus is. When $\sigma_d \leqslant 65$ kPa, the soil is not sensitive to the loading frequency of 1−3 Hz and can rebound fully.

The area S of hysteresis curve of remolded weak expansive soil firstly increases slowly and then increases sharply with the increase of σ_d. When $\sigma_d \leqslant 65$ kPa, S tends to 0, and the soil can be regarded as a good viscoelastic body. When σ_d is less than 80 kPa, the curves of S with σ_d are overlapped at different frequencies. When $\sigma_d > 80$ kPa, the time-delay curve S becomes sensitive to the change of frequency, and the curve of S with σ_d has obvious separation.

The frequency and consolidation stress ratio, the unclosed degree of hysteresis curve ε_p decreases with increasing confining pressure. When $\sigma_d \leqslant 80$ kPa, the soil is in the stage of elastic deformation; for different confining pressures, frequencies and consolidation stress ratios, the ε_p tends to zero and the overlap is higher. When $\sigma_d > 80$ kPa, the soil changes from the elastic deformation stage to the plastic deformation stage, and the loading endpoint cannot return to the starting point, and ε_p increases exponentially with the increase of dynamic stress amplitude.

Under the condition of single-step loading, the ε_p, d, S of the hysteretic curve of the remolded weak expansive soil decrease with the increase of vibration number N_f, showing cyclic hardening characteristics. When $N_f < 20$, the soil is in the stage of plastic deformation, and ε_p, d, S decrease sharply with the increase of vibration number. When $N_f > 20$, the curves of ε_p, d, S with the vibration number gradually flatten and tend to be stable. The overall variation law can be expressed by Eqs. (5)−(7), and the fitting effect is good.

The hysteretic curve and backbone curve of remolded weak expansive soil are basically coincident under single-stage and multi-step loading. The influence of multi-step loading history on the hysteretic curve and the backbone curve of expansive soil is small. It is feasible to study the change law of hysteresis curve of expansive soil under different loading conditions through graded loading.

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