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Experimental study on critical dynamic stress of coarse-grained soil in railway subgrade

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Abstract: The coarse-grained soil is widely used as the filling in the railway subgrade, which is directly subjected to the long-term effect of the dynamic cyclic train loads transmitted from the track structure. Investigation of its dynamic behavior and plastic deformation characteristics under the dynamic train loads may provide ideas for the subgrade performance evaluation and settlement control. GDS dynamic triaxial tests were used to investigate the dynamic response of coarse-grained soil in railway subgrade. By introducing the plastic strain rate and shakedown theory, the evolution law of axial plastic strain of subgrade under different frequencies, confining pressures and cyclic dynamic stress ratios is divided into three types: plastic shakedown, plastic creep and incremental plastic failure, based on which the critical dynamic stress levels of plastic shakedown and plastic creep state are determined. Results show that the critical cyclic stress ratio of coarse-grained soil increases with the increase of confining pressure, while decreases with the increase of loading frequency. Based on the fitting analysis of the experimental results, an empirical formula of critical dynamic stress with confining pressure as variable is proposed, which can provide theoretical basis for the dynamic stability evaluation of subgrade at any depth.

Keywords: GDS dynamic triaxial tests; coarse-grained soil; axial plastic strain; critical cyclic stress; shakedown theory

1 Introduction

The coarse-grained soil has been widely used in high-speed railway subgrade structures because of its good compaction performance, large compression density and high shear strength. However, due to the discrete characteristic of the coarse-grained soil filling, the subgrade is the weakest and most unstable structure in the entire high-speed railway structure system, and is the main factor leading to track deformation. Train load has the characteristics of low frequency and low amplitude, which is a long-term cyclic load. Although the stress induced by train load is much smaller than the static shear strength of the subgrade filling, subgrade filling will experience excessive accumulated plastic deformation under hundreds of thousands or even millions of load cycles, which will lead to the failure of subgrade structure and cause engineering problems, such as uneven track and differential settlement. *Code for Design of Railway Earth Structure* (TB 10001-2016)[1] has made clear provisions on the gradation and compaction density of subgrade filling, but it still lacked a clear understanding of the dynamic stress and cumulative deformation law of the coarse-grained soil under the train load.

The shakedown theory was first applied to study the dynamic response of elastic-perfectly plastic materials under cyclic loading. This means that the structure only experiences plastic deformation under the initial limited number of cyclic loads and experiences pure elastic response under subsequent cyclic loading. Since the cumulative plastic deformation in the structure is always within the allowable safety limit, the structure will not be damaged. If the dynamic stress level continues to increase, the plastic deformation in the structure will accumulate, and the structure will be destroyed eventually due to excessive plastic deformation. Werkmeister et al.[2] found that discrete non-cohesive materials are granular materials, which can only bear compressive stress but not tensile stress under traffic load. Therefore, the behavior of the coarse-grained soil and other granular materials under cyclic loading is quite different from that of elastic-plastic materials like metals, which can be more properly classified into

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the three types shown in Fig.1.

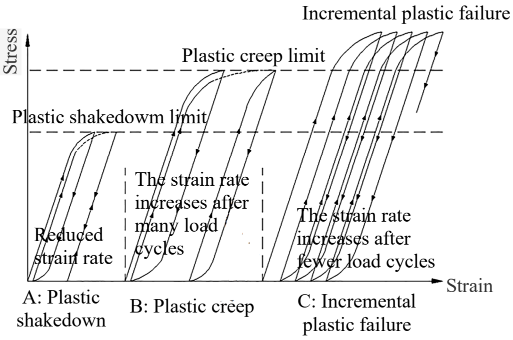


Fig. 1 Mechanical behavior of granular material under cyclic loading

(1) Plastic shakedown zone (Zone A): Under the dynamic load with a small amplitude, the plastic deformation of granular material occurs only in the initial several load cycles. However, with the increase of the number of loading, the plastic deformation tends to be stable. It only shows pure elastic response in the subsequent load cycle, and the corresponding maximum stress level is the plastic shakedown limit.

(2) Plastic creep zone (Zone B): there is obvious accumulation of plastic deformation in the structure with the increasing magnitude of cyclic load. The plastic deformation shows hysteresis in each cycle. However, after certain cycles of loading, the plastic deformation remains nearly constant and presents a stable hysteresis loop. The structure is still in a safe state without sudden collapse, at which the structure is in the state of plastic creep. But it will eventually be destroyed due to the continuous reciprocation of plastic deformation, which is also called alternating plastic collapse.

(3) Incremental plastic failure zone (Zone C): the structure will experience large plastic deformation and the plastic deformation rate will increase continuously when subjected to large amplitude of cyclic load. After certain cycles of load, the structure will be destroyed due to excessive plastic deformation, at which the structure is characterized by incremental plastic failure, which is also known as ratcheting failure.

The cumulative plastic deformation of subgrade is the main reason that affects the service performance of high-speed railway. In recent years, scholars have carried out a large number of studies on the cumulative plastic deformation of the coarse-grained soil in railway subgrade and obtained important research results. Suiker et al.[3] revealed the relationship between axial cumulative deformation, confining pressure and cyclic stress of ballast materials. Lackenby et al.[4] studied the influence of confining pressure and principal stress amplitude on the cumulative plastic deformation of the ballast and the ballast breakage. They pointed out that there is an optimal confining pressure range related to the amplitude of axial deviator stress, so that the crushing rate of ballast under cyclic load is the lowest, and the range of optimal confining pressure is related to the amplitude of applied axial deviator stress. Indraratna et al.[5] studied the influence of cyclic loading frequency on the cumulative deformation and particle breakage, and found that the axial cumulative strain and the amount of crushing of the railway ballast increased with the increase of loading frequency. Sun et al.[6] investigated the deformation and deterioration mechanism of railway ballast under cyclic load through high-frequency dynamic triaxial test. Results indicated that the deformation and particle breakage of the ballast increased with the increase of loading frequency, amplitude and confining pressure, and showed different mechanisms of deformation and different types of particle breakage. Werkmeister et al.[2] carried out dynamic triaxial tests on different types of granular materials under drainage conditions, and found that the samples present three states under different stress levels: plastic shakedown, plastic creep and incremental plastic failure. They suggest using plastic strain rate as the basis for judging the critical state. Wang et al.[7] and Liu et al.[8] carried out research on cumulative plastic strain and critical dynamic stress state of Qinghai-Tibet railway subgrade through dynamic triaxial test, and obtained similar conclusions. Tang et al.[9] conducted undrained tests on saturated clay samples at different subgrade depths from a field, determined the critical cyclic stress ratio at each depth by introducing the cyclic stress ratio and analyzing the development law of pore pressure and axial plastic strain, and then revealed the critical influence depth of traffic load by using the shakedown theory.

Due to the discrete characteristic, the complexity of plastic deformation and many other influencing factors of the coarse-grained soil under cyclic loading, there are relatively few studies on the shakedown behavior of the coarse-grained soil in the existing research. Therefore, it is necessary to carry out a large number of experimental studies to comprehensively reveal the dynamic behavior of materials under cyclic loading. In this paper, the GDS dynamic triaxial test system is used to test the coarse-grained soil on the surface of subgrade of high-speed railway based on the existing research. The development law of axial plastic strain of the sample under different working conditions is analyzed through the step-by-step loading dynamic cycle stress ratio (CSR). The critical stress level of the plastic shakedown and plastic creep state of the coarse-grained soil is determined.

2 Testing conditions and scheme

2.1 Testing device

The test adopts the GDS dynamic triaxial test system shown in Fig.2. It consists of pressure chamber, drive system, confining pressure control system, back pressure control system, signal regulatory & data acquisition system, and GDS distributed digital control system (DCS), etc.

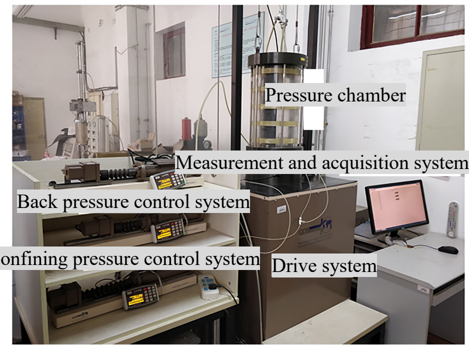


Fig. 2 GDS dynamic triaxial test system

2.2 Soil sample preparation

The soil used in the test was taken from the surface layer of subgrade of a high-speed railway construction site. Considering that the particle size of the soil sample is relatively dispersed, 2−3 times the amount of soil sample required was taken from the site to avoid some particle size missing or too little due to improper sampling. After stirring evenly, the samples were sampled by the method of equal division, so that the collected soil samples were consistent with the field construction soil on site.

According to relevant provisions of *Code for Soil Test of Railway Engineering* (TB 10102-2010)[10], the sample was prepared with a compaction coefficient of 90%. The diameter of the sample is 100 mm and the height is 200 mm. According to the sample diameter, the maximum particle size of the sample soil was determined to be 20 mm. The soil selected from surface layer of subgrade was evenly divided into 4 parts, and then several parallel sieve analysis tests were carried out, and finally the corresponding gradation curves were achieved as shown in Fig.3. The amount of particles with particle size of 2−20 mm accounts for about 70%. This soil is coarse-grained with no other impurities[1]. The coefficient of uniformity coefficient for the soil sample is $C_u > 15$, and the coefficient of curvature $C_c \in (1, 3)$, which indicates that the soil is a well-graded fine breccial soil and does not contain other impurities such as clay, which meets the gradation requirements of *Code for Design of High Speed Railway* (TB 10621-2014)[11].

According to the provisions of compaction test in *Code for Soil Test of Railway Engineering* (TB10102-2010)[10], heavy-duty Z2 compaction instrument was used to conduct the compaction test on the surface filling of subgrade, and the designed degree of compaction was 90%. The maximum dry density and optimum moisture content of the sample obtained from compaction test are $\rho_{dmax} = 2.29$ g/cm^3 and $\omega_{opt} = 5.33\%$, respectively, as shown in Fig.4.

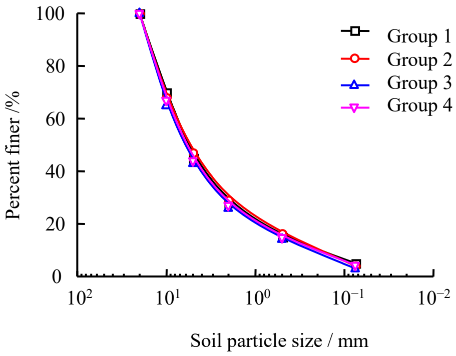


Fig. 3 Gradation curves of subgrade material

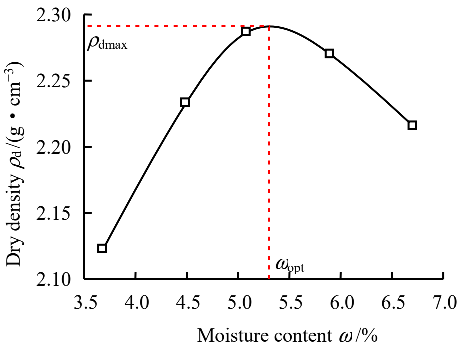


Fig. 4 Relationship curve between dry density and moisture content of subgrade material

2.3 Loading condition

According to the conditions of the test device regime and relevant research experience, sine wave shown in Fig.5 was used to simulate the cyclic loading of the train. As the coarse-grained soil samples have different strength parameters under different confining pressure conditions and the deformation characteristics of different cyclic loading are also different, so it is not useful to study the deformation characteristics of samples under different confining pressures at the same load amplitude. In this paper, the cyclic stress ratio (CSR) is introduced to represent the dynamic stress level, which is defined as the ratio of dynamic load sine wave amplitude *A* to

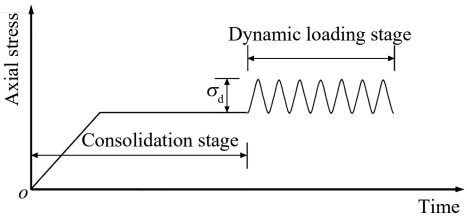


Fig. 5 Loading scheme for dynamic stress in the tests

the consolidated undrained shear strength τ_{cu} of the sample. As the amplitude of the dynamic load sine wave $A = \sigma_d/2$, and $\tau_{cu} = q_{cu}/2$ for the consolidated undrained test, so the cyclic stress ratio can be expressed as

$$\mathrm{CSR} = \frac{A}{\tau_{cu}} = \frac{\sigma_d/2}{q_{cu}/2} = \frac{\sigma_d}{q_{cu}} \tag{1}$$

where σ_d is the axial dynamic stress value; $\sigma_d = \sigma_1 - \sigma_3$, σ_1 is the total axial stress of triaxial test, σ_3 is the confining pressure; and q_{cu} is the deviator stress at failure.

The frequency f of subgrade structure under train load is affected by the speed of train, length of single carriage, bogie spacing, wheel axis distance and other factors, and the most influential factor on subgrade soil is the passing frequency of train, that is, the passing frequency of a single carriage, which can be calculated as

$$f = \frac{v}{L} \tag{2}$$

where f is the frequency of dynamic load acting on the subgrade structure (Hz); v is the speed of train(km/h); L is the distance (m), referred to as the perturbation wavelength[12], and is taken as the length of a carriage in this paper. Considering the length of a single carriage of CRH3 high-speed train(L = 24.775 m), the test equipment conditions, time consuming and other factors, we take 90 km/h as the normal operation speed of ordinary freight train, 320 km/h as the normal operation speed of high-speed railway to perform triaxial tests. The loading frequencies corresponding to the two vehicle speeds are 1 Hz and 3.6 Hz, respectively.

2.4 Criterion of coarse-grained soil shakedown state

Werkmeister et al.[2] carried out cyclic triaxial tests on gravel filling with different gradations, obtained the range of strain rate under different types of plastic deformation development law in combination with results from numerical simulation, and thus, proposed the criteria for the three types of behavior of the coarse-grained soil as shown in Table 1. The plastic strain rate $\dot{\varepsilon}_p$ can be defined as

$$\dot{\varepsilon}_p = \frac{d\varepsilon_p}{dN} \tag{3}$$

where $d\varepsilon_p$ is the plastic strain increment in each load cycle and N is the number of cycles.

It can be seen from Table 1 that the strain rate of the coarse-grained soil under cyclic loading is not 0 when it reaches the plastic stability state, but it stabilizes in a small range for variation. Since the plastic strain rate is very small and the plastic strain induced by the subsequent load cycle is approximately 0, pure elastic response is assumed. In other words, there is no memory history of the load after the cumulative plastic strain of the material reaches the shakedown state. Therefore, under the condition of lower stress level, considering the accuracy and stability of test equipment reading, the plastic strain rate $\dot{\varepsilon}_p = 1\times10^{-5}$ is taken as the limit of plastic shakedown state for coarse-grained soil based on the research of Werkmeister et al.[2]. The standard range as the criterion for plastic shakedown state is shown to be reliable according to verification results from cyclic loading tests with high numbers of cycle.

Table 1 Relationship between elastic-plastic response and strain rate of unbound aggregate materials

Evolution form of deformation	Strain rate	Notes
Plastic shakedown	$< 1\times10^{-5}$	Ideal state of designed materials
Plastic creep	1×10^{-5}–8×10^{-5}	Allowable state within controllable range
Incremental plastic failure	$> 8\times10^{-5}$	Avoid

2.5 Testing program

The dynamic triaxial test of the coarse-grained soil was carried out using the GDS dynamic triaxial apparatus. The sample was put into the back pressure chamber for back pressure saturation through special sample preparation equipment. The sample was considered to be fully saturated when the pore water pressure coefficient $B \geqslant 0.96$. And then isotropic consolidation was carried out, finally the dynamic cyclic loading was applied under undrained conditions. Sine wave was used to simulate the train dynamic load with frequencies of 1 Hz and 3.6 Hz. The dynamic load amplitude is proportional to the cyclic stress ratio CSR with the proportional coefficient equal to the deviator stress q_{cu}. Testing confining pressures are 20, 40, 60, 80 and 100 kPa, respectively, and the number of cyclic loading is 20 000. In the test, the cyclic stress ratio was first increased step by step, and the plastic strain rates of 1×10^{-5} and 8×10^{-5} were used as the critical limit standards for the three types of behavior of the coarse-grained soil. Finally two critical limit stresses that meet the requirements were determined by applying dynamic loads with different CSR values.

3 Experimental results and analysis

3.1 Consolidated undrained static shear tests

The axial dynamic cyclic loading in the test was determined using the cyclic stress ratio CSR, and the maximum axial stress q_{cu} of the sample can be obtained from consolidation undrained shear test($q_{cu} = 2\tau_{cu}$). The consolidated undrained shear strength envelope of the samples under different confining pressures is shown in Fig.6, the consolidated undrained strength parameters are $c_{cu} = 70.46$ kPa, $\varphi_{cu} = 40.8^{\circ}$.

According to the Mohr circle in Fig.6, the deviator stress q_{cu} at failure under different confining pressures can be calculated as

$$q_{cu} = \sigma_{1f} - \sigma_{3f} \tag{4}$$

where σ_{1f} and σ_{3f} are the maximum and minimum principal stresses at failure. The calculated deviator stress are shown in Table 2.

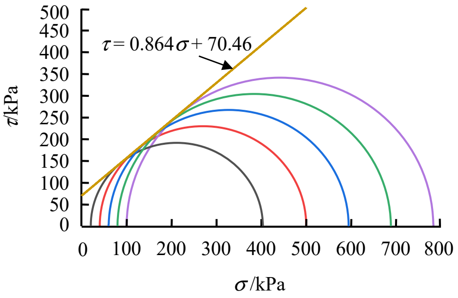


Fig. 6 Envelope of consolidated undrain shear strength for samples under different confining pressures

Table 2 Maximum deviatoric stress of samples for consolidated undrain shear test

confining pressure σ_3 /kPa	20	40	60	80	100
deviatoric stress q_{cu} /kPa	383.42	460.18	534.40	608.30	682.94

3.2 Cumulative deformation of coarse-grained soil

The results of axial plastic strain for different loading frequencies, confining pressures, and cyclic stress ratios, are shown in Fig.7 and Fig.8. The development laws of axial cumulative strain are basically the same under different loading frequencies and cyclic stress ratios. According to different plastic strain rates, the behavior can be classified into three types: plastic shakedown, plastic creep and incremental plastic failure.

3.2.1 Effect of cyclic stress ratio

Figures 7 and 8 show that the axial plastic strain of the sample increases with the increase of the cyclic stress ratio under constant loading frequency and confining pressure, implying that the increase of axial dynamic stress will exacerbate the development of permanent deformation under a given confining pressure. When the samples is in the plastic shakedown state (the axial plastic strain rate is less than or equal to 1×10^{-5}, as shown in Fig.7(a), the cyclic stress ratios are 0.10, 0.20, 0.30 and 0.35, respectively), the development laws of axial plastic strain are approximately the same. At the beginning of loading, the axial plastic strain increases rapidly, accompanied by an obvious accumulation of plastic strain, and the accumulation rate decreases gradually with the increase of the number of cycles, and the axial plastic strain mainly occurs in the first 1 500 load cycles. The plastic strain accumulation rate gradually slows down and the axial plastic strain tends to be stable in the subsequent load cycle, indicating that the internal structure of soil is strong enough to resist the cyclic load, although the samples experiences axial plastic strain accumulation stage, and the plastic deformation tends to reach dynamic stability quickly.

With the increase of cyclic stress ratio, the dynamic stability of the sample will be broken. As the number of cycle load increases, although the axial plastic strain rate of the specimen decreases gradually, the axial plastic strain continues to accumulate and does not reach a stable state, resulting in the sample finally in a plastic creep state (the axial plastic strain rate is between 1×10^{-5} and 8×10^{-5}, as shown in Fig.7(a), with cyclic stress ratios of 0.40, 0.50, 0.60 and 0.65). It should be noted that the sample is still in a safe state at this time, and it will not collapse suddenly.

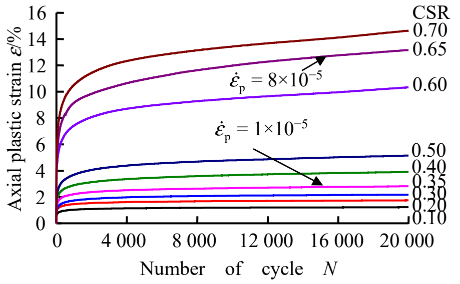
With the continuing increase of the cyclic stress ratio (as shown in Fig.7(a), when the cyclic stress ratio is 0.70), the axial dynamic stress exerted on the sample is greater than the yield limit of the material, which makes the material enter into the yield stage. The axial plastic strain of the sample increases continuously, and the accumulation of the plastic strain is maintained at a relatively high level. Finally, the sample will be destroyed due to excessive axial plastic deformation. It is foreseeable that when the cyclic stress ratio continues to increase, the sample will collapse rapidly due to excessive plastic strain accumulation in a relatively small number of cycles. Therefore, it is very important to strictly control the dynamic stress level in the subgrade structure caused by train wheel load in the design of railway subgrade structure, and it will be the key factor that determines whether the subgrade filling can reach the dynamic stable state under the load.

3.2.2 Effect of confining stress

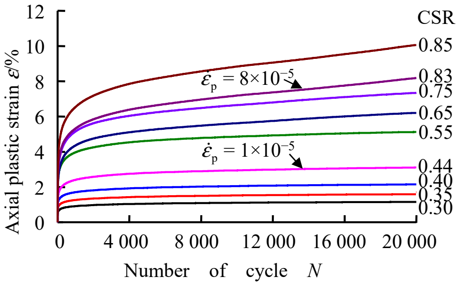
From Figs. 7 and 8, we can infer that the increase of confining pressure will lead to the increase of strength of sample particles after extrusion when other conditions remain unchanged, which makes the rate of plastic strain accumulation gradually slow down. When the confining pressure is large, the axial plastic strain rate increases rapidly in the initial stage of loading. With the increase of the number of cyclic loading, the cumulative rate gradually slows down and remains in the dynamic stable state. However, when the confining pressure is small, the plastic strain of the sample under the same cyclic stress ratio does not stabilize at the later stage of loading, while it still increases at a certain rate. The structure will eventually be in the alternating plastic state or incremental plastic failure state. The mutual constraint between the coarse-grained soil particles becomes tighter due to the larger confining pressure, which can greatly improve the ability of subgrade filling to resist external load damage[13−14]. Therefore, the critical cyclic stress ratio of plastic shakedown and plastic creep will gradually increase with the increase of confining pressure, as shown in Table 3.

3.2.3 Effect of loading frequency

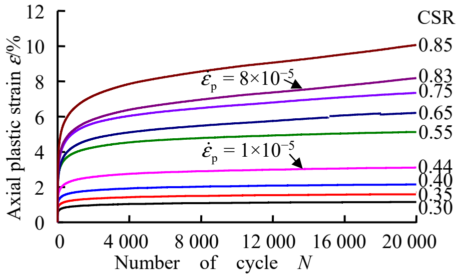
It can be seen from Figs. 7 and 8 that the axial plastic strain of the sample increases gradually with the increase of loading frequency under the same confining pressure and cyclic stress ratio, but the cumulative rate of plastic strain gradually slows down. Table 3 gives the critical dynamic stresses for the plastic shakedown state and plastic creep state of samples under different loading frequencies. It can be seen the critical dynamic stress of the sample is larger when the loading frequency is low ($f = 1$ Hz), and the critical dynamic stress decreases with the increase of the loading frequency ($f = 3.6$ Hz). The influence of loading frequency on the axial plastic deformation of the sample can be explained as follows: in the loading stage, plastic deformation occurs in the sample; when unloading, the plastic deformation will recover. However, the recovery of plastic deformation is not instantaneous, and it takes a certain time. The plastic deformation in the sample can be partially or mostly recovered with sufficient time when the loading frequency is low. When the loading frequency is high, only a small or very small part of the plastic deformation can be recovered. It can be predicted that when the loading frequency increases to a certain extent, the plastic deformation of the sample will not be recovered completely due to insufficient time. At the same time, increasing



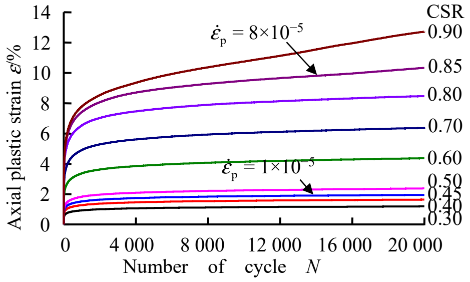
(a) Confining pressure 20 kPa



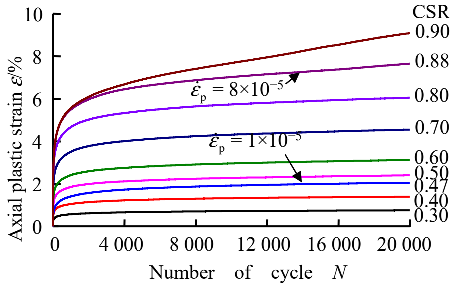
(b) Confining pressure 40 kPa



(c) Confining pressure 60 kPa

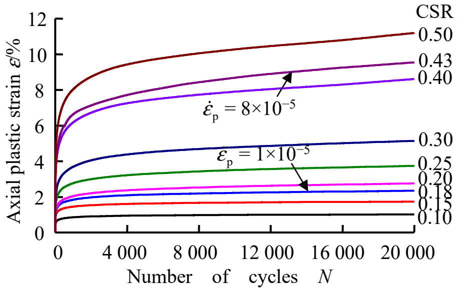


(d) Confining pressure 80 kPa

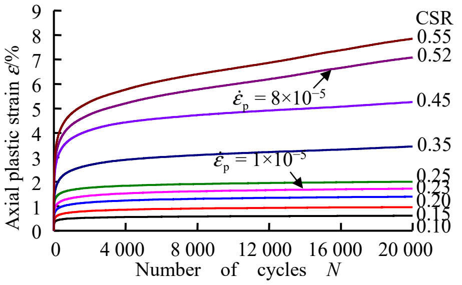


(e) Confining pressure 100 kPa

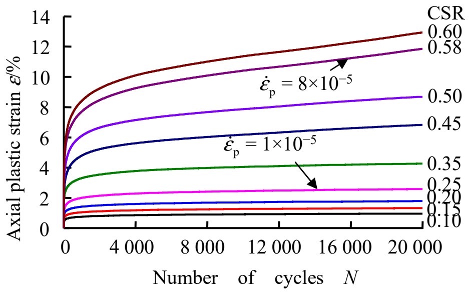
Fig. 7 Cumulative plastic strain ($f = 1$ Hz)



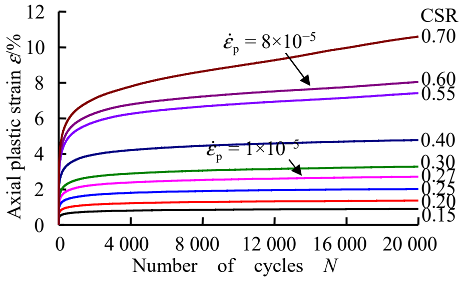
(a) Confining pressure 20 kPa



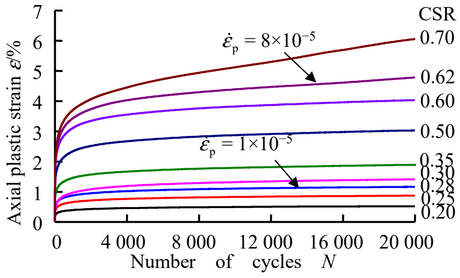
(b) Confining pressure 40 kPa



(c) Confining pressure 60 kPa



(d) Confining pressure 80 kPa



(e) Confining pressure 100 kPa

Fig. 8 Cumulative plastic strain(f = 3.6 Hz)

the loading frequency will not cause the change of the critical dynamic stress in the sample.

3.3 Analysis of critical cyclic stress

According to the experimental results, confining pressure has an important influence on the axial plastic deformation. Therefore, the analysis of the critical stress level of the sample is related to its confining pressure. Based on the dynamic triaxial test, Dawson et al.[15] pointed out that the critical stress between different mechanical responses of subgrade filling under dynamic load can be described as

$$\sigma_1 = \alpha\left(\frac{\sigma_1}{\sigma_3}\right)^{\beta} \tag{5}$$

where σ_1 is the total axial stress(kPa); σ_3 is the confining pressure (kPa); α and β are the test parameters.

Two critical stress values under different confining pressures at frequencies of 1.0 Hz and 3.6 Hz can be determined from Figs. 7 and 8, as listed in Table 3. The results of the two frequencies are plotted in the form of scatter points in Fig.9. The empirical formulas of critical stress levels for the plastic shakedown and plastic creep state can be fitted respectively.

The critical stress expression of plastic shakedown obtained by fitting is

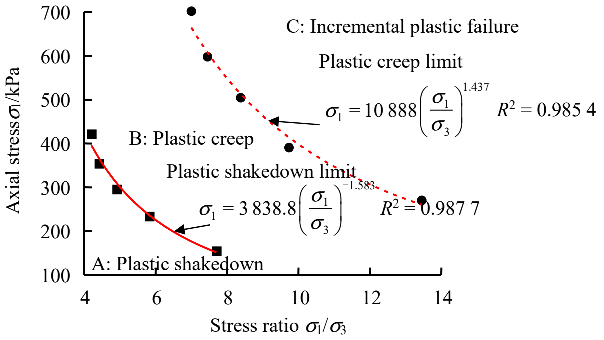
Table 3 Critical stress values of samples under cyclic loading

Frequency /Hz	Confining pressure σ_3/kPa	Deviator stress q_{cu}/kPa	Plastic shakedown limit			Plastic creep limit		
			CSR	σ_1/kPa	σ_1/σ_3	CSR	σ_1/kPa	σ_1/σ_3
1.0	20	383.42	0.35	154.20	7.71	0.65	269.22	13.46
	40	460.18	0.42	233.28	5.83	0.76	389.74	9.74
	60	534.40	0.44	295.14	4.92	0.83	503.55	8.39
	80	608.30	0.45	353.74	4.42	0.85	597.06	7.46
	100	682.94	0.47	420.98	4.21	0.88	700.99	7.01
3.6	20	383.42	0.18	89.02	4.45	0.43	184.87	9.24
	40	460.18	0.23	145.84	3.65	0.52	279.29	6.98
	60	534.40	0.25	193.60	3.23	0.58	369.95	6.17
	80	608.30	0.27	244.24	3.05	0.60	444.98	5.56
	100	682.94	0.28	291.22	2.91	0.62	523.42	5.23

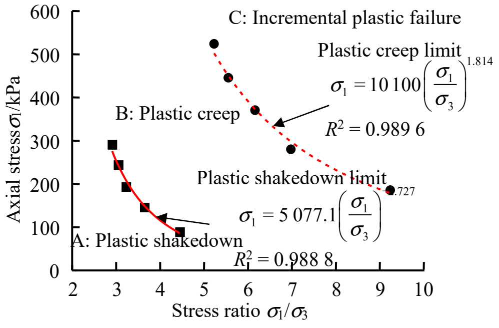
$$\begin{aligned} \sigma_1 &= 3\,838.8\left(\frac{\sigma_1}{\sigma_3}\right)^{-1.583} & f &= 1.0\ \text{Hz} \\ \sigma_1 &= 5\,077.1\left(\frac{\sigma_1}{\sigma_3}\right)^{-2.727} & f &= 3.6\ \text{Hz} \end{aligned} \tag{6}$$

The critical stress of plastic creep is obtained by fitting is

$$\begin{aligned} \sigma_1 &= 10\,888\left(\frac{\sigma_1}{\sigma_3}\right)^{-1.437} & f &= 1.0\ \text{Hz} \\ \sigma_1 &= 10\,100\left(\frac{\sigma_1}{\sigma_3}\right)^{-1.814} & f &= 3.6\ \text{Hz} \end{aligned} \tag{7}$$



(a) Frequency 1 Hz



(b) Frequency 3.6 Hz

Fig. 9 Critical stress of samples with different loading frequencies

Leng et al.[13] carried out dynamic tests on 1:1 full-scale subgrade structure model under different axle load conditions (23, 25, 28, 30 t) in the Subgrade Laboratory of Central South University, and obtained the results of dynamic stress variation with depth. The critical dynamic stress level of the subgrade structure at any depth under the loading frequency of 1 Hz can be obtained through Eq. (6). The relationship between the amplitude of critical dynamic stress and the depth of subgrade structure can be obtained by subtracting the confining pressure at the same depth from the critical dynamic stress. The comparison of result with the test data from Leng et al.[13] is shown in Fig.10. The depth h in the plot is converted from the confining pressure. It can be clearly seen that the two critical dynamic stress amplitude curves divide the stress space of the subgrade structure into three regions in the depth, which correspond to the three elastic-plastic stress states of the coarse-grained soil filling under cyclic loading. When the dynamic load of the subgrade at any depth is in zone A (plastic shakedown zone), its internal structure can resist the effect of external load and make the structure remain in the dynamic stable state, although the subgrade structure has small plastic deformation. At this time, the subgrade structure is in an ideal working state. If it is in zone B, the subgrade structure is safe within a certain service time. However, the cumulative plastic deformation will continue to increase with the increase of time, and the structure will eventually cause certain fatigue damage due to the repeated plastic deformation. Therefore, regular maintenance are needed. When it is in zone C, and the subgrade structure will enter into the yielding stage, which will lead to bearing failure due to excessive accumulated plastic deformation or damage due to sudden collapse of the structure. This is not allowed for the design of subgrade structure, and it needs to be redesigned according to its load conditions.

The comparison result in Fig.10 shows that the dynamic stress in subgrade increases with the increase of the axle load, and it gradually decreases with depth. However, the critical dynamic stress amplitude of the coarse-grained soil increases with depth. The test results are always within the critical dynamic stress amplitude curve of plastic shakedown, which indicates that samples in full-scale model test are in the shakedown state under the dynamic load.

In practical engineering, the three-dimensional stress of subgrade changes with the train load, and the critical stress of shakedown deformation of the coarse-grained

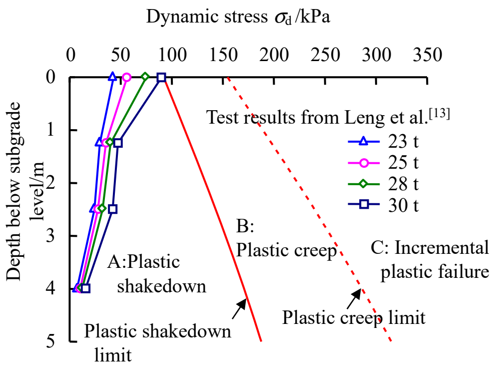


Fig. 10 Comparison of critical dynamic stress of subgrade with measured maximum dynamic stress

soil is closely related to the confining pressure. And the empirical equation of critical dynamic stress of the coarse-grained soil is presented in this paper, which can determine the maximum axial stress under a certain confining pressure. If the axial stress exceeds the maximum axial stress under long-term load, the subgrade structure will be damaged directly due to excessive permanent deformation. If the axial stress is lower than the maximum axial stress, the subgrade structural layer will not increase with the time. After reaching the shakedown state, the plastic strain rate of the coarse-grained soil filling is very small, almost negligible. The permanent deformation will eventually reach a stable value. Therefore, it is more convenient to evaluate the dynamic stability of the coarse-grained soil under cyclic dynamic load from the perspective of dynamic stress.

4 Conclusions

The dynamic response of the coarse-grained soil filler is divided into three states: plastic shakedown, plastic creep and incremental plastic failure based on the shakedown theory. The development law of axial plastic strain of sample was systematically studied through dynamic triaxial tests with different loading frequencies, confining pressures and cyclic stress ratios. Some conclusions were drawn as follows:

The shakedown theory can reasonably and reliably describe the elastic-plastic mechanical behavior of the coarse-grained soil filler under cyclic loading. The dynamic triaxial test results show there are three types of elastic-plastic mechanical behavior of the sample, according to the development law of axial plastic strain. The plastic strain rates of 1×10^{-5} and 8×10^{-5} can be used to determine the adjacent response behavior, which correspond to the critical stress levels of plastic stability and plastic creep, respectively.

Under the same conditions, the axial plastic strain of the coarse-grained soil filling increases with the increase of cyclic stress ratio and loading frequency. The critical cyclic stress ratios of the plastic shakedown and plastic creep increase with the increase of confining pressure and decrease with the increase of loading frequency.

Based on the critical cyclic stress ratio of the sample, the empirical equation of critical stress of the coarse-grained soil filling with confining pressure as the variable is proposed. This provides a theoretical basis for reasonably evaluating the dynamic stability of the subgrade at any depth under train load.

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