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Research Article

Research on Cumulative Deformation Characteristics of Subgrade Filling under Cyclic Train Loading

Junkai Yao ,[1,2] Yangsheng Ye,[1,2] Degou Cai ,[1,2] Zongqi Bi,[1,3] and Hongye Yan[1,2]

[1]*State Key Laboratory for Track Technology of High-Speed Railway, China Academy of Railway Sciences Corporation Limited, Beijing 100081, China*
[2]*China Academy of Railway Sciences Corporation Limited, Beijing 100081, China*
[3]*Beijing Tieke Special Engineering Technology Corporation Limited, Beijing 100081, China*

Correspondence should be addressed to Degou Cai; caidegou@126.com

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The smoothness of high-speed railway is extremely strict. As an important part of the high-speed railway foundation, the subgrade structure has strict deformation requirements. It is necessary to ensure that the subgrade structure does not have plastic cumulative deformation under the long-term cyclic load of the train, which is the most critical geodynamic problem in high-speed railway subgrade. This paper studied the cumulative deformation characteristics of subgrade filling under cyclic train loading through the cyclic triaxial test, three types of accumulative plastic deformation trends, and the value of critical volume shear strain was discussed, which would provide the theoretical support for the dynamic design of high-speed railway.

1. Introduction

The subgrade is an important part of the foundation of the high-speed railway line, which bears the train's cyclic loading directly. In China's high-speed railway standard [1], ballastless track subgrade settlement after construction is not more than 15 mm. The 15 mm of deformation includes the settlement of the foundation and the deformation of the subgrade, and the postconstruction settlement of the foundation occupies the main part. Therefore, it is necessary to ensure that the subgrade structure does not have plastic cumulative deformation under the long-term cyclic loading of the train, which is the most critical geodynamic problem in high-speed railway subgrade. However, the high-speed railway foundation is compacted by the filling material, so it is necessary to understand the plastic accumulation deformation development law of the high-speed railway coarse-grained soil filling material under the trainload accurately.

A large number of scholars have studied the plastic accumulation deformation of soil under cyclic train load. Morgan [2] carried out triaxial tests of coarse sand under cyclic loading, the effects of deviatoric stress and confining pressure on cumulative plastic deformation have been discussed. The results show that the cumulative plastic deformation increases with the increase of deviatoric stress and decreases with the increase of confining pressure. Barksdale's [3] research shows that the development of cumulative plastic deformation is directly related to the increase of deviant stress and the decrease of confining pressure. Brown and Hyde's [4] study pointed out that the ratio of deviatoric stress to confining pressure directly affects the axial cumulative plastic deformation. Muhana et al. [5] and Rondón et al. [6] research results show that changing loading frequency has little effect on soil plastic deformation.

In general studies, the trend of plastic cumulative deformation is divided into stable and divergent states, and the critical strain and dynamic stress of the boundary states have been studied. ZHOU Shen-Gen [7] studied the accumulation deformation characteristics of unsaturated sand and gravel under low confining pressure, pointed out that there is critical dynamic stress in subgrade filling under cyclic dynamic stress. When the dynamic stress exceeds the critical dynamic stress, the accumulated strain of soil increases rapidly with the increase of vibration times and finally reaches failure. When the dynamic stress is less than the critical dynamic stress, the cumulative strain of coarse-grained soil filler develops stably and converges with the increase in vibration times. When the ratio of dynamic stress to confining pressure is below 0.2, the cumulative plastic deformation produced by 100,000 times of loading is below 0.2%, and it can reach stability soon. In Vucetic and Dobry [8, 9] research, the dynamic modulus ratio and shear strain characteristics of cohesive soils with different plastic exponents are studied, and the effect of plastic critical volumetric strain is discussed. A critical volumetric strain limit of 0.51 is proposed. According to Cai and Xin-Wen [10], the relationship curve between cumulative plastic strain and load action times, the plastic deformation trend of filling under cyclic loading is divided into two types: development and attenuation. Based on the volumetric plastic strain, they studied the cumulative deformation trend of the filling under cyclic loading divided into three states: stable state, critical state, and unstable state in Minassian [11] study. Qu et al. [12] reveal the method of seismic coefficient simulation of dynamic load, and its seismic design can be used as a reference for the dynamic design of subgrade. Based on the analysis of Werkmeister [13], the variation law of axial cumulative strain rate of filling, the cumulative plastic strain was divided into three kinds, namely plastic shakedown, plastic creep, incremental failure, and the critical limit of plastic strain increment within the number of cycles has been studied. Luo et al. [14] studied the characteristics of cumulative deformation evolution of subgrade bed filling under cyclic loading. Four types of critical states were proposed: rapid stabilization, slow stabilization, slow failure, and fast failure.

In conclusion, a large number of studies have been carried out on the deformation law, influencing factors, and boundary state of long-term plastic cumulative deformation of soil under cyclic loading. However, relatively few studies have been conducted on the train cyclic loading plastic cumulative deformation law of high-speed railway subgrade coarse-grained soil filling, which has the features of high density, unsaturated low confining pressure. There are few systematic studies and systematic data accumulation on the dynamic characteristics of typical filling of China's high-speed railways in different groups, and few studies on the relationship between plastic cumulative deformation law and long-term dynamic stability of subgrade structure.

Therefore, in view of China's high-speed rail high-speed train cyclic loading amplitude and frequency characteristics, the cyclic triaxial test reveals the cumulative deformation characteristics of high-speed railway subgrade coarse-grained soil under high-speed train load, and critical strain and dynamic stress of the boundary states are discussed in this paper, which provides a theoretical basis for the dynamic design of high-speed railways.

2. Materials and Methods

2.1. Equipment. The cyclic triaxial test uses the GDS large triaxial cycle test system. The main components of the instrument include an axial vibration exciter, confining pressure controller, axial displacement sensor, hole pressure, and confining pressure sensor, signal-regulating device, and dynamic control system. The confining pressure is applied through the pore at the top of the confining pressure chamber, and axial load is applied through the bottom shaker. The test instrument has the functions of shaft closed-loop control and stress-strain adaptive control, and the sensor has high testing accuracy. It can test the dynamic characteristics of the filling (10^{-4}~10^{-3} strain range) under the cyclic loading of the high-speed train.

2.2. Materials. The coarse-grained soil filler of China's high-speed railways, especially the subgrade bed filling affected by dynamic force, has strict restrictions on the grading, shape, and fine particle content, which keeps the dynamic parameters within a small range. In this paper, the typical coarse-grained soil of high-speed railways is taken as the representative.

The filling of Beijing-Xiong'an Intercity Railway was used to carry out the test. Based on the on-site filling screening of 500 kg, the average gradation of typical filling was obtained. The diameter of the dynamic triaxial sample $D = 150$ mm, height $H = 300$ mm, and the maximum particle size should not exceed 30 mm. The test filling grading was optimized by the elimination method and equivalent substitution method. The grading of the triaxial test is shown in Table 1, and the grading curve of the filling sample is shown in Figure 1.

China's high-speed railway foundation has a good waterproof structure, the subgrade filling under the closed layer, and the change of water content is small. The characteristics of the unsaturated coarse-grained filling of high-speed railways are low water content and drainage conditions. Therefore, in order to simulate the real state of high railway subgrade filling, the unsaturated dense filling with the optimal moisture content was used as the test sample. The maximum dry density and optimal moisture content of the filling were obtained through Platt's compaction test, as shown in Figure 2. The filling used in the test was mixed at the optimal moisture content, then it was kept static and sealed for 24 h to make the moisture more uniform. The sample is prepared by the layered vibration method, which is divided into 6 layers. After each compaction layer, the top surface of the layer is brushed before the next layer is compacted, and the last layer is leveled. The dry density of the test samples should be controlled above 95% of the maximum dry density (> 2.25 g/cm^3), and the dry density of the tests in the same group should be kept consistent as far as possible.

2.3. Method. A hierarchical loading method was used for cyclic triaxial test loading (as shown in Figure 3). The consolidation and drainage triaxial methods were used in the test. The amplitude of dynamic stress is applied from small to most levels. The loading waveform is sinusoidal, the load size is 0.3 kN~4.0 kN, the actual simulated dynamic stress of the train is $2\sigma_d = 16.9$ kPa~226.4 kPa, and the loading frequency is 5 Hz (simulated train speed = 300 km/h). The uniform load

Table 1: Filling grading of cyclic triaxial test.

Filling grading	Mesh aperture(mm)									
	60	30	20	10	5	3	1	0.5	0.25	0.075
Average value of Beijing-Xiong'an intercity railway	100	90.9	69.9	53.5	43.4	33.3	28.0	23.5	16.3	2.2
Cyclic triaxial test	—	100.0	75.0	60.0	50.0	35.0	30.0	25.0	16.0	3.0

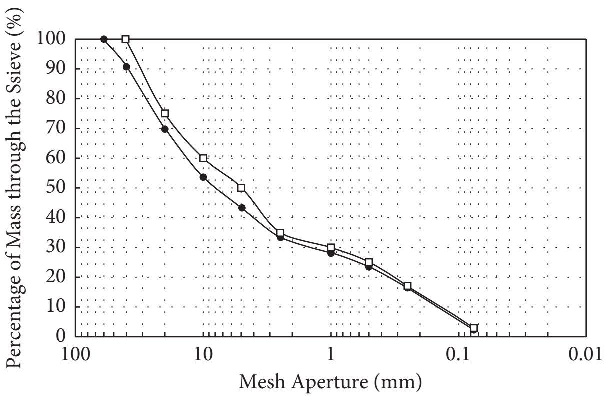

Figure 1: Gradation curve of cyclic triaxial test Sample.

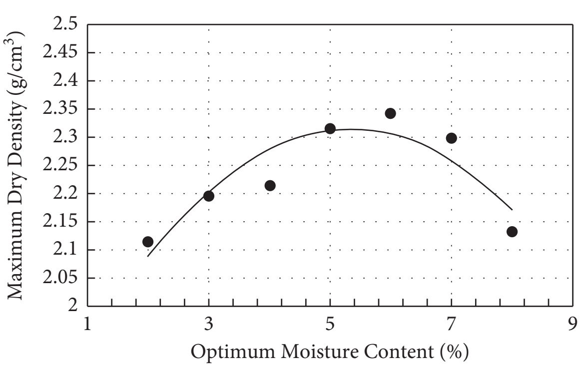

Figure 2: Sample gradation curve.

of CRTSIII plate-type ballastless track in China is 13.7 kPa, and the confining pressure $\sigma_3 = \sigma_1 = 13.7$ kPa is applied. The number of cyclic loading times of each stage dynamic stress is at least $\Delta N = 10000$ times. If it is not stable, the convergence standard is that the cumulative deformation within 1000 times of cyclic loading is not more than 0.01%. After the sample configuration is completed, the confining pressure is applied to the installation instrument for consolidation for 24 h. After that, 0.1 kN dynamic cyclic loading was applied for 10,000 times to eliminate the coupling error of the system. The large-scale cyclic triaxial test process of coarse-grained filling is shown in Figure 4.

3. Results

3.1. Plastic Cumulative Deformation Law. Figure 5 shows the variation curve of the axial strain of the sample with the number of cycles when the dynamic stress is 16.9 kPa, 113.2 kPa, and 226.4 kPa for 10000 cycles. The cyclic curve in the figure is a schematic diagram, mainly designed to describe the dynamic strain and cumulative plastic strain of the filling under different dynamic load levels. Under cyclic loading, the axial deformation of the specimen is composed of recoverable spring back deformation and unrecoverable accumulated deformation, the elastic deformation of the specimen increases with the increase of loading load. The cumulative deformation statistics of each load level are shown in Table 2. When the load is less than 28.3 kPa, the axial accumulated deformation of soil develops rapidly at the beginning of loading, then the growth rate decreases and the sample tends to be relatively stable near $N = 2000$. When the dynamic load is greater than 28.3 kPa and less than 192.4 kPa, the plastic cumulative deformation of the filling develops slowly under the cyclic loading, and the axial cumulative deformation of the specimen is basically stable. When the load exceeds the limit of 226.4 kPa, the axial cumulative deformation increases rapidly with the number of cycles, and the deformation rate increases gradually.

Three types of accumulative plastic deformation trend states were proposed in the paper, including initial compaction, stabilization stage, and rapid destruction. The test results are consistent with the classification of different deformation trends of filling plastic cumulative deformation in previous studies. The plastic deformation in the initial compaction stage is caused by filling compaction. In the rapid destruction state, the plastic deformation accumulates massively, and finally, the shear failure occurs. Under different cyclic loading, the cumulative plastic deformation presents different state characteristics with the increase of cyclic time, and if there is critical dynamic stress or critical dynamic load of the filling as the limit value, the cumulative plastic deformation of the filling would converge under long-term train load.

3.2. Dynamic Stress and Strain Characteristics. Figures 6 and 7 show the hysteresis curves of the filling under cyclic loading with different dynamic stress levels. Under different dynamic stress levels, the hysteresis circle with the cycle times of $N = 8000$ in the dynamic stress stability stage of all load levels is taken. The stress and strain of the filling hysteresis curve all start from 0. When the loading stress is small, the hysteresis loop of the filling is close to the line shape, which indicates that the filling damping is relatively small, and the filling with high density is close to the elastomer at the low dynamic stress level. With the increase of dynamic stress level, the damping of the filling increases, and the viscoelastic properties of the filling become more obvious. With the increase in strain grade, the slope of the hysteresis cycle is basically the same. In the range of cyclic

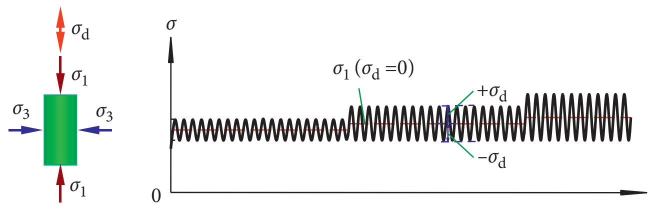

Figure 3: Hierarchical loading method.

Figure 4: GDS large scale cyclic triaxial test of coarse-grained filling.

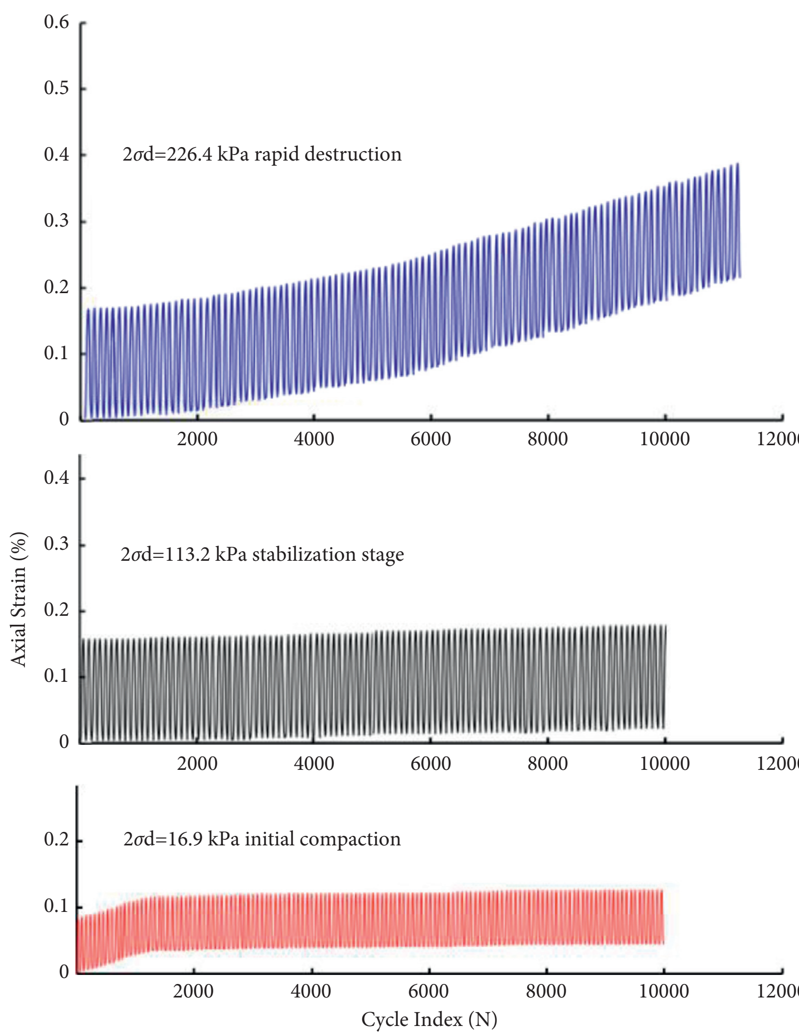

Figure 5: Axial strain versus loading cycles N.

Table 2: Plastic cumulative deformation characteristics of filling under different dynamic loads.

Dynamic Load(kN)	0.3	0.8	1	1.5	2	2.4	3	3.4	4
Dynamic stress $2\sigma_d$ (kPa)	16.9	45.3	56.7	84.9	113.2	135.8	169.8	192.4	226.4
Plastic deformation trend	Initial compaction		Stabilization Stage						Rapid destruction
Accumulated plastic strain(%)	0.034	0.032	0.013	0.007	0.012	0.019	0.022	0.022	0.160

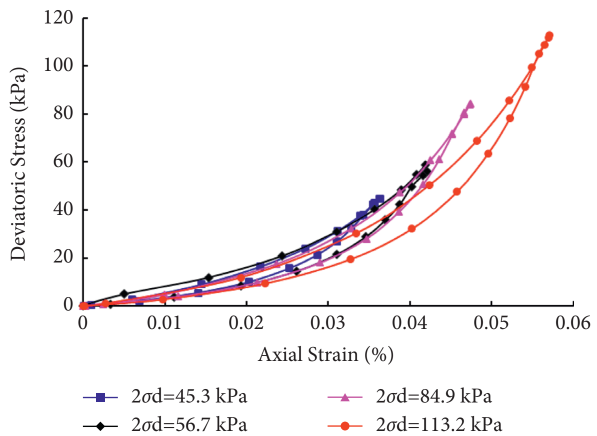

Figure 6: Hysteretic curve with different dynamic stress (cycle times $N = 8000$).

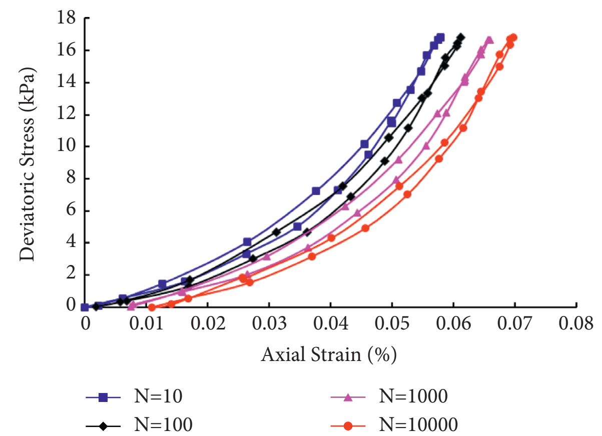

Figure 8: Hysteretic curve of different cycle times (dynamic stress $2\sigma_d$ = 16.9 kPa).

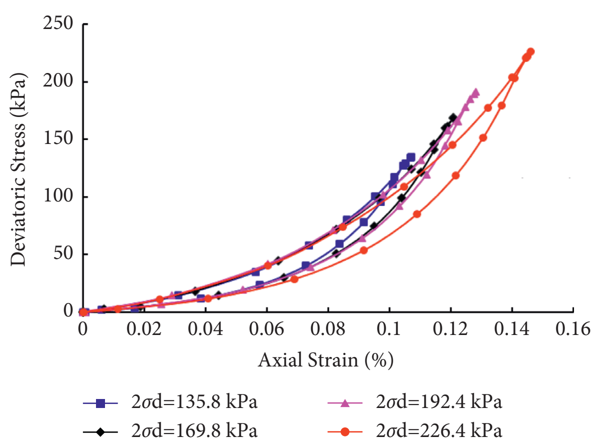

Figure 7: Hysteretic curve of different dynamic stress (cycle times $N = 8000$).

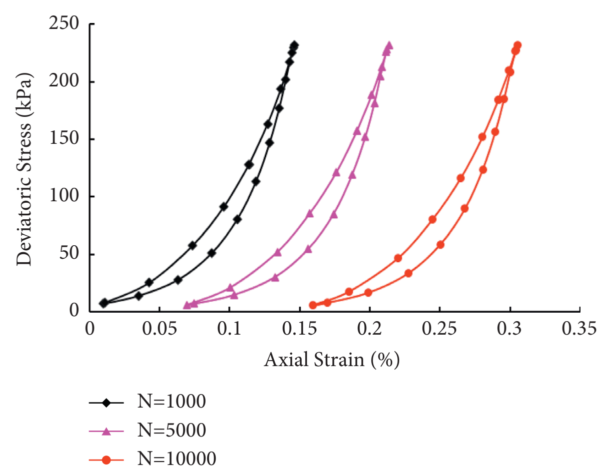

Figure 9: Hysteretic curve of different cycle times (dynamic stress $2\sigma_d$ = 226.4 kPa).

loading of high-speed trains, the dynamic modulus of filling does not change significantly.

The stress-strain curves of the samples with $2\sigma_d$ = 16.9 kPa in the initial compaction state and $2\sigma_d$ = 226.4 kPa in the rapid destruction state with different cyclic times are shown in Figures 8 and 9, and cumulative axial strain at different cycles is also identified on the axial strain. Different loading times have little effect on the hysteretic curve under the stabilization stage, so it is not discussed emphatically. The plastic strain rates at different stages are shown in Table 3.

In the initial compaction stage, the vertical strain rate decreases rapidly, and the deformation rate is $3.67E^{-5}$ in the cycle time range of 0–100, $1.1E^{-5}$ in the cycle time range of 100–1000, and rapidly decreases to $1.13E-6$ in cycle time range of 1000–10000. The plastic deformation increases rapidly in the initial stage, gradually decreases after the number of cycles is more than 2000, and finally remains stable. In this case, the filling does not undergo long-term plastic accumulation deformation. The main concern with subgrade is postconstruction settlement. The initial compaction process of soil occurs before filling or laying ballastless track. The deformation caused by insufficient compaction of soil in the initial stage will not cause too much of a harmful impact on ride comfort. Therefore, when the plastic cumulative deformation trend of filling is in the initial compaction state and the stabilization stage, it is acceptable for the high-speed railway subgrade.

Table 3: Plastic cumulative deformation characteristics of filling under different dynamic loads.

Dynamic load (kN)		0.4			4.0	
Dynamic stress 2 σ_d (kPa)		16.9			226.4	
Cycle times	0~100	100~1000	1000~10000	0~1000	1000~5000	5000~10000
Axial strain rate (ε/cycle time)	$3.67E^{-5}$	$1.10E^{-5}$	$1.13E^{-6}$	$1.10E^{-5}$	$1.55E^{-5}$	$1.76E^{-5}$

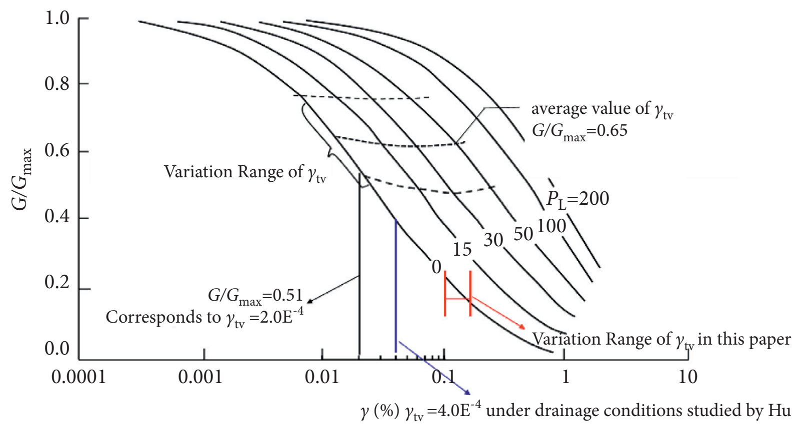

Figure 10: Critical volumetric effect strain γ_{tv} in the curve of relation between γ and modulus reduction.

In the rapid destruction stage, the plastic deformation of the filling increases rapidly and is in a divergent state. The axial strain rate is $1.10E^{-5}$ in the cycle time range of 0~1000, and the axial strain rate is $1.55E-5$ in the cycle time range of 1000~5000, and the axial strain rate is $1.76E-5$ in the cycle times range of 5000~10000. The plastic deformation rate of the filling keeps increasing, and the plastic deformation trend of the filling has been unable to converge and would continue to increase until shear failure. In this case, a large amount of plastic cumulative deformation will occur to the filling material, and the long-term train load will have a great impact on the deformation of the subgrade. The strain per 1000 cycle times is greater than $1E^{-4}$, which is the unbearable value for high-speed railway subgrade construction.

4. Discussions

The dynamic design of high-speed railway subgrades in China is based on the control of critical volumetric effect strain (γ_{tv}) of subgrade filling. On the basis of the critical volumetric effect strain theory, the dynamic design system of high-speed railway subgrade structure with precise control of dynamic deformation has been established, which supported China's high-speed railway infrastructure large-scale rapid construction (Zhang et al. [15]]). The dynamic design theory is based on the research results of Vucetic [16]. The relationship between the cumulative effect of soil accumulated deformation and dynamic strain was studied. In order to basically avoid plastic accumulation, the shear modulus ratio should be controlled above 0.51, which is shown in Figure 10.

The critical volumetric effect strain proposed by Vucetic provides great help for the theory of plastic deformation of soil under cyclic loading. However, the research results are based on the statistical results of a large number of experimental studies on clay and sand. Some studies have shown that the strain limit corresponding to the critical state is slightly higher than that corresponding to the modulus ratio of 0.51 for high density nonviscous coarse-grained soil filling under drainage conditions. According to the analysis of Hu and Li [17], the maximum value of critical volumetric strain is about $1.3E^{-4}$ under the condition of undrained water, and up to $4E^{-4}$ under the condition of drained water. The critical stress of high-speed railway filling is studied in the paper, under the confining pressure of 28.3 kPa and drainage condition. The critical dynamic stress range of China's high-speed railway group A filling is 200 kPa~220 kPa, the corresponding critical dynamic strain is $1.1E^{-3}$~$1.3E^{-3}$. Wenquan et al. [18] studied the critical dynamic stress as 250 kPa~275 kPa of heavy-duty railway gravel filling with 6% moisture content under 30 kPa confining pressure, which is consistent with the test results in this paper. The dynamic characteristics of different types of filling differ greatly under different load characteristics and stress drainage conditions. Therefore, it requests pointed research into dynamic characteristics and critical dynamic strain γ_{tv}. In addition, it is worth noting that the value of the dynamic modulus ratio of the critical dynamic strain edge is applicable in the elastic range of small strain. When the dynamic strain is greater than $1E^{-4}$, the attenuation rate of the dynamic modulus is fast, which can easily lead to the error of the value of the dynamic modulus in subgrade design. The value of dynamic modulus, damping, and other dynamic parameters of filling with different characteristics under different strain conditions is worth further discussion.

According to the measured data, the dynamic load range of China's high-speed railway ballastless track subgrade surface is 9.50 kPa~18.50 kPa. Therefore, the dynamic strain of the filling is much lower than the critical state strain under the actual vibration load of high-speed train operation. According to the current design criteria, the dynamic characteristics of filling are extremely strong. There is basically no plastic deformation caused by long-term train cyclic loading. Therefore, taking the modulus ratio of 0.51 as the limit value of the convergence state of plastic cumulative deformation is a conservative and relatively safe method for subgrade dynamic design. Dynamic characteristics tests of high-speed railway filling with high density and low moisture content under low confining pressure and drainage conditions should be carried out. Systematic information about the plastic cumulative deformation law and critical state of different filling types would be obtained. On this basis, a more refined subgrade dynamic design could be carried out, and the thickness and filling of different structural layers of high-speed railway subgrades can be designed more reasonably to improve the economy.

5. Conclusions

(1) Based on the cyclic triaxial test, this paper carries out research on the plastic cumulative deformation development law of typical Chinese high-speed railway groups. A filling under cyclic loading was analyzed to determine the characteristics of the filling hysteresis curve. Within the dynamic stress cycle range of 16.9 kPa~226.4 kPa, the shape of the high-speed railway filling hysteresis loop is similar, and the dynamic modulus change is relatively small.

(2) Three types of accumulative plastic deformation trends states were proposed in the paper, including initial compaction, stabilization stage, and rapid destruction. They were studied by analyzing accumulative plastic strain and dynamic strain characteristics. The accumulative plastic deformation in the initial compaction state was mainly caused by filling compaction and generally stabilized at the number of cycles $N = 2000$. When the plastic cumulative strain rate does not decrease under cyclic loading, the filling is in a state of rapid destruction, which is considered to have reached the critical state of nonconvergence of plastic cumulative deformation.

(3) Combined with the dynamic design method of high-speed railways in China, the value of critical volume shear strain is discussed. The strain limit corresponding to the critical state is slightly higher than that corresponding to the modulus ratio of 0.51 for high density nonviscous coarse-grained soil filling under drainage conditions. Taking the modulus ratio of 0.51 as the limit value of the convergence state of plastic cumulative deformation is a conservative and relatively safe method for subgrade dynamic design, which could be optimized.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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