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Study on dynamic characteristics of cement-stabilized expansive soil subgrade of heavy-haul railway under immersed environment

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Abstract: The dynamic characteristics of subgrade is aggravated under the interaction of immersed infiltration and dynamic loads of trains, which affects the safety of train operation and long-term stability. Based on the engineering background of cement-stabilized expansive soil subgrade of Hao-Ji heavy-haul railway(Haolebaoji-Ji'an), field excitation tests of subgrade with four million cycles were carried out under dry and immersed conditions to investigate the dynamic characteristics. Large-scale excitation equipment, combined with dead weights, were used to simulate the dynamic behavior of heavy-haul trains with 25-30 t axle load. The test results show that the variations of dynamic stress and acceleration along the depth of subgrade are consistent, and decay rate is 80% at the base of subgrade. The influence of immersed infiltration and dynamic load of train is more significant at the interface of between the subgrade bottom and fill. Under the same loading conditions, the dynamic stress at the interface under the immersed condition is 28% larger than for the dry condition. The acceleration is much less sensitive to the immersed environment than the dynamic stress. At the same time, the dynamic stress level along subgrade depth is much lower than the critical dynamic stress of fill in the same location. The cumulative deformation of subgrade surface under cyclic loading of 4 million times is less than 5 mm and remains stable, which indicates that the improved expansive soil with 3%-5% cement content can be used as the subgrade bottom and fill to meet the dynamic stability requirements of subgrade. The research results can provide theoretical reference for high-quality construction and maintenance of the improved expansive soil subgrade of heavy-haul railway.

Keywords: cement-stabilized expansive soil subgrade; dynamic characteristics; excitation test; heavy-haul railway

1 Introduction

Nowadays, the construction of heavy-haul railway is becoming the main direction in the development of freight railway in many countries. Compared with ordinary railway and high-speed railway, the dynamic deformation induced by heavy-haul train is more prominent due to its larger axle load and longer marshalling, which not only affects the operation safety, but also needs stricter requirements on service performance of the relevant subgrade system[1–2]. In view of the complexity of the dynamic system of railway subgrade, scholars used the theory of classical mechanics to analyze it at the early stage. For example, Winkler[3] developed the model of elastic foundation beam for the mechanical analysis of tracks in 1867, and Fryba[4] verified the rationality of the model. Meanwhile, Kenney[5] used this model to analyze the steady-state response of foundation beam under moving loads with a constant speed. In China, Zhai et al.[6] and Chen and Bian[7] have conducted a number of research on the coupling vibration mechanism of the train–track–subgrade–foundation system, and reached a consensus that it is necessary to consider the interaction of trains, tracks, subgrade and foundation in the study of the dynamic effect of trains on the track structure. With the continuous improvement of theoretical research and the rapid development of computer technology, Mei et al.[8] conducted numerical simulation of the track–subgrade structure and found the range of the dynamic stress of subgrade is 74.60 –119.37 kPa under the train with the axle load of 25–40 t and the speed of 120 km/m. The classical theoretical analysis and numerical simulation are based on many assumptions and simplifications. In comparison, testing is still the most direct and reliable way to investigate the problem. For example, Leng et al.[9] performed full-scale subgrade model tests and found that the amplitudes of dynamic stress are 64.0, 74.9 and 90.1 kPa for trains with axle loads of 25, 27 and 30 t under the speed of 80 km/h, respectively. In 2013, the China Academy of Railway Sciences carried out the dynamic test of trains on Shuo-Huang railway, and the results show that the range of dynamic stress of subgrade is 110.1–123.0 kPa for trains with axle loads of 23–30 t.

The above research mainly focuses on the subgrade

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at the dry state. In recent years, the demand for maintenance is increasing with the application of refined railway construction, and many subgrade damages occur in the area with high precipitation. Some scholars began to investigate the coupling effect of rainfall infiltration and traffic loading. For example, Wang[11] and Hooputra et al.[12] studied the influence of rainfall intensity and duration on the dynamic response of highway subgrade using finite element modeling. Wang et al.[13] conducted field excitation tests on Yun Gui high-speed railway and found that the dynamic stress, velocity and acceleration of the subgrade increased for a certain extent after subgrade immersion compared to those at dry state. Currently, there are few cases of field excitation test on the improved expansive soil subgrade in China, and the dynamic characteristics analysis of improved expansive soil subgrade under rainfall infiltration is also limited. The total length of the Hao–Ji heavy-haul railway is 1837 km with a design transmission capacity of 200 million t / a, and part of the lines uses mixed traffic. Among them, the part between Sanmenxia to Jingmen passes through the Nanyang basin (typical expansive soil area), which includes about 211 km of expansive soil and the improved soil volume is about $1,581\times10^4$ m^3. This paper explores the dynamic characteristics of cement improved expansive soil subgrade of heavy-haul railway under the immersion environment through field excitation test.

2 Field excitation testing program

This paper selects the improved expansive soil subgrade at the section DK948+275 of Sanmenxia–Jingmen railway for the field excitation test, and an additional test is conducted for comparison on the adjacent section DK948+175 where the coarse-grained fill is used. The basic design parameters and test conditions of the two sections are shown in Table 1.

2.1 Dynamic loading simulation

The exciter is ZBS60 vibrator, which has been used in dynamic testing on railway subgrade for many times showing good working performance. The mass of vibration exciter is relatively small, so it needs to be combined with dead weights. According to the method by Yang et al.[14], the contact surface between dead weights and subgrade is a square with a side length of 1.5 m. The dead weights were placed in the form of steps, and the height of the first and second steps are 150 mm and 1 200 mm, respectively. Meanwhile, the dead weights should meet the requirements of stability and crack resistance in the process of exciting vibration. The references [8–10] show the dynamic stresses of subgrade are around 80–128 kPa, and the dynamic stress of loading curve (sinusoidal curve) ranges from 70 to 140 kPa by adjusting excitation frequency and eccentric moment. Meanwhile, considering the dynamic stress of the actual subgrade is a flexible load, a 0.15 m cushion is laid under the excitation table (the material is the same as the subgrade), so that the simulated dynamic stress is close to the actual value.

2.2 Immersion simulation

The pit method was used in the immersion test. After the excitation test at dry state was completed, the test pits were excavated with the dimension of 3.5 m× 3.5 m×0.2 m (length × width × height) at the location of original section, and the formwork was set up around the pit. Then the waterproof was laid inside the formwork to form a closed reservoir. Since there was no water source near the field, the sprinkler truck was used to inject water into the pit, and the height of injection was 20 cm. When the water level reached this height, the drop in water level was observed every 10 min. After repeating water injection twice, the excitation test was started after an interval of 24 hours in order to ensure the water can infiltrate sufficiently.

2.3 Sensor layout

At the center of the left track, dynamic earth pressure and acceleration sensors are placed at 0, 0.6, 1.5, 2.5, 3.5 m and 4.5 m below the top surface of subgrade. At the position of 0.5 m and 1.5 m offset from the center of the left track, two dynamic earth pressure and acceleration sensors are respectively placed at the top and the bottom of subgrade. 10 testing positions are set on the section, and the layout of the sensors are shown in Fig.1.

2.4 Factors affecting the test

The test results are affected by sensor type, measuring range, accuracy, sensitivity and other factors. Combined with the characteristics and the types of sensors[9, 12], finally, JMYYJ-1503 m resistance dynamic earth pressure cell and CA-YD-117 piezoelectric type acceleration sensor (parameters are shown in Table 2) were selected and the data were collected by IMC acquisition system with 60 channels.

The sensor installation and data acquisition process are shown in Fig.2.

Table 1 Test section design parameters and conditions

Section	Filler category			Test items		Loading times	Service environment
	Top of subgrade	Bottom of subgrade	Embankment				
DK948+275	Group A filler	5% cement improved expansive soil	3% cement improved expansive soil	Dynamic earth pressure	Acceleration	4 million	Dry and immersion
DK948+175	Group A filler	Group A filler	Group B filler	Dynamic earth pressure	Acceleration	4 million	Dry

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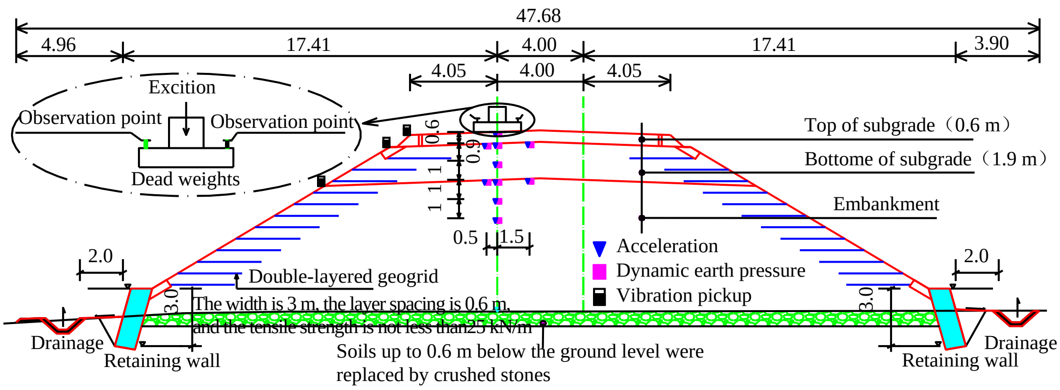
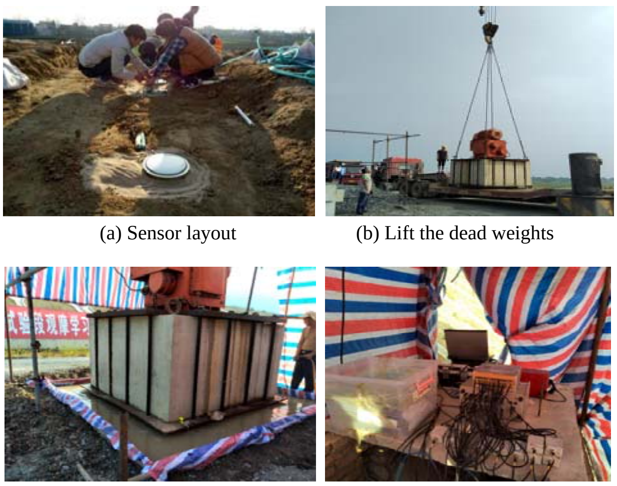


Fig. 1 Cross-sectional view of test component layout (unit: m)

Table 2 Main technical parameters of components

Type	Measuring range	Accuracy	Sensitivity	Applicable temperature/℃
JMYJ-1503 m	0.3 MPa	≤0.08% F.S	0.1 kPa	–25–60
CA-YD-117	≤20 g	—	100 mV/g	–40–80



(a) Sensor layout (b) Lift the dead weights

(c) Simulation of immersion process (d) Loading and testing

Fig. 2 Test procedures of field excitation

3 Analysis of test results

3.1 Reliability of test data

Table 3 shows the dynamic stress amplitudes on subgrade surface, obtained by different methods. It can be seen from Table 3 that the solution of Boussinesq theory is close to the results of model test, but they are both smaller than the results of excitation test in this paper. Meanwhile, the difference between the theoretical solution, model test result, and excitation test result decreases with the increase of axle load, and the result of excitation test is about 1.3 times of the model test result and theoretical solution for the case with an axle load of 30 t. The difference between the results of excitation test and model test is induced not only by the difference in test system, but also by the speed. The results of excitation test are basically consistent with results of driving test on Shuo-Huang railway under the same loading condition, and the error is about 6% when the axle load is 30 t, which is relatively small.

Table 3 Comparison of dynamic stress amplitudes on subgrade surface

Data Sources	Peak dynamic stress of subgrade under different axle loads (120 km/h)/ kPa			
	21 t	25 t	27 t	30 t
Excitation test	83.02	98.57	107.42	116.07
Model test (80 km/h) [9]	56.30 (23 t)	64.00	74.90	90.10
Theoretical solution [13]	—	73.90	82.70	88.60
Test results of Shuo–Huang line [10]	—	117.70	119.30	123.00

Figure 3 shows the attenuation curves of dynamic stress along the depth of subgrade. Although there are some differences in the test system, subgrade filler and speed between excitation test and model test, the attenuation law of dynamic stress along the depth of subgrade is highly consistent. In addition, the maximum attenuation coefficient of excitation test and model test reaches 0.22 within the range of subgrade (2.5 m), and the amount of attenuation is close to 80%.

According to Table 3 and Fig.3, both the peak value and attenuation curve can verify the reliability of the test results. The measuring range of dynamic earth pressure is 0.2 MPa, while the maximum dynamic stress of subgrade is 116.07 kPa, which is about 58.03% of the measureing range. This can ensure the sensors are in good working condition during the test.

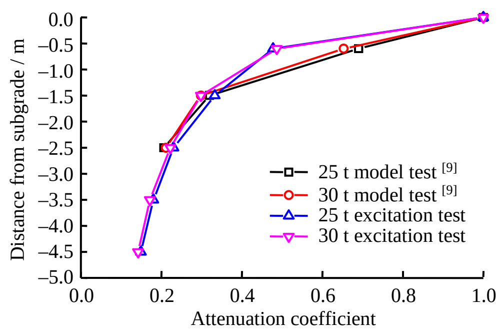


Fig. 3 Dynamic stress and acceleration test curves

3.2 Analysis of dynamic stress testing results

Figures 4 and 5 show the variation and attenuation curves of dynamic stress along the depth of subgrade under different loading conditions. It can be seen from Fig.4(a) that under dry condition the difference in dynamic stress of each loading case is mainly the amplitude on subgrade surface. When the axle load of passenger train is 21 t and the passenger train speeds are 120, 140, 160, 180 and 200 km/h, the corresponding dynamic stresses of subgrade are 83.02, 89.13, 92.61, 96.13 and 103.02 kPa, respectively, increasing by 7.4%, 3.9%, 3.8% and 7.2%. When the heavy-haul train runs at 120km/h and the axle loads are 25 t and 30 t, the dynamic stresses of subgrade are 98.57 kPa and 116.07 kPa, respectively, and the dynamic stress increases by 17.75% when the axle load increases from 25 t to 30 t. The comparison shows the dynamic stress amplitude of the heavy-haul train with a speed of 120 km / h and axle load of 25–30 t is about 1.1–1.3 times of that of passenger train with axle load of 21 t and a speed of 120– 200 km/h.

It can be seen from Fig.5(a) the attenuation coefficients of the top and bottom of the subgrade are 0.38–0.41 and 0.18–0.22, respectively at the dry state, and the attenuation amount can reach 40% and 80%, respectively. Even so, when the heavy-haul train runs at 120 km/h and the axle load is 25–30 t, there are still large dynamic stresses on the top and bottom surfaces of the subgrade, reaching 47.07–56.50 kPa and 22.67–25.80 kPa, respectively, which cannot be ignored.

It can be seen from Fig.4(b) that the obtained dynamic stress of improved expansive soil subgrade at the section of DK948+275 is close to that of the subgrade with coarse-grained filler at the section of DK948+175, and the difference is within 3 kPa. This indicates the dynamic stress transmitted to the subgrade is less affected by the site conditions. As the same filler were used for the top of the subgrade, the difference in dynamic stress at this position is small. However, the difference in dynamic stress is much larger near the bottom of the subgrade, especially at the filler interface between the top and bottom of subgrade. Compared with the coarse-grained filler subgrade, the dynamic stress at the interface of the cement improved expansive soil subgrade decreases by 8–10 kPa, and the same law is also shown in Fig.5(b). It shows that the cement improved expansive soil can reduce the dynamic response of the subgrade structure to a certain extent, which is also beneficial to ensure the working performance during its service life.

It can be seen from Fig.4(c) that the dynamic stress of subgrade is basically the same under dry and immersed conditions. This indicates that the excitation system is stable under the same loading condition. When the subgrade is immersed, the dynamic stress increases first and then decreases along depth, and the difference reaches the maximum at 1.5 m below the subgrade surface, which is about 1.02–1.28 times of the dynamic stress in dry condition. This is mainly due to the relative increase of water content, which makes the pore water pressure increase, the effective stress decrease, and the corresponding dynamic stress attenuation decrease. Moreover, the distribution value of dynamic stress along the depth and the attenuation coefficient (refer to Fig.5(c)) are not much different under the immersed and dry condition. It also shows cement improved expansive soil subgrade has good compaction and sealing properties, and the quality of subgrade filler is high, which is not easy to be affected by rainfall during service. In addition, the expansive soil subgrade of heavy-haul railway is designed with perfect drainage system. In case of extreme rainfall environment, the infiltration of rainfall into the subgrade is relatively small during service, which is far less compared to this test. Therefore, whether it is under dry or immersed condition, the difference in dynamic stress of cement improved expansive soil subgrade of heavy haul-railway is relatively small during service, and the variation is also insignificant.

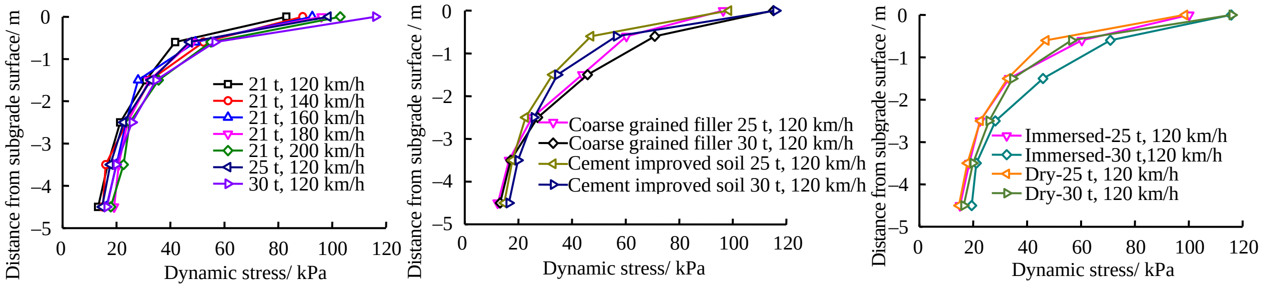
3.3 Analysis of acceleration

Figures 6 and 7 show the variation and attenuation curves of acceleration along the depth under different loading conditions. The method of data comparison and analysis is the same as those shown above.

It can be seen from Fig.6(a) and Fig.7(a) that the acceleration increases with the increase of train speed under dry condition. When the axle load of train is 21 t and the speeds are 120, 140, 160, 180 and 200 km/h, the acceleration amplitudes of subgrade are 1.3, 1.6, 2.5, 3.9 and 5.5 m^2/s, respectively, and the corresponding increasing rates are 23.08%, 92.31%, 200% and 323%, respectively. When the axle load increases from 25 t to 30 t, the acceleration amplitude of subgrade reaches 9.8 m^2/s for the same speed. It can be seen that the sensitivity of subgrade acceleration affected by speed is much higher than that of axle load. Compared with the measured dynamic stress, the consistency of acceleration attenuation curve along the depth is slightly lower under different test conditions.

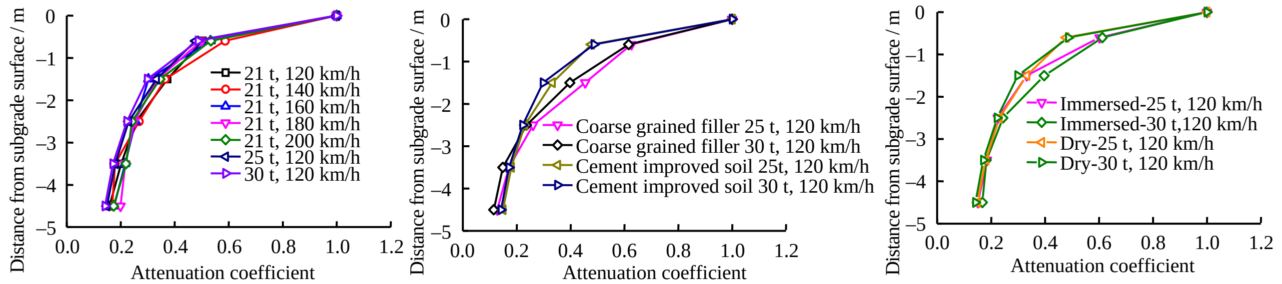
It can be seen from Fig.6(b) and Fig.7(b) that the accelerations of cement improved expansive soil section are smaller than those of the coarse-grained filler section, and the difference basically reaches the maximum at the interface between the top and the bottom of the subgrade, with the former being about 50% of the latter. Comparing the acceleration amplitudes of the two sections, it can be seen that the differences are 1.3 m/s^2 and 1.5 m/s^2 for passenger train speed of 120 km/h and the axle loads of 25 t and 30 t, respectively. Meanwhile, due to the small difference of excitation transfer at the top of the subgrade, the difference in acceleration is mainly considered to be induced by the difference in subgrade stiffness between two sections, which also indicates that cement improved expansive soil has certain advantages in reducing acceleration transfer.

It can be seen from Fig.6(c) and Fig.7(c) that the accelerations of subgrade of cement improved expansive soil under dry state and immersed state are nearly equal. The difference within the range of subgrade is relatively small, which is controlled within 0.5 m/s^2. This shows that the influence of immersion environment on acceleration is weak compared to that of dynamic stress.



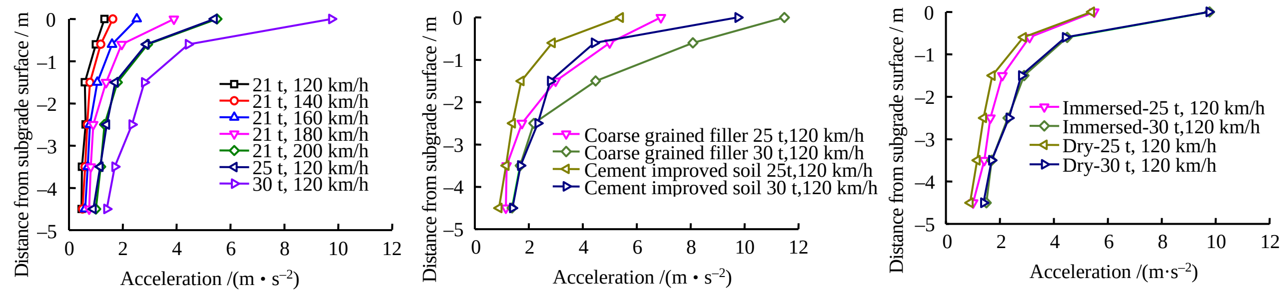
(a) Dry-cement improved expansive soil section (b) Comparison between dry improved soil and coarse grain (c) Comparison between dry and immersed improved soils

Fig. 4 Depth change curves of dynamic stress along roadbed under different test conditions



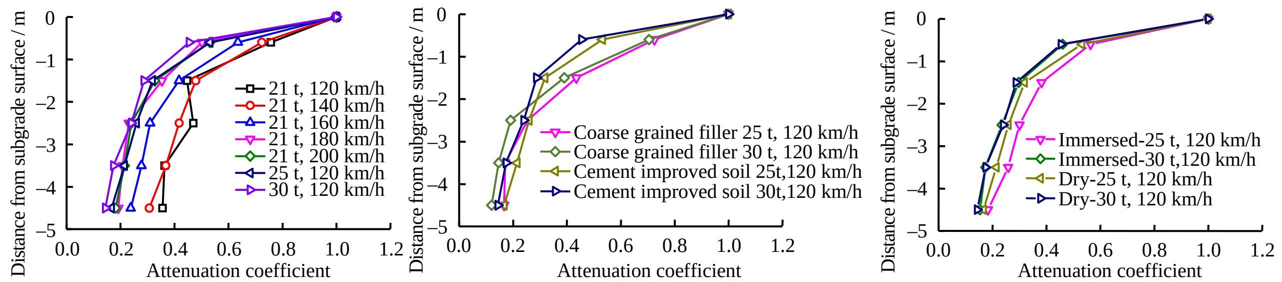
(a) Dry-cement improved expansive soil section (b) Comparison between dry improved soil and coarse grain (c) Comparison between dry and immersed improved soils

Fig. 5 Attenuation curves under different test conditions



(a) Dry-cement improved expansive soil section (b) Comparison between dry improved soil and coarse grain (c) Comparison between dry and immersed improved soils

Fig. 6 Depth change curves of acceleration along roadbed under different test conditions



(a) Dry-cement improved expansive soil section (b) Dry-comparison between improved soil and coarse grain (c) Comparison between dry and immersed improved soils

Fig. 7 Acceleration attenuation curves under different test conditions

4 Long-term dynamic stability analysis of immersed subgrade

4.1 Influence range of dynamic load

When the excitation acts on the subgrade, the dynamic stress is distributed both horizontally and vertically, and the vertical influence depth is the most concerned[8]. In this paper, the ratio of dynamic stress to static stress is used to discuss the vertical influence depth of dynamic stress (influence depth=dynamic-static stress ratio> 0.2) [13-16], as shown in Fig.8.

It can be seen from Fig.8 that the dynamic stress gradually decreases along the depth, while the static stress increases with the depth. According to the results of the excitation tests in this paper, the dynamic– static stress ratio at the depth of 2.5 m (0.33–0.44) is greater than 0.2. In addition, the dynamic-static stress ratios at the depth of 3.5 m and 4.5 m are 0.23–0.26 and 0.14–0.19, respectively. This indicates that the vertical influence depth reaches 3.5–4.5 m, which has exceeded the design thickness of subgrade(2.5 m (0.6 m+1.9 m)). Therefore, it is necessary to evaluate the dynamic stability of subgrade structure in service.

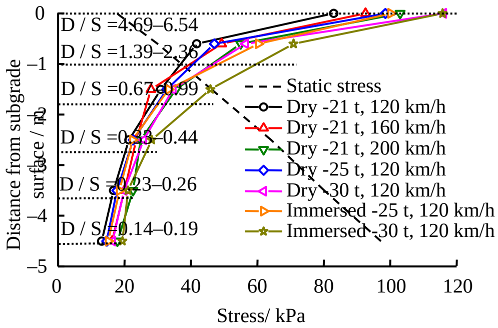


Fig. 8 Dynamic and static stress curves along with subgrade depth

4.2 Stability analysis of subgrade dynamic strength

In this paper, the stability of dynamic strength of subgrade is evaluated by means of critical dynamic stress method[12, 16]. When the dynamic stress of subgrade is lower than the critical dynamic stress of filler at the same position, the stable state is reached, otherwise it is the unstable state. Meanwhile, the dynamic stress required for the evaluation is obtained from the excitation tests in this paper. The critical dynamic stress of cement improved expansive soil filler is selected based on the author's previous research results[17], and the determination of critical dynamic stress of group A fillers on the top surface of subgrade refers to the existing study[18], the detail of which is shown in Table 4.

Table 4 Critical dynamic stress of fill (1 HZ)

Filler	Confining pressure / kPa	Critical dynamic stress/ kPa	Average / kPa
Remolded plain expansive soil[17]	30	22.3–31.5	26.90
	60	28.6–34.9	31.75
3% cement improved expansive soil[17]	15	151.2–185.7	168.45
	30	157.5–203.5	180.50
	60	182.3–233.1	207.70
5% cement improved expansive soil[17]	15	142.5–208.1	175.30
	30	148.3–233.5	190.90
	60	202.5–249.7	226.10
Group A coarse-grained filler[18]	15	100–125	112.50
	30	100–125	112.50
	60	125–150	137.50

Table 5 shows the comparison between the dynamic stress of subgrade obtained by excitation tests and critical dynamic stress of filler. It can be seen that the dynamic stress of subgrade is slightly higher under the immersed condition.

It can be seen from Table 5 that the dynamic stresses at the bottom and top of the subgrade and underneath the subgrade are lower than the critical dynamic stress at the corresponding position under different train loading conditions. The results show that the dynamic strength of subgrade is stable when 5% and 3% cement improved expansive soils are used as fillers for the bottom of subgrade of the heavy-haul railway and for the embankment below respectively.

Table 5 Comparisons of subgrade stress level with critical dynamic stress of fill

Depth/ m	Dynamic stress / kPa		Critical dynamic stress / kPa	Evaluation result
	25 t,120 km/h,	30 t,120 km/h		
0.0–0.6	60.3–100.2	70.9–115.8	257.0–380.0	Stable
0.6–2.5	22.5–60.3	28.2–70.9	148.8–233.1	Stable
2.5–4.5	15.1–22.5	19.4–28.2	142.5–249.7	Stable

4.3 Stability analysis of subgrade dynamic deformation

Figure 9 shows the cumulative deformation curve of subgrade versus number of cycles. It can be seen from Fig.9 that as the number of cycles increases, the cumulative deformation of subgrade develops rapidly, then slowly, and finally stays stable under cyclic excitation loading. The cumulative deformation mainly occurs during the first 1.5 million cycles, which is about 80% of the total deformation, and the cumulative deformation is limited within 5 mm. It shows that the compression deformation of cement improved soil subgrade is relatively small under the cyclic dynamic loading of heavy haul, and the dynamic deformation is at a stable state. The difference between the test results of cumulative deformation of cement improved expansive soil subgrade and the coarse-grained filler is small, which indicates that the strength and stiffness of expansive soil improved by cement are close to those of the coarse-grained filler.

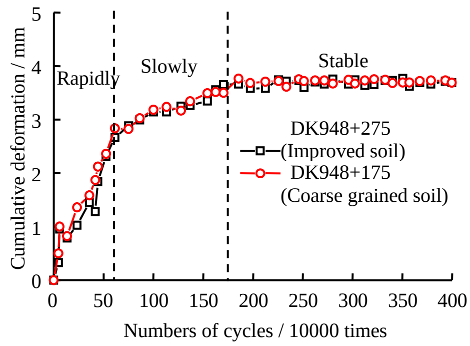


Fig. 9 Cumulative deformation of subgrade surface

5 Conclusions

Based on the engineering background of Hao–Ji heavy-haul railway, the field excitation test was carried out to explore the dynamic characteristics of cement improved expansive soil subgrade under water immersed environment. The main conclusions are as follows:

The results of field excitation test are compared with results obtained by theoretical calculation, field running test and full-scale model test of heavy-haul railway. The dynamic stress amplitude on subgrade surface measured by field excitation test is larger than those from indoor model test and Boussinesq theoretical solution. The error is relatively small compared with existing field driving test. Meanwhile, it is found that the attenuation law of dynamic stress along the depth is consistent with that of the model test, which shows that the dynamic characteristics of subgrade structure under the loading of heavy-haul train can be effectively simulated by the excitation test.

When the subgrade is immersed, the dynamic stress in the subgrade increases in an arc form along the depth. The difference in dynamic stress between the dry and immersed cases reaches the maximum at 1.5 m, and the dynamic stress of immersed subgrade is about 1.02–1.28 times of that of dry subgrade. However, the difference in acceleration is relatively small, the value of which is within 0.5 m/s^2. Meanwhile, there is no significant difference between the test results of dry subgrade and immersed subgrade. This indicates that cement improved expansive soil subgrade has good compaction and sealing properties, and its service life is less affected by rainfall environment.

Considering the test section, the critical dynamic stress is much greater than the measured one of the subgrade at the same location. The cumulative deformation of subgrade surface is controlled within 5 mm after 4 million cycles of on-site cyclic excitation, which indicates that the strength and deformation of subgrade are stable when 5% and 3% cement improved expansive soil are used as bottom subgrade and embankment filler respectively.

Through the field excitation test, the dynamic characteristics of the improved expansive soil subgrade of heavy-haul railway are explored under the immersed environment. The deficiency is the lack of consideration on the influence of material deterioration and other factors on dynamic characteristics of subgrade. Therefore, the long-term monitoring data can be used for further research at the later stage during the operation period.

References

[1] WANG Xin-zhi, CHEN Min, WEI Hou-zhen, et al. Experimental study on dynamic response of calcareous sand subgrade under vehicle load[J]. Rock and Soil Mechanics, 2018, 39(11): 4093–4101.

[2] LI Peng, LING Xian-zhang, ZHANG Feng, et al. Field testing and analysis of embankment vibrations induced by heavy haul trains[J]. Shock and Vibration, 2017, 1–14.

[3] LÜ Wen-qiang, LUO Qiang, LIU Gang, et al. Structural analysis and design method for subgrade bed of heavy haul railway[J]. Journal of the China Railway Society, 2016, 38(4): 74–80.

[4] FRYBA L. History of Winkler foundation[J]. Vehicle System Dynamics, 1995, 24: 7.

[5] KENNEY J T J, CALIF PASADENA. Steady-state vibration of beam on elastic foundation for moving load[J]. Journal of Applied Mechanics, 1954(11): 359–364.

[6] ZHAI Wan-ming, CAI Cheng-biao, WANG Kai-yun. Dynamics assessment method for design of high speed railway plan and profile[J]. High Speed Railway Technology, 2010, 1(1): 1–5.

[7] CHEN Yun-min, BIAN Xue-cheng. The review of high-speed railway track foundation dynamics[J]. China Civil Engineering Journal, 2018, 51(6): 1–13.

[8] MEI Hui-hao, LENG Wu-ming, NIE Ru-song, et al. Random distribution characteristics of peak dynamic stress on subgradesurface of heavy haul railway[J]. Rock and Soil Mechanics, 2019, 40(4): 1603–1613.

[9] LENG Wu-ming, MEI Hui-hao, NIE Ru-song, et al. Full-scale model test of heavy haul railway subgrade[J]. Journal of Vibration and Shock, 2018, 37(4): 1–6, 18.

[10] SHI Bin. Study on the impact of heavy-haul freight transportation on railway facilities and strengthening measures[D]. Shijiazhuang: Shijiazhuang Tiedao University, 2018.

[11] WANG Ying-ying. Research on deformation characteristics of roadbed induced by rainfall infiltration and traffic loads[D]. Nanchang: East China Jiaotong University, 2016.

[12] HOOPUTRA H, ESE H, ELL H, et al. A comprehensive failure model for crashworthiness simulation of aluminum extrusions[J]. International Journal of Crashworthiness, 2004, 9(5): 499–463.

[13] WANG Liang-liang, YANG Guo-lin, FANG Yi-he, et al. In-situ tests on dynamic character of fully-enclosed cutting subgrade of high-speed railways in expansive soil areas[J]. Chinese Journal of Geotechnical Engineering, 2014, 36(4): 640–645.

[14] YANG Guo-lin, QIU Ming-ming, HE Xu, et al. Tests for working property of water-proof layer of cutting subgrade in expansive soil under vibrating load[J]. Journal of Vibration and Shock, 2016, 35(5): 1–7, 20.

[15] SU Qian, BAI Hao, HUANG Jun-jie, et al. In-situ tests on long-term dynamic characteristics of low embankment on rigid foundation[J]. Chian Civil Engineering Journal, 2011, 44(Suppl.1): 147–151.

[16] XIAO Shi-wei, LEI Chang-shun. Loading characteristics and dynamic response analysis of subgrade for heavy haul rilway[J]. Journal of Railway Enggineering Society, 2014(4): 51–56.

[17] SHANG Yong-hui, XU Lin-rong, HUANG Ya-li, et al. Experimental study on the dynamic features of cement-stabilized expansive soil as subgrade filling of heavy haul railway[J]. Journal of Engineering Science and Technology Review, 2017, 10(6): 136–145.

[18] MEI Hui-hao, LENG Wu-ming, LIU Wen-jie, et al. Experimental study on accumulative plastic strain of coarse grained soil filling material under continuous dynamic load[J]. Journal of the China Railway Society, 2017, 39(2): 119–126.