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Research Article

Vibration Behavior and Reinforcement Effect Analysis of the Slab Track-Subgrade with Mud Pumping under Cyclic Dynamic Loading: Full-Scale Model Tests

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Mud pumping occurring in the subgrade bed can gradually deteriorate the performance of the slab track-subgrade, negatively affecting the comfort and safety of high-speed railway. In this paper, a full-scale model of the slab track-subgrade was established to analyze the vibration behavior of the model in normal condition and before and after mud pumping reinforced, as well as the reinforcement effect of mud pumping using low-viscosity epoxy resin. The research results show that the vibration acceleration and displacement and the settlement of the model in normal condition stabilize gradually with the increasing number of loading cycles. Under the upper layer of the subgrade bed saturated by water, mud pumping occurs in the subgrade bed as soon as the second loading stage reaches to 3.0×10^4 cycles, and the deterioration of mud pumping increases gradually with the increasing number of loading cycles. Moreover, a large volume of slurry composed of water and fine particles is squeezed out of the subgrade bed after the model is subjected to the second cyclic loading stage of 2.0×10^6 cycles, causing contact loss between the concrete base and the subgrade bed, which makes the acceleration and displacement of the concrete base increase abnormally compared with the model in normal condition, as well as the cumulative settlement of the subgrade bed. The model with significant mud pumping in the upper layer of the subgrade bed was reinforced by using low-viscosity epoxy resin. This effectively controlled the abnormal acceleration and displacement of the concrete base and restored the support capability of the subgrade bed for the concrete base of the slab track structure.

1. Introduction

The slab track structure, which has several advantages of high stability, high geometric regularity, uniform track stiffness, and low maintenance, has been widely applied in the construction of high-speed railways in a number of countries and regions [1–4]. The Shinkansen in Japan, and the Shanghai-Ningbo, Shanghai-Hangzhou, and Shijiazhuang-Taiyuan high-speed railway in China are extensively paved with the slab track (Figure 1). In order to control the temperature effects of the slab track structure on the subgrade section, the track slab is designed as a unit plate type, and the concrete base has an expansion joint at regular intervals along the line, such as the regular intervals of CRTS I slab ballastless track are 20.108 m. The expansion joint of the concrete base is filled with waterproof materials to prevent water from penetrating into the subgrade bed.

The slab track-subgrade consisting of the slab track superstructure and the geotechnical substructure has obvious structural layer features. As well as strictly controlling the compaction quality of the graded crushed stone used in the upper layer of the subgrade bed, some waterproof measures including the expansion joint of the concrete base and the joint gap between the concrete waterproof layers on the subgrade surface filled with the waterproof materials must be performed to ensure the that the slab track-subgrade has long-term stability. However, owing to the aging of the sealed materials in the expansion joint and the joint gap,

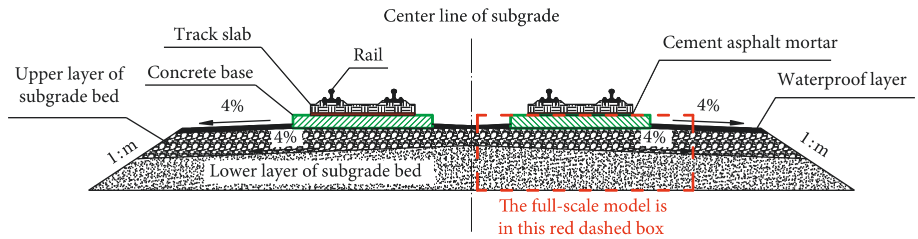


Figure 1: The cross section profile of the slab track-subgrade close to the expansion joint of the concrete base.

some cracks are generated in the expansion joint of the concrete base, leading to rainwater permeating into the subgrade bed. The graded crushed stone in the upper layer of the subgrade bed is subjected to the repeated combined effects of water and dynamic stress when the high-speed railway train is moving across the slab track-subgrade. Therefore, over time, there have been some cases of mud pumping occurring in the slab track-subgrade [5, 6], as shown in Figure 2. The authors have carried out a field investigation to analyze the characteristics and reasons for mud pumping occurring in the subgrade bed prior to this research. The survey results show that mud pumping only occurs in areas with the expansion joint of the concrete base, where some cracks are generated to supply paths for rainwater permeating into the subgrade bed. If rainwater cannot be quickly drained out of the upper layer of the subgrade bed after rainwater permeates into the upper layer of the subgrade bed through the cracks, the upper layer of the subgrade would be affected by combined effect of water and dynamic stress under the high-speed trains. Under the high-speed trains, a repeated pumping action occurs in the contact layer between the concrete base and upper layer of the subgrade bed when water continues to gather in there, leading to a large amount of fine particles in the upper layer of the subgrade bed being carried out, as shown in Figure 2. Due to a large amount of fine particles being carried out, contact loss formed between the upper layer of the subgrade bed and the concrete base can detrimentally affect the longitudinal stiffness of the slab track-subgrade.

At present, many researchers have conducted laboratory and field tests to analyze the pore water pressure development in the contact layer between the pavement and subbase and the ballast track bed, as well as the influence of the excess pore water pressure on fine particle migration [7–12]. Furthermore, various remedial measures are proposed to reinforce mud pumping in the highway subgrade and ballast track [13–16]. However, only a few researchers focus on mud pumping in the slab track-subgrade. In these studies, Zhang et al. and Liu et al. [5, 6] performed several field investigations and on-site tests to analyze the characteristics of mud pumping in the slab track-subgrade of high-speed railway, as well as the vibration characteristics of the slab track-subgrade with mud pumping, including acceleration, velocity, and displacement. Cai et al. [17] analyzed mud pumping mechanism of subgrade surface layer in slab ballastless track zone based on the physical model tests and studied the dynamic responses between the base plate and the subgrade surface layer in different conditions of gap length and gap size based on numerical modeling. Pham et al. [18] carried out large-scale triaxial tests to research dynamic characteristics and mud pumping mechanism of graded gravel used as the upper layer of subgrade bed of the slab track. In a word, the issues of mud pumping occurring in the slab track-subgrade have yet to attract the attention of researchers, which is not the same as the settlement and vibration of the slab track-subgrade induced by high-speed trains which attracted wide concern [19–22]. Because mud pumping occurring in the slab track-subgrade of high-speed railway has not been so serious formerly, it begins to be prevailing in recent years. Yet, mud pumping of the slab track-subgrade has not attracted sufficient attention. Especially, there is no research on the internal characteristics of mud pumping occurring in the subgrade bed and the distribution of injected reinforcement materials under the slab track, because the slab track is not allowed to lift in practice. The study on vibration behavior of the slab track-subgrade induced by mud pumping occurring in the subgrade bed under high-speed trains is not sufficient. Besides, the operational management departments of high-speed railway currently lack the reinforcement experience and existing specifications for reinforcing mud pumping of the slab track-subgrade.

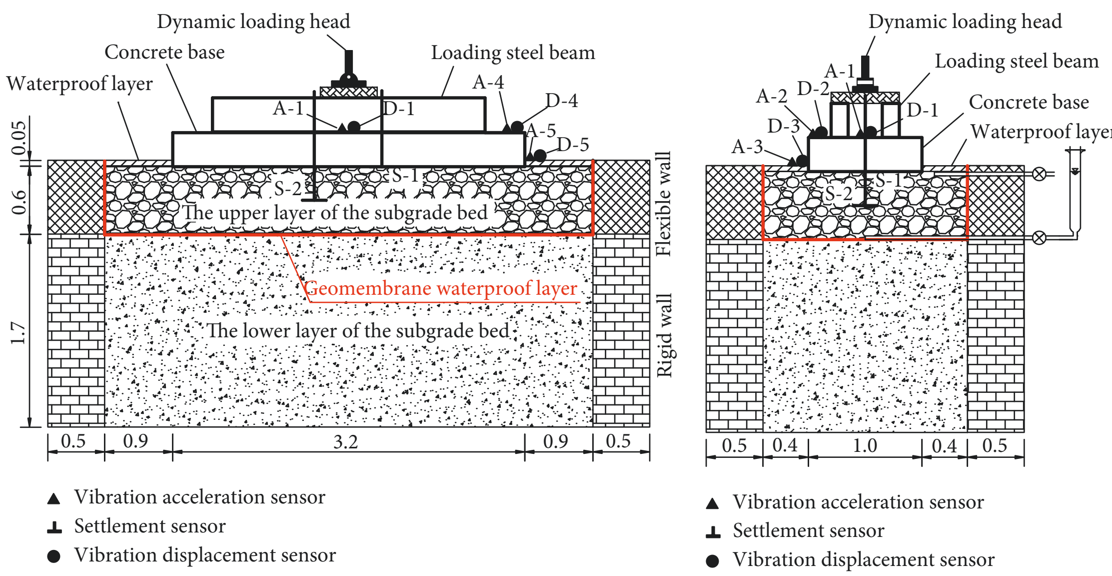
Therefore, in this paper, a full-scale model of the slab track-subgrade was established to analyze the characteristics of mud pumping occurring in the slab track-subgrade and the dynamic behavior of the slab track-subgrade with mud pumping and after mud pumping reinforcement under cyclic dynamic loading, as well as the reinforcement effect based on the injection of low-viscosity epoxy resin.

2. Full-Scale Model Setup

2.1. Experimental Schemes. The full-scale model of the slab track-subgrade within red dashed box in Figure 1 was established, as shown in Figure 3. The horizontal width and longitudinal length of the model are 5.0 m and 1.8 m, respectively. This research mainly focused on the upper layer of subgrade bed and the concrete base of the slab track, as well as the interaction between them under the cyclic loading. Therefore, the structural optimization for the slab track structure was performed. The full-scale model did not need to build the interlayer cement asphalt mortar and track slab. Besides, the longitudinal length of the prototype concrete base is 20.0 m. The indoor model is difficult to build such a long concrete base. According to the characteristics of mud pumping in the slab track-subgrade during operation

(a) (b)

Figure 2: Mud pumping occurring in the slab track-subgrade.



(a) (b)

Figure 3: The full-scale model: (a) cross section and (b) longitudinal section profiles (units in meter).

and the dimensions of the model tank, the concrete base built in this full-scale model is only 1.0 m, as shown in Figure 3(b). Moreover, the rigid wall is designed around the lower layer of subgrade bed. In order to reduce the influence of the boundary conditions on the tests, around the upper layer of subgrade bed concerned particularly was designed into flexible wall.

According to Chinese high-speed railway specification [23], the upper and lower layers of the subgrade bed are conventionally filled with the graded crushed stone and group A or B packing, respectively. This paper mainly focuses on the interaction between the concrete base and the upper layer of the subgrade bed when the upper layer of the subgrade bed is affected by water. During high-speed railway operation, rainwater permeates into the subgrade bed through the cracks in the expansion joint of the concrete base. If the fine particle content of the graded crushed stone is more than specified value of Chinese high-speed railway specification or the permeability coefficient of the upper layer of subgrade bed is less than 5×10^{-5} m/s [23], some of the rainwater will gather in the graded crushed stone in the upper layer of subgrade bed, even which saturates the graded crushed stone in some areas of upper layer of subgrade bed under the slab track for some time. When the high-speed train moves across the section at high speed, the graded crushed stone affected by water under the slab track may produce mud pumping, as shown in Figure 2. According to Su et al., [5, 6, 18, 24] carried out several field investigations on the characteristics and reinforcement method of mud pumping of the slab track-subgrade and performed large-scale triaxial tests for graded crushed stone with different water content, Cai et al. [17] investigated mud pumping mechanism of subgrade surface layer in slab ballastless track zone, and Duong et al. [12] studied the mud pumping and interlayer creation phenomena in railway substructure; mud pumping occurs in the graded crushed stone subjected to cyclic dynamic loading when the graded crushed stone is in the near saturated conditions. In other words, the graded crushed stone with high water content, which is near saturated state, can produce mud pumping under cyclic dynamic loading. However, the critical water content parameter is uncertain or different. Therefore, in this paper, the upper layer of subgrade bed was designed into saturated state to analyze the mud pumping. So, a waterproof layer composed of geomembrane was installed between the upper and lower layers of the subgrade bed and wrapped around the side of the upper layer of the subgrade bed. The concrete base was placed on the subgrade surface. The subgrade surface outside of the concrete base was paved by the concrete waterproof layer.

According to a variety of on-site tests, model tests, and numerical analysis on the dynamic soil pressure of subgrade bed under the slab track [20–22, 25–27], the dynamic soil pressure at the subgrade surface under high-speed trains is mainly in the range of 13–30 kPa, which is less than code value 100 kPa [23]. Indoor and outdoor model tests usually take the actual dynamic soil pressure to apply on the subgrade surface rather than code value. Therefore, the loading system in this research was controlled to output a sine wave load with an upper limit of 96 kN and frequency of 5 Hz applying on the loading steel beam. Under the sine wave load, the dynamic soil pressure at subgrade surface is mainly in the range of 25–30 kPa.

The cyclic dynamic loading applied to the model was divided into three stages:

(1) In the first stage, 2×10^6 cycles were applied to the loading steel beam to simulate the slab track-subgrade put into operation after the full-scale model was established. The graded crushed stone was in optimum water content.

(2) In the second stage, the upper layer of the subgrade bed was injected with water and immersed for 48 h to make the graded crushed stone in saturation after the first stage was completed. Then, the full-scale model was loaded for another 2×10^6 cycles. The main item in this stage was to simulate the effect of water on the upper layer of the subgrade bed under the dynamic loads.

(3) In the third stage, if mud pumping occurs in the upper layer of the subgrade bed during the second stage, the model was reinforced using low-viscosity epoxy resin after water drained out. Finally, after reinforcement, further 2×10^6 cycles were applied. In this stage, the upper layer of subgrade bed was not injected with water again.

2.2. Filling and Control of the Subgrade Bed. In this research, the upper and lower layers of the subgrade were filled by the graded crushed stone and group A packing, respectively. According to Chinese specifications [28, 29], a variety of sieve tests were conducted to obtain the nonuniform coefficient and curvature coefficients of the graded crushed stone and group A packing (Table 1), as well as the grain-size distribution curve of the graded crushed stone, as shown in Figure 4. The test results show that the nonuniform coefficients of the graded crushed stone and group A packing are greater than 15, and their curvature coefficients are between 1 and 3. Besides, the grain-size distribution of the graded crushed stone can meet the requirements of the Code for Design of High Speed Railway (China) [23]. Therefore, the graded crushed stone and group A packing can be used as filler for the upper and lower layers of subgrade bed in this full-scale model, respectively.

Table 1: Gradation indexes of the graded crushed stone and the group A packing.

Gradation indexes	Graded crushed stone	Group A packing
Nonuniform coefficient C_u	27.80	22.47
Curvature coefficient C_c	1.05	2.05

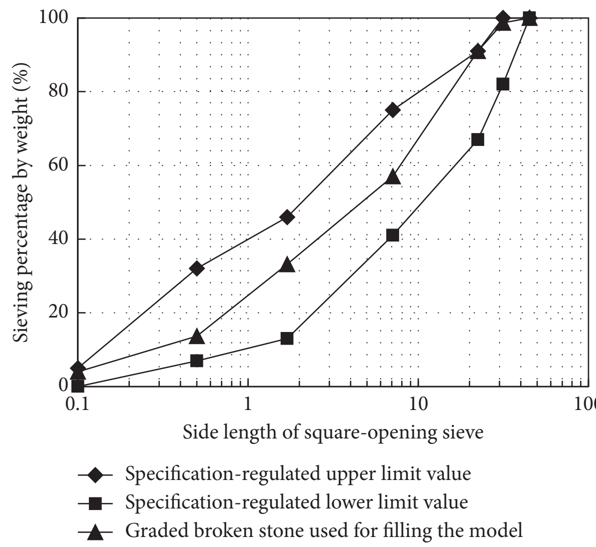


Figure 4: Grain-size distribution curves of the graded crushed stone.

The graded crushed stone and group A packing with optimum water content were used to fill the upper and lower layers of the subgrade bed of the model, respectively. In the filling process of the model, the compaction quality of the subgrade bed in this full-scale model was strictly controlled according to Chinese specifications for high-speed railway [23, 29].

2.3. Test Items. The main test items included vertical vibration acceleration and displacement of the concrete base plate and the subgrade surface, as well as the cumulative settlement of the upper layer of the subgrade bed. All the test sensors were installed at the relevant test positions, as shown in Figure 3. During all the loading stages, all sensor signals were collected by a dynamic acquisition system and converted into the vibration acceleration and displacement and settlement datum through amplification, filtering, and sampling processes of voltage signals of all the sensors based on the Fourier transform principle. The corresponding

(a)

(b)

FIGURE 5: A large amount of slurry squeezed out of the subgrade bed.

process software is installed in the dynamic acquisition system in computer.

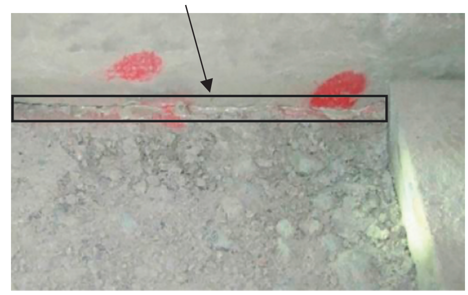
3. Mud Pumping Characteristics of the Slab Track-Subgrade Saturated by Water

In the second loading stage, mud pumping occurs in the saturated upper layer of the subgrade bed once 3.0×10^4 cycles have been applied. After that, mud pumping gradually deteriorates with the increasing number of loading cycles. After the second loading is completed, a large amount of slurry is squeezed out of the subgrade bed based on visual observation, as shown in Figure 5.

In order to analyze the internal characteristics of mud pumping in the upper layer of the subgrade bed, the concrete waterproof layer close to the concrete base was broken and excavated to the upper layer of subgrade bed after the second loading stage was completed, as shown in Figure 6. It was found that mud pumping only occurs at the top surface of the subgrade bed under the concrete base. There is one slurry layer between the upper layer of the subgrade bed and the concrete base.

In this full-scale model, the gradation indexes and compaction quality of the graded crushed stone used to fill the upper layer of the subgrade bed meets the Chinese specifications for high-speed railway. But significant mud pumping still occurs seriously in the upper layer of the subgrade bed under the cyclic dynamic loading, when the graded crushed stone in the upper layer of the subgrade bed is saturated. These results indicate that, even if the graded crushed stone for the upper layer of the subgrade bed meets the requirements of the current specifications of high-speed railway, if water permeates into the upper layer of the subgrade bed under the slab track structure and cannot be quickly drained out, mud pumping will still occur in the upper layer of the subgrade bed under long-term repeated train loads. Thus, except for strictly controlling the performance and compaction quality of the graded crushed stone in the upper layer of the subgrade bed, greater action should be placed on preventing water from permeating into the subgrade bed. Additionally, the optimized design performed for the subgrade bed makes it have the function of rapid drainage in the future. With the help of the function of rapid drainage, water can be quickly drained out of the upper layer of the subgrade bed once water permeates into the subgrade bed again through the cracks in the expansion joint of the concrete base. The aim is to protect the graded crushed stone in area near the concrete base of the slab track structure from being affected by water for a long time.

(a)



(b)

FIGURE 6: The internal characteristics of mud pumping between the subgrade bed and the concrete base.

4. Reinforcement Method for Mud Pumping

4.1. Materials. Mud pumping occurring in the slab track-subgrade can cause contact loss between the subgrade bed and the concrete base and intensify the vibration of the slab track structure [5, 6, 30]. Therefore, mud pumping must be immediately reinforced to ensure the operational comfort and safety. Nighttime possessions of high-speed railway in

China conventionally last 4 h, and the maximum time between the beginning of maintenance and the first train after a recovery line is usually less than 6 h. For this reason, the cured materials used for reinforcing mud pumping must have characteristics of early strength, low expansion rate, and good water stability. In this research, low-viscosity epoxy resin, which is composed of two components and has been applied in the actual project of mud pumping reinforcement, was used for strengthening the model with mud pumping after the second loading stage.

Based on a variety of laboratory tests according to the specifications for low-viscosity epoxy resin [31–35], the mixed slurry performance parameters of low-viscosity epoxy resin and the cured material properties of the mixed slurry were obtained and are listed in Tables 2 and 3, respectively.

All performance indices of the mixed slurry and cured material of low-viscosity epoxy resin meet the requirements proposed by the design and management departments of high-speed railway. Especially when the cured materials were maintained for 2 h, the compressive strength of the cured materials is 19 MPa, which is greater than the required indicators and meets the requirements of early strength for the cured material. Therefore, low-viscosity epoxy resin can be used to reinforce mud pumping in the full-scale model.

4.2. Reinforcement Procedures. After the second loading stage was completed, visual observation of the full-scale model was conducted to analyze the mud pumping characteristics before reinforcement. Then, mud pumping in the model was reinforced according to the procedures outlined below.

4.2.1. Drilling for the Injected Holes and Drain Holes. The injected holes and drain holes of the full-scale model are shown in Figure 7. The diameters of both the injected holes and drain holes are 12 mm. The depth of the injected holes is 100 mm below the top surface of the subgrade bed, allowing the mixed low-viscosity epoxy resin to be injected into the upper layer of the subgrade bed and squeezing the mud pumping slurries out of the subgrade surface through the drain holes.

4.2.2. Installation of Injected Pipes. After the injected holes were cleaned up, the injected pipes were inserted into the injected holes. The gap between the injected hole and the injected pipe was sealed by quick-setting cement mortar with an initial coagulation time of 10–15 min.

4.2.3. Injection of the Mixed Epoxy Resin. The mixed epoxy resin was injected into the upper layer of the subgrade bed under the concrete base using low-pressure control grouting equipment. The injection procedures were strictly followed from the center to the edge of the concrete base, as shown in Figure 7. The maximum injected pressure of each hole is not beyond 0.2 MPa by controlling the grouting equipment. In the injected process of the model, the concrete base was measured to avoid being lifted. The full-scale model after reinforcement is shown in Figure 8.

Table 2: The major performance parameters of the mixed slurries.

Test item	Required indicators	Detection value
Slurry density (kg/m^3)	>1000	1060
Viscosity (mPa)	≤100	76
Gelation time (min)	≤30	21

4.2.4. The Third Loading Stage Applied to the Model. After the mixed slurries were injected into the model cured for 2–4 h, the third loading stage was applied to the full-scale model.

5. Vibration and Settlement of the Slab Track-Subgrade in Normal Condition and Mud Pumping and after Reinforcement

5.1. Vertical Vibration Acceleration. Under cyclic loading stages, the variation of the vertical vibration acceleration of the full-scale model of the slab track-subgrade with the number of loading cycles are shown in Figure 9.

When the upper layer of the subgrade bed is in normal condition, the vertical vibration acceleration stabilizes gradually after 8.0×10^5 cycles, as shown in Figure 9(a). After the first loading stage was completed, the graded crushed stone in the upper layer of the subgrade bed was saturated using water. Then, under the second loading stage, mud pumping begins to occur in the model after 3.0×10^4 cycles. Moreover, mud pumping in the upper layer of the subgrade bed deteriorates gradually with the increasing number of loading cycles, causing a large volume of slurries composed of water and fine particles being squeezed out of the subgrade bed. At the same time, the vertical vibration acceleration of the concrete base increases quickly, as shown in Figure 9(b). However, the vertical vibration acceleration of the subgrade surface close to the concrete base decreases slightly with the number of loading cycles.

After the model with mud pumping in the upper layer of the subgrade bed was reinforced, the vertical vibration accelerations remain stable under the third loading stage, as shown in Figure 9(c). The stable value of the vertical vibration acceleration of the model after reinforcement is approximately equal to that of the model in the first loading stage.

After 5.0×10^5 cycles in each loading stage, the time-history curves of the vertical vibration acceleration of test points A1 at the concrete base center and A3 at the subgrade surface are shown in Figures 10 and 11. While the upper layer of the subgrade bed is in the normal and mud pumping states and the state after mud pumping reinforcement, the average vertical vibration acceleration amplitudes of the test point A1 in three seconds are 0.332, 0.582, and 0.280 m/s^2, respectively, and those of the test point A3 are 0.146, 0.050, and 0.145 m/s^2. The average value ratios of the vertical vibration acceleration amplitude of the test points A1 to A3 are 2.27 : 1, 11.64 : 1, and 1.93 : 1, respectively. Obviously, the

Table 3: The major mechanical properties of the cured materials.

Test item	Required indicators and cured time	Detection value
Tensile strength (MPa)	≥6 (2 h)	8
	≥10 (24 h)	13
	≥15 (7 d)	18
Compressive strength (MPa)	≥15 (2 h)	19
	≥20 (24 h)	28
	≥30 (7 d)	39
Elongation at break (%)	≥2 (7 d)	4.6
Shrinkage ratio (%)	≤2 (7 d)	1.2
Adhesive strength (MPa)	≥3 (7 d)	5.3

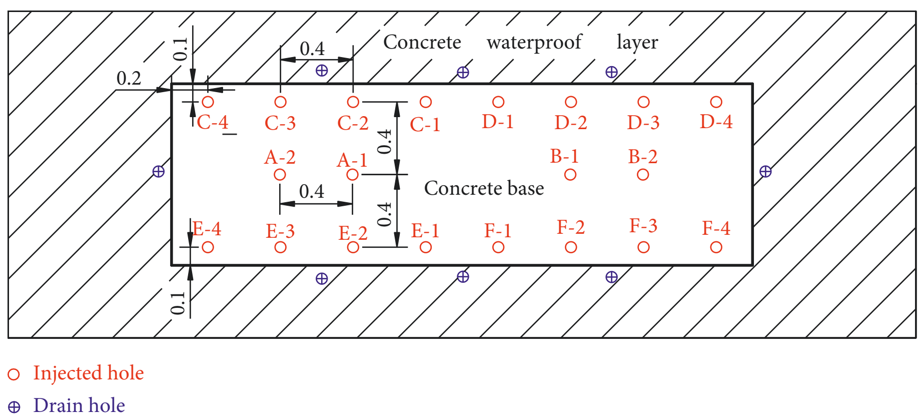


Figure 7: The layout of the injected holes and drain holes of the model.

(a) (b) (c)

Figure 8: The full-scale model with mud pumping after reinforcement.

vibration acceleration ratio of the concrete base to the subgrade surface under the upper layer of the subgrade bed producing mud pumping is much greater than that of the upper layer of the subgrade bed in normal condition. After mud pumping in the upper layer of the subgrade bed was reinforced, the vibration acceleration ratio of the model is basically equal to that of the model in normal condition.

Based on the combination of above vibration acceleration and mud pumping characteristic, it indicates that the deterioration of mud pumping in the subgrade bed can significantly intensify the vibration of the slab track structure, due to contact loss between the concrete base and the upper layer of the subgrade bed formed by a large amount of fine particles being squeezed out. Besides, the reinforcement

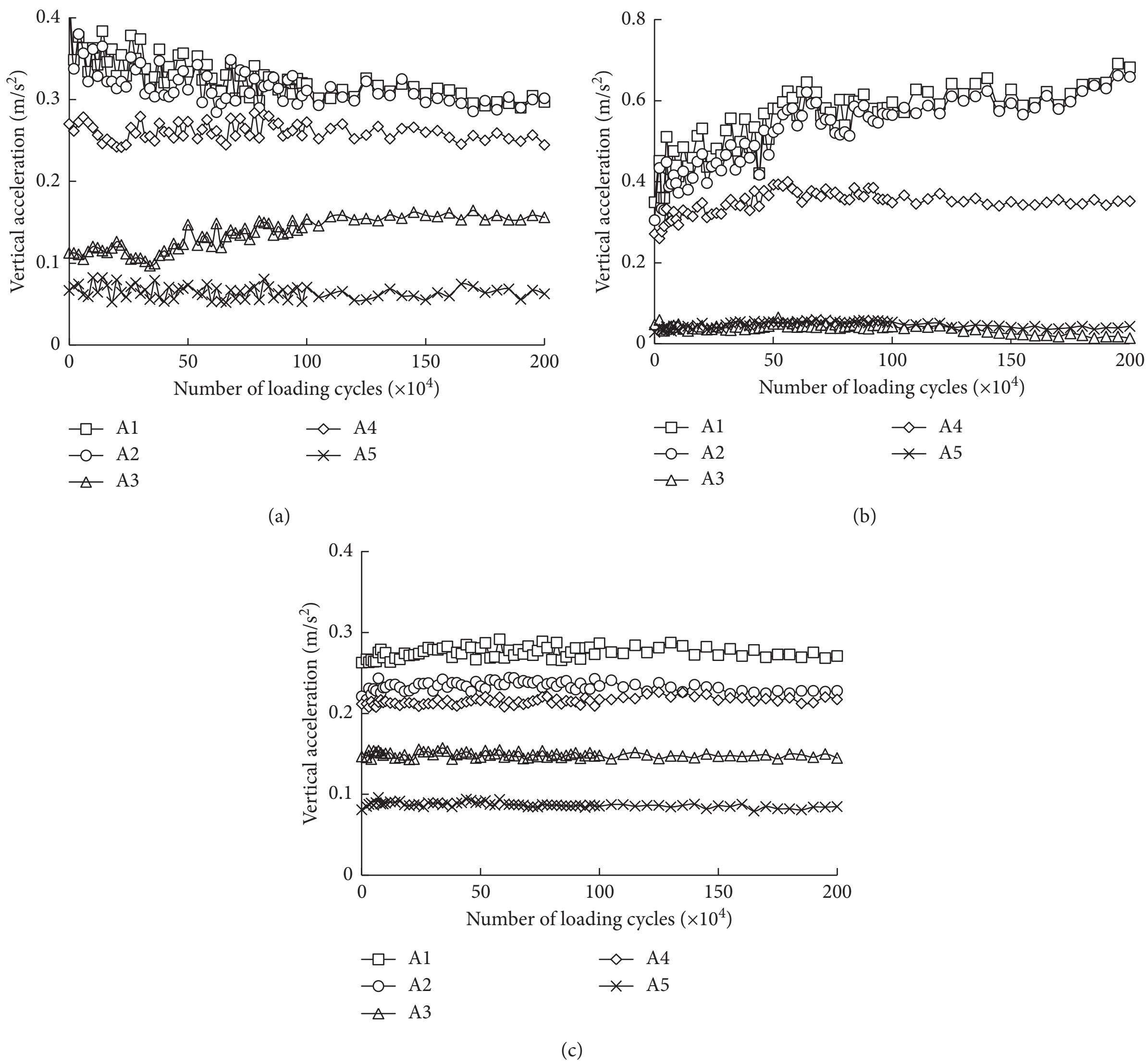


Figure 9: The variation of vertical vibration acceleration of the model with the number of loading cycles. (a) The upper layer of the subgrade bed in normal condition (stage 1). (b) The upper layer of the subgrade bed in saturation (stage 2). (c) The model after mud pumping reinforcement (stage 3).

procedures based on the injection of low-viscosity epoxy resin for mud pumping in the subgrade bed under the concrete base can control effectively the abnormal vibration of the slab track-subgrade in this research.

5.2. Vertical Vibration Displacement. When the upper layer of the subgrade bed in this full-scale model is in normal condition, saturation condition, and after mud pumping reinforcement condition, the relationships between the vertical vibration displacement of the model and the number of loading cycles are shown in Figure 12.

Figure 12(a) shows that the vertical vibration displacement of the model gradually stabilizes with the increasing number of loading cycles when the upper layer of the subgrade bed is in normal condition. When the graded crushed stone in the upper layer of the subgrade bed is saturated, the vertical vibration displacement of the concrete base increases quickly under the cyclic dynamic loading, as shown in Figure 12(b). And the vertical vibration displacement of the subgrade surface close to the concrete base decrease slightly. After the second cyclic dynamic loading stage is completed, the maximum vertical vibration displacement of the concrete base is 0.55 mm at the center, which is 2.29 times that of the upper layer of the subgrade bed in normal condition under the first cyclic dynamic loading. Under the third cyclic dynamic loading stage, the vertical vibration displacement of the model after reinforcement can stabilize gradually, as shown in Figure 12(c).

In this research, the displacement of D3 point in normal condition (stage 1) is larger than that of D4 point while in saturation condition (stage 2) and reinforcement condition (stage 3), the displacement of D3 point in normal condition

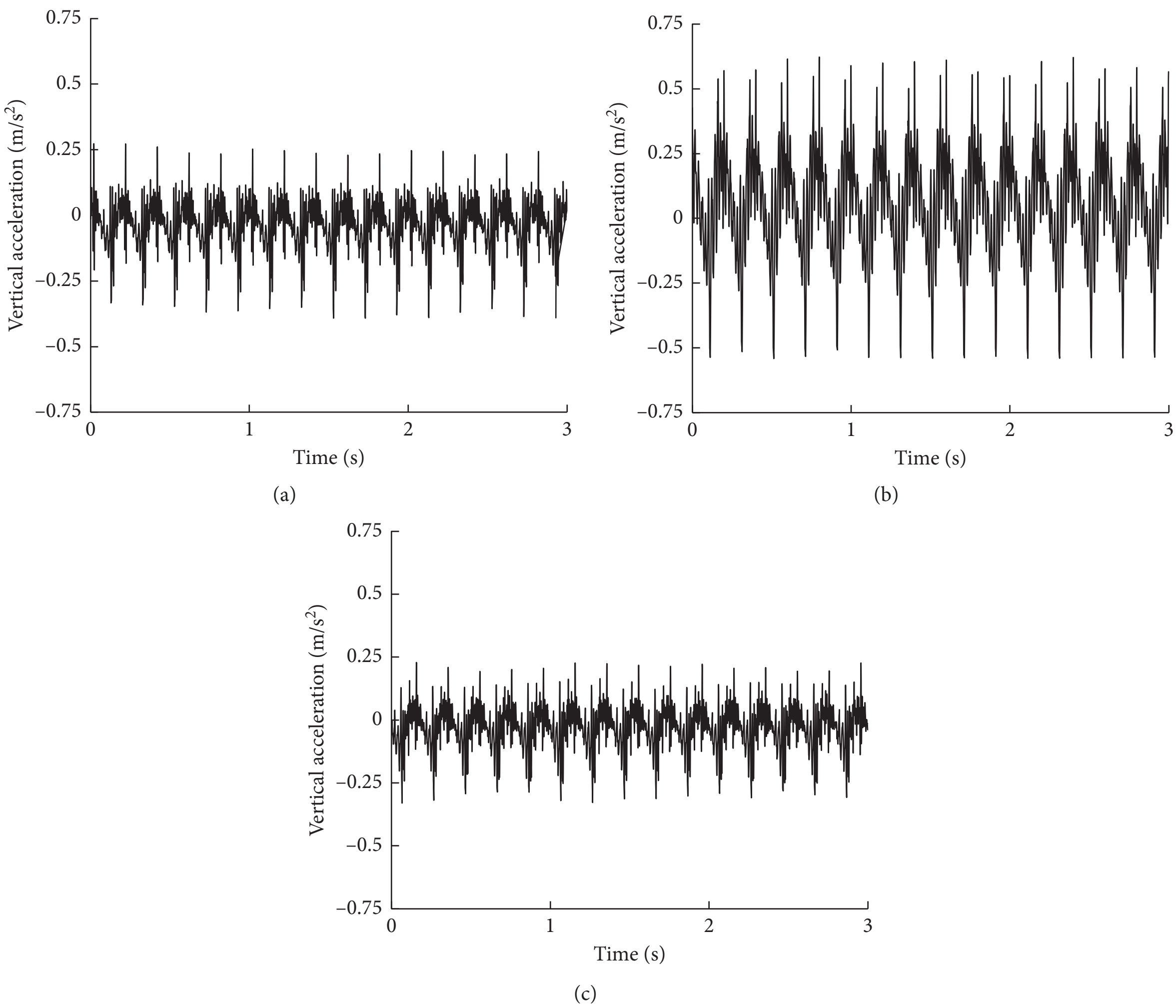


Figure 10: Time-history curve of vertical vibration acceleration of the test point A1. (a) The upper layer of the subgrade bed in normal condition (stage 1). (b) The upper layer of the subgrade bed in mud pumping (stage 2). (c) The model after mud pumping reinforcement (stage 3).

is smaller than that of D4 point, during each cyclic loading stage. This may be related to the strength of graded crushed stone, the stiffness of the upper layer of subgrade, and the stiffness of the concrete base. Especially, the strength of graded crushed stone and the stiffness of the upper layer of subgrade are significantly affected by water. But the reasons for the relationship between D3 point and D4 point are not analyzed in this research.

The reasons for the increase of the vibration of the concrete base under the cyclic dynamic loading are the decrease of the supported strength and stiffness of the subgrade bed to the concrete base caused by the upper layer of the subgrade bed being saturated and a large amount of fine particles being squeezed out of the subgrade bed by mud pumping. Furthermore, the reinforcement procedures for mud pumping in the upper layer of the subgrade bed can restore the supported capability of the subgrade bed to the concrete base so that the vibration displacement of the concrete base remains stable under the third cyclic dynamic loading.

Besides, the vibration of the concrete base on the mud pumping area increases abnormally with the deterioration of mud pumping in the upper layer of the subgrade bed, which affects the operational comfort and safety. Therefore, mud pumping once occurring in the subgrade bed should be reinforced as quickly as possible to ensure the longitudinal stiffness uniformity of the slab track-subgrade.

5.3. Cumulative Settlement of the Subgrade Bed. When the upper layer of the subgrade bed is in the normal and saturation states and the state after mud pumping reinforcement, the relationship between the cumulative settlement of the subgrade bed and the number of loading cycles is shown in Figure 13.

When the upper layer of the subgrade bed is in normal condition (during the first cyclic dynamic loading stage), the cumulative settlement at the surface and the middle position of the upper layer of the subgrade bed under the concrete base center stabilize gradually with the increasing number of

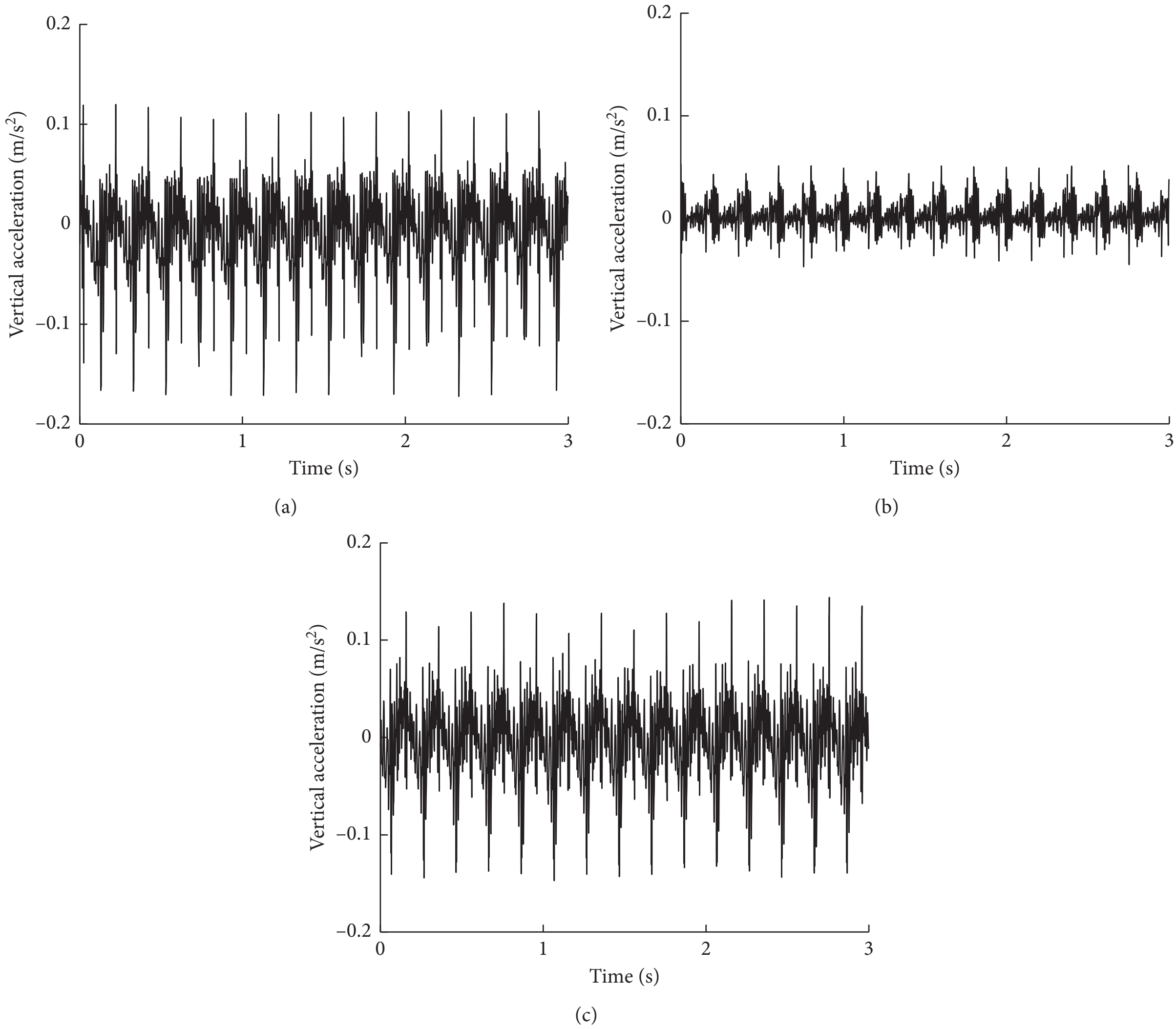


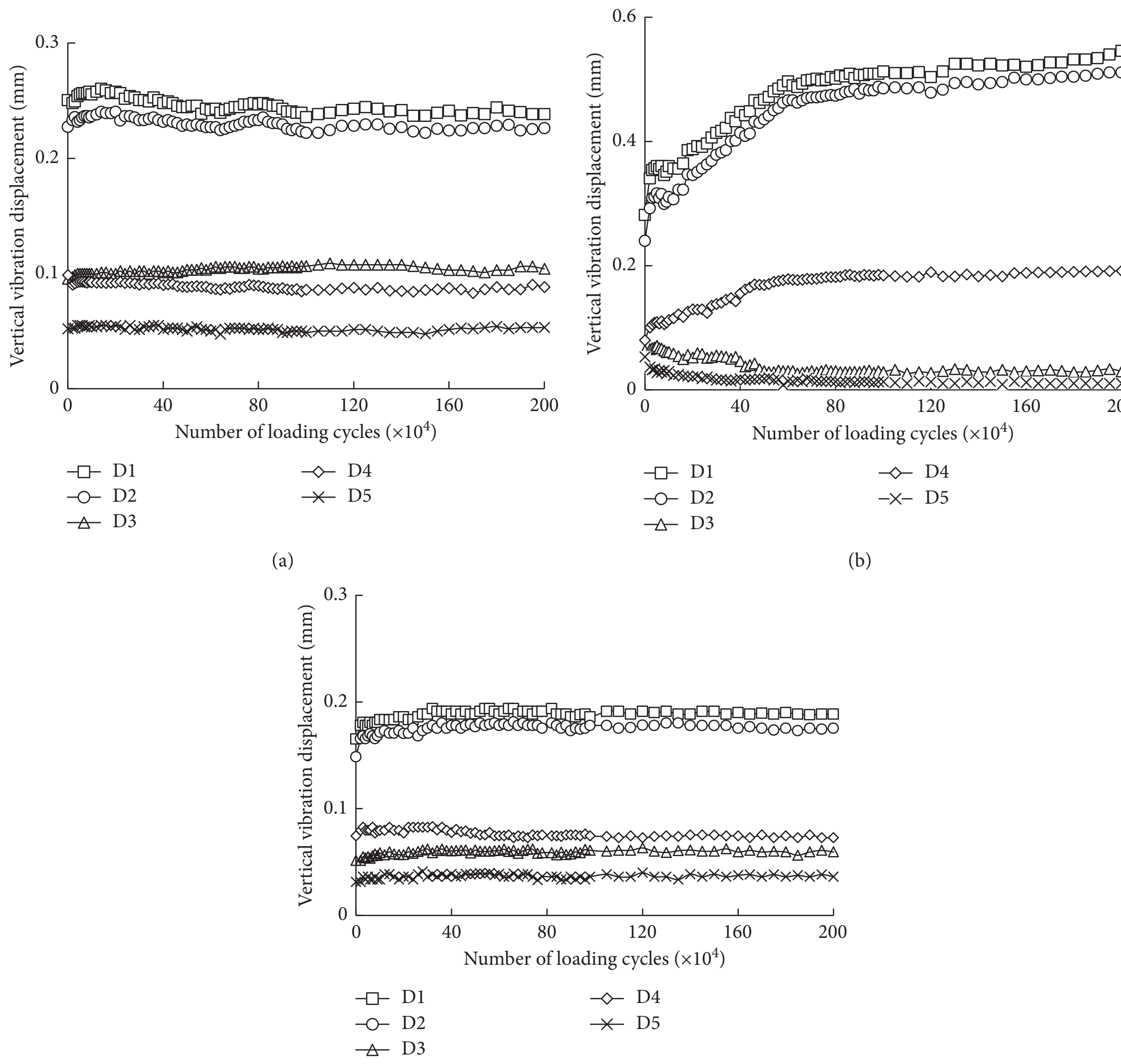
Figure 11: Time-history curve of vertical vibration acceleration of the test point A3. (a) The upper layer of the subgrade bed in normal condition (stage 1). (b) The upper layer of the subgrade bed in mud pumping (stage 2). (c) The model with mud pumping after reinforcement (stage 3).

loading cycles and finally reach to 0.89 mm and 0.71 mm after the first loading stage is completed, respectively. However, after the upper layer of subgrade bed is saturated by water (during the second cyclic dynamic loading stage), the cumulative settlement at same position as the first cyclic dynamic loading stage increases continually with the increasing number of loading cycles and finally reaches to 3.22 mm and 1.92 mm after the second cyclic dynamic loading stage is finished, respectively. The main reasons for the increase of the cumulative settlement during this stage are a large amount of fine particles squeezed out of the upper layer of the subgrade bed and an impact force of the concrete base to the subgrade bed formed due to the interspace between the concrete base and the upper layer of the subgrade bed right under the cyclic loading position.

After the upper layer of the subgrade bed with mud pumping was reinforced, the cumulative settlement stabilizes gradually with the increasing number of loading cycles.

Based on the aforementioned vertical vibration acceleration and displacement and the cumulative settlement of the full-scale model, the model after mud pumping reinforced according to the aforementioned reinforcement procedures has good long-term dynamic stability.

5.4. The Cured Material Filling Effect of Low-Viscosity Epoxy Resin. After finishing all of the loading stages, the concrete base of the full-scale model was lifted, as shown in Figure 14. There is one layer of the cured materials of low-viscosity epoxy resin formed between the concrete base and the upper layer of the subgrade bed, which can fill effectively the interspace between the concrete base and the upper layer of the subgrade bed and cement the fine particles gathering at the surface of the subgrade bed. Therefore, the reinforcement procedures based on low-viscosity epoxy resin injection can effectively handle the mud pumping occurring in the upper layer of the subgrade bed under the concrete base and



(a)

(b)

(c)

Figure 12: The variation of the vertical vibration displacement of the model with the number of loading cycles. (a) The upper layer of the subgrade bed in normal condition (stage 1). (b) The upper layer of the subgrade bed in saturation (stage 2). (c) The model after mud pumping reinforcement (stage 3).

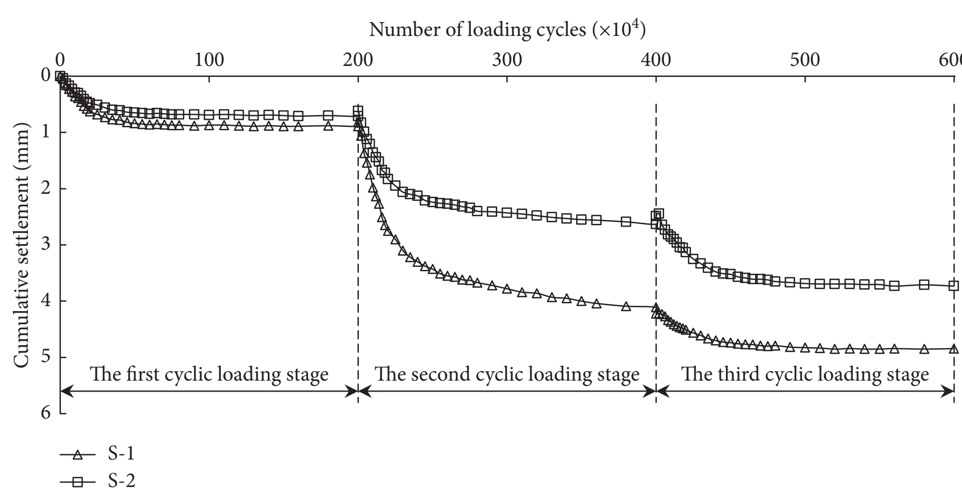


Figure 13: The variation of cumulative settlement of the subgrade bed with the number of loading cycles.

(a) (b)

Figure 14: The cured material layer of low-viscosity epoxy resin between the concrete base and the upper layer of the subgrade bed.

improve the abnormal vibration of the concrete base of the slab track structure.

6. Conclusions

In order to analyze the vibration of the slab track-subgrade in normal conditions, producing mud pumping, and after mud pumping reinforcement under cyclic dynamic loading, a full-scale model of the slab track-subgrade was established in this paper, and the reinforcement effect by the injection of low-viscosity epoxy resin was analyzed. The following conclusions are drawn from this research:

(1) Under cyclic dynamic loading, the vibration and cumulative settlement of the full-scale model of the slab track-subgrade can stabilize gradually with the increasing number of loading cycles during the first loading stage, when the upper layer of the subgrade bed is in normal condition after the model was established. However, after the upper layer of the subgrade bed is saturated by water, the vibration acceleration and displacement of the concrete base of the slab track structure increases continually and that of the subgrade surface decreases slightly in the second loading stage, as well as the continual increase of the cumulative settlement of the subgrade bed, due to contact loss between the concrete base and the upper layer of the subgrade bed caused by mud pumping.

(2) During the second loading stage, the model with the upper layer of the subgrade bed in saturation begins to mud pump in the upper layer of the subgrade bed as soon as the number of loading cycles reaches 3.0×10^4, and the deterioration of mud pumping in there increases continually with the increasing number of loading cycles, causing a large volume of slurry composed of water and fine particles. After the second loading stage is completed, mud pumping only occurs in the contact layer between the top layer of subgrade bed and the concrete base plate. Moreover, there is one slurry layer locating on the subgrade surface under the concrete base and even the interspace forming between the concrete base and the subgrade surface at the model center, causing contact loss between the subgrade bed and the concrete base. Therefore, the support capability of the subgrade bed to the concrete base has been reduced significantly to intensify the vibration acceleration and displacement of the concrete base under cyclic dynamic loading.

(3) After the model with mud pumping was reinforced by low-viscosity epoxy resin injection, the vibration acceleration and displacement of the concrete base stabilize gradually and restore to the normal level as the first loading stage under cyclic dynamic loading, as well as the cumulative settlement of the subgrade bed stabilizing gradually. This indicates that the reinforcement method can improve and control the abnormal vibration of the concrete base. Besides, the cured materials of low-viscosity epoxy resin can fill effectively the interspace between the concrete base and the subgrade bed based on the reinforcement procedures, which can restore the supporting capability of the subgrade bed for the concrete base and improve its vibration.

Based on the results of the full-scale model in this research, mud pumping occurring in the subgrade bed under the slab track-subgrade can deteriorate the support capability of the subgrade bed to the slab track structure and intensify the abnormal vibration of the slab track structure. Furthermore, the reinforcement method based on the injection of low-viscosity epoxy resin can restore the support capability and handle with the abnormal vibration. But the reinforcement method can be extensively used as an example to guide the field construction of mud pumping reinforcement, and more comprehensive studies are needed to provide a basis for the material composition design and practical application of low-viscosity epoxy resin in the reinforcement projects of the slab track-subgrade with mud pumping.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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