Mud pumping in high-speed railway: in-situ soil core test and full-scale model testing

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Abstract Mud pumping induced by moving train loads on rainwater-intruded roadbed causes intensive track vibrations and threatens safety of high-speed trains. In this paper, a vehicle–track–subgrade finite element model was established to analyze the dynamic responses of a ballastless track, and results showed that the concrete base and roadbed were detached because of the whipping effect arising from the rainwater intrusion channel. An in-situ soil core test showed that the intruded rainwater accumulated in roadbed to form standing water and saturated the roadbed. The flapping action of the concrete base caused by the whipping effect led to mud formation mixed with fine particles and rainwater, which migrated upward under the pore-water pressure (PWP) gradient. Mud pumping resulted from continuous particle migration in the saturated roadbed under moving train loads: under normal roadbed condition, coarse and fine particles were uniformly distributed in the roadbed; in early period of mud pumping, fine particles migrated downward to bottom of the roadbed because of the rainwater infiltration flow; in middle stage of mud pumping, fine particles migrated upward and gathered at the roadbed surface under PWP gradient; in later period of mud pumping, fine particles were entrained and removed with the dissipation of excess PWP. Moreover, a full-scale physical model was established to reproduce mud pumping, and polyurethane injection remediation against mud pumping was validated on this physical model. The remediation method was applied to an in-situ mud pumping. The deviation of the vertical track profile reduced remarkably and remained at a low level within half a year, showing a good long-term service performance of the polyurethane remediated roadbed.

Keywords Ballastless track · Mud pumping · Rainwater intrusion · Particle migration · Polyurethane injection

1 Introduction

High-speed railway (HSR), which is characterized by safety, high efficiency, and environmental friendliness, is the key to national economic development, and it also addresses important strategic significance on the sustainable development of the country. Additionally, HSR is an important cornerstone for the implementation of the national Belt and Road Initiative. As an earthwork structure directly exposed to the natural environment factors (such as the extreme precipitation), fine particles in roadbed are fluidized and begin to

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migrate, which leads to occurrence of mud pumping in the roadbed of HSR. Mud pumping is a common distress in railway, which occurs in both ballasted track and ballastless track of HSR (see Fig. 1). Mud pumping has always been a complex problem confused both domestic and foreign scholars, and related cases are also frequently reported [4–12]. For ballasted track, mud pumping causes hardening of the ballast layer and uneven settlement of subgrade [12–14]. For ballastless track, mud pumping results in void areas under the concrete base, intensive track vibrations and track dislocations [4, 15–18], thereby threatening the safety of train operations in serious conditions [3, 18–22].

As shown in Fig. 2, the HSR has two typical structural forms: the ballasted track and ballastless track. For the ballasted track, granular ballast is laid directly on the subballast layer to form a trackbed, and then discrete concrete sleepers are laid on the trackbed to form a sleeper panel. For the ballastless track, the granular trackbed is replaced by concrete slabs with high integrity (including the track slab and concrete base). In practice, the concrete base with a length of 20 m is directly poured on the roadbed surface, and an expansion gap with a width of 0.02 m is set between two adjacent concrete bases; the center of the expansion gap is filled with plastic foam to prevent rainwater intruding into the roadbed [4, 23–25]. The roadbed at the railway shoulder beyond the concrete base is covered with concrete capping layer with a slope of 4% to enhance the surface drainage capacity of track structure. Compared to the open-ended trackbed of the ballasted track allowing free rainwater intrusion into the trackbed, the roadbed of the ballastless track is a concealed structure because of the covering effect of the concrete capping layer, which is in a fully enclosed state; therefore, rainwater can hardly intrude into the roadbed [4, 25]. However, based on the field observations on an intercity HSR line at southeast China, rainwater primarily induced the mud pumping distress in the ballastless track. To prevent rainwater intrusion into the roadbed, a longitudinal drainage ditch between the double lines was added to enhance the surface drainage capacity of ballastless track [26]. In addition, a rubber water barrier was added at the expansion gap to block rainwater intrusion [27]. However, although serious dredging and blocking measures are undertaken to prevent rainwater infiltration, mud pumping continues to occur and creates voids under the concrete base (see Fig. 2).
Ballasted track is the traditional and early used track structure of HSR, therefore, mud pumping in ballasted track was widely studied, which involved in-situ observations, mechanism investigation, and corresponding prevention measures [7, 8, 12, 13, 28–36]. Based on previous studies, ground water is the main water source inducing mud pumping in ballasted track, which continuously eroded and saturated the roadbed, leading to the interpenetration between ballast particles and the underlying subballast layer under moving train loads [7, 8]. During the loading and unloading of the cyclic train loads, the volume of the void area created between sleeper and trackbed changes sharply, which results in suction in the void area and causes fine particles to migrate upward to the surface of ballast layer, thereby forming mud pumping [13, 34]. For ballastless track, the existing studies have shown that mud pumping is the phenomenon of fine particle migration driven by excess pore-water pressure (PWP) generated by moving train loads on saturated roadbed [3, 4, 15, 16, 18, 20, 25, 26, 37–40]. However, the channel of rainwater intruding into the roadbed, the distribution conditions of the intrusion rainwater, and the migration mechanism of fine particles all remain unclear. Besides, as a new type of track structure, structural form, properties of filling materials, and soil stress conditions of the ballastless track are different from those of the ballasted track. Therefore, directly applying relevant theories on mud pumping of ballasted track to explain that of ballastless track is inappropriate. Moreover, proposing a targeted and effective treatment on mud pumping is a challenge because of the unclear formation mechanism of mud pumping.

In this study, based on numerical simulation, in-situ soil core test and full-scale physical model test, the rainwater intrusion channel into the roadbed, distribution conditions of the intruded rainwater, and migration laws of fine particles were revealed. In addition, the whole process of mud pumping in ballastless track was reproduced, and effectiveness of the polyurethane injection remediation on mud pumping was verified on the full-scale physical model. Furthermore, the remediation method was applied to the in-situ mud pumping, showing a successful engineering application of the polyurethane injection remediation on mud pumping of ballastless track.

### 2 Formation of mud pumping in ballastless track
#### 2.1 Intrusion channel of rainwater

Based on the in-situ investigation and statistical analysis of regional precipitation data, rainfall was the main water source inducing mud pumping of ballastless track; however, the intrusion channel of rainwater into the roadbed remained unclear. Therefore, in view of the dynamic characteristic of ballastless track, a vertical coupling dynamic finite element model (FEM) of vehicle-track-subgrade identical to the in-situ conditions was established to reveal the initial formation of rainwater intrusion channel. Because of the covering effect of the overlying track slab, the vertical temperature variations of the track structure are mainly concentrated at a depth of 0.45 m below the surface of the track slab; the temperature at the bottom of the concrete base (beyond a depth of 0.45 m) remains almost unchanged, and the vertical temperature gradient of the concrete base is small with a maximum temperature variation of 1.34 °C [41, 42]. Therefore, the warping effect of the concrete base caused by the temperature gradient is negligible, and the vertical temperature gradient of the track structure is not considered in this numerical simulation model. The CRH3 (China Railway High-speed) train was used as the train model with four carriages [43], and the matching parameters were listed in Table 1. The filling material in the expansion gap was not considered in this FEM because of the smaller stiffness compared with that of the concrete base, and the interactions between each layer of the track-subgrade structure were simulated using a linear elastic model. The matching parameters for the track-embankment structures of the ballastless FEM are summarized in Table 2 in accordance with previous studies [25, 44–47].

The established FEM has a length of 80.56 m, which includes the peripheral zone (20.16 m × 2), transition zone (10.05 m × 2), and analysis zone (20.14 m). The analysis zone mainly focuses on a 20.14-m-long concrete base. 

| Track components | Modulus (Pa) | Poisson’s ratio | Density (kg/m³) |
|------------------|-------------|----------------|-----------------|
| Track slab       | 3.8 × 10¹⁰  | 0.20           | 2500            |
| CA mortar        | 6.3 × 10⁸   | 0.30           | 1800            |
| Concrete base    | 3.0 × 10¹⁰  | 0.20           | 2500            |
| Roadbed          | 3.0 × 10¹⁰  | 0.35           | 2000            |
| Subgrade         | 2.0 × 10⁸   | 0.35           | 1920            |
| Subsoil          | 7.5 × 10⁷   | 0.30           | 1900            |
Components of the FEM and the corresponding geometric details of the ballast track are shown in Fig. 3a and b, and the observation points for the dynamic response analysis are laid on side of the concrete base as shown in Fig. 3c. In the vehicle model of CRH3, a speed boundary along train travelling direction was imposed on the centroid of the vehicle body, bogie, and wheel to simulate the actual running train with different speeds. The interaction between the wheel and rail adopts a nonlinear Hertz contact relationship in the normal direction, and the tangential direction uses frictionless contact. The nonlinear contact relationship between the wheel and rail can be achieved by using ABAQUS to customize the stress and interference, both of which can be calculated on the basis of the train axle load and nonlinear Hertz contact formula mentioned in the corresponding literature [48]. Two values of train speeds (180 and 360 km/h) were applied in this coupling FEM to analyze the dynamic response of track structure under moving train loads.

Figure 4 shows the dynamic response variations of the concrete base under moving train loads with different train speeds. The upward displacement (rebounding displacement) at the end of the concrete base is larger than that in the middle, and the displacement differences at the above-mentioned locations are further enlarged at a higher train speed (see Fig. 4a), indicating that the displacement response of the concrete base presents a whipping effect, which intensifies with the increase of train speed. Rebounding displacement indicated an evident detachment between the concrete base and roadbed, and the detachment provides the main channel for rainwater intrusion into the roadbed. In addition, the rainwater intrusion channel enlarges with the increase of train speed. Correspondingly, the contact pressure between the concrete base and roadbed is also analyzed, and the results are shown in Fig. 4b. The contact pressure at the end of the concrete base is higher than that in the middle, also implying the whipping effect in the concrete base under moving train loads.

In general, the dynamic response caused by the moving train loads at end of the concrete base was higher than that in the middle, and the response differences increased with train speed probably because of large stiffness differences between the concrete base and roadbed and the less...
constraint at end of the concrete base. The response contours of the concrete base shown in Fig. 5 provide a comprehensive understanding of the dynamic response variations of concrete base during train operation corresponding to the situation that the train moves to center of the analysis area in longitudinal direction. As shown in Fig. 5a, both ends of the concrete base are displaced upward, and the ends have been evidently upturned, indicating that the detachment is formed between the concrete base and roadbed. Accordingly, Fig. 5b shows that the contact pressure at the bottom of the concrete base near the end has a negative value (the specified stress downward is positive), which indicates that no contact is found between the concrete base and roadbed, that is, an evident detachment occurs in the concrete base and roadbed, and the detachment provides intrusion channel for rainwater into the roadbed.

For a newly built track-subgrade structure of the ballastless HSR, an expansion gap of width 20 mm is set between the two adjacent concrete bases; this provides an unconstrained and free end of the concrete base. Because of the large differences in stiffness between the concrete base and roadbed, the dynamic response at the end of the concrete base is much higher than that in the middle, indicating a whipping effect under moving train loads. The whipping effect of the dynamic response of the concrete base is an inherent structural property of the ballastless track that leads to the detachment of the concrete base and roadbed layer, creating a rainwater intrusion channel. With the deterioration of mud pumping, the supporting condition of the roadbed is further weakened, thereby intensifying the whipping effect and further widening the detachment and promoting the formation of the rainwater intrusion channel. In addition, the whipping effect leads to the flapping action between the concrete base and roadbed, which may facilitate the infiltration rate of intruded rainwater and simultaneously provide favorable conditions for mixing the fine particles and rainwater in the roadbed. For the ballastless track that has suffered from mud pumping, the whipping effect of the track structure is remarkable under the action of moving train loads because the loss of fine particles in roadbed causes void areas under the concrete base after the occurrence of mud pumping. Therefore, the whipping effect and mud pumping are a mutual promotion process and form a vicious circle.
2.2 Distribution of intruded rainwater and fine particle migration

An in-situ soil core test on substructure filling materials was conducted at the mud pumping area to reveal the distribution conditions of the rainwater that intruded into the roadbed and mud formation. The obtained soil samples were tested for water content and particle size distribution (PSD). The soil core test was selected on an intercity HSR in southeast China, and the core test unit was based on a concrete base (K242+510–K242+530), which suffered mud pumping. A total of six vertical sampling boreholes were arranged along the track center and track side of the railway line along the longitudinal direction, among which labels from V1 to V3 are located at the track center and labels from V4 to V6 are located at the track side (see Fig. 6a). The outer diameter of the soil sampler was 102 mm with inner diameter of 78 mm, and the length of the soil sampler was 0.8 m to obtain roadbed and subgrade filling materials (see Fig. 6b). The vertical soil sampling apparatus and geometrical details of the soil samples are shown in Fig. 6c. Distributions of boreholes and relative positions are shown in Fig. 6a and b.

After completion of the soil core test, the obtained soil samples were divided into small sections in a length of about 0.15 m, and the water content of each soil section was analyzed separately. The water content variations of soil samples along the vertical depth were obtained in Fig. 7. Notably, the different locations of the interface seen in Fig. 7 were probably caused by poor construction control. For both soil samples at the track center and track side, the water content in roadbed was higher than that in subgrade, and it reached the maximum at the interface between the roadbed and subgrade, indicating that the intruded rainwater accumulated in the roadbed. This accumulation occurred probably because of the lower permeability of the subgrade [17, 25, 49], leaving the intruded rainwater in roadbed to continue to infiltrate down at a reduced rate; horizontal infiltration is also an important infiltration route for the intrusion of rainwater [46]. Therefore, the intruded rainwater continuously accumulated in the roadbed and eventually formed the standing water. With continuation of rainfall and occurrence of extreme precipitation, the amount of intruded rainwater into the roadbed increased, further saturating the roadbed and providing favorable conditions for the formation of mud pumping.

The boundary conditions of rainwater intrusion into the roadbed varied at different positions of the concrete base. For the position approaching to the corner of the concrete base (V4 and V6 in Fig. 6a), two rainwater intrusion boundaries with the side crack caused by whipping effect and expansion gap were found. For the position close to end of the concrete base (V1 and V3 in Fig. 6a), only one intrusion boundary with an expansion gap was observed. For the position close to the side of the concrete base (V5 in Fig. 6a), only one intrusion boundary with the side crack was observed. For the position in the track center (V2 in Fig. 6a), no rainwater intrusion boundary was found. Given the different rainwater intrusion boundaries, the development of mud pumping around the concrete base is also different. Based on the above-mentioned analysis, the detachment at the end of the concrete base caused by the whipping effect provides the main channel for rainwater intrusion into the roadbed; therefore, mud pumping near the end of the concrete base is more serious than that at other positions of the concrete base. In addition, an endoscopic observation was performed in the boreholes after the completion of soil core test. Mud pumping primarily occurred in the roadbed, and the underlying subgrade was less affected. Simultaneously, the formation and development of mud pumping could be divided into four stages: the original state of the roadbed, the early period of mud pumping, the middle stage of mud pumping, and the later period of mud pumping. Based on the different rainwater intrusion boundaries and field observations on mud pumping, the locations at V2 and V5 correspond to the original state of roadbed and the early period of mud pumping, respectively. The locations at V1, V3, and V6 correspond to the middle stage of mud pumping, and the location at V4 corresponds to the later period of mud pumping.

Soil samples from these positions (V2, V5, V1, and V4 in Fig. 6a) corresponding to the different periods of mud pumping were taken for PSD analysis according to the code for the soil test of railway engineering [50]. The PSD variations of the roadbed material at different periods of mud pumping are displayed in Fig. 8. Results of endoscopic observations corresponding to each period of mud pumping are also shown in Fig. 8, where H represents the distance from the observation point to the bottom of the concrete base. The PSD of the roadbed material is uniformly distributed at the original state of the roadbed (see Fig. 8a). For the early period of mud pumping, the fine particles in the roadbed accumulate at the bottom layer of the roadbed (see Fig. 8b). Fine particles in the roadbed migrate downwards to the bottom of the roadbed with the infiltration flow of the intruded rainwater. For the middle stage of mud pumping, fine particles begin to accumulate at the roadbed surface (see Fig. 8c) probably because the excess PWP in saturated roadbed caused by moving train loads results in the migration of fine particles upward, and the excess PWP formed in the roadbed is the internal driving force for the migration of fine particles [7, 8, 18, 46, 51–53]. For the later period of mud pumping, fine particles in the roadbed are lost (see Fig. 8d) because they are entrained and removed with dissipation of the excess PWP, forming mud pumping. The above-mentioned PSD evolutions of the roadbed depict the whole process of particle migration during the formation of mud pumping. The PSD analysis results for the soil samples show that the migrating particles (i.e., the fine particles) have a diameter of less than 7.1 mm (see Fig. 8);
this result can be further verified using the PSD analysis of the pumped mud obtained from the testing field [4].

2.3 Formation of mud pumping

Based on the results of the numerical simulation and in-situ soil core test, a model is initially proposed to depict the formation of mud pumping in the roadbed of ballastless HSR. For a newly built ballastless HSR line, the dynamic response of the track structure presents a whipping effect under moving train loads. The whipping effect results in the rebounding displacement of the concrete base, which in turn causes a detachment between the concrete base and roadbed, providing the major channel for rainwater intruding into the

Fig. 6 Schematic diagram of the vertical soil core test (unit: m): a layouts of boreholes; b A–A cross-sectional view; c the vertical sampling apparatus and soil sampler
roadbed. Given the less permeable subgrade, the intruded rainwater accumulates at the roadbed and continuously saturates the roadbed, and the concrete base continuously flaps on the saturated roadbed caused by the whipping effect, which results in the mixing of fine particles with rainwater in the roadbed to form mud. Consequently, the mud mixture migrates upward from the pores of coarse particles under the PWP gradient. Figure 9 depicts migration process of fine particles and mud pumping formation from the original state of the roadbed.

For a newly built substructure of ballastless HSR, the coarse and fine particles are uniformly distributed in the roadbed layer, presenting a normal roadbed condition (see Fig. 9a). After the rainwater intrusion channel is formed, the rainwater pours into the roadbed under the condition of extreme precipitation and long-term rainfall. Under a large rainwater infiltration flow, a downward vertical infiltration gradient of rainwater is formed, promoting the downward migration of the fine particles (see the blue line in Fig. 8b), presenting the early period of mud pumping. As the permeability of the underlying subgrade is low (about $1.0 \times 10^{-6} \text{ cm/s}$) [46, 49], the infiltrated rainwater accumulated in the roadbed and finally formed a standing water, saturating the roadbed layer. Under moving train loads, PWP was generated in the saturated roadbed. Because of the densely moving trains with a high speed, the loading frequency is relatively high; therefore, the PWP further forms excess PWP before dissipation, as observed in physical modelling tests [8, 18, 46]. The fine particles accumulated at the bottom of roadbed are driven to migrate upwards and accumulate at the roadbed surface under the PWP gradient from the bottom to the top, indicating the middle stage of mud pumping. Finally, with the dissipation of excess PWP, the accumulated fine particles in roadbed surface are entrained and removed to form mud pumping, and the pumped mud gathers around the expansion gap, implying the later period of mud pumping (see Fig. 9b). Fine particles in the roadbed are lost after the formation of mud pumping, which creates a void area under the concrete base, affecting the ride comfort of the operating train and endangering the safety of train operation in severe cases. Notably, for the case of continuous rainwater intrusion into the subgrade, fine particles in the subgrade will probably also migrate upwards to the top of the roadbed surface under the action of the PWP gradient to form mud pumping.

3 Polyurethane injection on mud pumping remediation

3.1 Polyurethane injection materials

In recent years, polymer materials have been widely used in subgrade settlement restoration of railway because of the excellent properties with strong plasticity, high strength, and short time of strength formation [17, 46, 47, 54]. Polyurethane stabilization improved the stiffness of the ballast and subballast layer and effectively reduced the subgrade settlement of ballasted track [35, 36, 54–56]. Based on the full-scale physical model test, the effectiveness of polyurethane injection was verified in subgrade settlement restoration and track structure uplift of ballastless track [57, 58]. Given the successful application of polyurethane injection remediation on mud pumping in previous studies, an optimized polyurethane injection method is recommended for mud pumping remediation of ballastless track.

The polyurethane material is a two-component non-aqueous reactive lightweight rigid foam material, which is primarily composed of urethane produced by mixing the isocyanate (component A) and hydroxyl compound (component
B) in an appropriate volume ratio, and the ratio is adjustable. The isocyanate has unique chemical properties, and it can react with other compound with active hydrogen to form various chemical chains, which changes the structure and characteristics of the polyurethane chain. Therefore, some structural chains and groups with high cohesive energy can be added in the isocyanate to improve and optimize the performance of polyurethane injection materials based on the actual need of mud pumping remediation [46, 47].

The isocyanate molecule contains many unsaturated groups with “–N=C=O”; therefore, it has high chemical reactivity. The injection material used in this paper is a rigid polyurethane foam material produced by a rapid polymerization reaction with isocyanate and polyl polyether compound in a volume ratio of 1:1. The unsaturated group of “–N=C=O” in isocyanate undergoes a polymerization reaction with the “–OH” group in polyl to form polyurethane, which constitutes the main skeleton of the polyurethane material. In addition, an appropriate amount of water can be added to the mixture, and the “–N=C=O” group in isocyanate undergoes a foaming reaction with the “–OH” group in water to generate CO₂, which creates the expansion force to make a denser roadbed by filling the void areas caused by mud pumping. The polymerization reaction and foaming reaction equations are shown in Eqs. (1) and (2), respectively.

![Fig. 8 PSD variations of roadbed materials in different periods of mud pumping: a the original state of roadbed; b–d the early period, middle stage, and later period of mud pumping](image-url)
The polyurethane material must have good fluidity with a low viscosity of less than 200 mPa·s to ensure that the pores in the roadbed are fully filled with injection materials. Accordingly, the injection material is required to maintain a relatively high density and strength while squeezing out the standing water, and the polyurethane material has a higher retention rate of 85% in density and strength. During the process of polyurethane injection, the two-component slurry is first mixed in an injection gun under a high pressure, and then, the mixture is injected into a roadbed layer to ensure the effective drainage of the remaining standing rainwater and to avoid the excessive uplift of the track structure. The injection pressure is determined to be approximately 3.0 MPa by test, for which the two-component slurry is well mixed and undergoes complete polymerization and foaming reactions. In addition, as the injection material diffuses in the roadbed, the standing water is squeezed out, and the voids in the roadbed are fully filled, forming a polyurethane-stabilized roadbed. Correspondingly, the strength and supporting stiffness of the polyurethane-stabilized roadbed are enhanced, and they maintained a good long-term service performance [17].

3.2 Polyurethane injection method on mud pumping remediation

As the expansion gap of the concrete base is the main location for the occurrence of mud pumping, a full-scale physical model of ballastless track considering the expansion gap is built on the basis of the full-scale innovative HSR tester of Zhejiang University (ZJU-iHSRT). Based on the Code for design of HSR (TB10621-2014) [59], the track-subgrade model is built in a steel model box with a size of 15.0 m × 5.5 m × 6.0 m, and the geometric details of the constructed ballastless track are shown in Fig. 10a. The PSD of the roadbed adopts the PSD obtained from the in-situ soil core test, and dimensions of the track and substructure are consistent with those in the field. After construction of the physical model, the rainfall simulation device is installed. The dynamic loading system and dynamic response monitoring system are also installed, and the full-scale physical model of the ballastless track after construction is shown in Fig. 10b.

\[
\begin{align*}
\text{n OCN} & \text{-R-NCO} + \text{n HO} \rightarrow \left[ \text{H}_{\text{n}} \text{C} \text{-N} \text{-R} \text{-N} \text{-C} \text{-O} \right] \\
\text{2 R-NCO} + \text{H}_2\text{O} \rightarrow \text{R-N-C-N-R} + \text{CO}_2
\end{align*}
\]

Fig. 9 Schematic diagram of mud pumping formation in ballastless track: a coarse and fine particles distribute uniformly; b rainwater intrusion and fine particle migration

For the constructed physical model of ballastless track, the moving train test was first conducted under the normal subgrade condition to obtain the initial dynamic response of the track structure. Then, the rainfall device was turned on to simulate the process of long-term rainfall, and after the saturation of the roadbed, the moving train test was performed to reproduce the whole process of mud pumping in ballastless track (Fig. 10c). The polyurethane injection method was applied in mud pumping remediation based on the full-scale model, and the moving train test was also conducted on the remediated roadbed to verify the restoration effectiveness of polyurethane injection. Finally, the long-term loading test was conducted on the polyurethane-remediated roadbed, and after large loading cycles, the moving train test was performed to obtain the dynamic response of the track.
structure. For the long-term loading test, the train speed was 252 km/h corresponding to the average operating speed in the HSR line in southeast China, and the loading cycles are 360,000, which is equivalent to 5 months operation volume of the above-mentioned HSR line.

Polyurethane injection on mud pumping remediation primarily includes three steps, and the specific implementation process is as follows:

1. Water-blocking barrier formation: The injection holes are placed at both sides of the concrete base along the longitudinal direction, and the injection sequence starts from the track center to the expansion gap (along the direction of the red arrow in Fig. 11a). The depth of the injection hole reaches the bottom of the roadbed (approximately 0.4 m), and during injection, the synchronous injection at symmetrical positions is performed to avoid excessive track elevation. Accordingly, two longitudinal polyurethane walls along the trackside and two transverse polyurethane walls across the roadbed can be installed, and the lower permeability subgrade can be naturally used as the bottom water wall. Thus, a water-blocking barrier encircling the mud-pumping area is formed.

2. Water squeezing out and void filling: As shown in Fig. 11b and c, the injection pipe reaches to the bottom of the roadbed at an angle of 45° to obtain a wider injection stabilized area. The intruded rainwater can be squeezed out from the initial intrusion channel by high-pressure injection, while the voids are gradually filled with polyurethane materials, forming polyurethane-stabilized roadbed. Therefore, the stiffness of the roadbed is improved and strengthened to its initial status, thereby alleviating the dynamic response of the ballastless track and reducing the whipping effect of the track structure.

3. Blocking of water intrusion channel: After completing polyurethane injections, the intrusion channel of rainwater must be blocked. As shown in Fig. 11, the polyurethane material is injected into the roadbed with a width and thickness of 0.2 m and 0.05 m, respectively, to form a sealing layer. Simultaneously, the expansion gap and cracks along the track sides are also sealed.
using a silicone sealant, through which the intrusion channel of rainwater can be effectively blocked.

After reproducing mud pumping in ballastless track, the polyurethane injection remediation test is conducted in accordance with the three above-mentioned steps. Correspondingly, the injection pressure is about 3.0 MPa, and it can be precisely controlled by using a professional injection machine (Reactor 2 H-50, Graco, Shanghai, China). The injection holes are primarily distributed around the expansion gap where mud pumping frequently occurs, and the spacing between adjacent injection holes is one fastener or half a fastener spacing. During injection, polyurethane injection is performed in accordance with the first, second, and third rounds of injection (Fig. 11). Six displacement sensors (labeled from S1 to S6) and two vibration velocity sensors (labeled from D1 and D2) are installed on the track structure (Fig. 11a). Notably, the dynamic response of the track structure in various test conditions was analyzed by taking the average value of the dynamic response of the two parts of track structure (Fig. 11a).

Figure 12 presents the dynamic response variations of the track structure in four different testing cases. As shown in Fig. 12a, the maximum vertical displacement of the concrete base is nearly three times higher than that of the normal roadbed state after the occurrence of mud pumping, and after polyurethane injection remediation, the vertical displacement is reduced by nearly 50%, implying the good performance of polyurethane injection remediation on mud pumping. Vertical displacement is further reduced after large loading cycles, indicating that the injection material is further compacted, and the performance of the remediated roadbed is further enhanced. As shown in Fig. 12b, the vibration velocity amplitude of the track slab increases with the increase of train speed, and the maximum velocity amplitude increases approximately three times after the formation of mud pumping. The amplitude of vibration velocity is markedly reduced after polyurethane remediation, and the maximum value is reduced by about 35%. Accordingly, after large loading cycles, the velocity amplitude further reduces because the polyurethane-stabilized roadbed is further compacted, showing the good long-term service performance of the polyurethane-stabilized roadbed.

3.3 In-situ polyurethane injection on mud pumping remediation

As the polyurethane injection method on mud pumping remediation and the long-term service performance of the remediated roadbed have been effectively verified on the full-scale physical model of ballastless track, an in-situ mud pumping remediation test with polyurethane injection was conducted on a mud pumping suffered site. Accordingly, the in-situ injection is performed in accordance with the previously reported three steps of polyurethane injection. The performance of the remediated roadbed is analyzed on the basis of the recorded data of a track inspection car (vertical track profile, see Fig. 13). The deviator of the vertical track profile is $-9.58$ m at the mud pumping site, exceeding the tolerance of the vertical track profile for HSR [60]. However, on the third day of the polyurethane injection remediation, the deviator of the vertical track profile sharply decreases.
After remediation, the deviators of the vertical track profile are within the maintenance standard value [60], showing a good long-term performance of polyurethane injection on mud pumping remediation.

4 Conclusions

On the basis of the numerical simulation, in-situ soil core test, and full-scale physical model of ballastless track, the formation of mud pumping in roadbed of ballastless track was analyzed, and the effectiveness and engineering application of the polyurethane injection on mud pumping remediation was verified. The following conclusions were drawn on the basis of the results:

1. The dynamic response of the track structure presents a whipping effect under moving train loads. The whipping effect is an inherent structure property of the ballastless track, which results in detachment between the concrete base and roadbed, and the detachment provides main channel for rainwater intrusion into the roadbed.

2. The intruded rainwater accumulates in the roadbed to form standing water and saturates the roadbed. The flap-vibing action of the concrete base caused by the whipping effect leads to mud formation mixed with fine particles and standing water, which migrates upwards under the PWP gradient and finally forms mud pumping. Mud pumping results from fine particle migration under moving train loads. In the original state of roadbed, coarse and fine particles were uniformly distributed in the roadbed; in the early period of mud pumping, fine particles in roadbed migrate downward along with rainwater flow and accumulate at the bottom of roadbed; in the middle stage of mud pumping, the fine particles are driven to migrate upward and gather at the roadbed surface under the PWP gradient; in the later period of mud pumping, the accumulated fine particles in the roadbed surface are entrained and removed with the dissipation of excess PWP, to form mud pumping.

3. The whole process of mud pumping in roadbed of ballastless track is reproduced. After the formation of mud pumping, the dynamic response of track structure sharply increases and then decreases intensively after the polyurethane injection remediation. The verified polyurethane injection method was successfully applied to the in-situ mud pumping remediation, and the deviation of the vertical track profile reduced and remained below the maintenance level within half a year after remediation. The remediated subgrade structure presented a good long-term service performance.
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References

1. World Meteorological Organization. The global climate in 2015–2019. https://reliefweb.int/report/world/global-climate-2015-2019
2. Chi X, Yin Z, Wang X et al (2015) Spatiotemporal variations of precipitation extremes of China during the past 50 years (1960–2009). Theor Appl Climatol 124(3–4):555–564
3. Wan Z, Li S, Bian X et al (2022) Mud pumping in ballastless slab track of high-speed railway and its remediation. In: Advances in transportation geotechnics IV. Lecture Notes in Civil Engineering, Springer, Singapore
4. Bian X, Wan Z, Zhao C et al (2022) Mud pumping in the roadbed of ballastless high-speed railway. Géotechnique. https://doi.org/10.1680/jgeo.21.00135
5. Gomes CA, Ramos A (2022) A geomechanics classification for the rating of railroad subgrade performance. Railw Eng Sci 30(3). https://doi.org/10.1007/s40534-021-00260-z
6. Mei H, Satvati S, Leng W (2021) Experimental study on permanent deformation characteristics of coarse-grained soil under repeated dynamic loading. Railw Eng Sci 29(1):94–107
7. Duong TV, Cui YJ, Tang AM et al (2014) Physical model for studying the migration of fine particles in the railway substructure. Geotech Test J 37(5):895–906
8. Duong TV, Cui Y-J, Tang AM et al (2014) Investigating the mud pumping and interlayer creation phenomena in railway sub-structure. Eng Geol 171:45–58
9. Katsumi M, Nakamura T (2011) Development of the counter-measure against roadbed degradation under ballastless tracks for existing lines. In: The 9th World Congress on Railway Research, Lille
10. Katsumi M, Sekine E, Nakamura T (2006) Roadbed degradation mechanism under ballastless track and its countermeasures. Q Report of Rtri 47(4):222–227
11. Nguyen TT, Indraratna B (2021) Rail track degradation under mud pumping evaluated through site and laboratory investigations. Int J Rail Transp 10(1):44–71
12. Nguyen TT, Indraratna B, Kelly R et al (2019) Mud pumping under railtracks: mechanisms, assessments and solutions. Aust Geo J 54(4):59–80
13. Li D, Wilk S (2021) Recent studies on railway-track substructure at TTCI. Transp Saf Environ 3(1):36–49
14. Zhang S, Gao F, He X et al (2021) Experimental study of particle migration under cyclic loading: effects of load frequency and load magnitude. Acta Geotech 16(2):367–380

15. Huang J, Su Q, Cheng Y et al (2019) Improved performance of the subgrade bed under the slab track of high-speed railway using polyurethane adhesive. Constr Build Mater 208:710–722
16. Li Y, Leng W, Nie R et al (2022) Laboratory full-scale model test of subgrade mud pumping for ballastless track of high-speed railway. Int J Rail Transp 10(2):230–256
17. Wan Z, Bian X, Li S et al (2020) Remediation of mud pumping in ballastless high-speed railway using polyurethane chemical injection. Constr Build Mater 259:10–20
18. Wang T, Luo Q, Liu M et al (2020) Physical modeling of train-induced mud pumping in substructure beneath ballastless slab track. Transp Geotech 23:100332
19. Huang J, Su Q, Wang W et al (2018) Field investigation and full-scale model testing of mud pumping and its effect on the dynamic properties of the slab track–subgrade interface. Proc Instit Mech Eng F J Rail Rapid Transit 233(8):802–816
20. Liu K, Qiu R, Su Q et al (2021) Suffusion response of well graded gravels in roadbed of non-ballasted high speed railway. Constr Build Mater 284:122848
21. Liu K, Su Q, Yue F et al (2019) Effects of suffusion-induced contact variation on dynamic responses of saturated roadbed considering hydro-mechanical coupling under high-speed train loading. Comput Geotech 113:103095
22. Wan Z, Li S, Bian X et al (2020) Field observations on mud pumping of ballastless track in high-speed railway. In: Advances in environmental vibration and transportation geodynamics. Lecture Notes in Civil Engineering, Springer, Singapore
23. Qing S (2013) High-speed railway construction technology—subgrade engineering. China Railway Publishing House, Beijing (in Chinese)
24. Qing S (2013) High-speed railway construction technology—track engineering. China railway Publishing House, Beijing (in Chinese)
25. Wan Z, Xu W, Zhang Z et al (2022) In-situ investigation on mud pumping in ballastless high-speed railway and development of remediation method. Transp Geotech 33:100713
26. Liu T, Su Q, Zhao W et al (2015) Research on injection-repaired and reinforcement effects of subgrade frost boiling under ballastless track. J China Railw Soc 37(12):88–95 (in Chinese)
27. Pan Z (2014) Research on mud pumping and its remediation measures of ballastless high-speed railway from Shanghai to Nanjing. Railw Eng 3:74–77 (in Chinese)
28. Brough MJ, Ghatossa GS, Stirling AB et al (2006) Investigation of railway track subgrade part 2: case study. Proc Instit Civil Eng Transp 159(2):83–92
29. Indraratna B, Singh M, Nguyen TT (2020) The mechanism and effects of subgrade fluidisation under ballasted railway tracks. Railw Eng Sci 28(2):113–128
30. Huang Z, Su Q, Huang J et al (2022) Polyurethane grouting materials with different compositions for the treatment of mud pumping in ballastless track subgrade beds: properties and application effect. Railw Eng Sci 30(2):204–220
31. Cui Y-J, Duong TV, Tang AM (2013) Investigation of the hydro-mechanical behaviour of fouled ballast. J Zhejiang Univ-Sci A (Appl Phys Eng) 14(4):244–255
32. Cui Y-J, Lamas-Lopez F, Trinh VN et al (2014) Investigation of interlayer soil behaviour by field monitoring. Transp Geotech 1(3):91–105
33. Duong TV, Cui YJ, Tang AM et al (2015) Assessment of conventional French railway sub-structure: a case study. Bull Eng Geol Environ 74(1):259–270
34. Takatoshi I (1997) Measure for stabilization of railway earth structure. Japan Railway Technical Service, Tokyo, Japan
35. Woodward PK, El Kacimi A, Laghouache O et al (2012) Application of polyurethane geocomposites to help maintain track
geometry for high-speed ballasted railway tracks. J Zhejiang Univ-Sci A 13(11):836–849
36. Woodward PK, Kennedy J, Laghouache O et al (2014) Study of railway track stiffness modification by polyurethane reinforcement of the ballast. Transp Geotech 1(4):214–224
37. Leng W, Su Y, Teng J et al (2018) Analysis and evaluation on physical characteristics of fine-grained soils prone to mud pumping. J China Railw Soc 40(1):116–122 (in Chinese)
38. Cai X, Cai X, Liu K et al (2015) Study on mud pumping mechanism of subgrade surface layer in slab ballastless track zone. Sens Transduc IFSA Publ 186:154–160
39. Huang J, Su Q, Liu T et al (2019) Behavior and control of the ballastless track—subgrade vibration induced by high-speed trains moving on the subgrade bed with mud pumping. Shock Vib 2019:1–14
40. Su Y, Leng W, Teng J et al (2016) Analysis of subgrade soil mud pumping model. Electron J Geotech Eng 21(24):7667–7678
41. Wan Z (2015) Experimental study on temperature field characteristic of CRTS I twin-block ballastless track. Dissertation, Southwest Jiaotong University (in Chinese)
42. Yang R, Wan Z, Liu X et al (2015) Temperature field test of CRTS I twin-block ballastless track in winter. J Southwest Jiaotong Univ 50(3):454–460 (in Chinese)
43. Yang YB, Hung H (2009) Wave propagation for train-induced vibrations: a finite/infinite element approach. World Scientific, Singapore
44. Bian X, Jiang H, Chang C et al (2015) Track and ground vibrations generated by high-speed train running on ballastless railway with excitation of vertical track irregularities. Soil Dyn Earthq Eng 76:29–43
45. Jiang H (2014) Dynamic interaction of slab track structure subgrade system and accumulative settlement in high-speed railways. Dissertation, Zhejiang University (in Chinese)
46. Wan Z (2021) Study on the mechanism of mud pumping in the roadbed and its remediation of ballastless high-speed railway. Dissertation, Zhejiang University (in Chinese)
47. Duan X (2020) Dynamic behaviors of ballastless high-speed railway with uneven settlement excitation and the railway settlement control. Dissertation, Zhejiang University (in Chinese)
48. Zhai W (2020) Vehicle-track coupled dynamics: theory and application. Springer, Singapore
49. Yang R, Yang C (1989) New technology of preventing and remediating mud pumping in railway: application of geo-polymer. China Railway Publishing House, Beijing (in Chinese)
50. National Railway Administration of the People’s Republic of China (2010) Code for soil test of railway engineering. TB10102-2010/J1135-2010. Beijing: China Railway Publishing House (in Chinese)
51. Alobaidi I, Hoare DJ (1994) Factors affecting the pumping of fines at the subgrade subbase interface of highway pavements: a laboratory study. Geosynth Int 1(2):221–239
52. Alobaidi I, Hoare DJ (1996) The development of pore water pressure at the subgrade-subbase interface of a highway pavement and its effect on pumping of fines. Geotext Geomembr 14(2):111–135
53. Alobaidi IM (1991) Some aspects of the role of geocomposites in controlling pumping of fines in the foundations of flexible pavement. Dissertation, University of Birmingham
54. Gundavaram D, Hussaini SKK (2019) Polyurethane-based stabilization of railroad ballast: a critical review. Int J Rail Transp 7(3):219–240
55. Du Plooy RF, Gräbe PJ (2017) Characterisation of rigid polyurethane foam-reinforced ballast through cyclic loading box tests. J S Afr Inst Civ Eng 59(2):2–10
56. Sol SM, D’Angelo G (2017) Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks. Constr Build Mater 157:402–415
57. Bian X, Cheng C, Wang F et al (2014) Experimental study on dynamic performance and long-term durability of high-speed railway subgrade rehabilitated by polymer injection technology. Chin J Geotech Eng 36(3):562–568 (in Chinese)
58. Bian X, Duan X, Li W et al (2021) Track settlement restoration of ballastless high-speed railway using polyurethane grouting: full-scale model testing. Transp Geotech 26:100381
59. National Railway Administration of the People’s Republic of China (2014) Code for design of high speed railway. TB10621-2014. China Railway Publishing House, Beijing (in Chinese)
60. National Railway Administration of the People’s Republic of China (2013) Technical regulations for dynamic acceptance for high-speed railways construction. TB10761-2013/J1535-2013. China Railway Publishing House, Beijing (in Chinese)