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Discussion on Treatment Technologies for Mud Pumping Disease in Ballastless Track Subgrade

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Abstract: With the rapid development of high-speed railways, ballastless track, as an advanced track structure, plays a crucial role in providing high-speed and highly stable transportation services. However, over time, issues such as mud pumping disease have emerged in ballastless track structures, posing serious threats to track stability and operational safety. To address this problem, this paper combines practical case studies to thoroughly investigate treatment technologies for mud pumping disease in ballastless track subgrades, with a focus on the application of grouting technology. The study first evaluates the effectiveness of grouting through on-site core drilling and ground-penetrating radar (GPR) detection, followed by comparative analysis to verify its efficacy in improving subgrade stability and restoring support capacity. Experimental results demonstrate that after grouting treatment, track vibration amplitude significantly decreases, train running stability improves markedly, and no new mud pumping issues are observed in subsequent inspections.

Keywords: ballastless track, subgrade mud pumping, roadbed, grouting

Introduction

As a critical component of modern high-speed railways, ballastless tracks are widely adopted in China's passenger-dedicated lines and high-speed rail networks due to their low maintenance costs and superior structural stability. However, prolonged operation—particularly the dynamic loads generated by high-speed trains—can lead to various track deteriorations, among which subgrade mud pumping is the most prevalent. This issue not only compromises the structural integrity and service life of the track but also poses significant safety risks to railway operations. Consequently, developing effective remediation technologies for mud pumping has become imperative to ensure the long-term stability of high-speed rail systems. This study investigates the causes of mud pumping in ballastless track subgrades and proposes an efficient treatment solution leveraging grouting technology, aiming to provide technical insights for future railway infrastructure maintenance and rehabilitation.

1. Hazards of Mud Pumping in Ballastless Track Subgrades

Mud pumping in ballastless track subgrades is one of the most severe engineering challenges in high-speed rail and urban transit systems, directly jeopardizing track stability and operational safety. The term "mud pumping" refers to the upward migration of fine-grained particles from the subgrade or subbase into the track structure under cyclic loading and water infiltration, forming a slurry-like mixture. Unlike traditional ballasted tracks, ballastless tracks require dense, monolithic integration among the track slab, roadbed, and foundation to withstand repeated dynamic loads from high-speed trains.When mud pumping occurs, the mixture of fine soil and water infiltrates the lower track layers or even contacts the concrete track slab, creating localized weak zones. This disrupts the designed load-transfer mechanism, reduces structural rigidity, and leads to stress concentration, ultimately causing track slab cracking, settlement, and other defects. Moreover, to ensure smooth train operation,

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longitudinal and lateral track geometry must remain precise. Mud pumping-induced uneven support triggers irregular settlement of track slabs or sleepers, distorting track alignment. This results in increased vibration, noise, and wheel-rail impact forces, accelerating fatigue damage to both rolling stock and track components while raising maintenance costs. Mud pumping is closely associated with poor subgrade drainage, particularly in areas with heavy rainfall or high groundwater levels. Trapped water elevates subgrade moisture content, causing saturation and softening, which exacerbates mud pumping in a vicious cycle (Liu et al., 2019). Under combined effects of softening and mud pumping, the concrete track slab's underside becomes exposed to prolonged water immersion, accelerating corrosion, alkali-silica reactions, and other deterioration mechanisms. Furthermore, mud pumping complicates maintenance and repair. Given the monolithic nature of ballastless tracks, localized damage caused by mud pumping often necessitates disruptive interventions—such as rail cutting, excavation, backfilling, and track re-laying—leading to prolonged service interruptions and substantial economic losses. At a deeper level, conventional design approaches for subgrade thickness and drainage may fail to account for coupled hydro-mechanical behaviors in challenging geological conditions (e.g., silty clay, water-bearing sand, or soft soil layers). This mismatch between design assumptions and actual service environments underscores the need to reevaluate the multi-physical interactions between subgrades and track structures, calling for higher standards in design, construction, and maintenance strategies.

2. Overview of Ballastless Track Engineering

2.1 Mud pumping disease in ballastless track subgrade

A high-speed passenger dedicated line, which has been in operation for nearly five years, adopts the CRTS-I slab-type ballastless track system throughout its route. The upper structure of this system consists of prestressed track slabs, CA (cement asphalt) mortar layers, and reinforced concrete base slabs, while the lower structure comprises graded crushed stone layers and Class AB fill materials in the subgrade. During recent track inspections, it was observed that in certain sections, a slurry-like substance was being extruded from the joints between the concrete base slabs and the subgrade crushed stone layers onto the track surface, particularly during rainfall when the phenomenon became more pronounced. In some areas, localized voids had formed beneath the base slabs, leaving them partially suspended. If left untreated, this condition could pose significant threats to the safety and stability of high-speed railway operations.

2.2 Causes of mud pumping in ballastless track subgrade

2.2.1 Analysis of subgrade surface materials

The observed defects were primarily concentrated at the interface between the concrete base slab and the top crushed stone layer of the subgrade, indicating the need for focused evaluation of the composition and quality of the graded crushed stone layer. This upper subgrade layer consists of a specific proportion of coarse and fine aggregates, stone powder, and cement. According to original mix design calculations, sieve analysis, sample testing, and compaction test reports, both the material quality and compaction met all relevant national technical standards. Therefore, it can be concluded that the root cause of the defect does not lie in any physical or chemical deficiencies of the filler material itself (Liu & Cui, 2021).

2.2.2 Water infiltration as primary external factor

Detailed field investigations revealed that water penetration was the key external factor causing the slurry extrusion phenomenon. This manifests in two main aspects: First, there were evident deficiencies in the treatment of expansion joints between adjacent concrete base slabs, where ordinary fiberboard was typically used as filler material. Such materials exhibit poor sealing performance and are prone to waterproofing failure. Second, inconspicuous gaps formed between the side edges of base slabs and adjacent shoulder concrete surfaces, providing channels for surface water or rainwater to penetrate into the subgrade. Once water enters, the fine particles in the subgrade crushed stone undergo a mud-forming reaction under repeated dynamic train loads. Water softens the aggregates, enhances fluidity, and accelerates upward slurry migration through structural gaps. Thus, persistent water infiltration is identified as a dominant factor in this mud pumping phenomenon.

2.2.3 Impact of dynamic loads from high-speed trains

The dynamic response of high-speed railway track systems to train loads far exceeds that of conventional rail systems. Under high-speed operation, the impact forces exerted by trains on the track structure increase significantly. According to measured studies, when operating speeds increase from 80 km/h to 250 km/h, high-frequency impact forces in the wheel-rail contact zone can increase by up to 100%, with low-frequency response forces rising by approximately 80%. In such dynamic conditions, when the strength of the subgrade surface layer is compromised by water saturation, a "negative pressure suction" effect can develop beneath the concrete base slab. This causes fine particles and slurry to be repeatedly drawn upward, eventually extruding through joints to the track surface. This dynamic mechanism facilitates the surfacing of slurry and represents a critical pathway for high-frequency impact forces to induce defects (Zhang, 2021).

2.2.4 Insufficient adaptability of subgrade structural configuration

The structural configuration of high-speed railway subgrades plays a crucial role in preventing structural defects. Subgrade layer designs can generally be categorized into three types: the basic two-layer system (track bed laid directly on original subgrade), improved multi-layer systems (with additional protective layers between track bed and soil subgrade), and enhanced subgrade structures. Compared to the two-layer system commonly used in China's conventional lines, international high-speed railways typically employ specialized structural transition layers to mitigate stress transmission. For instance, French and German high-speed railways generally feature 25-30 cm protective subgrade layers, while Japan's Shinkansen systems typically incorporate 30 cm subgrade protection layers beneath the track structure, including 5 cm of asphalt concrete or hydraulic slag aggregate layers with excellent waterproofing and cushioning properties.

In some current Chinese line designs, concrete base slabs are installed directly on graded crushed stone layers without intermediate transition layers. While this design specifies clear requirements for compaction, strength, and deformation modulus of the crushed stone layer, it still shows significant gaps compared to international enhanced subgrade structures in withstanding repeated high-speed loading impacts. The absence of intermediate cushioning interfaces reduces the overall structural fatigue resistance, increasing the risk of upward slurry migration under dynamic loads. Therefore, this subgrade structural configuration may represent one of the fundamental causes behind the observed slurry extrusion and localized void formation phenomena.

3. Treatment Technology Solutions for Mud Pumping Disease in Ballastless Track Subgrade

3.1 Selection of grouting materials

3.1.1 Performance requirements for grouting materials

To effectively address localized instability caused by mud pumping in ballastless track structures, the selected grouting materials must meet specific performance criteria according to different application areas. Materials used for filling expansion joints in base slabs and sealing gaps between concrete base slab edges and shoulder concrete layers must possess the following characteristics: thermal stability to resist softening at high temperatures, crack resistance in low-temperature environments, strong corrosion resistance, and excellent bonding properties. Additionally, they should exhibit high elongation rates and good flow characteristics for injection, capable of natural curing in liquid state to form stable sealing structures.

For grouting materials filling voids between base slabs and graded crushed stone subgrade surfaces, more complex performance requirements apply. First, the material must demonstrate excellent fluidity to ensure penetration into fine pores and loosened areas. Second, its elastic modulus should be intermediate between concrete and graded crushed stone to provide effective mechanical transition and enhance interface layer compatibility. Furthermore, the material should possess hydrophilic properties and permeability to react effectively with residual water or muddy particles in moist conditions, achieving structural rehabilitation of partially pulverized subgrade materials. Finally, the cured material must form reliable bonds with concrete, with strength and durability meeting or exceeding the basic specifications of graded crushed stone subgrade layers (He et al., 2024).

3.1.2 Characteristics of selected grouting materials

Through comparative field tests of various materials, C202 polymer chemical grout was ultimately selected for expansion joints and structural sealing applications, while G205 polymer chemical grout was chosen for void filling between base slabs and graded crushed stone layers. Both materials consist of A and B components that can solidify within 0.5 hours, achieving compressive strength exceeding 30MPa after curing while maintaining excellent hydrophilic reactivity. During actual construction, these materials rapidly react with water upon injection to form consolidated foam with elastic strength, effectively filling and compacting internal structural voids.

3.1.3 Mechanism of grouting materials

During injection, the grouting materials chemically react with residual moisture in the structure to form high-strength foam structures. Under injection pressure, the foam disperses through structural voids via penetration, filling, and compaction, displacing existing water and air. Ultimately, this foam completely occupies voids between concrete base slabs and subgrade, significantly reducing local porosity. This process effectively restores support strength and overall load-bearing capacity in affected sections, ensuring track structure stability and operational safety.

3.2 Equipment selection

To ensure the efficiency and stability of grouting operations, the selection of grouting equipment must strictly meet the following technical requirements: First, the equipment must provide stable and continuous grouting pressure to avoid pressure fluctuations during construction that may affect grouting quality. Second, the grouting pressure should be strictly controlled within the range of 0.3-0.4 MPa, with routine operations recommended to be maintained at 0.1-0.2 MPa to prevent structural damage caused by excessive pressure. Third, the grouting flow rate of the equipment should not be less than 40 kg/h to meet the basic requirements for grouting speed during continuous field operations.

3.3 Implementation of remediation plan

The treatment of this defect adheres to a technical approach combining "sealing, filling, and drainage", with systematic construction procedures developed based on survey results.

During the pre-construction phase, ground-penetrating radar technology should first be used to conduct comprehensive scanning of sections affected by mud pumping disease, clearly identifying voids beneath concrete base slabs and the extent of defect propagation. Subsequently, grouting holes should be drilled at expansion joint locations between adjacent affected base slabs and at joint seams between base slabs and shoulder concrete. G202 grouting material should be used to seal these gaps, preventing rainwater and surface water from continuing to infiltrate the subgrade structure.

Next, grouting holes should be arranged along the track direction at 10 cm from both edges of the base slab, with spacing controlled at 50 cm, drilling depth around 30 cm, and hole diameter in the range of 8-10 cm. After drilling, grouting nozzles should be immediately installed to inject G205 polymer grout into void areas, achieving complete filling of voids beneath the concrete base slab and structural reinforcement, thereby enhancing subgrade support capacity (Han et al., 2025).

During the grouting construction process, professionals must be assigned to monitor grouting effectiveness in real time, with particular attention to whether grout leakage occurs at adjacent grouting hole locations. If grout is observed seeping from non-grouting holes, operations at the current hole location should be immediately suspended, the leaking hole sealed, and then alternative hole locations selected for supplementary grouting to ensure thorough grout injection and complete void filling.

Additionally, after completing the defect remediation, a blind pipe drainage system should be simultaneously installed to drain residual moisture that has entered the subgrade, preventing continuous future infiltration of rainwater or surface water, thereby reducing structural moisture risks and effectively controlling recurrent subgrade softening and mud pumping disease.

4. Analysis of Remediation Effectiveness for Mud Pumping Disease in Ballastless Track Subgrade

4.1 Quality inspection of grouting

Following the completion of mud pumping disease remediation, two technical methods were employed to conduct comprehensive quality inspection of the grouting: on-site core drilling method and ground-penetrating radar scanning.

First, in the application of the core drilling method, we drilled holes in the treated area and extracted corresponding core samples to directly observe the consolidation effect of grouting materials between the track slab and subgrade. The core samples revealed that the injected polymer chemical grout had completely cured, forming a uniform filling layer. The consolidated mass was robust without any signs of loosening or detachment. Particularly in the previously voided areas beneath the track slab, the foamed grout had formed a dense layer with thickness ranging from 1 to 6 mm. This layer exhibited high compactness and successfully eliminated voids between the base slab and subgrade, significantly enhancing track stability and load-bearing capacity (Li, 2023).

Second, through comparative analysis of ground-penetrating radar images before and after grouting, significant improvements were observed. Pre-grouting radar images showed distinct voids beneath the track slab with chaotic echo signals, indicating serious separation issues in the subgrade. Post-grouting, the radar images displayed smooth and continuous echo signals, demonstrating complete filling of voids between the base slab and subgrade and restoration of structural stability. Notably in the track center area, the radar waveforms returned to normal patterns without abnormal reflections caused by excessive voids, providing substantial evidence for the success of the remediation.

By combining these two inspection methods - core drilling and ground-penetrating radar - the conclusion is drawn that the grouting treatment effectively filled the voids, enhanced the stability of track structure, and successfully controlled the deterioration of mud pumping disease (Wang et al., 2022).

4.2 Remediation effectiveness

Through continuous monitoring of the treated subgrade, the actual effectiveness of the grouting measures can be evaluated. In the most severely affected sections, vibration monitoring was conducted on the track after grouting treatment. Measurement results showed that the vertical vibration amplitude of the repaired track slab during train passage was significantly reduced to approximately 0.10 mm, far lower than that observed prior to treatment. This indicates that the grouting treatment successfully restored the track structure to a high level of stability.

Additionally, dynamic testing of the treated sections using track inspection vehicles revealed reductions in peak vibration and long-wave interference values compared to pre-remediation conditions, demonstrating substantial improvements in track smoothness. The running stability of trains under high-speed conditions was markedly enhanced, which is closely related to the grouting treatment's effectiveness in improving the load-bearing performance of both the subgrade and track slab. These improvements optimized the dynamic response of trains at high speeds, reducing vibration levels and noise while significantly enhancing ride comfort and safety (Ding et al., 2022).

Notably, during follow-up inspections, no new mud pumping phenomena were observed in the treated sections, and the stability of the grouted areas was maintained over an extended period. This confirms the long-term effectiveness of grouting technology in restoring subgrade support capacity and eliminating the impacts of defects, validating the feasibility and advantages of this remediation approach.

Conclusion

In summary, this study conducted an in-depth investigation into remediation technologies for mud pumping disease in ballastless track subgrades, proposing grouting technology as an effective solution and verifying its practical application through multiple testing methods. The research demonstrates that grouting technology can effectively fill voids in the track subgrade, enhance the bonding strength between the subgrade and track structure, restore subgrade support capacity, and significantly improve train running stability. The treated track sections exhibited excellent stability with no recurrence of defects, confirming the long-term effectiveness and feasibility of grouting technology. Therefore, grouting technology provides a new technical approach for remediating ballastless track defects while offering strong support for the safe operation of high-speed railways.

Conflict of Interest

The author declares that he has no conflicts of interest to this work.

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