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OVERVIEW OF ADVANCES AND PRACTICES IN HIGH-SPEED RAILWAY EARTH STRUCTURES IN CHINA

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Abstract. High-speed railway (HSR) subgrade design and construction technology have advanced significantly in the past decade. This paper outlines these developments in railway earth structures in China, including HSR design principles, subgrade fill classification, subgrade deformation mechanisms, settlement control methods, transition zones, retaining structures, and deformation monitoring analysis and remediation. We present a conceptual framework for design and examine how factors such as track types and operation speeds influence the dynamic response of the subgrade. Furthermore, we discuss prediction methodologies, influential factors, and challenges associated with long-term subgrade deformation. The load transmission mechanisms and application scenarios are evaluated for foundation treatment methods such as geosynthetic-reinforced pile-supported embankment (GRPS) and pile-raft construction. Several retaining structures have been reviewed, including cantilever, geosynthetic reinforced soil, and anchored wall. Finally, innovative construction technologies for subgrade survey, design, construction, detection, and management are introduced.

Keywords: high-speed railway, transition zones, subgrade deformation, settlement control, earth structure

1. INTRODUCTION

The expansion of high-speed rail (HSR) infrastructure has revolutionized the global transportation network, improving connectivity and fostering economic growth. [1]. China's high-speed rail technology has advanced considerably, particularly in subgrade design concepts, deformation management, transition zones, and contemporary monitoring technologies. [1-3]. These advances enable high speeds while maintaining safety and durability. HSR systems require constant materials, construction technology, and maintenance improvements to be practical and durable.

Traditional narrow-gauge rails have limited train speeds and capacity in Vietnam's railway infrastructure. Recently, Vietnam has approved the construction of a high-speed railway that will connect the northern capital of Hanoi to Ho Chi Minh City in the south. This significant advancement in Vietnam's transportation infrastructure aims to address current limitations while building on successful international experiences. The project will span 1,541 kilometers, passing through 20 localities, with an estimated cost of US$ 67 billion. The high-speed railway project is a large-scale initiative that involves complex technologies and techniques. Therefore, investments must be strategic and synchronized, ensuring high safety standards and technical capability requirements. [4]. Vietnam also faces environmental challenges such as high precipitation, flooding, and soft soil, which affect track stability.

The latest HSR earth structure design strategies, subgrade fill classification and compaction, subgrade deformation and settlement control, transition zones and retaining structures, and deformation monitoring, analysis, and remediation are discussed in this paper. The insights presented here may provide valuable guidance for Vietnam's upcoming HSR development.

2. HSR SUBGRADE DESIGN: CONCEPTS AND METHODS

2.1. HSR subgrade concepts

Typically, HSR comprises high-speed trains, operation control systems, and infrastructure systems (Fig. 1). Engineers must ensure that the system has high stability, efficiency, and compatibility across all components. HSR infrastructure includes tracks, subgrades, bridges, tunnels, and other supporting elements that must work together seamlessly.

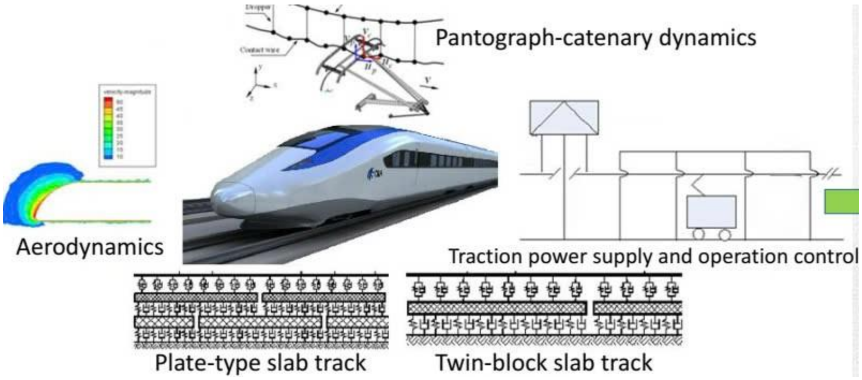


Figure 1. High-speed rail infrastructure showing key components and their relationships.

Several technical issues must be addressed in subgrade design, including subgrade dynamics, design theories, and settlement control. For subgrade dynamics, designers must consider the dynamic characteristics of materials, coupled vehicle-track-subgrade dynamics, and appropriate subgrade dynamic testing techniques. Design theories must account for multi-layer foundation systems and carefully designed transition zones. Settlement control demands highly stringent standards for high-speed trains, efficient ground improvement techniques, and innovative earthwork approaches.

In recent years, the design concept has shifted from a strength-based approach to a deformation-based one. With the emergence and development of high-speed and heavy-haul railways, additional subgrade design concepts have been refined, incorporating novel processes, technologies, materials, testing methods, equipment advancements, and continuous refinements and updates (Fig. 2).

a) Foam concrete b) Inteligent compaction c) Ground-penetrating radar

Figure 2. Advanced technologies in HSR construction: (a) innovative materials, (b) construction methods, and (c) testing techniques.

2.2. HSR subgrade design considerations

In the HSR subgrade design, several critical issues need to be considered. First, basic form design requires strengthening the upper roadbed by transitioning from natural deposits or fill to improved fill materials. This involves transitioning from single-layer to multi-layer systems to accommodate complex hydrothermal conditions. Rational multi-layer structural layouts ensure serviceability through essential functions such as drainage and sealing.

Second, the deformation control is key to HSR's infrastructure. The design approach has shifted from strength-focused considerations to deformation and durability control to ensure operational safety. Deformation control remains a core and challenging issue in HSR construction.

Finally, system compatibility is a fundamental principle for line serviceability. The goal is to minimize deformation and maintain track alignment and elasticity, thereby reducing the dynamic system effects that could compromise performance.

Engineers must consider several essential factors for roadbed design and dynamic testing technology. First, controlling cumulative deformation effects is crucial. It is necessary to prevent ballast penetration and erosion damage on the subgrade surface for ballasted tracks. Additionally, a robust dynamic testing framework must be established to monitor HSR subgrade and deformation control under the coupled effects of long-term cyclic loading from high-speed trains and various environmental factors. Figure 3 presents the relationship between soil strain and modulus ratio for dynamic calculation.

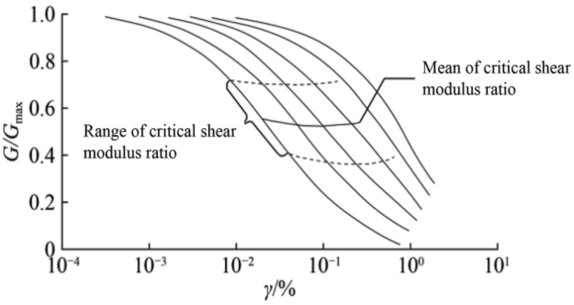


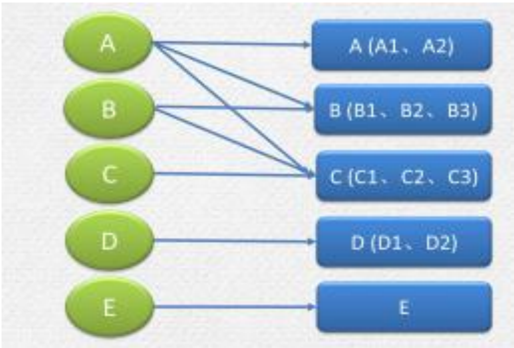
Figure 3. Relationship between soil strain and modulus ratio for dynamic subgrade design [1].

3. SUBGRADE FILL CLASSIFICATION AND COMPACTION

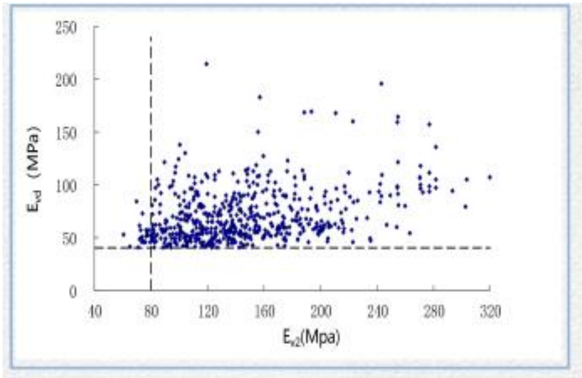
3.1. Subgrade Fill Classification

A new classification standard has been proposed to better categorize fill materials for HSR construction. This standard provides more precise grading levels and a comprehensive grouping system for fill particle gradation (Fig. 4a).

Each country develops railway subgrade standards with requirements for parameters K30, Ev, and Ed, as shown in Table 1 [1, 5-7]. The relationship between soil strain and the modulus ratio (Ed/Ev2) is fundamental for dynamic calculations in HSR, as it governs the subgrade's response to cyclic loading. In China, researchers have developed a correlation between Ed and Ev2 (Fig. 4 b). Normally, Ed is generally larger than Ev2 (Ed/Ev2 ≈ 1.2–2.5) because subgrade materials exhibit higher stiffness under dynamic loading due to reduced plastic deformation and inertial effects [1].



a) Fill classification system



b) Ev 2 vs. Evd correlation

Figure 4. (a) Standardized fill classification system and (b) correlation between key compaction parameters.

Table 1. Comparison of K30, Ev, and Ed for subgrade requirements of different countries [1, 5].

Country	K_{30} (MPa/m)	Ev (MPa)	Ed (MPa)	Notes
China	~50–100	~80–150	~100–200	The subgrade is typically well-reinforced, suitable for 300–350 km/h speeds.
Japan	~60–120	~100–180	~120–220	Shinkansen requires a highly stable subgrade, especially in earthquake-prone areas.
France	~40–80	~70–130	~90–180	TGV uses concrete and ballast subgrade, which are optimized for high speeds.
Germany	~50–90	~80–140	~100–190	CE system emphasizes subgrade durability for both passenger and freight transport.

3.2. Subgrade compaction

China's high-speed railways use a layered subgrade bed structure with surface and bottom layers. The surface layer is 0.7 meters thick for ballasted tracks, and the bottom layer is 2.3 meters thick, as illustrated in Figure 5. For ballastless tracks, the surface layer of the subgrade bed is 0.4 meters thick. In comparison, the bottom layer remains 2.3 meters thick (Fig.6). The surface layer is constructed using graded crushed stone with a maximum particle size of less than 60 millimeters. The bottom layer is filled with Group A and B fillers or chemically stabilized gravelly and sandy soils with a particle size of less than 60 millimeters. The requirements for requirements specify values for parameters K, K30, and Evd, as shown in Figures 5 and 6. Compared to the thickness of the subgrade bed for ballasted tracks, the thickness in China is thicker (3m) than in France, Germany, and Japan (2.0–2.7 m), indicating a concentration on deep load distribution for stability at high speeds [6, 7]. The layer composition of China's ballasted track design prioritizes load distribution over the ballast by using a thicker surface layer (0.7 m) than other designs (0.4–0.7 m). The Deformation Criteria for HSR in China are as follows:

For Ballasted Track Embankment (250–300 km/h)

+ Post-Construction Settlement (PCS): ≤ 5–10 cm (50–100 mm).
+ Transition Zone Settlement: ≤ 3 cm (30 mm).
+ Settlement Rate: ≤ 2 cm/a (20 mm per year).
+ Differential Settlement (Bend Angle): ≤ 1/1000 (i.e., the change in slope between two points should not exceed 0.1%).

For Ballastless Track Embankment (300–350 km/h)

+ Post-Construction Settlement (PCS): ≤ 15–30 mm.
+ Differential Settlement (Bend Angle): ≤ 1/1000.

Japan’s criteria are stricter than both the ballasted (≤ 50–100 mm) and ballastless (≤ 15–30 mm) track images, reflecting the Shinkansen’s focus on precision for speeds up to 320 km/h and seismic safety. In the case of France, the ballastless track image (≤ 15–30 mm) and China’s ballasted track criteria (≤ 20–30 mm), as TGV primarily uses ballasted tracks for speeds up to 320 km/h.

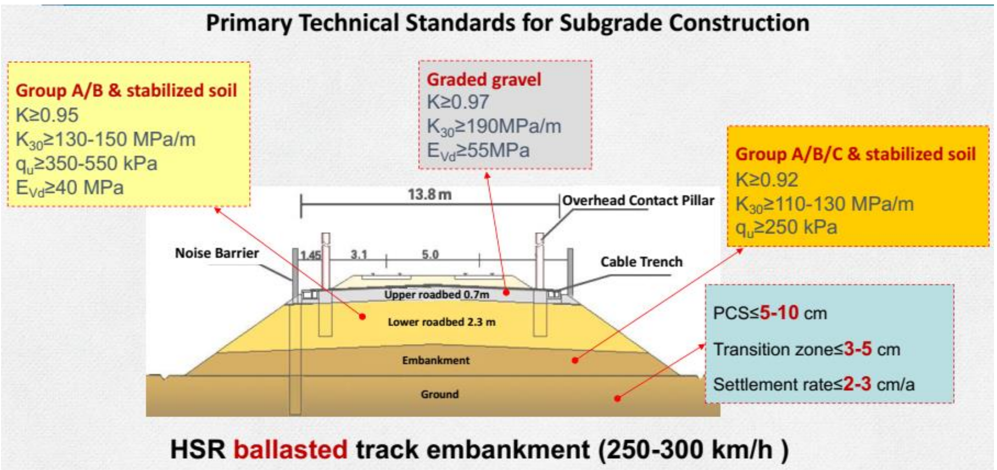


Figure 5. Technical standard for subgrade construction (HSR ballasted track embankment, v=250-300km/h).

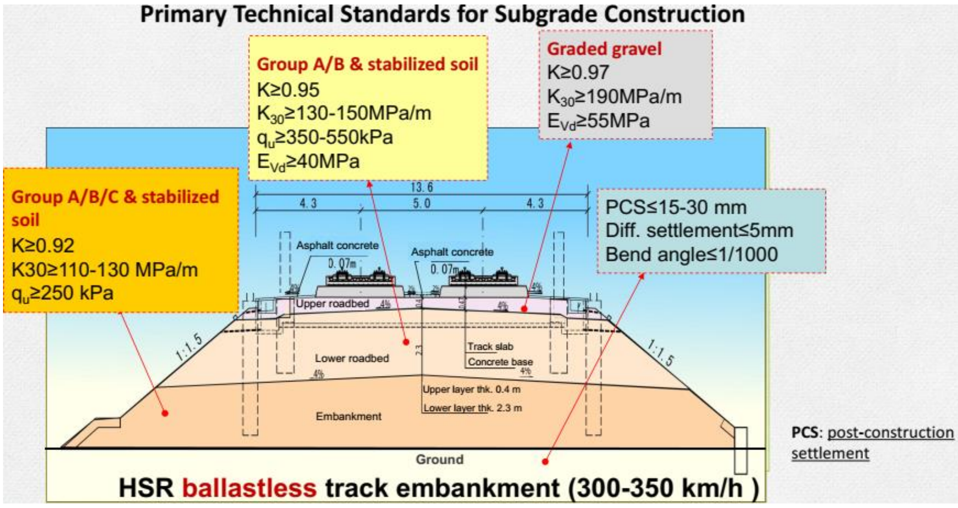


Figure 6. Technical standard for subgrade construction (HSR ballasted track embankment, v=300-350km/h).

4. SUBGRADE DEFORMATION AND SETTLEMENT CONTROL

4.1 Subgrade Deformation

Effective control of subgrade deformation and settlement is crucial for HSR stability, requiring assessment of technical, functional, and economic factors. Significant factors include train loading, which causes elastic (Δs) and cumulative deformation (Δd), as well as fill self-weight, which leads to embankment (Δm) and ground settlement (Δn) (Fig.7). Control strategies involve optimized material selection, structural reinforcement techniques, dynamic load management systems, and real-time monitoring to ensure the long-term durability and operational safety of HSR infrastructure.

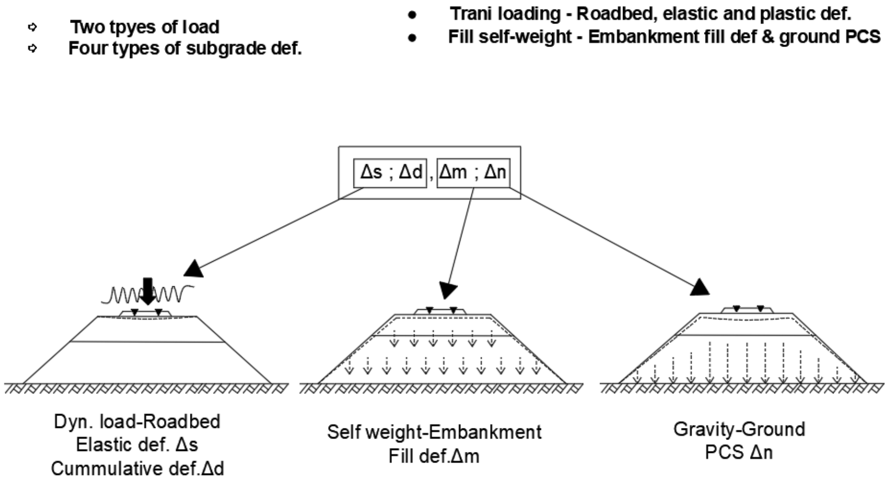


Figure 7. Types of settlement in HSR embankments due to different loading conditions.

For HSR trains at 300–350 km/h, dynamic stresses at the subgrade level are typically 20–100 kPa, causing elastic strains (Δs) of 0.01–0.1% in well-designed subgrades (e.g., Ed=90–220 MPa). This plastic (permanent) deformation(Δd) accumulates over repeated loading cycles due to cyclic shear stresses and vibrations. Excess pore water pressure (EPWP) exacerbates this in soft soils by reducing effective stress, leading to long-term settlement. For soft clays in Vietnam (G=1.8–7.1 MPa), shear strains can reach 0.5–1%, accumulating 5–15 mm of plastic settlement over 10,000 cycles without proper treatment. Δm is the settlement within the embankment due to its self-weight and consolidation of the fill material. For a 3.2 m embankment (Fig.6), using Group A/B materials, this settlement is typically small (e.g., 5–10 mm) if adequately compacted. Δn is the settlement of the natural ground beneath the embankment due to the applied load of the fill. Ground settlement can be significant without treatment due to consolidation and creep in soft soils like Vietnam's soft clays (undrained shear strength <14 kPa, depths 10–50 m).

4.2 Settlement control

4.2.1. Ground improvement

Soft soils generally have high water content, permeability, compressibility, and low shear strength, posing significant challenges to railway foundation stability. Without proper design considerations, cyclic train loading can lead to substantial subgrade settlement. Train loads are transmitted from the tracks through sleepers and slabs to the foundation. Their magnitude depends on train weight, traffic volume, and speed. Therefore, effective settlement control is crucial to maintaining the stability and safety of HSR operations on soft subgrade ground ([5, 8-11]).

The main objectives of ground improvement techniques are to reduce settlement and increase the shear strength of soil, especially when natural ground conditions do not meet stability or deformation control requirements. Soft soil improvement methods are broadly categorized into the following approaches: (1) **Drainage Consolidation**, which employs Sand drains or Prefabricated Vertical Drains (PVD) combined with surcharge preloading or vacuum preloading to accelerate soil consolidation and improve strength; (2) **Replacement for Two-Layer or Composite Foundations**, involving shallow replacement, deep mixing, and gravel columns to replace or reinforce weak soil layers with more substantial materials; (3) **Rigid Pile Support**, utilizing systems such as CFG (cement-fly ash-gravel) piles and concrete pipe piles to provide structural support and minimize settlement; (4) **Vibration and Compaction**, including techniques like vibro-compaction, blasting compaction, and lime-soil piles to densify loose soils and enhance load-bearing capacity; and (5) **Other Methods**, such as reinforcement, grouting, and dynamic compaction, which are chosen for specific ground conditions and project requirements.

Among recent innovations, geosynthetic-reinforced pile-supported embankments (GRPS) and pile-raft foundations have proven particularly effective for settlement control on soft soils.

4.2.2 GRPS – Geosynthetic-reinforced pile-supported embankments

Geosynthetic-reinforced pile-supported (GRPS) embankments have been extensively implemented in HSR projects, such as the Zhengzhou-Xi'an Passenger Line in loess areas and the Beijing-Shanghai HSR in soft clay regions. The system consists primarily of embankment fill, a geogrid-reinforced cushion layer, and supporting piles (Fig. 8). This method provides effective settlement control through two key mechanisms: soil arching and tensioned membrane effects, as shown in Figure 9 [1, 8, 12].

Cement-fly ash-gravel (CFG) Piles and Deep Cement Mixing (CDM) are used in GRPS systems for the Beijing-Shanghai HSR. This system provides high bearing capacity and reduces settlement. CFG piles are typically 0.5–1.0 m in diameter, spaced 2–4 m apart, and topped with pile caps to distribute loads effectively. Geogrids or geotextiles are layered above the piles, typically within a granular mattress (0.3–0.6 m thick), to transfer embankment loads to the piles, minimize differential settlement, and enhance stability. The Beijing-Shanghai HSR crosses extensive soft clay deposits (10–30 m), particularly in the Yangtze Delta, with high water content (30–60%), low shear strength (10–30 kPa), and high compressibility (compression modulus <5 MPa). The settlement monitoring shows effective control. Typical post-construction settlements range from 3–10 mm, with rates stabilizing at <0.01 mm/day within 100–150 days, meeting HSR requirements for ballastless tracks (<15 mm cumulative settlement).

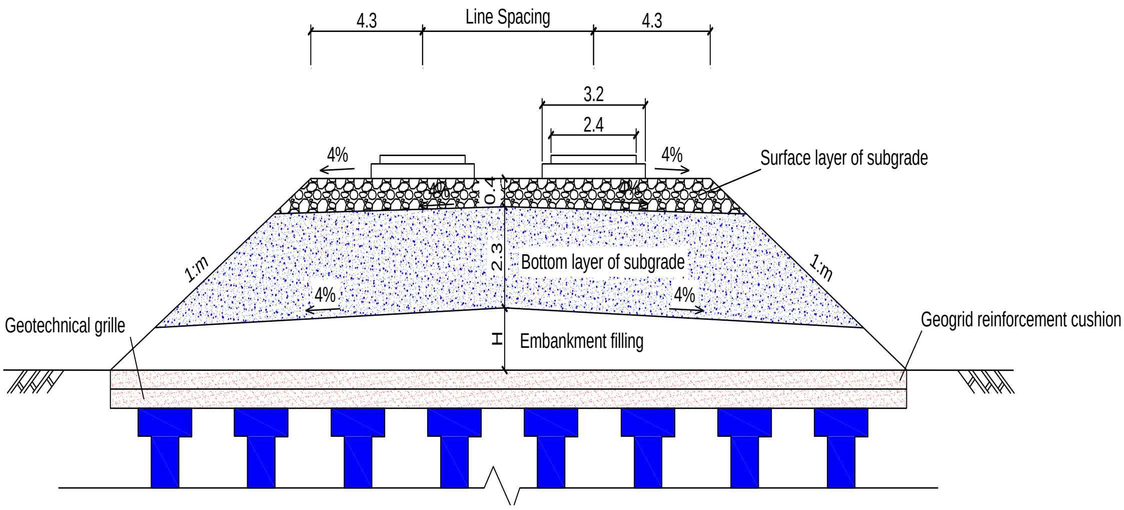
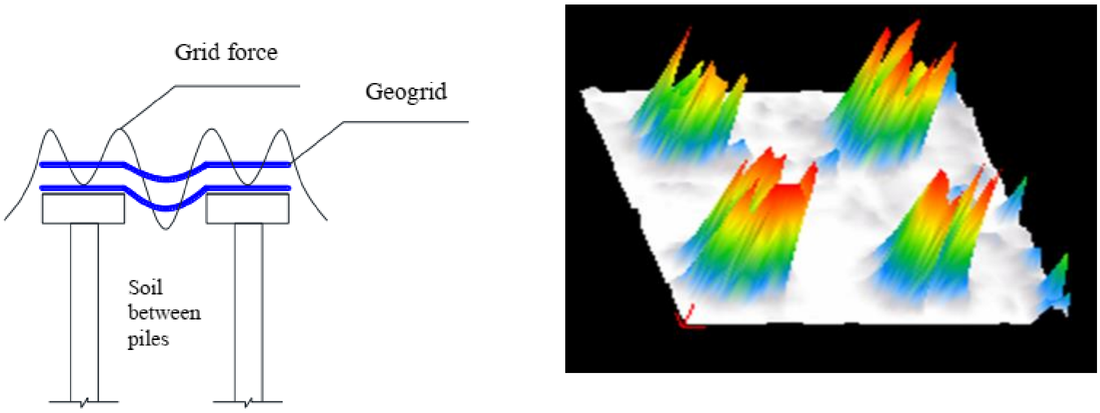


Figure 8. Schematic diagram of pile-net structure showing key components and load transfer mechanisms.



a) Failure modes of reinforced cushion, GRPS

b) Continuous stress distribution within the reinforced cushion, GRPS

Figure 9. Figure 9. (a) Potential failure models and (b) stress distribution patterns in GRPS systems.

4.2.3 Pile-Raft Foundation

Pile-raft structures, consisting of piles, a gravel cushion, and a reinforced concrete slab, are designed to minimize lateral deformation, stress concentration, and uneven settlement by integrating piles and slabs into a unified system. [1, 9, 10]. In this structure, the raft is directly connected to the piles or placed on connecting beams (Fig.10).

This method is widely used in high-speed railway projects with heavy loading conditions, such as the Beijing-Tianjin Passenger Line, Zhengzhou-Xi'an Passenger Line, and Beijing-

Shanghai HSR. Engineers can use theoretical methods or finite element analysis to calculate bearing capacity, settlement, and pore water pressures during construction and operation. [13].

Recent research shows that numerical modelling effectively captures the mechanical behavior of piled-raft systems and surrounding soils. This includes settlement accumulation patterns, excess pore water pressure distribution, and forces acting on piles [7]. Under cyclic loading, the piled-raft foundation is more susceptible to settlement than in static loading conditions. Specifically, piles are more prone to penetrating soil layers under vibrating loads than static loads.

The foundation for pile-raft structures in China consists of Cement-Fly Ash Gravel (CFG) piles ranging from 20 to 30 meters long and 0.4 to 0.6 m in diameter, spaced 1.2 to 3.0 m apart. A concrete raft, typically 0.5 to 0.8 m thick and often reinforced with geogrids, carries 20 to 30% of the load, while the piles support the remainder. This system uses soil arching to reduce soil stress to less than 20% of the total load. Post-construction settlement in these structures has been recorded at 3 to 10 mm, stabilizing within 100 to 150 days. This is well below China's maximum allowable limit of 15 mm for ballastless tracks. Internationally, similar approaches are used: in Japan (Shinkansen), prestressed concrete piles of 20–40 meters and 0.5–1.0-meter rafts are standard; in France (TGV), systems feature 15–25 meter piles and 0.5-meter rafts achieving post-construction settlements of 20–30 millimeters; and in Germany (ICE), pile lengths of 20–30 meters and 0.5–0.8-meter rafts are utilized, also achieving 20–30 millimeters of settlement [1, 6]. For Vietnam’s North-South HSR, a pile-raft system with 20–50 m piles, a 0.5–1.0 m raft, and geogrid reinforcement can meet the ballastless track criteria (PCS ≤ 15–30 mm, bend angle ≤ 1/1000).

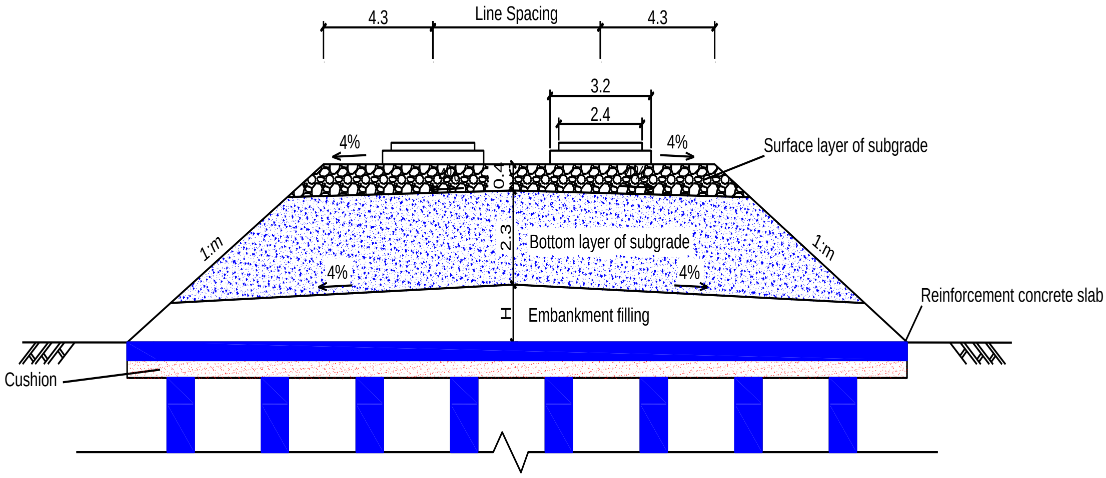


Figure 10. Schematic diagram of pile-raft structure.

5. TRANSITION ZONES AND RETAINING STRUCTURES

5.1 Fundamentals of railway transitions

Transition zones are crucial for minimizing differential settlement between various structural components in railway infrastructure (Fig. 11). These zones address stiffness variations at fill-to-cut transitions, where embankments meet cut sections. They ensure stability and uniform load distribution.

At subgrade-to-bridge interfaces, transition zones ensure smooth load transfer from flexible subgrades to rigid bridges, preventing abrupt changes compromising track performance. Similarly, at subgrade-to-tunnel transitions, transition zones mitigate track irregularities caused by sudden shifts in subgrade conditions. This enhances ride comfort and reduces maintenance demands. Effective design and reinforcement of these zones are essential for maintaining long-term track stability and operational efficiency. Engineers use lightweight fill materials such as expanded polystyrene (EPS) in embankments within transition sections to address these challenges. This reduces overall settlement and improves stability (Fig. 12a). Additionally, elastic sleeper transitions can be implemented in ballasted and ballastless track interfaces to accommodate stiffness differences, reducing abrupt changes in track support conditions (Fig. 12b).

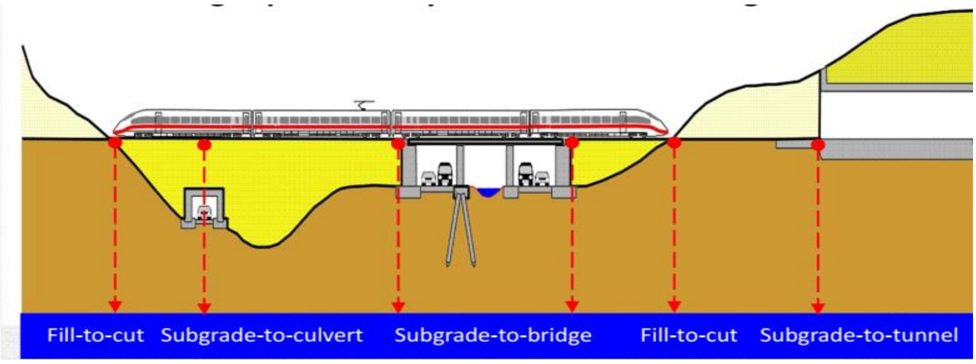


Figure 11. Transition zone configuration showing gradual stiffness adaptation between different structural elements.

a) Lightweight Fill (EPS)

b) Ballasted/Ballastless Track Elastic Sleeper Transition

Figure 12. Advanced solutions for transition zones: (a) lightweight materials and (b) elastic sleeper transitions.

5.2 Retaining structure

High-speed rail (HSR) infrastructure requires robust retaining structures to ensure long-term stability. These structures prevent differential settlement and maintain track alignment under dynamic loads. This section presents three types of retaining structures: anchored retaining walls, counterweight retaining walls, and reinforced retaining walls.

5.2.1. Anchored Retaining Structures

Anchored retaining walls are reinforced with prestressed anchors or tiebacks, providing additional lateral support. These structures are particularly effective in confined spaces, such as urban HSR corridors, where traditional retaining walls may lack sufficient stability. By transferring loads into stable soil strata, anchored retaining structures enhance resistance to landslides and soil movement, thereby ensuring long-term durability (Fig.13). HSR ground anchors are designed to withstand cyclic dynamic loads from trains traveling at speeds between 200 and 380 km/h, which create vibrations and induce fatigue stresses. To prevent anchor loosening and soil degradation, HSR standards mandate the analysis of high-frequency vibrations from 5 to 20 Hz. These anchors must maintain stability under 1,000,000 to 10,000,000 load cycles over a lifespan of 50 to 100 years, unlike highway anchors that experience less frequent dynamic loading. Additionally, pull-out tests for HSR anchors are conducted at 1.5 to 2 times the design load, in contrast to the 1.2 to 1.5 times required for general construction, thus ensuring a higher safety margin. Furthermore, while conventional anchors may not consider seismic loads in low-risk zones, HSR anchors must guarantee no disruption to the track during moderate earthquakes, specifically those with magnitudes ranging from 6 to 7.

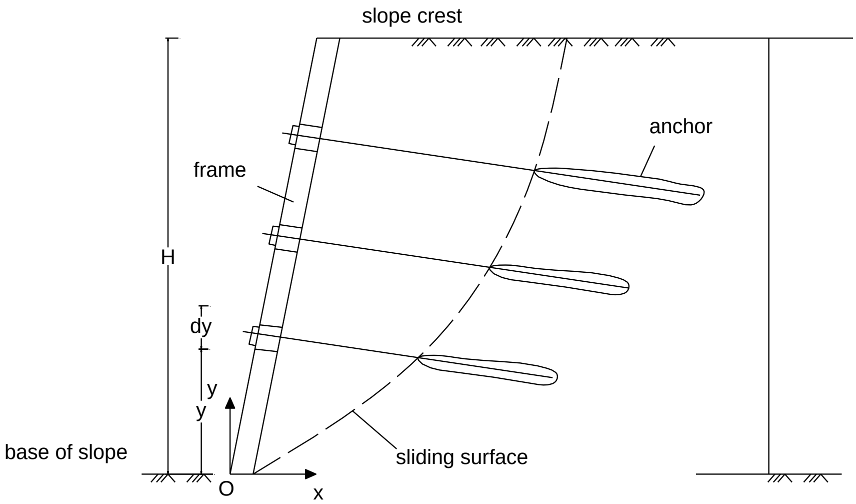


Figure 13 Ground anchor wall showing anchoring mechanism and load distribution.

5.2.2. Counterweight Retaining Walls

This method optimizes the weight distribution of counterweight retaining walls to enhance stability. It minimizes the risk of tilting or overturning due to high-speed train loads (Fig. 14). The counterweight design provides additional resistance against lateral earth pressure while occupying less space than conventional gravity walls. Counterweight walls, typically reinforced concrete, rely on their mass and geometry for stability, often taking shapes like rectangular, trapezoidal, or stepped profiles. For HSR, the settlement must remain below 5 mm for ballastless tracks; thus, walls are built on compacted foundations or shallow piles to reduce soil deformation. Dynamic loading should be considered in the design. Walls must also dampen vibrations from trains traveling at 200 to 380 km/h, which may necessitate thicker bases or additional backfill.

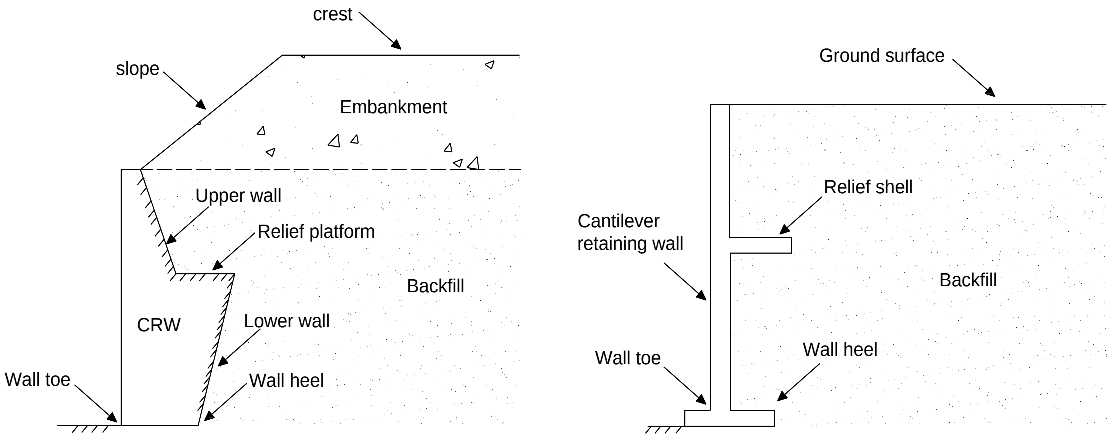
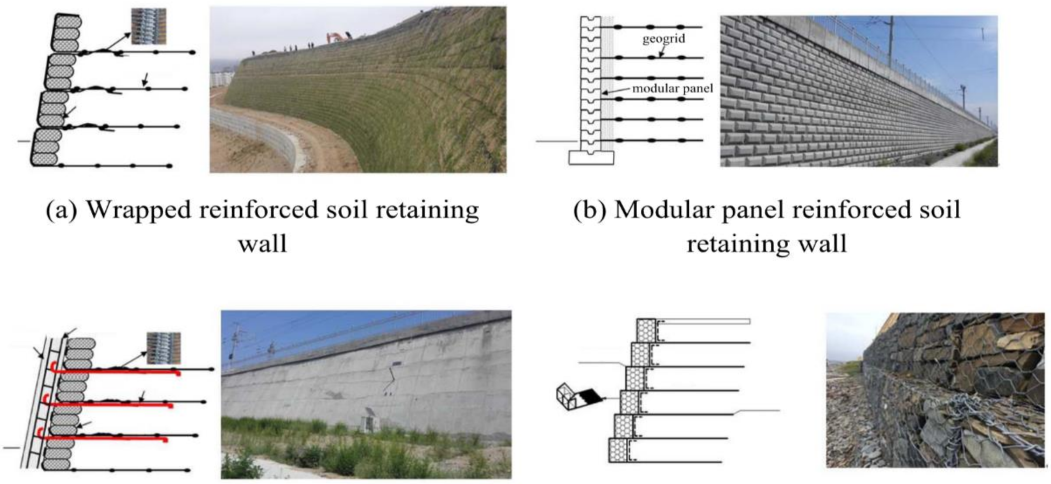


Figure 14. The counterweight retaining wall shows structural components and stabilizing mechanisms.

5.2.3. Reinforced Retaining Wall



(a) Wrapped reinforced soil retaining wall

(b) Modular panel reinforced soil retaining wall

© Integral rigid panel reinforced soil retaining wall

(d) Gabion reinforced soil retaining wall

Figure 15 Various reinforced retaining structures showing different configurations and applications in HSR projects [1].

Reinforced retaining walls incorporate geosynthetic materials, such as geogrids for soil reinforcement and geotextiles for filtration and separation, to improve soil strength and stability. These walls are cost-effective and provide excellent resistance against lateral earth pressure while allowing for greater flexibility in construction. Reinforced retaining structures are often combined with mechanically stabilized earth (MSE) techniques, creating a durable solution for embankments and cut slopes along high-speed rail corridors (Fig. 15).

Dynamic design considerations include modeling train loads as cyclic stresses between 50 and 100 kPa over up to 10 million cycles, according to TB 10093-2016 standards. Geogrids improve soil stiffness (E ≥ 50 MPa), reducing vibration amplification compared to unreinforced soil, with deformation verified through shake-table tests or numerical modeling like FLAC3D [14, 15]. In seismic areas, high-strength geogrids (≥100 kN/m) should be used in regions with accelerations of 0.2 to 0.4g, ensuring a Factor of Safety of at least 1.2 under seismic loads.

In China, reinforced retaining walls are effectively used. For example, the Shanghai-Hangzhou HSR employed geosynthetic walls ranging from 4 to 8 meters high, using geogrids with a strength of 60 kN/m to stabilize clay embankments, achieving a settlement of only 3 mm compared to 12 mm for gravity walls. For the Zhengzhou-Xi'an HSR, loess slopes were reinforced with geotextile-wrapped walls (Fig.15a), leading to a 60% reduction in concrete usage compared to counterweight designs. The Beijing-Tianjin HSR utilized modular block walls with geogrids (Fig. 15 b), conserving 25% of land near stations versus gravity walls.

6. DEFORMATION MONITORING, ANALYSIS, AND REMEDIATION

A comprehensive deformation monitoring, analysis, and remediation system has been developed to ensure quality and enhance railway subgrade performance and safety (Fig. 16). Each stage includes numerical modeling and analysis to strengthen railway subgrade performance and safety throughout the infrastructure's lifecycle.

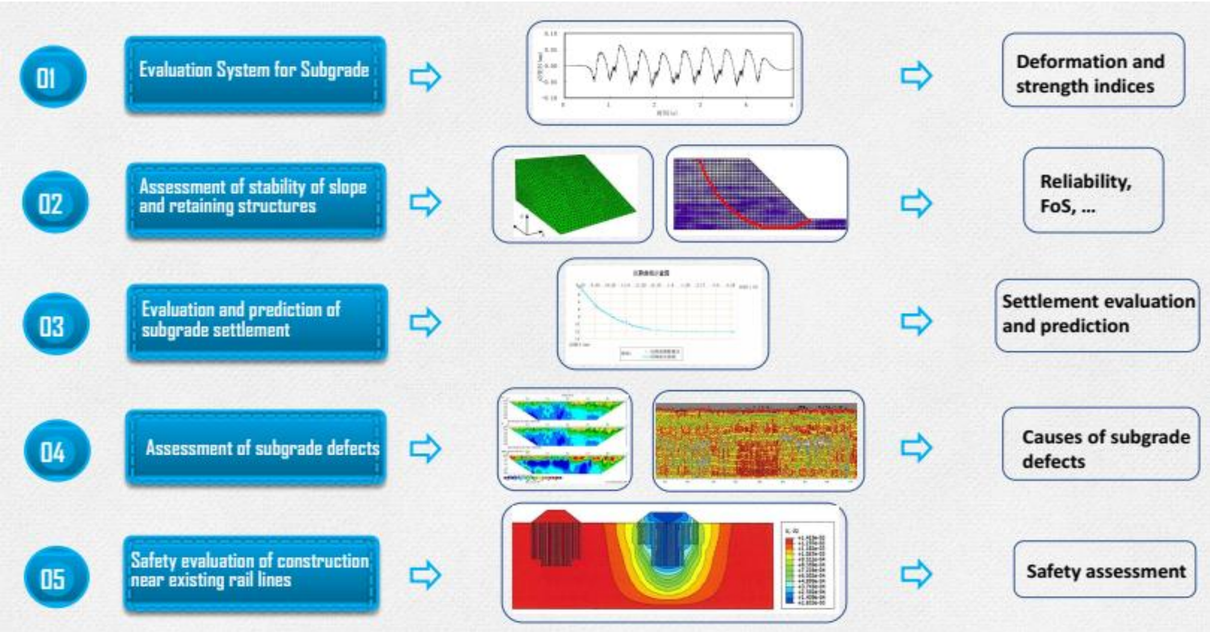


Figure 16. Process flowchart for deformation monitoring, analysis, and remediation in HSR infrastructure.

The following monitoring measures are critical for maintaining the integrity of HSR infrastructure:

- Comprehensive soil investigation using advanced techniques (Fig. 17)
- Continuous monitoring of subgrade settlement using precision instruments
- Systematic monitoring of heaved subgrade in expansive soil regions
- Monitoring of construction impact on adjacent infrastructure and environment
- Integrated 3D slope monitoring using laser scanning technology (Fig. 18).

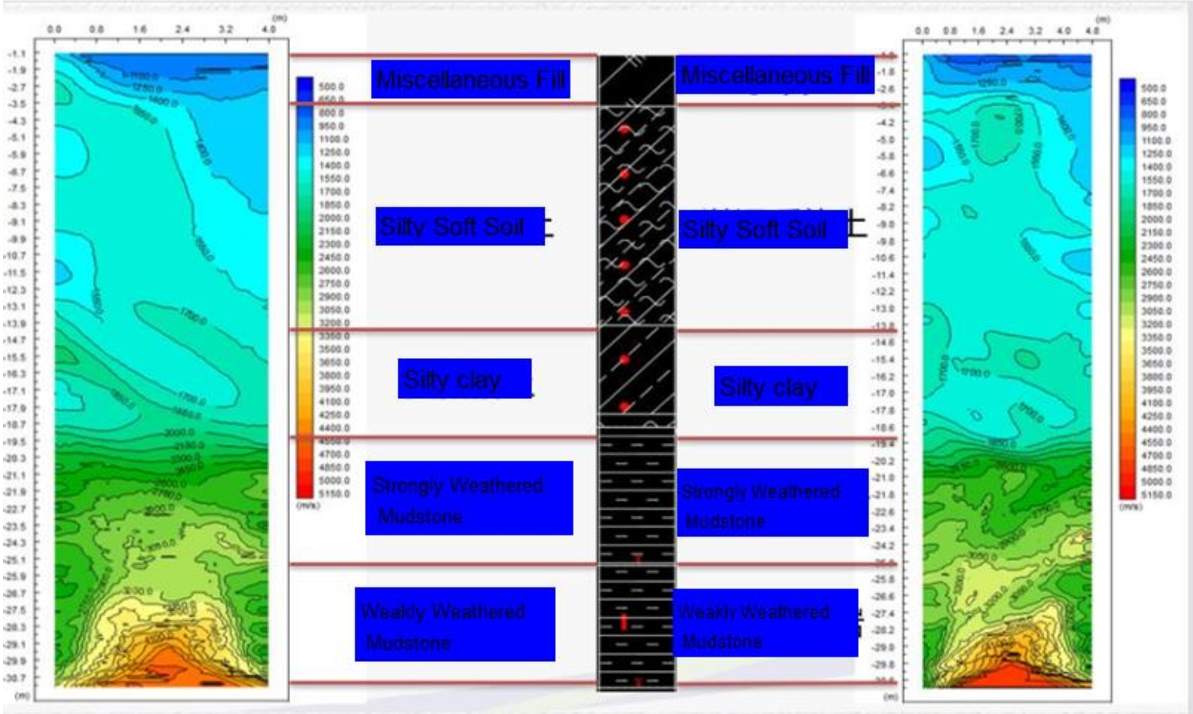


Figure 17. Cross-hole seismic CT imaging for detailed subsurface characterization.

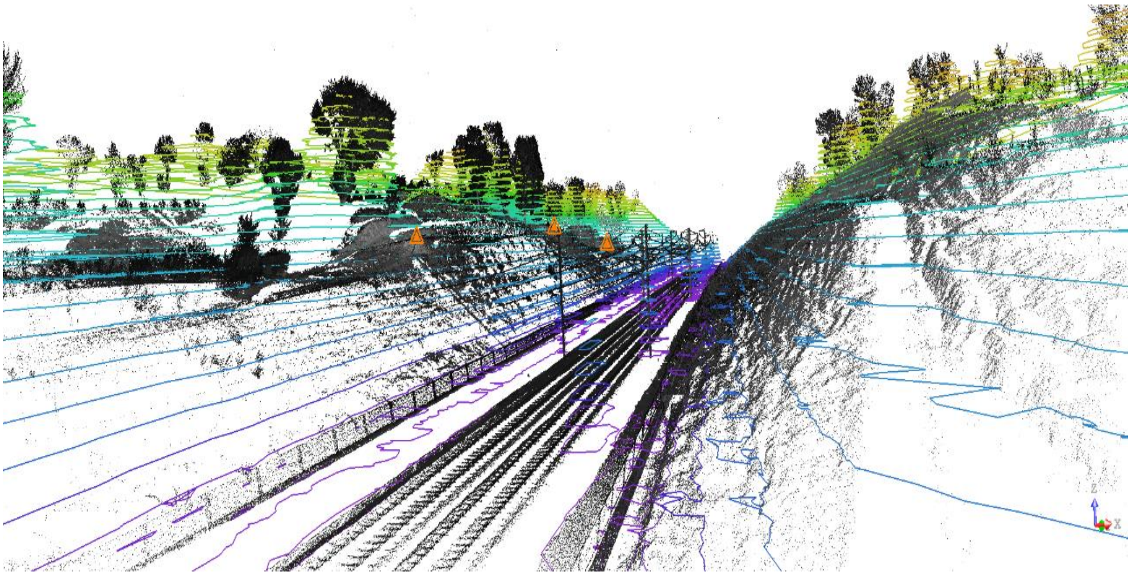


Figure 18. High-precision 3D scanning technology for slope stability monitoring.

7. CONCLUSION

This paper discusses the development of high-speed rail (HSR) infrastructure in China, focusing on advancements in subgrade engineering, settlement control, and material innovation. The use of advanced subgrade materials, intelligent compaction technologies, and improved quality control methods has significantly enhanced the stability and durability of the tracks. As a result, this has ensured safe and efficient operations at high speeds.

Vietnam's proposed design can incorporate standards from China and ballastless tracks, utilizing ground improvement and reinforcement to meet these criteria in soft soils, ensuring long-term stability and safety at 350 km/h.

For the North-South High-Speed Rail in Vietnam, strategies such as ground improvement, piled rafts, geogrids, and reinforced retaining walls can ensure the subgrade meets strict requirements, balancing technical, functional, and economic factors for long-term durability and safety.

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