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Study on the State Evolution and Long-Term Stability Control of Subgrades

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Abstract

As highway engineering in China shifts from large-scale construction to long-term maintenance, the influence of long-term subgrade stability on pavement service performance has become increasingly prominent. Current construction control practices mainly rely on stage-specific indicators such as the degree of compaction, which cannot fully capture the continuous evolution of subgrade conditions under traffic loading, moisture fluctuations, wetting–drying cycles, and freeze–thaw actions. From a life-cycle perspective, this paper analyzes the relationships among compaction state, moisture condition, and mechanical response, and discusses the effects of key parameters-including degree of compaction, porosity, water content, degree of saturation, matric suction, and resilient modulus-on subgrade performance. The study suggests that subgrade stability is jointly governed by fill material properties, compaction energy, moisture migration, particle rearrangement, and cumulative loading effects. Future evaluation should shift from single-index control based on compaction degree toward a coordinated assessment using multiple state parameters, thereby providing a basis for subgrade distress diagnosis, performance prediction, and maintenance decision-making.

Keywords

Subgrade State; Long-term Stability; Degree of Compaction; Moisture Condition; Resilient Modulus.

1. Introduction

As China’s highway infrastructure development gradually shifts from large-scale new construction to the stage of existing-network maintenance and quality enhancement, the primary technical focus of road engineering has shifted from “completion and opening to traffic” to the “maintenance of long-term service performance.” During road operation, distresses such as pavement cracking, settlement, rutting, and mud pumping are often first manifested in the pavement structural layers. However, their causes are not confined to pavement materials or surface-layer structures themselves; in many cases, they are closely associated with strength degradation, accumulated deformation, fluctuations in moisture condition, and structural rearrangement within the subgrade. Therefore, if treatment measures are directed only at visible pavement distresses while neglecting the long-term evolution of subgrade conditions, it is difficult to fundamentally ensure the durability and service safety of road structures.

As the fundamental load-bearing unit between the pavement structure and the natural foundation, the subgrade is responsible, on the one hand, for transmitting and dispersing vehicle loads, environmental loads, and additional stresses from the pavement structure. On the other hand, it must also adapt to complex service environments, including foundation settlement, groundwater fluctuations, rainfall infiltration, wetting–drying cycles, and freeze–thaw cycles. Previous review studies have indicated that the engineering problems of embankment subgrades are essentially closely related to their state characteristics. The subgrade state does not remain constant after construction but continues to evolve throughout the entire life cycle and gradually tends toward a dynamic equilibrium [1]. Therefore, from the perspective of long-term service, the understanding of subgrade performance should shift from single-stage construction quality acceptance to state control throughout the construction–operation process.

The “subgrade state” discussed in this paper can be understood as a multi-index integrated representation of subgrade bearing capacity, deformation stability, moisture migration characteristics, and structural integrity. Although the initial compaction state formed during construction is undoubtedly important, the fluctuation range of state parameters, the rate of deterioration during operation, and the lower performance limit under extremely adverse conditions exert more direct control over the long-term stability of roads. It is therefore evident that the key to long-term subgrade stability does not lie in pursuing an isolated “optimal initial state,” but rather in maintaining the relative stability of its mechanical and hydraulic states throughout the entire life cycle.

2. Limitations of Current Construction Control Indicators for Subgrades

2.1 Relativity of Degree of Compaction

In terms of its definition, the degree of compaction is generally expressed as the ratio of the in-situ dry density to the maximum dry density obtained in laboratory tests, and is therefore a typical relative indicator. However, the laboratory maximum dry density is not the absolute maximum density that a fill material can attain under all conditions. Instead, it is jointly affected by compaction energy, water content, testing method, particle composition, and material properties. The maximum dry density obtained under different compaction standards or testing conditions may vary, thereby influencing the evaluation results of field compaction degree (Fig. 1).

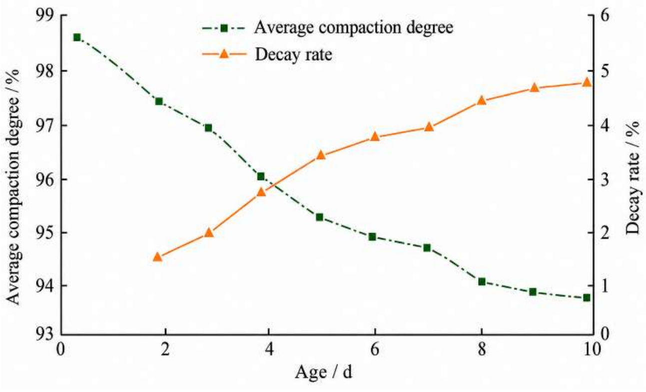


Fig. 1 Attenuation of degree of compaction with age

Sawangsuriya et al. [2] pointed out that the modulus of compacted soils is affected not only by dry density and water content, but also by matric suction and the soil structure formed during compaction. This indicates that although the degree of compaction can reflect the level of densification to some extent, it is difficult to reveal differences in particle arrangement, pore distribution, and structural state within the fill material. In other words, even when the same degree of compaction is obtained from field testing, subgrade soils formed under different moisture conditions, compaction methods, and gradation characteristics may still exhibit significant differences in internal structure and mechanical response. Using the degree of compaction alone as the basis for subgrade quality evaluation may therefore lead to the problem that the specified index is satisfied while the actual subgrade states differ.

2.2 Insufficient Characterization of Moisture Condition

Subgrade soil is a multiphase medium that is highly sensitive to moisture. Moisture-related state parameters, such as water content, degree of saturation, and matric suction, directly affect the effective stress, interparticle interaction, and pore water pressure of the soil. The degree of compaction mainly reflects the dry density level, but it cannot adequately characterize the influence of changes in moisture condition on strength and stiffness.During actual service, subgrades are subjected over long periods to rainfall infiltration, groundwater level fluctuations, capillary rise, wetting–drying cycles, freeze–thaw cycles, and changes in drainage conditions. As water content increases, soil suction decreases, and the cementation and interlocking effects between particles are weakened. Consequently, the resilient modulus, shear strength, and bearing capacity often decrease. This effect is particularly pronounced in unsaturated cohesive soils. Yang et al. [4] demonstrated through tests on compacted subgrade soils that the resilient modulus of soil is closely related to the post-construction moisture condition and suction variation, and that the degree of compaction cannot independently explain the evolution of subgrade stiffness. If construction control focuses only on compaction degree while neglecting parameters such as water content and matric suction, it is difficult to accurately evaluate the long-term stability of subgrades under complex moisture environments.

2.3 Insufficient Adaptability to Different Fill Materials

Different types of subgrade fill materials exhibit significant differences in particle composition, plasticity characteristics, pore structure, and hydraulic response, and the mechanisms controlling their mechanical properties are not the same. For cohesive soils, water content, plasticity index, and matric suction have significant effects on shear strength and resilient modulus. For sandy soils, graded crushed stone, and rockfill materials, particle gradation, skeleton structure, pore connectivity, and interparticle interlocking usually play dominant roles. For soil–rock mixtures, the coarse-particle skeleton and the filling state of fine particles jointly determine the compaction effect and deformation characteristics.The same degree of compaction does not mean that different fill materials possess the same bearing capacity and deformation stability. This is particularly true for soil–rock mixture subgrades and rockfill subgrades. Because of their high coarse-particle content, wide particle-size distribution, and large variation in pore scale, different structures may form after compaction, such as skeleton-supported, fine-particle-filled, or suspended dense structures. These different structures correspond to distinct load-transfer paths, deformation compatibility, and moisture migration characteristics. Therefore, as a unified control indicator, the degree of compaction cannot fully reflect the structural differences and service-performance differences among subgrades constructed with different fill materials.

2.4 Insufficient Reflection of Service-Period Evolution

The current compaction-degree control system mainly serves construction-stage quality acceptance and emphasizes the initial densification state after filling is completed. However, the subgrade is a concealed engineering structure that is subjected to traffic loading and environmental effects over a long period, and its state does not remain unchanged after construction. Under the effects of overburden load, repeated vehicle loading, water-content variation, and time-dependent behavior, the dry density, porosity, particle contact mode, and mechanical parameters of the fill body may all undergo continuous adjustment.Existing studies have shown that, under post-construction changes in moisture environment, compacted soils exhibit evident later-stage evolution in the relationships among modulus, suction, and water content [3]. This means that meeting the compaction-degree requirement during construction only indicates that the subgrade satisfies the densification requirement at a specific time and under a specific moisture condition; it does not guarantee long-term stability during operation. With the occurrence of moisture migration, fine-particle loss, particle rearrangement, and local softening, the subgrade may experience stiffness degradation, accumulated settlement, mud pumping, wetting-induced softening, and uneven deformation. The degree of compaction is therefore clearly stage-dependent and cannot meet the requirements of life-cycle performance evaluation for subgrades.

2.5 Insufficient Multi-Parameter Collaborative Control

The long-term stability of subgrades is jointly controlled by compaction state, moisture condition, material structure, and external loading. No single indicator can fully reflect their service performance. The degree of compaction mainly characterizes dry density, while the resilient modulus can reflect mechanical response to a certain extent. However, neither can comprehensively describe the state evolution of subgrades under hydro-mechanical coupling. In particular, under the combined effects of extreme rainfall, freeze–thaw cycles, groundwater level fluctuations, and heavy traffic loading, subgrade performance degradation is often the result of multi-factor coupling rather than insufficient compaction alone. The current subgrade construction control system still has the limitation of "emphasizing initial densification while neglecting service-period state evolution." In the future, subgrade quality evaluation should gradually shift from single-index control based on degree of compaction to collaborative control using multiple state parameters. Specifically, on the basis of compaction degree, indicators such as water content, degree of saturation, matric suction, porosity, resilient modulus, settlement deformation, and particle-structure characteristics should be incorporated to establish a comprehensive evaluation system capable of reflecting both construction-stage quality and service-period performance evolution.

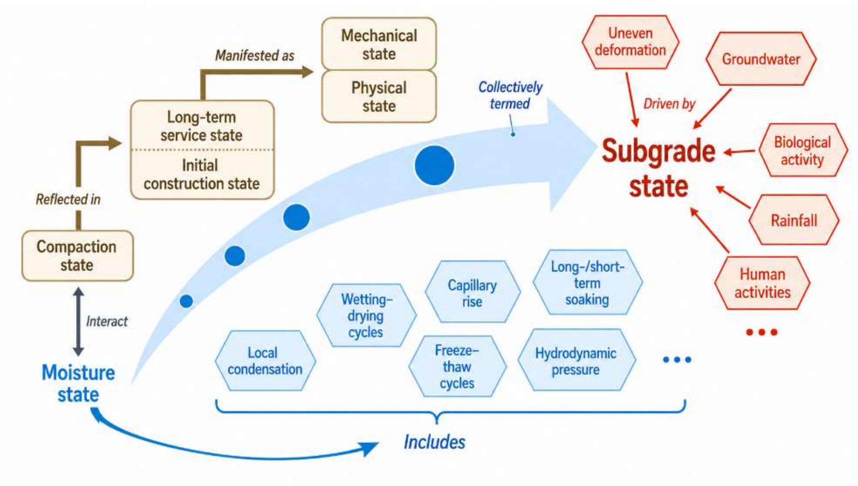


Fig. 2 Diagram of subgrade state

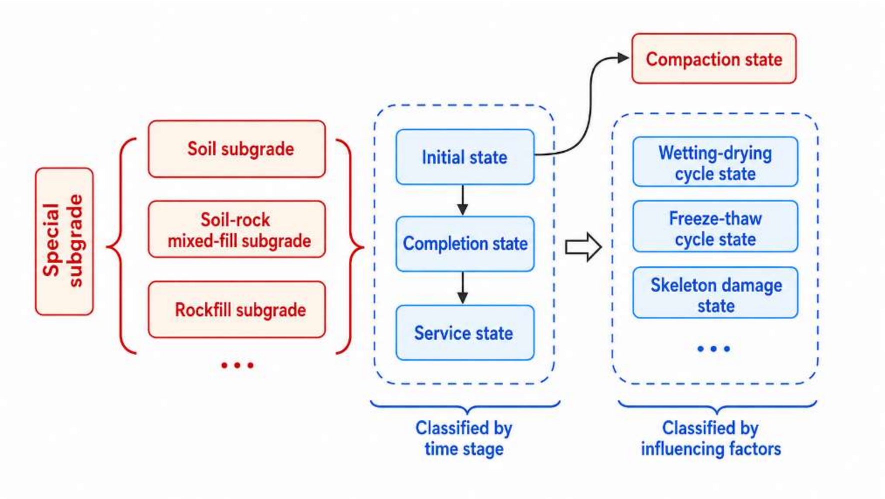


Fig. 3 Schematic diagram of subgrade state classification

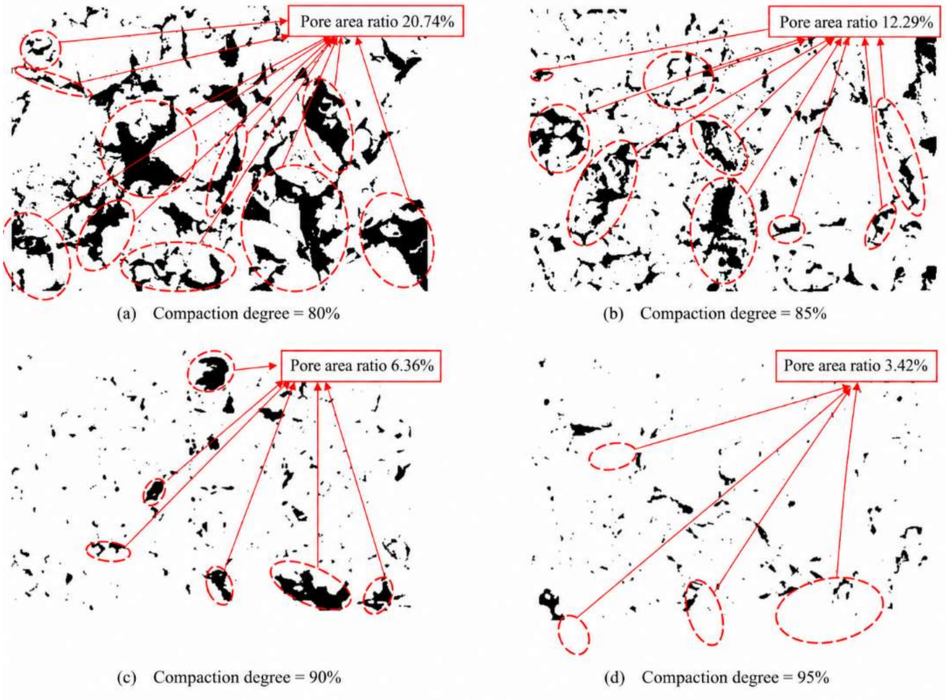
In summary, as a traditional construction control indicator, the degree of compaction still plays an irreplaceable fundamental role in subgrade quality acceptance. However, its relativity, stage-dependence, and single-index nature make it difficult to independently characterize the long-term service performance of subgrades. To meet the requirements of life-cycle stability control for roads, it is necessary to move beyond the single compaction-degree evaluation model and establish a multi-index collaborative control method from the perspectives of compaction state, moisture condition, structural state, and mechanical response. Such an approach can provide a more reliable basis for evaluating long-term subgrade stability and making maintenance decisions.

3. Evolution of Subgrade State Parameters and Their Mechanical Response

3.1 Evolution of Compaction State Parameters

The compaction state of a subgrade can be characterized by various indicators, such as degree of compaction, porosity, settlement difference, solid volume fraction, and air volume fraction. Among these, the degree of compaction mainly reflects the relative density of the fill material during construction, whereas porosity, air volume fraction, and particle contact state can better represent the internal structural characteristics of the fill. With the increase in traffic loading levels and the development of construction equipment, subgrade compaction technology has gradually evolved from light compaction to high-energy compaction methods, such as heavy compaction, vibratory compaction, impact rolling, and dynamic compaction. However, different compaction techniques involve different modes of energy input, particle movement paths, and pore compression mechanisms. Therefore, even when the same degree of compaction is achieved, different mesostructures and mechanical states may still be formed.

Compaction energy is an important factor affecting the compaction state(Fig. 4). In general, an increase in compaction energy helps increase dry density, reduce porosity, and improve short-term bearing capacity; however, such improvement is not linear. For coarse-grained soils and soil–rock mixtures, excessive compaction energy may induce particle breakage, thereby altering the original gradation, skeleton structure, and pore distribution. When the compaction energy exceeds a reasonable range, over-compaction may even damage the soil structure, resulting in reduced strength and deformation stability. Therefore, subgrade compaction control should not simply pursue a higher degree of compaction. Instead, a reasonable state-control range should be determined by considering fill material type, moisture condition, particle gradation, and compaction energy.



(a) Compaction degree = 80%
(b) Compaction degree = 85%
(c) Compaction degree = 90%
(d) Compaction degree = 95%

Fig. 4 Pore distribution under different degrees of compaction (binary images)

3.2 Evolution of Moisture State Parameters

Compared with the compaction state, the moisture state better reflects the dynamic changes in subgrades under service environments. The moisture state of a subgrade can generally be characterized by indicators such as water content, degree of saturation, consistency, matric suction, and the soil–water characteristic curve. In regions where hydrothermal coupling is significant, the effects of temperature gradient, hydraulic conductivity, diffusivity, and freeze–thaw processes on moisture migration should also be considered. Since subgrades are exposed to an open environment over a long period, their moisture conditions are jointly affected by rainfall infiltration, evaporation, groundwater level fluctuation, capillary rise, pavement-covering effects, and drainage conditions, showing significant regional, seasonal, and time-dependent characteristics. Matric suction serves as an important link between the moisture state and mechanical performance. Han and Vanapalli [5] showed that there is a significant nonlinear relationship between the resilient modulus of compacted subgrade soil and suction, and that this relationship is jointly influenced by soil type, water content, and external stress state. Lim et al. [6] further indicated that, for compacted clay, matric suction affects not only the resilient modulus but also engineering bearing indicators such as CBR. Therefore, water content alone is insufficient to fully describe the moisture state of unsaturated subgrade soil. It is preferable to combine water content, degree of saturation, and matric suction to establish a more explanatory evaluation index for the hydraulic state of subgrades.

After a subgrade reaches equilibrium moisture content, its moisture condition is not necessarily close to the optimum moisture content during construction(Figure 5). In humid regions, groundwater level and long-term soaking may exert a continuous influence on the water content of deep subgrade layers. In arid and semi-arid regions, the alternating effects of evaporation, capillary rise, and rainfall infiltration may lead to repeated fluctuations in moisture condition. Wetting–drying cycles and freeze–thaw cycles can also alter the soil–water characteristic curve, causing different suction levels under the same water content and resulting in an evident hysteresis effect. As the number of cycles increases, the pore structure and water occurrence forms of the soil may gradually become stable; however, the initial cycles often cause more pronounced structural disturbance and performance degradation.

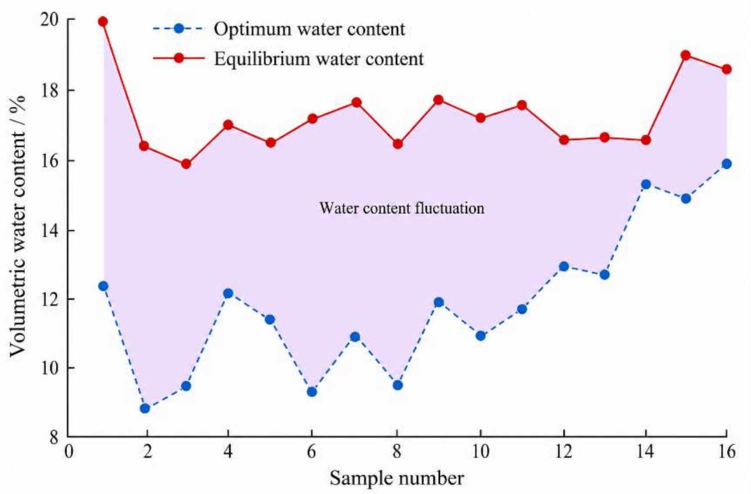


Fig. 5 Variation of Optimal and Equilibrium Moisture Content of Different Soil Samples

3.3 Correlation of Mechanical Parameters under State Changes

The evolution of subgrade mechanical performance is essentially the result of the combined effects of compaction state, moisture state, and material structure. The compaction state determines the initial skeleton structure and pore characteristics of the fill material, while the moisture state affects soil strength and stiffness by altering matric suction, effective stress, interparticle cementation, and pore water pressure. Liu Weizheng et al. [7] conducted experimental research on the dynamic resilient modulus of compacted subgrade soil under varying water contents, and pointed out that changes in water content significantly affect the dynamic resilient modulus of subgrade soil. They further showed that this variation can be described using predictive models. From the perspective of pavement rutting prediction, Rahman et al. [8] also confirmed that changes in water content can markedly alter the resilient modulus of subgrade soil and further influence the long-term deformation response of pavement structures.Different fill materials exhibit different mechanical responses to state changes. For cohesive soils, water content and matric suction are key factors affecting strength, stiffness, and deformation characteristics. For coarse-grained fills such as sandy soil, aeolian sand, and graded crushed stone, particle gradation, density, and pore connectivity play more prominent roles in controlling mechanical performance. For soil–rock mixtures or rockfill subgrades, the coarse-particle skeleton, fine-particle filling state, and degree of particle breakage jointly determine their macroscopic mechanical behavior. Therefore, although certain correlations exist among parameters such as resilient modulus, CBR, shear strength, cohesion, and internal friction angle, these correlations are often jointly affected by soil type, water content, degree of compaction, and testing path, making it difficult to describe them using a single empirical formula.

From the perspective of long-term service, the degradation of mechanical performance induced by changes in subgrade state exhibits significant nonlinearity and path dependence. Wetting weakens interparticle adsorption and structural strength, thereby reducing resilient modulus, shear strength, and bearing ratio. Although drying may restore suction to some extent, the mechanical performance may not fully recover to its initial level because wetting–drying cycles can disturb the pore structure and promote the development of microcracks. Therefore, subgrade performance evaluation should be based on the continuous chain of “compaction state–moisture state–structural evolution–mechanical response,” so as to reveal the mechanisms by which changes in state parameters affect long-term stability.

3.4 Loading Effects and State Evolution Models

In addition to environmental factors, traffic loading is an important external factor driving the continuous evolution of subgrade state. Vehicle loads are repetitive, random, and time-dependent. Their effects depend not only on load magnitude, frequency, and number of cycles, but also on water content, degree of compaction, fill structure, and drainage conditions. Under short-term loading, the subgrade mainly exhibits recoverable elastic deformation. Under long-term repeated loading, plastic strain gradually accumulates and may undergo different development stages, such as stable, metastable, and unstable stages. When the subgrade water content increases or pore water pressure rises, the amplification effect of repeated loading on permanent deformation becomes more pronounced, making the subgrade more prone to settlement, mud pumping, cracking, and local instability.Chu et al. [9] investigated the permanent deformation characteristics of unsaturated subgrade soil under cyclic loading and pointed out that water content, stress level, and loading frequency all influence the accumulation process of permanent deformation. This indicates a clear coupling effect between traffic loading and moisture state. At the mesoscopic scale, cyclic loading can induce particle migration, rearrangement, force-chain adjustment, and pore-structure reorganization. With the participation of water, fine-particle migration and moisture migration may reinforce each other, further weakening the overall stability of the fill. For widely graded fills and soil–rock mixture subgrades, particle migration, fine-particle loss, and skeleton loosening are more prominent, and they constitute important causes of long-term differential settlement and local collapse.

Traditional unsaturated soil mechanics, fatigue damage theory, creep theory, and cumulative deformation models can explain, to some extent, the performance changes of subgrades under environmental and loading effects. However, they still have limitations in dealing with multi-factor coupling, time-varying parameters, and nonlinear degradation. In recent years, with the development of intelligent monitoring and data analysis technologies, subgrade state assessment has gradually shifted from single empirical models to data-driven models. Zou et al. [10] used gene expression programming and artificial neural network methods to predict the resilient modulus of compacted subgrade soil under the effects of freeze–thaw cycles and water-content variation. Their results showed that machine-learning methods can effectively capture the nonlinear relationships among environmental factors, stress states, and material parameters. In the future, combining field monitoring, laboratory testing, and intelligent algorithms will help improve the accuracy of long-term subgrade performance prediction and distress early warning.

4. Conclusion

In summary, the long-term stability of subgrades is not determined solely by the degree of compaction during construction, but is the result of the combined effects of compaction state, moisture state, fill structure, and external loading. The compaction state determines the initial structural foundation of the subgrade; the moisture state controls the degradation process of strength and stiffness; traffic loading drives deformation accumulation and structural rearrangement; and fill composition and particle gradation influence the specific manifestations of these processes. Although the current construction control system centered on the degree of compaction plays a fundamental role in engineering practice, it still has certain limitations in meeting life-cycle service requirements. Future research should be further deepened in the following aspects. First, a subgrade state index system incorporating degree of compaction, porosity, water content, degree of saturation, and matric suction should be established. Second, the structural evolution mechanisms of different fill materials under the coupled effects of wetting–drying cycles, freeze–thaw cycles, and traffic loading should be clarified. Third, the correlation between long-term field monitoring and laboratory-controlled testing should be strengthened. Fourth, subgrade state prediction models integrating mechanism-based models and data-driven methods should be developed. These efforts can provide a more reliable theoretical basis and technical support for evaluating long-term subgrade stability, diagnosing service-period distresses, and making maintenance decisions.

Acknowledgments

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