Influence of soft subgrade conditions on derailment risk

Chihping Kuo[1*]

[1] Department of Civil and Construction Engineering, National Yunlin University of Science and Technology, Yunlin, Taiwan

The safety of railway operations is inextricably linked to the dynamic stability of the underlying subgrade, particularly in regions prone to soft soil characteristics. This study investigates the quantitative relationship between soil relative density (D_r), accumulative plastic settlement, and the consequent risk of train derailment. A dual-approach methodology was employed: (1) extensive stress-controlled cyclic triaxial tests (MTS) to simulate repetitive train axle loading, and (2) a full-scale field monitoring program to validate the laboratory models.

The results reveal a critical non-linear sensitivity of subgrade performance to compaction quality. Specifically, reducing the relative density from 80 % to 50 % resulted in a six-fold amplification of accumulative plastic settlement under identical cyclic loading conditions. This dramatic increase in deformation creates severe differential settlement, particularly at transition zones, leading to rapid deterioration of track geometry (e.g., track twist and vertical irregularities). By coupling these geotechnical behaviors with a vehicle-track dynamic model, this paper demonstrates that such settlement amplification significantly increases the wheel unloading rate, pushing the derailment coefficient beyond safety thresholds. The findings provide a theoretical basis for establishing stricter compaction criteria (D_r) to mitigate derailment risks in soft subgrade engineering.

1 Introduction

The dynamic stability of railway embankments is a prerequisite for the safe and efficient operation of modern rail systems. As the foundation supporting the superstructure, the subgrade must sustain millions of cyclic load applications induced by moving trains without experiencing excessive permanent deformation. However, in regions characterized by heavy rainfall or high groundwater levels, the subgrade soil is frequently subjected to a coupled effect of saturation and cyclic stress. Under these conditions, the mechanical integrity of the soil does not remain constant but evolves over the service life of the infrastructure, posing a significant challenge to track geometry maintenance and derailment prevention.

A critical failure mechanism observed in railway engineering involves the progressive degradation of granular subgrade materials. Although construction specifications typically mandate a high degree of compaction—corresponding to an initial relative density (D_r) of 80 % to 90 %—to ensure stiffness and bearing capacity, these initial properties are highly susceptible to hydraulic deterioration. When the subgrade becomes saturated, the repetitive cyclic loading from passing trains accelerates the generation of excess pore water pressure (EPWP). In granular soils, this accumulation of EPWP reduces effective stress, triggering cyclic liquefaction or cyclic mobility, where the soil skeleton loses its interparticle contact forces. Concurrently, in subgrades with significant fines content, the high hydraulic gradients induce internal erosion and the upward migration of soil slurry, a phenomenon known as mud pumping. These hydro-mechanical processes—liquefaction and mud pumping—are the primary drivers that cause the subgrade relative density to deteriorate drastically from its dense state to a loose state ($D_r \approx 50$ %). This transition creates a metastable structure characterized by massive stiffness loss and amplified plastic accumulation. The resulting large-scale weakening leads to severe differential settlement and track distortion, thereby increasing the risk of vehicle derailment.

Despite the widespread recognition of these phenomena, few studies have quantitatively mapped the full evolution of derailment risks as the subgrade transitions from a dense state to a liquefied or pumped-out loose state. To bridge this gap, this study employs a comprehensive dual-validation approach. First, stress-controlled cyclic triaxial tests (MTS) were conducted to simulate the long-term stiffness degradation and liquefaction potential of saturated soils under repetitive axle loads. Second, these laboratory findings were validated against in-situ monitoring data obtained from a full-scale operational railway section. The primary objective of this research is not only to elucidate the mechanism of derailment induced by soft soil but also to propose scientifically grounded improvement strategies. Specifically, this paper demonstrates the necessity of enhancing compaction standards to mitigate the risks of liquefaction and mud pumping, ensuring the long-term dynamic stability of railway tracks.

2 Literature review

The long-term performance of railway tracks is governed by the cumulative plastic deformation of the subgrade. Early studies by [1] established the fundamental power-law models relating cumulative strain to the number of load cycles. Subsequent research has highlighted that the resilient modulus (M_r) of granular soils is not constant but degrades significantly under high-cycle fatigue loading. However, most classical settlement models assume a relatively stable drainage condition, which often fails to predict the catastrophic failure observed in soft, saturated subgrades.

In regions with high groundwater tables, the degradation of subgrade stiffness is accelerated by hydro-mechanical instability, primarily manifesting as mud pumping and cyclic liquefaction. Mud Pumping: [2] described mud pumping as

* Corresponding author: cpkuo@yuntech.edu.tw

the upward migration of fine particles from the subgrade into the ballast layer, driven by high cyclic pore water pressure and hydraulic gradients. This loss of fines creates voids within the soil matrix, leading to a volumetric contraction and a rapid decrease in relative density (D_r). [3] further identified that the intermixing of ballast and soft subgrade creates a "slurry" layer, which dramatically reduces the shear strength of the foundation interface. Cyclic Liquefaction: for saturated granular subgrades, [4] and later [5] defined the conditions for cyclic liquefaction, where the buildup of excess pore water pressure (EPWP) reduces the effective stress to near zero. Even without full liquefaction, the phenomenon of "cyclic mobility" can cause the soil to transition from a dense state ($D_r \approx 80$ %) to a loose, flowable state ($D_r \approx 50$ %). Recent laboratory studies using cyclic triaxial apparatus have confirmed that once this phase transformation occurs, the rate of plastic settlement increases exponentially.

While the geotechnical mechanisms of settlement are well-documented, the link between subgrade softening and vehicle derailment remains under-explored. Existing railway safety standards typically focus on track geometry irregularities (e.g., gauge, alignment) without explicitly accounting for the transient stiffness variations of the subgrade. Dynamic simulations by [6] have shown that track stiffness abruptions can amplify wheel-rail interaction forces. However, few studies have quantitatively integrated MTS-derived degradation curves of pumping-prone soils directly into derailment criteria such as Nadal’s formula or the Wheel Unloading Rate. Consequently, there is a lack of theoretical frameworks that correlate the degree of relative density loss directly to the safety margins of train operations.

The detrimental impact of mud pumping extends beyond the subgrade, critically compromising the mechanical performance of the overlying ballast layer. As subgrade fines migrate upward under cyclic hydraulic gradients, they accumulate within the ballast voids, a phenomenon technically defined as "ballast fouling". [7, 8] conducted extensive large-scale permeameter and cyclic triaxial tests on fouled ballast. Their findings revealed that the intrusion of plastic fines (clay/silt slurry) coats the angular surfaces of ballast aggregates. This creates a "lubrication film" at the particle-to-particle contact points, which significantly reduces the inter-particle friction angle and destroys the mechanical interlocking that provides ballast with its shear strength. Research by [9] utilizing image analysis further demonstrated that this fouling process prevents the re-orientation of ballast particles into a stable matrix, causing the ballast layer to behave more like a "matrix-supported" soft composite rather than a "skeleton-supported" granular medium. Beyond mechanical lubrication, [10] emphasized the hydraulic consequences of mud pumping. The accumulation of fines clogs the macropores of the ballast, drastically reducing its permeability. This converts the ballast layer—originally designed as a free-draining material—into a quasi-undrained system. Under high-speed train loads, this entrapped water generates excess pore water pressure within the ballast layer itself, further decreasing the effective stress and accelerating the rate of plastic settlement and lateral spreading [11]. [12] established the classic "Fouling Index (FI)" to quantify the degree of contamination. However, recent studies suggest that even a moderate level of mud pumping (e.g., Void Contaminant Index > 20 %) can lead to a disproportionate loss of track modulus. This stiffness degradation directly feeds into the differential settlement discussed in previous sections, creating a feedback loop that exacerbates the derailment risk.

3 Methodology

To realistically simulate the dynamic response of the railway subgrade under operational conditions, a large-scale model test box with dimensions of $1.5\ \mathrm{m}(L) \times 1.5\ \mathrm{m}(W) \times 2.0\ \mathrm{m}(H)$ was utilized. The rigid boundaries of the container were treated to minimize side friction, ensuring that the stress distribution mimics the semi-infinite half-space of a natural subgrade. A servo-hydraulic MTS actuator was mounted on a rigid reaction frame to apply vertical cyclic loads directly to the simulated track structure (sleeper and ballast) placed atop the subgrade model. The dimensions of the test box were sufficient to minimize boundary effects on the vertical stress distribution within the zone of influence.

The subgrade soil used in this study was retrieved directly from a section of an existing railway line where severe mud pumping and subgrade softening had been documented. This ensures the experimental results are highly relevant to actual field failure mechanisms. The preparation of the subgrade model involved a rigorous reconstitution process: 1. Drying and Pulverization: The field-retrieved soil was oven-dried and pulverized to ensure homogeneity. 2. Compaction Control: To investigate the effect of initial stiffness, the soil was reconstituted into the test box in layers. The compaction energy was strictly controlled to achieve target Relative Densities (D_r) (e.g., ranging from the loose state of 50 % to the dense state of 80 %). 3. Saturation: Following compaction, a bottom-up water saturation method was employed. Water was introduced slowly from the base drainage layer to displace air voids, ensuring a fully saturated condition ($S_r \approx 100$ %) to simulate the worst-case scenario of rainfall infiltration or high groundwater levels.

The cyclic loading protocol was designed to replicate the actual stress history induced by passing trains. Based on in-situ measurements of axle loads, a sinusoidal waveform was adopted for the MTS actuator. 1. Maximum Amplitude: The peak vertical load was set to 73.5 kN (7.5 tonnes), representing the impact of a heavy axle load on a single rail seat / sleeper section. 2. Frequency: A loading frequency of 1 Hz was selected to simulate the typical dominant frequency of the train-track system at operational speeds. This load-controlled cyclic testing allowed for the continuous monitoring of accumulative plastic settlement and pore water pressure generation as the number of cycles increased.

To validate the laboratory simulation results and investigate the in-situ coupling effect of rainfall and train loading on subgrade stability, a comprehensive monitoring system was installed at the identified vulnerable track section. The instrumentation array comprised four key components designed to capture the hydrological boundary conditions, dynamic stress input, and structural deformation response:

1. Rain Gauge & Piezometers: A tipping-bucket rain gauge was installed on-site to record real-time precipitation intensity and duration. To correlate rainfall events with subgrade saturation levels, pore water pressure transducers (piezometers) were embedded at varying depths within the subgrade. These sensors were critical for monitoring the generation and dissipation of Excess Pore Water Pressure (EPWP) during train passage, serving as direct indicators of potential liquefaction or mud pumping initiation.
2. Wheel-Rail Load Cells: To quantify the actual dynamic impact exerted by passing trains, load cells (or rail-mounted strain gauges) were installed at the rail seats / sleeper interface. This data provided the precise axle load spectrum and loading frequency, which were subsequently used to calibrate the input waveform (7.5 T, 1 Hz) for the large-scale laboratory tests.
3. Displacement Transducers (LVDTs): High-precision displacement transducers were positioned to measure the vertical deflection of the track structure. These sensors captured both the transient elastic rebound during train passage and the accumulative plastic settlement over long-term operation. The differential settlement data obtained from these gauges served as the primary input for the derailment risk analysis.
4. Data Synchronization: All sensor outputs were connected to a high-speed data acquisition system. The sampling rate was set sufficiently high (e.g., > 200 Hz) to capture the peak dynamic responses of the pore pressure and rail deflection without aliasing effects.

Figure 1a shows the large-scale soil box used in this experiment; Figure 1b presents the post-experiment results for the foundation soil with 50 % relative density, revealing that mud pumping caused severe foundation weakening.

(a) (b)

Figure 1. The before and after of the cyclic-loading test using the large-scale soil box: (a) the large-scale soil box used in this experiment and (b) the post-experiment results.

4 Results and Discussion

Comparing track foundation soils of identical material at relative densities of 80 % and 50 %, the experiments showed significant differences as shown in Figure 2. The case with 80 % relative density reached a final settlement of 45 mm in 65,000 seconds; in contrast, the case with 50% relative density reached a final settlement of 170 mm in just 15,000 seconds.

Observations showed that the former soil maintained uniform settlement of the track structure; however, the latter caused the ties to deform or fracture. This resulted in a non-parallel and asymmetric track alignment, which could lead to derailment.

Practically, improving the relative density of the foundation soil while performing ballast maintenance is an effective measure to prevent significant foundation weakening.

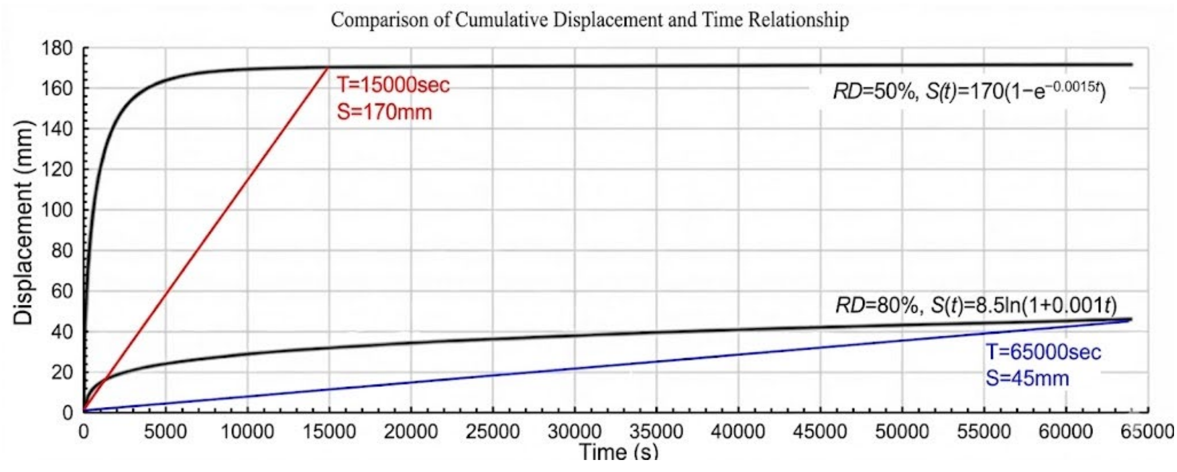

Figure 2. Test results: cumulative displacement and time relationship.

References

1. D. Li, E.T. Selig, Cumulative plastic deformation for fine-grained subgrade soils. J. Geotech. Eng. **122**(12), 1006–1013 (1996).
2. B. Indraratna, M. Singh, T.T. Nguyen, S. Leroueil, A. Abeywickrama, R. Kelly, T. Neville, Laboratory study on subgrade fluidization under undrained cyclic triaxial loading. Can. Geotech. J. **57**(11), 1767–1779 (2020).
3. I. Alobaidi, D.J. Hoare, 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 (1996).
4. H.B. Seed, I.M. Idriss, Simplified procedure for evaluating soil liquefaction potential. J. Soil Mech. Found. Div. **97**(9), 1249–1273 (1971).
5. K. Ishihara, Stability of natural deposits during earthquakes, in Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 1 (1985), pp. 321–376.
6. W. Zhai, K. Wang, C. Cai, Fundamentals of vehicle–track coupled dynamics. Veh. Syst. Dyn. **47**(11), 1349–1376 (2009).
7. B. Indraratna, L. Su, C. Rujikiatkamjorn, A new parameter for classification and evaluation of railway ballast fouling. Can. Geotech. J. **48**(4), 322–326 (2011).
8. B. Indraratna, N. Tennakoon, S. Nimbalkar, C. Rujikiatkamjorn, Behaviour of clay-fouled ballast under drained triaxial testing. Géotechnique **63**(5), 410–419 (2013).
9. E. Tutumluer, W. Dombrow, H. Huang, Laboratory characterization of coal dust fouled ballast behavior, in Proceedings of the AREMA 2008 Annual Conference and Exposition (American Railway Engineering and Maintenance-of-Way Association, 2008).
10. Y.J. Cui, F. Lamas-Lopez, V.N. Trinh, N. Calon, S.C. D'Aguiar, J.C. Dupla, A.M. Tang, J. Canou, A. Robinet, Investigation of interlayer soil behaviour by field monitoring. Transp. Geotech. **1**(3), 91–105 (2014).
11. N. Tennakoon, B. Indraratna, C. Rujikiatkamjorn, S. Nimbalkar, T. Neville, The role of ballast fouling characteristics on the drainage capacity of rail substructure. Geotech. Test. J. **35**(4), 629–640 (2012).
12. E.T. Selig, J.M. Waters, Track geotechnology and substructure management (Thomas Telford, London, 1994).