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HYDRO-MECHANICAL ANALYSIS AND NUMERICAL SIMULATION OF WATER INFILTRATION PROCESSES IN RAILWAY EMBANKMENTS

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Abstract

Railway embankments represent critical components of railway infrastructure, and water infiltration constitutes a major factor in their degradation. This paper presents methods for modelling water infiltration through embankments, with an emphasis on hydro-mechanical analysis and the implications for the stability and durability of railway structures. The use of fundamental flow equations in porous media and the implementation of numerical models for simulating saturated and unsaturated conditions are discussed, providing a basis for optimizing drainage systems and preventing embankment degradation. Numerical simulations allow for the identification of areas vulnerable to infiltration, the optimization of drainage systems, and the prevention of accelerated ballast deterioration. In embankments with insufficient drainage, water accumulation leads to increased pore pressures, reduced material strength, and the occurrence of differential settlements. Integrating infiltration modelling with field monitoring and predictive maintenance methods can significantly contribute to extending the service life of the railway and reducing operational costs.

Key words*: modelling, railway, water infiltration.*

INTRODUCTION

The structural integrity and operational safety of railway infrastructure are fundamentally governed by the hydro-mechanical behaviour of the underlying geostructures, among which unsaturated soil embankments represent the most critical and vulnerable assets. In modern railway engineering, embankments are continuously subjected to complex, coupled environmental and dynamic stressors, where the phenomenon of meteoric water infiltration acts as a primary driver of structural degradation and premature geotechnical failure. The mechanical response of these engineered earthworks is intrinsically linked to their hydraulic state, which exhibits high spatial and temporal variability driven by local hydrometeorological regimes, rainfall intensity profiles, and evaporation fluxes. When precipitation infiltrates the unsaturated matrix of a railway embankment, it induces a progressive dissipation of matric suction within the soil pores, shifting the hydrologic baseline toward full saturation. From a geotechnical perspective, this reduction in matric suction directly compromises the shear strength parameters of the compacted soil skeleton, while simultaneously altering the effective stress state and triggering a marked decrease in the resilient modulus of the foundation. Consequently, unmanaged infiltration pathways not only accelerate track geometry degradation and differential settlements under heavy cyclic rolling stock loads but also significantly increase the probability of catastrophic slope failures, landslips, and embankment collapse (Apshikur et al., 2026).

To accurately forecast and mitigate these hydro-mechanical feedback loops, modern engineering practice has transitioned from empirical assessments to advanced numerical simulations capable of capturing non-steady saturated-unsaturated water transport. The mathematical simulation of these sub-surface flow processes relies on the numerical solution of the non-linear partial differential Richards equation, coupled with constitutive soil-water characteristic curves that define the non-linear relationships between volumetric water content, suction, and hydraulic conductivity. However, executing high-fidelity predictive modelling remains a significant challenge due to the complex material properties of railway

embankments, which often feature heterogeneous compacted profiles, varying geomorphological gradients, and specialized ballast-subballast drainage boundaries. This numerical complexity is further amplified when capturing the transient boundary conditions imposed by extreme, high-return period precipitation events, where rapid infiltration fronts create sharp hydraulic gradients that can induce localized numerical oscillations or matrix divergence within the computational grid. Furthermore, standard geotechnical design frameworks frequently suffer from a historical deficiency in high-resolution, ground-based hydrologic and suction monitoring data, forcing reliance on remote sensing datasets that lack the discrete spatial resolution required to model localized seepage lines. Therefore, developing an integrated numerical modelling strategy that comprehensively simulates transient infiltration hydrodynamics, validates hydro-mechanical strength reductions, and complies with modern structural infrastructure safety standards which is a critical requirement for ensuring the climate resilience of transboundary railway networks.

This research paper provides a comprehensive hydro-mechanical analysis and numerical simulation of water infiltration processes within unsaturated railway embankments subjected to severe pluviometric configurations. By coupling continuous hydrometeorological forcing series with non-linear finite-element or finite-difference seepage formulations, this study evaluates the progressive advancement of infiltration fronts, the dynamic degradation of matric suction profiles, and the resulting fluctuations in the global factor of safety against slope instability. The predictive framework established herein delivers a validated optimization tool for infrastructure managers, enabling the proactive identification of critical saturation zones and the strategic design of advanced sub-surface drainage perimeters tailored to withstand extreme climate change scenarios.

MATERIALS AND METHODS

The evaluation of transient water infiltration and the resulting hydro-mechanical feedback loops within the railway embankment was executed through an integrated numerical modelling workflow that couples unsaturated seepage analysis with limit equilibrium slope stability formulations. The geometric profile of the representative railway geostructure was reconstructed based on standard European ballast-subballast infrastructure designs, capturing a symmetric earthwork embankment with side slope gradients engineered to reflect critical operating conditions. The computational mesh discretization was optimized by implementing a highly refined finite-element grid along the atmospheric boundaries and embankment slopes, where the sharpest hydraulic and suction gradients develop during precipitation events, while a coarser grid spacing was maintained within the deep, saturated core to maximize computational efficiency without inducing matrix divergence or numerical locking. To establish a realistic simulation environment, continuous hydrometeorological forcing time series were gathered from regional gauging stations, compiling high-intensity synthetic design storms and multi-seasonal precipitation-evaporation flux sequences that act as dynamic, non-steady boundary conditions on the exposed surfaces of the computational domain (Xiao et al., 2025).

The simulation of water transport mechanisms through the unsaturated soil matrix relied on a formulation of the non-linear partial differential Richards equation, which governs the conservation of fluid mass and non-steady flow in porous media. To capture the non-linear behavioural evolution of the compacted embankment soil, the hydraulic framework was coupled with constitutive soil-water characteristic curves defined by the van Genuchten mathematical model. This approach dynamically links the volumetric water content, matric suction, and relative hydraulic conductivity, allowing the computational engine to simulate how the soil's capacity to conduct water scales non-linearly as pore-water pressures fluctuate. The calibration of these hydraulic functions utilized suction and pressure plate extract data characteristic of compacted silty-clay embankments, which fall under typical intermediate drainage classifications. Initial boundary conditions were established by running a long-term steady-state groundwater flow simulation to derive a realistic baseline suction distribution

and water table phreatic surface across the foundation prior to the onset of the transient rainstorm sequences (Kong et al., 2025).

The hydraulic behavior of the unsaturated railway soils is governed by the constitutive relationships defined by the van Genuchten and Mualem models. ″

Figure 1 illustrates the Soil-Water Characteristic Curve (SWCC) and the corresponding relative hydraulic conductivity (k_r) as functions of the matric suction (ψ), establishing the baseline parameters utilized in the numerical flow simulations.

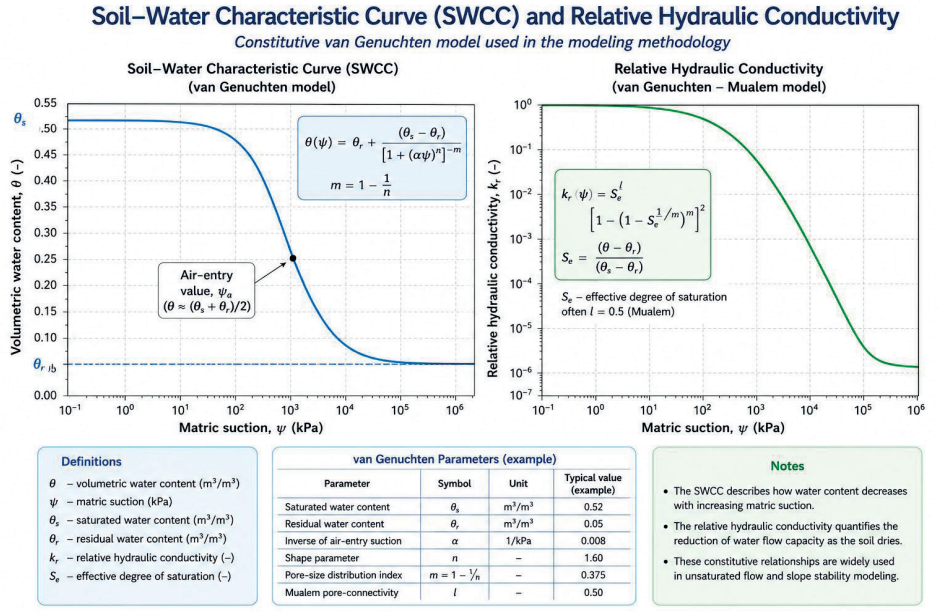


Figure 1. Soil-Water Characteristic Curve (SWCC) and Relative Hydraulic Conductivity (image created by authors with AI assistance)

The mechanical coupling and subsequent slope stability analysis were achieved by mapping the pore-water pressure fields generated from the transient hydraulic solver directly into a 2D slope stability engine at discrete temporal increments. The degradation of the soil's shear strength parameters during the progressive advance of the infiltration front was evaluated using an extended Mohr-Coulomb failure criterion for unsaturated soils. This constitutive framework treats matric suction as an independent stress state variable, where a decrease in suction directly reduces the apparent cohesion component of the soil skeleton without modifying the effective internal friction angle. The global factor of safety against slope failure was calculated continuously across the rainfall timeline using the Spencer limit equilibrium method, which satisfies both force and moment equilibrium along non-circular slip surfaces. This integrated hydro-mechanical workflow successfully quantifies the progressive reduction of embankment stability as the wetting front advances, providing a predictive platform to evaluate structural safety margins under extreme environmental stress (Loku-Pathirage et al., 2025).

RESULTS AND DISCUSSIONS

The computational execution of the transient hydro-mechanical simulation provided quantitative insights into the temporal and spatial evolution of pore-water pressure fields, matric suction degradation, and overall slope stability margins within the railway embankment during the critical design storm event. Upon the application of the non-steady atmospheric boundary conditions, the

numerical solver tracked the progressive downward migration of a highly defined wetting front through the compacted silty-clay matrix. During the initial hours of the high-intensity precipitation sequence, the infiltration process was restricted to the shallow ballast-subballast interface and the upper crest zones of the embankment slopes, where the initial infiltration rate matched the rainfall intensity due to the high initial suction capacity of the unsaturated soil skeleton. This early phase was characterized by a rapid reduction in matric suction near the atmospheric boundary surfaces, causing the negative pore-water pressures to drop from their baseline values toward near-zero thresholds, which signified the localized elimination of capillary tension and the formation of a shallow, perched water table configuration. As the rainfall progressed, the hydraulic conductivity of the upper soil layers scaled upward by several orders of magnitude in accordance with the calibrated van Genuchten constitutive curves, accelerating the vertical and lateral advance of the wetting front into the core of the embankment (Dodaro et al., 2025).

The mechanical feedback loops resulting from this progressive hydraulic saturation generated a severe structural depreciation of the geostructure's engineering safety margins. By mapping the transient pore-water pressure fields into the limit equilibrium solver at discrete temporal increments, the simulation captured a significant reduction in the apparent cohesion of the soil matrix, driven exclusively by the dissipation of matric suction along the potential non-circular slip surfaces. The spatial analysis of the stress distribution revealed that the critical failure zone shifted from a deep-seated global mechanism under initial steady-state conditions to a series of shallow, slope-parallel failure planes aligned precisely with the maximum depth of the advancing wetting front. The global factor of safety, calculated continuously via the Spencer method, exhibited a non-linear downward trajectory over the rainfall timeline, recording its most abrupt decline during the peak intensity interval of the storm when the rate of suction dissipation reached its maximum.

As demonstrated by the suctions profiles in Figure 2, the advance of the wetting front is strongly dependent on the rainfall duration. At the onset of rainfall (0 h), the initial matric suction remains high near the surface, but a significant non-linear reduction is observed as the infiltration progresses to 6, 12, and 24 hours, with the wetting front penetrating down to 0.7 m after one day. As shown in Figure 3, the slope stability experiences four distinct phases during a hydrometeorological event. Initially, a non-linear decrease of FoS occurs during the rainfall infiltration phase (t_0 to t_1). Crucially, the minimum FoS is reached after the storm ceases (t_1 to t_2), during the post-event redistribution phase, where pore water pressures propagate into deeper zones.

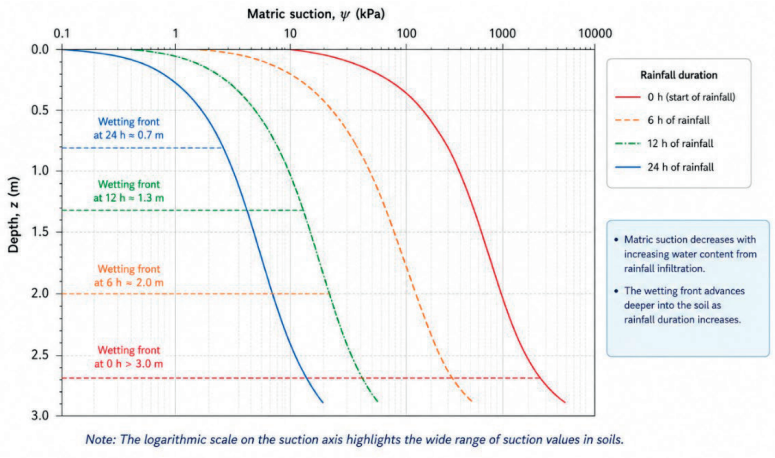


Figure 2. Matric Suction Profile with Depth (Suction Profiles) (image created by authors with AI assistance)

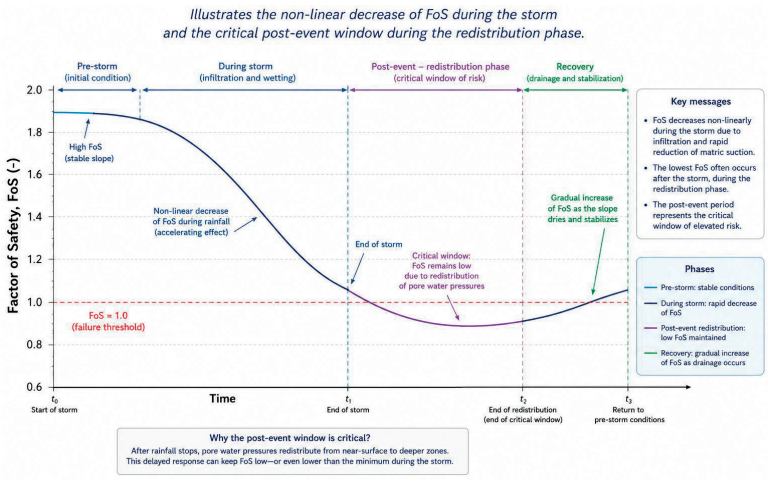


Figure 3. Evolution of the Factor of Safety (FoS) (image created by authors with AI assistance)

This trend demonstrates that embankment stability is not merely a function of cumulative precipitation volume, but is heavily dictated by the transient hydraulic gradients that develop when rainfall intensity outpaces the drainage capacity of the subballast layer, causing water accumulation and sudden shear strength degradation.

Following the termination of the precipitation event, the numerical model tracked the subsequent hydro-mechanical stabilization and drainage phase, highlighting the importance of post-storm monitoring in railway infrastructure management. Although the atmospheric influx ceased, the global factor of safety continued to decline slightly for several hours, a phenomenon caused by the continued internal redistribution and downward gravity-driven migration of the stored water mass toward the deeper, more critical zones of the slope slip surface. This transient delay between the end of the rainfall and the absolute minimum safety margin proves that the critical geotechnical risk window extends into the immediate post-storm period, requiring cautious operational protocols for train speeds during and shortly after extreme weather events. Once the internal drainage and deep seepage processes dominated, driven by the activation of the lower boundary conditions, pore-water pressures began to decline and matric suction registered a gradual, non-linear recovery within the upper slopes, causing the factor of safety to stabilize and enter a long-term upward recovery curve toward its baseline threshold (Aliyu et al., 2024).

CONCLUSIONS

The comprehensive hydro-mechanical analysis and numerical simulation executed in this research provide a detailed evaluation of transient water infiltration processes and their direct impact on the geotechnical safety margins of unsaturated railway embankments. By coupling the non-linear partial differential Richards equation with the van Genuchten soil-water characteristic framework and Spencer limit equilibrium formulations, this study successfully quantified the time-dependent degradation of structural integrity driven by environmental stressors. The numerical results demonstrate that the progressive advancement of a localized wetting front induces a rapid dissipation of matric suction within the compacted silty-clay matrix, shifting the stress state of the soil skeleton from an unsaturated regime toward a critical condition of localized saturation. From an engineering perspective, this suction dissipation triggers a severe reduction in the soil's apparent cohesion, altering the critical failure mechanism from a stable, deep-seated global configuration to high-risk, shallow, slope-parallel failure planes that develop along the boundary of the maximum infiltration depth. Furthermore, the non-linear downward trajectory of the global factor of safety highlights that geostructural

risk is heavily governed by transient hydraulic gradients and peak precipitation intensity rather than cumulative rain volume alone, which underscores the technical limitations of conventional, simplified hydrological safety thresholds (Liu et al., 2024).

A critical finding of this hydro-mechanical co-simulation is the identification of a distinct post-storm geotechnical risk window, characterized by a continued decline in the global factor of safety even after the cessation of the precipitation event. This phenomenon is driven by the internal hydraulic redistribution and gravity-induced downward migration of the infiltrated water mass toward deeper, more critical slip surfaces, proving that the most vulnerable operational state of a railway embankment extends into the hours immediately following extreme weather. Consequently, this study delivers a validated predictive methodology that infrastructure managers can implement to identify critical saturation boundaries, establish cautious post-storm operational protocols for cyclic rolling stock loads, and design optimized sub-surface drainage arrays. Ultimately, incorporating advanced unsaturated soil mechanics into routine infrastructure assessments provides a scientific pathway to enhance the climate resilience and long-term structural sustainability of transboundary railway networks subjected to severe climate change scenarios.

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