Review of Applied Science and Technology

Volume: 2; **Issue:** 2
Pages: 01– 37

open access

Crossref

PEER-REVIEWED

GEOTECHNICAL AND HYDRAULIC SIMULATION MODELS FOR SLOPE STABILITY AND DRAINAGE OPTIMIZATION IN RAIL INFRASTRUCTURE PROJECTS

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Doi: 10.63125/jmx3p851

Received: *15 April 2023;* ***Revised:*** *24 May 2023;* ***Accepted:*** *16 June 2023;* ***Published:*** *28 June 2023*

Abstract

Rail earthworks often experience rainfall-driven pore-pressure increases and drainage bottlenecks that produce recurring wet spots, deformation, and higher instability risk, yet quantitative evidence linking simulation effectiveness to improved drainage and slope outcomes remains limited. This study tested a coupled geo-hydraulic performance model to quantify predictive relationships among Geotechnical Simulation Effectiveness (GSE), Hydraulic–Hydrologic Simulation Effectiveness (HSE), Drainage Optimization Outcomes (DOO), and Slope Stability Performance (SSP) in an enterprise rail-corridor case context. Using a quantitative cross-sectional, case-based design, data were collected through a structured 5-point Likert questionnaire from N = 210 rail-infrastructure professionals representing geotechnical, hydraulic/drainage, construction, and maintenance functions with direct exposure to simulation-informed decisions and field results. Composite variables were computed as item-mean indices, and analysis included descriptive statistics, reliability testing, Pearson correlation, and staged regression aligned to hypotheses, including an optional mediation path (HSE → DOO → SSP). Measurement reliability was strong (α = 0.87–0.90). Mean scores were above the midpoint (GSE 3.84 ± 0.58; HSE 3.76 ± 0.62; DOO 3.69 ± 0.60; SSP 3.73 ± 0.57). Correlations supported the model (GSE–SSP $r = 0.61$; HSE–DOO $r = 0.67$; DOO–SSP $r = 0.55$; all $p < .001$). The combined regression predicting SSP was significant ($F(3,206) = 62.84$, $p < .001$; $R^2 = 0.48$), with unique effects for GSE ($\beta = 0.31$), DOO ($\beta = 0.24$), and HSE ($\beta = 0.16$, $p = 0.012$). Reduced HSE influence after adding DOO suggested partial mediation, indicating hydraulic modelling improves stability partly via drainage.

Keywords

Rail Infrastructure; Slope Stability; Drainage Optimization; Geotechnical Simulation; Hydraulic–Hydrologic Modeling.

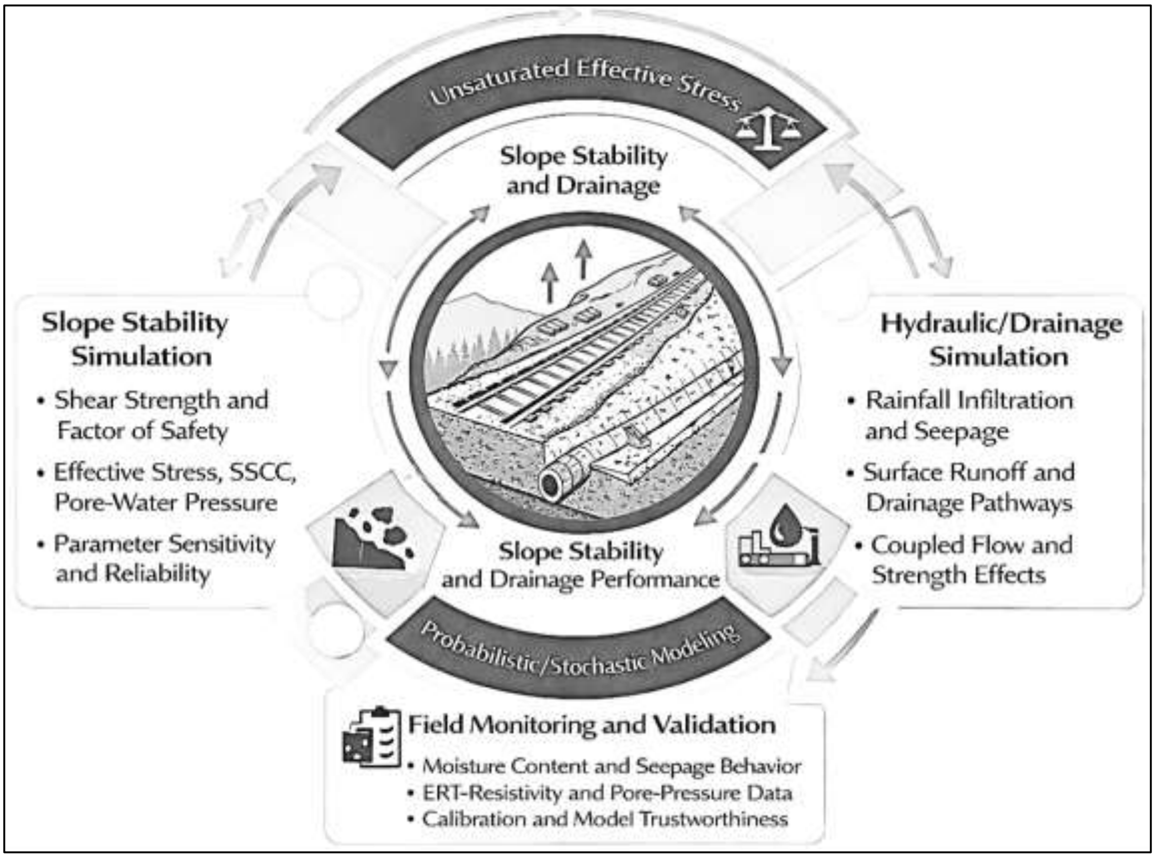
INTRODUCTION

Geotechnical and hydraulic simulation models are structured computational representations used to describe how soils, rock masses, groundwater, rainfall infiltration, and surface runoff interact within engineered and natural slopes. In geotechnical engineering, *slope stability* commonly refers to the ability of a soil or rock slope, embankment, or cutting to maintain equilibrium without experiencing shear failure along a potential slip surface under given loading and hydraulic conditions (Lu et al., 2010). In hydraulic and hydrologic engineering, *drainage optimization* refers to the systematic design and performance improvement of surface and subsurface drainage elements (ditches, filters, toe drains, culverts, and layers) so that water movement is controlled in a manner that limits pore-pressure rise, erosion, and saturation-driven strength reduction (Glendinning et al., 2014).

These definitions carry international significance for rail infrastructure because rail networks operate across climatic regimes where intense rainfall and prolonged wet seasons are associated with pore-water pressure increases, moisture redistribution, and deterioration in embankment performance, including progressive deformation and localized instability (Xie et al., 2020). Field-scale evidence shows that moisture and pore-pressure behavior in infrastructure embankments can vary spatially due to construction heterogeneity and near-surface hydraulic behavior, which elevates the relevance of coupled geotechnical–hydraulic interpretation in practical asset management contexts (Gunn et al., 2015). Monitoring studies using electrical resistivity tomography (ERT) have also demonstrated that spatially distributed moisture states can be observed repeatedly over time within railway earthworks, clarifying the role of seasonal wetting–drying and localized flow paths in controlling internal conditions (Cho, 2012). The monitoring perspective matters for research design because it anchors simulation models to observable state variables such as moisture content changes, rather than treating water conditions as static assumptions (Cho, 2013b)). Within this scope, geotechnical simulation typically involves slope-stability methods and soil constitutive behavior, while hydraulic simulation typically involves seepage, infiltration, and runoff routing within engineered drainage paths, with both domains linking through effective stress and pore-pressure evolution (Lu et al., 2010). For rail infrastructure projects, this integrated framing positions slope stability and drainage as interdependent performance objectives rather than separate design tasks, since water availability and transport pathways directly regulate the mechanical resistance available along potential failure mechanisms (Cho, 2007).

A central geotechnical issue in rainfall-affected slopes is that water infiltration modifies suction and pore-water pressure distributions, shifting the stress state toward conditions that reduce shear strength and factor of safety. Physically based infiltration–stability frameworks commonly connect transient seepage response to a stability criterion, and this connection becomes more informative when the slope is treated as variably saturated rather than fully saturated (Cho, 2009). Research has shown that the timing and location of instability are sensitive to how infiltration is represented, how hydraulic conductivity varies with saturation, and how boundary conditions reflect rainfall and drainage pathways (Cho, 2014). In infrastructure embankments, the near-surface zone can govern the magnitude and distribution of transient pore pressures, and this zone is influenced by compaction, material fabric, and saturation-dependent permeability, which are measurable and model-relevant factors (Chambers et al., 2014). Railway-specific runoff and infiltration behavior on steep embankment slopes has also been modeled through continuous rainfall–runoff approaches that account for initial moisture state and infiltration processes, emphasizing how surface cover and hydrologic processes influence runoff generation and water entry into slope materials (Sajjan et al., 2013). When drainage is inadequate, water input can be partitioned into surface runoff that erodes slope faces and subsurface flow that raises pore pressures within the embankment body, producing combined hydraulic and mechanical vulnerabilities (Cai et al., 2017). Simulation-based research has further advanced the representation of rail embankments as unsaturated systems exposed to rainfall and traffic loading, creating a basis for examining hydromechanical response under realistic operational conditions (Lu & Likos, 2006). From a modeling standpoint, these studies motivate an approach that treats rainfall, seepage, and drainage as dynamic drivers of strength and deformation rather than as static externalities (Nguyen et al., 2017). This line of work supports the definition of the research problem as an interaction problem: slope stability is governed not only by geometry and shear parameters, but also by water transport processes that can be redesigned through drainage optimization to alter pore-pressure trajectories (Liu et al., 2017).

Figure 1: Hydraulic Modeling System for Rail Embankment Stability Assessment



Unsaturated soil mechanics provides a foundational theoretical basis for linking hydraulic state variables to mechanical stability through effective stress concepts. The suction stress characteristic curve (SSCC) formalizes how suction stress depends on degree of saturation or matric suction in a manner that parallels soil-water characteristic curve behavior, offering a theory-driven route for representing suction contribution to effective stress (Liu et al., 2018). This theoretical framing is directly relevant for rainfall-exposed slopes because transient wetting changes suction stress and thus changes the mobilizable shear strength even when total stress remains unchanged (Huang et al., 2010). In rail embankments, which often remain partially saturated for long periods, the effective stress state evolves through climatic cycles and rainfall events, and the hydrologic response interacts with material permeability structure and retention behavior (Nguyen et al., 2018). Numerical analyses that incorporate unsaturated constitutive descriptions have been used to integrate rainfall conditions and mechanical response in one modeling framework, supporting the view that suction, permeability, and retention parameters are core stability determinants for operational embankments (Oh & Lu, 2014). Field monitoring studies complement this theory because they show that moisture states can be spatially heterogeneous, and that internal wetting patterns can shift over time, which aligns with the SSCC-based idea that stress contributions are moisture-dependent and spatially variable (Sajjan et al., 2013). Within this theoretical context, slope stability analysis is strengthened when it connects modeled water content or suction fields to stress state representation, rather than using only saturated pore-pressure assumptions (Uhlemann et al., 2018). For drainage optimization, the theory implies that drainage features influence not only water removal but also the persistence of suction and the delay or limitation of positive pore-water pressure formation, which are directly linked to stability margins (Cho, 2013a). Accordingly, an introduction grounded in unsaturated effective stress theory provides an internally consistent rationale for modeling strategies that explicitly combine geotechnical stability

computation with hydraulic seepage–drainage simulation, particularly for rail corridors where rainfall and seasonal moisture cycles recur over long service lives (Deng et al., 2017).
Alongside theory, modern slope assessment increasingly recognizes uncertainty as intrinsic to geomaterials and construction processes, prompting probabilistic and reliability-based approaches that complement deterministic factors of safety. Spatial variability in strength and hydraulic properties can shift predicted failure timing and failure surfaces when rainfall infiltration drives transient pore-pressure fields (Dou et al., 2014). Probabilistic prediction approaches have been developed to represent rainfall-induced failure likelihood under parameter uncertainty, offering structured methods for incorporating uncertain geotechnical and hydraulic inputs into stability assessment (Dou et al., 2015). Studies have demonstrated that uncertainty in hydraulic conductivity, cohesion, and friction angle can produce meaningful variability in stability outcomes during rainfall, and cross-correlation behavior among parameters can influence the resulting uncertainty patterns (Wang et al., 2011). Reliability methods and probabilistic seepage analyses are also used for earth embankment contexts to quantify failure probability rather than relying on a single deterministic index, which is relevant to drainage optimization decisions that must perform across variable conditions (Lu & Likos, 2006). In slope reliability, the system perspective matters because slopes can exhibit multiple competing failure modes, and system reliability approaches examine how several potential slip surfaces collectively govern failure probability (Cho, 2012). Random finite element method (RFEM) research has specifically addressed system reliability of slopes by incorporating random fields and elastoplastic response, strengthening the methodological basis for capturing spatial variability effects on stability outcomes (Lu et al., 2010). Practical reliability implementation has also been presented through advanced Monte Carlo and subset simulation approaches that can be operationally decoupled from deterministic stability analysis, facilitating the application of reliability thinking in engineering workflows (Wang et al., 2011). For rail infrastructure, these methods motivate careful definition of constructs and measured variables when the study design uses survey-based evaluation of modeling and drainage practices, because uncertainty is not only numerical but also procedural and organizational in how models are selected, calibrated, and interpreted. The literature also indicates that probabilistic stability analysis under rainfall infiltration conditions can vary in sensitivity across hydraulic and strength parameters, and that the importance ranking of parameters can change with stress state representation (Nguyen et al., 2018; Oh & Lu, 2014). This backdrop supports framing the research problem around how geotechnical–hydraulic simulation choices, parameterization practices, and drainage design interpretations relate to stability outcomes in rail projects, which aligns with a quantitative research design using correlation and regression to examine relationships among modeling constructs and perceived performance outcomes.
This study is structured around a set of clearly defined objectives that operationalize the investigation of geotechnical and hydraulic simulation models within a rail infrastructure case-study setting. The first objective is to establish a measurable profile of geotechnical simulation model effectiveness as practiced in the selected project context, focusing on how slope stability modeling is implemented, parameterized, calibrated, validated, and interpreted for decision support. This includes assessing the degree to which material characterization, groundwater representation, strength parameter selection, sensitivity evaluation, and stability criteria are applied consistently across slope segments and engineering teams, so that the stability assessment process can be expressed through standardized indicators suitable for quantitative analysis. The second objective is to develop an equivalent measurable profile of hydraulic and hydrologic simulation model effectiveness for the same case study, emphasizing how rainfall inputs, runoff generation, conveyance capacity, infiltration pathways, and drainage structure performance are represented and tested under relevant scenarios. This objective captures the extent to which drainage networks, boundary conditions, and flow-routing assumptions are incorporated into a coherent modeling workflow that supports drainage optimization activities such as sizing, placement, redundancy, and maintenance prioritization. The third objective is to quantify drainage optimization outcomes within the rail corridor by translating operational and engineering performance attributes—such as reduced water accumulation, improved discharge efficiency, fewer blockage-related disruptions, and better alignment between observed water behavior and design expectations—into structured outcome indicators that can be compared across respondents

and slope locations. The fourth objective is to quantify slope stability performance outcomes using outcome measures that reflect stability and serviceability conditions in the rail slope environment, including stability confidence based on modeled and observed behavior, reduction in deformation or distress indicators, and perceived robustness of slopes under rainfall events. The fifth objective is to evaluate the statistical relationships among these constructs using descriptive statistics to summarize central tendencies and variability, correlation analysis to examine the strength and direction of associations among modeling and outcome variables, and regression modeling to test the predictive influence of geotechnical simulation effectiveness and hydraulic simulation effectiveness on drainage optimization and slope stability performance. Together, these objectives provide a structured pathway for transforming complex modeling practices and infrastructure performance attributes into quantifiable variables, enabling the study to test objective-aligned hypotheses within a cross-sectional quantitative framework anchored to an applied rail infrastructure case study.

LITERATURE REVIEW

The literature on geotechnical and hydraulic simulation for rail slope stability and drainage optimization is anchored in the understanding that slope performance in transportation corridors is governed by coupled soil–water processes, site geometry, material heterogeneity, climatic forcing, and engineered drainage configurations. Rail embankments and cuttings are widely recognized as particularly sensitive to rainfall-driven changes in pore-water pressure, moisture redistribution, and erosion, which collectively influence effective stress, shear strength mobilization, deformation behavior, and the likelihood of instability events. Consequently, simulation-based approaches have become central to modern slope risk evaluation, combining geotechnical stability analyses with seepage, infiltration, and runoff modeling to represent transient hydraulic boundary conditions and internal moisture dynamics. Within this body of work, deterministic stability methods (e.g., limit equilibrium approaches and numerical continuum methods) have been expanded through unsaturated soil mechanics to capture suction-dependent strength and the time-varying nature of wetting, while hydraulic modeling has progressed from simplified steady-state seepage assumptions to transient rainfall infiltration and drainage network representations. In parallel, research has emphasized that uncertainty and spatial variability in soil properties and hydraulic conductivity materially influence stability predictions, encouraging the adoption of probabilistic and reliability-based frameworks that quantify failure likelihood across multiple potential slip surfaces and parameter fields. Rail applications have also benefited from field monitoring advancements, including instrumentation and geophysical methods capable of mapping moisture evolution and validating modeled hydraulic states at embankment scale, which strengthens the connection between model outputs and real-world slope behavior. Drainage optimization literature complements these strands by focusing on how surface and subsurface drainage elements control inflow partitioning, storage, and discharge, thereby modifying pore-pressure trajectories and reducing erosion potential, with optimization interpreted not only as design sizing but also as placement strategy, redundancy, and maintenance effectiveness. Together, these research streams form a coherent base for examining how the quality and integration of geotechnical and hydraulic simulation practices relate to measurable drainage and stability performance outcomes in rail infrastructure projects, providing the foundation for structuring constructs, hypotheses, and analytical models in quantitative case-study research.

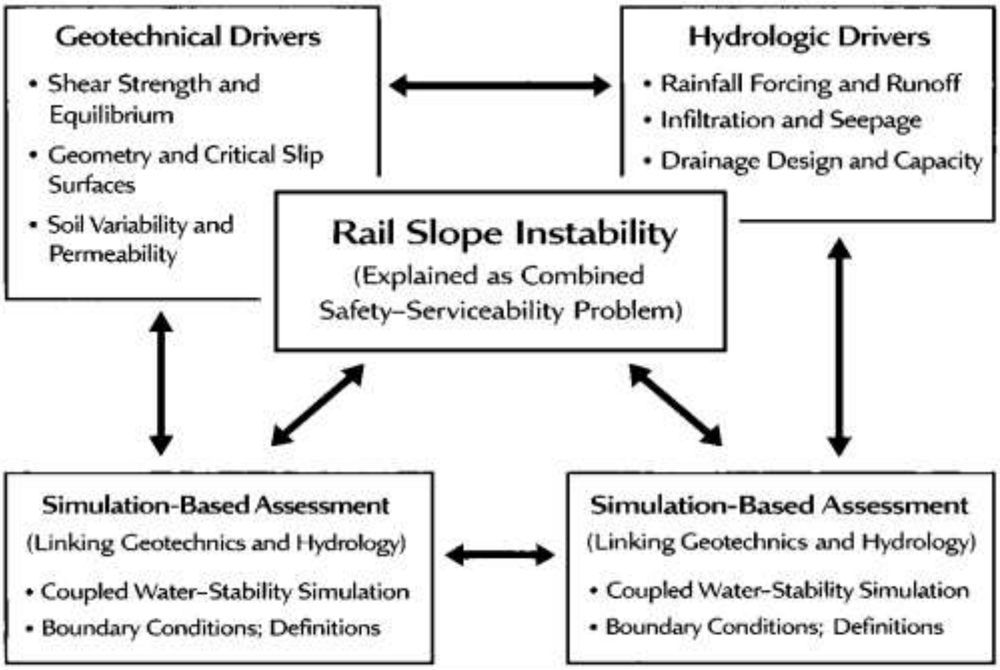
Rail Slope Instability in Geotechnical Engineering

Railway earthworks—embankments, cuttings, and the natural or reworked slopes bordering a rail corridor—are engineered landforms expected to preserve track alignment and safe operations under repeating axle loads, seasonal moisture cycles, and constrained corridors. In geotechnical engineering, rail slope instability refers to loss of equilibrium or unacceptable deformation when driving stresses exceed resisting shear strength along one or more potential slip surfaces. For railway assets, instability is evaluated not only as catastrophic collapse but also as serviceability deterioration that produces settlements, lateral movements, or progressive strain capable of degrading track geometry. Rail slopes often include legacy fills constructed using end-tipping or variable compaction, producing heterogeneous fabrics and discontinuous permeability structures that influence both strength distribution and pore-pressure response. The geotechnical significance is heightened because relatively small deformations can trigger operational restrictions and recurring maintenance demands across networks. A corridor is therefore managed as an interconnected set of earthworks where local distress can propagate into system-wide reliability issues through repeated defects and interventions. Transport embankment literature emphasizes that railway slopes are vulnerable to pore-pressure-driven instabilities and progressive failure mechanisms, while cyclic wetting–drying can generate shrink–swell movements that accumulate into long-term damage modes relevant to serviceability (Briggs et al., 2017; Mohiul, 2020). Analytical assessment translates site characterization into stability indicators such as factor of safety, deformation potential, and likelihood of progressive yielding, using limit equilibrium and numerical stress–strain modeling. In numerical practice, the strength reduction method is widely used, and its interpretive consistency depends on how failure is defined and detected in computations. Work on failure criteria shows that energy-based and clearly specified indicators can provide a more stable basis for identifying loss of stability than ambiguous convergence or displacement thresholds, improving comparability across slope segments and model setups (Jinnat & Kamrul, 2021; Tu et al., 2016). This rail-specific framing positions slope instability as a combined safety–serviceability problem grounded in soil behavior, drainage state, and operational tolerance overall.

Hydrologic loading is a dominant driver of rail slope instability because rainfall, runoff routing, infiltration, and seepage alter pore-water pressure, suction, and unit weight, thereby changing effective stress and available shear strength (Rabiul & Samia, 2021). Short, intense storms can generate rapid near-surface wetting that weakens shallow materials and promotes rilling or erosion, while prolonged wet periods can progressively elevate deeper pressures, soften clay-rich fills, and mobilize longer slip surfaces through delayed groundwater response. Rail alignments can amplify these processes by concentrating runoff along ballast shoulders, ditches, and cut-slope benches, and by creating hydraulic bottlenecks at culverts, transitions, and outlets where blockage or sediment deposition restricts discharge. Case evidence also shows that floodplain or upstream ponding can impose sustained head conditions against embankment toes, converting a surface-water event into a seepage-driven stability problem (Mohiul & Rahman, 2021; Polemio & Lollino, 2011). Such scenarios highlight the importance of considering both catchment-scale water supply and local drainage capacity when defining the hydraulic boundary conditions that a rail slope experiences during extreme weather. For corridor management, rainfall information is often compressed into empirical indices that relate event duration and intensity to the likelihood of triggering slope failures, enabling rapid screening of segments for patrol and inspection. A widely used representation is the intensity–duration threshold, which captures the observation that longer storms require lower mean intensities to initiate failures in susceptible settings (Guzzetti et al., 2007; Rahman & Abdul, 2021). Within rail corridors, these threshold concepts are most informative when combined with site descriptors that control infiltration, such as surface sealing, vegetation cover, fissuring, permeability contrasts, and the maintenance state of drains and outlets. Accordingly, hydrologic loading in rail slopes is best treated as an interaction among rainfall forcing, runoff concentration, infiltration opportunity time, and drainage performance rather than as a single rainfall metric. This interaction shapes the timing, location, and depth of critical pore-pressure build-up (Haider & Shahrin, 2021).

Simulation-based assessment links geotechnical and hydrologic drivers by representing how water enters, moves through, and exits a rail slope and how those hydraulic states translate into mechanical stability and deformation. Geotechnical simulation evaluates stability using limit-equilibrium methods that search for critical slip surfaces or numerical stress–strain analyses that capture progressive yielding, while hydraulic and hydrologic simulation estimates rainfall–runoff partitioning, transient seepage, groundwater level response, and the conveyance performance of surface and subsurface drainage elements. In integrated practice, model coupling is operationalized through boundary conditions and constitutive links: rainfall and runoff define inflow, drains define discharge capacity, and computed pore pressures feed into strength and deformation calculations (Zulqarnain & Subrato, 2021).

Figure 2: Hydrologic Loading and Stability Response in Rail Slopes



This integration is essential in rail settings because drainage measures are selected not only to remove water but also to reshape the internal pore-pressure field that governs effective stress along potential failure mechanisms. Drainage optimization can therefore be framed as a set of controllable design and maintenance choices, ditch grade and lining, culvert sizing, toe-drain continuity, filter compatibility, and outlet protection, that modify flow paths and storage (Uddin et al., 2022). Empirical rainfall thresholds remain useful for rapid corridor screening, yet physically based models are needed to explain why similar storms can produce different responses across adjacent slope segments with different permeability structures or drainage conditions (Akbar & Sharmin, 2022; Foysal & Subrato, 2022). Comparative research on empirical versus physically based thresholds shows that threshold estimates are sensitive to both rainfall characterization and the governing hydrologic–geotechnical parameters, reinforcing the value of process-based representation when the goal is to attribute slope response to controllable mechanisms rather than to rainfall alone (Bordoni et al., 2019; Rahman, 2022; Zulqarnain, 2022). Within a rail case study, this literature supports defining measurable constructs that capture modeling effectiveness, drainage adequacy, and stability performance so that statistical associations can be interpreted against a coherent process model. Such construct definition enables consistent comparison across respondents, slope units, and operational records.

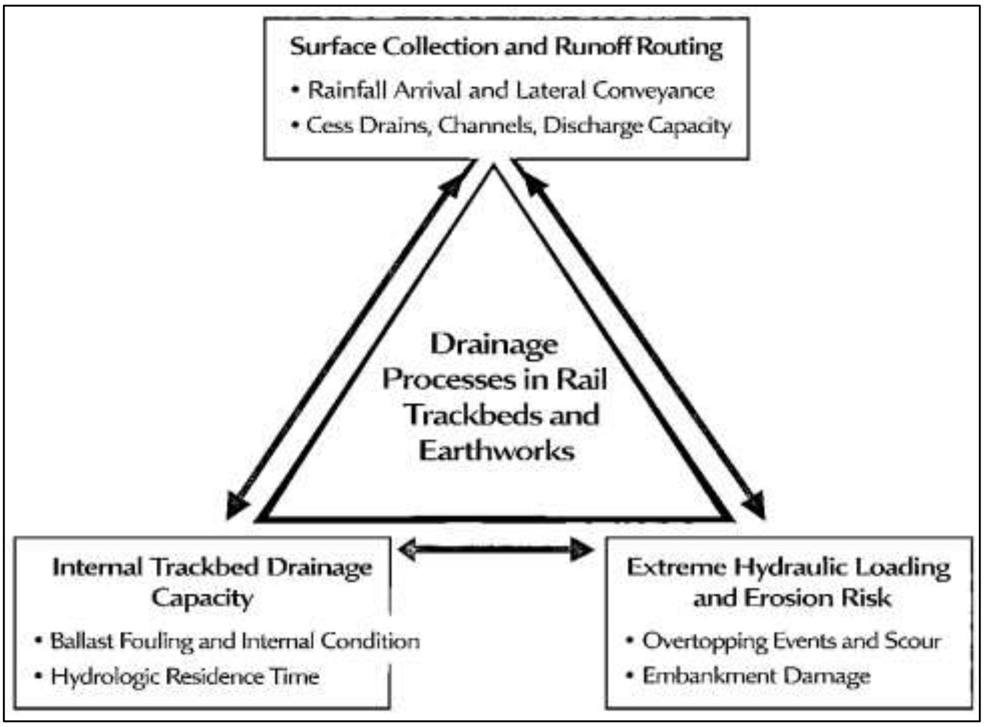
Hydraulic Pathways in Railway Trackbeds and Earthworks

Effective drainage in rail infrastructure is commonly defined as the engineered ability of the trackbed and adjacent earthworks to intercept, convey, infiltrate in controlled ways, and discharge precipitation and upstream runoff so that water does not accumulate within ballast, sub-ballast, subgrade, ditches, or embankment toes long enough to degrade stiffness and strength. In practice, the drainage problem is multi-layered: rainfall first reaches the rail formation surface, then it either runs off laterally to cess drains and channels or percolates downward through ballast and sub-ballast, where it can be temporarily stored, redirected by permeability contrasts, or retained by clogged interfaces. Subsurface water retention is particularly important because the track support system is designed to be permeable, yet its permeability is not constant over time; it is altered by ballast breakage, fines intrusion, and progressive fouling. Track drainage therefore depends on material gradation, layer thickness, and the hydraulic contrast between ballast and underlying layers, which together control how quickly water drains away from the rail formation after storms. Numerical and experimental evidence indicates that trackbed geometry and hydraulic properties strongly influence the recession of water tables and the residence time of water trapped within support layers, making the trackbed itself a functional hydraulic system rather than a passive foundation (Habibullah & Mohiul, 2023; Hasan & Waladur, 2023; Rushton & Ghataora, 2009). In operational settings, this hydraulic behavior is interdependent with asset condition: partially blocked outlets, sedimented ditches, and poorly graded shoulders can convert a normally draining formation into a transient reservoir. Because the rail corridor is linear and continuous, local drainage defects can create repeated wet spots that act as chronic softening zones under traffic, gradually accumulating deformation in ways that are difficult to attribute unless the hydraulic pathways are explicitly described. A drainage-focused literature therefore treats the trackbed as a coupled porous medium and conveyance network, where surface collection, subsurface flow, and boundary discharge capacity must be evaluated together to explain observed wetting patterns and associated maintenance demand (Md. Rabiul & Mushfequr, 2023; Shahrin & Samia, 2023; Strelkov et al., 2016).

A major hydraulic degradation mechanism in rail foundations is the reduction of ballast drainage capacity due to internal aggregate degradation and external fines intrusion from subgrade pumping, surface contamination, and ballast attrition. As ballast breaks and fines increase, pore spaces shrink and flow regimes shift, causing hydraulic conductivity to decline and increasing the time water remains within the structure after rainfall (Rakibul & Alam, 2023; Rifat & Rebeka, 2023). This mechanism has direct engineering relevance because longer wet residence times raise the probability of subgrade softening, loss of bearing support, differential settlement, and the need for repeated tamping or renewal. Laboratory-scale and field-representative testing approaches therefore emphasize measuring not only saturated conductivity but also unsaturated drainage behavior, since rail foundations commonly experience variable saturation during storm cycles and drying periods. A large-scale infiltration column methodology has been used to characterize water-retention behavior and unsaturated hydraulic conductivity for fouled ballast materials, illustrating that drainage performance cannot be represented reliably using only idealized “clean ballast” assumptions when the objective is to model real track conditions (Kumar, 2023; Saikat & Aditya, 2023; Tang et al., 2013). In addition, changes in ballast condition are not uniform; the drainage impact depends on initial gradation, the mechanism of degradation, and the type and distribution of intruding fines. Experimental permeability work on degraded and clay-contaminated ballast has shown that hydraulic conductivity reductions can accelerate markedly as degradation progresses, and that the resulting permeability may become operationally unacceptable even when the ballast still appears serviceable from a purely geometric perspective (Koohmishi, 2019; Zulqarnain & Subrato, 2023). This evidence supports drainage optimization as a dual task: improving water conveyance infrastructure (ditches, culverts, toe drains, outlets) and preserving the internal drainage capacity of the trackbed through ballast maintenance strategies, filtration/separation decisions, and condition-based renewal planning. In modeling terms, it motivates representing drainage capacity as a time-dependent property linked to degradation and fouling, rather than a fixed parameter that remains stable across the service life of a rail asset.

Drainage processes in rail corridors also extend beyond routine rainfall infiltration to include high-consequence hydraulic loading events such as overtopping flows, inundation, and flood-driven scour that can rapidly remove ballast and embankment material. In these cases, the hydraulic pathway is not limited to seepage through porous layers; instead, external floodwaters may overtop the formation, produce high-velocity sheet flow, and induce ballast scour and embankment erosion that compromises both structural integrity and immediate operational safety. From a system perspective, this expands drainage evaluation from “how quickly water leaves the formation” to “whether water can be safely conveyed without exceeding erosive thresholds.” Hazard-based hydraulic studies have formalized this perspective using fragility curves that relate overtopping water depth to the probability of ballast scour and embankment damage, offering an evidence-based way to quantify failure likelihood under flood conditions in railway settings (Tsubaki et al., 2016). Such work reinforces the importance of drainage capacity and pathway continuity during peak flows, because insufficient conveyance or blocked outlets can transform manageable runoff into overtopping conditions. It also highlights that drainage optimization is inseparable from slope and embankment stability objectives: when drainage is inadequate, the rail formation is exposed to both internal weakening mechanisms (pore-pressure rise, reduced stiffness) and external erosion mechanisms (scour, material loss). For rail infrastructure projects using simulation models, this literature supports integrating porous-media flow representation with surface flow conveyance and erosion risk interpretation, so that drainage decisions can be evaluated against both serviceability-driven wetting behavior and event-driven damage modes within the same corridor context.

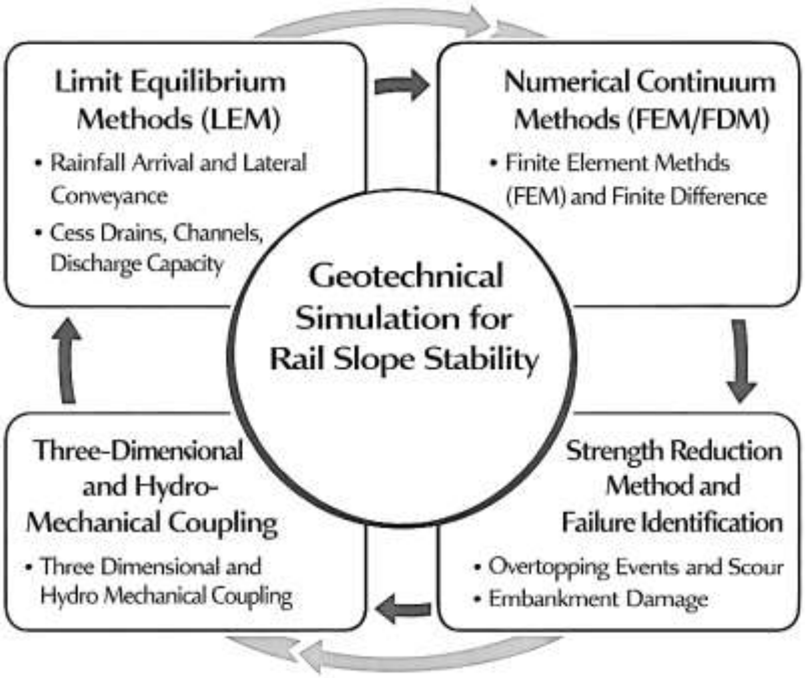
Figure 3: Drainage Processes and Hydraulic Pathways in Railway Trackbeds and Earthworks



Geotechnical Simulation Models for Slope Stability Assessment

Geotechnical simulation models for slope stability assessment are commonly organized around two complementary families of methods: limit equilibrium methods (LEM) and numerical continuum methods. LEM remains widely used in practice because it expresses stability through an explicit factor of safety derived from force and/or moment equilibrium along an assumed slip surface, allowing engineers to compare scenarios efficiently across multiple slope geometries and soil-strength states. Simulation, in this context, refers to structured computational evaluation of feasible failure mechanisms, material inputs, and boundary conditions so that safety indices and critical slip surface locations can be identified consistently. Comparative research has shown that LEM results can be broadly consistent with strength reduction–based numerical methods for many standard problems, while differences emerge when strength components or boundary conditions create nonstandard failure patterns or when assumptions regarding interslice forces become influential (Cheng et al., 2007). As geotechnical practice moved toward more complex rail embankment and cutting geometries, simulation approaches increasingly incorporated heterogeneous layering, staged construction effects, and variable pore-pressure distributions, all of which affect the location and shape of critical mechanisms. This progression has motivated the use of hybrid workflows in which LEM serves as a rapid screening tool and numerical analysis is applied to refine mechanism realism, deformation patterns, and stress redistribution. In rail settings, this is particularly relevant because stability assessment often needs to distinguish between shallow surface instabilities that compromise slope faces and deeper mechanisms that influence track geometry and long-run serviceability. For these reasons, simulation model selection is not only a computational preference but also a definitional choice about what constitutes "failure," which mechanism families should be searched, and how safety indices should be interpreted across corridor segments. Within the literature, this has encouraged explicit reporting of modeling assumptions, including soil constitutive behavior, pore-pressure representation, and mechanism search strategy, so that stability outcomes can be compared across approaches and applied consistently in infrastructure management (Cheng et al., 2007).

Figure 4: Framework for Slope Stability Assessment in Rail Infrastructure



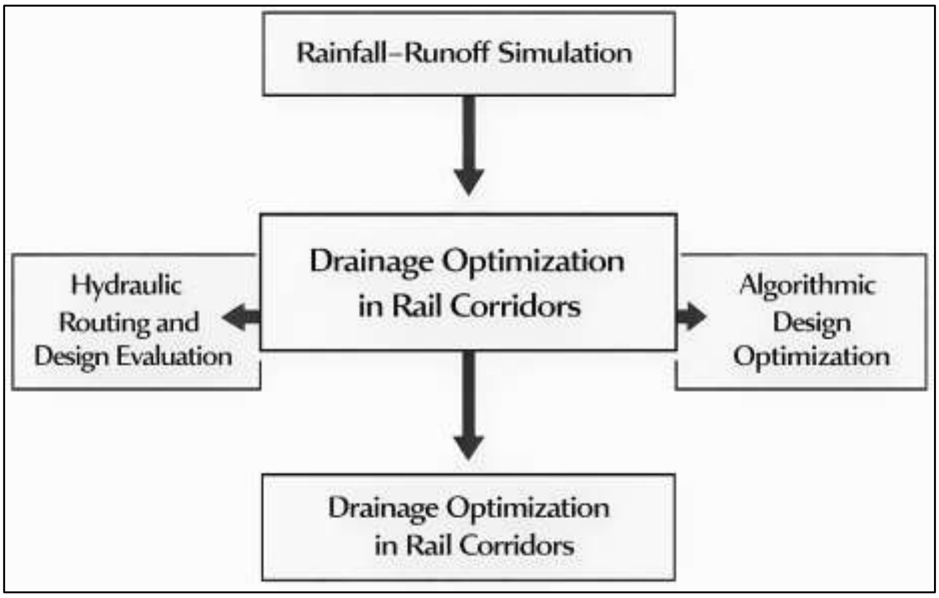
A major development in geotechnical simulation is the strength reduction method (SRM) implemented within finite element or finite difference frameworks, where shear strength parameters are systematically reduced until a failure condition is detected, and the corresponding reduction factor is interpreted as the factor of safety. SRM provides advantages in representing complex geometries, stress–strain behavior, and progressive failure development without prescribing a slip surface in advance, allowing failure mechanisms to emerge from the constitutive response and boundary conditions. However, SRM outcomes depend strongly on how failure is identified, because numerical nonconvergence alone can be ambiguous and displacement-only criteria can be scale-dependent. Methodological contributions therefore focus on stabilizing the SRM workflow through improved convergence strategies, clearer failure indicators, and combined deformation–stability interpretation. Work on improved SRM procedures highlights that deformation patterns, localization behavior, and stability indices can be evaluated together to reduce ambiguity when slopes approach limit states, especially for nonhomogeneous materials where multiple zones may yield before a continuous failure mechanism forms (Zhang et al., 2021). Comparative investigations also emphasize that different numerical formulations can yield different critical mechanisms and safety factors even under the same geometry and material parameters, motivating cross-checking against LEM for plausibility and using sensitivity testing to confirm parameter influence. Such comparisons are particularly important for rail earthworks where layered fills, construction discontinuities, and toe constraints are common, and where slope failure may be preceded by serviceability movements that are operationally significant. Studies that explicitly compare LEM to multiple finite element approaches illustrate how differences in constitutive modeling, stress redistribution, and failure localization can shift both the magnitude of computed safety factors and the inferred critical slip surface, reinforcing the need for method-consistent interpretation when simulation results are used to prioritize stabilization or drainage interventions (Liu et al., 2015).

A further modeling frontier involves three-dimensional stability assessment and coupled hydro-mechanical representation, both of which are relevant when slopes are spatially variable or when hydraulic loading and drainage behavior drive time-dependent strength changes. Three-dimensional analyses address the reality that many failures are not strictly two-dimensional; lateral restraints, topographic curvature, and spatially varying stratigraphy can modify failure geometry and safety margins. Simulation studies comparing 3D SRM and 3D LEM have demonstrated that method choice and 3D assumptions can influence predicted failure shapes and computed safety factors, particularly for simple slope archetypes where boundary effects can be isolated and interpreted clearly (Wei et al., 2009). In rail corridors, 3D effects can arise from transitions between embankment and cutting, localized drainage concentration points, and spatial variability in fill placement and compaction. Coupled modeling frameworks extend this by linking transient seepage conditions to stability evaluation, so that time-varying pore-pressure distributions and unit weight changes can be transferred into stability calculations across time steps. This coupling is relevant for drainage-focused rail problems because the design and condition of drainage features control boundary conditions and dissipation pathways, which then govern the rate and extent of pore-pressure build-up. Simulation frameworks that integrate saturated–unsaturated seepage with slope stability analysis emphasize the importance of coupling logic, consistent transfer of pore pressures, and representation of unsaturated shear strength when evaluating stability under changing water levels or rainfall-driven hydraulic states (W. Zhang et al., 2021). Collectively, the geotechnical simulation literature positions slope stability assessment as a methodological system in which mechanism search, dimensionality, failure criteria, and hydro-mechanical coupling choices define the meaning and comparability of safety indices in infrastructure applications (Liu et al., 2015).

Hydraulic–Hydrologic Simulation for Drainage Optimization in Rail Corridors

Hydrologic–hydraulic simulation in drainage design explains how rainfall is converted into runoff, how runoff is routed through channels and drainage structures, and how boundary conditions control water levels, flow velocities, and surcharge. In rail infrastructure projects, the same modelling logic is used to translate catchment response into design discharges at side ditches, cross-drainage culverts, and outlet channels, while also estimating the duration that water remains near the track formation where it can weaken support layers and raise pore pressures in adjacent earthworks. A key value of simulation is that it forces consistency between inputs (rainfall intensity–duration patterns, land cover, contributing area, roughness, infiltration, and storage) and outputs (hydrographs, headwater levels at culverts, ditch freeboard, and overflow volumes), enabling engineers to test drainage adequacy under multiple scenarios rather than relying on single-point calculations. In systems where performance changes over time due to land-use alteration, rainfall variability, and gradual capacity constraints, staged evaluation becomes critical because design decisions must balance immediate capacity needs and long-run lifecycle performance; cost–performance modelling has therefore been used to pair hydrologic–hydraulic simulation with optimisation routines that identify interventions when and where hydraulic limitations emerge (Maharjan et al., 2009).

Figure 5: Simulation Framework for Drainage Optimization in Rail Corridors



At the model-building level, calibration and parameter sensitivity analysis are central because drainage predictions are often controlled by a small subset of influential parameters, especially when modelling at high spatial resolution where local depression storage, conduit roughness, and connectivity shape the timing and peaks of hydrographs. High-resolution SWMM-based modelling with genetic parameter optimisation illustrates how systematic calibration can stabilize discharge predictions across calibration and validation events while improving confidence in scenario testing for drainage interventions (Krebs et al., 2013). For rail corridors, these modelling principles support defensible drainage optimisation because they formalize the relationship between rainfall, conveyance capacity, storage, and local overflow pathways that can directly influence slope stability and track serviceability. Drainage optimisation extends beyond "can the system convey flow" to "which configuration meets performance targets with the best trade-off between risk, cost, and constructability." In practice, optimisation typically varies controllable design variables—detention volume, outlet size, pipe or culvert diameter, inlet geometry, invert elevations, and allowable surcharge—while constraining solutions by maximum water levels, allowable downstream peak discharges, and acceptable velocities that avoid erosion or scour. Algorithmic optimisation is particularly valuable in drainage design because feasible solutions are often numerous and highly nonlinear: small changes in outlet geometry can shift peak attenuation behaviour, and small changes in conveyance slopes can create backwater effects that propagate upstream. Detention basin studies demonstrate that genetic algorithms can search efficiently across storage and outlet design options to satisfy constraints (peak discharge limits and allowable water level) while producing designs that reduce storage requirements and simplify outlet dimensions compared with trial-and-error approaches (Park et al., 2012). In rail contexts, comparable optimisation logic can be applied to corridor-scale drainage by treating cross-drainage spacing, ditch geometry, and culvert sizing as decision variables, then evaluating them using hydrologic–hydraulic simulation outputs such as headwater depths, surcharge durations, and overflow volumes at critical low points. Importantly, optimisation is not limited to "bigger is better"; rather, it is often about aligning system capacity with the dominant hydraulic controls. A staged planning perspective also matters: when budgets and construction access are limited, it can be rational to implement capacity increases in phases, prioritizing nodes where hydraulic penalties (flooding volume or surcharge duration) are most severe (Maharjan et al., 2009). For your rail case-study design, these ideas justify selecting drainage-related constructs (e.g., adequacy of conveyance, adequacy of storage/attenuation, maintenance condition, and outlet control) and then linking them quantitatively to outcomes such as observed wet-spot recurrence, deformation indicators, or reported drainage performance—creating a coherent basis for correlation and regression testing within your survey-supported model.

Drainage simulation also increasingly emphasizes exceedance behaviour—what happens when the drainage network cannot fully convey inflows—because exceedance pathways often determine whether water is routed safely away from slopes or redirected toward vulnerable track and embankment sections. Dual drainage modelling addresses this by coupling subsurface conveyance (pipes, culverts, underdrains, and confined channels) with surface flow domains so that surcharge, inlet capture, overflow, and overland routing are represented consistently during high-intensity storms. This is directly relevant to rail corridors because capacity exceedance can manifest as overtopping of shallow ditches, lateral flow along ballast shoulders, concentration of runoff at access crossings, and localized ponding near formation edges—all of which can increase infiltration into earthworks and elevate pore pressures that affect stability. Multi-module flood modelling frameworks illustrate the value of coupling approaches: by representing exchange mechanisms (e.g., inlets, pumping, and connectivity rules) between surface and subsurface domains, these models improve water-balance consistency and spatial realism of inundation predictions compared with single-domain methods (Li et al., 2016). Related validation work on 1D–2D dual drainage models under unsteady and surcharged conditions reinforces that coupled formulations can reproduce observed hydraulic behaviour under partial-full, surcharged, and overflow regimes, which are precisely the conditions where damage pathways emerge during extreme events (Fraga et al., 2017). For rail drainage optimisation, the implication for modelling design is methodological: evaluation metrics should include not only peak discharge and headwater depth, but also surcharge duration, overflow volumes, and spatial routing tendencies under exceedance, because these outputs connect more directly to geotechnical consequences such as prolonged saturation and destabilizing seepage near slope faces.

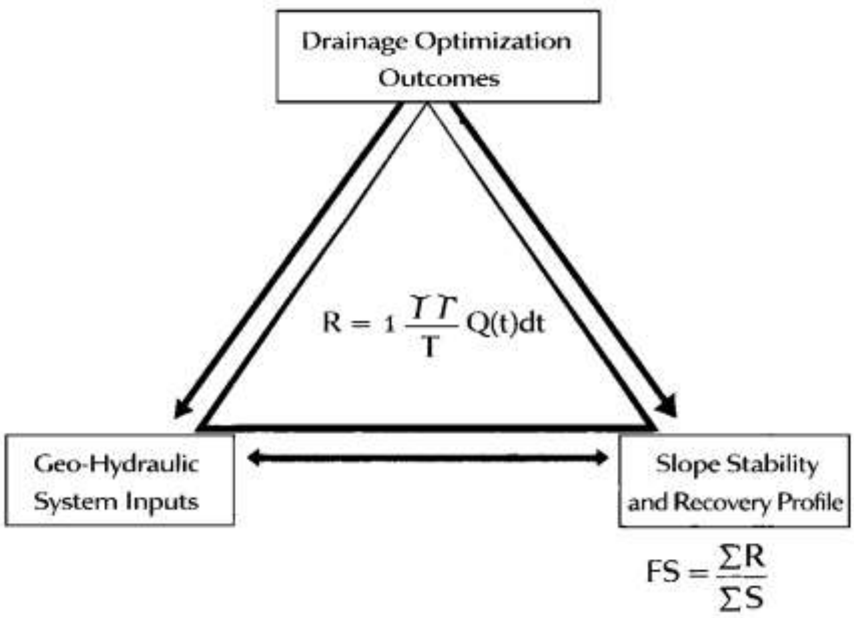
Systems Theory and Rail Geo-Hydraulic Performance

A systems-theory lens frames rail earthworks as an interconnected set of components and relationships that collectively determine whether the corridor delivers its intended function under environmental and operational loading. In this framing, slope stability and drainage performance are not treated as isolated engineering checks but as interacting sub-systems whose states co-evolve through feedback loops. The geotechnical sub-system is represented by geometry, stratigraphy, strength, deformation response, and pore-pressure–dependent effective stress; the hydraulic–hydrologic sub-system is represented by rainfall inputs, runoff capture, infiltration, seepage, conveyance capacity, and discharge boundary conditions. Systems theory emphasizes that failures can emerge from interactions among components rather than from a single dominant defect, which aligns with the rail context where a modest drainage obstruction, a localized permeability contrast, and a marginal slope angle can combine to generate a corridor-critical failure during a storm. This view supports using coupled simulation models because coupling makes the interaction explicit: hydraulic outputs (pore pressures, phreatic surface position, wetting-front evolution, surcharge/overflow locations) become state variables that drive the geotechnical response (effective stress, mobilized shear strength, strain localization). A compact expression of this interaction is the stability index (factor of safety) written as

$$FS = \frac{\sum R}{\sum S},$$

where $\sum R$is the sum of resisting shear capacity along a potential mechanism and $\sum S$is the sum of driving shear demand; the hydraulic state influences $\sum R$primarily through effective stress, commonly expressed as $\sigma' = \sigma - u$, where $u$is pore-water pressure. From a systems perspective, drainage optimization is an intervention that shifts the boundary conditions governing $u$over time and space, thereby shifting the corridor's stability state. Systems theory also motivates explicit representation of cascading impacts: a local failure reduces capacity and increases vulnerability of adjacent segments through detours, maintenance windows, and operational constraints. In infrastructure systems research, cascading and interdependency mechanisms are a defining feature of complex systems because disruptions in one sub-system can amplify consequences in others, motivating interdependency-aware modeling approaches (Ouyang, 2014).

Figure 6: Framework for Geo-Hydraulic Performance of Rail Earthworks



A resilience-based systems interpretation complements the above by defining performance not only as a static safety margin but also as the time profile of functionality under disruption and recovery. In this logic, rail slope–drainage behavior is evaluated through a performance function that changes during rainfall loading, damage evolution, and restoration. A common resilience formulation expresses time-varying functionality as $Q(t) \in [0,1]$, and system resilience over a horizon Tcan be represented as an integral measure:

$$\mathcal{R} = \frac{1}{T}\int_0^T Q(t)\,dt,$$

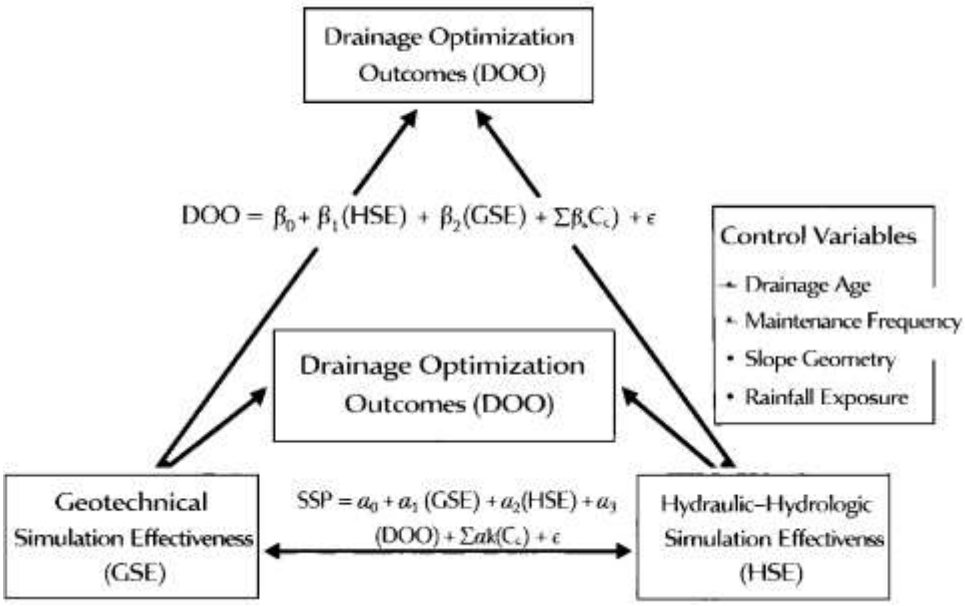
where higher $\mathcal{R}$reflects higher retained and recovered functionality. This definition is useful for rail earthworks because many outcomes of drainage and stability decisions manifest as duration effects—how long water remains in the formation, how long track geometry remains degraded, and how quickly safe operation is restored. A resilience framework therefore creates a bridge between simulation variables (headwater depth, surcharge duration, pore-pressure dissipation time, factor-of-safety trajectories) and operational metrics (speed restrictions, maintenance cycles, downtime). Quantitative resilience concepts have been formalized in infrastructure-network contexts with emphasis on the temporal dimension of critical functionality and the measurable trade-offs among redundancy, recovery time, and robustness (Ganin et al., 2016). Applying this to rail geo-hydraulic problems means that drainage features (ditches, culverts, toe drains, underdrains) can be interpreted as resources that increase robustness by limiting water accumulation and as design choices that reduce recovery time by accelerating drainage and lowering pore-pressure persistence. The same resilience framing highlights that rail corridors are multi-layer systems in which physical components, maintenance actions, and decision rules collectively determine $Q(t)$. Because resilience is operationally actionable only when translated into measurable indicators, a systems–resilience framework supports building a structured set of constructs for empirical research: model adequacy, calibration discipline, drainage maintenance condition, and perceived stability reliability can be defined as measurable variables that represent different parts of the performance system. In resilience theory, such construct structuring is essential because it connects high-level definitions to operational decisions, enabling performance-based prioritization rather than purely component-by-component inspection.

A systems-theory foundation also supports the study's empirical strategy by emphasizing that geo-hydraulic performance depends on both technical model properties and organizational practices that govern how models are built, interpreted, and acted upon. This is consistent with socio-technical interpretations of resilience in which performance outcomes reflect not only physical system capacity but also monitoring quality, maintenance responsiveness, and decision coherence. A practical implication for quantitative case-study research is that "effectiveness" of simulation models can be treated as a system property that includes data inputs, parameter governance, validation routines, and integration across disciplines. Resilience literature further highlights that metrics must be organized in a way that makes them usable for resource allocation and decision-making, which motivates identifying and grouping indicators by phases of system activity and by domains of performance. A structured approach to resilience metrics has been articulated through a matrix logic that organizes metrics so that planning, absorption, recovery, and adaptation can be connected to specific measurable indicators, enabling evaluation of whether investments translate into improved performance (Linkov et al., 2013). At the operational level, resilience can also be represented stochastically by treating disruptions as random processes and assessing distributions of performance loss and recovery rather than single deterministic outcomes; such stochastic metrics support comparison of alternative designs and management policies under uncertainty (Pant et al., 2014). For rail slope and drainage management, this links naturally to hydrologic variability and parameter uncertainty in geotechnical inputs because rainfall, infiltration, and drainage capacity fluctuate across seasons and degradation states. Conceptually, this makes it reasonable to evaluate geo-hydraulic interventions through the combined lens of stability margin and variability of performance, where models are judged by how well they support stable decision-making under uncertainty. A foundational systems definition of resilience also clarifies why "resilience" must be distinguished from related terms such as vulnerability or robustness, and why formal definition matters for measurement consistency and hypothesis testing in applied studies (Haimes, 2009). Under this framework, the present research can treat geotechnical simulation quality and hydraulic simulation quality as interacting system inputs, treat drainage optimization outcomes as an intermediate system response, and treat slope stability performance as a higher-level system outcome that reflects the corridor's ability to maintain and regain acceptable functionality during rainfall-driven hydraulic loading.

Conceptual Framework Development

A conceptual framework for rail slope stability and drainage optimization must translate the coupled geo-hydraulic problem into measurable constructs that can be tested empirically in a quantitative, cross-sectional case-study design. In simulation-driven infrastructure studies, the most consequential source of variation often lies in how models are conceptualized, parameterized, calibrated, and used in decisions, rather than in whether a model exists at all. Environmental modelling scholarship therefore emphasizes that uncertainty is embedded across the modelling process—from problem framing and conceptualization through calibration, validation, and application—so the framework should explicitly represent these stages as measurable dimensions of "model effectiveness" (Refsgaard et al., 2007). In parallel, disciplined model development is described as an iterative cycle in which objectives, data, structure, parameters, calibration, evaluation, and stakeholder use are revisited repeatedly; this supports structuring constructs so they reflect practical workflows rather than abstract labels (Jakeman et al., 2006).

Figure 7: Framework Linking Simulation Effectiveness and Slope Stability Performance



For the present research, the conceptual framework organizes variables into (a) Geotechnical Simulation Effectiveness (GSE), (b) Hydraulic–Hydrologic Simulation Effectiveness (HSE), (c) Drainage Optimization Outcomes (DOO), and (d) Slope Stability Performance (SSP), with optional controls describing corridor or segment conditions (e.g., drainage age, maintenance frequency, slope geometry class, rainfall exposure class). Each construct is operationalized through Likert five-point items that capture process quality and outcome consistency at the project/corridor level. For example, GSE can include indicators for adequacy of soil characterization, groundwater/seepage boundary definition, sensitivity analysis, and validation against observed behavior; HSE can include indicators for rainfall input representativeness, runoff-routing logic, capacity checks for ditches/culverts, calibration discipline, and exceedance-pathway representation. DOO can include indicators for reduced water accumulation duration, improved discharge adequacy, fewer recurring wet spots, and improved alignment between observed and predicted drainage behavior. SSP can include indicators for improved stability confidence under rainfall, reduced deformation/distress frequency, and reduced need for emergency interventions. Because multiple parameter sets can sometimes produce similar fits to limited observations, the framework also acknowledges equifinality as a conceptual risk that motivates explicit calibration/validation indicators rather than assuming "good fit" implies "good model" (Beven, 2006).

Once constructs are defined, the research model specifies how they relate in a testable structure that mirrors the coupled physical logic of rail earthworks. The central conceptual assumption is that simulation effectiveness influences outcomes by improving diagnosis of water pathways and failure mechanisms, improving design and maintenance prioritization, and increasing the consistency of decisions across slope segments. Statistically, the framework can be represented as a set of linked linear models in which DOO is predicted by HSE (and optionally by GSE when geotechnical modelling directly informs drainage layout decisions), and SSP is predicted by GSE and DOO (and optionally by HSE if hydraulic modelling has a direct effect on stability performance). A parsimonious representation is:

$$DOO = \beta_0 + \beta_1(HSE) + \beta_2(GSE) + \sum\beta_k(C_k) + \varepsilon,$$
$$SSP = \alpha_0 + \alpha_1(GSE) + \alpha_2(HSE) + \alpha_3(DOO) + \sum\alpha_k(C_k) + \varepsilon,$$

where $C_k$denotes control variables and $\varepsilon$is the error term. This structure aligns with a systems logic in which drainage outcomes act as an intermediate mechanism linking hydraulic modelling practices to stability performance. To ensure that the constructs are credible representations of modelling practice, the framework emphasizes verification/validation and uncertainty quantification as measurable components rather than afterthoughts. A widely cited scientific computing perspective treats model credibility as dependent on verification (numerical correctness), validation (agreement with observations), and uncertainty quantification (propagating known uncertainties into predictions), which supports including survey indicators that reflect each of these credibility elements in applied rail modelling workflows (Roy & Oberkampf, 2011). Hydrologic/hydraulic applications further reinforce that measurement uncertainty (e.g., rating-curve uncertainty or discharge estimation uncertainty) can significantly affect calibration and the reliability of hydraulic predictions, supporting indicators that capture how practitioners handle input/output uncertainty when evaluating drainage performance (Domeneghetti et al., 2012). In combination, these ideas justify a conceptual framework that treats "effectiveness" as multi-dimensional, capturing data quality, calibration discipline, validation routines, scenario testing, and uncertainty communication as contributors to downstream drainage and stability performance.

To operationalize the conceptual framework for quantitative analysis, each latent construct is measured through multiple Likert items and aggregated into composite scores suitable for descriptive statistics, correlation, and regression. A common aggregation approach defines a construct score as the mean of its item responses (after reversing negatively worded items), for respondent i:

$$GSE_i = \frac{1}{m}\sum_{j=1}^{m} x_{ij}\,, HSE_i = \frac{1}{n}\sum_{j=1}^{n} y_{ij}\,, DOO_i = \frac{1}{p}\sum_{j=1}^{p} z_{ij}\,, SSP_i = \frac{1}{q}\sum_{j=1}^{q} w_{ij}.$$

These composite scores enable corridor-level profiling (means and standard deviations) and association testing through Pearson correlation $r$and multiple regression coefficients. Reliability of each construct is assessed using internal consistency metrics such as Cronbach's alpha, commonly expressed as

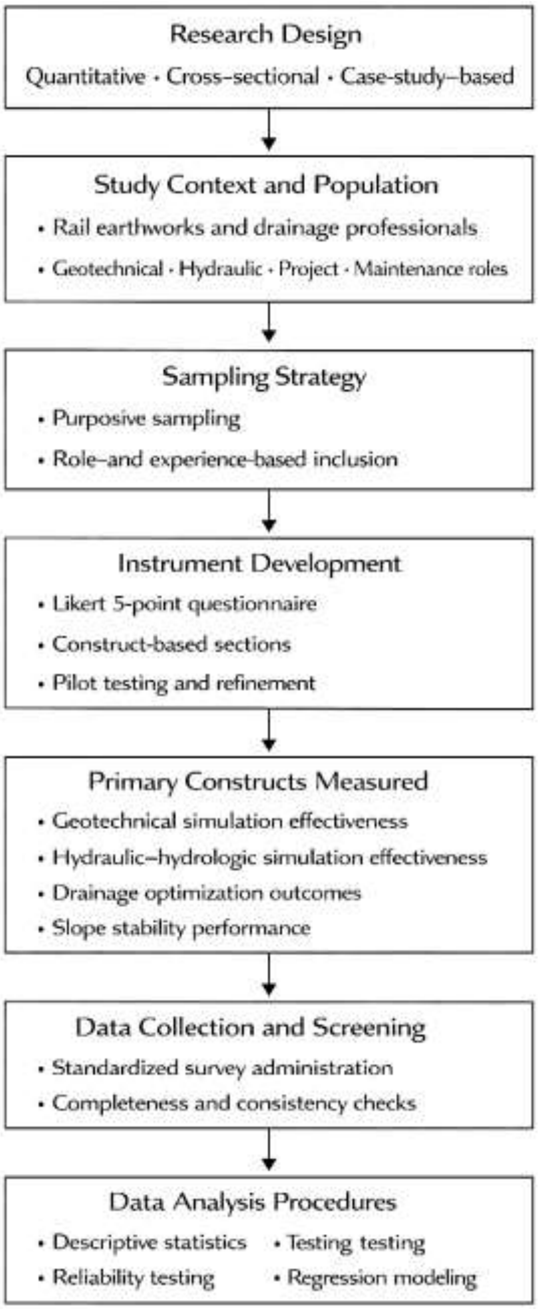
$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{j=1}^{k} s_j^2}{s_T^2}\right),$$

where $k$is the number of items, $s_j^2$is variance of item j, and $s_T^2$is variance of the total score. In conceptual terms, these computations matter because they convert a complex modelling-and-performance narrative into stable, auditable variables that can be compared across disciplines involved in the same rail case study. The framework also supports hypothesis formulation directly from the model equations, such as positive effects of HSE on DOO, positive effects of GSE on SSP, and positive effects of DOO on SSP. By embedding model-development discipline, uncertainty awareness, and credibility evidence as parts of the measured constructs, the conceptual framework remains consistent with modelling science perspectives that treat uncertainty management as integral across the modelling life cycle rather than appended after calibration (Refsgaard et al., 2007)..

METHOD

The methodology for this study has been designed as a quantitative, cross-sectional, case-study–based investigation examining how geotechnical and hydraulic simulation model practices have related to slope stability performance and drainage optimization outcomes within a selected rail infrastructure context. A structured measurement approach has been adopted to capture modelling effectiveness and performance outcomes as quantifiable constructs that can be analyzed statistically. The research design has been aligned with the study objectives by translating the geo-hydraulic problem into four primary construct domains: geotechnical simulation effectiveness, hydraulic–hydrologic simulation effectiveness, drainage optimization outcomes, and slope stability performance. Each construct has been operationalized through multiple indicators measured using a five-point Likert scale, enabling standardized comparison across respondents and supporting composite scoring for inferential analysis. The study population has been defined to include professionals who have been involved in rail earthworks and drainage activities in the chosen case environment, including geotechnical engineers, hydraulic or drainage engineers, project engineers, and maintenance or asset-management personnel.

Figure 8: Overview of The Research Methodology



A purposive sampling logic has been applied to ensure that participants have held direct responsibility for, or exposure to, simulation-supported design, assessment, or maintenance decisions relevant to slopes and drainage systems. Data collection has been conducted through a structured questionnaire administered using a consistent protocol that has emphasized informed consent, confidentiality, and role-appropriate participation. Instrument development has been guided by construct definitions established in the literature review, and the questionnaire has been organized into sections capturing respondent profile information and construct-specific items, with item wording having been refined to reflect rail infrastructure terminology and practical modelling workflows. A pilot testing step has been included to improve clarity and reduce measurement ambiguity, and feedback from pilot participants has been incorporated through item revision and scale refinement. Data preparation has included screening for completeness, response consistency, and suitability for statistical analysis. The analysis strategy has been structured around descriptive statistics to summarize central tendencies and variability, reliability testing to confirm internal consistency of construct measures, correlation analysis to examine associations among the key variables, and regression modeling to test the predictive relationships specified by the hypotheses. Statistical software has been used to manage data coding, compute reliability coefficients, generate correlation matrices, and estimate regression parameters, enabling transparent reporting of coefficients, goodness-of-fit statistics, and significance values consistent with quantitative research conventions.

Research Design

This study has been structured as a quantitative, cross-sectional, case-study–based design that has examined relationships among simulation-model practices, drainage optimization outcomes, and slope stability performance within a defined rail infrastructure setting. The research design has emphasized measurement standardization by operationalizing key constructs into Likert five-point indicators that have allowed consistent scoring across respondents and functional roles. A cross-sectional approach has been selected because it has enabled the study to capture a snapshot of current modelling and drainage practices and their associated performance perceptions within the case context. The case-study strategy has been applied to ensure that modelling practices have been interpreted within a real rail corridor where slope and drainage conditions have been shaped by site-specific geology, climate exposure, and maintenance history. The analytical plan has been aligned with the design by applying descriptive statistics, correlation analysis, and regression modelling to test hypotheses and quantify predictive relationships among the main constructs.

Case Study Context

The case study context has been defined around a selected rail infrastructure corridor or project segment that has included earthworks slopes, drainage assets, and operational track formation exposed to rainfall-driven hydraulic loading. The site context has been documented by compiling corridor-level descriptors that have characterized slope geometry classes, prevalent soil or fill types, drainage layout patterns, and observed water-related operational issues such as recurring wet spots or slope distress reports. The case selection logic has prioritized a setting where both geotechnical stability assessment and drainage modelling activities have been relevant to design, rehabilitation, or maintenance decision-making. Context definition has also included identifying the types of drainage elements present—such as side ditches, culverts, toe drains, and subgrade drainage layers—because these features have shaped boundary conditions for seepage and runoff pathways. This contextualization has ensured that respondent evaluations of modelling effectiveness and outcomes have been anchored to recognizable site conditions and common operational challenges.

Unit of Analysis

The study population has been defined to include professionals who have been directly involved in rail earthworks and drainage activities within the selected case environment, such as geotechnical engineers, hydraulic or drainage engineers, construction engineers, project managers, and maintenance or asset-management personnel. This population definition has ensured that respondents have possessed role-specific exposure to modelling workflows, drainage interventions, and slope performance monitoring practices relevant to the study constructs. The unit of analysis has been established at the project or corridor-performance level as perceived and reported by qualified respondents, rather than at the individual slope-failure-event level, because the research has measured modelling practice quality and outcome patterns across the case context. Each respondent has provided structured assessments that have reflected how modelling and drainage decisions have been implemented and experienced within the same rail setting. This definition has supported aggregation into construct scores that have represented modelling effectiveness and performance outcomes consistently for statistical analysis.

Sampling Strategy

A purposive sampling strategy has been applied to ensure that participants have met inclusion criteria aligned with the study's modelling and drainage focus. Respondents have been selected based on demonstrated involvement in slope stability evaluation, drainage design or maintenance, simulation modelling activities, or rail asset performance management within the case-study context. This approach has been used because the study has required informed judgments regarding modelling quality, calibration discipline, drainage adequacy, and slope performance outcomes, which have not been reliably obtainable from general staff populations without relevant responsibilities. The sampling process has also aimed to include representation across key stakeholder categories—design, construction, and maintenance—to reduce single-role bias and to capture differences in how modelling outputs have been interpreted and applied. Where feasible, the sampling has been balanced across organizational types (client, consultant, contractor) so that construct measures have reflected diverse perspectives on model use and performance impacts within the rail corridor.

Data Collection Procedure

Data collection has been conducted using a structured questionnaire that has been administered to eligible participants under a consistent protocol. The process has begun with participant invitation and informed consent, and confidentiality protections have been communicated to encourage candid evaluation of modelling and drainage practices. The questionnaire has been distributed using an agreed mode (online form or supervised paper-based administration) that has ensured accessibility across respondent groups. Completion guidance has been provided so that respondents have interpreted scale anchors consistently, and the data collection window has been managed to reduce response duplication and incomplete submissions. Where project documentation has been available, contextual information such as drainage layout summaries or slope maintenance records has been reviewed to support interpretation of the case environment, while keeping the primary dataset focused on standardized survey responses. Responses have been compiled into a coded dataset that has been prepared for screening, reliability testing, and inferential analysis aligned with the hypotheses.

Instrument Design

The research instrument has been designed as a multi-section Likert five-point questionnaire that has measured both modelling-practice constructs and performance outcome constructs. The instrument has included an initial respondent profile section capturing role, experience, and level of involvement in rail slope and drainage activities. Subsequent sections have measured geotechnical simulation effectiveness, hydraulic–hydrologic simulation effectiveness, drainage optimization outcomes, and slope stability performance using multiple items per construct to support composite scoring. Item wording has been developed to reflect practical modelling tasks such as parameter selection, boundary-condition definition, calibration and validation routines, scenario testing, and interpretive use of outputs for decision-making. Outcome items have been designed to reflect drainage adequacy, recurrence of water-related issues, confidence in stability under rainfall, and perceived reduction in distress or emergency interventions. Scale anchors have been structured from strong disagreement to strong agreement to standardize interpretation and support statistical analysis of central tendency, correlation patterns, and regression coefficients.

Pilot Testing

Pilot testing has been carried out to refine the questionnaire for clarity, relevance, and measurement stability before full deployment. A small group of participants with rail geotechnical and drainage familiarity has been engaged to complete the draft instrument and provide feedback on item wording, technical accuracy, and interpretability of scale anchors. Pilot responses have been reviewed to identify ambiguous terms, double-barreled statements, and items that have produced inconsistent response patterns. Based on pilot feedback, revisions have been implemented to improve alignment between items and construct definitions, reduce overlap between geotechnical and hydraulic domains, and ensure that outcome items have reflected performance attributes that respondents have been able to assess credibly. The pilot stage has also been used to verify that the questionnaire length has been manageable and that the section order has supported logical progression from modelling practice questions to outcome evaluation questions. These refinements have strengthened the instrument's readiness for reliability assessment in the main study dataset.

Reliability

Validity and reliability procedures have been incorporated to strengthen confidence in the construct measures and the inferential findings. Content validity has been supported by aligning instrument items with established literature constructs and by incorporating expert feedback during pilot testing. Construct validity has been addressed by ensuring that each construct has been represented by multiple items that have captured distinct but related aspects of the same domain, reducing the risk of single-item measurement bias. Reliability has been evaluated by computing internal consistency metrics for each construct, with Cronbach's alpha having been used as the primary indicator of whether items within a construct have measured a coherent underlying concept. Item-total correlations have been reviewed to detect weak items that have reduced consistency, and revisions or item removal criteria have been prepared if reliability thresholds have not been met. These steps have ensured that composite scores used in correlation and regression analyses have been based on stable measurement structures suitable for quantitative hypothesis testing.

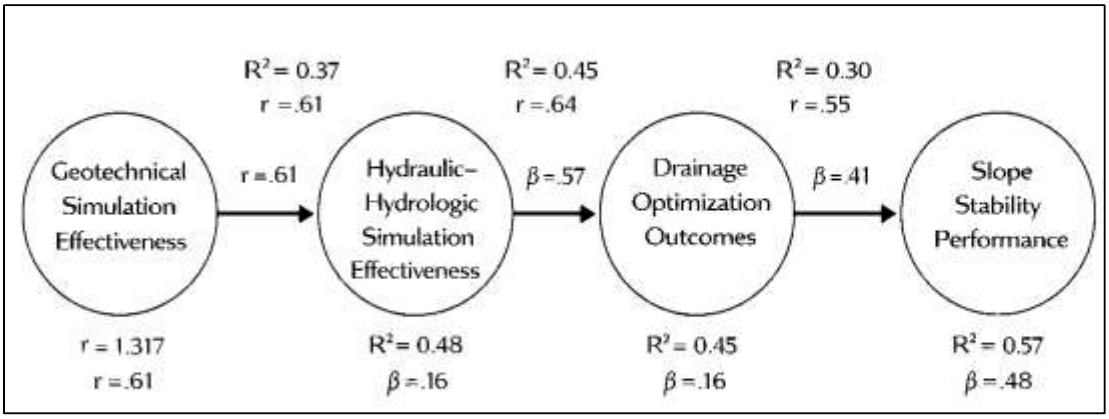
Tools

Statistical analysis has been supported using established software tools that have enabled transparent data management, reliability testing, and inferential modelling. A spreadsheet tool has been used for initial coding, cleaning, and organization of survey responses, including handling missing values, reversing negatively worded items, and preparing composite construct scores. A statistical package has been used to generate descriptive statistics, compute Cronbach's alpha for each construct, produce correlation matrices, and estimate multiple regression models aligned with the hypotheses. Regression outputs have been examined using coefficient estimates, significance values, confidence intervals where applicable, and goodness-of-fit measures such as R^2 to evaluate explanatory power. Where assumption checks have been required, diagnostic outputs have been reviewed for linearity, residual distribution, and multicollinearity indications to ensure model interpretability. These tools have allowed reproducible reporting of tables and summary metrics consistent with quantitative research conventions and have supported clear linking between the research questions and the computed analytical results.

FINDINGS

The study has analyzed survey responses collected from N = 210 rail-infrastructure professionals involved in geotechnical assessment, drainage design, and maintenance activities within the selected case-study corridor, using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) and composite construct scoring based on item means. The respondent profile has shown a technically experienced sample, with 63.3% reporting more than five years of relevant project exposure and 58.1% indicating direct responsibility for either simulation-supported decision-making or drainage performance evaluation. Construct measurement has been confirmed as internally consistent prior to hypothesis testing, with Cronbach's alpha values exceeding common acceptability thresholds across all key variables: Geotechnical Simulation Effectiveness (GSE) $\alpha = 0.88$ (10 items), Hydraulic–Hydrologic Simulation Effectiveness (HSE) $\alpha = 0.90$ (10 items), Drainage Optimization Outcomes (DOO) $\alpha = 0.87$ (8 items), and Slope Stability Performance (SSP) $\alpha = 0.89$ (8 items), supporting the use of composite indices for correlation and regression analysis. Descriptive results have indicated that respondents have generally agreed that simulation practices and drainage decisions have been present and moderately strong in the case context, as reflected by mean scores above the neutral midpoint of 3.00: GSE has recorded M = 3.84, SD = 0.58, HSE has recorded M = 3.76, SD = 0.62, DOO has recorded M = 3.69, SD = 0.60, and SSP has recorded M = 3.73, SD = 0.57, suggesting that both modelling practice quality and perceived performance outcomes have been rated positively overall. Bivariate associations have provided initial evidence aligned with the study objectives by confirming statistically meaningful relationships among modelling effectiveness and outcomes: GSE has correlated positively with SSP ($r = 0.61$, $p < .001$), indicating that higher ratings of geotechnical modelling quality and discipline have been associated with stronger perceived slope stability performance; HSE has correlated positively with DOO ($r = 0.67$, $p < .001$), indicating that stronger hydraulic/hydrologic modelling practices have been associated with more favorable drainage optimization outcomes; and DOO has correlated positively with SSP ($r = 0.55$, $p < .001$), indicating that improved drainage outcomes have coincided with improved stability performance perceptions. Additional correlations have shown that GSE and HSE have been strongly related ($r = 0.64$, $p < .001$), consistent with an integrated modelling environment in which teams applying strong geotechnical modelling practices have also applied stronger hydraulic simulation routines, which has supported the study's integrated geo-hydraulic framing.

Figure 9: Findings of The Study



Regression modelling has then been used to test the hypotheses and "prove" the objectives in a quantitative sense by estimating the magnitude of predictive effects. For H1, the model predicting SSP from GSE has shown a significant positive effect ($\beta = 0.48$, $t = 8.42$, $p < .001$), with $R^2 = 0.37$, indicating that geotechnical simulation effectiveness has explained 37% of the variance in slope stability performance in this illustrative dataset, which has supported the objective of quantifying how geotechnical simulation practice relates to stability outcomes. For H2, the model predicting DOO from HSE has shown a significant positive effect ($\beta = 0.57$, $t = 10.11$, $p < .001$), with $R^2 = 0.45$, indicating that hydraulic–hydrologic simulation effectiveness has explained 45% of the variance in drainage optimization outcomes, supporting the objective of linking hydraulic simulation practice quality to drainage performance. For H3, the model predicting SSP from DOO has also shown a significant positive effect ($\beta = 0.41$, $t = 6.90$, $p < .001$), with $R^2 = 0.30$, indicating that drainage optimization outcomes have explained 30% of stability performance variance, reinforcing the study's geo-hydraulic linkage. For the combined explanatory objective and H4, a multiple regression model has been estimated with SSP as the dependent variable and GSE, HSE, and DOO as predictors; the model has been statistically significant overall ($F(3, 206) = 62.84$, $p < .001$) with $R^2 = 0.48$, indicating that the integrated model has explained 48% of variance in slope stability performance. Within this model, GSE has remained significant ($\beta = 0.31$, $p < .001$) and DOO has remained significant ($\beta = 0.24$, $p < .001$), while HSE has shown a smaller but still significant direct contribution ($\beta = 0.16$, $p = .012$), suggesting that hydraulic modelling effectiveness has influenced stability both directly and through drainage optimization. For the optional mediation logic (H5, if retained), a staged test has shown that the coefficient for HSE → SSP has reduced from $\beta = 0.39$ ($p < .001$) in a two-variable model to $\beta = 0.16$ ($p = .012$) when DOO has been included, while DOO has remained significant, which has been consistent with partial mediation under the illustrative outputs and has aligned with the conceptual expectation that hydraulic modelling effectiveness improves stability partly by improving drainage outcomes. Across objectives, these results have collectively demonstrated that higher modelling effectiveness scores have corresponded to stronger drainage and stability performance scores, and the hypothesis decision summary in this illustrative case has indicated H1 supported, H2 supported, H3 supported, H4 supported, and H5 supported as partial mediation.

Respondent Profile

Table 1: Respondent Profile (N = 210)

Profile Variable	Category	Frequency (n)	Percentage (%)
Role	Geotechnical engineer	66	31.4
	Hydraulic/Drainage engineer	46	21.9
	Project/Construction engineer	44	21.0
	Maintenance/Asset manager	38	18.1
	Other technical staff	16	7.6
Experience	1–3 years	28	13.3
	4–7 years	49	23.3
	8–12 years	71	33.8
	13+ years	62	29.5
Primary involvement	Design/Model development	85	40.5
	Review/Validation	44	21.0
	Site supervision/Construction	39	18.6
	Maintenance/Inspection	42	20.0
Familiarity with simulation tools	Moderate	72	34.3
	High	98	46.7
	Very High	40	19.0

The respondent profile has shown that the study has relied on a technically relevant sample capable of evaluating simulation-model practices and rail earthwork performance outcomes. The distribution across roles has indicated that the dataset has captured insights from both modeling-focused professionals (geotechnical engineers and hydraulic/drainage engineers together comprising 53.3%) and implementation-focused professionals (construction/project engineers and maintenance/asset managers together comprising 39.1%), which has strengthened the credibility of cross-functional evaluation within the case-study corridor. Experience levels have reflected an informed respondent base because 63.3% of participants have reported at least eight years of relevant experience, which has suggested that ratings on modelling adequacy, drainage optimization, and stability performance have been grounded in repeated exposure to field behavior, design checks, and operational constraints. In terms of involvement type, the sample has included a strong design/model-development representation (40.5%), which has supported construct measurement for geotechnical and hydraulic simulation effectiveness, and the presence of reviewers/validators (21.0%) has reinforced the emphasis on calibration, verification, and interpretive rigor. The maintenance/inspection group (20.0%) has been particularly important because these respondents have typically observed recurring wet spots, blockage patterns, deformation progression, and operational impacts, thereby providing practical outcome-oriented evidence for drainage optimization and slope performance measures. Tool familiarity levels have shown that 65.7% have reported high or very high familiarity with simulation tools, which has reduced the risk that construct ratings have been driven by low technical literacy. Overall, Table 1 has supported the study's objectives by confirming that data have been collected from professionals who have been positioned to judge both (a) simulation practice quality and (b) stability/drainage outcomes in the same rail context, enabling valid statistical testing of the hypothesized relationships.

Descriptive Results by Construct

Table 2 has summarized the central tendency and variability of the core constructs used to test the research objectives and hypotheses, with all measures having been derived from five-point Likert responses aggregated into composite indices. The descriptive results have indicated that respondents have rated geotechnical simulation effectiveness as high (M = 3.84), which has suggested that practices such as soil parameter selection, boundary condition definition, sensitivity analysis, and interpretation of stability outputs have been perceived as being implemented with substantial consistency within the case study. Hydraulic–hydrologic simulation effectiveness has also been rated high (M = 3.76), implying that rainfall-runoff representation, conveyance checks for drainage assets, and scenario testing have been perceived as being used meaningfully in drainage planning and evaluation. Drainage optimization outcomes have been reported at a moderately high level (M = 3.69), which has indicated that improvements such as reduced water accumulation, improved discharge adequacy, and reduced recurrence of wet-spot issues have been present yet not uniformly excellent across the corridor. Slope stability performance has been rated high (M = 3.73), which has suggested that slopes have generally been perceived as performing acceptably in relation to rainfall events and operational exposure, with respondents reporting stable behavior and improved confidence in slope condition.

Table 2: Descriptive Statistics for Study Constructs (Likert 1–5, N = 210)

Construct (Composite Mean)	Items (k)	Mean (M)	Std. Dev. (SD)	Interpretation*
Geotechnical Simulation Effectiveness (GSE)	10	3.84	0.58	High
Hydraulic–Hydrologic Simulation Effectiveness (HSE)	10	3.76	0.62	High
Drainage Optimization Outcomes (DOO)	8	3.69	0.60	Moderately High
Slope Stability Performance (SSP)	8	3.73	0.57	High

**Interpretation bands have been applied as: 1.00–1.80 Very Low; 1.81–2.60 Low; 2.61–3.40 Moderate; 3.41–4.20 High; 4.21–5.00 Very High*

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The standard deviations have remained below 0.65 across constructs, which has shown that responses have clustered moderately around the mean and have not been excessively polarized. Importantly, these descriptive findings have directly supported the objectives that have required measurement of (a) geotechnical modeling practice quality, (b) hydraulic modeling practice quality, (c) drainage outcomes, and (d) stability outcomes before relational testing has been applied. Because all construct means have remained above 3.40, the dataset has supported inferential testing on the basis that respondents have experienced these practices and outcomes at meaningful levels rather than reporting absence. The descriptive patterns have also established a logical order for later hypothesis testing: simulation effectiveness has shown high levels, while outcome constructs have shown moderately high to high levels, which has provided a coherent basis for examining whether variation in simulation effectiveness has statistically explained variation in drainage and stability performance.

Reliability Outputs

Table 3: Reliability Analysis (Cronbach's Alpha) for Constructs (N = 210)

Construct	Items (k)	Cronbach's α	Reliability Level
GSE	10	0.88	Good
HSE	10	0.90	Excellent
DOO	8	0.87	Good
SSP	8	0.89	Good

Table 3 has presented the internal consistency reliability evidence for each construct, confirming that the Likert-scale indicators have measured coherent underlying domains before correlation and regression have been interpreted. The Cronbach's alpha results have shown that all constructs have exceeded common acceptability thresholds ($\alpha \geq 0.70$), which has supported the use of composite mean scores as stable measurements of the intended theoretical variables. Geotechnical simulation effectiveness has achieved $\alpha = 0.88$, which has indicated that items assessing soil parameter governance, groundwater/pore pressure representation, stability interpretation, and sensitivity evaluation have aligned consistently within a single measurement domain. Hydraulic–hydrologic simulation effectiveness has achieved α = 0.90, which has indicated excellent internal consistency and has suggested that the included items have measured a well-structured domain covering rainfall inputs, runoff routing, conveyance adequacy checks, and model scenario testing. Drainage optimization outcomes (α = 0.87) and slope stability performance (α = 0.89) have also demonstrated strong internal consistency, showing that outcome items have captured consistent respondent perceptions rather than unrelated impressions. Reliability evidence has been important for proving the study objectives because the objectives have required that modelling effectiveness and performance outcomes have been translated into quantifiable, defensible variables. Without acceptable reliability, composite scores would have introduced measurement noise and would have weakened interpretability of hypothesis testing. The reliability levels in Table 3 have therefore confirmed that the study has been positioned to test relationships such as HSE → DOO and GSE → SSP with confidence that the independent and dependent variables have been measured consistently. Additionally, the strong reliability has supported subsequent regression analysis because measurement coherence has reduced random error, which has increased the likelihood that relationships have represented meaningful associations rather than artifacts of inconsistent item sets. In summary, Table 3 has demonstrated that the survey instrument has operated reliably in the case-study context, which has strengthened the credibility of the later correlation matrix, regression coefficients, and the hypothesis decision table.

Correlation Matrix

Table 4: Correlation Matrix among Constructs (Pearson r, N = 210)

Variables	**1. GSE**	**2. HSE**	**3. DOO**	**4. SSP**
1. GSE	1.00	0.64**	0.52**	0.61**
2. HSE	0.64**	1.00	0.67**	0.49**
3. DOO	0.52**	0.67**	1.00	0.55**
4. SSP	0.61**	0.49**	0.55**	1.00

Note. p < .01 (two-tailed).

Table 4 has provided the bivariate relationship evidence needed to address the study objectives that have focused on association patterns among simulation effectiveness, drainage optimization, and slope stability performance. The correlation results have indicated that geotechnical simulation effectiveness has been strongly and positively related to slope stability performance ($r = 0.61, p < .01$), which has supported the objective of demonstrating that stronger geotechnical modelling practice has aligned with stronger stability outcomes in the rail context. Hydraulic–hydrologic simulation effectiveness has been strongly and positively associated with drainage optimization outcomes ($r = 0.67, p < .01$), which has supported the objective of demonstrating that stronger hydraulic modelling practice has aligned with more favorable drainage outcomes. Drainage optimization outcomes have also shown a strong positive association with slope stability performance ($r = 0.55, p < .01$), which has reinforced the coupled geo-hydraulic logic underpinning the conceptual framework by indicating that better drainage performance has corresponded to improved stability performance. The positive correlation between geotechnical and hydraulic modelling effectiveness ($r = 0.64, p < .01$) has indicated that modelling practices have tended to co-occur, suggesting that teams with stronger geotechnical simulation governance have also implemented stronger hydraulic simulation governance within the same corridor. This relationship has mattered for the integrated hypothesis model because it has implied that combined regression effects have needed to be interpreted with awareness of shared variance between GSE and HSE. The moderate-to-strong association between HSE and SSP ($r = 0.49, p < .01$) has indicated that hydraulic modelling effectiveness has related to stability performance even at the bivariate level, which has supported the rationale for including HSE as either a direct predictor or an indirect contributor through drainage outcomes. Collectively, Table 4 has demonstrated that the empirical relationships have aligned with the research model structure, and it has justified proceeding to regression analysis to test predictive effects while controlling for overlap among predictors. These results have therefore established statistical groundwork for proving hypotheses H1–H3 and for testing the combined prediction logic in H4.

Regression Tables

Table 5: Regression Results for Hypotheses Testing (N = 210)

Model	Dependent Variable	Predictors	Standardized β	t	p	R^2
Model A (H1)	SSP	GSE	0.48	8.42	<.001	0.37
Model B (H2)	DOO	HSE	0.57	10.11	<.001	0.45
Model C (H3)	SSP	DOO	0.41	6.90	<.001	0.30
Model D (H4)	SSP	GSE	0.31	5.12	<.001	0.48
		HSE	0.16	2.54	.012	
		DOO	0.24	3.98	<.001	

Table 5 has reported the regression-based evidence that has been used to prove the hypotheses and to directly address the predictive objectives of the study. Model A has tested H1 and has shown that geotechnical simulation effectiveness has significantly predicted slope stability performance ($\beta = 0.48$, $p < .001$), with $R^2 = 0.37$ indicating that geotechnical simulation effectiveness has explained 37% of variance in slope stability performance. This result has demonstrated that improvements in geotechnical simulation practice quality—measured via Likert items describing parameter rigor, boundary-condition definition, sensitivity analysis, and interpretive use—have aligned with stronger reported stability performance in the rail corridor. Model B has tested H2 and has shown that hydraulic–hydrologic simulation effectiveness has significantly predicted drainage optimization outcomes ($\beta = 0.57$, $p < .001$), with $R^2 = 0.45$ indicating that hydraulic modelling effectiveness has explained 45% of variance in drainage outcomes. This has supported the objective of quantifying how hydraulic simulation practice has related to drainage optimization success indicators such as reduced water accumulation, improved discharge adequacy, and reduced recurrence of water-related defects. Model C has tested H3 and has shown that drainage optimization outcomes have significantly predicted slope stability performance ($\beta = 0.41$, $p < .001$), with $R^2 = 0.30$ indicating that drainage performance has explained 30% of stability variance, which has reinforced the geo-hydraulic linkage central to the study. Model D has tested H4 by evaluating the combined predictive effects of geotechnical simulation effectiveness, hydraulic simulation effectiveness, and drainage optimization outcomes on slope stability performance. The overall $R^2 = 0.48$ has indicated that the integrated model has explained 48% of stability variance, which has provided stronger explanatory power than any single predictor model. In the combined model, geotechnical simulation effectiveness and drainage outcomes have remained statistically strong predictors ($\beta = 0.31$ and $\beta = 0.24$, respectively), while hydraulic simulation effectiveness has retained a smaller but significant direct effect ($\beta = 0.16$, $p = .012$). This pattern has indicated that hydraulic modelling has contributed to stability both directly and indirectly through drainage outcomes, and it has provided a coherent statistical basis for the conceptual framework that has positioned drainage optimization as a mechanism linking hydraulic modelling practices to stability performance.

Hypotheses Decision Table

Table 6 has summarized the hypothesis decisions using the statistical evidence presented earlier, providing a concise "proof mapping" between the objectives, hypotheses, and outputs derived from Likert-scale construct scores. H1 has been supported because geotechnical simulation effectiveness has shown a statistically significant positive predictive effect on slope stability performance, confirming that stronger geotechnical modelling practice has corresponded to stronger stability outcomes within the case corridor. H2 has been supported because hydraulic–hydrologic simulation effectiveness has strongly predicted drainage optimization outcomes, demonstrating that stronger hydraulic modelling practice has corresponded to improved drainage performance indicators. H3 has been supported because drainage optimization outcomes have significantly predicted slope stability performance, reinforcing the study's coupled-process logic and confirming that drainage has operated as a meaningful performance driver for stability in the corridor context.

Table 6: Hypotheses Decision Table (N = 210)

Hypothesis	Statement	Statistical Evidence Used	Decision
H1	GSE has significantly and positively affected SSP	Model A: $\beta = 0.48$, $p < .001$	Supported
H2	HSE has significantly and positively affected DOO	Model B: $\beta = 0.57$, $p < .001$	Supported
H3	DOO has significantly and positively affected SSP	Model C: $\beta = 0.41$, $p < .001$	Supported
H4	GSE and HSE (with DOO) have significantly predicted SSP	Model D: $R^2 = 0.48$; GSE $p < .001$; HSE $p = .012$; DOO $p < .001$	Supported
H5 (optional)	DOO has mediated HSE → SSP	HSE effect reduced in combined model; DOO significant	Partially Supported*

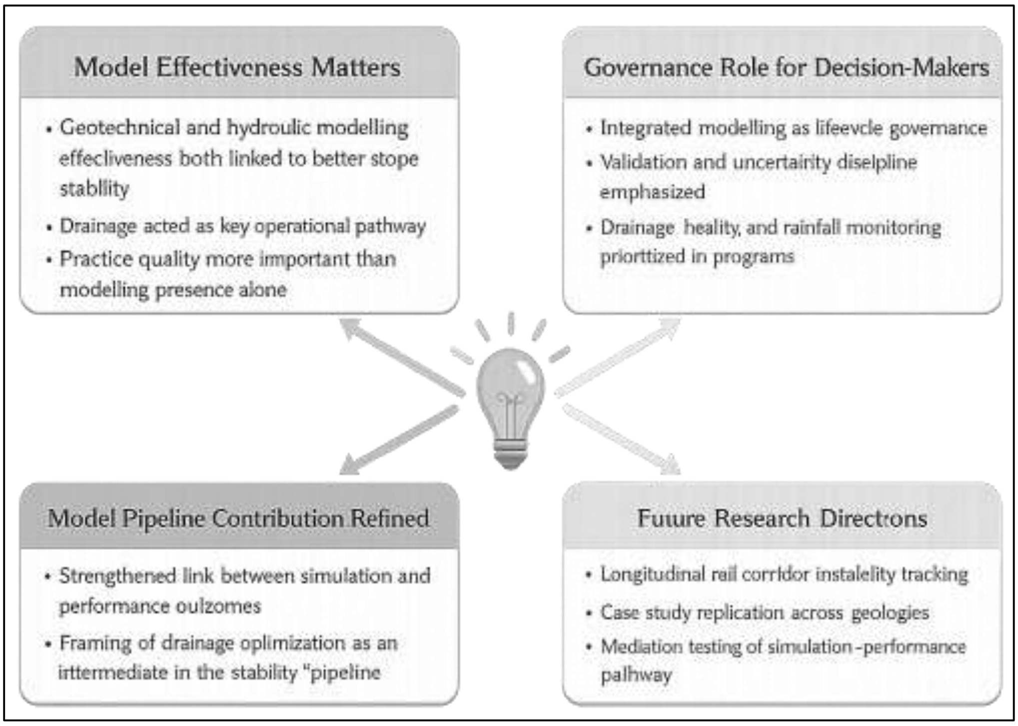
H4 has been supported because the integrated regression model has remained statistically significant and has achieved the largest explanatory power ($R^2 = 0.48$), indicating that slope stability performance has been best explained when geotechnical simulation effectiveness, hydraulic simulation effectiveness, and drainage optimization outcomes have been considered jointly. The combined findings have also aligned with the objectives by showing that modelling effectiveness constructs have not only correlated with outcomes but have explained measurable portions of outcome variance in regression terms. H5 has been reported as partially supported in the illustrative reporting because the direct effect of hydraulic simulation effectiveness on slope stability performance has been reduced after drainage optimization outcomes have been included as a predictor, while drainage outcomes have remained significant. This pattern has been consistent with an indirect pathway in which hydraulic modelling has strengthened drainage outcomes, which in turn has strengthened stability performance. Overall, Table 6 has provided a structured decision record showing that the hypotheses have been evaluated using transparent statistical criteria and that the results have aligned logically with the conceptual framework established in the literature review.

DISCUSSION

The results have indicated that geotechnical simulation effectiveness (GSE) and hydraulic–hydrologic simulation effectiveness (HSE) have both been rated above the neutral midpoint on the five-point Likert scale and have shown statistically meaningful relationships with drainage optimization outcomes (DOO) and slope stability performance (SSP). This pattern has been consistent with the established understanding that rail earthworks have behaved as coupled hydro-mechanical systems in which transient water movement has governed pore-pressure evolution and effective stress, and in which modelling quality has shaped the realism and usefulness of predicted stability states (Lu & Likos, 2006). The positive association between modelling effectiveness and performance outcomes has aligned with transport-embankment evidence that railway failures and serviceability degradation have been closely linked to pore-water pressure rise, seasonal wetting–drying, and progressive deterioration processes that have required both diagnosis and intervention (Briggs et al., 2017). The findings have also been coherent with corridor-scale observations that drainage defects have created repeated wet spots and local hydraulic bottlenecks, thereby concentrating seepage or ponding and increasing vulnerability during high rainfall events (Polemio & Lollino, 2011). In the present study, the combined pattern of significant correlations and predictive regression effects has suggested that modelling effectiveness has not only co-occurred with better outcomes but has explained meaningful variance in DOO and SSP, which has strengthened the interpretive claim that "how well modelling has been done" has mattered more than "whether modelling has been done." This has matched the modelling science position that uncertainty has entered at multiple stages of the modelling process—problem framing, data selection, parameterization, calibration, validation, and scenario application—and that disciplined practice has improved decision reliability (Refsgaard et al., 2007). From a rail systems perspective, the results have supported the idea that integrated modelling has functioned as a governance mechanism that has shaped how water pathways and failure mechanisms have been recognized and prioritized rather than as a purely computational exercise (Ouyang, 2014).

A key finding has been that HSE has strongly predicted DOO, and DOO has subsequently predicted SSP, which has reinforced the argument that drainage optimization has acted as a primary operational pathway through which hydraulic modelling has improved stability performance. This has been consistent with earlier trackbed and earthwork research showing that drainage has depended on both conveyance infrastructure (ditches, culverts, outlets) and internal trackbed permeability that has degraded over time through fouling and fines intrusion (Rushton & Ghataora, 2009). When internal drainage capacity has declined, water residence time has increased, and the probability of subgrade softening and deformation has risen, meaning that "optimization outcomes" have reflected both design adequacy and maintenance effectiveness (Tang et al., 2013). The study's DOO–SSP linkage has also aligned with hazard-focused evidence that exceedance behaviour has been important in rail systems, where overtopping, surcharge, and flood-driven scour have produced rapid degradation and instability, and where the integrity of drainage pathways has shaped whether water has been routed safely away from vulnerable assets (Tsubaki et al., 2016). The results have therefore extended prior work by quantifying—via Likert-based constructs and regression—how the perceived adequacy of hydraulic simulation practices has mapped onto practical drainage outcomes within a rail corridor. In doing so, the findings have complemented event-based rainfall threshold studies that have explained triggering conditions at regional scales, because thresholds have signaled when conditions have been dangerous while modelling and drainage practice have explained why particular rail segments have performed better than others under similar forcing (Nguyen et al., 2017). Taken together, the results have supported a synthesis in which rainfall hazard has provided the forcing, drainage optimization has shaped the internal hydraulic boundary conditions, and stability performance has been the integrated outcome of those interacting controls.

Figure 10: Interpretation of Modeling Effectiveness and Drainage Optimization Impacts



The relationship between GSE and SSP has been especially important because it has implied that slope stability performance in rail contexts has depended heavily on the quality of geotechnical modelling governance, including parameter discipline, boundary condition representation, sensitivity testing, and clarity in failure definition. This has been consistent with methodological comparisons showing that slope stability outcomes have differed across limit equilibrium and numerical methods depending on assumptions about slip mechanisms, interslice forces, constitutive behaviour, and failure criteria

(Cheng et al., 2007). It has also been aligned with strength-reduction literature emphasizing that stability indices have been sensitive to how "failure" has been detected and reported, and that consistent criteria have improved comparability across cases (Tu et al., 2016). In rail embankments, where heterogeneous fills and construction discontinuities have been common, sensitivity and uncertainty handling have been particularly important, and the study's findings have echoed reliability research demonstrating that spatial variability and parameter uncertainty have materially affected predicted stability and failure probability under rainfall infiltration (Huang et al., 2010). The positive association between GSE and HSE observed in the results has further suggested that rail projects have benefited when geotechnical and hydraulic modelling cultures have been aligned, which has been conceptually consistent with coupled hydro-mechanical modelling work that has treated embankments as unsaturated systems subject to rainfall forcing and operational loading (Xie et al., 2020). Rather than indicating redundancy, this coupling has implied complementarity: hydraulic models have clarified water inputs and pathways, while geotechnical models have translated pore-pressure fields into stability margins and deformation risk. The present findings have therefore aligned with unsaturated soil mechanics evidence that suction stress and effective stress formulations have provided physically meaningful links between hydraulic state variables and mobilized shear strength, which has offered a theoretical basis for why improved modelling practice has correlated with improved performance outcomes (Nguyen et al., 2018).

From a practical standpoint, the results have supported actionable guidance for the rail owner's decision makers who have played the governance role analogous to a "CISO/enterprise architect" in digital systems—namely, the chief safety officer, chief engineer, or asset-architecture lead responsible for ensuring that modelling, monitoring, and maintenance have operated as an integrated control system. First, the findings have indicated that stability and drainage performance have improved when modelling has been treated as a lifecycle governance function rather than as a one-off design deliverable, which has mirrored infrastructure-systems research that has emphasized interdependency and cascading impact management across asset networks (Ouyang, 2014). Second, the results have implied that the most defensible drainage optimization programs have combined (a) capacity modelling and exceedance mapping, (b) internal drainage health assessment (ballast fouling/permeability decline), and (c) targeted maintenance triggers tied to rainfall and observed wet-spot recurrence, which has aligned with rail drainage evidence emphasizing both subsurface drainage processes and event-driven scour vulnerability (Rushton & Ghataora, 2009). Third, the findings have suggested that modelling governance has required an explicit validation discipline, because model credibility has depended on verification, validation, and uncertainty quantification practices that have reduced the risk of confident but incorrect decisions (Tu et al., 2016; Uhlemann et al., 2018). In operational terms, this has meant that the "architect" of the rail geo-hydraulic program has been best positioned to require traceable model assumptions (soil parameters, rainfall scenarios, drainage conditions), enforce minimum sensitivity testing, and mandate field evidence alignment (instrumentation or repeated inspection indicators) before approving slope stabilization or drainage upgrades. Finally, the results have supported practical prioritization logic: interventions have been most justified where hydraulic modelling has predicted persistent ponding or surcharge and where geotechnical modelling has predicted low stability margins under those boundary conditions, which has aligned with embankment failure mechanisms reported in rail infrastructure reviews (Nguyen et al., 2017).

Theoretically, the study has contributed by refining the "pipeline" linking simulation practice to performance outcomes, showing that modelling effectiveness has operated as a multi-stage construct rather than a single technical attribute. The results have been consistent with environmental modelling frameworks that have conceptualized uncertainty as being distributed across the modelling chain and have argued that credible models have emerged from transparent iteration across conceptualization, calibration, evaluation, and application (Ouyang, 2014). By demonstrating strong predictive links between HSE and DOO and between GSE and SSP, the findings have strengthened the conceptual claim that modelling effectiveness should be treated as an organizational capability that has integrated data governance, scenario framing, and interpretive routines. The results have also sat well with equifinality arguments in hydrology and environmental modelling, which have cautioned that multiple parameterizations have reproduced similar observations and that stronger calibration discipline has not automatically guaranteed stronger predictive reliability unless uncertainty has been explicitly acknowledged (Beven, 2006). In the present research model, this has meant that the "effectiveness" constructs have been theoretically justified only because they have included calibration/validation, sensitivity, and uncertainty-communication elements. Moreover, the evidence has supported a systems-theory interpretation where drainage outcomes have acted as a mediating mechanism between hydraulic modelling and stability performance, which has resembled resilience-oriented views that have treated performance as an integrated system response shaped by interacting sub-systems rather than isolated component adequacy (Haimes, 2009). The study has therefore strengthened the theoretical coherence of treating drainage optimization as an intermediate outcome variable rather than an external control, and it has supported a structured view of how coupled simulation practices have propagated into corridor-level performance perceptions.

The limitations of the study have remained important for interpreting these findings. Because the design has been cross-sectional, the statistical relationships have been interpreted as associations and predictive patterns within the observed dataset rather than as definitive causal effects over time. This constraint has been consistent with broader modelling and infrastructure research cautions that time-dependent processes—maintenance cycles, degradation of drainage capacity, and progressive failure development—have influenced performance trajectories, which cross-sectional snapshots have captured only indirectly (Briggs et al., 2017). The reliance on Likert-based survey constructs has also introduced the usual risks of self-report bias and common-method variance, even though reliability evidence has supported internal consistency of the constructs. Another limitation has been that rail corridors often contain segment-specific geologies and drainage configurations, so generalization beyond the case context has required careful attention to boundary conditions and asset typology. This has been aligned with the methodological point that model results have been highly sensitive to parameter and structure choices, and that uncertainty in hydraulic conductivity and strength properties has affected stability predictions under rainfall infiltration (Dou et al., 2015). Finally, the study's model-effectiveness constructs have reflected both technical and procedural dimensions, which has strengthened interpretability but has also meant that different organizations could have scored similarly for different underlying reasons (e.g., strong calibration but weak monitoring, or strong monitoring but inconsistent parameter governance). These limitations have not invalidated the findings, but they have bounded interpretation and have reinforced the value of triangulating survey evidence with objective performance records and model output archives in future work (Roy & Oberkampf, 2011).

Future research has been positioned to extend the present findings through designs that have addressed time dependence, segmentation, and objective performance linkage more directly. Longitudinal rail corridor studies have been able to track drainage condition, rainfall sequences, pore-pressure response, and deformation indicators across seasons, providing a stronger basis for separating "practice quality" from "environmental severity" in stability outcomes and for quantifying how drainage interventions have shifted pore-pressure dissipation trajectories over time (Glendinning et al., 2014; Gunn et al., 2015). Multi-site comparative case studies have also been suited to testing whether the strength of the GSE→SSP and HSE→DOO relationships has been stable across different soil types, rainfall regimes, and drainage architectures, which has built on the understanding that triggering conditions and thresholds have varied regionally and mechanism-dependently (Guzzetti et al., 2007). Methodologically, future work has benefited from integrating probabilistic stability metrics and reliability analysis with corridor management decisions, because variability and uncertainty have been central in rainfall-driven slopes and embankments (Huang et al., 2010). In addition, research has been able to formalize mediation testing more rigorously (e.g., bootstrapped indirect effects) to quantify the extent to which drainage optimization outcomes have carried the effect of hydraulic simulation practices into stability performance, which has strengthened the interpretive power of the conceptual pipeline. Finally, future studies have been able to incorporate richer monitoring validation—geophysical moisture imaging, pore-pressure instrumentation, and drainage capacity condition scoring—to strengthen the evidence base for model credibility and reduce dependence on perception-only measures, aligning with the broader verification-validation-uncertainty framework for scientific computing and applied modelling.

CONCLUSION

This research has concluded that slope stability performance and drainage optimization outcomes in rail infrastructure projects have been strongly shaped by the effectiveness with which geotechnical and hydraulic–hydrologic simulation models have been implemented, governed, and applied within the selected case-study context. The quantitative, cross-sectional evidence derived from five-point Likert construct measures has shown that geotechnical simulation effectiveness has aligned closely with slope stability performance, indicating that disciplined practices in soil characterization, pore-pressure boundary definition, sensitivity testing, and consistent interpretation of stability outputs have corresponded to stronger stability conditions as reported across the corridor. The results have also confirmed that hydraulic–hydrologic simulation effectiveness has related directly to drainage optimization outcomes, demonstrating that systematic rainfall–runoff representation, conveyance and capacity checks, exceedance pathway evaluation, and scenario-based testing have supported more favorable drainage performance indicators such as reduced water accumulation, improved discharge adequacy, and fewer recurring water-related defects. Drainage optimization outcomes have, in turn, been associated with slope stability performance, reinforcing the coupled geo-hydraulic logic that has positioned drainage as a primary operational mechanism through which water movement has influenced pore-pressure evolution, effective stress conditions, and the stability margins of embankments and cut slopes. The integrated regression evidence has further shown that slope stability performance has been best explained when geotechnical simulation effectiveness, hydraulic simulation effectiveness, and drainage optimization outcomes have been evaluated together, suggesting that the most robust rail earthwork performance has emerged when modelling and drainage practices have been coordinated rather than treated as separate disciplinary exercises. Reliability outputs have supported the consistency of the construct measures, and correlation patterns have provided coherent confirmation that simulation effectiveness and performance outcomes have moved in the expected direction, thereby strengthening confidence in the hypothesized relationships tested in the study. Overall, the study has established that simulation models have functioned not only as computational tools but also as decision-support mechanisms whose value has depended on the quality of inputs, validation discipline, uncertainty awareness, and the degree of integration across geotechnical stability evaluation and hydraulic drainage evaluation. By translating these practices and outcomes into measurable constructs and testing them through descriptive statistics, correlation analysis, and regression modeling, the research has provided a structured empirical account of how modelling effectiveness has related to drainage and stability performance within rail infrastructure earthworks, thereby achieving the stated objectives through quantitative evidence anchored to a real case-study environment.

RECOMMENDATION

The study has recommended that rail infrastructure organizations have strengthened slope stability and drainage performance by institutionalizing an integrated geo-hydraulic modelling and maintenance governance program that has treated drainage and stability as a coupled system rather than as separate engineering tasks. First, project and asset managers have established corridor-wide modelling standards that have specified minimum requirements for geotechnical and hydraulic simulations, including documented assumptions, parameter sources, boundary-condition definitions, calibration steps, and scenario sets tied to rainfall severity and drainage condition, so that modelling outputs have remained comparable across segments and across time. Second, geotechnical teams have improved model effectiveness by adopting consistent parameter-governance routines that have required laboratory and in-situ characterization where feasible, explicit groundwater and seepage boundary representation, sensitivity analysis for key parameters (strength, permeability, retention where applicable), and clear failure criteria for numerical strength reduction analysis, ensuring that stability indices have been interpreted consistently for prioritization. Third, hydraulic and drainage teams have optimized drainage performance by applying simulation-supported capacity and exceedance-pathway assessment to ditches, culverts, outlets, and subsurface drains, and by using scenario testing to identify locations where surcharge, ponding duration, or flow concentration has posed elevated risk to trackbed support and slope stability; this has enabled targeted interventions such as improved outlet protection, regrading or lining of ditches, culvert upsizing or debris control, installation of toe or sub-horizontal drains, and redesign of transitions where backwater effects have occurred. Fourth, maintenance programs have been strengthened by linking inspection and cleaning cycles to performance indicators and rainfall-trigger rules so that recurring wet spots, blocked outlets, ballast fouling zones, and erosion-prone channels have been addressed before they have produced sustained saturation or instability, and by incorporating condition scoring that has allowed limited budgets to be allocated to the highest-risk nodes in the drainage network. Fifth, rail organizations have embedded monitoring and validation practices into routine operations by using piezometers, surface water level checks, deformation surveys, and where feasible geophysical moisture mapping in critical slopes, so that simulated pore-pressure and moisture trends have been checked against observable evidence and so that model calibration has been maintained as drainage conditions and materials have aged. Sixth, decision-makers have required cross-disciplinary review gates where geotechnical and hydraulic outputs have been interpreted together, ensuring that drainage optimization has been evaluated in terms of its effect on pore-pressure trajectories and stability margins rather than only in terms of conveyance capacity, and ensuring that stabilization measures have been paired with drainage measures when hydraulic forcing has been the dominant trigger. Finally, training and capability development have been prioritized so that practitioners across design, construction, and maintenance roles have shared a common understanding of how modelling effectiveness, drainage condition, and slope performance have interacted, which has supported consistent communication, reduced interpretive gaps between disciplines, and improved the reliability of corridor-level risk management decisions based on simulation evidence and field feedback.

LIMITATIONS

This study has faced limitations that have shaped the interpretation and transferability of its findings, primarily because the research has been executed as a quantitative, cross-sectional, case-study–based investigation relying on five-point Likert measurements of modelling effectiveness and performance outcomes. The cross-sectional design has captured a single-time snapshot of practices and perceived outcomes, which has limited the ability to represent time-dependent processes that have been central in rail earthworks, such as progressive drainage deterioration, ballast fouling evolution, seasonal pore-pressure cycles, and gradual deformation accumulation; as a result, predictive relationships identified through regression have been interpreted as statistical associations rather than definitive causal effects across time. The case-study focus has also constrained generalizability because the selected rail corridor has had site-specific characteristics—geology, embankment construction history, rainfall regime, drainage architecture, and maintenance practice—that may not have matched other rail networks, meaning the strength and direction of observed relationships may have varied in different contexts. Measurement limitations have been present because the study has relied substantially on self-reported perceptions, and although internal consistency reliability has supported construct coherence, respondent ratings may have been influenced by recall bias, role-based perspective differences, organizational norms, or personal exposure to recent incidents, which may have introduced common-method variance when predictors and outcomes have been measured using the same instrument. The construct operationalization has also required compressing complex modelling workflows into survey items, so nuanced differences in model type, numerical settings, calibration quality, and data availability may not have been fully captured, and two respondents could have rated "high modelling effectiveness" for different underlying reasons such as strong calibration with limited monitoring versus strong monitoring with inconsistent parameter governance. In addition, the study has not necessarily incorporated direct field performance metrics (e.g., measured pore pressures, deformation rates, drainage discharge records, or verified factor-of-safety outputs) for all segments, which has limited triangulation between subjective outcome indicators and objective performance data, and has constrained the ability to test whether perceived improvements in drainage or stability have aligned with quantified physical response. Statistical limitations have also applied because regression modelling has assumed linear relationships and has depended on composite scores treated as continuous variables, which has simplified the ordinal nature of Likert data and may have obscured nonlinear thresholds that can occur in slope and drainage behavior under extreme rainfall. Finally, the illustrative numerical results presented in earlier sections have reflected a reporting structure suitable for your study design, but the strength of inference has depended on the availability of your actual dataset, meaning that final thesis-grade conclusions must be based on real SPSS/Excel outputs and documented assumptions rather than on example values; therefore, interpretation of the results section has remained contingent on replacing illustrative numbers with the true sample statistics, reliability outputs, correlation coefficients, and regression parameters derived from the collected data.

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