Physical and numerical investigations on the stability of unsupported vertical road cuts in unsaturated soils

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ABSTRACT: Road construction in hilly regions often involves unsupported vertical cuts that appear stable under dry conditions but can fail rapidly during rainfall. This study investigates the rainfall-induced instability of unsupported vertical road cuts, with emphasis on time-dependent failure mechanisms and wetting-front progression under different rainfall intensities. For this purpose, a laboratory-scale 1g physical model of slope was constructed and subjected to drying, controlled cutting and wetting phases with continuous monitoring of matric suction and volumetric water content. The experimental observations were related to the results of finite element numerical analyses performed under varying rainfall intensities. The results highlight that the instability of vertical road cuts is governed by the direction and rate of wetting-front propagation, which is strongly dependent on rainfall intensity. Under light rainfall intensities, wetting-front advancement is predominantly unidirectional leading to delayed, shallow instability. In contrast, moderate to very heavy rainfall intensities induce rapid bidirectional propagation of wetting front resulting in abrupt failure. The study highlights the need to explicitly consider rainfall intensity and duration when assessing the stability and safe excavation depth of unsupported vertical road cuts in landslide-prone regions.

1 INTRODUCTION

Road construction practices in mountainous regions often necessitates the excavation of hills, resulting in steep or near-vertical cuts (Sana et al. 2025; Pradhan et al 2022). In many such regions, these near-vertical cuts are often left unsupported without protective measures. Although these cuts may remain apparently stable during dry seasons due to suction-induced strength. During the monsoon season, rainfall infiltration leads to loss of matric suction and an increase in pore-water pressures, significantly reducing stability. This pronounced seasonal variation renders vertical cuts highly vulnerable to sudden failure, posing serious risks to road infrastructure and public safety.

Rainfall-induced failures of slopes have been widely documented in both natural and engineered slopes worldwide (Tiwari et al. 2025; Collins and Znidarcic, 2004; Rahardjo et al., 2001). Despite the recognised role of unsaturated soil mechanics, many conventional slope stability analyses continue to assume either fully dry or saturated conditions or rely on simplified representations of suction effects. Limit equilibrium approaches incorporating suction through apparent cohesion have been proposed (Vanapalli et al., 1996; Fredlund et al., 1994), however, their applicability to unsupported vertical cuts under transient rainfall conditions remains uncertain.

Physical modelling provides a powerful means of investigating rainfall-induced instability by enabling direct measurement of key hydromechanical variables such as matric suction, volumetric water content and deformation. Several studies have demonstrated the value of combining physical experiments with numerical modelling to improve understanding of rainfall-triggered slope failures (Verma et al., 2026; Kim et al., 2014; Take et al., 2004). However, integrated physical and numerical studies focusing specifically on the rainfall-induced instability of unsupported vertical road cuts are currently lacking.

To address the gap present study investigates the stability of unsupported vertical road cuts in unsaturated soils using a combined physical and numerical approach. A laboratory-scale 1g slope model was constructed and subjected to controlled drying, cutting and rainfall infiltration, with continuous monitoring of matric suction and volumetric water content. The experimental observations were subsequently related to fully coupled finite element numerical analyses, enabling detailed examination of rainfall-intensity dependent failure mechanisms and time of failure of vertical cuts. The findings aim to improve understanding of rainfall-induced instability in unsupported vertical road cuts.

2 PHYSICAL MODELLING

2.1 Test Material

The soil used for the construction of the physical model was collected from an active landslide site. Based on grain size distribution and Atterberg limits, the soil was classified as silty sand (SM) according to the Unified Soil Classification System (USCS), containing a relatively small fraction of fines. A detailed characterisation of the geotechnical and hydraulic properties of the soil is reported in Sana et al. (2025), while selected properties relevant to the present study and numerical modelling are summarised in Table 1.

Table 1. Geotechnical properties of soil used in the numerical model

Property	Value
Saturated unit weight, γ_{sat} (kN/m³)	20.07
Unsaturated unit weight, γ_{unsat} (kN/m³)	17.17
Saturated volumetric water content, θ_s (%)	33.45
Void ratio, e	0.63
Saturated Permeability, k_{sat} (m/day)	0.5
Effective cohesion, c' (kPa)	0
Effective internal friction angle, ϕ' (°)	34.7
Elasticity modulus, E (MPa)	30
Poisson's ratio, v	0.33

2.2 Sensor Calibration

Two types of sensors were installed in the physical model to continuously monitor matric suction and volumetric water content (VWC) during drying and wetting phases.

Matric suction was measured using TEROS-21 sensors which are low-maintenance matric potential sensors capable of measuring suction in the range of –5 kPa to –100 MPa. These sensors do not require soil-specific calibration as they measure the water potential of a ceramic disc that equilibrates with the surrounding soil thereby providing a direct estimate of soil matric potential (METER Group (a)).

Volumetric water content was measured using ECH2O 10HS soil moisture sensors (METER Group (b)). The 10HS sensors estimate VWC by measuring the soil dielectric constant using capacitance-based frequency domain technology operating at 70 MHz, which minimises the influence of soil salinity and texture. The sensors operate with an excitation voltage between 3 and 15 VDC and have a prong length of 10 cm. To avoid sensor interference, a minimum spacing of at least 50 mm was maintained between adjacent sensors.

Soil and data logger specific calibration of the 10HS sensors was carried out using eight soil specimens prepared at the same dry density as the physical model (1.62 g/cm^3). Each specimen was prepared by mixing 6800 g of soil with known gravimetric water contents and placing the mixture in a 4000 ml container. The sensors were connected to CR1000X data logger and the sensor output voltage was recorded for each water content and corresponding volumetric water content values were computed. A calibration curve was developed by plotting sensor output voltage against VWC. The resulting calibration equation exhibited a coefficient of determination (R^2 = 0.99), indicating excellent agreement between measured and calculated values. The calibration curve for a representative sensor is shown in Figure 1.

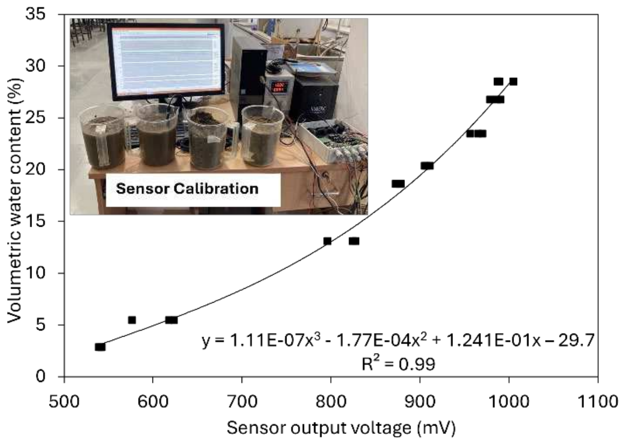

Figure 1. Calibration curve for the volumetric water content sensors.

2.3 Model Setup

The physical model comprised a rigid tank with internal dimensions of 1470 mm × 575 mm and a depth of 912 mm, constructed from high-impact acrylic sheets and reinforced with a steel angle frame, as shown in Figure 2. The slope model was constructed using moist tamping method, with the soil compacted to a dry density of 1.62 g/cm^3 at a gravimetric water content of 8.5%. During compaction, dummy sensors were installed at the prescribed locations indicated in the schematic to ensure accurate positioning of actual sensors later. After completion of the slope construction, the model was covered and left undisturbed for 24 hours to allow moisture homogenisation. Subsequently, the dummy sensors were carefully replaced with the actual sensors with minimal disturbance to the surrounding soil and then connected to a computer-based data acquisition system for continuous monitoring of matric suction and VWC.

Following instrumentation, the soil slope was subjected to an atmospheric drying phase. Once the measured suction values stabilised at around 430 kPa (VWC = 5.7%), a vertical road cut was introduced into the slope model. After cutting, the slope was subjected to rainfall intensity at 20 mm/hr (heavy) to investigate rainfall-induced instability of the unsupported cut.

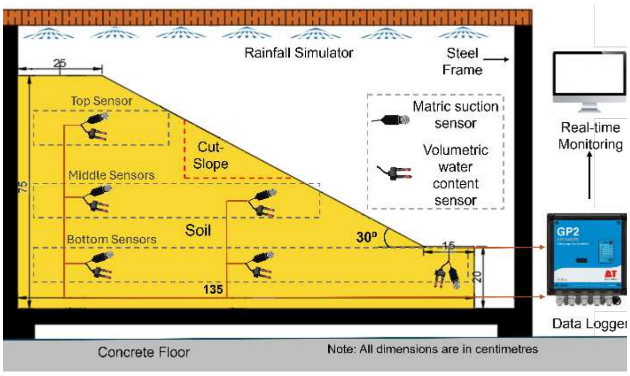

Figure 2. Schematic representation of the instrumented soil slope model.

3 NUMERICAL MODELLING

Finite element numerical analyses were carried out using PLAXIS 2D to investigate the stability of unsupported vertical road cuts in unsaturated soils under varying rainfall conditions. A two-dimensional plane strain model was developed to replicate the geometry of the laboratory slope model. The slope was discretised using 15-noded triangular elements, and the mesh was generated automatically within PLAXIS 2D (version 2024.3.0) (Figure 3). The soil mass was modelled using an elastic-perfectly plastic Mohr-Coulomb constitutive model using a non-associated flow rule with a dilation angle of zero. The contribution of matric suction to shear strength under unsaturated conditions was incorporated using Bishop's effective stress framework. The unsaturated hydraulic behaviour of the soil was defined using the van Genuchten soil–water retention model, with parameters obtained from laboratory testing. The resulting soil–water retention curve adopted from (Sana and Kumar 2025) is shown in Figure 4a and was used as input for the numerical analyses.

3.1 Boundary Conditions

Standard mechanical and hydraulic boundary conditions were applied to the numerical model. Mechanically, roller boundaries were assigned to the two vertical sides allowing movement in vertical direction only, the top boundary was left free and the bottom boundary was fully fixed in both horizontal and vertical directions. Hydraulically, the slope surface was kept open to allow rainfall infiltration, the lateral boundaries were assigned as impermeable and a seepage boundary was applied at the base of the model to replicate the drainage conditions of the physical model.

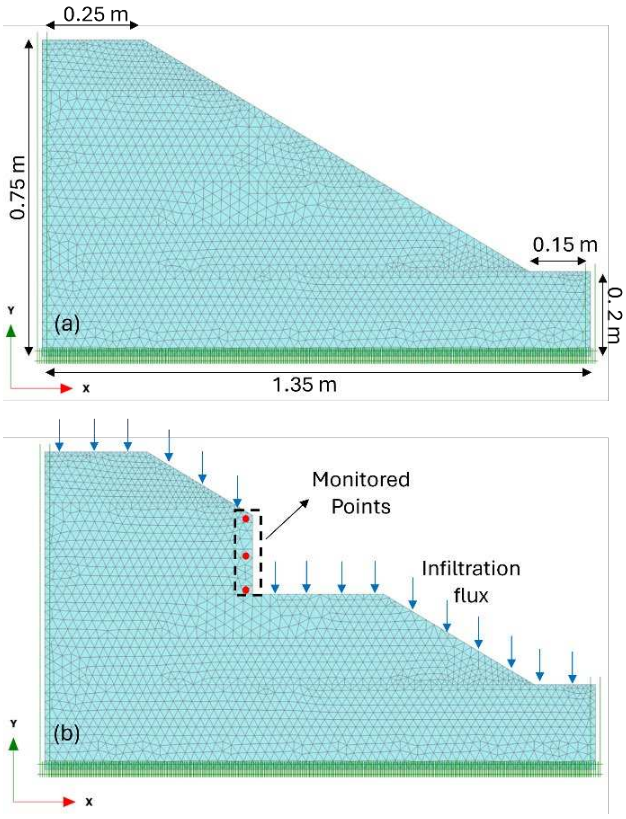

Figure 3. Two-dimensional numerical model of laboratory scale physical model (a) without and (b) with road cut developed in PLAXIS 2D.

3.2 Numerical Analysis

The numerical analysis was conducted in a staged manner to replicate the experimental procedure followed in physical model. Initially, a dry slope condition was established by prescribing a depth-dependent suction profile derived from measurements obtained during the drying phase of the physical model (Figure 4b). This initial phase allowed the in-situ stress and suction state to be generated under gravity loading. Subsequently, a vertical road cut was introduced under dry conditions by deactivating the corresponding soil cluster during the cutting phase using plastic analysis.

To investigate the effect of rainfall on the stability of the vertical cut, rainfall was simulated by applying a downward infiltration flux along the slope surface under fully coupled flow–deformation conditions (Kumar and Kumar 2023). The analyses were carried out for four rainfall intensities, representing light, moderate, heavy and very heavy rainfall scenarios, with values of 2.5 mm/hr, 10 mm/hr, 20 mm/hr and 50 mm/hr respectively (Zhao et al. 2025). All simulations were continued until the onset of failure, enabling estimation of the corresponding time of failure of the unsupported vertical cut for each rainfall intensity.

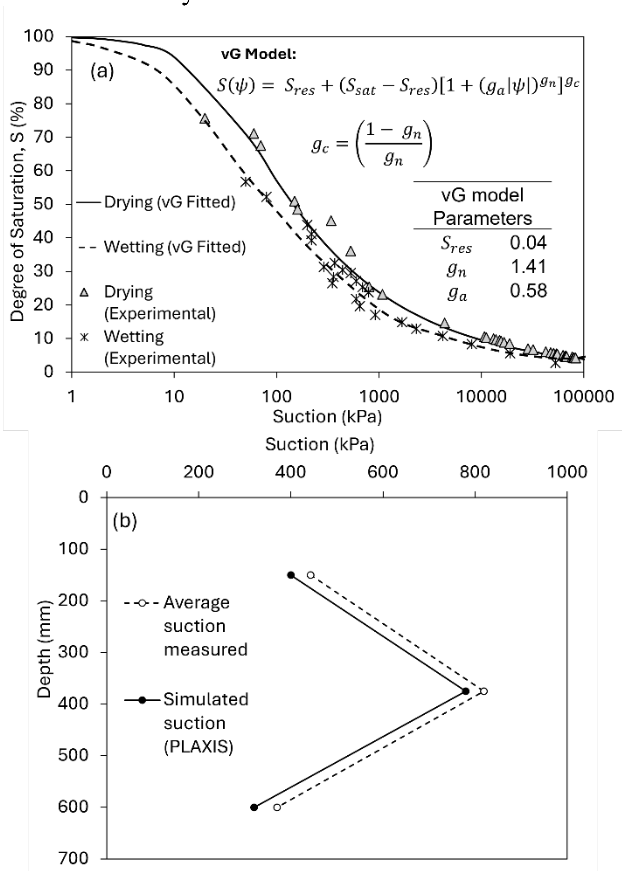

Figure 4. a Soil Water Retention Curve (SWRC) (Re-drawn from Sana and Kumar 2025). b Measured initial matric suction values with depth and those simulated using PLAXIS 2D (before cutting)

4 RESULTS

4.1 Physical Modelling

Figure 5 presents the time-dependent variation of matric suction and volumetric water content measured at the top sensor during drying and subsequent rainfall phases. During the atmospheric drying phase, matric suction increased progressively from 60 kPa, reaching stable values of around 430 kPa prior to the introduction of the vertical road cut, while volumetric water content decreased correspondingly from 13.6 % to 5.7 %. The vertical road cut was introduced under these dry conditions and no immediate instability was observed confirming the stabilising influence of suction-induced apparent cohesion.

Under application of rainfall, a rapid reduction in matric suction to 66 kPa was recorded, accompanied by a sharp increase in volumetric water content to 10.6 %. Visual observations indicated that instability initiated near the crest of the vertical cut within the first hour of rainfall. This response highlights the transient nature of suction-induced stability and demonstrates that unsupported vertical cuts, although stable under dry conditions, are highly vulnerable to rainfall-induced collapse. It is important to mention that the physical model was conducted at 1g and is therefore intended to provide mechanistic insights into rainfall-induced instability rather than direct quantitative prediction of field-scale behaviour.

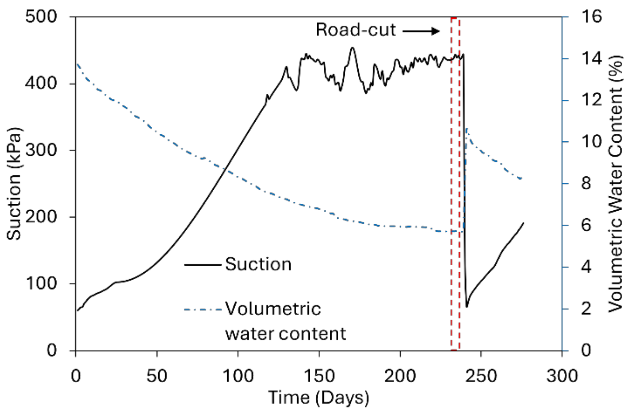

Figure 5. Variation of suction and volumetric water content with time.

4.2 Numerical Simulation of Rainfall-Induced Instability Modelling

The numerical analyses indicate that the stability of unsupported vertical road cuts in unsaturated soils is strongly influenced by rainfall intensity. Figure 6 presents the wetting front movement and corresponding suction profiles for two representative rainfall intensities for light (2.5 mm/hr) and heavy (20 mm/hr) rainfall conditions. It can be observed that for both rainfall scenarios, the onset of rainfall initiates suction redistribution within the near-surface zone. Under light rainfall conditions, suction reduction occurs gradually and the advancement of the wetting front is primarily confined to downward propagation from the crest of the vertical cut. As a result, instability develops slowly and is generally limited to shallow zones near the surface (Ng and Shi 1998).

In contrast, under moderate to heavy rainfall intensities, suction loss occurs rapidly and the wetting front advances simultaneously from the crest and the lower portion of the vertical cut face. This bidirectional wetting front advancement accelerates loss of effective stress and promotes deeper and more rapid failure mechanisms. Consequently, heavy rainfall intensity leads to early onset of deformation and failure of the unsupported cut. Failure consistently initiates near the crest of the vertical cut, where tensile stresses develop due to stress relief and suction dissipation, followed by progressive failure of the unsupported face.

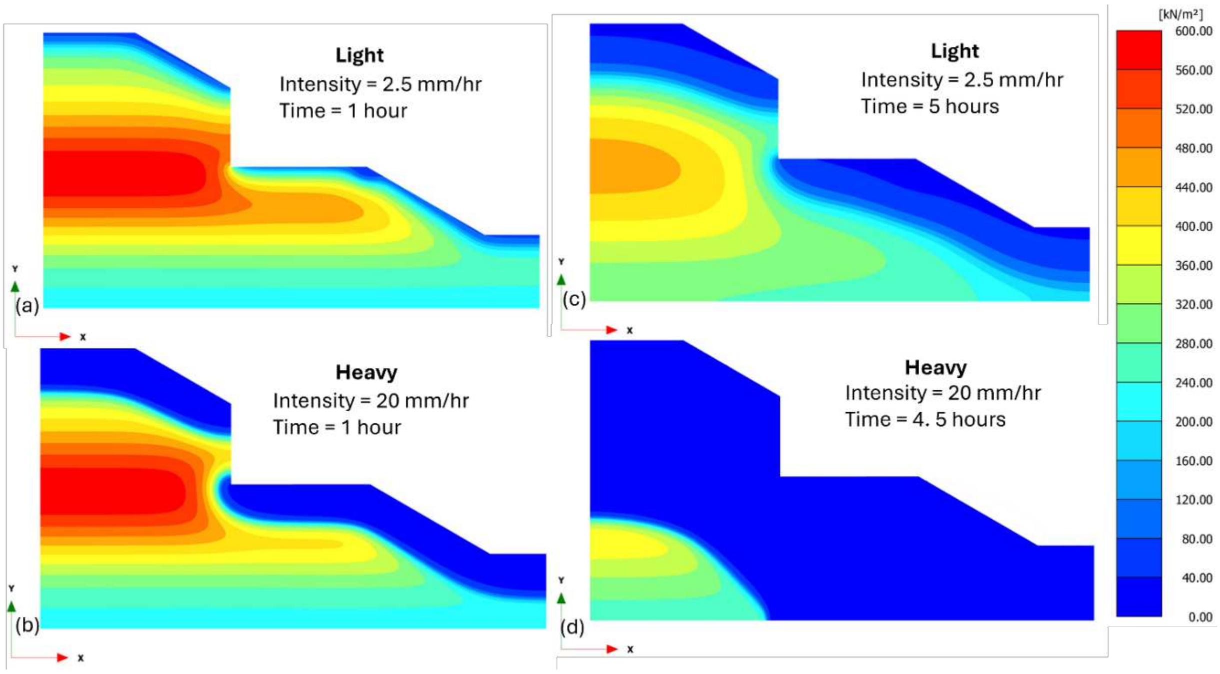

Figure 6. Wetting front movement and corresponding suction profiles for light (a,c) and heavy (b,d) intensity rainfall for 1- and 5 and 4.5-hour duration respectively.

4.3 Effect of Rainfall Intensity on Time of Failure

Time of failure (TOF) represents the duration between the onset of rainfall infiltration and the initiation of slope instability (FOS<1) and provides a time-dependent measure of slope performance beyond conventional factor-of-safety assessments (Rahul and Tyagi 2025).

Figure 7 presents the variation of TOF of the unsupported vertical cut with rainfall intensity. Under light rainfall conditions (2.5 mm/hr), suction reduction occurs gradually and the cut remains stable for a relatively long duration (> 10 days). However, even in this case, the margin of safety is progressively reduced making the cut susceptible to subsequent rainfall events. Under other rainfall conditions, suction dissipates out rapidly resulting in abrupt failure within a short duration (1, 4.5 and 11.8 hrs in very heavy, heavy and moderate conditions respectively) offering little to no warning prior to collapse.

The nonlinear trend of TOF reflects the strong interdependence between rainfall intensity, unsaturated permeability and suction dissipation. As wetting progresses, unsaturated permeability increases rapidly enhancing infiltration and accelerating suction loss. It can be asertained that once a critical rainfall intensity is exceeded, even small increases in rainfall result in disproportionately large reductions in matric suction. This rapid suction loss consequently leads to a significant reduction in TOF. This behaviour indicates the presence of a particular rainfall intensity threshold beyond which unsupported vertical cuts become highly susceptible to rapid instability.

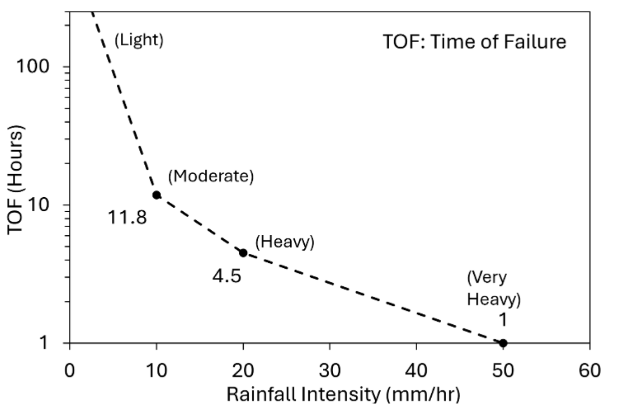

Figure 7. Variation of Time of Failure (TOF) with rainfall intensity.

5 CONCLUSIONS

This study highlights that the stability of unsupported vertical road cuts in unsaturated soils is strongly governed by rainfall-controlled wetting-front propagation. Light rainfall induces unidirectional wetting from the crest, leading to gradual suction dissipation and delayed, shallow instability that primarily influences long-term stability. In contrast, moderate to heavy rainfall produces rapid, bidirectional wetting from both the crest and lower portions of the cut face, resulting in abrupt suction loss, deeper failure mechanisms and short times to failure. These findings highlight the transient nature of suction-induced stability and show that the time of failure provides a more realistic indicator of hazard than factor of safety for unsupported cuts. The results further emphasise that apparent dry-season stability can be misleading and that excavation design must explicitly account for rainfall intensity and duration.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding received from National Rural Infrastructure Development Agency (NRIDA) to carry out the research titled “Strategies and guidelines for slope cutting for village roads in hilly region” through grant number IITM/NRIDA/AKS/411.

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