Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Reproducing Historical Slope Failure Processes Using a Physical Model

C.P. Kuo
National Yunlin University of Science and Technology, Yunlin, Taiwan, cpkuo@yuntech.edu.tw
T.Y. Chou
National Yunlin University of Science and Technology, Yunlin, Taiwan, m11116023@yuntech.edu.tw

ABSTRACT: The Erwanping landslide, triggered by Typhoon Morakot in 2009, represents a catastrophic dip-slope failure in the Alishan region. This study aims to reconstruct the failure mechanism and investigate the temporal evolution of slope instability under extreme rainfall. To achieve this, a comprehensive integrated approach combining large-scale physical modelling and numerical simulation was employed. A 1:500 scale physical model was constructed using in-situ geological materials to replicate the site topography and stratigraphy. The model was subjected to a rainfall simulation mimicking the specific hyetograph of Typhoon Morakot. Real-time monitoring of pore water pressure (PWP) variations and internal/surface displacements was conducted throughout the experiment. Experimental results were compared with pre- and post-disaster topographic data to validate the deformation characteristics. Furthermore, a numerical analysis was performed to simulate the entire failure process. The comparative analysis reveals a high degree of consistency between the physical model, numerical results, and the actual event, particularly regarding the temporal sequence of failure onset and deformation trends. The study successfully reproduces the progressive failure process and confirms that the rapid rise in groundwater level within the dip slope was the primary trigger. These findings provide a verified basis for future early warning thresholds and the design of effective engineering remediation measures for similar geological settings.

1 INTRODUCTION

The Alishan Mountain Range in central Taiwan is renowned for its steep terrain, rich forestry resources, and the historic Alishan Forest Railway. Among the critical locations along this route is Erwanping, situated at an elevation of approximately 2,000 meters. The toponym "Erwanping" carries significant historical and geographical implications; it translates literally to "Twenty Thousand Pings" (where one ping is approximately 3.3 square meters). The name originated from the Japanese colonial era, describing the rare, extensive flat terrace formed by ancient landslide deposits. This broad, flat terrain initially served as a timber loading yard and later became the site for the Erwanping Railway Station and the Alishan Youth Activity Center. However, this seemingly stable platform masks a fragile geological history, as the flat surface is essentially the remnant of historical slope failures, making it inherently susceptible to reactivation. The Erwanping area is located within the Nanchuang Formation of the Miocene age, which primarily consists of sandstone and shale interbeds. The structural orientation of the bedding planes strikes north-northeast and dips towards the west, roughly parallel to the topographic slope surface. This configuration defines Erwanping as a classic dip slope. The slope angle ranges between 20 to 30 degrees, while the bedding dip angle is slightly gentler, creating a potential failure mechanism along the weak bedding planes or the interface between the bedrock and the overlying colluvium. The surficial geology is dominated by thick colluvial soil deposits—loose, unconsolidated mixtures of rock fragments and soil—which possess high permeability but significantly reduced shear strength upon saturation.

The Alishan region is known as one of the rainfalls centers of Taiwan due to the orographic lifting effect. However, the meteorological event of August 2009 was unprecedented. Typhoon Morakot brought record-breaking precipitation to Southern Taiwan, with a long-duration, high-intensity rainfall pattern. The Alishan meteorological station recorded a cumulative rainfall of 3,060 mm within a 100-hour period from August 6 to August 10, approaching the region's average annual precipitation in a single event. The maximum 24-hour rainfall exceeded 1,600 mm, surpassing the 200-year return period. Such extreme hydrological loading induced a rapid rise in groundwater levels, generating immense pore water pressure within the slope mass. Under the combined influence of the adverse dip-slope geology and the extreme rainfall of Typhoon Morakot, a catastrophic deep-seated landslide occurred at the Erwanping site. The failure initiated as the shear strength of the saturated colluvium and the weak sandstone-shale interface deteriorated. The landslide exhibited a retrogressive failure mode, causing the slope edge near the railway station to collapse significantly. Approximately 350,000 cubic meters of soil mass slid downslope into the Erwanping Creek. The disaster severely damaged the roadbed of the Alishan Forest Railway, leaving the rails suspended in mid-air, and threatened the structural integrity of the adjacent Youth Activity Center. The collapse also severed the connection to the main external road, Provincial Highway 18. The related figures are shown in Figure 1. and 2.

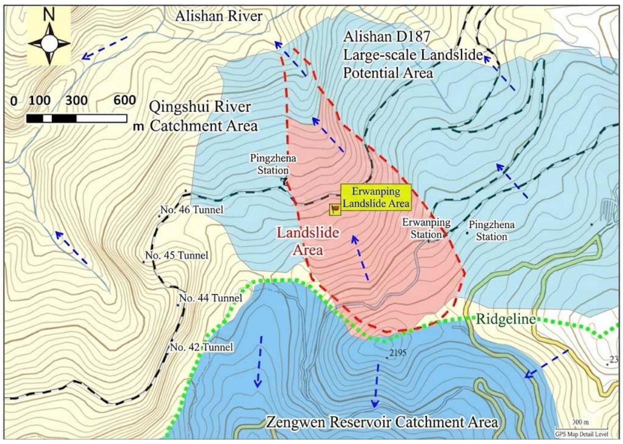

Figure 1. View of the landslide area of Erwanping.


Figure 2. The scarp of the landslide that induced losses of railway foundations in Alishan Mountain.

2 MOTIVATION AND METHODOLOGY

While the geological triggers of the Erwanping landslide have been discussed in post-disaster surveys, accurately reconstructing the temporal evolution of the failure remains a challenge. Understanding the precise timing of deformation relative to rainfall intensity is crucial for developing early warning systems. Therefore, this study aims to reconstruct the failure process through a rigorous integration of methods: a large-scale (1:500) physical model test utilizing in-situ materials to replicate the specific topography and rainfall hyetograph of Typhoon Morakot, validated by numerical simulations. This approach allows for a detailed observation of pore water pressure variations and slope deformation trajectories, providing critical insights for future disaster mitigation in dip-slope regions.

Large-Scale Physical Modelling Setup To accurately replicate the failure mechanism of the Erwanping landslide, a large-scale physical model test was conducted in a rigid soil flume with dimensions of 6m (length) × 2m (width) × 3m (height). The model geometry was constructed based on a 1:500 scale of the pre-disaster topography of the Erwanping dip slope. The photo of the tank is shown in Figure 3., and the sectional profile of geological stratum and terrain is shown in Figure 4. A water showering system is installed for simulating rainfall shown as Figure 5.


Figure 3. The front view of the tank for physical simulation.

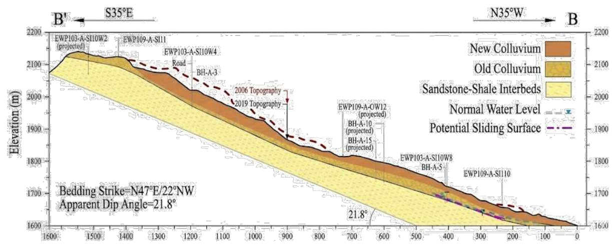

Figure 4. The sectional profile of the r physical simulation.

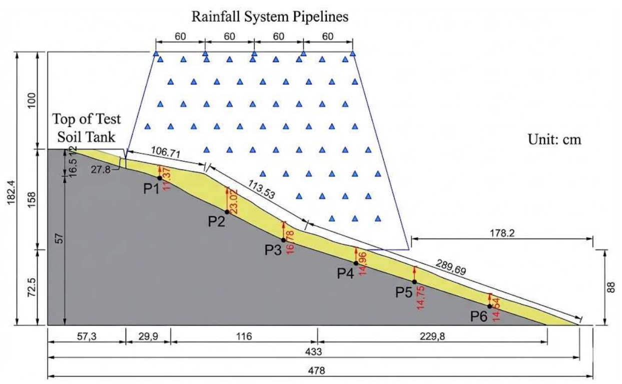

Figure 5. The illustration of rainfall simulating system.

To ensure geological representativeness, in-situ soil and rock materials were collected directly from the landslide site. These materials were processed and reconstituted within the flume to simulate the specific stratigraphy of the Nanchuang Formation, strictly controlling the density and moisture content to match field conditions. The bedding planes and the weak interface between the bedrock and the overlying colluvium were carefully reconstructed to allow for the observation of translational sliding behaviour. Artificial Rainfall Simulation and Testing Procedure The triggering mechanism was simulated using a custom-designed artificial rainfall system installed above the flume. The system was calibrated to reproduce the specific rainfall hyetograph of Typhoon Morakot (August 2009), rather than a constant rainfall intensity. This approach allowed for the realistic simulation of the infiltration process, pore water pressure (PWP) accumulation, and the subsequent reduction in effective stress over time. The experiment focused on driving the slope to failure through this hydrological loading. During the simulation, the model slope exhibited a progressive failure mechanism, characterized by episodic displacements and the development of tension cracks. A comprehensive monitoring array, including PWP transducers, soil moisture sensors, and displacement gauges (LVDTs), was installed at critical locations to capture the real-time hydro-mechanical response of the slope.

Numerical Simulation using PLAXIS To validate the experimental findings and extend the analysis, numerical modelling was performed using the Finite Element Method (FEM) software, PLAXIS. The numerical model geometry was identical to the physical model setup. The constitutive models and material parameters (e.g., cohesion, friction angle, permeability) were calibrated based on laboratory tests of the in-situ materials used in the physical experiment. A fully coupled flow-deformation analysis was conducted to simulate the transient seepage conditions induced by the Morakot rainfall pattern. The numerical study aimed to reproduce the stress-strain behaviour and the evolution of the safety factor observed in the physical model.

Comparative Analysis and Validation The validity of the study was established by cross-referencing the results from the physical model and the PLAXIS simulation. Key performance indicators, including the time-history of pore water pressure, the magnitude of surface displacement, and the timing of the critical failure onset, were compared. The consistency between the physical observations and numerical predictions serves to verify the proposed failure mechanism and demonstrates the capability of the numerical model for future predictive applications. The meshes and dimensions of numerical simulation is shown as Figure 6.

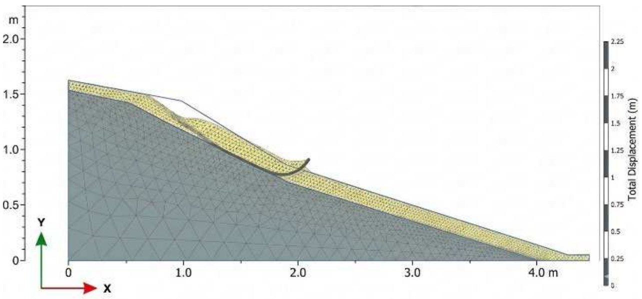

Figure 6. The illustration of numerical simulating.

3 RESULTS AND DISCUSSION

The present study reconstructed the failure mechanism of the Erwanping landslide triggered by Typhoon Morakot through an integrated approach combining large-scale physical modelling and numerical simulation. Based on the experimental and analytical results, the following findings are drawn:

Successful Replication of Failure Mechanism: The large-scale physical model (1:500 scale), constructed with in-situ geological materials, successfully reproduced the dip-slope failure process. The experiment confirmed that the catastrophic failure was driven by the infiltration of extreme rainfall (Morakot hyetograph), which led to a rapid rise in pore water pressure and a critical reduction in shear strength along the weak bedding planes.

3.1 Temporal Consistency and Validation

A comparative analysis between the physical model and the PLAXIS numerical simulation revealed a high degree of temporal concordance. The timing of the failure onset and the trend of slope deformation in the numerical model closely matched the physical observations and the actual disaster timeline. This validates the capability of the finite element model to capture the transient hydro-mechanical response of the slope under extreme weather conditions.

3.2 Deformation Characteristics

Both the physical and numerical models demonstrated that the landslide exhibited a progressive and retrogressive failure mode. The observed displacement trajectories and internal stress changes provided clear evidence of the kinematic behaviour of the dip slope prior to the massive collapse, highlighting the correlation between rainfall intensity peaks and accelerated displacement.

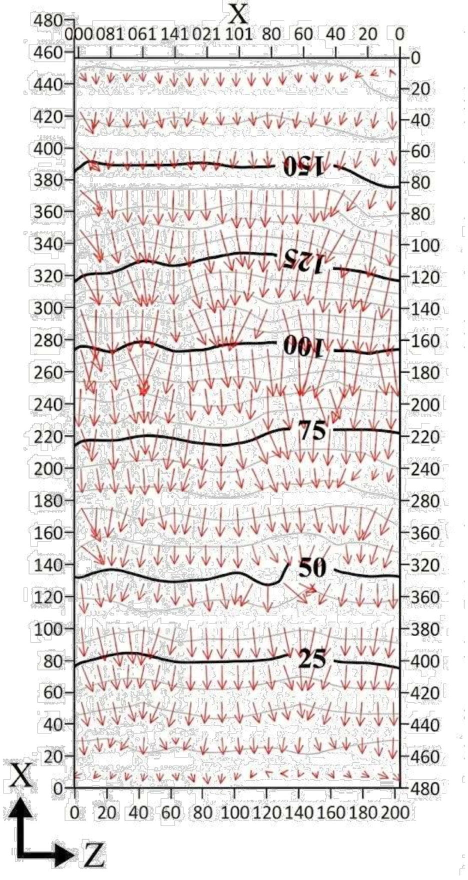

Figure 7. The vectors of slope surface movements.

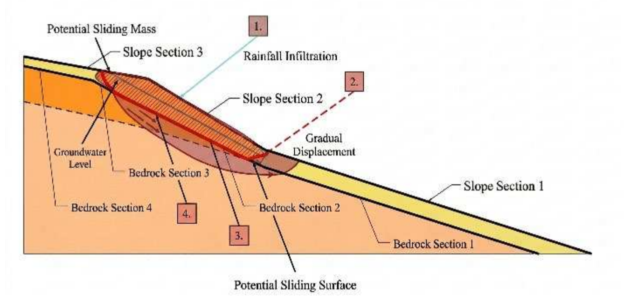

Figure 8. The evaluation on each step of the sliding process.

The study demonstrates a strong correlation between the numerical simulations and physical model tests, particularly regarding potential sliding zones and displacement trends. The analysis confirms that slope stability in the Erwanping area is heavily dependent on hydrological conditions; specifically, prolonged, and heavy rainfall raises the groundwater table, reducing shear strength and triggering failure, whereas lighter rainfall does not induce critical instability.

Mechanistically, rainfall infiltration increases the self-weight of the upper soil layer while groundwater accumulation along the bedrock interface weakens the soil strength. This leads to a retrogressive failure mechanism, initiating at the slope toe and progressively developing upward. While both models accurately matched the pre- and post-disaster topography, the physical model displayed a clear sliding trend rather than a complete collapse. This distinction suggests that scale effects and boundary effects in the laboratory setting constrained the full extent of the slope failure, a limitation inherent to reduced-scale physical modelling.

In this study, after the slope model is subjected to rainfall, the upper soil mass increases its self-weight due to infiltration. The soil at the interface between the second and first slope sections is compressed, causing it to gradually displace. Over time, the groundwater level accumulates above the second and third bedrock sections, reducing the shear strength of the soil. Localized sliding occurs in the soil below the interface of the third and second slope sections. A progressive failure develops from the toe of the slope towards the crest.

4 SUGGESTIONS

Based on the validated findings of this study, the following recommendations are proposed for future disaster mitigation and engineering practice:

4.1 Establishment of Early Warning Thresholds

Since the study confirmed the strong correlation between rainfall patterns, pore water pressure accumulation, and slope displacement, it is recommended to utilize the calibrated numerical model to establish precise rainfall intensity-duration (I-D) thresholds for the Erwanping area. These thresholds can serve as a scientific basis for the local early warning system to evacuate residents and halt railway operations proactively.

4.2 Engineering Remediation Strategies

Given that the failure was triggered by groundwater saturation, future remediation works should prioritize subsurface drainage efficiency. It is suggested to use the verified numerical model to simulate the effectiveness of various drainage designs (e.g., horizontal drains or drainage tunnels) to ensure they can handle extreme rainfall events like Typhoon Morakot.

4.3 Long-term Monitoring

Continuous monitoring of deep-seated displacement and groundwater levels at the site is essential. Data from these monitoring systems should be used to continuously update and refine the numerical model, ensuring the long-term safety of the Alishan Forest Railway and the surrounding infrastructure.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by funding agency "National Science and Technology Council, Taiwan".

REFERENCES

Gallage, C., Abeykoon, T., & Uchimura, T. (2021). Instrumented model slopes to investigate the effects of slope inclination on rainfall-induced landslides. *SOILS AND FOUNDATIONS*, 61(1), 160–174. https://doi.org/10.1016/j.sandf.2020.11.006

Moriwaki, H., Inokuchi, T., Hattanjii, T., Sassa, K., Ochiai, H., & Wang, G. (2004). Failure processes in a full-scale landslide experiment using a rainfall simulator. *Landslides*, 1(3), 277–288. https://doi.org/10.1007/s10346-004-0034-0

Tohari, A., Nishigaki, M., & Komatsu, M. (2007). Laboratory rainfall-induced slope failure with moisture content measurement. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(5), 575–587. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:5(575)