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INTEGRATED GEOTECHNICAL AND HYDROLOGICAL ASSESSMENT OF RAINFALL-INDUCED SLOPE FAILURE AT MOUNT TUNAK

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ABSTRACT: Slope stability is a critical concern in geotechnical engineering, particularly in regions with high rainfall where infiltration can reduce soil shear strength. This study assesses the effects of rainfall infiltration combined with external loading on slope stability at Mount Tunak, Lombok, Indonesia. Rainfall intensities for multiple return periods were derived from Rembitan Station records (2014–2023), and soil properties were characterized through laboratory and in-situ investigations. Numerical analyses were conducted using PLAXIS 2D V.24 with sensitivity evaluations on cohesion, internal friction angle, and permeability. The initial Factor of Safety (SF) ranged from 1.263 to 1.074, indicating marginal stability, and validation using the Limit Equilibrium Method (LEM) in Rock Science yielded similar values (1.201–1.197). Under rainfall infiltration associated with a 10-year return period, the SF decreased to 1.044–0.895, representing a critical condition. Reinforcement using soldier piles with lengths of 5 m, 8 m, and 12 m increased the SF by 2.20%–84.58%. The results demonstrate that rainfall-induced pore pressure significantly governs slope instability and confirm that soldier piles are an effective mitigation strategy for safeguarding infrastructure in tourism-oriented hilly terrains.

Keywords: Slope Stability, Rainfall Infiltration, PLAXIS 2D, Soldier Pile, Finite Element Method

1. INTRODUCTION

Slope instability represents one of the major challenges in the fields of geotechnical and environmental engineering, particularly in tropical regions, as it often triggers landslide disasters that result in physical, economic, and social losses and pose serious threats to human safety [1-5]. In hilly areas with high rainfall intensity such as Lombok Island, prolonged and intense rainfall can induce water infiltration into the slope mass, increasing positive pore water pressure while reducing effective stress and shear strength, ultimately decreasing slope stability [6 -8].

This phenomenon becomes increasingly complex when combined with geotechnical factors such as the physical and mechanical properties of soil (cohesion, internal friction angle, and unit weight), steep topographic conditions, and heterogeneous subsurface geological structures [9-11]. Therefore, a comprehensive analysis that integrates both geotechnical and hydrological aspects is essential to fully understand slope failure mechanisms and to formulate effective mitigation measures [8, 12-14].

In recent years, numerical approaches such as the Finite Element Method (FEM) have been widely adopted for slope stability assessment, as they enable the simulation of transient rainfall infiltration, pore pressure evolution, and stress–strain response within a consistent analytical framework [4,5,9,12,14]. Unlike the traditional Limit Equilibrium Method (LEM), which often neglects coupled hydro-mechanical interactions and progressive deformation, FEM provides a more realistic representation of slope behavior under varying hydrological and loading conditions.

Slope stability analysis using FEM has been extensively employed in recent studies to investigate the interaction between geotechnical and hydrological factors [14,15]. This approach allows simultaneous evaluation of stress–strain behavior and pore pressure evolution, thereby offering results that more accurately reflect field conditions [14]. [15] has developed a machine learning and metaheuristic optimization-based model to predict slope Factor of Safety (FOS) in debris flow-prone areas, achieving an accuracy exceeding 85%. These findings underscore the growing importance of numerical approaches that integrate geotechnical and hydrological aspects in slope stability assessment.

Within numerical modeling, the Hardening Soil Model (HSM) has become increasingly popular, as it effectively represents nonlinear stress–strain behavior, stress-dependent stiffness, and the differences in response between loading and unloading/reloading phases [2]. Several recent studies in tropical environments have demonstrated that the implementation of HSM in FEM analysis yields more representative estimations of deformation and Factor of Safety (FOS), particularly for very stiff to hard clay soils characterized by high Standard Penetration Test (NSPT) values [12,14,16] .

Mount Tunak, located in the southern part of Lombok Island, is characterized by steep hilly topography, varied soil composition ranging from sandy clay to volcanic breccia, and high annual rainfall. The rapid development of tourism infrastructure in this area has increased the potential for slope instability, particularly during intense rainfall periods. Several incidents of cracks and minor landslides along access roads leading to eco-cottage areas have been reported, highlighting the urgent need for a comprehensive slope stability assessment to support safe and sustainable tourism development [2].

This study presents an integrated geotechnical and hydrological assessment of slope stability in the Mount Tunak area using PLAXIS software with the Hardening Soil Model (HSM) to simulate pre and post-extreme rainfall conditions. The objectives are to identify slope failure mechanisms, reassess the Factor of Safety (FOS) under critical scenarios, and evaluate the effectiveness of slope reinforcement using soldier piles. The findings are expected to advance FEM-based slope stability analysis under tropical conditions and provide scientific insights to support disaster mitigation planning in hilly tourism regions.

2. RESEARCH SIGNIFICANCE

This study is of considerable significance as it integrates geotechnical and hydrological approaches to comprehensively assess slope stability at Mount Tunak, a landslide-prone area within an ecotourism zone. In contrast to previous studies that primarily focused on geological mapping or qualitative observations, this research quantitatively evaluates the factor of safety under critical conditions by incorporating both soil and hydrological parameters. The findings are expected to address existing knowledge gaps, advance the scientific understanding of slope stability analysis, and provide practical recommendations for sustainable slope management and disaster risk reduction in similar hilly regions.

3. STUDY AREA

Mount Tunak, located within the Tunak Nature Tourism Park in Mertak Village, Central Lombok, Indonesia, lies about 25 km east of the Mandalika Special Economic Zone (SEZ). The 1,219.97-hectare park comprises coastal hilly terrain with elevations of 0–40 m above sea level and slope gradients of 24°–45°, geographically positioned between 08°51′–08°57′ S and 116°18′–116°24′ E.

The study area is underlain by the Pengulung Formation, composed of breccia, lava, tuff, and limestone with sulfide minerals and quartz veins. Field observations indicate intrusive basement rocks overlain by tuff and thick soil deposits, with several fault structures intersecting the area [17].

Based on rainfall data from 2014–2023 at the Rembitan Station, annual precipitation ranges from 1162 to 2075 mm per year, with peak intensity between November and March (BBWS NT I, 2025). The high rainfall significantly affects infiltration and groundwater fluctuations, increasing slope failure susceptibility [18]. The area has been developed for ecotourism with cottages, access roads, and supporting facilities near the slopes. In recent years, several slope failures along access roads have caused cracks and minor landslides, posing risks to infrastructure and tourism facilities. The landslide site within the Tunak Nature Tourism Park is located in Mertak Village, as illustrated in Fig. 1.

4. METHOD

This study was carried out through several systematic stages, consisting of a desk study, field investigation, laboratory testing, and numerical modelling [19,20]. Each stage is described in detail as follows:

4.1 Desk Study

The initial stage involved a desk study to collect information related to the landslide event. Data were obtained from open-access sources, including online news reports, internet databases, Google Maps, and other freely available materials. This stage aimed to provide an overview of the general conditions of the study area and previous slope failure occurrences. Based on secondary data, the landslide at Mount Tunak occurred following three consecutive days of heavy rainfall within the Tunak Nature Tourism Park in January 2021. Although the total monthly rainfall of 320 mm is considered low according to The Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG), the sustained high-intensity rainfall served as the immediate trigger for the slope failure.

4.2 Field Investigation

Field investigations were conducted to obtain primary data on the landslide conditions. These activities included visual inspections and drone-based surveys to identify slope morphology, potential triggering factors, soil characteristics, and both structural and non-structural damages to nearby infrastructure. Geometric measurements of the landslide area were also performed to determine the extent of the affected zone and the dimensions of cracks on the surrounding ground surface. Soil sampling was carried out through geotechnical drilling down to the hard soil layer.

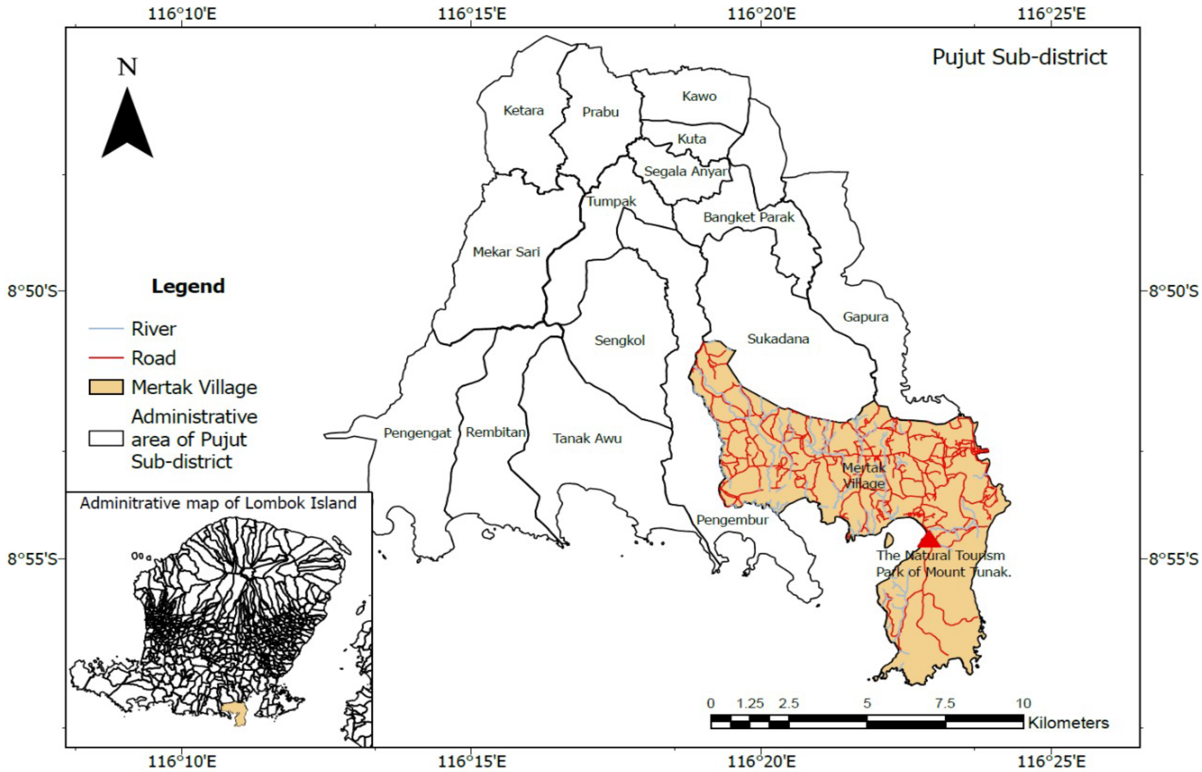

Fig. 1 Location of the landslide

Three boreholes were drilled at the upper, middle, and lower sections of the landslide area to collect both undisturbed and disturbed soil samples for laboratory testing.

4.3 Laboratory Testing

Soil samples were obtained from deep boring investigations conducted at several boreholes within the study area. Both disturbed and undisturbed samples were collected to represent the in-situ soil conditions of the slope. Undisturbed soil samples were collected using thin-walled tube samplers following ASTM D1587, whereas disturbed samples were obtained using split-spoon samplers during the Standard Penetration Test (SPT) in accordance with ASTM D1586**.** The recovered samples were carefully sealed and labeled with borehole number, depth, and location, then stored in wooden core boxes to minimize moisture loss and prevent structural disturbance (Fig. 2). Laboratory tests were conducted to determine the physical and mechanical properties of the soil samples. The physical properties included natural water content (ASTM D2216), soil density (ASTM D7263), and the shear strength was obtained from direct shear tests (ASTM D3080).

The results of these laboratory analyses were subsequently interpreted to derive key geotechnical parameters such as unit weight, cohesion, internal friction angle, and modulus of elasticity. These parameters served as essential input data for the numerical modelling of slope stability using PLAXIS 2D.

4.4 Numerical Modelling

Numerical modelling in this study was performed using PLAXIS 2D Version 24, which employs the Finite Element Method (FEM). The model simulated the slope's response to external loads and hydrological effects induced by rainfall infiltration. The external loads considered included the structural load from a cottage located at the crest of the slope and traffic loads applied near the toe area.

The slope geometry was developed based on stratigraphic information obtained from borehole investigations and laboratory test results. Each soil layer was assigned its corresponding geotechnical parameters, including elastic modulus, cohesion, internal friction angle, and unit weight. To realistically capture the nonlinear stress–strain response of the soil, the Hardening Soil Model (HSM) was adopted in this study, as it provides a more reliable representation of soil stiffness and plastic hardening compared to the conventional Mohr–Coulomb model [2,4]. The Hardening Soil Model (HSM) parameters used in Plaxis were derived from a combination of field investigation data and laboratory test results. A summary of these parameters is presented in Table 1.

Fig. 2 Soil samples in wooden core boxes

The slope model was discretized using 15-node triangular elements to ensure higher accuracy in capturing stress–strain behavior within the soil mass. Boundary conditions were applied to simulate in-situ constraints, where the model base was fixed, and the vertical boundaries were defined as rollers to prevent horizontal displacement. Rainfall infiltration corresponding to a 10-year return period was applied as a transient flux boundary on the slope surface, while traffic and structural loads were imposed as surface loads. The simulation was divided into three main stages: (1) the initial slope condition without rainfall, (2) the slope condition subjected to rainfall infiltration, and (3) the reinforced slope condition.

The stabilizing structure was modeled as a row of cast-in-place soldier piles, represented by embedded beam elements in PLAXIS 2D. Each pile had a diameter of 0.6 m and a center-to-center spacing of 1.2 m, with an elastic modulus of 27 805 MPa and a unit weight of 24 kN/m³, representing reinforced concrete. Three pile length variations were analyzed, namely 5 m, 8 m, and 12 m, to assess the influence of embedment depth on slope stability. The interaction between the pile and soil was simulated using the embedded beam interface formulation in PLAXIS, which allows the transfer of shear and normal stresses along the pile shaft. The soldier pile installation layout and its details are presented in Fig. 3.

5. RESULTS

5.1 Hydrological Data Analysis

The hydrological data were obtained from rainfall records at the Rembitan Observation Station, the nearest station to Mount Tunak Nature Tourism Park, covering 2014–2023. The annual maximum daily rainfall was extracted and tested for consistency using the Rescaled Adjusted Partial Sums (RAPS) method. After confirming data homogeneity, a frequency analysis was conducted to determine rainfall intensities for various return periods.

The rainfall hyetograph was used to represent temporal variations in rainfall intensity throughout the simulation period. In this study, the hyetograph was developed based on maximum daily rainfall data recorded at the Rembitan Climatology Station, which were converted into rainfall intensities corresponding to a 10-year return period. The selection of this return period followed the guidelines of SNI 8460:2017 and SNI 03-3424-1994, while also considering the characteristics of the Mount Tunak area—designated as a conservation-based tourism zone with a moderate risk level. The 10-year return period was deemed appropriate for slope stability analysis in this region, taking into account the availability of reliable and continuous rainfall data from 2014 to 2023. The Intensity–Duration–Frequency (IDF) curve was employed to establish the relationship between rainfall intensity, duration, and frequency, thereby forming a realistic pattern of extreme rainfall distribution. Rainfall intensity was presented in mm/hour on the IDF curve for hydrological analysis purposes and subsequently converted to mm/day when input into the PLAXIS model to comply with the rainfall boundary condition format. Infiltration was modeled as a time-dependent boundary condition applied to the slope surface, with the infiltration rate determined based on rainfall intensity and soil permeability. During the transient simulation, PLAXIS calculated water movement, pore pressure buildup, and the formation of the saturated zone, which dynamically influenced slope stability.

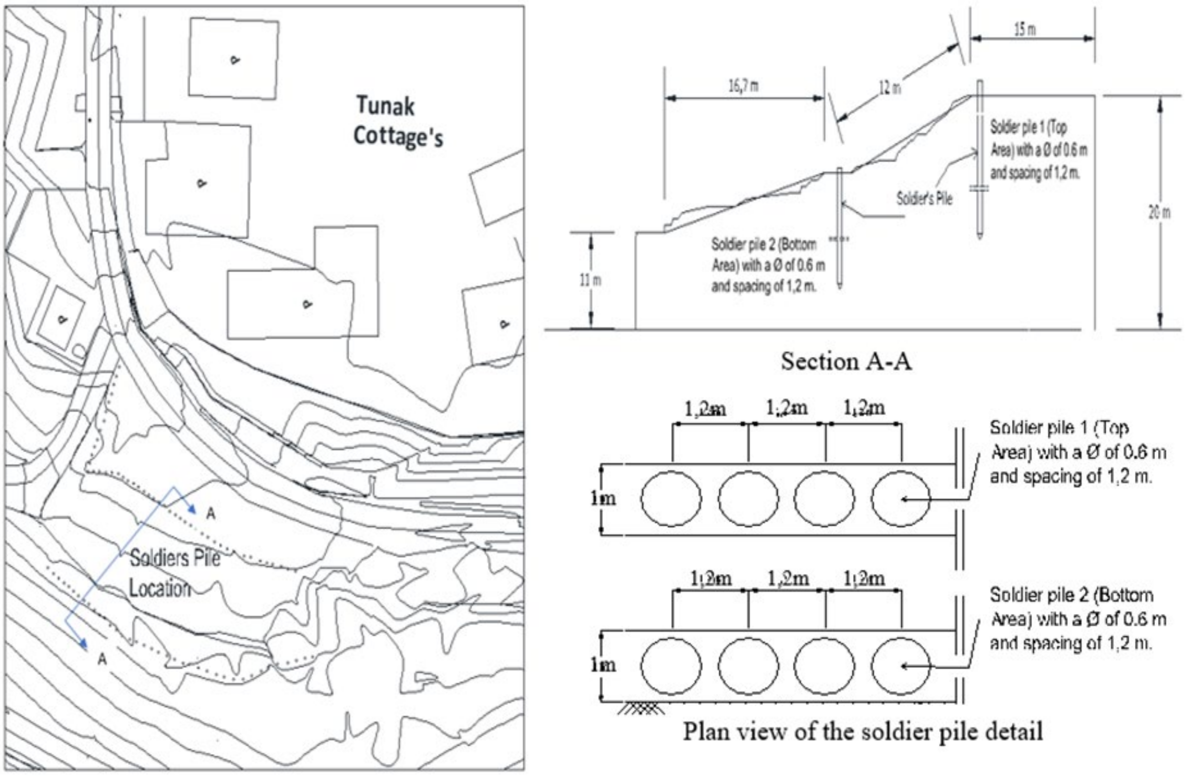

Fig. 3 Layout and section details of the soldier pile installation

5.2 Field and Laboratory Test Results

The slope in the Mount Tunak Nature Tourism Park area has an inclination of 30°–42°, with a landslide zone approximately 65 m long and 40 m wide. A horseshoe-shaped tension crack, 5–15 cm wide and up to 65 cm deep, was identified at the crest of the slope. The failure is classified as a shallow rotational slide, extending close to a restaurant building located about 5 m from the slope edge. The primary triggering factors include soil saturation due to prolonged rainfall and seepage from septic tanks, steep slope inclination, plastic silty clay soil with low cohesion, inadequate drainage conditions, and additional loads from structures at the crest. The landslide caused structural and environmental impacts, including floor cracking in buildings, deformation of access roads, damage to drainage channels and stabilizing vegetation, and reduced comfort and safety for visitors.

The coefficient of permeability (k) was obtained from field permeability tests conducted using the falling head method in SPT boreholes, immediately after performing the Standard Penetration Test (SPT) at every 5-meter depth interval. Subsequently, the coefficient of permeability (k) at specific depths was determined through a correlation method. The borehole data obtained from three locations, combined with the laboratory test results, were utilized as soil input parameters for the numerical modeling in Plaxis. A summary of the derived soil parameters is presented in Table 1.

5.3 Numerical Analysis Results

Numerical simulations using PLAXIS 2D Version 24 were conducted by performing a sensitivity analysis on key parameters, namely cohesion (±20%), internal friction angle (φ) (±2°), and permeability varying by one order of magnitude (k/10, k, 10·k), considering the relatively high uncertainty in permeability measurements. The analysis results indicate that under the initial condition without rainfall infiltration, the safety factor (SF) of the slope ranges from 1.263 to 1.074, suggesting that the slope is stable but approaching marginal stability. This condition is attributed to the dry state of the soil, which leads to low pore water pressure, resulting in higher effective stress and shear strength. Although the slope remains stable under these conditions, its stability may decrease with increasing moisture content or additional loading at the crest. The FEM analysis conducted using PLAXIS was validated through a Limit Equilibrium Method (LEM) analysis in RockScience, employing the Morgenstern–Price slice method to assess slope stability. The LEM analysis yielded a safety factor (SF) ranging from 1.201 to 1.197. Overall, both FEM and LEM results indicate that the slope is stable but approaching marginal stability.

Table 1. Hardening Soil Model (HSM) Parameters for Plaxis

Layer	Depth (m)	Soil Type	γ_{unsat} (kN/m³)	γ_{sat} (kN/m³)	c_{ref} (kPa)	φ_{ref} (°)	$E50_{ref}$ (kPa)	Eur_{ref} (kPa)	ψ (°)	ν	k (m/s)
1	0–7	Silty clay & clay (stiff–hard)	18.15	19.0	20.59	24.17	1000	2000	0	0.3	1.47×10^{-8}
2	7–13	Clay with silty clay & limestone	15.99	17.0	23.53	27.80	1200	2400	0	0.3	4.51×10^{-9}
3	13–16	Silty clay with limestone, high plasticity	19.42	20.5	29.00	21.02	1500	3000	0	0.3	3.98×10^{-9}
4	16–20	Clay breccia with limestone fragments	13.73	15.0	24.25	25.23	1300	2600	0	0.3	5.53×10^{-9}

The difference in SF values between the two methods (FEM: 1.263–1.072; LEM: 1.201–1.197) arises from the distinct analytical principles, where FEM accounts for nonlinear soil behavior and detailed variations in pore water pressure, whereas LEM employs simplified assumptions regarding slip surfaces and pore pressure distribution. These findings collectively confirm that the slope stability may decrease under conditions of increased moisture content or additional loading at the slope crest. Fig. 4 and 5 present the results of the FEM analysis using PLAXIS (SF = 1.076) and the LEM analysis using RockScience (SF = 1.197).

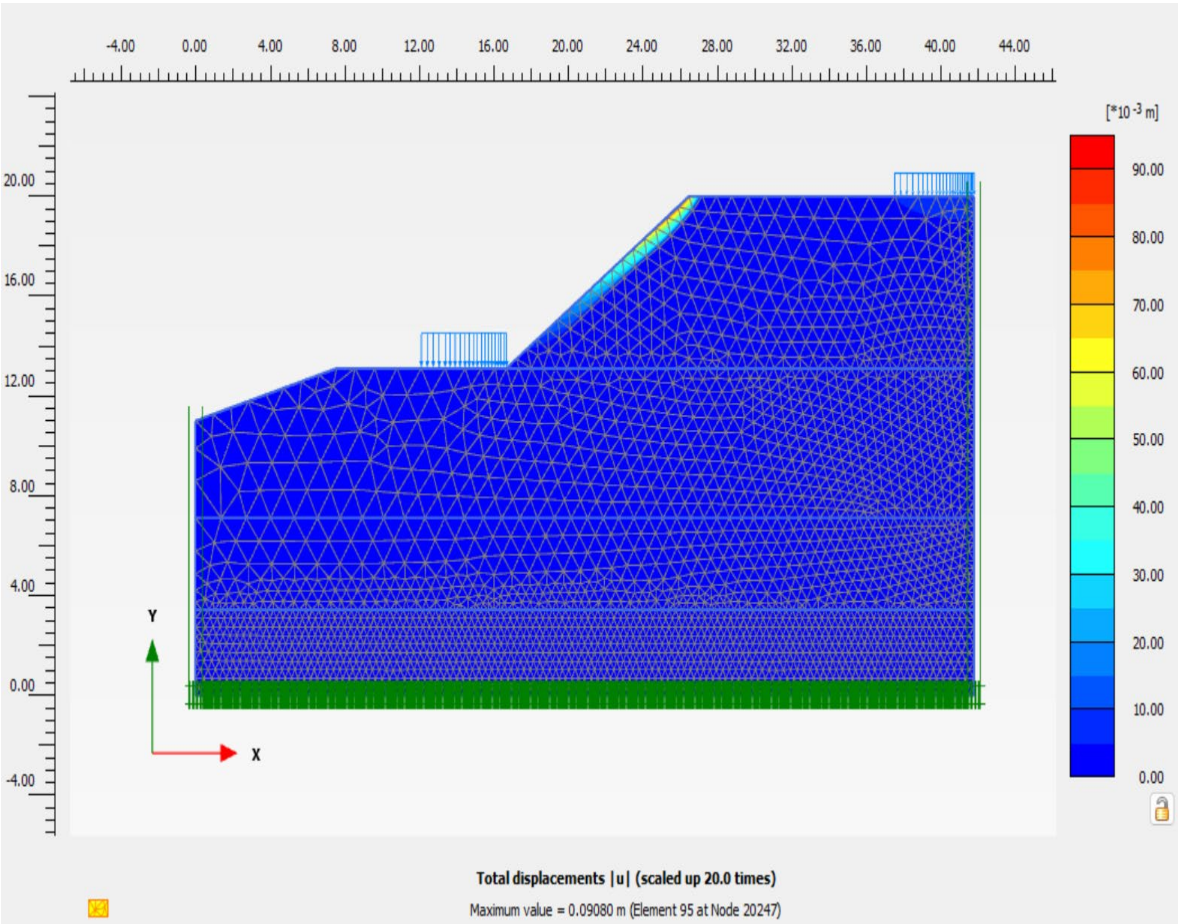

Fig. 4 Results of PLAXIS 2D Version 24 Analysis for the Initial Slope Condition without Rainfall

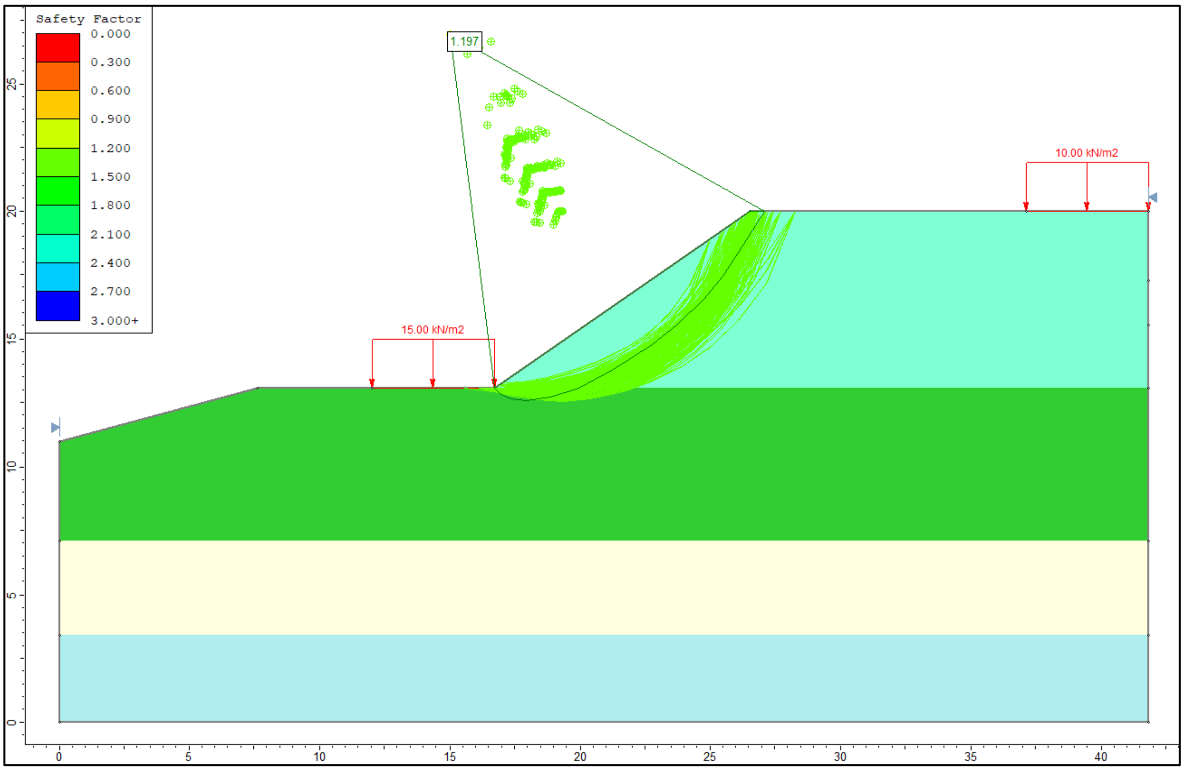

Fig. 5 Results of RockScience Analysis for the Initial Slope Condition without Rainfall

The second slope simulation was conducted by applying rainfall infiltration corresponding to a 10-year return period. The analysis results indicate that the slope safety factor decreased from a range of 1.263–1.074 to 1.044–0.895, representing a reduction of 2.97–19.24%. This finding suggests that the slope has reached a critical state of instability, as the safety factor falls below the minimum acceptable threshold. The third simulation involved the application of slope reinforcement using soldier piles with varying lengths of 5 m, 8 m, and 12 m. For a pile length of 5 m, the safety factor ranged from 1.000 to 1.232, corresponding to an improvement of 4.21–35.08%. For a pile length of 8 m, the safety factor ranged from 1.223 to 1.272, indicating an increase of 2.20–42.12%. Meanwhile, for a pile length of 12 m, the safety factor ranged from 1.092 to 1.652, demonstrating a substantial improvement of 4.60–84.58%. The Safety Factor ranges corresponding to pile lengths of 5 m, 8 m, and 12 m are summarized in Table 2, whereas the resulting improvements in safety performance are illustrated in Fig. 6.

Table 2. Safety Factor Range for Different Pile Lengths

Pile length (m)	Minimum SF	Maximum SF
5	1.000	1.232
8	1.223	1.272
12	1.092	1.652

In the simulation model, soldier piles were represented as structural beam elements incorporating soil–pile interface elements to realistically simulate shear and bending interaction. The pile fixity depth was determined based on soil stiffness, with the pile toe assumed to be fully restrained. Installation effects were not considered, focusing solely on post-installation performance. The design loads consisted of a structural load of 10 kN/m² applied at the slope crest and a traffic load of 15 kN/m² applied at the toe. The piles were spaced at 1.2 m (≈2D) with embedment depths of 5 m, 8 m, and 12 m.

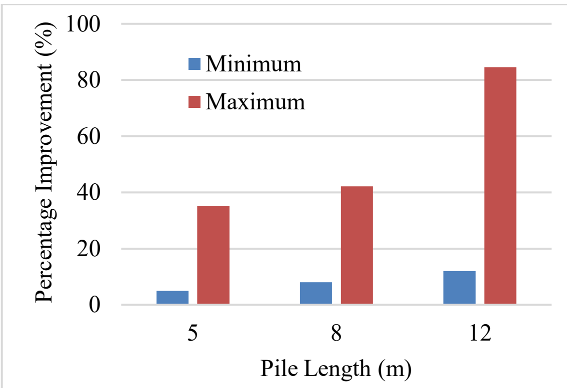

Fig.6 Percentage Improvement of Slope Safety Factor Based on Pile Length

From an engineering perspective, the use of bored cast-in-place soldier piles in the TWA Tunak area is effective and constructible, requiring no heavy driving equipment and causing minimal environmental disturbance. Considering the trade-off between stability and cost, the 8 m pile provides a reasonable balance, offering moderate safety improvement at lower expense. However, for maximum slope stability and enhanced protection of the tourism infrastructure, the 12 m pile is recommended, as it yields substantially higher safety factors.

6. CONCLUSION

Based on the integrated geotechnical and hydrological analyses of slope stability in the Mount

Tunak area, several key conclusions can be drawn as follows:

1. The slope failure mechanism in the study area is primarily influenced by the combined effects of rainfall infiltration and external loading, which increase pore water pressure and consequently reduce the shear strength of the soil. Laboratory and field investigations indicate that variations in the physical and mechanical properties between soil layers, including differences in NSPT values and permeability, contribute to non-uniform deformation behavior along the slope.
2. The numerical simulation using PLAXIS 2D with the Hardening Soil Model (HSM) reveals that the Factor of Safety (FOS) under the initial dry condition is relatively stable at ranged from 1.263 to 1.074, and validation using the Limit Equilibrium Method (LEM) in RockScience yielded similar values (1.201–1.197). The Factor of Safety (FOS) decreases to 1.044–0.895 when the slope is subjected to rainfall infiltration with a 10-year return period and external loading. This condition indicates that the slope is in a critical state and potentially susceptible to failure.
3. The application of soldier piles is proven effective in improving slope stability under rainfall-induced conditions. Numerical analysis shows that pile lengths of 5 m, 8 m, and 12 m increase the Safety Factor (SF) to 1.000–1.232, 1.223–1.272, and 1.092–1.652, respectively. Longer piles consistently reduce lateral displacement and enhance stress redistribution within the soil mass, leading to a significantly higher stabilizing effect against pore-pressure-driven failure mechanisms.
4. Overall, this study highlights that the combined influence of geotechnical and hydrological factors must be carefully considered in slope stability assessments, particularly in tropical regions with high rainfall intensity such as Mount Tunak. The numerical approach using the Finite Element Method (FEM) with the Hardening Soil Model provides a more realistic representation of soil behavior and can serve as a reliable basis for designing landslide mitigation and slope stabilization strategies in hilly tourism areas.

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