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Geological Characterization and Seismic Slope Stability Assessment Using the Limit Equilibrium Method in the Kalawara-Kulawi Area

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Abstract: *This study provides a comprehensive geological characterization and evaluates the slope stability in Segment 5 of the Kalawara-Kulawi Road, a highly earthquake-prone zone in Central Sulawesi. Field investigations and laboratory analyses, including Petrography, X-Ray Fluorescence (XRF), and kinematic analysis, were conducted to assess the rock mass quality. The computational stability analysis was performed using the Limit Equilibrium Method (LEM) with the Morgenstern-Price slice method. Geological results indicate that the slope consists of highly weathered Quartz Monzonite with a Rock Mass Rating (RMR) of 28 (Class IV - Poor Rock) and high vulnerability to toppling and wedge failures. Geotechnically, the static condition shows a marginally stable state with a Factor of Safety (FS) of 1.145. However, under a pseudostatic seismic load representing the maximum design earthquake (Kh = 0.45), the FS decreases sharply to 0.535, explicitly indicating a global shear failure. Therefore, geometric modification and integrated structural reinforcements are urgently recommended.*

Keywords: *Slope Stability, Limit Equilibrium Method, Factor of Safety, Seismic Load, Pseudostatic.*

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I. INTRODUCTION

Slope stability is a critical issue in infrastructure development, particularly in steep terrains with complex geological conditions (Das, 2010). Landslides are frequent disasters in Indonesia, causing large-scale impacts on the environment, transportation facilities, and public safety. Central Sulawesi, specifically Segment 5 of the Kalawara–Kulawi Road, is classified as a high-risk area. This region is composed of geologically vulnerable materials and is located in an active seismic zone traversed by the Palu-Koro fault. Previous studies recorded thousands of shallow landslides in this region following the 2018 Mw 7.5 Palu earthquake (Shao et al., 2023).

Fundamentally, slope stability is determined by the Factor of Safety (FS), which is mathematically defined as the ratio of the soil's resisting shear strength capacity to the mobilized shear stress acting on the potential slip surface (Duncan et al., 2014). The shear strength of the soil is governed by the Mohr-Coulomb failure criterion, represented by the equation $\tau_f = c' + \sigma' \tan\phi'$, where c' is the effective cohesion, σ' is the effective normal stress, and ϕ' is the effective internal friction angle (Das, 2007). When the value of FS drops below 1.0, the slope is considered to be in a state of failure, while a value between 1.0 and 1.5 indicates a marginal or critical stability state (Hoek & Bray, 1981).

In geotechnical engineering practice, the Limit Equilibrium Method (LEM) is widely adopted for stability analysis (Bayati et al., 2025). LEM evaluates stability by dividing the soil mass above the potential slip surface into vertical slices and analyzing the force and/or moment equilibrium. Among the various LEM approaches, the Morgenstern-Price method is considered highly rigorous and reliable because it simultaneously satisfies both force and moment equilibrium conditions on each soil slice, accommodating variations in shear strength and pore water pressure (Syah et al., 2020).

Furthermore, the integration of seismic parameters is crucial for slopes located in active earthquake zones. The most common approach for seismic evaluation is the pseudostatic analysis, which simulates the dynamic earthquake load as a constant horizontal inertia force applied to the soil mass (Martino et al., 2020). The magnitude of this force is determined by the Horizontal Seismic Coefficient (K_h). According to the Indonesian National Standard for Geotechnical Design (SNI 8460:2017) (Badan Standardisasi Nasional, 2017), the K_h value is derived from the Peak Ground Acceleration (PGA) with a 50% reduction factor to accommodate the elastic-plastic deformation tolerance of the slope materials without global failure.

Therefore, this study aims to evaluate the slope stability in Segment 5 of the Kalawara–Kulawi Road by comprehensively integrating the geotechnical parameters and the theoretical framework of the Morgenstern-Price Limit Equilibrium Method under both static and pseudostatic (seismic) conditions.

II. EXPERIMENTAL PROCEDURE

2.1 Study Area and Soil Sampling

The research was conducted at Segment 5 of the Kalawara-Kulawi Road, specifically in the mountainous area of Salua Village, Kulawi District, Sigi Regency, Central Sulawesi, Indonesia. Primary data were obtained through field investigations and undisturbed soil sampling from Borehole 02 (BH.02). The site investigation and sampling procedures were carried out in accordance with the Indonesian National Standard for Geotechnical Investigation, SNI 8460:2017 (Badan Standardisasi Nasional, 2017). Subsequent laboratory tests were conducted to determine the physical and mechanical properties of the soil, including sieve analysis, unit weight tests, and direct shear tests to obtain the cohesion (c) and internal friction angle (ϕ) of the materials.

2.2 Geotechnical Parameters

Based on the laboratory testing and the Unified Soil Classification System (USCS), the stratigraphy of the slope at the study location is divided into three main layers. The top layer consists of Silty Sand (SM), while the middle and bottom layers consist of Gravelly Sand (SP) characterized by high density and low cohesion. The specific geotechnical parameters for each layer used in the stability analysis are summarized in Table 1.

Table 1. Geotechnical Parameters of the Study Area (BH.02)

Layer Position	USCS Soil Type	Bulk Unit Weight, γ (kN/m³)	Cohesion, c (kPa)	Friction Angle, ϕ (°)
Top Layer	Silty Sand (SM)	16.94	0.68	32.32
Middle Layer	Gravelly Sand (SP)	17.47	1.47	34.73
Bottom Layer	Gravelly Sand (SP)	18.15	1.56	35.15

2.3 Geological and Rock Mass Characterization

To comprehend the underlying failure mechanisms, advanced geological characterizations were performed. Petrographic thin-section analysis was conducted to identify the mineralogical composition of the bedrock. Geochemical elements were analyzed using X-Ray Fluorescence (XRF) testing to detect alteration levels. Furthermore, structural discontinuities (strike/dip) were mapped in the field using a geological compass to perform a kinematic analysis via stereographic projection. The overall rock mass quality was then quantified using the Rock Mass Rating (RMR) system established by Bieniawski, (1989), incorporating parameters such as Uniaxial Compressive Strength (UCS), Rock Quality Designation (RQD), and discontinuity conditions.

2.4 Slope Stability Modeling

The numerical modeling for the slope stability was performed using GeoStudio/SLOPE/W software. The slope geometry was reconstructed based on the actual field topographic data extracted from drone photogrammetry. The Limit Equilibrium Method (LEM) employing the Morgenstern-Price formulation was utilized to calculate the Factor of Safety (FS). This specific method was selected because it rigorously satisfies both force and moment equilibrium equations for all slices, thereby providing a highly accurate estimation of the critical slip surface (Syah et al., 2020).

2.5 Pseudostatic Seismic Load Calculation

To evaluate the slope's performance under earthquake conditions, a pseudostatic analysis was incorporated. According to the Indonesian Seismic Hazard Map (SNI 1726:2019) (Badan Standardisasi Nasional, 2019), the Peak Ground Acceleration (PGA) for the Salua Village area is 0.9g. In accordance with the geotechnical design requirements stipulated in SNI 8460:2017, the Horizontal Seismic Coefficient (K_h) is calculated by applying a 50% reduction factor to the maximum PGA. This reduction is applied to account for the elastoplastic deformation tolerance of the slope materials during shaking without experiencing global failure. Therefore, a K_h value of 0.45 was applied as a constant horizontal inertial force in the dynamic modeling.

III. RESULTS AND DISCUSSIONS

3.1 Geological and Kinematic Analysis

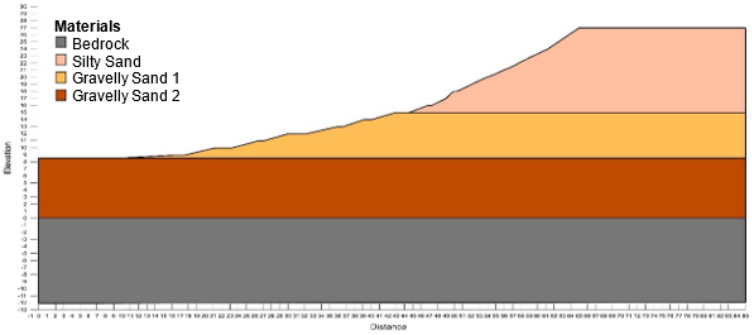
The petrographic analysis revealed that the bedrock in the study area is Quartz Monzonite, characterized by a holocrystalline and porphyritic texture dominated by plagioclase, feldspar, and quartz. X-Ray Fluorescence (XRF) analysis validated this finding, showing high Fe contents (12.27%) and significant Light Elements (53.18%), which chemically indicates a high degree of weathering and hydrothermal alteration. This severe alteration significantly deteriorates the mechanical strength of the rock mass.

Kinematic analysis using stereographic projections identified that the slope is highly susceptible to structural failures, specifically showing a 25.00% probability for toppling failures and a 1.05% risk for wedge sliding along the intersecting discontinuity planes. Based on these structural conditions, combined with a low average Uniaxial Compressive Strength (UCS) of 15.30 MPa and heavily fractured joints, the Rock Mass Rating (RMR) was calculated at 28. This classifies the material as Class IV (Poor Rock), confirming its high vulnerability to global failure when subjected to external dynamic forces.

3.2 Static Slope Stability Analysis

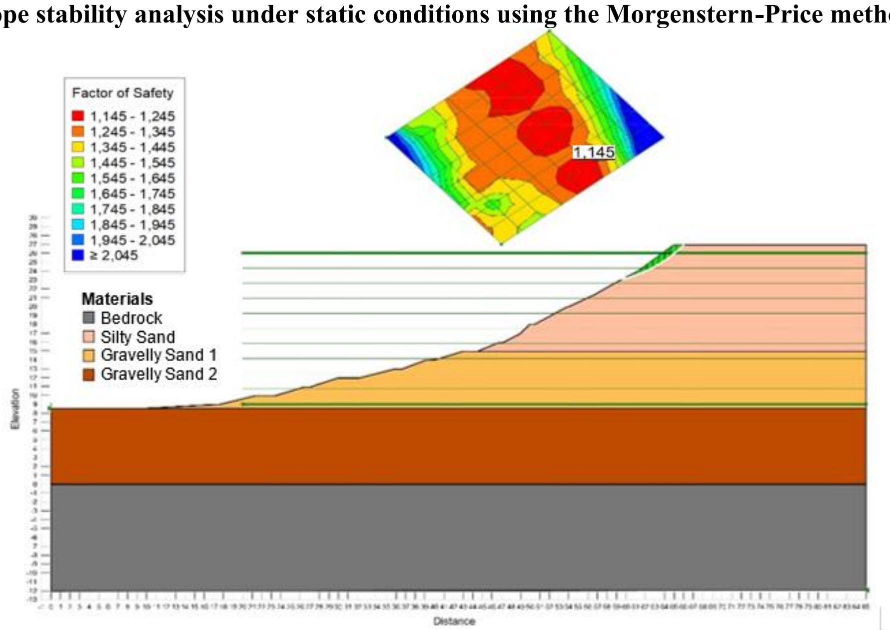
The initial phase of the stability assessment was conducted under static loading conditions, which assumes that the slope is solely influenced by gravitational forces and the self-weight of the soil mass, without any external seismic interference. The analysis was performed using the Morgenstern-Price slice method to simultaneously satisfy both force and moment equilibrium.

Figure 1. Geometry modeling of the existing slope at Segment 5, Kalawara-Kulawi Road



The simulation results for the static condition yielded a Factor of Safety (FS) of 1.145. According to geotechnical design principles, an FS value between 1.0 and 1.5 indicates that the slope is in a marginally stable or critical state (Hoek & Bray, 1981).

Figure 2. Slope stability analysis under static conditions using the Morgenstern-Price method

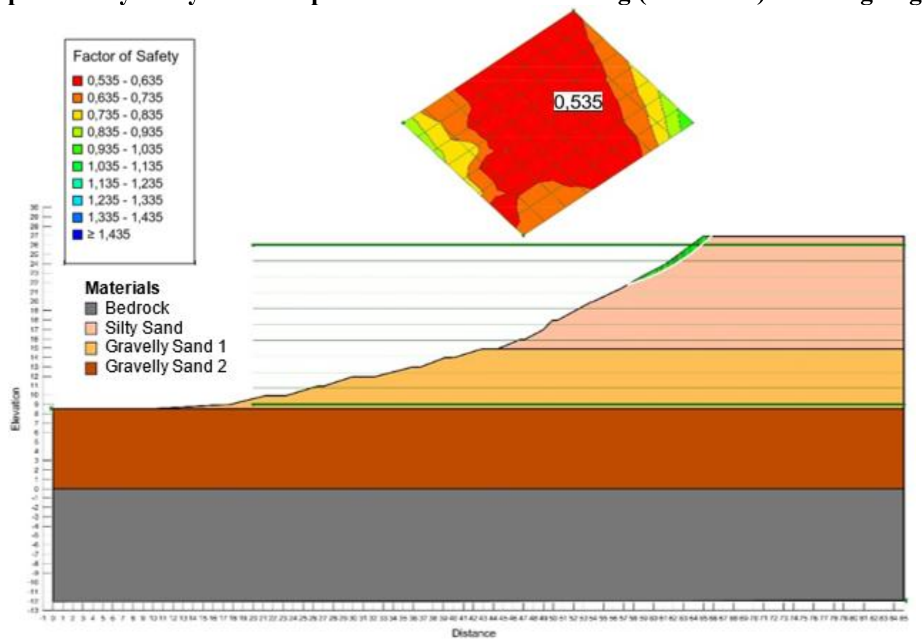


In this marginal state, the resisting forces provided by the soil's shear strength (cohesion and internal friction) are almost equal to the driving forces generated by the slope's steep geometry and soil mass. Although the slope does not exhibit immediate signs of global failure under normal dry conditions, the safety margin is exceptionally narrow. Because the FS value is below the conventionally recommended safe limit (FS ≥ 1.5) for permanent infrastructure, the existing slope is categorized as highly sensitive to any environmental alterations, such as increased pore water pressure during heavy rainfall or external dynamic loads (Martino et al., 2020).

3.3 Pseudostatic Seismic Analysis

Given that the Kalawara-Kulawi area is traversed by the active Palu-Koro fault, evaluating the slope's performance under dynamic loads is mandatory. The seismic stability was analyzed using the pseudostatic approach, simulating the earthquake effect as a constant horizontal lateral force. Based on the SNI 8460:2017 standard, a Horizontal Seismic Coefficient (K_h) of 0.45 was applied to the model, representing the maximum design earthquake for the region with an accommodated elastic-plastic deformation tolerance (Badan Standardisasi Nasional, 2017).

Figure 3. Slope stability analysis under pseudostatic seismic loading (Kh = 0.45) resulting in global failure



The application of the seismic load resulted in a significant degradation of the slope's stability. The Factor of Safety decreased significantly from 1.145 down to 0.535. This value falls significantly below the minimum seismic safety tolerance of FS > 1.1 mandated by geotechnical standards. Mechanistically, the seismic wave propagation provides a large-scale additional lateral driving inertia force to the soil mass. Since the gravelly sand (SP) and silty sand (SM) layers at the site possess relatively low cohesion (ranging from 0.68 to 1.56 kPa), the soil matrix lacks the necessary binding strength to counteract the sudden surge in lateral stress.

The simulation explicitly confirms that under the design earthquake scenario, the driving forces absolutely exceed the resisting forces. The critical slip surface extends from the crest to the toe of the slope, indicating that the entire slope face will experience a large-scale global shear failure.

3.4 Implication for Landslide Mitigation

The numerical evidence from both static and pseudostatic analyses proves that the existing natural slope configuration at Segment 5 of the Kalawara-Kulawi Road is critically unsafe. The slope's inability to independently withstand maximum seismic acceleration dictates that mitigation efforts cannot rely solely on superficial treatments. Comprehensive geotechnical interventions, such as slope geometry modification (terracing) integrated with structural reinforcements (e.g., retaining walls or soil nailing) and proper subsurface drainage systems, are urgently required to ensure the long-term serviceability and safety of the transportation infrastructure.

IV. CONCLUSION

Based on the integrated geological and geotechnical investigations at Segment 5 of the Kalawara–Kulawi Road, several critical conclusions can be drawn. Geologically, the bedrock consists of highly altered Quartz Monzonite. Kinematic and rock mass characterizations indicate a high susceptibility to toppling and wedge sliding, with a Rock Mass Rating (RMR) of 28 classifying the material as Class IV (Poor Rock). This severely degraded rock mass significantly diminishes the overall resisting shear strength of the slope.

Under normal static loading conditions, the slope is only in a marginally stable state, yielding a Factor of Safety (FS) of 1.145. However, seismic activity acts as the primary catalyst for global slope failure in this region. The application of a pseudostatic seismic load representing the maximum design earthquake (Horizontal Seismic Coefficient, K_h = 0.45) significantly deteriorates the slope's stability, reducing the FS to an unstable state of 0.535.

This confirms that the driving inertial forces generated during a severe earthquake will inevitably exceed the resisting strength of the poor rock mass, leading to a large-scale global shear failure.

Consequently, relying solely on the natural slope configuration is geotechnically unsafe for long-term infrastructure serviceability. It is strongly recommended to implement an integrated geotechnical mitigation strategy. This robust approach must include slope reprofiling (terracing) to reduce the driving mass, the installation of proper subsurface drainage systems (horizontal drains) to alleviate pore water pressure, and the application of rigid structural reinforcements, such as soldier piles or soil nailing, to securely withstand extreme lateral seismic stresses.

Conflict of interest

There is no conflict to disclose.

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