GeoScienceEd *7(3) (2026)*

Jurnal Pendidikan, Sains, Geologi, dan Geofisika

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Hydroclimatic Context and Deterministic Stability of Weathered Limestone Road-Cut Slopes along the Maros-Bone Corridor, Indonesia

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DOI: https://doi.org/10.29303/goescienceed.v7i3.3163

Article Info
Received : 27 Juli 2026
Revised : 11 Agustus2026
Accepted : 30 Agustus2026

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Abstract: Road-cut slopes in tropical carbonate terrain are affected by the interaction of geometry, weathering, material strength, and seasonal water input. This study evaluated two weathered limestone road-cut slopes along the Maros-Bone corridor, South Sulawesi, Indonesia, using engineering-geological observations, laboratory properties, the Simplified Janbu method, and independent regional rainfall data. Site 1 in Cenrana is approximately 15 m high with a 43° inclination, whereas Site 2 in Mallawa is approximately 18 m high with a 55° inclination. Representative parameters were c = 12 kPa, φ = 21°, and γ = 12.7 kN/m³ for Site 1 and c = 14 kPa, φ = 28°, and γ = 13 kN/m³ for Site 2. The calculated factors of safety were 1.043 and 1.002, indicating very limited stability margins. Regional climate records for 2023 showed 3,336 mm of annual rainfall over 132 rainy days, with 94.1% occurring from November to April and monthly peaks of 1,091 mm in February and 803 mm in January. The rainfall data were used as hydroclimatic context rather than hydraulic model input. The findings indicate that weathering and seasonal wetness may aggravate Site 1, while steep geometry is especially critical at Site

Keywords: Engineering Geology; Hydroclimatic Context; Limestone; Road-Cut Slope; Simplified Janbu

Citation: Malik, D. P., Mahyuni, E. T., Suba, S., Mas, A. A. M., Mardjuni1, S. N., & Ma'rief, A. A. (2026). Hydroclimatic Context and Deterministic Stability of Weathered Limestone Road-Cut Slopes along the Maros-Bone Corridor, Indonesia. *Jurnal Pendidikan, Sains, Geologi, Dan Geofisika (GeoScienceEd Journal)*, *7*(3), 5194–5200. https://doi.org/10.29303/goescienceed.v7i3.3163

Introduction

Slope instability is a recurrent geotechnical problem along transportation corridors because road excavation modifies natural geometry, removes toe support, exposes weathered materials, and changes drainage pathways. The response of a cut slope is controlled by the interaction between slope height and inclination, lithology, weathering, discontinuities, shear strength, water conditions, and external loading. In tropical regions, these controls are particularly important because intense weathering and seasonal rainfall can reduce the mechanical competence of near-surface materials and increase the likelihood of slope movement (Triana et al., 2020; Tamanak, 2020; Anom et al., 2021).

Recent road-slope studies confirm that unfavorable geometry and geological condition must be evaluated together. Sari (2019) showed that empirical, kinematic, numerical, and limit-equilibrium approaches provide complementary information for road-cut slopes, while Pradhan and Siddique (2020) demonstrated the value of numerical assessment for landslide-prone highway rock slopes. Komadja et al. (2021) documented the combined geological and geotechnical controls on debris-slope instability along a national highway in India, and Çakıner et al. (2024)

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emphasized the influence of engineering geometry and material properties in motorway slope assessment. Comparable road-corridor investigations in Ethiopia also show that instability commonly reflects the joint effects of slope geometry, saturation, and spatially variable ground conditions (Kinde et al., 2024; Garo et al., 2024; Hussen et al., 2024).

Water is a major destabilizing factor because infiltration can increase water content and unit weight, alter suction, raise pore-water pressure, and reduce effective shear resistance. Rainfall-related changes in slope stability have been demonstrated experimentally and numerically in residual, colluvial, and excavated slopes (Nguyen et al., 2020; Chen et al., 2021; Wang et al., 2021; Huang et al., 2022; Yu et al., 2024). For a deterministic analysis with factors of safety close to unity, an independent hydroclimatic record can provide important regional context, even when rainfall is not explicitly coupled to pore-water-pressure calculations. Such contextualization is particularly relevant in weathered carbonate terrain where infiltration pathways may be spatially heterogeneous.

Limit-equilibrium analysis remains widely used in engineering practice because it provides a direct factor of safety for potential slip surfaces and can be applied efficiently to measured slope geometries. Indonesian studies have applied Bishop and Janbu formulations to mine slopes, embankments, and excavation slopes, demonstrating the sensitivity of the factor of safety to geometry, saturation, and material strength (Pasole et al., 2020; Amri et al., 2021; Arsyad & Anaperta, 2021; Kristiansyah & Anaperta, 2021; Cahyono, 2021; Muzdalifah et al., 2022; Krostanto & Hutapea, 2023; Amin & Cahyono, 2024). Recent international studies likewise combine limit-equilibrium and numerical approaches to improve interpretation of marginal slopes (Mebrahtu et al., 2022; Rahman et al., 2023).

The Maros-Bone road is an important inter-regency corridor in South Sulawesi that crosses hilly terrain and contains road-cut slopes immediately adjacent to traffic. Field observations identified two limestone slopes in Cenrana and Mallawa with different geometries and weathering conditions. The present study therefore aims to (1) characterize their engineering-geological and geotechnical conditions, (2) determine their deterministic factors of safety using the Simplified Janbu method, and (3) interpret the resulting stability margins against independent regional rainfall seasonality. By combining slope-scale geotechnical data with official hydroclimatic records, the article extends the original undergraduate dataset into a broader engineering-geological assessment while retaining the deterministic slope model as the baseline analysis (Suba, 2024).

Method

Study Area and Research Design

The study used a quantitative engineering-geological and geotechnical approach at two road-cut slopes along the Maros-Bone corridor, Maros Regency, South Sulawesi, Indonesia. Site 1 is located in Cenrana District and Site 2 in Mallawa District. Both slopes are dominated by limestone but differ in height, inclination, and degree of weathering. The slope geometry, field observations, and laboratory dataset originated from the undergraduate investigation of Suba (2024) and were restructured for the present article. The research sequence comprised field reconnaissance, slope-geometry measurement, rock sampling, laboratory testing, deterministic limit-equilibrium modeling, and an additional secondary hydroclimatic analysis.

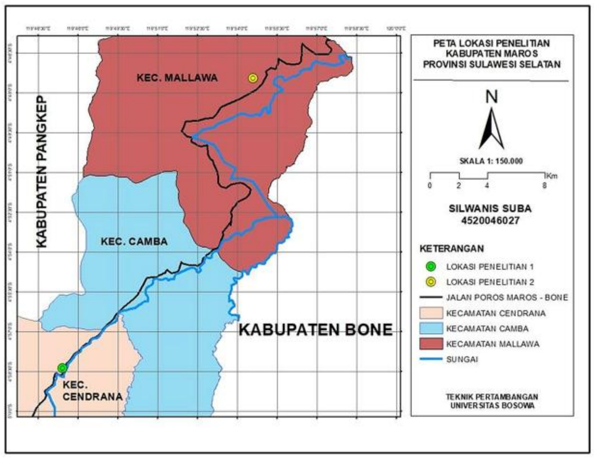

Figure 1. Location of the investigated slopes along the Maros-Bone road corridor, South Sulawesi.

Field and Laboratory Investigation

Fieldwork included direct engineering-geological observation, GPS positioning, measurement of slope height and inclination, photographic documentation, and rock sampling. Observations focused on lithology, weathering, vegetation condition, and visible evidence of water. The degree of weathering was assessed from field appearance and the degradation of the limestone exposure. The field configuration was treated as a single road-cut slope at each location.

Laboratory testing included physical-property measurements and direct shear tests. The physical dataset contains water-content, degree-of-saturation, and porosity values from three limestone specimens at each site. Direct shear testing provided the cohesion (c) and internal friction angle (φ) used in the stability models. The representative unit weight (γ) was taken from the material-property dataset used in the original Rocscience Slide analyses.

Secondary Hydroclimatic Data

Monthly rainfall and rainy-day data for calendar year 2023 were obtained from Maros Regency in Figures 2024, compiled by BPS-Statistics of Maros Regency from the Meteorology, Climatology, and Geophysics Agency (BMKG) climate-station records (Badan Pusat Statistik Kabupaten Maros, 2024). The series was summarized as annual rainfall, annual rainy days, monthly maxima, and wet-season concentration. Because the Maros Climatology Station is a regional station and is not collocated with either investigated slope, the rainfall record was not converted into pore-water pressure and was not used to recalculate the Simplified Janbu factors of safety. It was used only as an independent hydroclimatic context for interpreting the field evidence of water and the practical significance of stability margins close to unity.

Table 1. Engineering-geological characteristics and model parameters.

Parameter	Site 1	Site 2
Location	Cenrana	Mallawa
Lithology	Limestone	Limestone
Height	15 m	18 m
Slope angle	43°	55°
Weathering	Advanced; locally complete	Moderate; stronger at crest
Cohesion, c	12 kPa	14 kPa
Friction angle, φ	21°	28°
Unit weight, γ	12.7 kN/m³	13 kN/m³

Simplified Janbu Analysis

Slope stability was analyzed in Rocscience Slide V5.0 using the Simplified Janbu method. The potentially sliding mass was divided into vertical slices, and the minimum factor of safety was searched using circular trial surfaces. The modeling sequence consisted of defining project settings, constructing the measured slope geometry, assigning the representative material parameters, specifying the slip-surface search, computing the analysis, and interpreting the minimum factor of safety. The analysis represents the static deterministic conditions reported in the original study; transient rainfall infiltration, explicit pore-water-pressure changes, seismic loading, and probabilistic parameter variability were not modeled.

For interpretation, the source study treated values below approximately 1.10 as indicating an insufficient static stability margin. The Indonesian geotechnical design standard was used only as a design-context reference rather than as a substitute for project-specific verification (Badan Standardisasi Nasional, 2017). Because both calculated values are close to unity, the results are interpreted primarily in terms of relative stability margin and engineering significance.

Result and Discussion

Engineering-Geological Conditions

Site 1 in Cenrana is an approximately 15-m-high limestone road cut inclined at 43°. The exposure shows advanced weathering, with some surface portions approaching complete weathering. Surface-water indications were observed during the field investigation, and vegetation was reduced on parts of the slope. The physical-test dataset indicates natural water contents of 20.86-29.17%, degrees of saturation of 67.80-75.76%, and porosities of 39.22-51.95%. These values are consistent with a weathered, relatively porous material in which water-related changes can influence mechanical behavior.

Site 2 in Mallawa is higher and steeper, with an approximate height of 18 m and an inclination of 55°. The limestone is generally moderately weathered, although stronger alteration occurs near the crest. Natural water content ranges from 14.63% to 20.37%, degree of saturation from 45.83% to 72.22%, and porosity from 35.29% to 57.14%. The higher cohesion and friction angle measured for Site 2 do not necessarily imply greater slope stability because its geometry produces a larger gravitational driving component.

Table 2. Selected physical-property ranges of limestone samples.

Property	Site 1	Site 2
Natural water content	20.86-29.17%	14.63-20.37%
Saturated water content	30.77-41.67%	23.17-44.44%
Degree of saturation	67.80-75.76%	45.83-72.22%
Porosity	39.22-51.95%	35.29-57.14%

Regional Hydroclimatic Context

The 2023 Maros Climatology Station record shows a strongly seasonal rainfall regime. Annual rainfall totaled 3,336 mm over 132 rainy days. Rainfall peaked in February (1,091 mm) and January (803 mm), and these two months alone accounted for 56.8% of the annual total. Approximately 94.1% of the annual rainfall occurred from November through April, whereas August and September recorded no rainfall and October recorded only 3 mm (Badan Pusat Statistik Kabupaten Maros, 2024). This pattern indicates a pronounced wet-season hydroclimatic setting. The record is regional rather than site-specific, so it cannot establish rainfall-triggered failure at either slope; however, it provides an independent basis for prioritizing wet-season monitoring and drainage assessment.

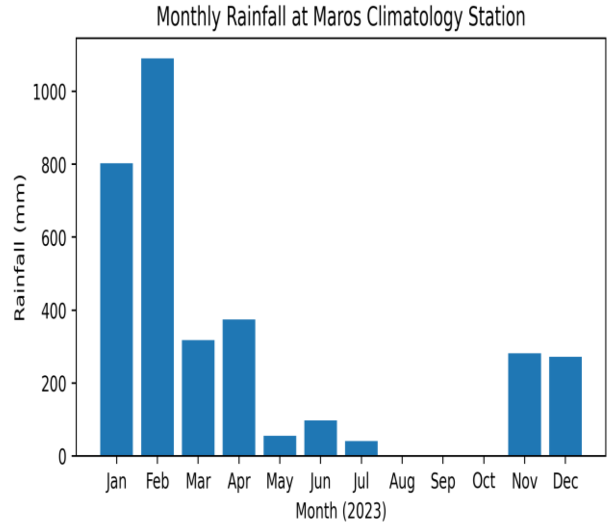

Figure 2. Monthly rainfall at Maros Climatology Station in 2023. Source: BPS-Statistics of Maros Regency (2024), based on BMKG data.

Factor of Safety and Stability Margin

The Simplified Janbu analysis yielded a minimum factor of safety of 1.043 for Site 1 and 1.002 for Site 2. Both values indicate a very limited stability margin under the modeled static conditions. Site 2 is the more critical location because its factor of safety is only 0.002 above unity, meaning that the calculated resisting and driving conditions are almost balanced.

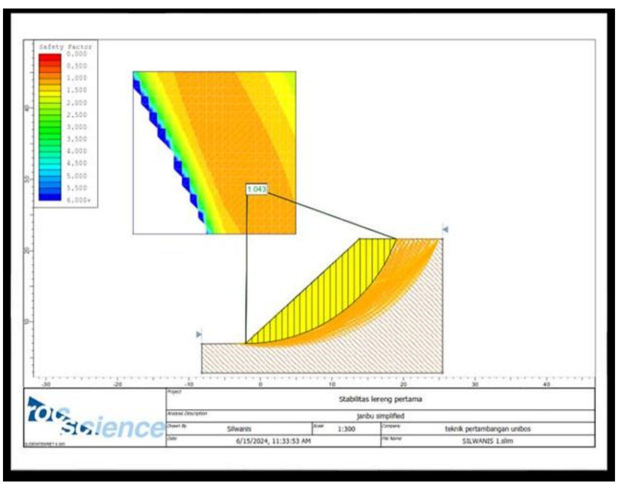

Figure 3. Simplified Janbu output for Site 1, showing a minimum factor of safety of 1.043.

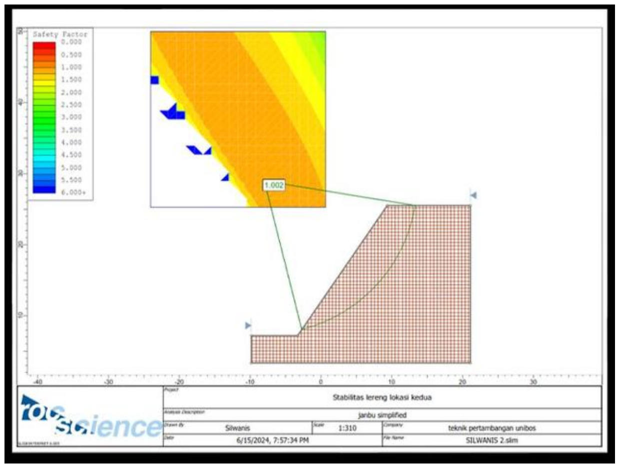

Figure 4. Simplified Janbu output for Site 2, showing a minimum factor of safety of 1.002.

Table 3. Deterministic stability results.

Indicator	Site 1	Site 2
Factor of safety	1.043	1.002
Shear strength	39.9476 kPa	47.3449 kPa
Mobilized shear stress	38.2853 kPa	47.2377 kPa
Strength-stress difference	1.6623 kPa	0.1072 kPa
Interpretation	Very limited margin	Near limiting equilibrium

Influence of Geometry, Weathering, and Water

The comparison between the two slopes demonstrates that stability is governed by the interaction of material strength and geometry rather than by a single parameter. Site 2 has higher cohesion and friction angle than Site 1, but its 55° inclination and greater height produce the lower factor of safety. Similar behavior has been reported in road-cut and motorway studies in which increased slope angle, toe modification, and unfavorable geometric configuration offset otherwise competent material properties (Xu et al., 2021; Çakıner et al., 2024). Indonesian limit-equilibrium studies also show that reducing slope angle or changing geometry can substantially increase factor of safety (Pasole et al., 2020; Arsyad & Anaperta, 2021; Prinanda & Anapert, 2021; Amin & Cahyono, 2024).

At Site 1, the gentler slope is counterbalanced by stronger weathering, higher observed saturation ranges, and field evidence of water. The independent rainfall record strengthens the hydroclimatic interpretation: Maros received 3,336 mm of rainfall in 2023, with 94.1% concentrated between November and April and particularly high monthly totals in January and February (Badan Pusat Statistik Kabupaten Maros, 2024). In weathered limestone, such prolonged seasonal water input may sustain infiltration through pores, joints, and altered surface zones, thereby creating conditions under which effective shear resistance can deteriorate.

This interpretation is consistent with rainfall and saturation studies reporting progressive reductions in slope stability as pore-water conditions worsen (Nguyen et al., 2020; Chen et al., 2021; Wang et al., 2021; Huang et al., 2022). Cahyono (2021) similarly reported a marked reduction in factor of safety between unsaturated and saturated highwall conditions, and Muzdalifah et al. (2022) showed persistently unsafe factors of safety under different groundwater assumptions. Nevertheless, the regional rainfall series was not measured at the slope locations and was not coupled to pore-water-pressure modeling; it therefore supports a hydrological plausibility argument rather than a causal claim of rainfall-triggered failure.

The extremely small strength-stress difference at Site 2 (0.1072 kPa) indicates that modest changes in pore-water pressure, erosion, additional loading, or progressive weathering could alter the modeled condition. Studies that compare limit-equilibrium and finite-element methods show that marginal slopes benefit from multi-method evaluation because differences in assumed failure mechanism and stress redistribution may affect the predicted critical condition (Mebrahtu et al., 2022; Rahman et al., 2023; Garo et al., 2024). Hussen et al. (2024) further found that saturation and method choice can materially influence predicted road-slope performance.

Engineering Implications and Study Limitations

The results justify prioritizing both locations for additional geotechnical assessment. Potential engineering measures include slope regrading, surface and subsurface drainage, erosion control, removal of loose weathered material, and retaining or reinforcement systems where required. However, stabilization should not be selected solely from the present deterministic factors of safety. Each candidate measure should be reanalyzed using revised geometry and hydrological assumptions, and the final design should satisfy the applicable Indonesian geotechnical requirements (Badan Standardisasi Nasional, 2017).

The present study has four main limitations. First, only two cross-sections were evaluated, so the results should not be generalized to the entire Maros-Bone corridor. Second, each model used a representative parameter set even though the physical-test results show material variability. Third, the added rainfall record is regional rather than site-specific and was not coupled to transient infiltration or pore-water-pressure calculations; seismic effects and traffic-induced dynamic loading were also not explicitly modeled. Fourth, the stability calculation relied on the Simplified Janbu method only. Future work should therefore include repeated sampling, discontinuity mapping, site rain gauges, piezometric monitoring, sensitivity or probabilistic analysis, and comparison with other limit-equilibrium or numerical methods. Such multi-method and hydrological assessments have improved interpretation of rainfall-sensitive and road-cut slopes in recent studies (Ongpaporn et al., 2022; Amarasinghe et al., 2024; Kinde et al., 2024; Yu et al., 2024).

Conclusion

The two investigated road-cut slopes are composed of weathered limestone but show different controlling conditions. Site 1 in Cenrana is approximately 15 m high with a 43° inclination and is characterized by advanced weathering, relatively high porosity, and surface-water indications. Site 2 in Mallawa is approximately 18 m high with a 55° inclination and is generally moderately weathered, with stronger alteration near the crest. The Simplified Janbu analysis produced factors of safety of 1.043 and 1.002, respectively, indicating very limited deterministic stability margins. The added 2023 hydroclimatic record shows 3,336 mm of annual rainfall over 132 rainy days, with 94.1% concentrated from November to April. This regional rainfall pattern does not modify the calculated factors of safety and should not be interpreted as direct evidence of rainfall-triggered failure; rather, it provides an independent context indicating that seasonal water input deserves explicit consideration in future site-scale monitoring and modeling. Site 1 appears particularly sensitive to the interaction of weathering and water-related conditions, whereas Site 2 remains especially critical because of its steeper and higher geometry. Final stabilization design should therefore be supported by site-specific rainfall and piezometric monitoring, parameter-variability analysis, comparison with other stability methods, and redesign simulations.

Acknowledgements

The authors gratefully acknowledge the Faculty of Mining and Earth Sciences, Universitas Bosowa, for supporting the field and laboratory activities. The slope-scale field, geometry, and laboratory dataset originated from Silwanis Suba's undergraduate research; the present article extends that dataset through an updated literature synthesis and an independent analysis of regional 2023 hydroclimatic data from BPS-Statistics of Maros Regency/BMKG

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