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Slope Stability Analysis with Rainfall and Earthquake Effects on Limestone Formations: A Case Study in Gorontalo Outer Ring Road Section, Indonesia

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ABSTRACT

The Gorontalo Outer Ring Road in Indonesia, a national route connecting three regions, is vital for enhancing economic development in the area. However, landslide problems are a significant concern in the Gorontalo region, threatening road safety and infrastructure stability. Landslide mitigation starts with slope stability analysis to provide recommendations for improving slope conditions and preventing landslides. This study aims to assess the Factor of Safety (FoS) values under the combined influence of rainfall and earthquakes at the study location. The methodology employed involves slope stability analysis that incorporates the effects of rainfall and earthquake-induced loads (Kh). Three conditions are analyzed: a condition without rainfall and earthquakes, a condition with rainfall effects, and a condition with earthquake coefficients. Slope stability analysis is carried out using Seep/W and Slope/W from Geostudio 2021 software. The results indicate that under normal conditions (without rainfall and earthquakes), the FoS value is 1.150, while under the influence of rainfall, the FoS value decreases to 0.818, and under the influence of earthquake coefficient, the FoS value becomes 0.746, indicating a significant risk of slope failure. These findings highlight that landslides in the study area are mainly triggered by the effects of rainfall and seismic activity, which significantly weaken the slope stability. On the other hand, the potential for landslides is considerably lower under dry conditions without seismic disturbances. The study underscores the importance of considering both rainfall and earthquake factors in landslide risk assessment and management.

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تحليل استقرار المنحدر مع تأثير هطول الأمطار والزلازل على تكوينات الحجر الجيري: دراسة حالة في مقطع الطريق الدائري الخارجي في جورونتالو، اندونيسيا

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الملخص

يعد طريق جورونتالو الدائري الخارجي في اندونيسيا، وهو طريق وطني يربط بين ثلاث مناطق، طريقاً حيويًا لتعزيز التنمية الاقتصادية في المنطقة. ومع ذلك، تشكل مشاكل الانهيارات الأرضية مصدر قلق كبير في منطقة جورونتالو، مما يهدد سلامة الطرق واستقرار البنية التحتية. يبدأ التخفيف من الانهيارات الأرضية بتحليل استقرار المنحدر لتقديم توصيات لتحسين ظروف المنحدر ومنع الانهيارات الأرضية . تهدف هذه الدراسة إلى تقييم قيم عامل الأمان (FoS) تحت التأثير المشترك لهطول الأمطار والزلازل في موقع الدراسة. تتضمن المنهجية المستخدمة تحليل استقرار المنحدر الذي يتضمن تأثيرات هطول الأمطار والأحمال الناجمة عن الزلازل(Kh) . تم تحليل ثلاث حالات : حالة بدون هطول الأمطار والزلازل، حالة مع تأثيرات هطول الأمطار ، وحالة مع تأثير معاملات الزلازل. تم إجراء تحليل استقرار المنحدر باستخدام Seep/W و Slope/W من برنامج Geostudio 2021. تشير النتائج إلى أنه في ظل الظروف العادية بدون هطول الأمطار والزلازل، تكون قيمةFoS 1.150 ، بينما انخفضت قيمة FoS إلى 0.818 تحت تأثير هطول الأمطار ، وأصبحت 0.746 تحت تأثير معامل الزلازل، مما يشير إلى خطر كبير لانهيار المنحدر . وتسلط هذه النتائج الضوء على أن الانهيارات الأرضية في منطقة الدراسة ناجمة في المقام الأول عن التأثيرات المشتركة لهطول الأمطار والنشاط الزلزالي، مما يضعف بشكل كبير استقرار المنحدر . من ناحية أخرى، فإن احتمالية حدوث الانهيارات الأرضية أقل بكثير في ظل الظروف الجافة دون اضطرابات زلزالية . وتؤكد الدراسة على أهمية مراعاة كل من عوامل هطول الأمطار والزلازل في تقييم مخاطر الانهيارات الأرضية وإدارتها.

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Introduction

Gorontalo Outer Ring Road (GORR) is a national road that connects three regions (Gorontalo Regency, Bone Bolango Regency, and Gorontalo City). The purpose of this infrastructure is to improve the economy of the three regions and connect the airport area with the port area. In addition, it reduces traffic in Limboto City and Gorontalo City. This development is considered important and has an impact on the programs of the Gorontalo Provincial Government. The location of the GORR road construction is in Gorontalo Regency, which has a length of about 15.9 km. The topographical conditions of Gorontalo Province make it a challenge in road construction, especially for slope excavation, as geologically the Gorontalo region was originally an active ancient volcanic caldera. The cessation of volcanic activity was caused by the formation of the Gorontalo faults (Pholbud et al., 2012). The formation of these faults has an impact on rock resistance and forms a steep topographic appearance that is prone to landslides.

Many studies on landslides have been conducted in Gorontalo Province. Research on the type and distribution of landslides in the Alo Watershed used field observations and geophysical methods (Lihawa et al., 2015). Bone Bolango Regency is one of the areas where landslides often occur, since the slopes in the area have a high degree of weathering and steep slopes exceeding 40° (Al-Jawadi, 2021). The reconstruction of landslide events and mechanisms at one point of the GORR segment has been carried out by Usman et al. (2018), which helps researchers to determine or identify slopes that have the potential for landslides along this road segment.

In this research, slope stability analysis is conducted at several slope locations on the GORR in the form of the influence of high rainfall and seismic data. Slopes that have the potential for landslides are analyzed for slope stability to obtain the safety factor of the slope. This analysis uses Geostudio Seep/W and Slope/W packages to determine the stability of the slope at the research location.

The research location is along the Gorontalo Outer Ring Road (GORR) planning section of Gorontalo Regency, Gorontalo Province. Gorontalo Regency is geographically bordered by North Gorontalo Regency (north), Boalemo Regency (west), Tomini Bay (south), and Gorontalo City (east). The GORR road section is part of the national road planning project of the Gorontalo National Road Implementation Center. Administratively, the research location is in two sub-districts, namely the Tibawa sub-district and the West Limboto sub-district. The location can be reached by motorized vehicle within about 45 minutes from Gorontalo City.

Based on the geology of the research site, there are three formations, namely the Bilungala Volcano Formation, Clastic Limestone Formation, and Lake Deposits. The Bilungala Volcanic Rocks, dated from the Middle Miocene to Early Late Miocene, consist of volcanic breccia, tuff, and lava. These formations, estimated to be from the Late Pliocene to Pleistocene (Trail et al., 1974, in Bachri and Ratman,1993), comprise calcarenite, calrudite, and coral limestone. Additionally, the Pleistocene to Holocene deposits consist of claystone, sandstone, and gravel (Bachri and Ratman, 1993). The research area is within the Clastic Limestone Formation, which is composed of calcarenite, calcirudite, and coral limestone. Calcarenite and calcirudite are white, compact, and contain fossils of algae and mollusks. Coral limestone is white and solid.

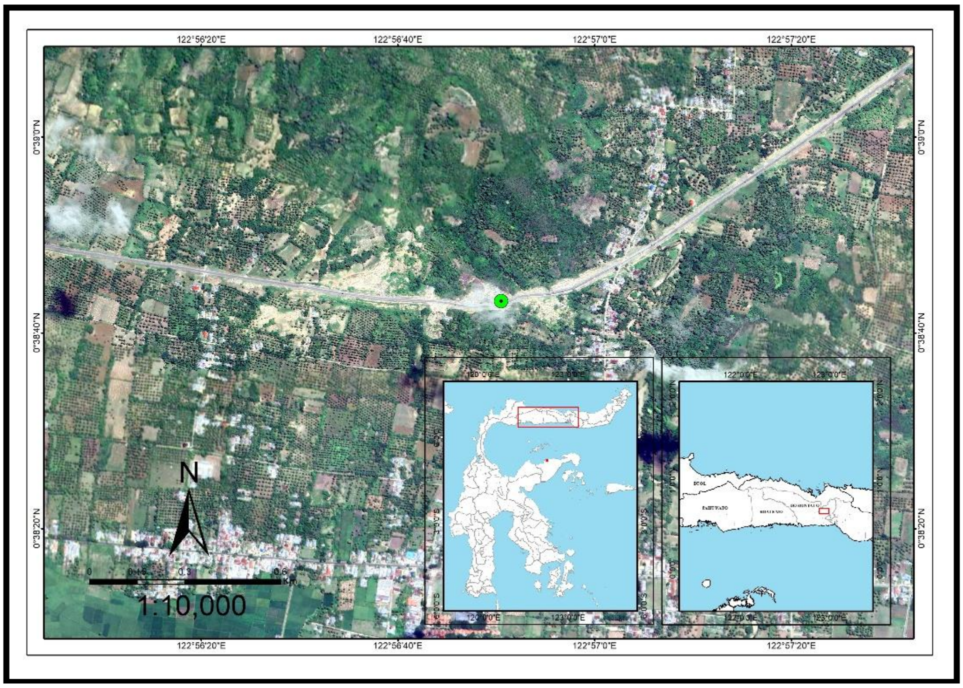

Fig. 1. Study area.

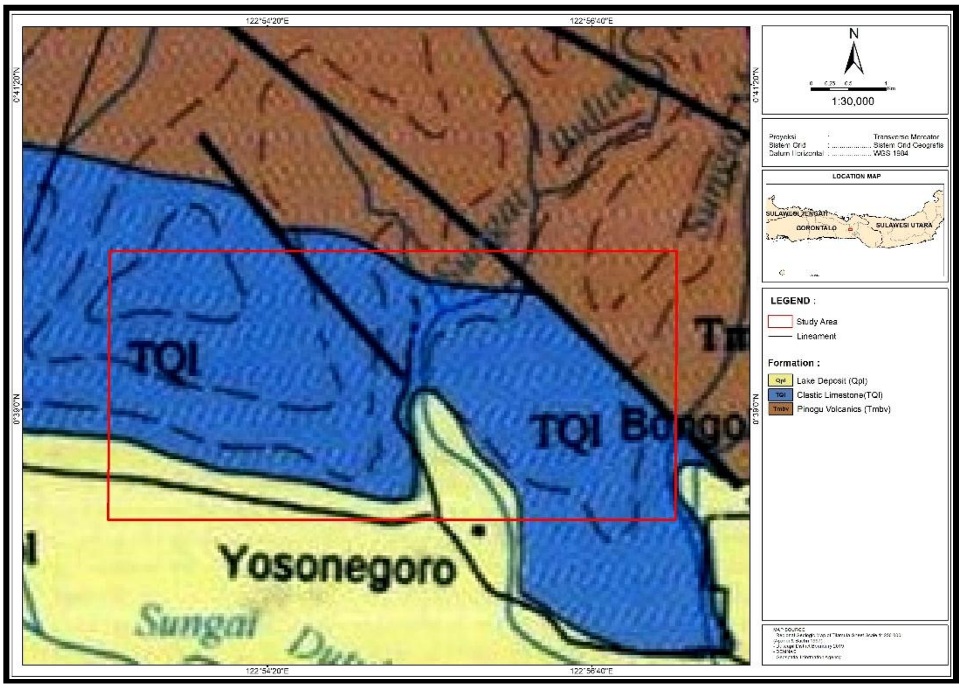

Fig. 2. Geological map of the study area

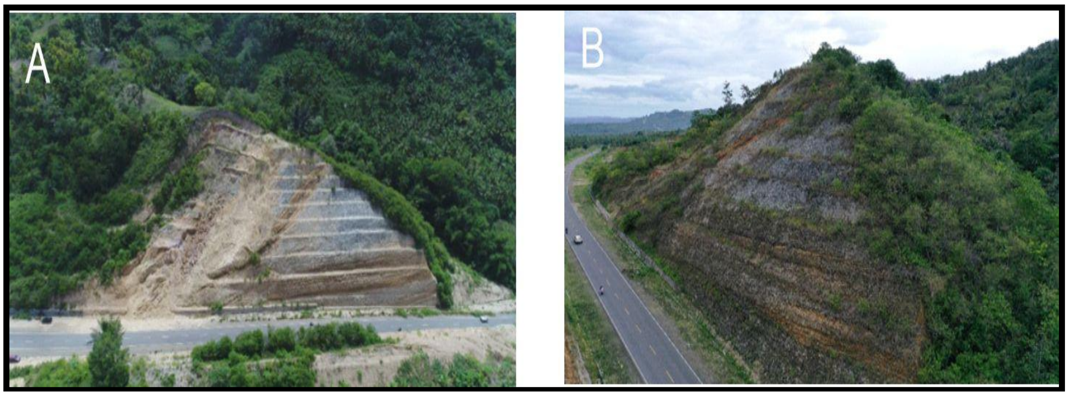

Fig. 3. Slope condition experiencing landslide in 2019 (A), Slope condition in 2024 (B).

Materials And Methods

The slope stability analysis in this study involves simulations under three conditions: slope stability analysis without the influence of rain and earthquakes, slope stability analysis under the influence of rain, and slope stability analysis under the influence of the seismic load coefficient.

Rainfall Modeling

Rainfall modeling using SEEP/W software is implemented to determine the infiltration conditions at the beginning of the rainfall and the development of infiltration over time. From the modeling, it can be explained how the infiltration process helps in landslide occurrence, how the saturation process takes place starting at the foot of the slope, then heading towards the head of the slope, and how the development is because of low, medium, and high rainfall conditions.

Rain analysis in this study is in the form of rain variations that will design rainfall modeling, where in the rain analysis, the groundwater level data are required to get the condition of the slope during rainfall. In this analysis, the groundwater level at the study site has a height of 2 m, taken from the Sulawesi II River Basin data that occurred in July 2024. To determine the average rainfall intensity that occurs in the study area, rain measurements are taken from the Limboto Raya Isimu watershed rain measurement station.

Seismic load coefficient

The determination of the earthquake load coefficient in this study is obtained either by using the pseudo-static method or by calculating using the earthquake load value. The calculation of the earthquake load coefficient value is carried out in this study on the earthquake acceleration map within 10 years, based on the 2017 Indonesian earthquake map (PusGen, 2017) (Fig. 4).

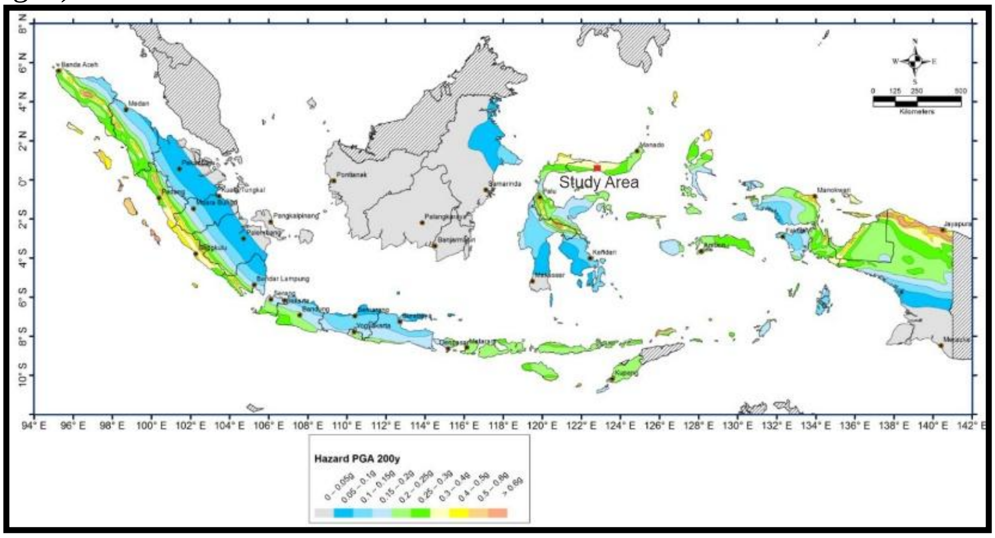

Fig. 4. Indonesia earthquake acceleration map in 2017 (PusGen, 2017).

Table 1: Site classification based on the correlation of field and laboratory soil investigations (Ministry of PUPR, 2015).

Site Class	V_s ($\frac{m}{Second}$)	N_{SPT}	S_u
SA (Hard Rock)	> 1500	N/A	N/A
SB (Rock)	750 to 1500	N/A	N/A
SC (hard, highly compacted soil and soft rock)	350 to 750	>50	≥100
SD (medium soil)	175 to 350	15 to 50 < 15	50 to 100 <50
SE (soft soil)	<175	<15	<50
	Or, any soil profile containing more than 3 meters of soil with the following characteristics: 1. Plasticity Index (PI) < 20 2. Water content (w) ≥ 40% 3. Undrained shear strength (Su) < 25 kPa		
SF (specialized soils, which require specific geotechnical investigations and specific response analysis)	Any soil layer profile that has one or more of the following characteristics: - Prone to failure or collapse due to seismic loads, such as easily liquefiable soils, highly sensitive clays, or weakly cemented soils. - Highly organic clay and/or peat (thickness H > 3 m). - Very high plasticity clay (thickness H > 7.5 m with Plasticity Index (PI) > 75). - Soft to medium-stiff clay layer with a thickness of H > 35 m and undrained shear strength (Su) < 25 kPa.		

Table 2: Amplification factor for PGA (FPGA).

Site classification (according to Table 1)	SPGA				
	PGA ≤ 0.1	**PGA = 0.2**	**PGA = 0.3**	**PGA = 0.4**	**PGA ≥ 0.5**
Hard Rock (SA)	0.8	0.8	0.8	0.8	0.8
Rock	1.0	1.0	1.0	1.0	1.0
Very Compact Soils and Soft Rocks	1.2	1.2	1.2	1.2	1.2
Medium Soil	1.6	1.6	1.6	1.6	1.6
Soft Soil	2.5	2.5	2.5	2.5	2.5
Special Soil	SS	SS	SS	SS	SS

Description: SPGA = The PGA value at the bedrock (SB), referring to the 2010 Indonesia Earthquake Map; SS = A location requiring geotechnical investigation and site-specific response analysis.

The peak acceleration at the ground surface can be obtained using the following equation:

$$PGAM = FPGA \times SPGA \quad (1)$$

Where: *PGAM* = Peak ground acceleration at the surface based on site classification; *FPGA* = Amplification factor for PGA; *SPGA* = PGA value at the bedrock (SB).

The data from the 10-year earthquake acceleration map based on the 2017 earthquake map allows for the calculation of the Peak Ground Acceleration (PGA) used in this study, which is a PGA of 0.3g (PusGen, 2017). The PGA is calculated concerning the specific site and considering amplification factors, including soil classification and site coefficient Factor Peak Ground Acceleration (FPGA). Soil classification is determined based on the average value of N-SPT with calculation procedures according to Indonesian Standards (SNI 8560: 2017). Based on the obtained data from the PUPR office, the soil classification in the study area is a medium soil site class (SD) with an average N-SPT of 36.32. The soil classification is then used to determine the site coefficient (FPGA), and then processed to obtain the earthquake load coefficient (Kh) used in the study. The earthquake coefficient (Kh) is expressed as:

$$Kh = \frac{PGAM}{g} \qquad (\mathbf{2})$$

Where: *PGAM* or Modified peak ground acceleration = adjusted peak ground acceleration considering the influence of site classification, expressed in gal (cm/s²); Kh = Seismic load coefficient representing the horizontal seismic load as a fraction of gravitational acceleration; $g =$ gravitational acceleration constant equals to 980 cm/s² (PUPR, 2004).

GeoStudio Seep/W and Slope/W

Geostudio Office is a software package for geotechnical and geo-environmental modeling, integrating SLOPE/W, SEEP/W allowing data transfer between modules (Pradana, 2012 in Siregar, 2019). This feature offers flexibility for both academics and professionals to solve various geotechnical and geo-environmental issues, such as landslides, dam construction, and mining. SLOPE/W is specifically designed to calculate the Factor of Safety (FoS) for soil and rock slopes, utilizing limit equilibrium methods (LEM) with different slip surface conditions, pore water pressures, soil properties, and loading conditions (Hidayah et al., 2012 in Siregar, 2019). Geostudio SLOPE/W 2018 has been widely applied in slope stability analysis, particularly using Slope/W and Seep/W. Essential soil parameters for input include cohesion, unit weight, and shear strength angle. The calculation process in GEOSLOPE/W follows the limit equilibrium method (LEM) by dividing the soil mass into slices, evaluating shear strength against driving forces.

Slope Stability Modelling

The limit equilibrium method (LEM) is used in slope stability modeling to determine the factor of safety (FoS) in landslide-prone areas (Geo-Slope International Ltd, 2021). One of the methods in LEM is the wedge method, which is applied to inhomogeneous soils and seepage flow in soils with irregular characteristics. FoS is defined as the ratio of the resisting moment to the collapse-causing moment. A simplified Bishop's method is used to calculate the forces around the soil wedge plane, resulting in getting FoS values close to field conditions (Liong and Herman, 2012).

FoS values can also be approximated through moment and force balance-based models (Geo-Slope International Ltd, 2002). The calculation of FoS is done through slope stability modeling using the GeoStudio-Slope/W program, which allows modeling of slope stability in different soil types, complex stratigraphy, landslide surface planes, and pore water pressure conditions (Geoslope Office, 2021). The slope geometry is based on a 2D soil model for slope stability analysis. In this analysis, Bishop's method is simplified by adding necessary parameters as shown in the following equation.

$$FoS = \frac{\sum_{n=1}^{n=p} (c' b_i + (w_n\, a - ub)\ tan\, \phi)}{\sum_{n=1}^{n=p} W_n \, sin\, an + \sum_{n=1}^{n=p} KhW} \qquad (3)$$

Where: FoS = the factor of safety; W_n = the n-th sectional weight (kN); c' = the effective soil cohesion (kN/m^3); ϕ = the internal friction angle (°); u = the pore water pressure; Kh = the seismic coefficient.

The results of this analysis are the distribution of potential sliding plane surfaces and the distribution of slope Factor of Safety (FoS) values for the study area in a 2D model. The analysis specifically focuses on rainfall and earthquake conditions.

The slope stability analysis carried out in this simulation is based on the state of safety factor (FoS) value analysis. This simulation illustrates the shape of the slope that has a slope height of 60 m and a slope of 56 °. The slope length is 73 m (Fig. 5).

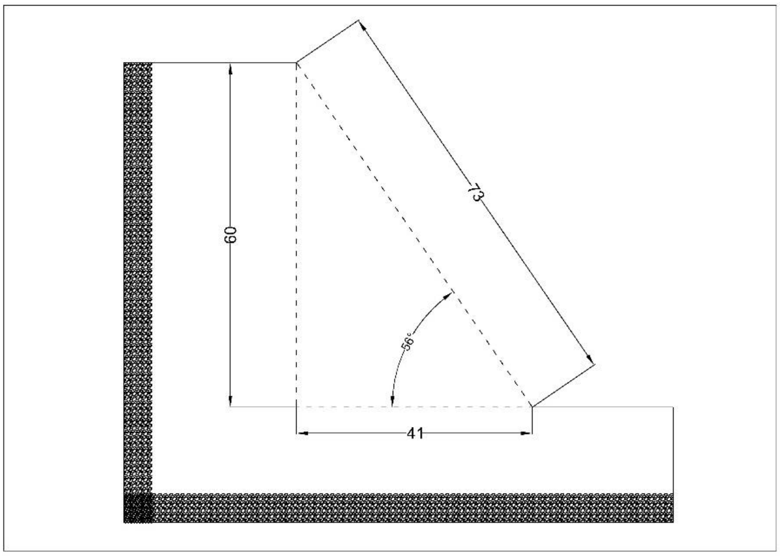

Fig. 5. Slope geometry in the study area.

Results

Mechanical soil properties

The soil parameters used in the analysis include specific unit weight (y), cohesion (c), inner friction angle (u), soil permeability (k), and moisture content (%) obtained through soil sampling at the research site and further processed using soil mechanics testing at the civil laboratory of Hasanuddin University.

The slope stability analysis in this study is conducted using modeling with the assistance of Geostudio 2021 software. To determine and calculate the Factor of Safety (FoS) of the slope, this study applied the Limit Equilibrium Method (LEM) based on the Morgenstern and Price method (1965). The slope stability modeling in this research includes three scenarios: conditions without the influence of rainfall and earthquakes, conditions with the influence of rainfall, and conditions with the influence of earthquakes, utilizing the Geostudio modules Seep/W and Slope/W. Mechanical soil parameters are incorporated into the analysis.

For the slope stability analysis under the influence of rainfall, the Seep/W program is used to perform transient analysis and determine the groundwater table (GWT). Subsequently, the results were input into Slope/W to calculate the Factor of Safety. This analysis is carried out from conditions without rainfall to conditions after rainfall.

For the slope stability analysis under the influence of earthquakes, Slope/W is used directly to calculate the FoS. By the seismic load analysis, the earthquake load coefficient is utilized, which had been calculated beforehand. The modeling provides a comprehensive assessment of slope stability under varying conditions of rainfall and seismic activity.

Table 3: Recapitulation of mechanical soil parameters for slope stability modelling.

Material	Soil Mechanic Parameter				
	γ_{sat}	c'	Φ	Water Content	Permeability (k)
	(Kn/m^3)	KPa	°	%	(cm/sec)
Soil	27	15	32	0,45	6.13E-06

Geological Survey

The slope is located at coordinates 0°38'43.22" N and 122°56'50.51" E. Based on field observations, the site has a slope inclination of 56° and a height of 30 m. This location is part of the clastic limestone unit, with lithology consisting of calcirudite and calcilutite layers.

Fresh calcirudite limestone appears gray. It is characterized by medium sand-sized grains (1/2 – 1 mm), sub-angular grain shape, well-sorted texture, open packing, and good porosity. These properties make calcirudite relatively more stable due to better cohesion and its ability to allow water drainage, thereby reducing pore pressure accumulation that can lead to slope instability.

Meanwhile, weathered calcilutite appears yellowish-brown and is composed of very fine-grained clay-sized particles ranging from 1/256 to 1/6 mm. The rock texture has well-sorted grains, closed packing having poor porosity and permeability. As a result, calcilutite tends to retain water, increasing pore pressure within the rock mass and potentially reducing the shear strength of the slope. Additionally, weathering further weakens its load-bearing capacity and increases the risk of slope instability, particularly during heavy rainfall or seismic activity.

Overall, slope stability is highly influenced by the characteristics of the underlying rock. The calcilutite layer, which is more susceptible to weathering and water accumulation, can form a weak zone that raises the risk of landslides, whereas the more stable calcirudite layer can help support the slope mass. However, under steep slope conditions and external factors such as heavy rainfall and earthquakes, the potential for instability remains a critical concern.

Slope Stability Analysis (Without the Effects of Rain and Earthquake)

The slope stability analysis in this simulation is conducted under conditions without external disturbances such as rainfall or seismic activity. The analysis focuses on determining the Factor of Safety (FoS) to represent the stability of the slope in its natural state. This simulation provides an understanding of the baseline stability conditions in the study area, offering insights into the potential slope behavior under undisturbed circumstances.

The results of the slope stability analysis reveal that, under conditions without rainfall or seismic influences, the FoS across the study area is distributed with a value of 1.150. This value indicates a relatively stable slope condition under normal circumstances (Fig. 6), serving as a reference point for further analysis involving external factors such as rainfall and earthquakes.

Slope Stability Analysis (With Rainfall Effects)

The slope stability analysis conducted in this simulation is based on the assessment of the Factor of Safety (FoS) under the influence of rainfall. In this analysis, rainfall data are incorporated to simulate the impact of precipitation on slope stability in the study area. The simulation represents the stability conditions of the slope by evaluating the Factor of Safety values at the study location.

The results of the slope stability analysis under rainfall conditions indicate that the distribution of the Factor of Safety (FoS) in the study area is 0.818 (Fig. 7).

Slope Stability Analysis (With Earthquake Effects)

The slope stability analysis in this simulation is conducted based on the Factor of Safety (FoS) assessment under the influence of the seismic coefficient. In this analysis, earthquake data are incorporated to simulate their impact on slope stability in the study area. This simulation represents the slope stability conditions by evaluating the Factor of Safety values at the study location.

The results of the slope stability analysis under the influence of the seismic coefficient indicate that the distribution of the Factor of Safety (FoS) in the study area is 0.746 (Fig. 8).

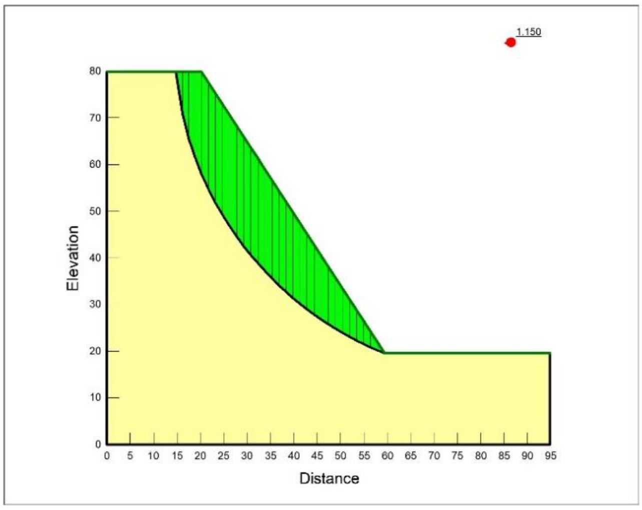

Fig. 6. Slope profile geometry illustration using GeoStudio-Slope/W software (without rainfall and earthquake effects).

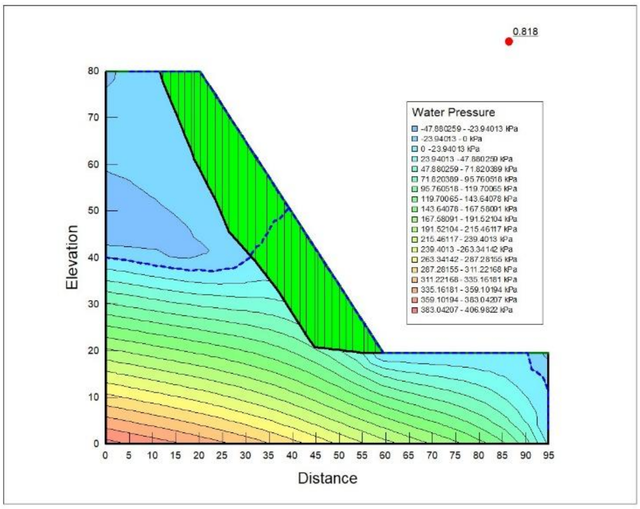

Fig. 7. Slope profile geometry illustration using GeoStudio-Slope/W software (rainfall effects).

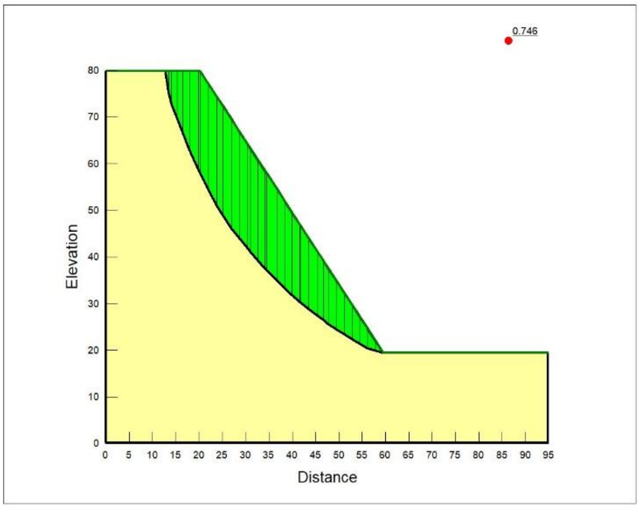

Fig. 8. Slope profile geometry illustration using GeoStudio-Slope/W software (earthquake effects).

Discussion

The study area is characterized by geological features, where most slopes consist of clastic limestone with alternating layers of calcirudite and calcilutite. According to Grabau's (1904) classification, calcirudite is composed of gravel-sized grains, while calcilutite consists of very fine grains resembling clay. The fine-grained nature of calcilutite has a significant impact on slope stability as it creates weak zones within the rock mass, which can act as initial failure points.

Under normal conditions without external disturbances such as heavy rainfall or seismic activity, slope stability analysis indicates that the Factor of Safety (FoS) remains within safe limits, as defined by the National Standardization Agency of Indonesia (SNI 8560:2017). This suggests that the slopes are generally stable and show no significant potential for landslides.

However, this situation changes drastically when heavy rainfall or earthquakes occur. The analysis reveals a significant decrease in the FoS values, with many slopes showing FoS values <1. Such conditions indicate severe slope instability. The reduction in stability is primarily caused by an increase in shear stress within the slope material that exceeds its shear strength. For instance, heavy rainfall infiltrates the slope material, increasing pore water pressure and reducing the soil's effective stress. Similarly, seismic activity generates dynamic forces that exacerbate slope instability by disrupting the balance of forces acting on the slope.

The combined effects of these factors, such as the infiltration of rainwater increasing pore water pressure and seismic vibrations adding driving forces, result in a loss of equilibrium between resisting and driving forces. This ultimately triggers slope failures or landslides. The situation is further exacerbated for slopes composed of calcilutite, as this material contains inherent weak zones that are more susceptible to deformation and displacement. Additionally, groundwater flow and seismic vibrations intensify the impact on the slip surface, further increasing the risk of slope instability (Al-Jawadi, 2024).

From these findings, it can be concluded that heavy rainfall and seismic activity are the primary triggers for landslides in the study area. The vulnerability of calcilutite to failure highlights the need for special attention in areas dominated by this rock type. Therefore, implementing appropriate mitigation measures is crucial to reducing the risk of landslides, especially under extreme environmental conditions.

Conclusion

The findings of this study indicate that the potential for landslides in the study area is strongly influenced by the type of rock present on the slopes, particularly clastic limestone comprising calcirudite and calcilutite. Calcilutite, with its clay-sized grains, contains weakness zones that significantly affect slope stability. Slope stability analysis under normal conditions, without the influence of rainfall or earthquakes, shows that the Factor of Safety (FoS) values generally meet the stability standards set by SNI 8560:2017, indicating stable slopes. However, under the influence of rainfall and seismic activity, the analysis reveals FoS values < 1, signifying increased soil shear stress exceeding its shear strength, leading to slope instability. These findings confirm that rainfall and earthquakes are the primary triggers of landslides in the study area, with calcilutite exacerbating the potential for failure. Therefore, landslide risk management in this region must account for these factors, with particular attention to the geological characteristics and weather conditions affecting slope stability.

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