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Slope Stability Analysis Using Foam Mortar as Lightweight Fill Material with Concrete Retaining Wall and Concrete Canvas Reinforcement on The Lakuan–Laulalang National Road, Tolitoli Regency

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Abstract
The Lakuan–Laulalang National Road at KM 529+600 in Tolitoli Regency is located in a hilly area with steep slopes and weathered soil that are highly susceptible to landslides, particularly during the rainy season. This study aims to identify the geotechnical characteristics of the slope and to evaluate the effectiveness of foam mortar as a lightweight fill material combined with a concrete retaining wall (DPT) and Concrete Canvas (CC) in improving slope stability. The analysis was carried out using the Finite Element Method (FEM) with RS2 software under three reinforcement scenarios. The results show that the existing slope condition has Factors of Safety (FS) of 0.89 under static conditions and 0.51 under seismic conditions. The use of foam mortar increases the FS; however, the combination of foam mortar, concrete retaining wall, and Concrete Canvas provides the most optimal performance, with FS values of 1.55 (static) and 1.12 (seismic) and minimal deformation. Therefore, this reinforcement system is considered an effective and technically feasible solution for landslide mitigation at the study site and may serve as a reference for similar geotechnical conditions.
Keywords: Slope stability; foam mortar; lightweight fill; concrete retaining wall; Finite Element Method (FEM).

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I. INTRODUCTION

Slope instability remains a major geotechnical challenge for road infrastructure in Indonesia, particularly in mountainous corridors with steep terrain and weathered soil formations. The Lakuan–Laulalang National Road at KM 529+600 in Tolitoli Regency represents a critical segment where edge-slope failures frequently threaten roadway integrity and traffic safety.

A landslide occurred at this location in April 2024, and due to limited budget allocation, only temporary protective measures were installed before permanent works could be executed. These constraints highlight the need for stabilization methods that are structurally reliable, rapidly deployable, and cost-efficient.

Foam mortar has a low density, is easy to apply, and can reduce lateral pressure on slopes. A case study on the Antapani Flyover in Bandung City shows that the use of foam mortar resulted in a settlement of 3.53 cm with a safety factor (SF) of 2.74, which is significantly better compared to conventional embankments that produced a settlement of 13.79 cm with an SF of only 1.36 [1].

Conventional countermeasures such as reinforced concrete retaining walls and bored piles, while effective, often require longer construction time. Foam mortar has emerged as a suitable lightweight embankment material due to its low unit weight and reduced lateral earth pressure. However, in high-risk slopes adjacent to ravines, additional reinforcement is necessary to ensure long-term stability.

Therefore, this study evaluates slope stability under three engineering scenarios: (1) foam mortar without reinforcement, (2) foam mortar with a concrete retaining wall, and (3) foam mortar combined with a concrete retaining wall and Concrete Canvas. The objective is to identify the most effective stabilization system based on factor of safety (FS) and deformation behavior under existing geotechnical conditions.

1.1.1 Mass Movement and Landslides

Mass movement of soil or rock on slopes is commonly referred to as landslides. A landslide occurs when soil, rock, or a mixture of both moves downslope under the influence of gravity, typically along a slip surface that represents the weakest zone of the slope. This phenomenon is prevalent in hilly regions with tropical climates. Landslides are classified as slope movements [6,37], and are defined as the sliding of material from a potentially unstable slope [14]. When the displacement becomes excessive, the event escalates into a natural disaster.

Landslides can be classified into several types: fall, topple, slide, slump, flow, lateral spread, and complex movement [11]. Landslides occur primarily due to gravitational forces acting on steep slopes. Two key factors contribute to their occurrence: predisposing factors, which make the slope susceptible to failure, and triggering factors, which initiate the movement. Common triggers include rainfall, topographic conditions, geological characteristics of the rock, and land-use practices [2].

1.1.2 Slope Stability

On an inclined or non-horizontal ground surface, the gravitational component tends to move soil downslope. When gravitational forces become sufficiently large to exceed the shear resistance that the soil can mobilize along the potential slip surface, slope failure may occur. The evaluation of this condition is referred to as slope stability analysis [15]. Slope stability can be assessed by calculating the factor of safety using data on soil physical properties, soil mechanics principles, and slope geometry. The primary objective of slope stability analysis is to ensure safe and economical design for construction projects [39].

1.1.3 Application of RS2-Rocscience

RS2 is a powerful finite element stress analysis software designed for both surface and underground mining applications. It is widely used in various engineering projects and supports functions such as support design, slope stability analysis, groundwater seepage, and probabilistic analysis. RS2 offers multiple support modeling options, including liner elements for shotcrete, concrete, steel sets, retaining walls, piles, multi-layer composite liners, geotextiles, and more.

Slope stability analysis is highly complex and involves numerous variables. The accuracy of the analysis depends significantly on the precision of input parameters that reflect actual field conditions. Detailed calculations and inherent uncertainties—represented through probabilistic parameters—make manual computation time-consuming and less optimal in terms of accuracy. Consequently, the use of slope stability analysis software has become increasingly widespread across industrial and educational sectors. However, certain prerequisites must be met before effective utilization of such tools.

1.1.4 Foamed Mortar Lightweight Material

Foamed mortar lightweight material is a mixture of water, cement, fine aggregate, and foam agent, with varying proportions depending on the target compressive strength. This material has a significantly lower density (γt) compared to conventional embankment materials, ranging from 0.6 kN/m^3 to 0.8 kN/m^3, whereas typical selected fill materials have a density of approximately 1.8 kN/m^3 and exhibit higher compressive strength [32].

In addition to its low density, foamed mortar offers ease of application similar to conventional concrete, as it does not require compaction and hardens naturally. During the hardening process, its compressive strength increases while eliminating active earth pressure or additional lateral loads.

Foamed mortar lightweight material provides several advantages and optimal applications [31], including:

1. Reducing embankment weight when used as fill material while maintaining adequate bearing capacity, making it suitable as a subgrade layer for pavement foundations.
2. Minimizing lateral earth pressure on structures such as bridge abutments, as the hardening process results in negligible lateral pressure.

1.1.5 Concrete Canvas (Geosynthetic Cementitious Composite Mats)

Concrete Canvas is a flexible, cement-impregnated fabric that hardens upon hydration, forming a thin, durable, waterproof, and fire-resistant concrete layer. Supplied in roll form, it enables rapid installation without the need for conventional mixing or heavy equipment. The material consists of four main components: a hydrophilic layer, fiber matrix, dry cementitious powder, and a PVC backing [28]. Concrete Canvas is available in three thicknesses—CC5, CC8, and CC13 (5 mm, 8 mm, and 13 mm respectively)—and is widely used for slope protection, ditch lining, and erosion control. Compared to traditional shotcrete, its application is up to ten times faster, cost-effective, and environmentally friendly. In certain cases, it can be combined with steel mesh and soil nailing for structural slope stabilization, making it an efficient solution for civil infrastructure projects across construction, mining, and energy sectors.

1.1.6 Retaining Wall

The most commonly used retaining wall type is the cantilever wall, typically constructed from reinforced concrete. The stability of a cantilever wall relies on the weight of the soil mass above the base slab, allowing the stem and base slab dimensions to be relatively thin. This type of wall is generally limited to a maximum height of approximately 8 meters [32].

1.2 Research Methodology

The study site is located along the Lakuan–Laulalang National Road at KM 529+600, Pinjan Village, Tolitoli Regency, Central Sulawesi Province. Geographically, the research area lies at Latitude 1.298659° S and Longitude 276.769144° E.

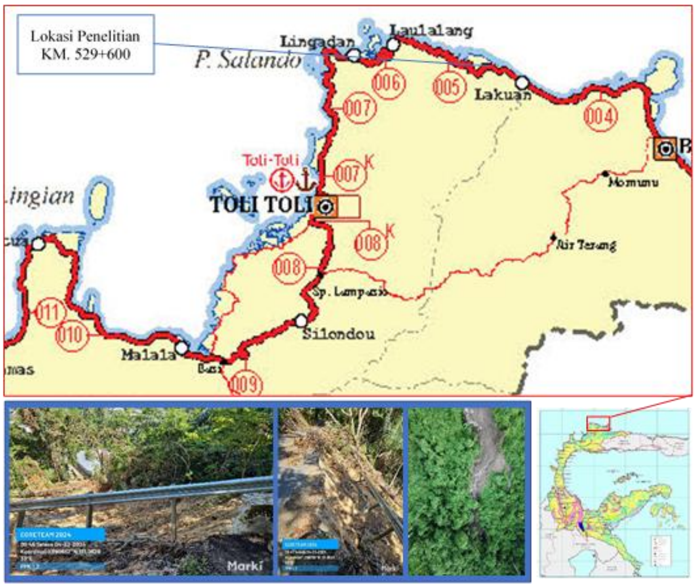

Figure 1: Research Location Map

The landslide occurred on the lower side of the road along a slope with an inclination of approximately 45 degrees. Field measurements indicate that the landslide length (or treatment width) is about 30 meters, with the depth of displaced material varying between 2 and 4 meters [22]. Based on the classification, the landslide is categorized as a circular slide, where the slope material moves downslope along a slip surface with a circular geometry [37].

1. Data Collection

In this study, primary data were obtained through field observations and direct interviews with relevant agencies. These included site documentation, field surveys to collect slope geometry and road geometric data, as well as geoelectrical testing.

Secondary data were gathered to support the analysis and provide additional context for problem-solving and determining alternative solutions. These consisted of technical planning documents, specifications of Concrete Canvas and foamed mortar used, laboratory test results for soil parameters, and geological data.

2. Data Analysis

This study employed a systematic approach to synthesize data from field surveys, laboratory tests, and literature review to establish design parameters for slope stability analysis using the Finite Element Method (FEM). The process began with a comprehensive review of soil mechanics, slope stability principles, FEM theory, and relevant standards [32]. Design parameters for non-soil materials, including foamed mortar, Concrete Canvas, and retaining walls, were identified based on unit weight, compressive strength, and elastic modulus.

Field and laboratory data were then processed, including soil classification using USCS, shear strength testing, and geoelectrical analysis with Wenner-Schlumberger configuration. Correlation between resistivity profiles and borehole data validated stratigraphy and identified weak zones. From this synthesis, shear strength and elastic parameters were determined for FEM modeling in RS2.

Subsequently, numerical analysis was conducted to evaluate slope stability under existing conditions and three reinforcement scenarios: substitution of fill with foamed mortar, combined with retaining walls and Concrete Canvas. Each scenario was analyzed for factor of safety (FS) and displacement. Finally, a comparative assessment identified the most effective and technically feasible reinforcement system as the recommended solution.

II. RESULT AND DISCUSSION

The results obtained are as discussed below

2.1.1. Geotechnical Characteristics of the Slope at Lakuan–Laulalang National Road KM 529+600

Laboratory tests at two borehole points revealed similar soil classifications, dominated by clayey sand (SC). Both locations exhibited low plasticity index, low cohesion, and relatively good internal friction angles, indicating soils with moderate bearing capacity and low to medium permeability. The main difference lies in variations of moisture content and porosity: BH-01 showed greater changes with depth, while BH-02 remained more stable. This suggests that BH-01 has more diverse saturation levels across layers, whereas BH-02 is more consistent. Although their technical characteristics are generally similar, BH-01 requires special attention due to its variable stratigraphic conditions [22].

2.1.2. Correlation of Geoelectrical and Borehole Data

The interpretation of the correlation between geoelectric testing data and drilling data can be illustrated as follows:

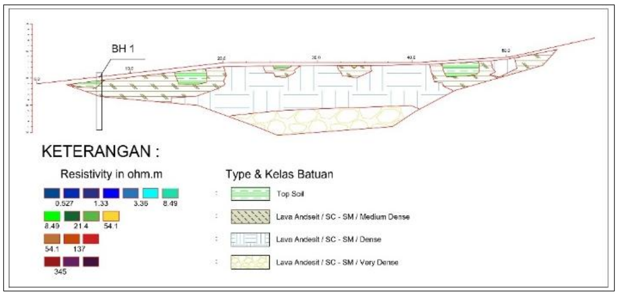

Figure 2: Interpretation of Correlation Between Resistivity and Drilling Data on Cross Section at KM 529+600

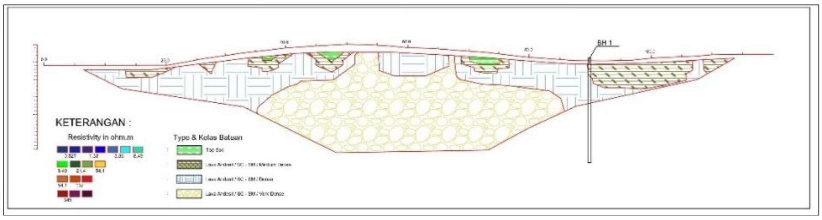

Figure 3: Interpretation of Correlation Between Resistivity and Drilling Data on Longitudinal Section at KM 529+600

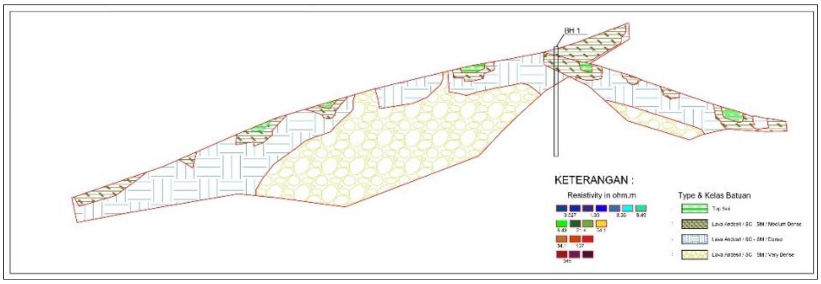

Figure 4: 3D Interpretation of Correlation Between Resistivity and Drilling Data at KM 529+600

The interpretation of geoelectrical modeling shows resistivity values ranging from approximately 0.5 to 345 Ωm. Zones with very low to low resistivity (±0.5–8.5 Ωm) are interpreted as topsoil layers, typically loose, fine-grained, and with high moisture content. Such saturated materials exhibit low resistivity due to electrolyte conduction through pore fluids [33].

Medium to moderately high resistivity values (±8.5–54 Ωm) indicate weathered andesite lava or materials with moderate porosity, classified as SC–SM (clayey sand to silty sand) with medium density. Weathered igneous rocks with fractures or pore fluids generally show reduced resistivity compared to fresh rock [33].

Higher resistivity zones (±54–137 Ωm) correspond to dense andesite lava with lower porosity and limited fluid conduction, resulting in increased resistivity. Very high resistivity zones (>137–345 Ωm) represent highly compact andesite or near-fresh rock conditions, where massive, dense, and minimally fractured igneous rocks restrict electrical conduction [33].

Table 1: Correlation of Resistivity Values, Lithology, and Material Classification.

Kedalaman (m)	Rentang Resistivitas (Ωm)	Litologi	Kelas Tanah/ Batuan	Tingkat Kerapatan	Karakteristik	Acuan Telford
0 - 1	0,5 – 8,5	Top Soil	-	Lepas	Material halus, kandungan air tinggi,konduksi elektrolit	Material jenuh air → resistivitas rendah
1 – 4	>8,5 – 54	Lava andesit, lapuk/berpori	SC-SM	*Medium Dense*	Porositas sedang, rekahan, terisi fluida.	Pelapukan dan Fluida menurunkan resistivitas
4 - 18	>54 – 137	Lava andesit, relatif kompak.	SC-SM	*Dense*	Lebih masif, porositas rendah.	Material lebih padat → resitivitas meningkat
18 - 30	>137 – 345	Lava andesit, sangat kompak.	SC-SM hingga kompak	*Very Dense*	Masif, minim rekahan dan fluida.	Batuan beku segar → resistivitas tinggi

2.1.3. Slope Stability Analysis Using RS2-Rocscience Application

1. Existing Condition

The results show a Safety Factor (SF) of 0.89 under static conditions and 0.51 under seismic conditions, both far below the minimum stability standard. Maximum deformation reached 0.17 m (static) and 0.14 m (seismic), indicating the slope is in a critical state, though not yet in total failure. Without reinforcement, the slope is highly susceptible to landslides, especially during heavy rainfall or seismic activity.

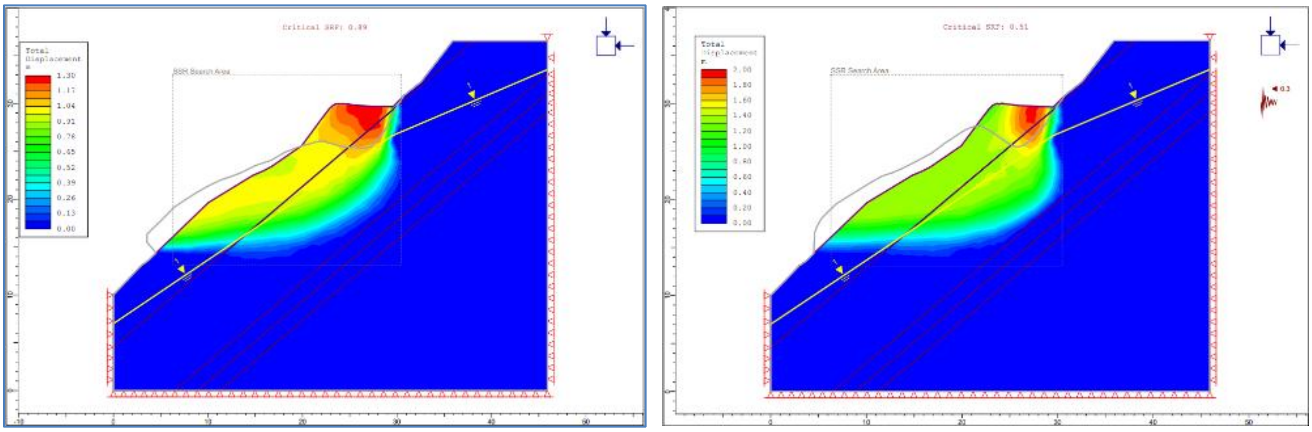

Figure 5: Safety Factor (SF) of Existing Slope Under Static and Dynamic Conditions

2. Reinforcement of Retaining Wall Using Ordinary Fill

Modeling and analysis of slope safety factor (SF) using RS2 software are as follows:

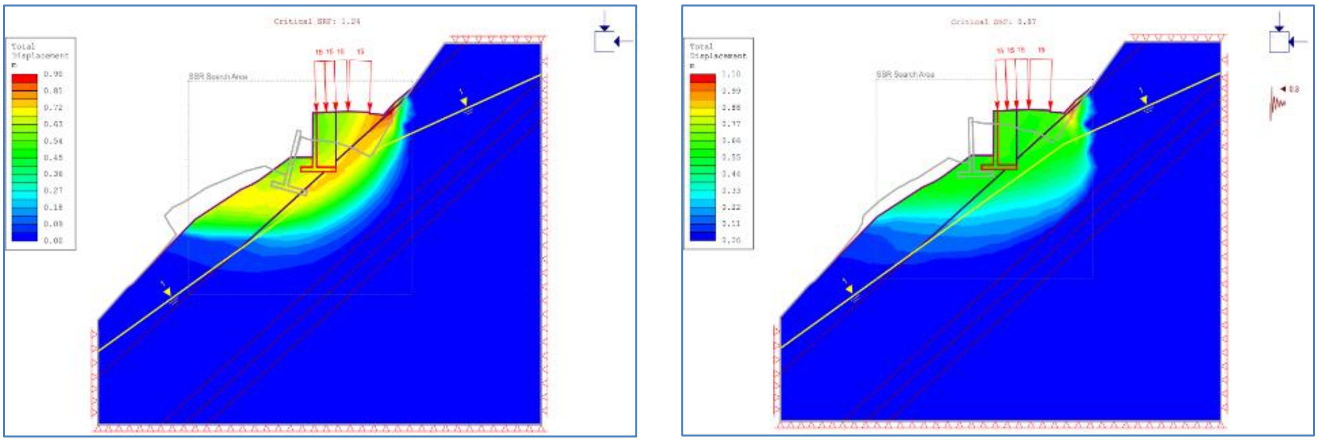

Figure 6: Safety Factor (SF) of Slope with Retaining Wall Reinforcement Using Ordinary Fill Under Static and Dynamic Conditions

The cantilever retaining wall shows safety factors of 1.503 for sliding (Safe), 1.53 for overturning (Not Safe), and 3.22 for bearing capacity (Safe). RS2 analysis indicates slope stability with SF = 1.24 and 0.90 m deformation under static conditions, dropping to SF = 0.87 and 1.10 m deformation during seismic loading. These results suggest the wall is stable against sliding and bearing but fails in overturning, while the slope is near failure. Design improvements are required; this study proposes foam mortar as a lightweight fill to reduce lateral loads and improve overall stability.

3. Lightweight Foam Mortar Without Reinforcement

Slope Modeling using Lightweight Foam Mortar Without Reinforcement Under static conditions, the Safety Factor (SF) increases to 1.27 with 0.50 m deformation. Under seismic conditions, SF drops to 0.95 with deformation reaching 0.70 m. These results indicate that foam mortar alone is insufficient to withstand dynamic loads, making structural reinforcement necessary.

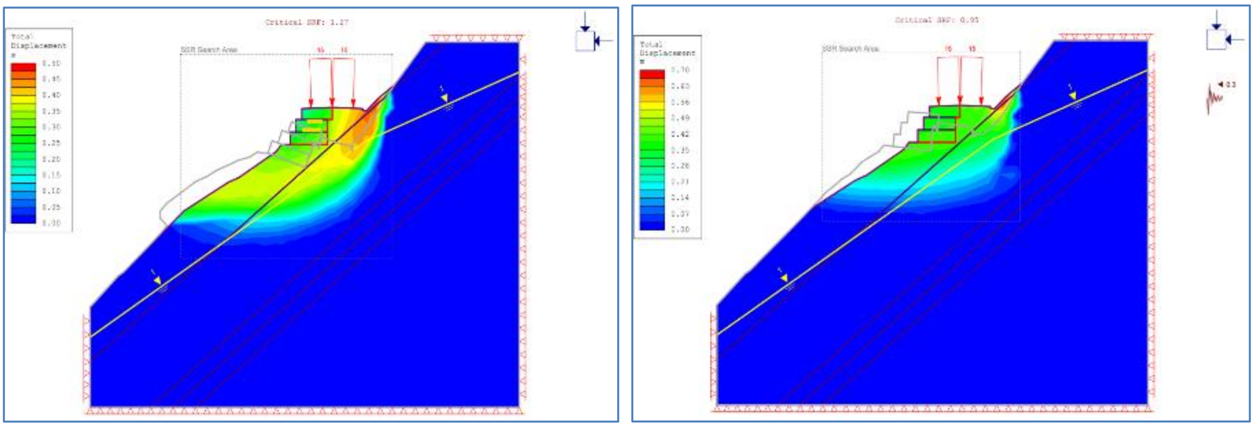

Figure 7: Safety Factor (SF) of Slope using Lightweight Foam Mortar without Reinforcement Under Static and Dynamic Conditions

4. Lightweight Foam Mortar With Retaining Wall Reinforcement

Slope Modeling using Lightweight Foam Mortar with Reinforced Concrete Retaining Wall Under static conditions, the Safety Factor (SF) reaches 1.46 with 0.40 m deformation, while under seismic conditions SF decreases to 1.03 with 0.50 m deformation. Compared to Scenario 1 (Foam Mortar without reinforcement), SF shows a marginal increase of 0.19 (from 1.27 to 1.46) under static conditions and 0.08 (from 0.95 to 1.03) under dynamic conditions.

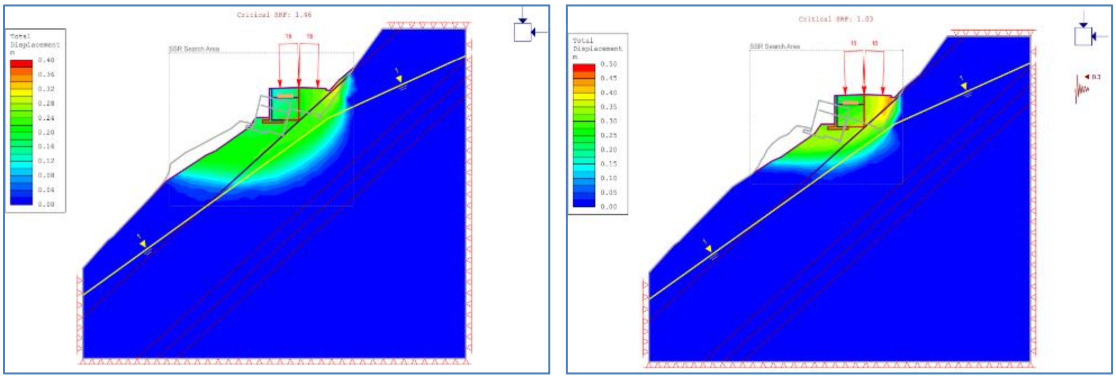

Figure 8: Safety Factor (SF) of Slope using Lightweight Foam Mortar with Reinforcement Under Static and Dynamic Conditions

5. Lightweight Foam Mortar With Retaining Wall Reinforcement and Concrete Canvas

Static analysis shows SF = 1.55 with 0.18 m deformation, meeting slope stability standards. The combination of materials and structural elements effectively reduces lateral loads and controls soil deformation. Under seismic conditions, FS reaches 1.12 with 0.40 m deformation, satisfying the minimum pseudostatic stability criterion (>1.1) and demonstrating that this reinforcement combination can maintain slope stability under seismic loading.

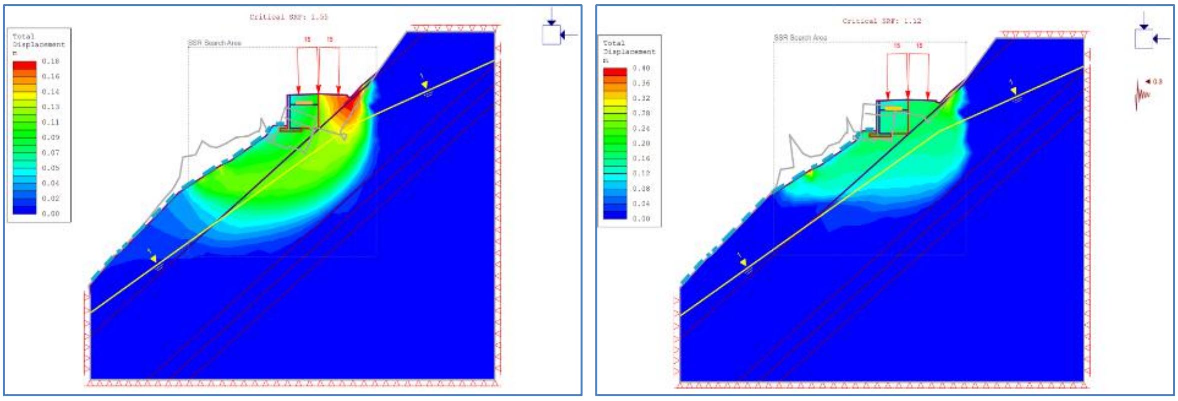

Figure 9: Safety Factor (SF) of Slope using Lightweight Foam Mortar with Reinforcement and Concrete Canvas Under Static and Dynamic Conditions

III. CONCLUSION

This study assessed slope stability on the Lakuan–Laulalang National Road using lightweight foam mortar as lightweight fill combined with reinforced concrete retaining walls and Concrete Canvas. The geotechnical investigation revealed a steep slope (±45°) composed of clayey sand with low cohesion, moderate permeability, and a highly weathered zone at shallow depth, making it prone to failure. Numerical modeling with RS2 showed that the existing condition is critically unstable, with Safety Factors (SF) of 0.89 under static and 0.51 under seismic conditions. Conventional reinforcement improved stability but remained below the minimum standard for dynamic loading. Foam mortar significantly reduced lateral pressure and deformation, and its combination with structural elements further enhanced performance. The best scenario—foam mortar combined with a concrete retaining wall and Concrete Canvas—achieved SF values of 1.55 (static) and 1.12 (seismic), meeting stability criteria and minimizing deformation. This integrated approach effectively addresses slope instability by reducing load, providing structural strength, and protecting against erosion and water infiltration, making it the most feasible solution for the study location.

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