Elephant Grass Root Reinforcement for Mitigating Earthquake-Induced Debris Flow in Saturated Volcanic Soil

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ABSTRACT

Indonesia's volcanic slopes are instable due to their high porosity, rapid saturation, and frequent seismic activity. Vegetation-based bioengineering offers a sustainable alternative to conventional structural solutions, but with rainfall and earthquake loading, effectiveness is reduced. This study examines how elephant grass roots (Pennisetum purpureum cv. Odot), influence the behavior and stability of saturated volcanic soil under dynamic conditions. Consolidated-Undrained (CU) triaxial tests, direct shear tests, pore-water pressure measurements, and shaking-table simulations of local earthquake acceleration, were examined throughout the experiments. Slope stability was evaluated using a pseudo-static approach to estimate changes in shear strength, pore-water pressure, Factor of Safety (FOS), and debris-flow length. The laboratory tests indicate that elephant grass roots increase soil cohesion by over 300% and reduce pore water pressure from 100 kPa to 60 kPa. Consequently, the FOS increased from 0.95–1.00 in non-vegetated slopes to 1.10–1.23 in vegetated conditions, and the debris flow length decreased by up to 18% demonstrating the significant biomechanical potential of elephant grass for stabilizing volcanic slopes under dynamic loading.

Keywords-elephant grass; bioengineering; debris flow; earthquake

I. INTRODUCTION

Volcanic soil has high permeability, which allows rainwater to be easily absorbed [1], but exhibits low shear strength under saturated conditions. The position of the groundwater table is critical to slope stability because increased pore water pressure reduces effective stress and shear resistance [2]. As water content increases, weak soil bonds and high porosity cause a decrease in shear strength, making volcanic soil prone to instability and failure under load [3]. The weakness of volcanic soil can lead to significant particle degradation under load, affecting its mechanical properties and stability. Engineering applications require careful consideration of these characteristics to prevent excessive deformation and ensure soil stability [4]. High rainfall intensity is the most common trigger for debris flow. For instance, a rainfall intensity of 35–40 mm in 1 h triggered debris flows in the Tatra Mountains and the Alps [5]. Similarly, in the Wenchuan region, rainfall with a peak intensity of 38.7 mm/h caused significant debris flow [6]. Debris flows can also occur due to earthquakes. Post-earthquake debris flows often originate from loose deposits left behind by seismic landslides. Subsequent rainfall reactivates these materials, causing high-speed flows that can travel long distances [7]. Efforts to reduce the risk of landslides on mountain slopes can be broadly categorized as structural or non-structural, with each approach having advantages and challenges. Structural measures are highly effective at stabilizing slopes against static and dynamic loads [8], including physical constructions designed to control or reduce the impact of landslides and soil erosion. Standard structural measures include Sabo dams, gabions, and retaining walls [9]. Vegetation-based slope stabilization is a more environmentally friendly and cost-effective alternative to structural engineering methods, using the mechanical and hydrological properties of plant roots to significantly improve slope stability while complying with environmental sustainability principles. However, careful selection of plant species and implementation tailored to site conditions, soil type, slope gradient, and rainfall intensity are essential to maximize its effectiveness [10]. Bioengineering techniques that use local plant species, such as jatropha and lemongrass, have shown promising results in slope stabilization [11]. The type of force that roots develop during shear is significantly influenced by their orientation. Roots located in front of the tree trunk relative to the shear direction tend to create compressive forces due to their low orientation angle. In contrast, roots located on the sides and behind the trunk predominantly develop tensile forces [12]. The root deflection angle also plays a significant role. Roots with higher deflection angles increase friction stress at the root-soil interface, thereby increasing the shear resistance of the soil [13]. Root density and Root Area Ratio (RAR) generally decrease with soil depth, affecting the composite shear strength of roots and soil [14]. Concentrating roots in the upper soil layer provides significant additional cohesion and enhances slope stability. Elephant grass is known for its rapid growth and ability to produce significant biomass in a short period of time [15]. The roots of elephant grass significantly increase soil cohesion and internal friction angle, both of which are important for slope stability. Laboratory tests show that adding elephant grass roots to soil samples increases cohesion. Optimal strengthening is observed at a root content of 0.3% and a root length of 3 cm [16]. Research in Malang, Indonesia demonstrates that vegetation roots can significantly increase slope stability by improving FOS due to their mechanical properties and density [17]. However, this research focused primarily on static conditions, not considering seismic loads. Research in Chile analyzed the role of vegetation in slope stability under static and pseudo-static (seismic) conditions. It was shown that tree roots contribute to apparent cohesion and reduce displacement caused by earthquakes [18]. Authors in [19] developed a vegetation slope stability model incorporating hydro-mechanical parameters, such as root cohesion and soil water content, to evaluate the impact of vegetation on slope stability, showing that vegetation significantly increased the slip limit ratio FOS, compared to bare slopes. Numerical analyses and experimental results indicate that a combination of elephant grass and vetiver grass can reduce erosion by over 90% on slopes, thereby significantly improving stability [20]. While the study discusses the general benefits of elephant grass roots in improving soil stability, the behavior when subjected to earthquake loads after rainfall, particularly with regard to Odot elephant grass (Pennisetum purpureum cv. Odot), remains unclear. This study presents an experimental approach to testing the reinforcement mechanism of elephant grass roots on the shear behavior of water-saturated volcanic soil. This study focuses on the combined effects of high rainfall–induced soil saturation and seismic loading, which represent critical triggering factors for slope instability on volcanic terrains in Indonesia, where slope gradients commonly exceed 40°. Under these conditions, slopes are highly susceptible to shallow landslides and debris flows. Particular emphasis is given on the behavior of saturated volcanic soil reinforced by grass roots during earthquake loading. A pseudo-static laboratory approach was used to evaluate changes in shear strength, pore-water pressure, FOS, and debris-flow potential. These findings aim to provide a scientifically grounded, practical reference for environmentally sustainable and economically viable, vegetation-based slope mitigation strategies in Indonesia's active volcanic regions, particularly in remote areas where implementing conventional structural countermeasures is challenging.

II. METHODOLOGY

A. *Location and Sampling*

Soil samples were collected from the slopes of Mount Abang in the Batur Caldera of the Kintamani District in Bali Province. The elevation in this area ranges from 1,110 m to 1,517 m above sea level. The slope material consists predominantly of loose, brown, sand-clay deposits extending along the hillside. The slope inclination ranges from 40° to 80°, and the area is bordered by hills that are part of the Batur Caldera structure. The lithology comprises slightly to moderately weathered lava, volcanic breccia, and tuff breccia. This location was selected due to its young volcanic ash layers, which have a loose structure, high permeability, and frequent seismic activity. Such volcanic lithological conditions are highly susceptible to landslides and debris flows. Soil sampling was conducted at depths of 0.5–1.0 m to represent the active root zone. Authors in [21] showed that vegetation significantly increases soil shear strength, such as Dicranopteris linearis roots, by up to 11.53%. Additionally, elephant grass roots increased the shear strength of tropical soils. This species is most commonly cultivated in tropical regions, such as Indonesia. It has a deep fibrous root system reaching more than 1.2 m, high root density, tolerance to waterlogging, and rapid growth. The elephant grass samples used in this study were cultivated from seedlings prepared in the Soil Mechanics Laboratory, specifically the mini or Odot variety.

B. *Laboratory Testing*

Soil property tests indicate that the sample is classified as silt with fine sand. The physical analysis shows a natural water content of 21%, a saturated condition (γ_{sat}) of 34%, a particle specific gravity of 2.63, and a plasticity index of 8%. These results indicate that the soil exhibits non-plastic behavior. CU triaxial tests were conducted according to standard procedures specified in ASTM D7181 [22] and SNI 03-2455-2004 [23] to determine the shear strength parameters, such as the internal friction angle (φ'), effective cohesion (c'), and the stress-strain relationship of the soil samples. The tests were performed under two conditions: soil without vegetation (control) and soil reinforced with three-month-old elephant grass roots. The CU triaxial test on saturated soil without roots yielded an effective cohesion (c') of 0.10 kPa and an internal friction angle (φ') of 29.54°. In comparison, the effective cohesion (c') was 0.20 kPa and the effective friction angle (φ') was 31.44°. Soil samples reinforced with elephant grass roots exhibited improved shear strength. Cohesion increased to 0.28 kg/cm², and the internal friction angle rose to 33.57°. The effective cohesion (c') increased significantly, reaching 0.71 kg/cm², while the effective friction angle (φ') increased to 36.15°. Additional shear strength testing was conducted using a direct shear apparatus at normal stress levels of 50 kPa, 100 kPa, 150 kPa, and 200 kPa. The shear strength parameters (cohesion and internal friction angle) were derived using the Mohr-Coulomb failure criterion. Unconfined-Undrained (UU) triaxial tests were also performed to determine the relationship between pore water pressure and deviator stress during loading. Triaxial test specimens were prepared in a cylindrical shape, measuring 38 mm in diameter and 76 mm in height, in accordance with standard laboratory practice and relevant testing standards. The plant roots were distributed throughout the entire height of the soil specimen, rather than being confined to the surface layer [24]. During preparation, the soil was carefully compacted in layers and the elephant grass roots were mixed and oriented to resemble a natural fibrous root network within the active root zone. The earthquake acceleration used in the experiment was generated by adjusting the shaking table motor to 5.5 Hz. This configuration was designed to produce vibration accelerations that approximate the characteristics of the 2021 earthquake in Abang Batudinding Village, as shown in Figure 1. To ensure compatibility between the generated acceleration and actual earthquake conditions, an accelerometer was installed on the shaking table to record the vibration response directly. The recorded acceleration data were analyzed to produce a graph of the acceleration during testing, which provided a more accurate understanding of soil movement phenomena and the test model's response. The shaking table frequency was adjusted based on historical earthquake records, with maximum vibration occurring for approximately 3–5 s.

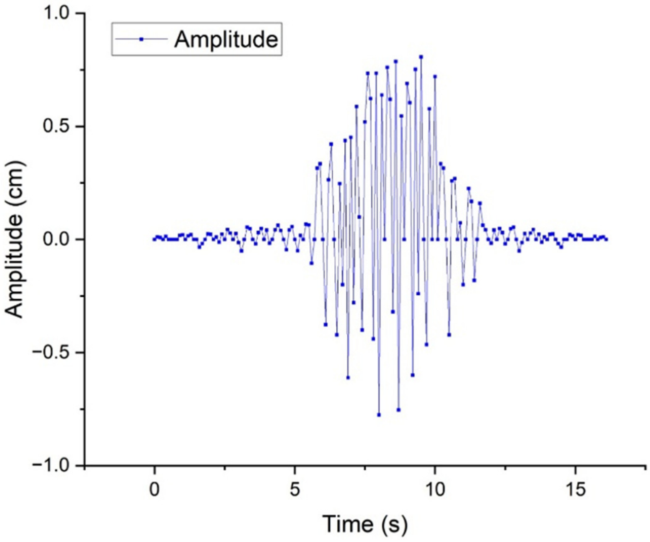

Fig. 1. Earthquake acceleration setup on the shaking table.

C. Analysis

Slope stability evaluations involving vegetation, such as elephant grass (Pennisetum purpureum), commonly use an approach integrating statistical analysis and hydro-mechanical modeling. The collected data are incorporated into analytical or numerical models, such as steady-state or transient solutions of the Darcy-Richards equation, to calculate the slope FOS for mechanical contributions, including root cohesion (c_r), and hydrological effects, such as matric suction (ψ):

$$FOS = \frac{(c' - u_w \backslash tan\{\phi^b\})}{\left\{\left[\gamma_d(H_0 - Z) + \gamma_w \int_z^{H0} \theta \, dZ\right] sin\phi \, cos\phi\right\}} + \frac{tan\{\phi'\}}{tan\{\phi\}} \quad (1)$$

where γ_d is the dry unit weight of the soil, γ_w is the unit weight of water, z is the depth, and ϕ is the slope angle. The depth addressed in this study is the root zone depth. The root distribution of elephant grass typically forms a triangular pattern [25] in this depth range, as portrayed in Figure 2.

Fig. 2. Root system structure of elephant grass.

III. RESULTS AND DISCUSSION

A. Influence of Vegetation on Soil Shear Strength

Testing was carried out by collecting soil samples to obtain cohesion values and pore-water pressure at each growth interval of the elephant grass. The cohesion and pore-water pressure values were then measured and analyzed according to predetermined plant ages. Figure 3 displays an inverse relationship between soil cohesion and pore-water pressure as the root index increases. Soil cohesion increases from approximately 8 kPa at a root index of 0 to over 30 kPa at a root index of 4, reflecting the root system's contribution to soil mass stabilization through root reinforcement and enhanced shear resistance. As root density and development increase, the soil structure becomes more stable. Roots resist shear forces and bind soil particles, improving the integrity of the soil matrix. Conversely, pore-water pressure tends to decrease with an increasing root index, indicating that the root network enhances micro-drainage and reduces pore-water pressure accumulation, which could otherwise weaken the soil. Therefore, root development plays a significant role in improving soil stability on slopes. On the other hand, pore water pressure shows a significant decrease, from about 100 kPa at a root index of 0 to approximately 60 kPa at a root index of 4. This reduction in pore water pressure is associated with the roots' ability to enhance infiltration, accelerate drainage, and absorb water through transpiration. The pore water pressure test involved taking measurements at various soil depths to compare conditions between non-vegetated and elephant grass-covered slopes. The aim of this measurement is to determine the influence of root presence on the distribution of pore water pressure within the soil profile. This reveals the differences in stability levels between the two slope conditions, as shown in Figure 4.

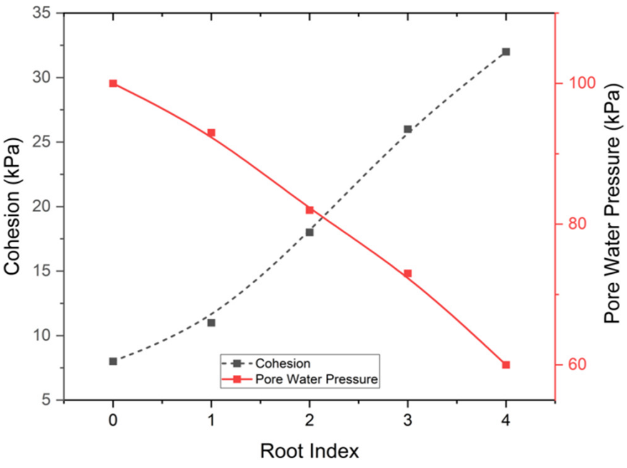

Fig. 3. The relationship between increased cohesion and reduced pore water pressure due to root growth.

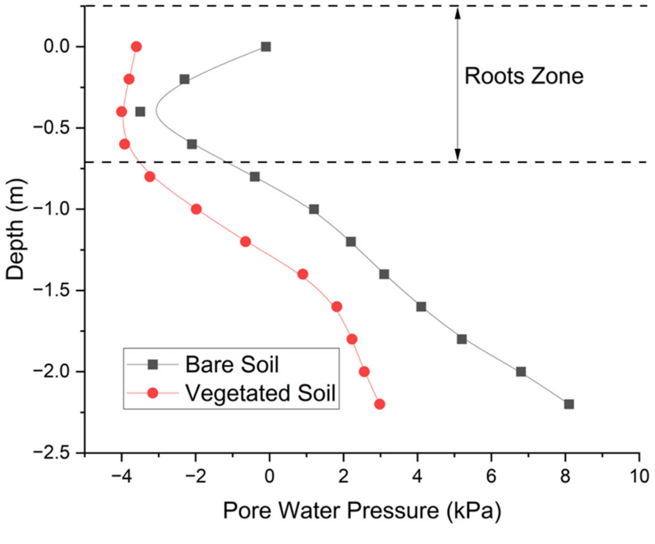

Fig. 4. Pore water pressure from the test results.

The reduction in pore water pressure contributes directly to an increase in the soil's adequate shear strength, thereby enhancing slope stability. Overall, the graph confirms that root system development significantly affects slope stability by increasing cohesion and reducing pore water pressure. These effects enhance the stability of both natural and engineered slopes. The observed increase in vegetative cohesion, up to 300%, is due to the bonding and frictional interactions between the root system and the soil matrix. These interactions function as a micro-reinforcing net. This mechanism, known as apparent cohesion, improves the stability of shallow soil layers. Additionally, microscopic observations of the samples reveal that elephant grass roots encourage the formation of soil particle aggregates, thereby increasing local density and interparticle roughness. This process explains the rise in c' values as vegetation matures.

B. Influence of Vegetation on Factor of Safety

Analysis of the FOS indicates that vegetation, particularly elephant grass, significantly increases slope stability. Under non-vegetated conditions (BS_45 and BS_60), FOS values decrease within the range of approximately 0.95–1.05 at various depths, as presented in Figure 5.

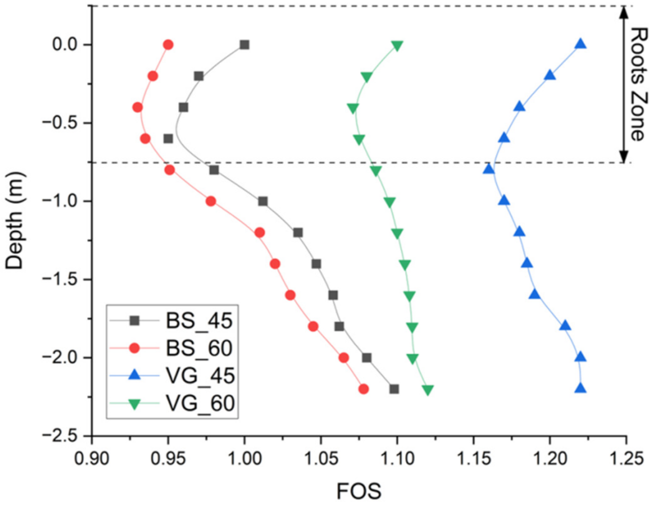

Fig. 5. FOS obtained from the model test scenarios.

This indicates that the slope is approaching its stability threshold, especially at shallow depths. These areas are more sensitive to changes in pore water pressure and dynamic earthquake loading. This observation aligns with previous research indicating that slopes without root systems are more susceptible to reductions in shear strength due to seismic vibrations and increased pore water pressure. These calculations are also consistent with studies on the influence of vegetation on landslides, which show that decreasing slope inclination increases the FOS value. Therefore, vegetation is more effective at enhancing stability on relatively gentle slopes [26]. For slopes reinforced with vegetation (VG 45 and VG 60), the FOS values consistently increase across all depths, even under an earthquake acceleration condition of 5.5 Hz. On the 45° slope, the FOS ranges from 1.15 to 1.23, indicating enhanced resistance to potential slope failure. This improvement is attributed to elephant grass roots, which reinforce the soil through anchoring and binding mechanisms while reducing pore water pressure through increased infiltration and transpiration. For the 60° slope, vegetation still significantly increases the FOS value, though the overall values are slightly lower than those on the 45° slope. The FOS for VG 60 ranges from 1.10 to 1.18, which is substantially higher than the range of 0.92 to 1.00 observed in the non-vegetated condition. These results demonstrate that vegetation can enhance slope stability under steeper and more critical geometric conditions. However, the smaller magnitude of improvement relative to the 45° slope suggests that the effectiveness of vegetation is influenced by slope angle and root-zone depth.

C. Discussion

The FOS generated by grass roots was found to be comparable to that of tree root systems. An increase in FOS occurs with increasing root length, reaching up to 33% at a depth of 2 m [27]. However, elephant grass has limited root length because its root system develops mainly within the surface layer and spreads laterally. Vegetation is most effective on slopes with moderate inclines. On steeper slopes, the root reinforcement effect becomes more pronounced; however, its marginal contribution decreases as root depth exceeds a certain threshold [28]. Additionally, FOS decreases with increasing slope angle, indicating reduced stability on steeper slopes [29]. The results of the Length of Debris Flow (LDF) test under a 5.5 Hz shaking table acceleration, presented in Table I, show that slopes without vegetation (BS_45 and BS_60) have lower FOS values and produce longer LDFs. On the 45° slope, an FOS of 0.980 results in an LDF of approximately 0.957 m. In contrast, on the 60° slope, an FOS of 0.951 results in an LDF of 0.983 m. These results suggest that less stable slopes (characterized by FOS <1.0) tend to experience longer debris movement because the soil becomes more susceptible to weakening and loss of bearing capacity under dynamic earthquake loading. These findings are consistent with the results in [30, 31], showing that seismic energy strongly influences LDF, and vegetation can act as a retention element that helps restrain or reduce such flows.

TABLE I. DEBRIS FLOW TESTING RESULTS DURING THE EARTHQUAKE

Scenario	FOS	LDF (m)
BS_45	0.980	0.957
BS_60	0.951	0.983
VG_45	1.160	0.797
VG_60	1.086	0.863

Under vegetated slope conditions (VG 45 and VG 60), FOS values increase significantly, reducing LDF. On the 45° slope, an FOS of 1.160 produces an LDF of 0.797 m, and on the 60° slope, an FOS of 1.086 produces an LDF of 0.863 m. These results confirm that vegetation strengthens slopes and reduces the potential for mass movement. Further analysis reveals a negative correlation between FOS and LDF: the higher the FOS value, the shorter the LDF. A simple linear approach to the data expresses the general relationship between FOS and LDF as:

$$LDF = (580 - 890FOS + 227.13\,F)/1000 \qquad (2)$$

where LDF is the debris flow length (m), FOS is the safety factor, and *F* is the vibration frequency (Hz).

IV. CONCLUSIONS

The presence of elephant grass significantly increases the shear strength of saturated volcanic soil. This is indicated by an increase in cohesion of over 300% and a reduction in pore water pressure from approximately 100 kPa to 60 kPa as the root index increases. The combination of mechanical reinforcement by roots and improved drainage-transpiration capacity plays a significant role in stabilizing shallow volcanic slopes. Improved soil strength due to vegetation directly increases the Factor og Safety (FOS). Without vegetation, the FOS ranges from 0.95 to 1.00, indicating a high potential for instability, particularly on steep slopes. After planting elephant grass, the FOS increases to between 1.10 and 1.23, demonstrating much greater stability, even under dynamic earthquake loading at 5.5 Hz. These results highlight the effectiveness of bioengineering in reducing the vulnerability of volcanic slopes. The Length of Debris Flow (LDF) model tests reveal a negative correlation between slope stability and debris runout distance. Slopes without vegetation produce longer LDF values (0.957–0.983 m), whereas vegetated slopes produce shorter LDF values (0.797–0.863 m). Vegetation effectively reduces the potential for material runout by increasing slope stability and mitigating the weakening of slopes caused by seismic loading. The modeling results indicate a linear equation: LDF = (580 - 890 FOS + 227.13 F)/1000, to represent the behavior of vegetation-based debris flow mitigation.

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