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Behavior of Saturated Volcanic Soil Slopes with Grass Roots Under Seismic Response

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Abstract – *Landslides on mountain slopes triggered by rainfall and earthquakes pose a significant risk to the slopes on Bali Island. This study examines the behavior of saturated volcanic soil reinforced with a combination of elephant grass and vetiver roots under earthquake forces. The methodology includes triaxial testing on vegetated soil and model testing to assess the reduction in landslide-prone areas due to vegetation. Triaxial test results indicated increased soil cohesion and internal friction angle when reinforced with vetiver and elephant grassroots. Cohesion in non-vegetated soil was measured at 0.20 kg/cm^2, which increased to 0.65 kg/cm^2 with root reinforcement. Model testing results aligned with consolidated undrained triaxial tests, demonstrating that the combination of vetiver and elephant grass reduced the landslide area by up to 64.1% on 45-degree slopes and up to 52.1% on 60-degree slopes.* ***Copyright © 2024 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Bioengineering, Volcanic Soil, Vetiver, Elephant Grass, Seismic*

Nomenclature

F_i	Safety factor
N_i	Normal forces
l_i	Length of the slip surface
T_{ti}	Shear strength
c_i	Cohesion
C_{ri}	Shear strength to the presence of roots
φ	The angle of soil friction
u_i	Pore water pressure
l	Base length of slip surface
c_r	Additional cohesion
θ	The angle of shear distortion
t_r	Total of mobilized tensile stress

I. Introduction

A field assessment on the eastern side of Mount Batur Caldera in Cemara Landung Village following the landslide event on October 18, 2021, identified the area as highly prone to landslides (Fig. 1) [1]. The landslide was triggered by an earthquake, exacerbated by prior heavy rainfall [2], [3].

Site visits and visual inspections of the post-landslide conditions revealed that the village is on a vulnerable mountain slope with limited vegetation. The soil in the region is predominantly sandy silt, derived from the weathering of volcanic rocks, which increases its susceptibility to landslides.

A deep understanding of disasters can significantly reduce their risks and impacts, mainly since debris flows move swiftly and have substantial destructive potential.

Thus, comprehensive environmental knowledge is crucial for effectively mitigating such threats [4].

Rainfall-induced erosion is a natural process that cannot be entirely prevented [5], [6], making its management through bioengineering techniques a sustainable approach to soil conservation.By employing natural vegetation, bioengineering reduces erosion while promoting environmental health, addressing the immediate effects of erosion and bolstering ecosystem resilience as a viable long-term solution for maintaining soil stability [7]. Grass planting is the most commonly used biotechnological method for soil preservation, as it effectively reduces surface erosion. Grass provides rapid soil stabilization, more efficiently than trees, and offers ground cover that protects soil from raindrop impact and preserves moisture, making it ideal for erosion control and a sustainable choice for landscape protection [8], [9].

Research shows that Elephant grass (*Pennisetum purpureum*) is a powerful natural solution for erosion control due to its robust root system, soil coverage ability, and economic value as livestock feed, which benefits farmers and ranchers alike.

Fig. 1. Landslide in Cemara Landung village in October 2021

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Integrating elephant grass into soil and water conservation strategies is vital for sustaining agricultural lands in Indonesia and worldwide. Erosion and landslides can be effectively managed through grass vegetation, particularly by combining elephant grass with vetiver grass. This combination has reduced surface runoff by 55.48% on a 45° slope and 53.89% on a 60° slope [10].

A Consolidated Undrained (CU) triaxial test was performed in the laboratory to measure changes in shear strength to investigate the effects of reinforcing volcanic soil with a combination of elephant grass and vetiver grass roots. Additionally, a model test was conducted under seismic loads to observe variations in slope surface behavior. Testing volcanic slopes reinforced with this specific combination of vetiver and elephant grass under these conditions is unprecedented, making this study a valuable step forward in developing related testing methodologies.

The following is the structure of the paper. Section II provides a review of the literature. Section III outlines the data and methodology used in this study. Section IV presents the results and discussion, focusing on the analysis of soil stress and physical model testing. Finally, Section V concludes the paper.

II. Literature Review

Landslides are geomorphological evolution and can cause geological disasters. The main factors causing landslides are rain and earthquakes that occur on slopes.

Landslides due to a combination of rain and earthquakes occurred in Hokkaido, Japan, due to an earthquake with a magnitude of 6.7 that caused 4000 landslide areas in 2018 [11]. A similar incident also occurred in Indonesia due to an earthquake and rain, which initiated a landslide mechanism [12].

Vegetation is essential in maintaining slope stability, especially in areas prone to landslides due to earthquakes and rain [13]. Research shows that plant roots contribute significantly to slope reinforcement and reduce the risk of landslides during earthquakes. Root reinforcement effectively mitigates shallow landslides and controls surface erosion [14]. Environmental factors influence shallow landslide susceptibility, including terrain and soil properties, hydrological conditions, and land use. Among these, land use significantly impacts landslide susceptibility, primarily through the stabilizing effect of vegetation, as plant roots enhance soil reinforcement [15].

Root Reinforcement (RR) adds root-induced forces to resist deformation and displacement due to gravity. RR can be distinguished based on the orientation of the shear plane (i.e., horizontal or vertical). The activation of root stress in tension, compression, bending, and shear mechanisms has been demonstrated through field observations validated by field and laboratory tests [16].

The contribution of the root reinforcement use The Mohr-Coulomb failure criterion can be adapted by adding a term that reflects the combined effects of root tensile strength and their spatial arrangement within the soil [17].

The local failure of the slope is based on the ratio of local shear strength to local stress. The slice-based method is versatile and can be applied to a wide range of slip surface geometries, not just limited to the commonly described circular arc. It can handle different slip surfaces, including those parallel to the slope. While the circular arc slip surface is often used in explanations and descriptions of the method, the approach is flexible enough for more complex or non-circular slip surfaces, making it suitable for various slope stability analyses. The local factor of safety (F_i) at the base of a slice, where shear forces (T_i) and regural forces (N_i) are acting (Fig. 2), can be expressed using the Mohr-Coulomb equation:

$$T_i = \frac{1}{F_i}\left[c_i l_i + (N_i - u_i l_i)\tan\varphi\right] \tag{1}$$

where c_i and φ are cohesion and angle of soil friction, u pore water pressure, and l is the base length of the slip surface. If the soil is rooted, the increased soil shear strength can be expressed as [18]:

$$T_{ti} = \frac{1}{F_i}\left[c_i l_i + C_{ri} l_i + (N_i - u_i l_i)\tan\varphi\right] \tag{2}$$

where T_{ti} is the shear strength (kN) of the soil reinforced by roots, T_i (kN) is the shear strength of the soil, and C_{ri} (kN) is the increase in shear strength due to the presence of roots. This increases the shear strength of the root-soil matrix, known as the additional cohesion (c_r). The additional cohesion is described as follows [19]:

$$C_r = t_r\,(\cos\theta\tan\varphi' + \sin\theta) \tag{3}$$

where θ is the angle of shear distortion in the shear zone, φ' is the soil friction angle, and t_r is the total mobilized tensile stress.

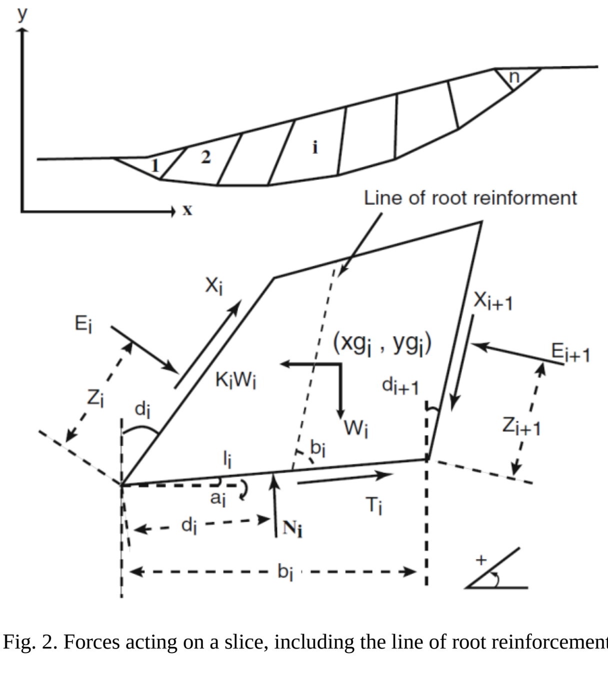


Fig. 2. Forces acting on a slice, including the line of root reinforcement

The contribution of root reinforcement in increasing soil cohesion has been studied since the 1970s. The research was conducted using laboratory tests, shaking tables, and field experiments. One model used in laboratory testing is the Slope Stability physical model [14]. Seismic action can be simulated realistically and effectively by shaking a table, and it is a standard method used to study the ground motion response characteristics of slopes. The horizontal inertia force due to the earthquake has the most significant impact on the horizontal displacement of the slope surface compared to the vertical displacement. The difference in slope structure affects slope stability failure [20].

The shaking table test shows that the soil on the accumulated slope will be thrown out when the simultaneous action of the corresponding crack angle and significant vertical seismic acceleration occurs [21]. Slope failure behavior is assessed based on the displacements before and after the landslide resulting from the model test [22]. The displacement and deformation measurement is done using markers, colored layers, or photo techniques [23]. Comparing the displacement and strain fields of the two test devices shows that, during most earthquakes, the horizontal displacements in the X direction at the top and base of the bare slope are greater than those of the hill reinforced with vegetation [20].

In a shaking table test, the earthquake acceleration (ε) fluctuates as the slope elevation increases, a phenomenon referred to as the dynamic response of high slopes (Fig. 3).

The long-distance propagation of waves dissipates a large amount of energy because of material damping, which always reduces response at the crest of the slope [24].

III. Material and Methods

The testing procedure began with laboratory experiments using the Triaxial MBT No. SO-600 series machine in the Soil Mechanics Laboratory at the Faculty of Engineering and Planning, Warmadewa University. Disturbed volcanic soil samples were gathered from the foothills of Mount Abang.

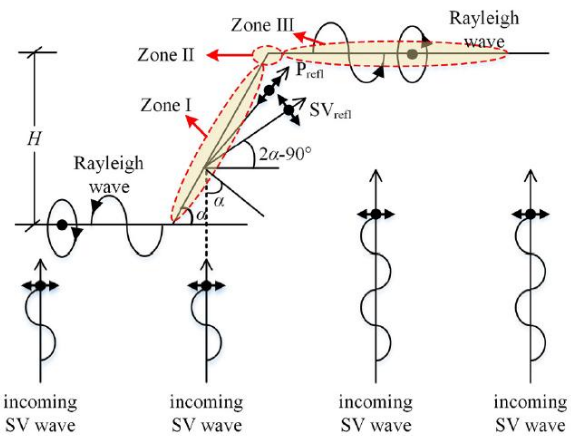


Fig. 3. Incoming SV wave propagation on a single surface slope [24]

Testing was conducted on two re-molded soil models: one without reinforcement from vetiver and elephant grassroots and another incorporating both types of roots.

The objective was to assess the impact of these natural reinforcements on the mechanical properties of volcanic soil, mainly focusing on shear strength and stability under different conditions. This approach offers valuable insights into the effectiveness of plant root systems for slope stabilization in volcanic regions [25].

The Triaxial CU testing followed standard protocols outlined in ASTM D4767, ASTM D7181, and SNI 03-2455-2004 to measure adequate shear strength (φ'), effective cohesion (*c*'), and the stress-strain relationship in soil samples.

This test aimed to assess soil mechanical strength, particularly regarding the enhancement of slope stability through the use of plant roots as natural reinforcement materials (Fig. 4).

Vetiver and elephant grass samples were cultivated under controlled conditions to produce optimal roots, facilitating an analysis of their effects on volcanic soil behavior.

This procedure enabled direct observation of the interaction between soil and root systems, anticipated to improve soil cohesion and enhance slope stability against mechanical or seismic forces.

Physical modeling was conducted to examine the impact of added earthquake forces on vegetated slopes. The earthquake force testing utilized a 5×3 m shaking table powered by a 5.5 HP motor capable of handling a maximum load of 1.2 tons (Fig. 5).

The vibration settings on the shaking table are adjusted by controlling the motor frequency to simulate an earthquake magnitude comparable to the 2021 landslide event, which registered 4.8 SR (Fig. 6). The shaking continues until a landslide occurs on the slope, allowing for an assessment of the vegetation's ability to resist earthquake-induced forces [26].

Testing commenced once the vegetation roots had extended to the base of the test box. The vetiver roots reached approximately 40 cm and achieved stability at around seven weeks of growth [19]. The modeling included six scenarios with varying slope angles and vegetation conditions (Table I).

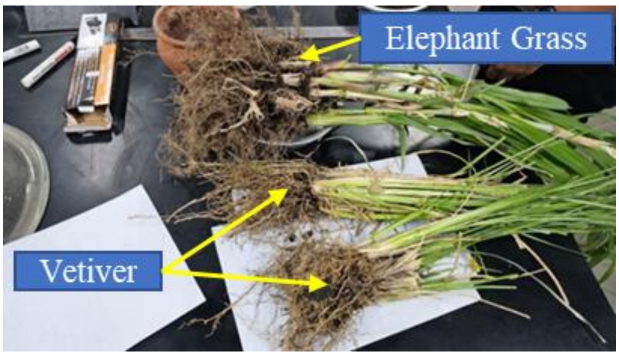


Fig. 4. Vetiver and Elephant Grass sample

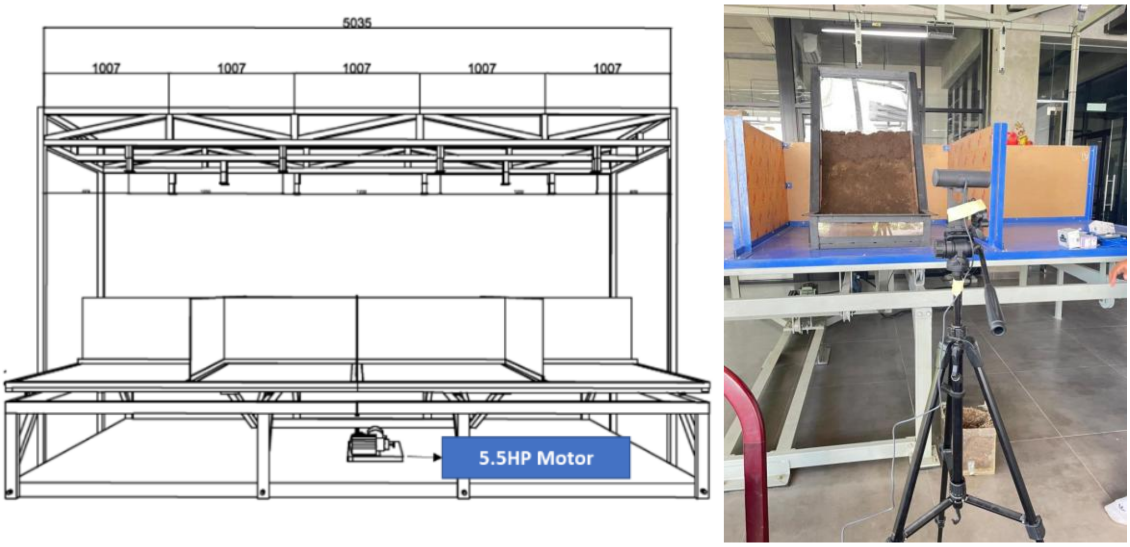


Fig. 5. Shaking table

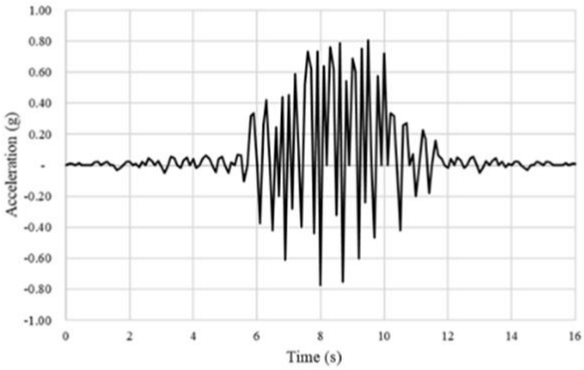


Fig. 6. Shaking table amplitude

TABLE I
PHYSICAL MODEL SCENARIO

Scenario	Code	Setting
Scenario-1	BS-1	45º bare soil slope
Scenario-2	V-1	45º slope with Vetiver
Scenario-3	VE-1	45º slope with vetiver+elephant grass
Scenario-4	BS-2	60º bare soil slope
Scenario-5	V-2	60º slope with Vetiver
Scenario-6	VE-2	60º slope with vetiver+elephant grass

IV. Results and Discussion

IV.1. Soil Stress Analysis

The shear test and Mohr-Coulomb strength theory were applied to investigate root-soil interactions, which are essential for soil stability analysis. Although root growth patterns can be irregular in natural settings—potentially complicating root growth assessments—this variability is disregarded in re-molded samples. The CU triaxial test provides a more realistic measure of soil strength (Figs. 7).

In soil samples without roots, cohesion (*c*) is measured at 0.10 kg/cm² with a friction angle (φ) of 29.54º, while effective cohesion (*c*') reaches 0.20 kg/cm² with an effective friction angle (φ') of 31.44º (Figs. 7). In contrast, samples reinforced with vetiver and elephant grass roots demonstrate a cohesion (*c*) of 0.25 kg/cm² and a friction angle (φ) of 31.89º, along with an effective cohesion (*c*') of 0.65 kg/cm² and an effective friction angle (φ') of 34.82º (Figs. 8). Results from the Consolidated Undrained (CU) triaxial test show a significant increase in cohesion and internal friction angle in samples containing plant roots [27]. The shear strength of volcanic soil is strongly influenced by principal stress, which can characterize the strength of an elastoplastic soil block [28]. Failure in volcanic soil reinforced with roots occurs at a principal stress of around 420 kPa, indicating this as the limiting stress level.

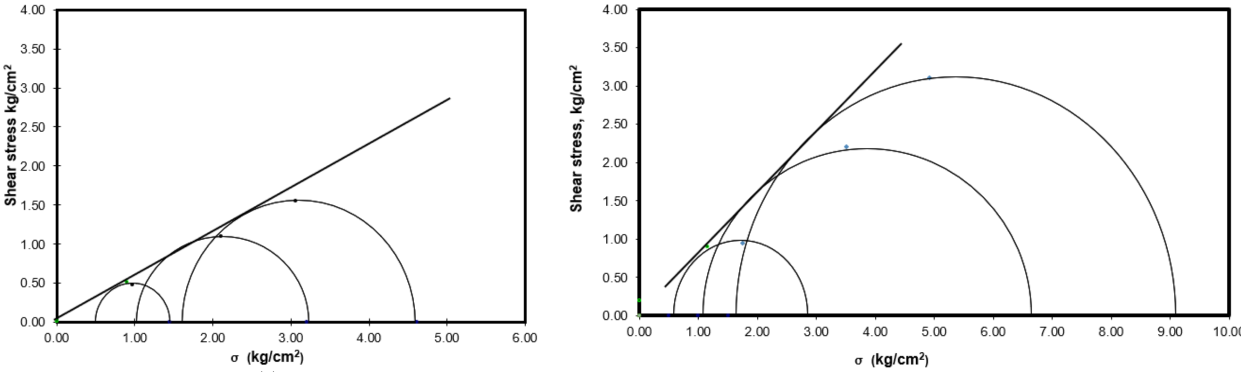
IV.2. Physical Model Test

The experimental model was constructed with a steel box featuring transparent acrylic walls (0.8×0.6×1.0 m) to observe root development. This design enabled the formation of two specific slope angles, 45°, and 60°, chosen to reflect the typical terrain slopes of the research site, closely simulating real-world conditions [29]. The transparent walls provided a unique advantage by allowing researchers to directly monitor root growth and behavior on different slopes without disturbing the soil structure [7]. This setup was essential for examining how varying slope gradients influence plant rooting dynamics in natural settings [30].

Expansive soil slopes are susceptible to landslides and collapse due to the soil's tendency to expand and contract with moisture-level fluctuations. Expansive soil absorbs large amounts of water during the rainy season, leading to significant volume expansion.

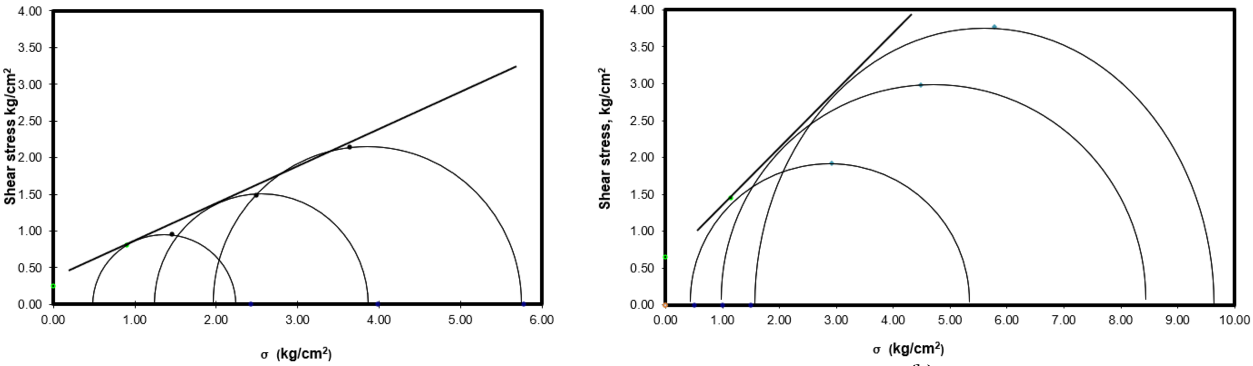
Conversely, during the dry season, the soil shrinks rapidly [31]. This ongoing cycle of expansion and contraction weakens the soil structure, ultimately contributing to slope instability [32].

The initial test results were obtained by saturating the soil to simulate slope conditions caused by rainfall. Soil saturation was measured using a Soil Moisture meter, reaching a 70-75% saturation level.



(a) (b)

Figs. 7. Total Mohr (a) and effective Mohr (b) of Volcanic landslide in bare soil



(a) (b)

Figs. 8. Total Mohr (a) and effective Mohr (b) of Volcanic landslide in planted soil

Subsequently, testing was conducted using a shaking table, where the deformation and collapse of the slope in bare soil conditions were observed and categorized into three distinct stages. *Stage 1*: No noticeable slope deformation is observed during the initial testing phase, with earthquake acceleration below 0.2 g. Only minor surface cracks appear on the slope, indicating the early onset of stress but without significant structural impact.

The hill remains intact mainly at this stage, with minimal surface disruptions (Fig. 9(a)). *Stage 2*: As the acceleration increases to approximately 0.5 g, the slope exhibits signs of instability. Small collapses start to occur, marking the initial stages of slope failure. The previously formed cracks continue to widen, suggesting a progressive weakening of the soil structure. These developments indicate that the slope is nearing a critical stability threshold (Fig. 9(b)). *Stage 3*: A more significant collapse is initiated when acceleration reaches between 0.7 g and 0.8 g. The failure begins in the middle portion of the slope, where the soil is most vulnerable, and propagates upwards, causing changes in the upper sections of the hill. This chain reaction leads to a material shift towards the toe of the slope, accumulating debris.

(a) (b) (c)

Figs. 9. Slope deformation of volcanic bare soil

The process reflects a complete slope destabilization under higher seismic forces, culminating in a significant structural failure (Fig. 9(c)).

The deformation stages observed in the test results revealed an accumulation of soil mass on the slope, leading to buckling failure. These findings align with previous studies on slopes in China affected by the Wenchuan Earthquake [33]. The results from the bare soil tests also correspond with documented slope behavior in Cemara Landung Village following the October 2021 Earthquake (Fig. 10). Post-earthquake observations showed significant deformation, particularly in the topsoil layer. This consistency suggests that the physical model used in the tests can be considered accurate and valid in replicating actual field conditions [34].

The bare soil model used has been well verified against actual conditions in the field. As a next step, testing was carried out on slopes planted with vetiver vegetation with a slope of 45 and 60 degrees. The test results on a slope with a slope of 45 degrees planted with vetiver showed that the landslide area was reduced by 37% (Table II), and on a slope with a slope of 60 degrees, the landslide area further decreased to 30.6% (Table III).

The deformation of the slope overgrown with vetiver vegetation was proven to be able to change locally, especially in the area around the roots and the surface layer of the soil [35].

Fig. 10. Slope deformation of volcanic bare soil after earthquake

TABLE II
CHANGES IN LANDSLIDE AREA ON 45° SLOPE

Condition	Slide Area (m^2)	% Reduction
Bare Soil	0.0908	0.0%
Vetiver	0.0572	37.0%
Vetiver + Elephant Grass	0.0326	64.1%

TABLE III
CHANGES IN LANDSLIDE AREA ON 60° SLOPE

Condition	Slide Area (m^2)	% Reduction
Bare Soil	0.0493	0.0%
Vetiver	0.0342	30.6%
Vetiver + Elephant Grass	0.0236	52.1%

This indicates that vetiver functions effectively as a natural reinforcement, able to reduce the risk of landslides, especially on sandy soils (Fig. 11, Fig. 12) [36]. On the 45° vegetated slope (Fig. 13(a)), fractures appear along the paths between areas of vegetation, with a depth ranging from 2 to 5 mm. In contrast, on the 60° vegetated slope (Fig. 13(b)), fractures appear along the paths between areas of vegetation, the fractures are more extensive, exhibiting a longer length and a slightly deeper profile, with depths ranging between 3 and 5 mm.

Combining vetiver vegetation with elephant grass has produced better slope deformation than vetiver alone. On a slope with a slope of 45°, this combination resulted in a reduction in landslide area of 64.1% (Table II), while on a slope with a slope of 60o, the reduction in landslide area was recorded at 52.1% (Table III).

The success of this combination is due to the synergistic effect of the two types of vegetation. Elephant grass, with roots that spread evenly in the topsoil layer, creates a stronger bond on the surface soil, which plays an essential role in reducing the movement of soil masses during the landslide process. In addition, the distribution of elephant grassroots also increases water infiltration into the soil, which in turn helps maintain slope stability by reducing pore water pressure and preventing erosion.

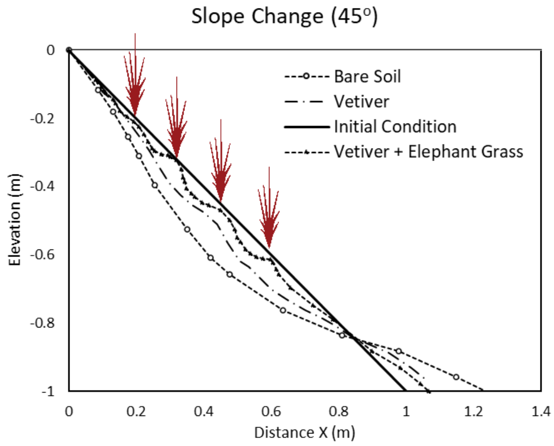


Fig. 11. Deformation of 45° due to earthquake

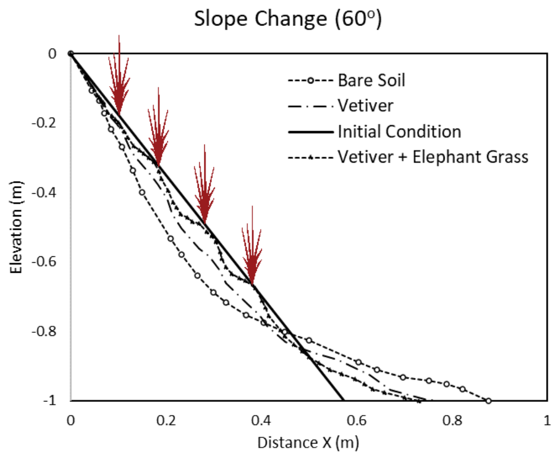


Fig. 12. Deformation of 60° due to earthquake

(a) (b)

Figs. 13. Fracture pattern on 45º (a) and 60º(b) vegetated slope

Combining these two types of vegetation strengthens the surface's soil structure. It contributes to overall slope stabilization, making it an effective solution in landslide risk mitigation, especially in areas prone to high rainfall and earthquakes.

V. Conclusion

The study results demonstrated that adding root reinforcement to volcanic soil on Mount Batur significantly enhanced slope stability. Triaxial tests revealed that bare soil had a friction angle of 29.54° and an effective cohesion of only 0.20 kg/cm². With vetiver and elephant grassroots incorporation, the friction angle increased to 31.89°, and effective cohesion rose to 0.65 kg/cm², confirming that root reinforcement improves the mechanical properties of volcanic soil by enhancing both friction angle and cohesion. Additionally, root reinforcement effectively reduced landslide areas; shaking table tests indicated that vetiver roots alone reduced landslide areas by 37% on a 45° slope and 30.6% on a 60° slope. The combination of vetiver and elephant grass roots proved even more effective, reducing landslide areas by 64.1% on a 45° slope and 52.1% on a 60° slope. These findings show that using a combination of roots yields more optimal stabilization results for volcanic slopes.

Root reinforcement has also proven effective in enhancing stability in topsoil, particularly in soil layers less than 20 cm deep. This added stability is crucial for preventing landslides, which frequently originate in these shallow soil layers, especially in volcanic soils prone to erosion and landslides triggered by earthquakes or heavy rainfall.

This study also has important implications for field conditions. The deformation patterns observed on bare soil slopes align with the landslide phenomenon witnessed during the October 2021 earthquake. Slope deformation typically starts with minor material collapses, followed by the development of cracks, and ultimately leads to significant landslides. Future research should incorporate a numerical model for comparison to enhance the findings from physical testing. Such a model would offer a more detailed and precise analysis of soil behavior, enabling more comprehensive predictions regarding slope stability.

Overall, this study proves that employing root reinforcement, mainly through the combination of vetiver and elephant grass, is highly effective in enhancing the stability of volcanic slopes and minimizing the risk of landslides.

Future research should include long-term monitoring of root reinforcement effects on slope stability. This could involve regular assessments of vegetation health, root growth, and soil properties over extended periods to evaluate the sustainability of the enhancements observed.

Furthermore, incorporating a numerical model to simulate the behavior of root-reinforced slopes under different environmental conditions (e.g., varying moisture levels, seismic activities, and rainfall patterns) would enhance the understanding of slope stability dynamics.

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