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Proceeding Paper

Static Stability Analysis of Bamboo Grid-Reinforced Slopes †

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Abstract: The current work investigates the behavior of a bamboo grid-reinforced slope, which utilized 2D numerical analyses using the finite element program MIDAS GTS NX (340) 2023 v1.1. The results and discussion of the study revealed the effectiveness and stability of the bamboo grid-reinforced slope. The percentage of safety factor increment for bamboo grid-reinforced slope is 80% compared to an unreinforced slope. Bamboo grids can reduce 92.54% of the total displacement of the slope. Applying a bamboo grid reduces horizontal stress, vertical stress, significant principal stress, minor principal stress, and total internal forces by 51.67%, 43%, 42.66%, 49.87%, and 23.54%, respectively. The numerical analyses showed that the bamboo grid was able to resist the applied loads and maintain its stability. Some researchers in their study found that PET geogrids provide better stability performance than other geogrids. As the geogrids are made up of different materials such as plastic, nylon, etc., they are not friendly to the environment. Bamboo is a biodegradable natural element that may be a suitable replacement for geogrid material.

Keywords: slope stability; bamboo grid; factor of safety

1. Introduction

Slope failure has been recognized as a prevalent natural calamity that has the potential to result in significant losses of both property and human lives. Slope failures are caused by various external factors, including geological pressures, the mechanisms of weathering and erosion, and additional anthropogenic elements exacerbated in mountainous regions with significant relief [1,2]. Performing slope stability analysis using computer software is straightforward for engineers, provided the slope configuration and soil parameters are well-defined. Nevertheless, choosing an appropriate approach for analyzing slope stability is complex. It requires a diligent collection of field conditions and observations of failures to gain insight into the underlying mechanisms that govern slope stability.

According to a review conducted by Anusha R. and Kindo E.C. [3], using bamboo as a soil reinforcement can enhance the unconfined compressive strength. This improvement can be attributed to the increased friction resulting from the interaction between the ground and the coarse surface of the bamboo. In addition to the enhanced compressive strength value, there is a drop in reduction and a lack of uniformity in the reduction. Using bamboo grids on peat soils demonstrates a notable enhancement in bearing capacity. The utilization of a bamboo grid has been employed as a means of reinforcing a shallow foundation. Bamboo grids can potentially enhance the load-bearing capability of shallow foundations [4,5].

Limit equilibrium analysis methods (LEMs) are a basic and conventional technique for slope stability evaluations. Because of their ease of use, low formulation complexity, and quick computation times, LEMs are often employed in slope stability studies and can be used to calculate FS. LEMs examine the polyhedral force vector closure or incurring moments in an equilibrium condition and a potential slippery mass at the summit of the imagined slip surface. The Fellenius, Bishop, Janbu, modified Swedish, Lowe–Karafiath, Morgenstern–Price, and USACE methods are among the equilibrium methods used to

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estimate the FS. When determining the factor of safety (FS), the majority of these techniques yield findings that are comparable, with the estimated value differences typically being less than 6%. The Mohr–Coulomb relationship, which is regarded as one of the most crucial failure parameters for stability assessments in geomaterials, is used by the majority of limit equilibrium techniques to estimate the shear stress and resistance over the slip surface in all forms of failures. Traditional stability analysis methods, impacted by the stabilization process, struggle to produce reliable results because of the evaluation uncertainties in FS values [6–10]. In contrast, complicated problems can be solved by various means, which obtain the relationship between shear strain and slope. The finite element method, a numerical simulation technique, divides the geometry into relatively small parts and uses the theory of superposition to solve the physical problem. It then measures the stress and strain in those elements before reassembling them. The finite difference method, however, takes a different tack. Using finite difference formulations, such as forward, backward, and central differences, it breaks the problem down into smaller time steps and aids in predicting the stresses and strains for the subsequent time step based on the current time step. Investigating the embankment's stability is best achieved using the gravity increase approach (finite element approach). The reason for this is that an increase in the rate of gravity loading on the embankment can be used to replicate the structure's construction rate [11].

2. Methodology

Su and Shao [12] performed a study on the static stability of the slope to determine the effectiveness of a slip circle by using integral mean value theory to study the global safety factor based on displacement analysis. In the current investigation, the unreinforced slope provided by Su and Shao [12] is stabilized by using the bamboo grid to find the response of sloping ground based on seismic stability analysis. The slope geometry (Figure 1) and soil properties (Table 1) are considered as per [12] to find the effectiveness of sloping ground based on seismic stability analysis. Ten bamboo grids of 1 m spacing were used to stabilize the slope, whose properties are mentioned in Table 1 [13]. The computer program MIDAS GTS NX (340) 2023 v1.1, which is software that is easily accessible, was used to build the numerical method known as finite element analysis (FEM), utilized in the current investigation. Stage 1 consists of the creation of geometry and the assignment of material properties. Mesh generation was carried out in stage 2, where very fine meshes of 0.1 m were chosen for accurate results. A gravity loading was applied in stage 3 to ensure the analysis was performed due to the self-weight of the slope.

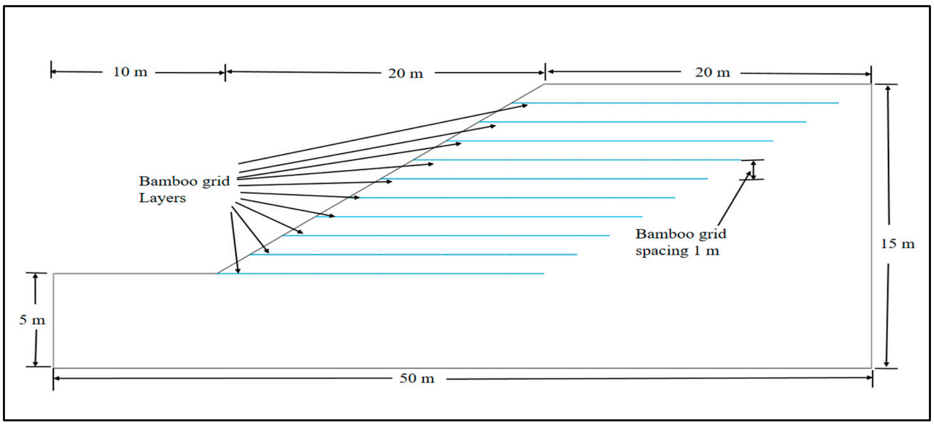


Figure 1. Slope geometry [11].

Table 1. Material properties.

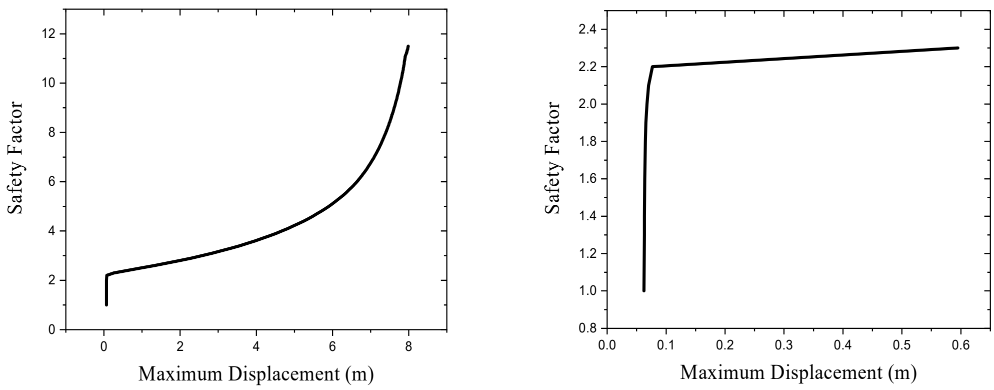
Parameters	Value
Frictional angle of soil (ϕ)	20° [12]
Cohesion value of soil (c)	28.7 kN/m^2 [12]
Modulus of elasticity of the soil (E)	10,000 kN/m^2 [12]
Unit weight of soil (γ)	18.8 kN/m^3 [12]
Poisson's ratio of soil (ν)	0.49 [12]
Slope angle (β)	26.7° [12]
Material model for soil	Mohr–Coulomb [12]
Name of the bamboo species	Bambusa Bambos [13]
Unit weight of bamboo grid	9.512 kN/m^3 [13]
Young's modulus of bamboo grid	2,500,000 kN/m^2 [13]
Tensile strength of bamboo grid	253 kN/m [13]

3. Results and Discussion

After analyzing the reinforced and unreinforced slope using the finite element method, some results were compared regarding the safety, displacement, and stress analysis factors.

3.1. Stability of Slope Based on Factor of Safety

Figure 2 shows the variation of the safety factor with respect to maximum displacement for unreinforced slope and bamboo grid-reinforced slope. After many iterations, the final safety factor was 11.5 and 2.3 for bamboo grid-reinforced and unreinforced slopes, respectively. The safety factor is a key parameter to define slope stability, in which a lower safety factor results in more stability. Bamboo grids increased the safety factor by 80% compared to unreinforced slopes. Samal and Sahoo [14] studied the effectiveness of geogrid-reinforced slope by using the finite element method in which five types of geogrids were used. Among the five types of geogrids, PET geogrid performed well in terms of factor of safety as it increased the safety factor by 18%. After a comparison between the performance of the bamboo grid and PET geogrid, it was found that the bamboo grid-reinforced slope was more stable in terms of the safety factor.



(**a**) (**b**)

Figure 2. Variation of factor of safety with maximum displacement: (**a**) bamboo grid-reinforced slope; (**b**) unreinforced slope.

3.2. Stability of Slope Based on Displacement

The displacement of different slope portions is the key parameter in slope stability. The contour showing the total displacement of the unreinforced slope is shown in Figure 3, where the area below the face of the slope is more vulnerable zone, and the maximum total displacement of that area is 7.98 m.

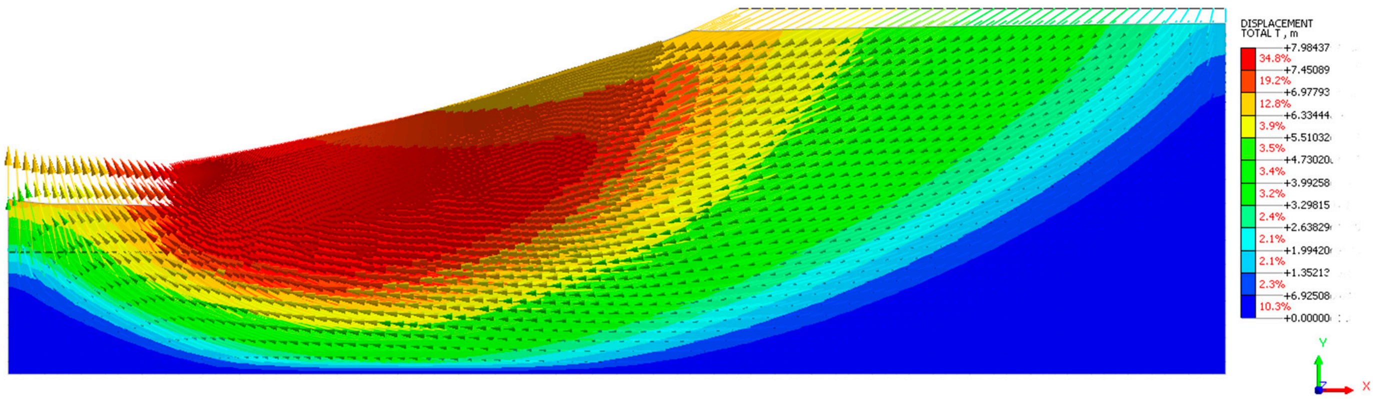


Figure 3. Contour showing total displacement for unreinforced slope.

The contour showing the total displacement for the bamboo grid-reinforced slope is shown in Figure 4. The maximum total displacement was observed below the face but was less vulnerable than the unreinforced slope. The maximum total displacement for a bamboo grid-reinforced slope was found to be 0.595 m. So, the bamboo grids can reduce 92.54% of total displacement compared to unreinforced slopes. Hence, a bamboo grid-reinforced slope is more stable than an unreinforced slope in total displacement. As per [14], PET geogrids can reduce total displacement by 97%. The difference in percentage reduction in the total displacement between bamboo grids and PET geogrids is found to be 4.46.

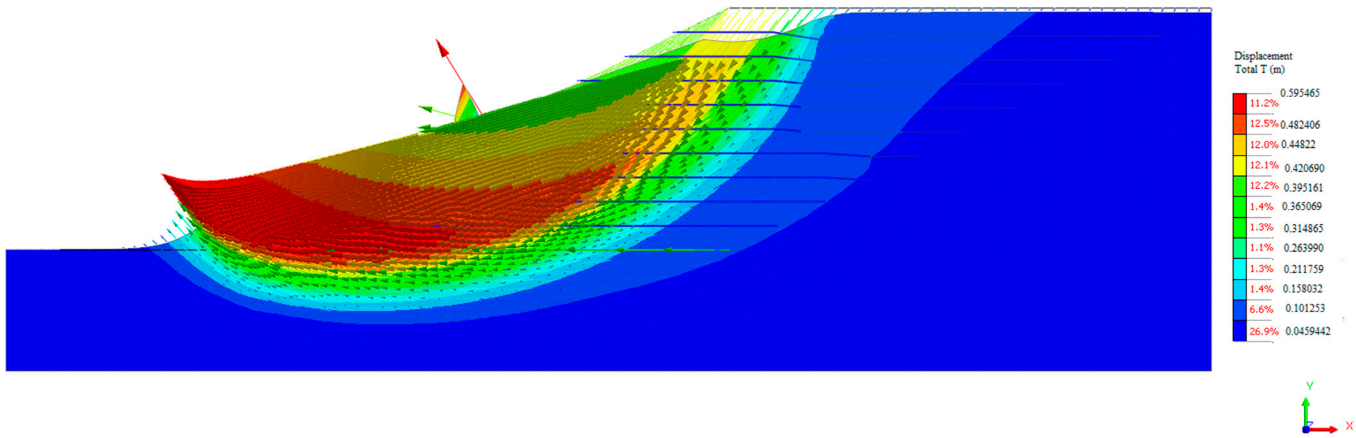


Figure 4. Contour showing total displacement for bamboo grid-reinforced slope.

Additionally, the reduced total displacement of the bamboo grid-reinforced slope indicates that the bamboo grids effectively enhance the stability and strength of the slope. This is crucial in areas prone to landslides or erosion, as it provides a more secure and reliable solution for slope stabilization. The findings from this study highlight the potential of bamboo grids as a sustainable and cost-effective option for slope reinforcement and the mitigation of slope failure.

3.3. Stability of Slope Based on Stress Analysis

The development of stresses in various slope portions is a crucial parameter of slope stability. Horizontal stress development for an unreinforced slope is shown in Figure 5. The maximum stresses in the X-direction were found at the slope crest, which is 290.83 kN/m^2.

Similarly, the development of stresses in the X-direction for bamboo grid-reinforced slope is shown in Figure 6. The maximum value was found to be 140.55 kN/m^2. Hence, the bamboo grids can reduce 51.67% of horizontal stress compared to unreinforced slopes.

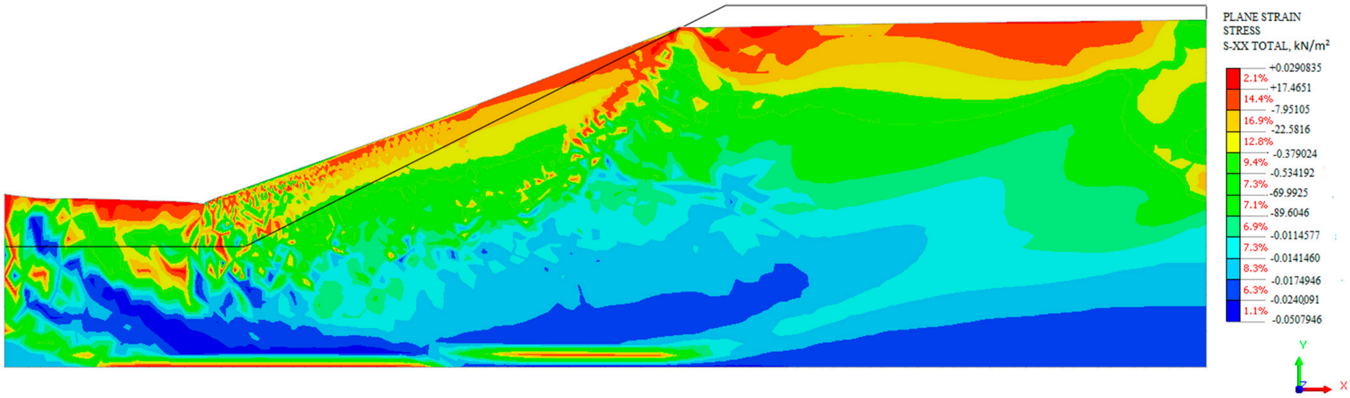


Figure 5. Development of stress in X-direction for unreinforced slope.

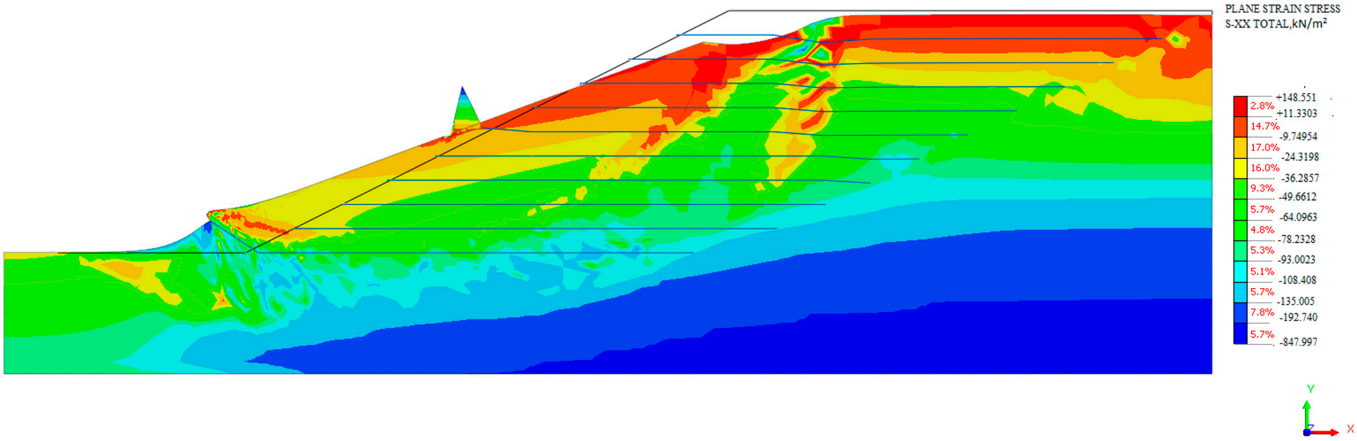


Figure 6. Development of stress in X-direction for bamboo grid-reinforced slope.

The development of stresses in the vertical direction for unreinforced slope is shown in Figure 7. The maximum vertical stress is found to be 297.38 kN/m^2.

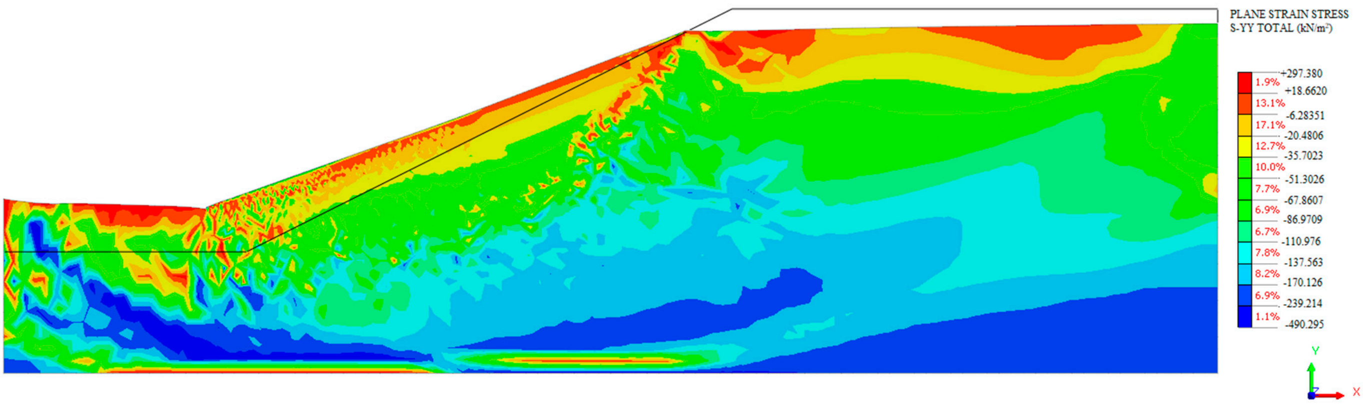


Figure 7. Development of stress in the Y-direction for unreinforced slope.

Similarly, the vertical stress for the bamboo grid-reinforced slope is shown in Figure 8. The maximum value was found to be 169.477 kN/m^2. Hence, the bamboo grids can reduce 43% of vertical stress compared to an unreinforced slope.

The major and minor principal stress plays a crucial role in slope stability. The distribution of major principal stress for unreinforced slope is shown in Figure 9, where the maximum value is found as 298.85 kN/m^2.

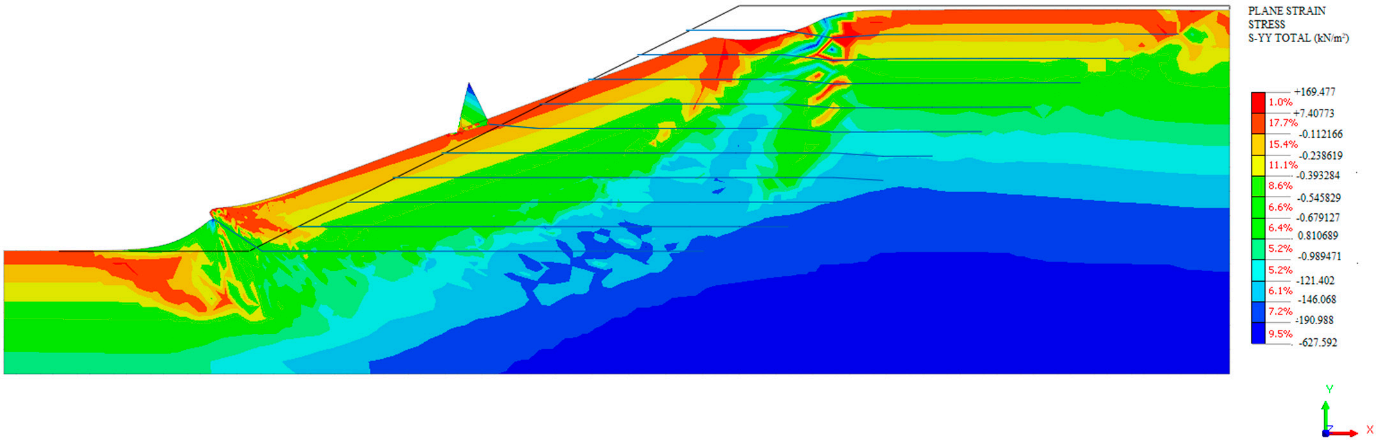


Figure 8. Development of stress in the Y-direction for bamboo grid-reinforced slope.

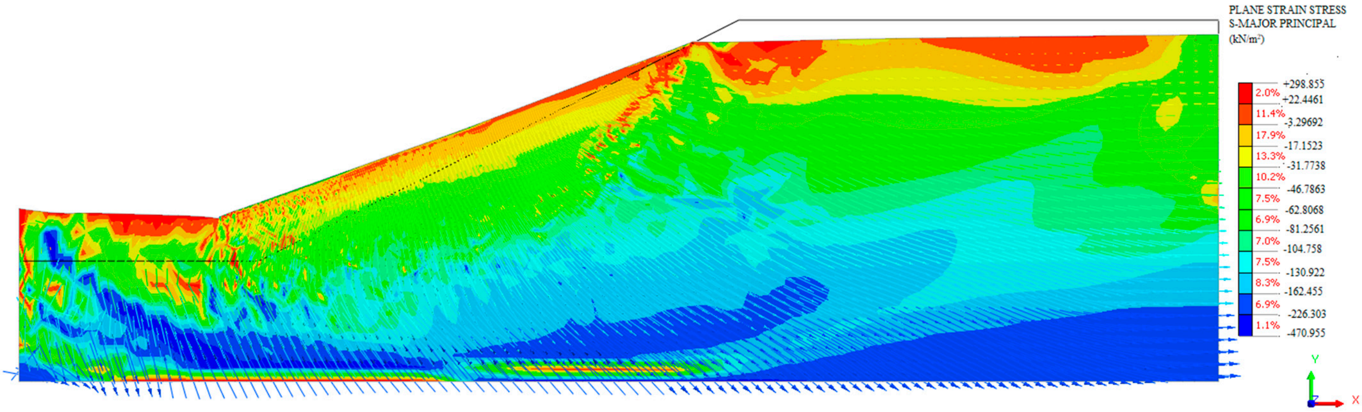


Figure 9. Major principal stress for unreinforced slope.

Similarly, the distribution of major principal stress for bamboo grid-reinforced slope is shown in Figure 10, where the maximum value is 171.35 kN/m^2. Hence, a bamboo grid can reduce 42.66% major principal stress compared to an unreinforced slope.

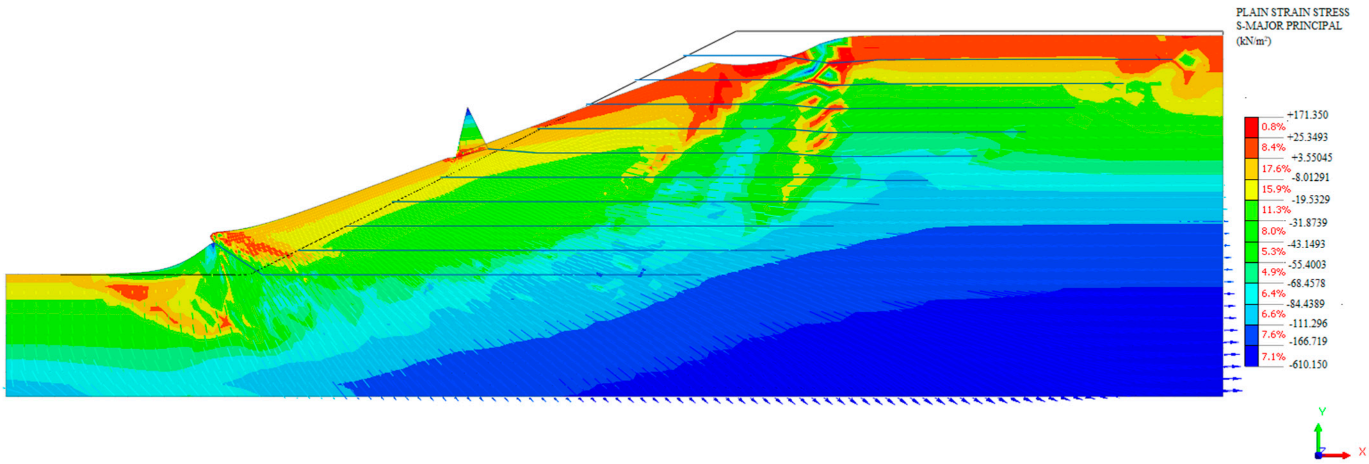


Figure 10. Major principal stress for bamboo grid-reinforced slope.

The contour showing the distribution of minor principal stress for an unreinforced slope is mentioned in Figure 11, where the maximum value was found to be 282.54 kN/m^2.

In Figure 12, the maximum value was found to be 141.62 kN/m^2. Hence, the bamboo grids can reduce 49.87% of minor principal stress compared to unreinforced slopes.

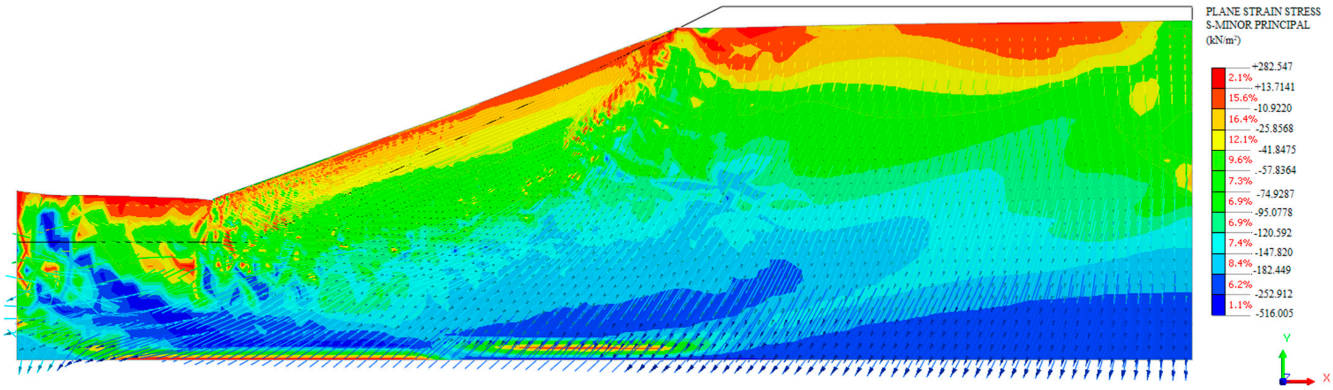


Figure 11. Minor principal stress for unreinforced slope.

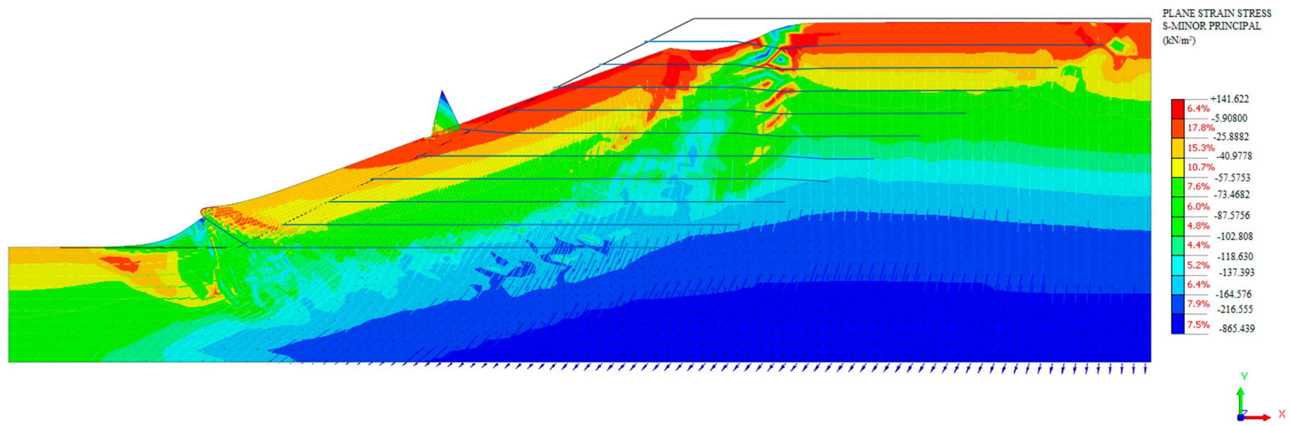


Figure 12. Minor principal stress for bamboo grid-reinforced slope.

Due to the weight of the soil, certain forces develop inside various parts of the slope, called internal forces. The total internal forces for unreinforced slopes are shown in Figure 13, where the maximum value is 178.92 kN. Maximum internal forces are seen at the base up the slope, which has an upward direction. Also, certain internal forces developed at the toe portion in the horizontal direction.

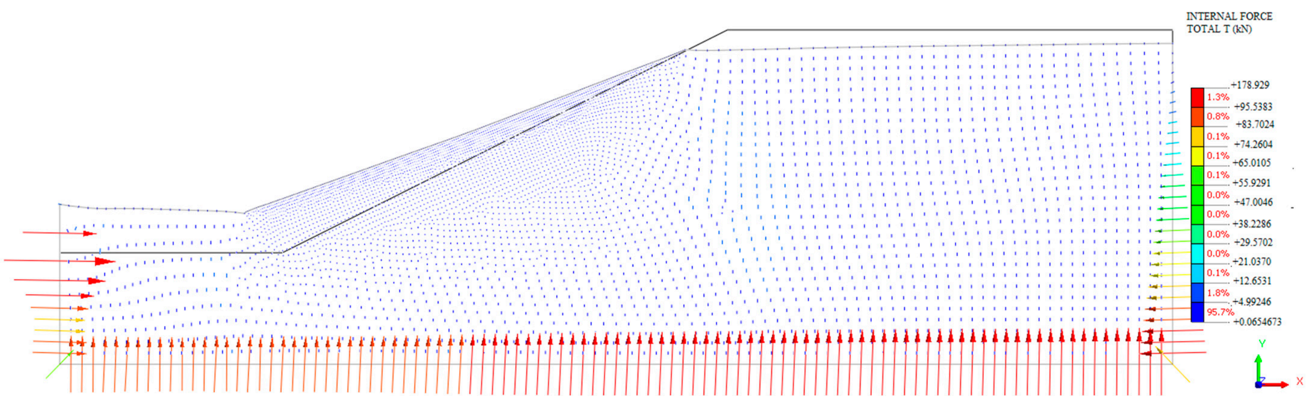


Figure 13. Development of total internal forces for unreinforced slope.

Similarly, the development of the total internal forces for bamboo grid-reinforced slope is shown in Figure 14, where the observed maximum value is 136.81 kN. Here, maximum internal forces are developed at the base of the slope in an upward direction. Hence, bamboo grids can reduce 23.54% of total internal force compared to the unreinforced slope.

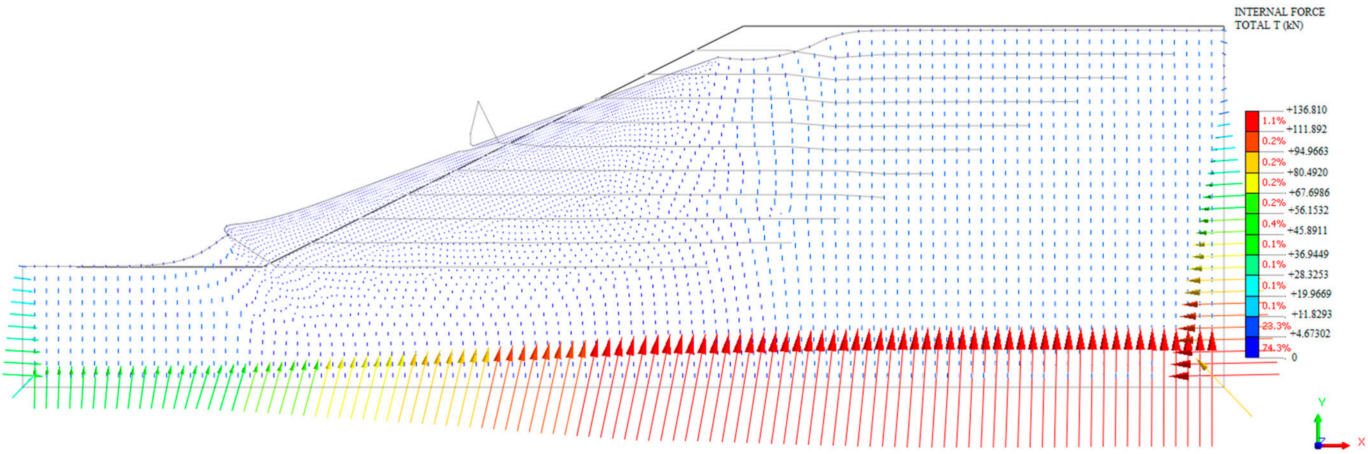


Figure 14. Development of total internal forces for bamboo grid-reinforced slope.

Various failure conditions arose at different slope areas, such as plastic, unloading/reloading, tension failure, and cap failure. The material status for the unreinforced slope is shown in Figure 15, where most of the plastic failures are seen as part of the slope and slope body. Very few observations regarding unloading/reloading are seen.

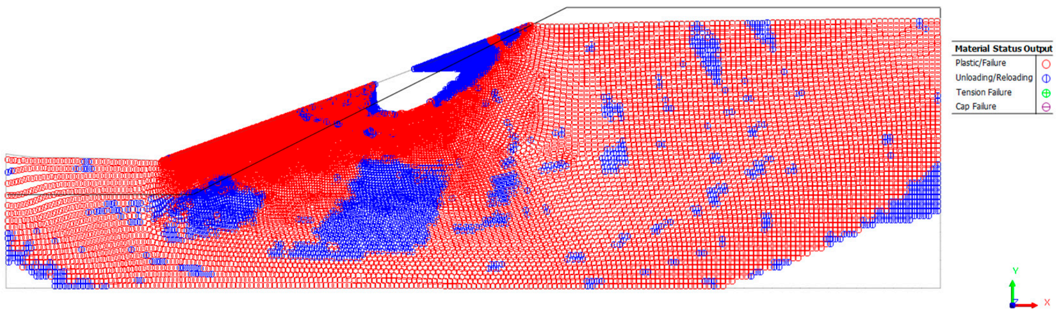


Figure 15. Material status for unreinforced slope.

Similarly, the material status for the bamboo grid-reinforced slope is shown in Figure 16. Here, plastic failures are seen at the slope body. After inserting the bamboo grid, the plastic failure at the face part of the slope was completely reduced.

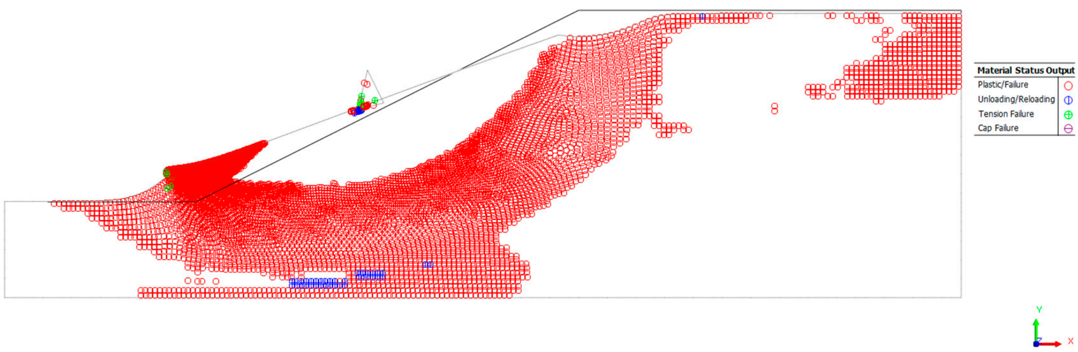


Figure 16. Material status for bamboo grid-reinforced slope.

4. Conclusions

The purpose of the present study was to find the effectiveness of the bamboo grid in stabilizing the slope by using finite element analysis. Different parameters of the slope were evaluated, such as factors of safety, deformation, stresses, and internal forces upon which the stability performance was evaluated for unreinforced and reinforced slopes. The factor of safety of a bamboo grid-reinforced slope was found to be higher than that of a geogrid-reinforced slope. Similarly, the deformations were reduced after the inclusion of bamboo grids. Other parameters, such as horizontal stress, vertical stress, major principal stress, minor principal stress, and total internal forces, were reduced after using bamboo grids. Thus, a bamboo grid-reinforced slope is more stable than a geogrid-reinforced slope. In terms of factor of safety, the bamboo grid performed well as compared to the PET geogrid. The performances of bamboo grids and PET geogrids are nearly equal in terms of displacement. The bamboo grid was also able to reduce plastic failure in the slope. The fact that bamboo is a biodegradable material is the main disadvantage in terms of durability concerns. Hence, further studies are required to improve the durability of bamboo grid by using different coating and treatment methods.

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References

1. Virdi, N.S.; Sah, M.P.; Bartarya, S.K. *Project Report: Landslide Hazard Zonation in the Beas and Satluj Valleys of Himachal Pradesh, Phase-I Satluj Valley*; Technical Report; Wadia Institute of Himalayan Geology: Uttarakhand, India, 1995; p. 132.
2. Badanagki, M.; Li, F.; Armstrong, C. Comparison between Newmark Time History Analysis and Finite Element Method for Estimating Seismically Induced Slope Displacement. In *Atlantis Highlights in Engineering, Proceedings of the TMIC 2022 Slope Stability Conference (TMIC 2022), Toronto, ON, Canada, 12–13 December 2022*; Atlantis Press: Paris, France, 2023; pp. 171–178.
3. Anusha, R.; Kindo, E.C. Behaviour of Bamboo Reinforced Soils—State of Art. In Proceedings of the Indian Geotechnical Conference, Kerala, India, 15–17 December 2011.
4. Waruwu, A. Bamboo reinforcement in shallow foundation on the peat soil. *J. Civ. Eng. Res.* **2014**, *4*, 96–102.
5. Waruwu, A.; Rika, S.D. Behavior of soil peat with reinforcement of bamboo grid. *IOSR J. Eng.* **2015**, *5*, 29–36.
6. Azadi, A.; Irani, A.E.; Azarafza, M.; Bonab, M.H.; Sarand, F.B.; Derakhshani, R. Coupled Numerical and Analytical Stability Analysis Charts for an Earth-Fill Dam under Rapid Drawdown Conditions. *Appl. Sci.* **2022**, *12*, 4550. [CrossRef]
7. Nanehkaran, Y.A.; Licai, Z.; Chengyong, J.; Chen, J.; Anwar, S.; Azarafza, M.; Derakhshani, R. Comparative analysis for slope stability by using machine learning methods. *Appl. Sci.* **2023**, *13*, 1555. [CrossRef]
8. Azarafza, M.; Akgün, H.; Ghazifard, A.; Asghari-Kaljahi, E.; Rahnamarad, J.; Derakhshani, R. Discontinuous rock slope stability analysis by limit equilibrium approaches—A review. *Int. J. Digit. Earth* **2021**, *14*, 1918–1941. [CrossRef]
9. Azarafza, M.; Bonab, M.H.; Derakhshani, R. A novel empirical classification method for weak rock slope stability analysis. *Sci. Rep.* **2022**, *12*, 14744. [CrossRef] [PubMed]
10. Nanehkaran, Y.A.; Pusatli, T.; Chengyong, J.; Chen, J.; Cemiloglu, A.; Azarafza, M.; Derakhshani, R. Application of Machine Learning Techniques for the Estimation of the Safety Factor in Slope Stability Analysis. *Water* **2022**, *14*, 3743. [CrossRef]
11. Ullah, S.; Khan, M.U.; Rehman, G. A brief review of the slope stability analysis methods. *Geol. Behav.* **2020**, *4*, 73–77. [CrossRef]
12. Su, Z.; Shao, L. A three-dimensional slope stability analysis method based on finite element method stress analysis. *Eng. Geol.* **2020**, *280*, 105910. [CrossRef]
13. Hegde, A.; Sitharam, T. Experiment and 3D-numerical studies on soft clay bed reinforced with different types of cellular confinement systems. *Transp. Geotech.* **2017**, *10*, 73–84. [CrossRef]
14. Samal, R.; Sahoo, S. Importance of PET geogrid in the enhancement of hill slope's safety factor: A finite element approach. *Eng. Res. Express* **2023**, *5*, 025028. [CrossRef]