Innovative Geocell-Based Slope Stabilization for Sustainable Protection: A Case Study of a Radio Tower Site in Kodagu, India

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1. Introduction

Slope stability issues are among the most critical challenges worldwide, particularly in regions like India, where three primary factors trigger landslides: rainfall, seismic activity, and human-induced disasters [1–4]. Each of these factors contributes uniquely to slope instability, making it essential to address them individually and comprehensively. The United Nations' Sustainable Development Goals (SDGs), specifically Goals 9 and 11, emphasize the importance of building resilient infrastructure and ensuring safe, sustainable human settlements [5]. Achieving these goals requires a nuanced understanding of the complex causes behind slope failures. It is important to recognize that no single disaster can be attributed to a solitary cause; each event is unique and influenced by a variety of factors that vary from one location to another.

The present study focuses on designing and implementing slope protection measures for the entire hillock at the All India Radio (AIR) site in Kodagu. This effort aims to safeguard both the radio tower and the adjacent road. The study proposes a hybrid retention system incorporating geocells and geogrids based on an extensive spatial stability analysis and validated through numerical methods such as the Limit Equilibrium Method (LEM) and Finite Element Method (FEM). Crucial findings from the reconnaissance revealed significant issues associated with unscientific construction practices, which exacerbated slope instability. Problems were particularly evident after recent construction activities, which led to noticeable damage during the 2022 monsoon season. The unscientific methods contributed to weakened slope integrity, resulting in damage to the existing structures and heightened vulnerability to landslides. The hybrid retention system, which integrates geocells and geogrids, is designed to address both seismic and rainfall-induced stability problems. This system has been validated through detailed spatial stability studies and numerical simulations, ensuring its effectiveness in mitigating slope instability and protecting the site from future damage by upholding SDGs 9 and 11.

2. Site Reconnaissance and Soil Characteristics

2.1. History of the site

The study site is situated in the Kodagu district of Karnataka, India (Figure 1), a region renowned for its hilly terrain and status as a popular tourist destination. Historically, this area has been prone to landslides, particularly during the monsoon season. Evidence of numerous landslides in past years underscores the region's susceptibility to such natural hazards. Figure 2 highlights the Kodagu district, delineating a buffer zone that marks the locations of historical landslides in proximity to the current study site. The map clearly demonstrates the recurrence of landslides in this area, reinforcing the critical need for a comprehensive investigation into effective slope protection systems. Given the terrain's vulnerability, this study focuses on identifying potential hotspots where slope failure could occur. To facilitate this analysis, Digital Elevation Models (DEMs) were sourced from local databases [16]. These DEMs are integral to assessing the topography and identifying areas most at risk of landslides, thereby aiding in the development of more resilient slope protection strategies.

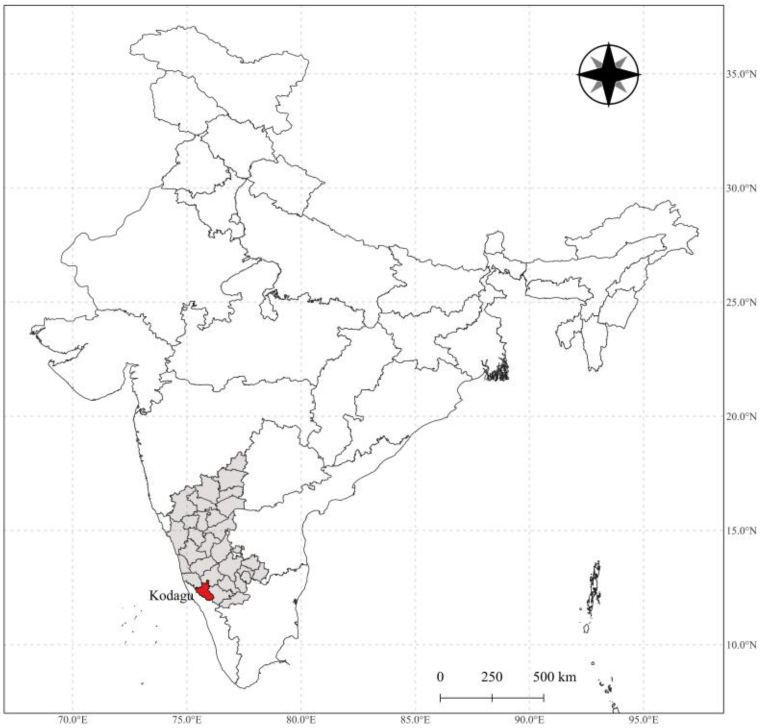

Figure 1: Kodagu District in India

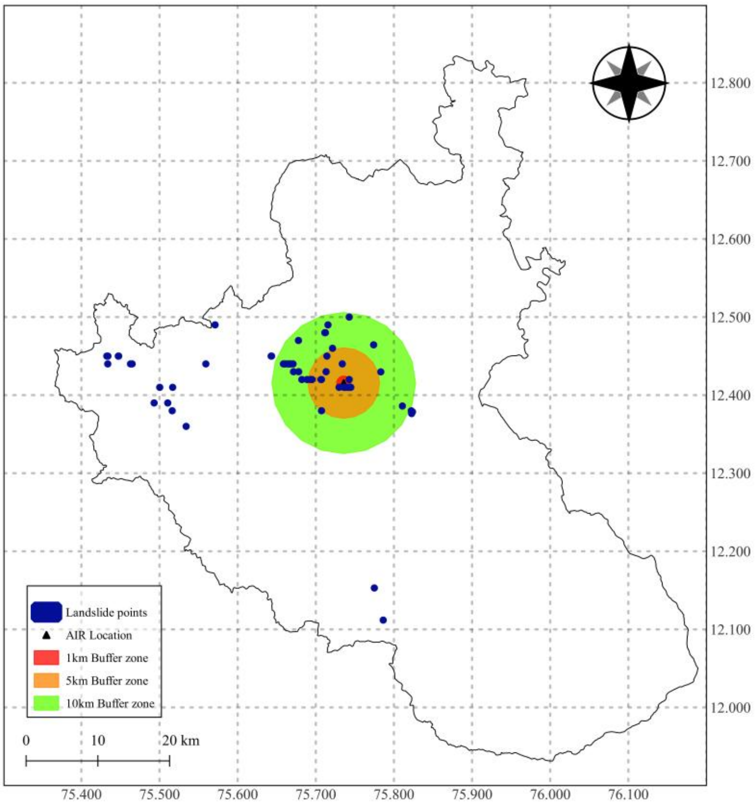

Figure 2: Previous landslide within 10 km of the study location

2.2. Reconnaissance of the site

The current condition of the site has been categorized into two distinct areas based on a detailed reconnaissance survey. In July 2022, a failure resembling a landslide occurred in the region due to intense rainfall. The slope in this area varies between 75 to 90 degrees, classifying it as steep. The All India Radio (AIR) Kodagu radio transmission tower is situated at an elevation of +1081.00 meters above mean sea level (Figure 3). Figure 5 shows the Study area, and Figure 5 illustrates the present situation at Location 1, where a translational failure has occurred across the slope surface. This failure was triggered by water infiltration into the ground, primarily due to the presence of weep holes in a retaining wall located above the slope. During periods of heavy rainfall, these weep holes allow excess water to seep into the soil, reducing its strength and stability.

To mitigate this risk, it is essential to implement an effective drainage system. Adequate drainage will enhance slope stability by preventing water accumulation and minimizing the loss of soil strength during heavy rainfall. The analysis suggests that this drainage solution should extend over a distance of 21 meters, far beyond the initially affected zone of 5.5 meters, to ensure safer and more durable protection of the slope. Figure 6 depicts the current condition of Location 2, where a major circular failure has occurred. This failure is primarily attributed to the direction of the weep holes in the recently constructed retaining wall. To reinforce this slope, support should be provided for a distance of 5 meters, with a height of 8.6 meters, along with the installation of adequate drainage facilities on the upstream side. These measures will help reduce excess water infiltration, which is crucial for maintaining slope stability. To temporarily safeguard the slope, the AIR authorities have deployed tarpaulins to prevent further water infiltration into the soil. In addition to these measures, soil samples were collected from Locations 1 and 2 for further analysis. These samples will undergo sieve analysis and triaxial tests to understand the soil properties better and inform the design of more effective slope stabilization techniques.

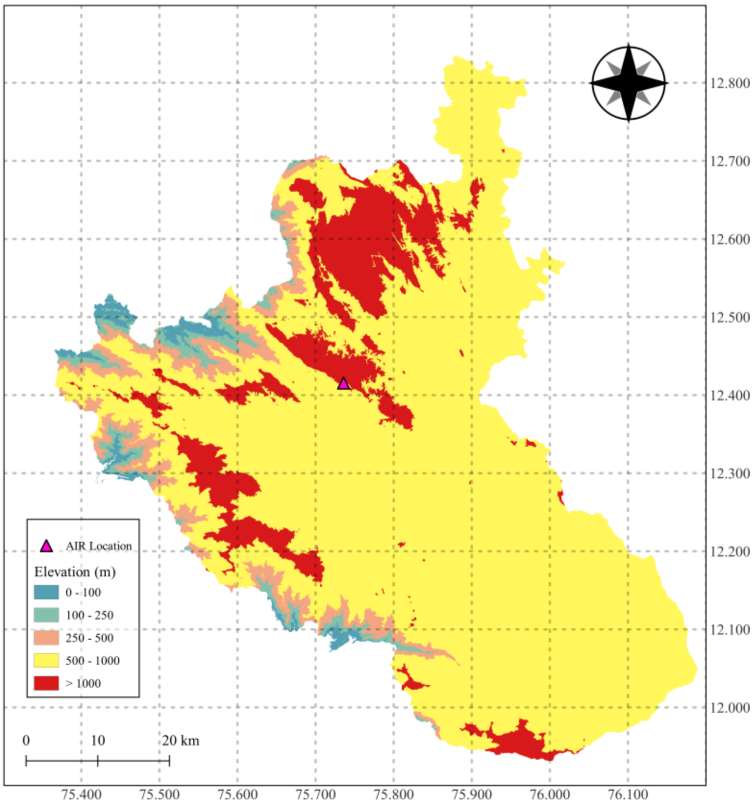

Figure 3: The Elevation map of Kodagu

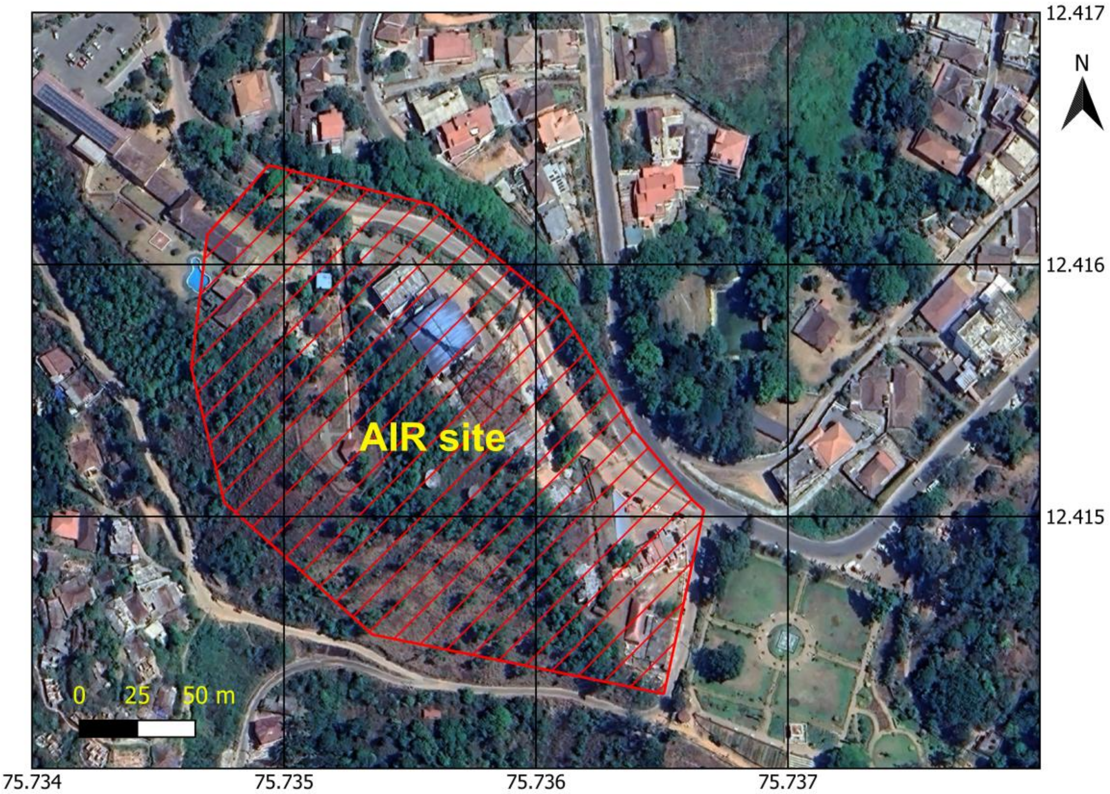

Figure 4: AIR site study area

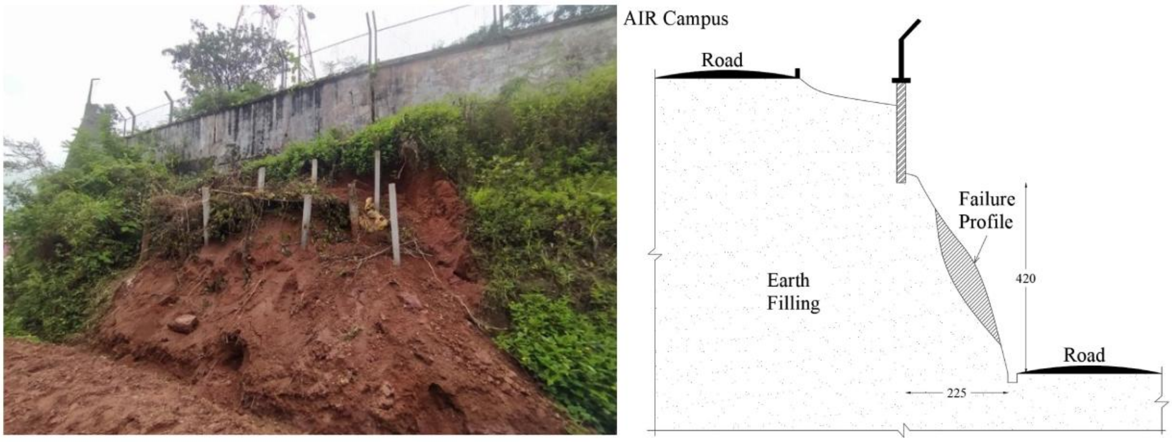

Figure 5: Slope failure observed in the Location 1 site

Figure 6: Slope failure observed in Location 2 site

2.3. Soil Parameters

A comprehensive series of undisturbed soil samples was meticulously collected from the site, ensuring that the integrity of the in-situ conditions was maintained for accurate testing. All testing procedures adhered strictly to the Indian Standards [21, 22], which govern the methodologies for soil classification and strength determination. The results of these tests are summarized in Table 1. From the sieve analysis performed on the samples, the soil was classified as Silty Sand (SM), with an average composition of 84% sand, 14% silt, and 2% clay. This classification is critical for understanding the soil's behaviour under various loading conditions. In addition, a consolidated drained triaxial test was conducted on the samples, which were prepared at field density to replicate the in-situ conditions accurately. This test provided essential parameters for soil mechanics, including the Elastic Modulus, Cohesive Strength, and the Angle of Internal Friction. These parameters are crucial for assessing the soil's deformation characteristics and its shear strength under long-term loading conditions, which are key factors in the design and stability analysis of the site. Figure 7 shows the Particle size distribution and the soil water characteristic curve of the soil sample collected from location 1. A superior Arya-Paris model was used to obtain the soil water characteristic curve (SWCC) [23].

Table 1: Soil characteristics

Parameters	**Values**
Soil type	Silty Sand (SM)
The average Cohesive strength	54 kN/m^2
The average angle of internal friction	24^o

Average Field Density	15.6 kN/ m^3
Elastic modulus	18480 kN/ m^2

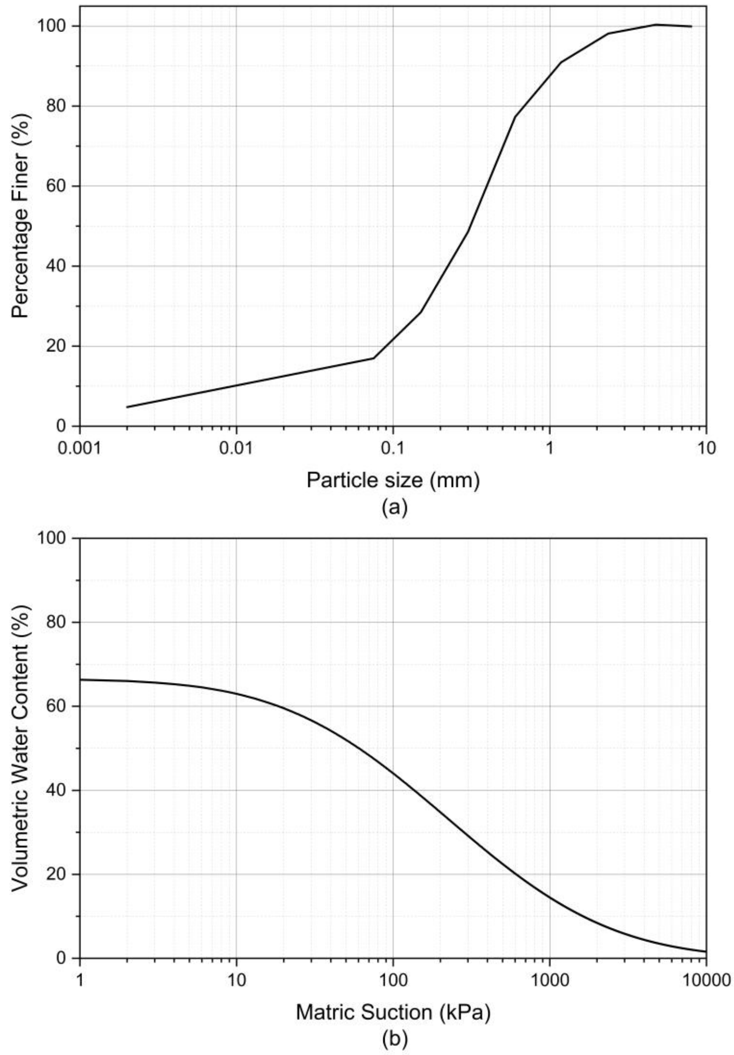

Figure 7: (a) Particle size distribution and (b) Soil water characteristic curve of the silty sand

3. Methodology

3.1. Spatial LEM analysis

The spatial analysis was carried out using Scoop3D, a sophisticated hazard mapping software developed by the U.S. Geological Survey (USGS) [33]. This software is specifically designed for detailed three-dimensional slope stability analysis, making it a valuable tool for assessing landslide hazards. High-resolution digital elevation maps (DEMs) were acquired to conduct the study, and the area of interest was carefully extracted for focused analysis. The input parameters for the analysis included both soil properties and unsaturated soil parameters, which were derived from previous studies and literature [34, 35]. These parameters are crucial for accurately modelling the

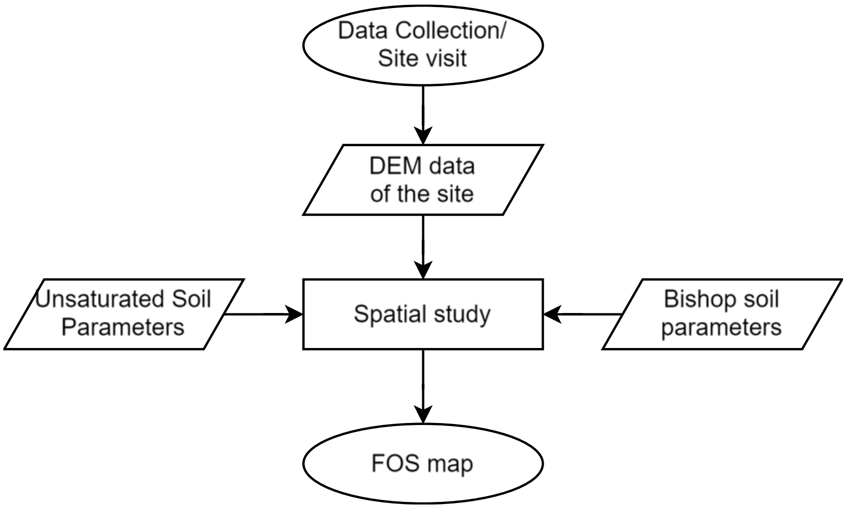

Figure 8: methodology adopter for spatial LEM analysis

3.2. Numerical Analysis

Table 2: Parameters considered for FEM and LEM analysis

Parameter	**Value**
Geocell Properties	
Pocket size	0.25x0.21x0.2 m
Axial Rigidity (EA)	550 kN/m
Shear Rigidity (GA)	275 kN/m
Infill material properties	
Unit Weight	20 kN/sq.m
Young’s Modulus	10 MPa
Cohesive strength	0 kPa
The angle of internal friction	30 Degrees
Geogrid Properties	
Axial Rigidity (EA)	500 kN/m
Shear Rigidity (GA)	250 kN/m
Equivalent Composite Soil Model (Geocell)	
Density	20 kN/cu.m

Young’s Modulus	1000 MPa
Cohesion	30 kPa
The angle of internal friction	36 Degrees

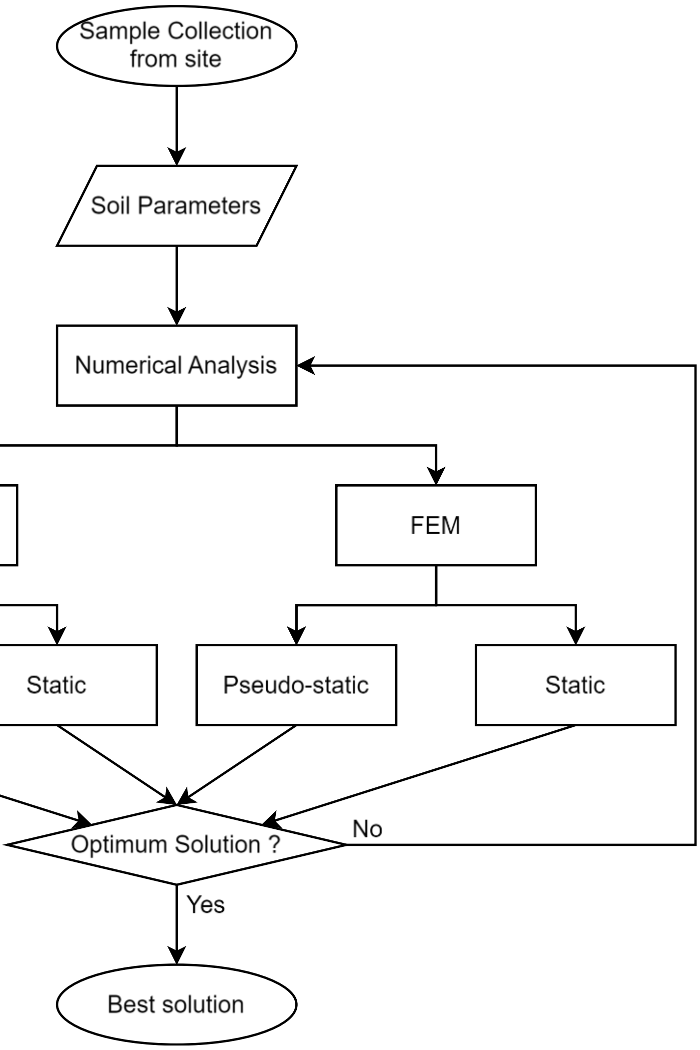

Figure 9: Methodology flow chart for numerical analysis

The geocell used in this study has been modelled based on previously established dimensions, specifically a pocket size of 250 x 210 x 200 mm [32]. Figure 10 illustrates the three-dimensional representation of the geocell model and the arrangement employed in this research. The material properties assigned to the geocell are consistent with those of a three-dimensional geotextile, with the specific values detailed in Table 2. For optimal drainage, gravel has been selected as the infill material. The geocells are arranged using a bottom-to-top stacking approach, where each successive layer is placed directly above the previous one. This stacking method creates a composite structure that functions as a 2-meter-wide retaining wall with 7-meter-wide geogrids found by considering trial and error. To enhance the stability of the system, a stepping offset of 0.1 meters is incorporated between each layer, and geogrids are provided, resulting in a stepped profile that effectively distributes loads and improves the overall performance of the retaining structure.

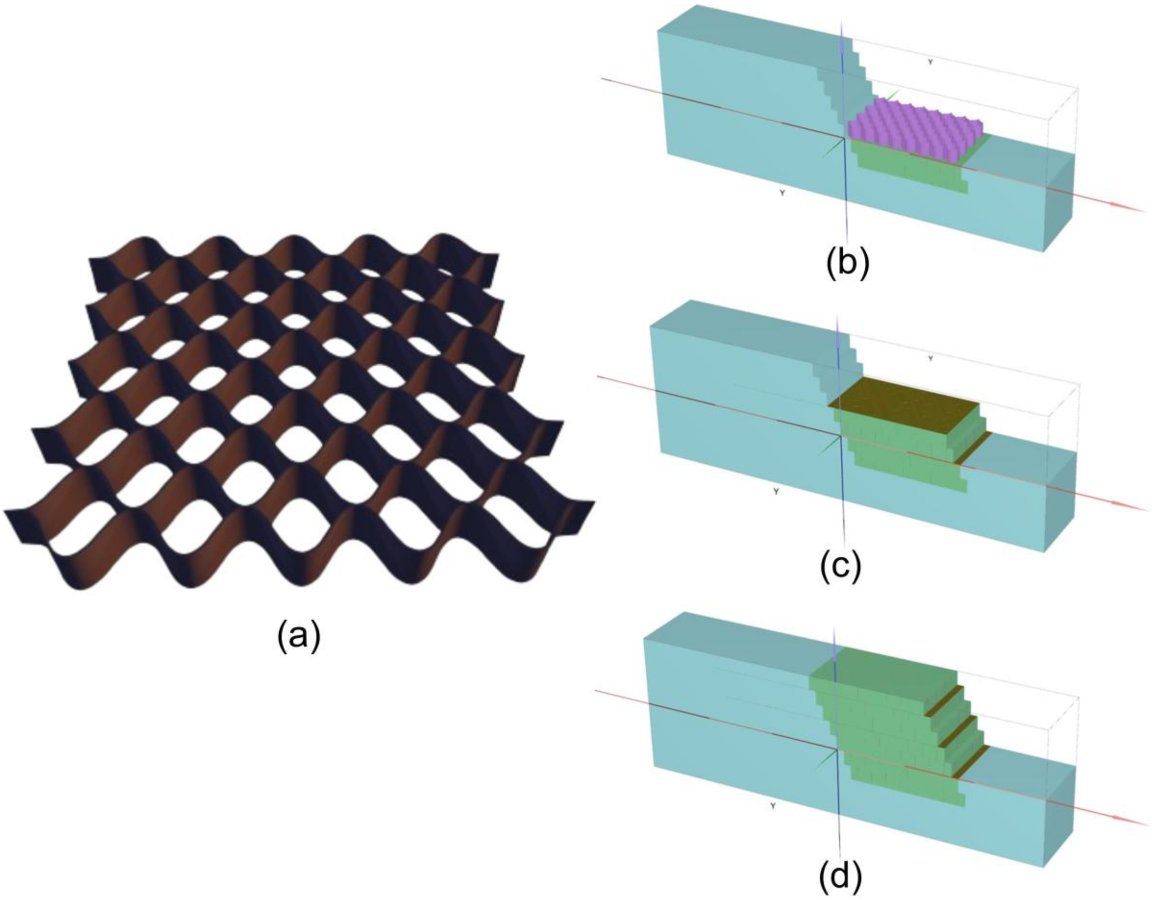

Figure 10: (a) Three-dimensional perspective view of the Geocell used (b) initial step by laying the geocell (c) secondary steps after filling the infill geogrids are placed (d) typical completed structure

4. Results and discussion

4.1. Spatial FOS

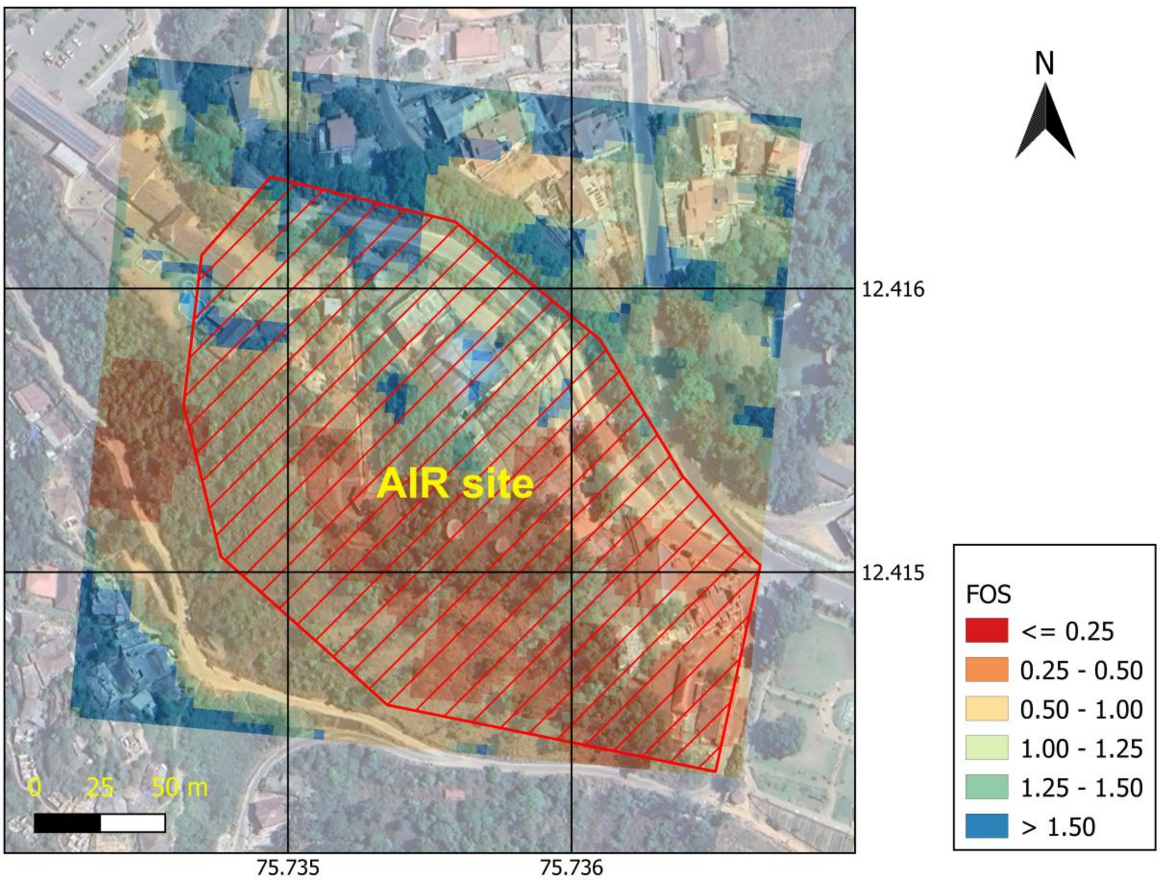

Figure 11: The Factor of safety of the area using the Spatial FOS analysis

Figure 12: Three-dimensional representation of the DEM with the FOS values given in Figure 11

4.2. Numerical Analysis

4.2.1. Limit Equilibrium Method Analysis

The four cases previously discussed were analyzed using the Limit Equilibrium Method (LEM) to determine the most critical scenario for assessing rainfall impact later in the Finite Element Method (FEM) analysis. Figure 13 illustrates the unreinforced cases, while Figure 14 presents the reinforced cases. Through a process of trial and error, it was concluded that the optimal solution involved using a 2-meter-wide geocell in combination with 7-meter-wide geogrids, spaced vertically at 0.6 meters with a 0.1-meter stepping offset for the geocell retaining structure. The 0.1-meter offset also provides space for planting vetiver plants, which can contribute additional biotechnical stabilization to the slope [45]. This integrated reinforcement system demonstrated promising results, as depicted in Figure 16 and Figure 18, for static and pseudo-static analyses, respectively. In contrast, Figure 15 and Figure 17 show the outcomes for the unprotected slope, highlighting the effectiveness of the reinforcement strategy. The analysis is performed in all the important LEM methods such as Bishop, Fellinius, Spencer, Janbu and Morgenstern [46].

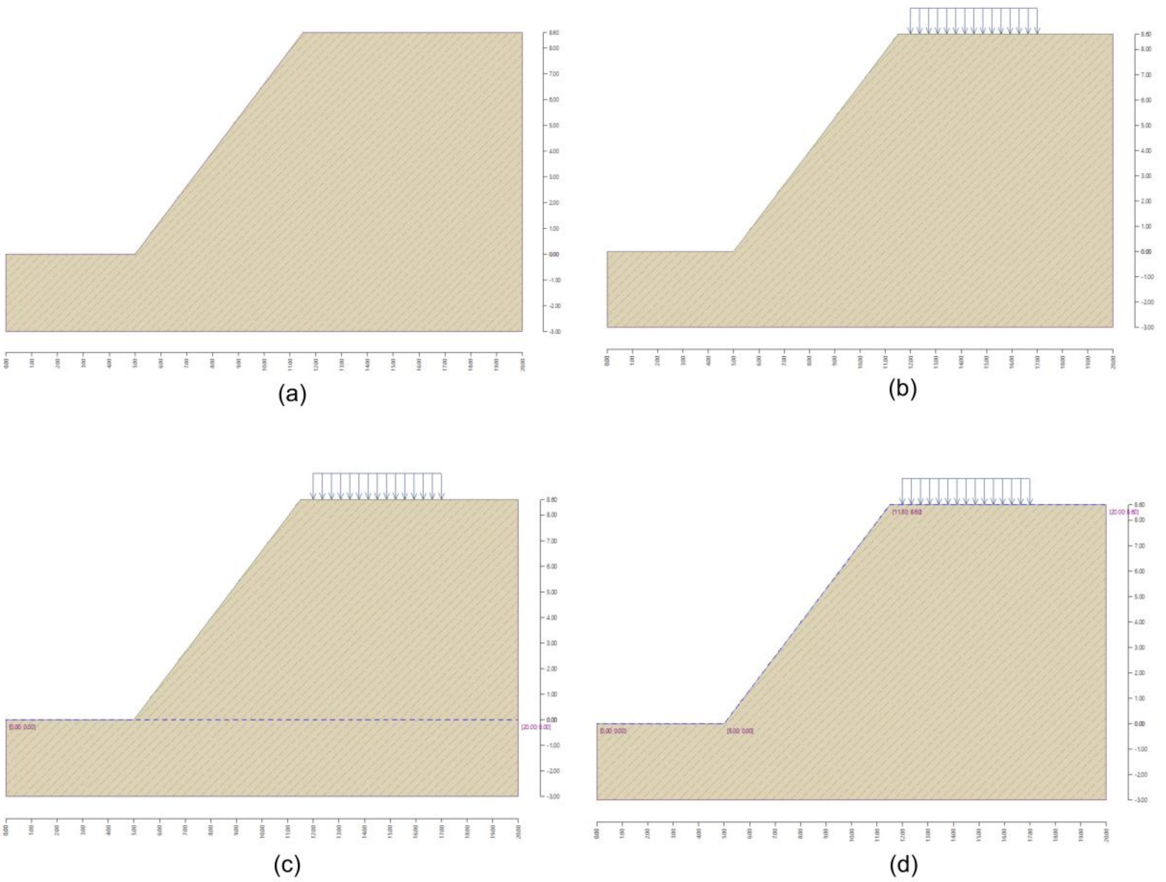

Figure 13: LEM analysis performed for (a) Soil slope, (b) Soil slope + surcharge, (c) Soil slope + surcharge + Water table till bottom and (d) Soil slope + surcharge + Fully saturated condition

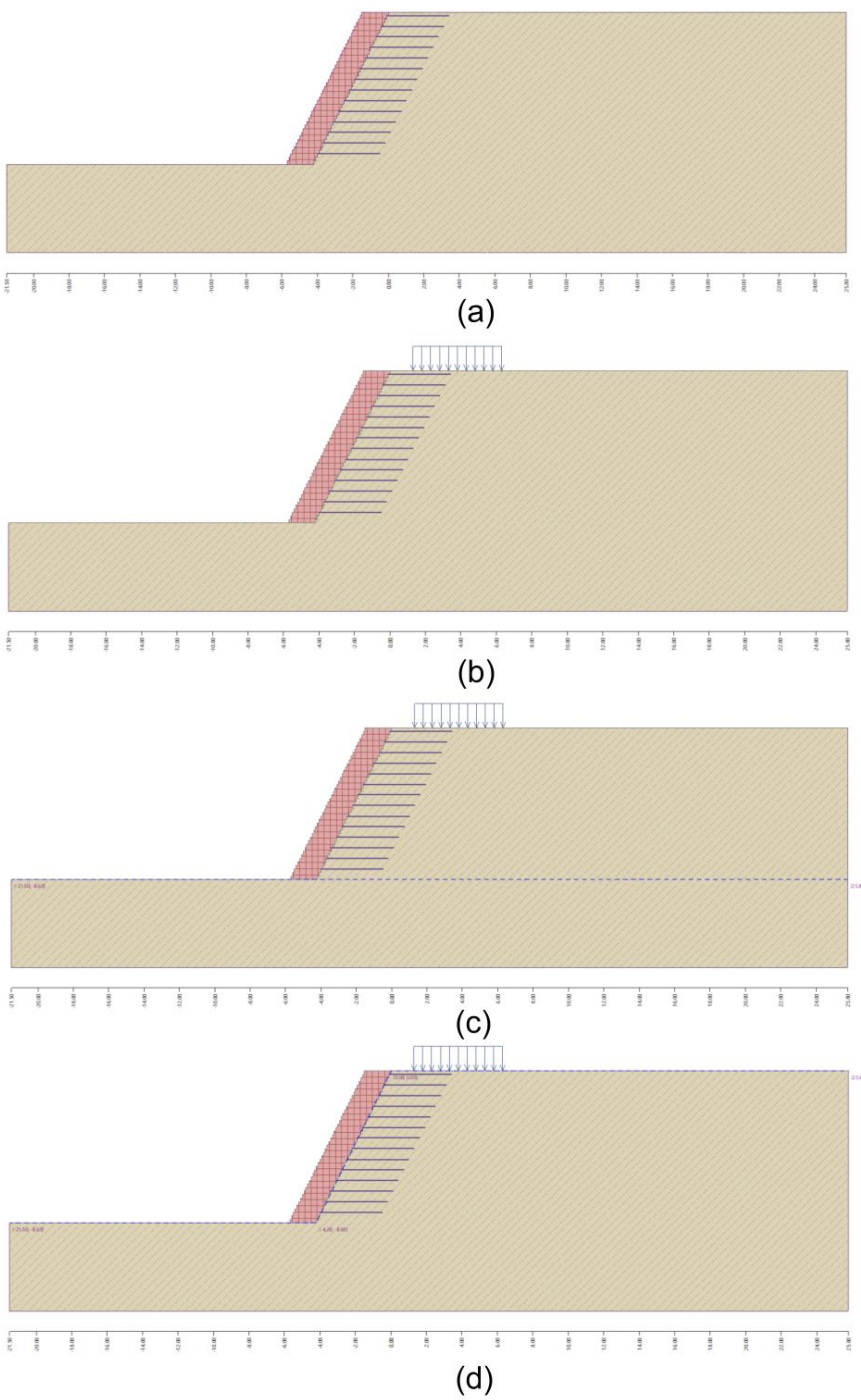

Figure 14: LEM analysis performed for (a) Reinforced soil slope, (b) Reinforced soil slope + surcharge, (c) Reinforced soil slope + surcharge + Water table till bottom and (d) Reinforced soil slope + surcharge + Fully saturated condition

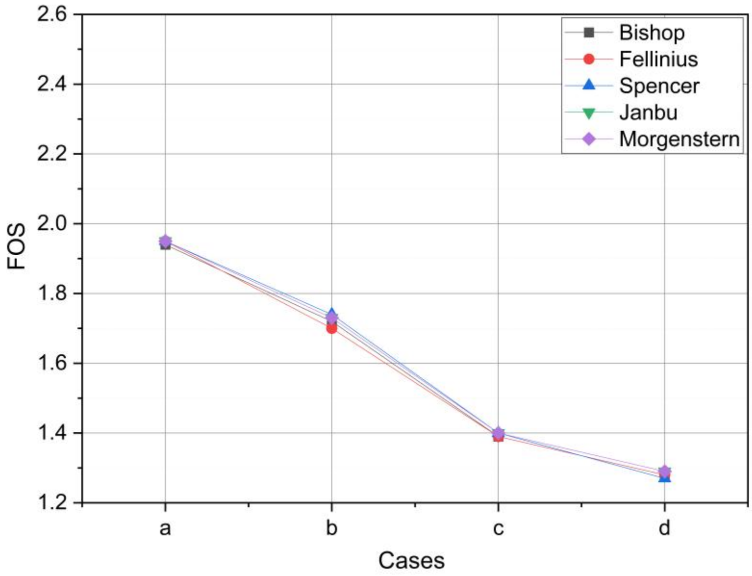

Figure 15: Factor of safety obtained for various cases of the soil slope for different LEM techniques

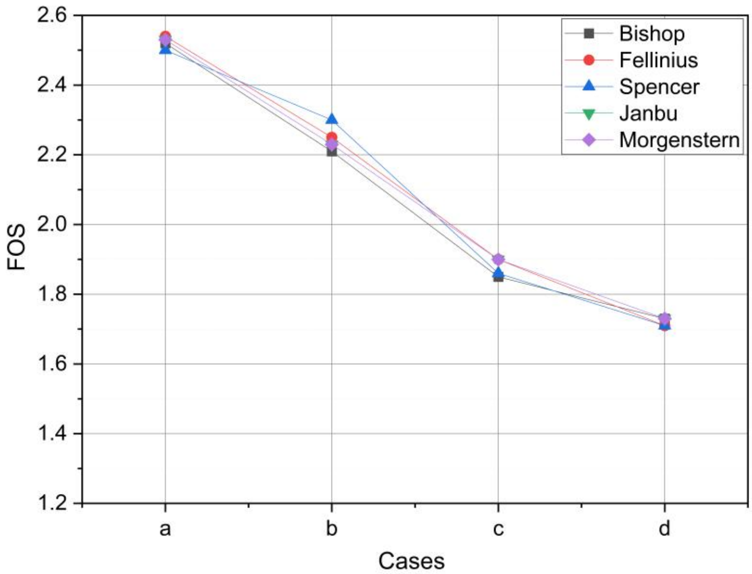

Figure 16: Factor of safety obtained for various cases of the reinforced soil slope for different LEM techniques

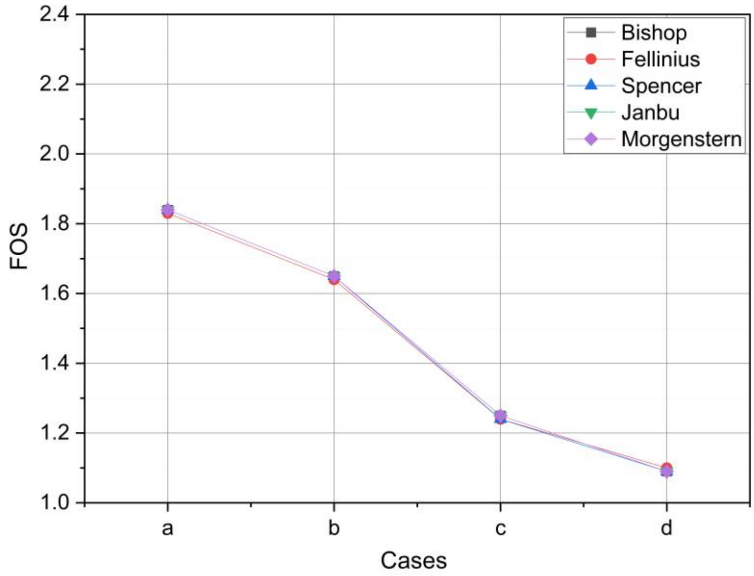

Figure 17: Factor of safety obtained for various cases of the soil slope for different LEM techniques considering pseudo-static analysis

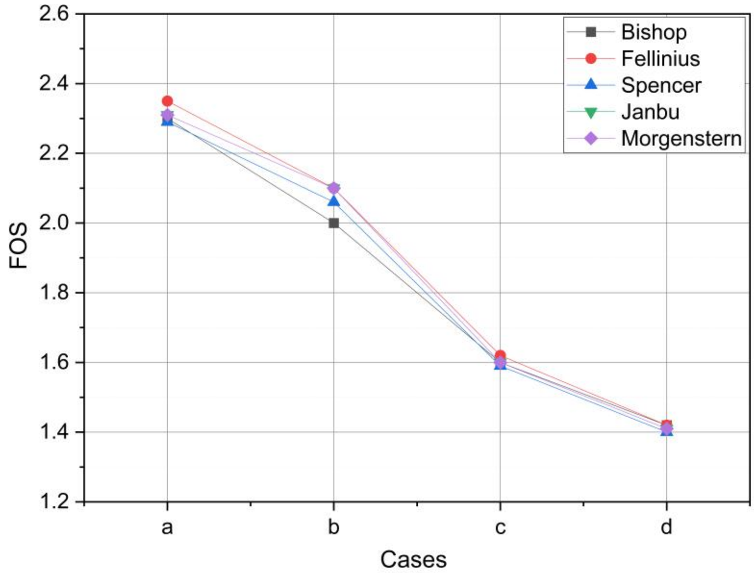

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Figure 18: Factor of safety obtained for various cases of the reinforced soil slope for different LEM techniques considering pseudo-static analysis

Figure 15 presents the static analysis of the existing soil slope under the four conditions outlined in Figure 13. In this analysis, Case A is approximately 12% safer than Case B, while Case B offers more than 23% greater safety compared to Case C. Additionally, Case C is around 8% safer than Case D. Figure 16, which depicts the reinforced soil slope conditions as described in Figure 14, shows a similar pattern. In this scenario, Case A is 14% safer than Case B, Case B is approximately 19% safer than Case C, and Case C is about 7% safer than Case D. Across all analyses, Case D, characterized by a soil slope subjected to a surcharge of 25 kN/m and fully saturated conditions, consistently yielded the lowest safety values. This trend is also evident in Figures 17 and 18, which show the pseudo-static analysis of the same profiles presented in Figures 13 and 14. In the unreinforced section, the Factor of Safety (FOS) for Case A is 1.68 times that of Case D. For the reinforced section, the FOS for Case A is 1.62 times that of Case D. Notably, the lowest recorded FOS is for the unreinforced soil slope in the pseudo-static condition, with a value of 1.09. However, with the proposed reinforcement technique, this value improved to 1.42, representing a 30% increase in safety. To assess the effects of rainfall, the same section under Case D conditions was replicated in FEM software to determine whether the provided reinforcement technique is sufficient to ensure stability under such adverse conditions.

4.2.2. Finite Element Method Analysis

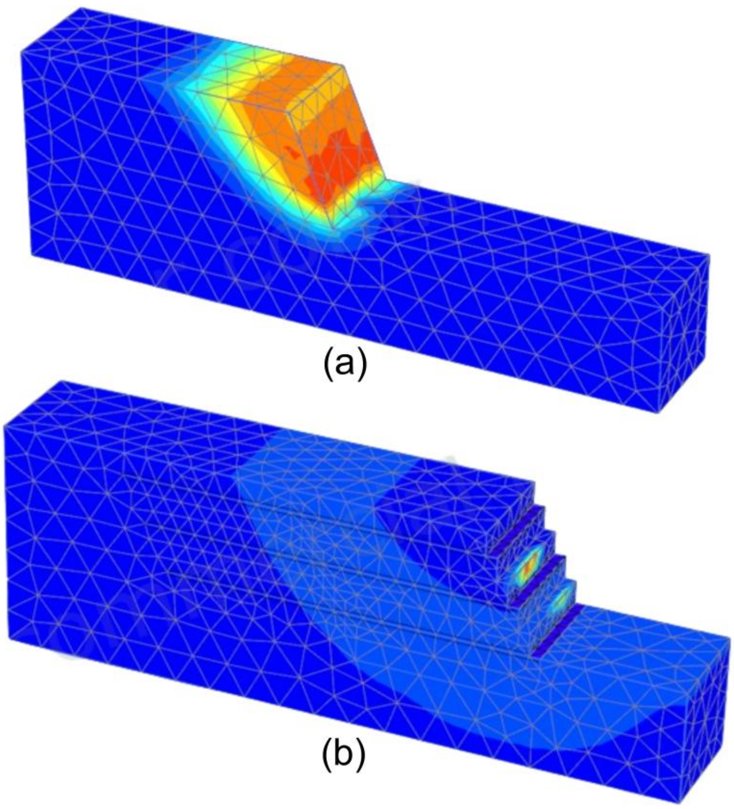

Figure 19: Fem analysis of the slope for (a) existing soil slope (b) reinforced soil slope

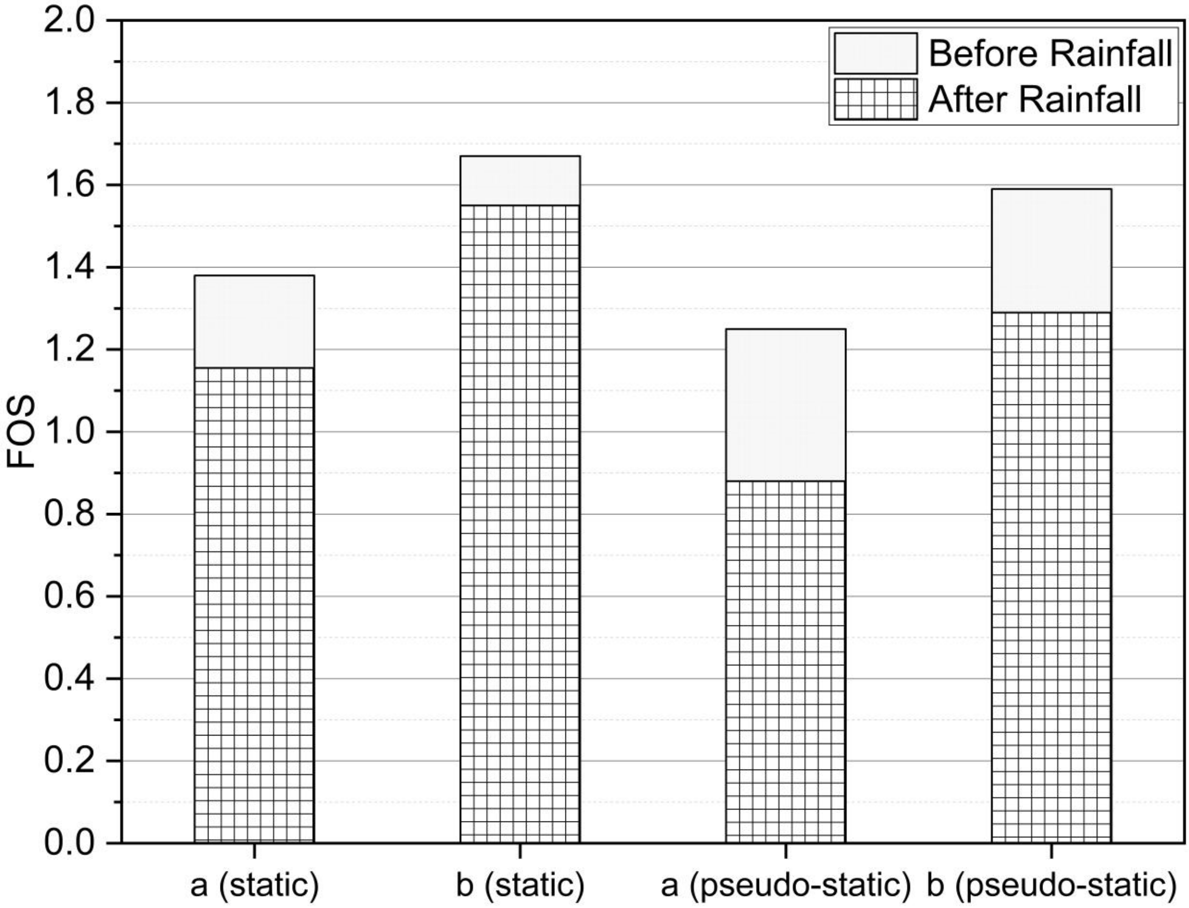

Figure 20: FEM analysis results for static and pseudo-static analysis

Table 3: Summary of the FEM analysis results

Analysis	Without reinforcement		With reinforcement	
	Before Rainfall	After Rainfall	Before Rainfall	After Rainfall
Static Analysis	1.39	1.16	1.67	1.55
Pseudo-static analysis	1.25	0.88	1.59	1.29

According to the analysis results, the FOS for Profile A experienced a reduction of 16% under static conditions and approximately 29% under pseudo-static conditions. It was observed that the soil slope in Profile A would collapse under pseudo-static conditions following rainfall, as the FOS fell below 1. For Profile B, which incorporates the proposed reinforcement technique, the FOS decreased by 7% under static conditions and by about 18% under pseudo-static conditions. This indicates that the reduction in FOS due to rainfall is significantly lower in the reinforced profile, demonstrating the effectiveness of the reinforcement technique, especially under rainfall conditions. The most critical situation observed in the unreinforced condition, where the FOS was dangerously low FOS of 0.88, saw 1.46 times more improvement in safety with the current reinforcement technique, resulting in an FOS of 1.29. According to Indian standards [39], the required safety factor for such hillside protection systems should be greater than 1.2, indicating that the proposed reinforcement method meets and exceeds this criterion. Figure 21 illustrates the design of the typical protection system designated for the critical section, as well as for the entire All India Radio (AIR) site. This design is particularly targeted at the landslide-prone areas identified in the spatial FOS analysis, ensuring comprehensive protection across the site.

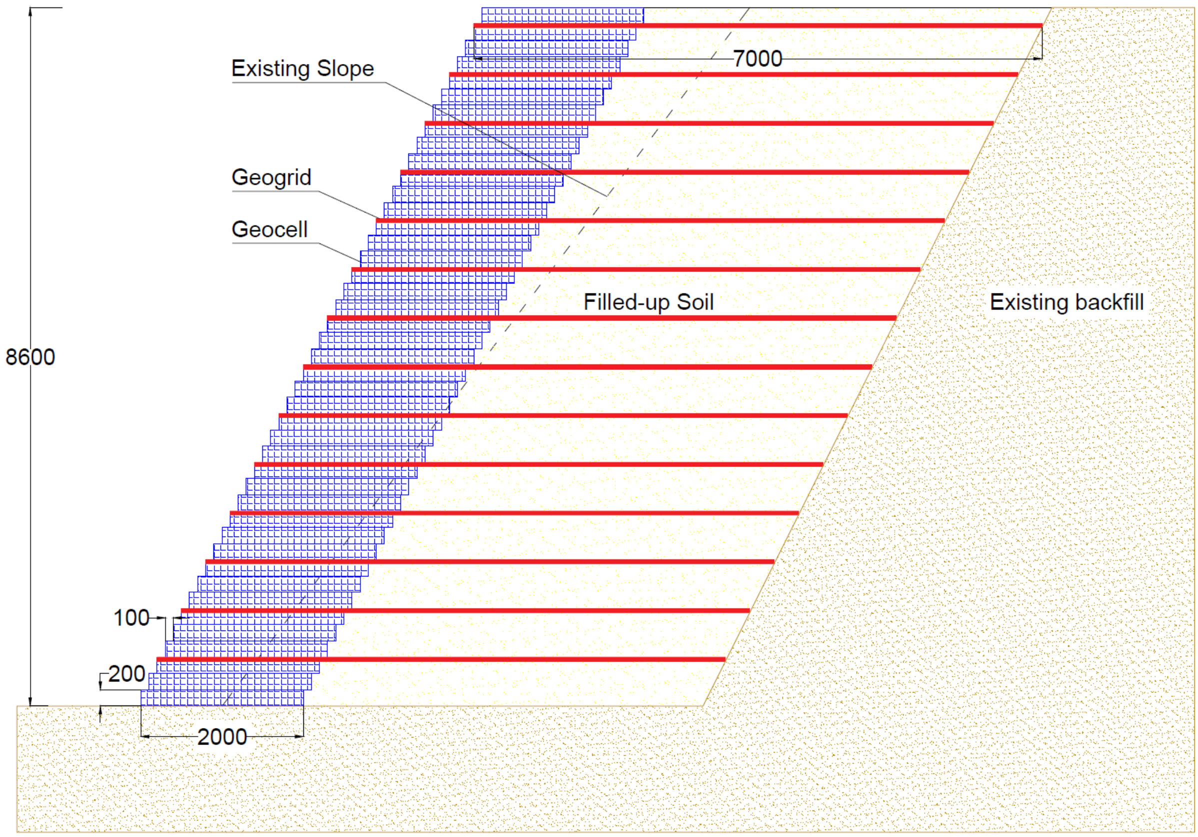

Figure 21: Reinforcement design (in mm) provided for the identified critical slope of the region