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Probabilistic Analysis of Slope Using Finite Element Approach and Limit Equilibrium Approach around Amalpata Landslide of West Central, Nepal

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Abstract

The stability study of the ongoing and recurring Amalpata landslide in Baglung in Nepal's Gandaki Province is presented in this research. The impacted slope is around 200 meters high, with two terraces that have different slope inclinations. The lower bench, located above the basement, consistently fails and sets others up for failure. The fluctuating water level of the slope, which travels down the slope masses, exacerbates the slide problem. The majority of these rocks are Amalpata landslide area experiences several structural disruptions. The area's stability must be evaluated in order to prevent and control more harm from occurring to the nearby agricultural land and people living along the slope. The slopes' failures increase the damages of house existing in nearby area and the erosion of the slope. Two modeling techniques the finite element approach and the limit equilibrium method were used to simulate the slope. The findings show that, in every case, the terrace above the basement is where the majority of the stress is concentrated, with a safety factor of near unity. Using probabilistic slope stability analysis, the failure probability was predicted to be between 98.90% and 100%.

Keywords

Finite Element Approach, Limit Equilibrium Method, Slope, Factor of Safety

1. Introduction

In nature, landslides occur often, particularly in mountainous areas, yet it is still unclear how predictable they are. Critical in nature, landslides are caused by a variety of reasons. The increasing number of human operations is causing landslides to occur more frequently every day. The Himalayan area is particularly susceptible because of its high relief, complicated geology, immature rock mass, high rainfall intensity, and several other local characteristics. It is also youthful and active. The stability of both naturally occurring and artificially created slopes has been extensively studied for decades. Deterministic analysis methods use a mean value of required mechanical parameters. In areas prone to landslides, slope stability problems are characterized by a variety of uncertainties, including geological anomalies, inherent anisotropy in rock mass properties, variable environmental conditions, and human roles in design and construction. Because the mean value of input parameters is taken into account for slope stability analysis, slope failure may occasionally occur even when the computed factor of safety is greater than the probability.

A range of each geo-mechanical parameter that indicates the uncertainties in the rock mass is provided by the probabilistic analysis. The impact of spatial variability of soil parameters on likelihood of failure using a random field theory known as the Random Limit Equilibrium approach (RLEM) and a circular slip limit equilibrium approach [1]. Since the 1970s, slope engineers have been familiar with probabilistic slope stability analysis, or PSSA [2]. The ideas and tenets of PSSA have been thoroughly thought out, established, and recorded in the literature over the last several decades [2] [3] [4] [5] [6]. The principles in assessing the uncertainty of rock characteristics and the useful methods for PSSA based on Monte Carlo simulation were outlined [2]. The frequency of landslides in the seismically active Himalayan region and its estimated magnitude are not fully implicit. The dynamic and young Himalayan rocks, along with their load-deformation behavior, pose a serious threat to the stability of slopes. The high intensity rainfall exacerbates this issue further because of the high porosity and wettability of the rock mass. Studies by [7] [8] [9] [10], and [11] have presented the findings of probabilistic stability analyses that took into account the regional variability of soil parameters and used the limit equilibrium method (LEM). The pore water pressure also plays a significant role in reducing the rock's strength. The evolution of risk associated with uncertainty necessitates the use of probabilistic concepts and methodology [2]. Advanced numerical analysis techniques, including the Finite Element Method (FEM), the Finite Difference Method, the Differential Equation Method, and Hybrid Methods, have been employed to ensure a higher level of confidence in the results of numerical analyses. This is made possible by a growing comprehension of computational tools and technology [12]. FEM is increasingly being applied to FEM slope analysis. The Shear Strength Reduction (SSR) approach is one of the most popular techniques for performing FEM slope analysis, as reported by [13]. The basic idea of the SSR approach is to systematically reduce the shear strength of the material envelope by a factor of safety and compute FEM models of the slope until deformations are unacceptably large or the solutions do not converge.

In addition to numerical approaches and convectional limits, soft computing techniques like neural networks, fuzzy logic, adaptive neural-fuzzy inference systems, and support vector machines have been employed in the study of landslide hazard zones [14] [15]. These techniques were based on the researcher's experience and/or extensive case histories. Numerous researchers have worked on the slope stability problem of the Amalpata landslide. The factor of safety is currently calculated using the traditional kinematic analysis method with the Markland formula in addition to various numerical approaches [16]. Some researchers [17] dated the landslide event by neo-tectonic movement in the region.

The goal of the current study is to examine the stability of a 200-meter-high slope in the landslide-prone Amalpata area of Baglung District, Gandaki Province, Nepal. Due to its extreme vulnerability, the area's slopes have seen two significant landslides in 2009 and 2023 in addition to several smaller ones that are recorded virtually yearly, particularly during the monsoon season. The research examines the risk analysis of slope stability for a segment of the Amalpata Village area. Two distinct techniques for slope stability analysis have been employed: FEM and the limit equilibrium method with probabilistic approach. A probabilistic technique to studying the slope would be too risky due to its vulnerability. To assess the degree of risk connected to the slope's stability, a probabilistic technique could be taken into consideration.

2. Study Area

The landslide in the study region was given the name "Amalpata-Binamare landslide" in honor of the Binamare village, which is located in Jaimini Municipality's Ward No. 5 in the province of Gandaki (**Figure 1**). This landslide had some impact on Binamare village. From 28˚10'12.16"N, 83˚38'17.90"E to 28˚10'14.35''N, 83˚38'22.32''E, the impacted region is located. Its elevation ranges from 2753 ft to 2289 ft above sea level. There are 2 - 4 households, with a total population of roughly 20, that are impacted by the Amalpata-Binamare landslides.

3. Geology of Study Area

Geologically study area lies in Lesser Himalaya and stratigraphically consists Kuncha Formation and Benighat Slate, fine grained, thick to thin banded dark gray to black color slate, crenulated greenish grey to soppy phyllite. Then the slope is concave and plane type, presence of topographical break along the slope, agricultural land use plus settlement, slope angle of 35˚ - 40˚. The location of the settlement in terms of geomorphology is at top of the slope. At the toe of the landslide there exists small shear zones having with is about 5 m and 15 meter length.

4. Methodology

The two units of the Amalpata slope Geometry are based on the differences in

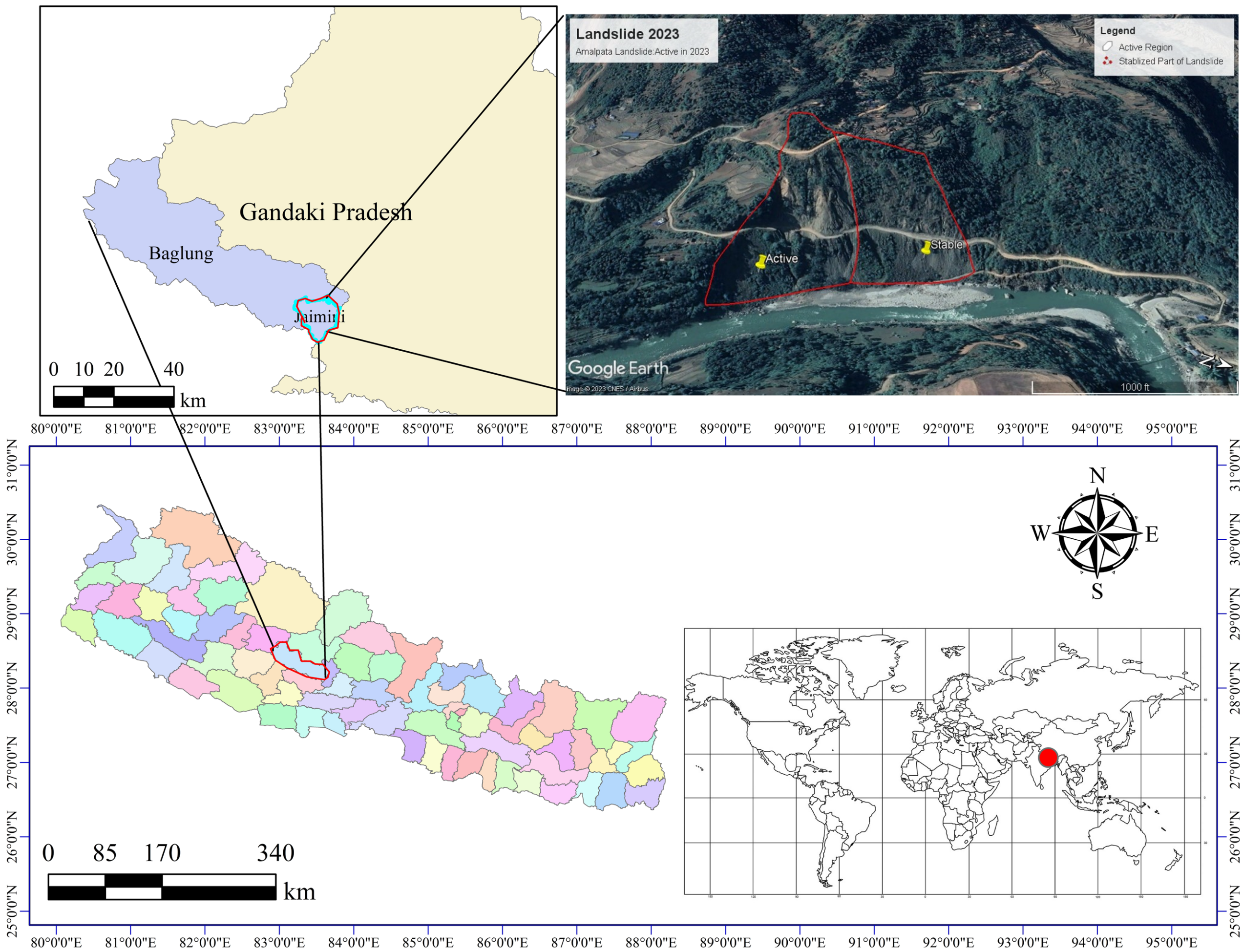
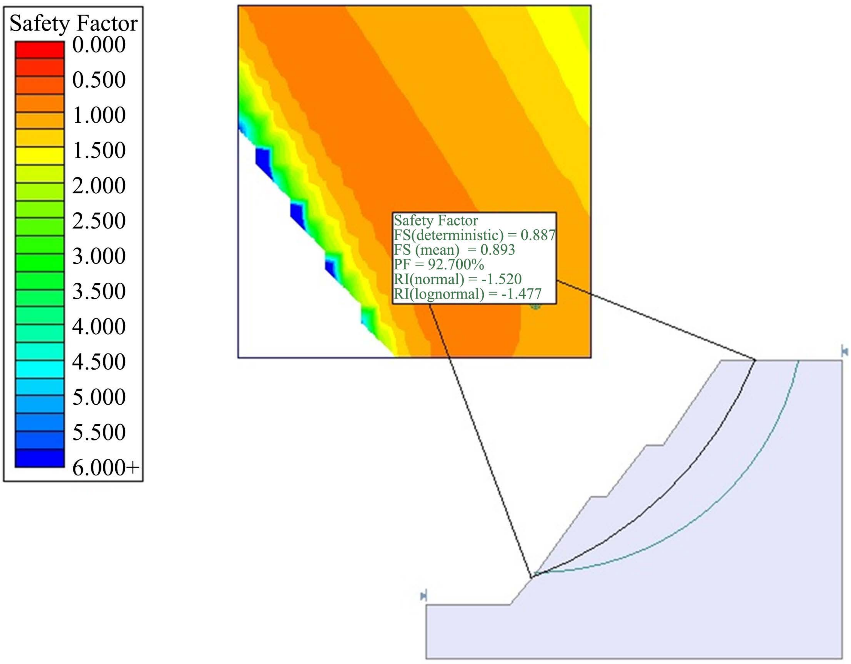
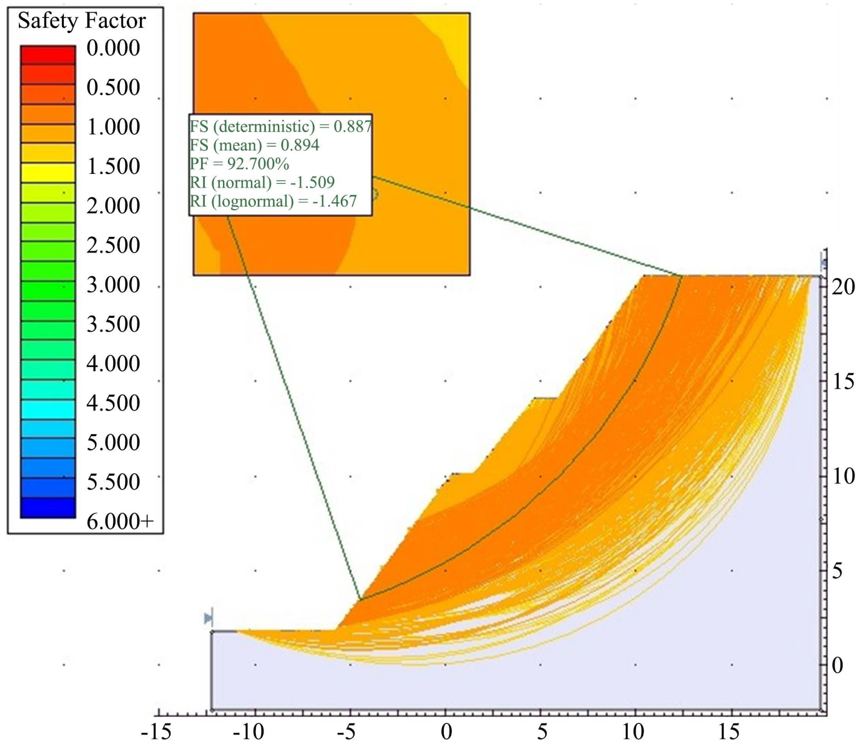


Figure 1. Study area location map.

the geo-mechanical and lithological characteristics of the slope material. Using Slide and Phase 2 software, probabilistic risk was combined with a combination of deterministic method by limit equilibrium method and FEM to investigate the area's slope stability. PSSA is based on Monte Carlo simulation, developed in Slide, and has the advantage of being user-friendly interfaced without requiring a deep knowledge of statistical and mathematical backgrounds. Figure 2 shows the simulation of the slope geometry, stratigraphy, and geo-mechanical characteristics. A slope may have infinitely many slip surfaces. These slip surfaces may experience a slope failure. The critical slip surfaces are identified using the grid method. Bishop's method examined a total of around 3980 valid slip surfaces in order to investigate the slope's safety. Using a different set of randomly generated input variables for each analysis, probabilistic analysis was performed on the global minimum slip surface located by the deterministic slope stability analysis. The factor of safety was then computed N (where N is the number of samples; 1000) times for the global minimum slip surface. The analysis has calculated the reliability index (measure of the level of confidence or safety margin in a system or structure), probability of failure (it is the likelihood that a slope will not perform



(a)



(b)

Figure 2. (a) Bishop method of slope stability analysis with FOS; (b) Multiple slip surfaces.

its intended function under specified conditions), mean factor of safety (mean factor of safety is the average or expected value of the factor of safety over a given population or range of scenarios), and deterministic factor of safety (It is the factor of safety calculated based on deterministic or fixed values for material properties, loads, and other parameters). The factors of safety of the slope are frequently determined using the Bishop (1955), Janbu (1954, 1957), and Spencer (1967) methods. Strong correlations between slip surfaces can sometimes significantly reduce the difference between the total probability of slope performance and that of the critical slip surface. Accordingly, a fair estimate of slope reliability is determined by doing a probabilistic study of the most significant slip surface [2] [18]. The statistical method of representative probabilistic describes the uncertainty in input parameters such as cohesiveness, angle of friction, and unit weight. For every input parameter, the normal probabilistic distribution has been taken into consideration. Histograms display the true random samples for cohesiveness, friction angle, and unit weight that were produced using Monte Carlo sampling techniques (**Figure 3**) and Latin hypercube method (**Figure 4**). Additionally, data with a Bishop factor of safety less than 1 is indicated on the plots. It is evident that failure corresponds to the lowest friction angles for the random variable of friction. The "Slide" presents two sampling techniques: Monte Carlo and Latin Hypercube. The latter technique has been proposed as a way to more accurately generate the random sampling of input parameters needed for Monte Carlo simulation. The advantage of Latin Hypercube sampling over Monte Carlo method is that it produces a more uniform and smoother sampling of the probability density function for defined input variables. This is because the latter method is based on "stratified" sampling, which involves random selection within a stratum [19]. Phase 2, which is very simple and has the ability to import "Slide" files, is used in FEM analysis. This reduces the amount of time needed for simulation. The slope was divided using uniform six-triangular meshes, which produced a total of 1442 elements and 2670 nodes. The Mohr-Coulomb failure criteria were applied in light of the plastic behavior of the materials. The input parameters for numerical simulation are provided in **Table 1**.

5. Results and Discussion

The slope stability risk assessment, including the methods used (deterministic, probabilistic, and Finite Element Method—FEM) and specific details about Bishop's method were carried out for this slope. Additionally, the consideration of slips surfaces and the application of probabilistic analysis to the global minimum

Table 1. Input parameter for slope materials.

S.N.	Property	Units	Value
1.	Cohesion	kPa	7
2.	Friction angle	deg	22
3.	Poission's ratio	-	0.18
4.	Model of materials	Mohr-Coulomb	Mohr-Coulomb
5.	Angle of slope	(˚)	65˚

slip surface identified through deterministic analysis. In Figure 2(b), it seems there is a representation of all slip surfaces considered in the slope stability analysis using Bishop's method. This figure likely illustrates the geometry and Characteristics of these slip surfaces. And also seems to highlight slip surfaces with a factor of safety less than 1.5. The factor of safety is a crucial parameter in slope stability analysis, representing the ratio of resisting forces to driving forces. A factor of safety less than 1 indicates instability (Figure 2(a) and Figure 2(b)).

Probabilistic analyses were conducted using Ordinary/Fellenius, Bishop simplified, Janbu simplified, Janbu Corrected, Spencer, GLE/Morgenstern-Price, Corps of Engineers #1, and Corps of Engineers #2 methods in the slope stability assessment. Surprisingly, the probabilistic factor of safety closely aligned with the deterministic factor of safety across the various methods employed (Figure 5). The probability of failure was consistently observed in the range of 91.40% to 98.90% using different methods (Table 2).

For instance, employing the Bishop simplified method reveals that 926 out of 1000 data points exhibit a factor of safety less than 1, corresponding to a 92.70% probability of failure (Figure 2(a)). The reliability index for Bishop's method is approximately 1, suggesting an unstable slope. In standard practice, a reliability index of less than 3 is considered prone to failure.

Using scatterplots, two random variables can be plotted against one another on the same plot, allowing for the analysis of the relationships between the variables (Figure 6(a) and Figure 6(b)). A convergence plot is useful for determining whether or not the probabilistic analysis is converging to a final solution, or whether more samples are required. Here, the convergence plot for Bishop's method indicates that the mean factor of safety curve becomes constant after the 600 samples, so 1000 samples are sufficient to determine the factor of safety and the probabilistic failure (Figure 7(a) and Figure 7(b)). Additionally, the probability of the failure curve is converging to final value, *i.e.* 13.5%.

Table 2. Deterministic and probabilistic safety factors derived from diverse techniques.

S.N.	Methods	Factor of Safety		Probability of Failure (%)	Reliability Index
		Deterministic	Probabilistic		
1.	Ordinary/Fellenius	0.835	0.842	98.30	2.358
2.	Bishop Simplified	0.887	0.893	92.70	1.52
3	Janbu Simplified	0.828	0.834	98.90	2.476
4.	Janbu Corrected	0.872	0.879	95.00	1.714
5.	Spencer	0.879	0.889	93.50	1.575
6.	GLE/Morgenstern-Price	0.880	0.889	94.10	1.573
7.	Corps of Engineers#1	0.886	0.894	92.10	1.492
8.	Corps of Engineers#2	0.889	0.897	91.40	1.45

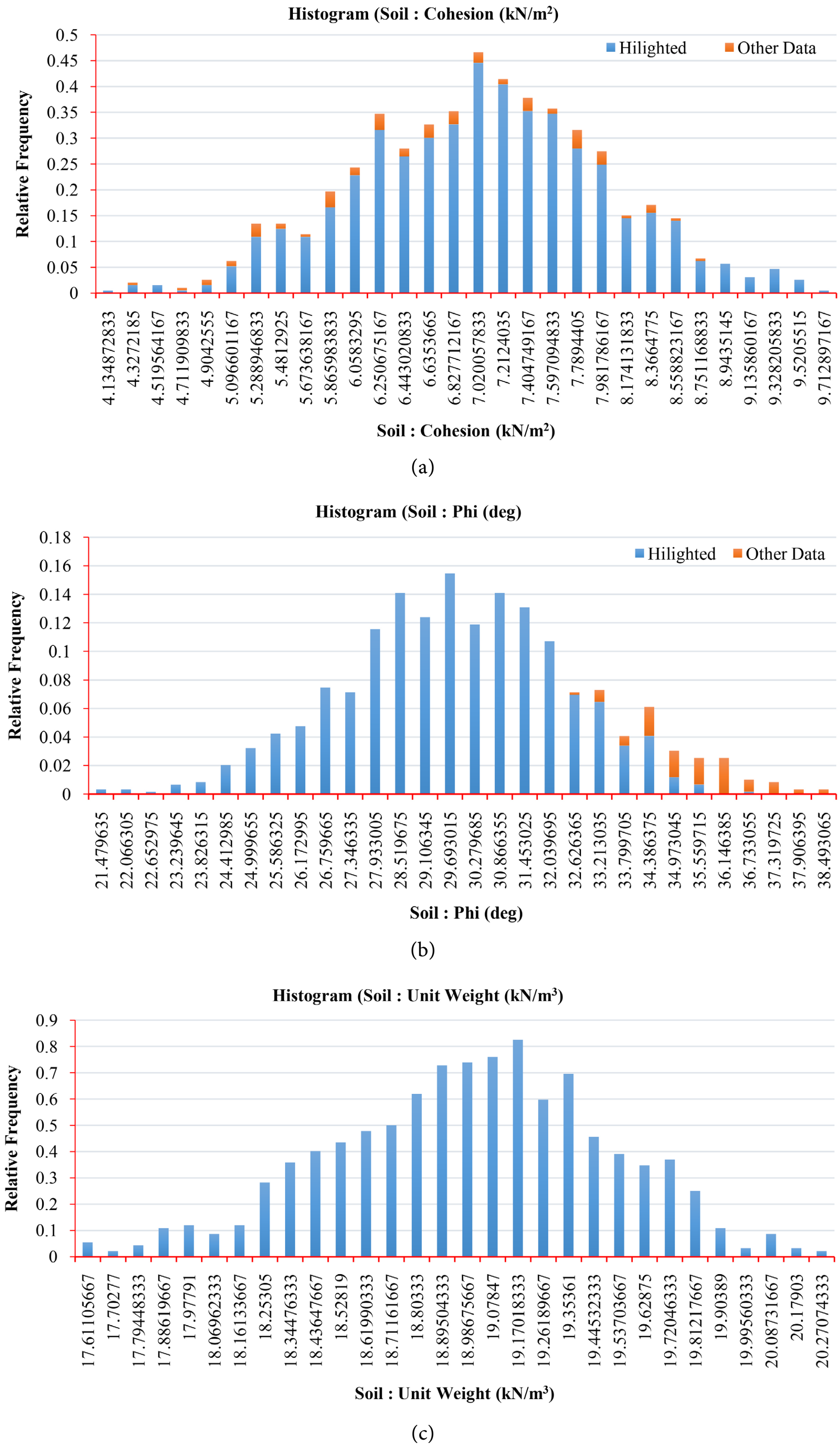


Figure 3. Probabilistic distribution for input parameter for slope materials (a) Cohesion, (b) Friction and (c) Unit weight using Monte Carlo Method.

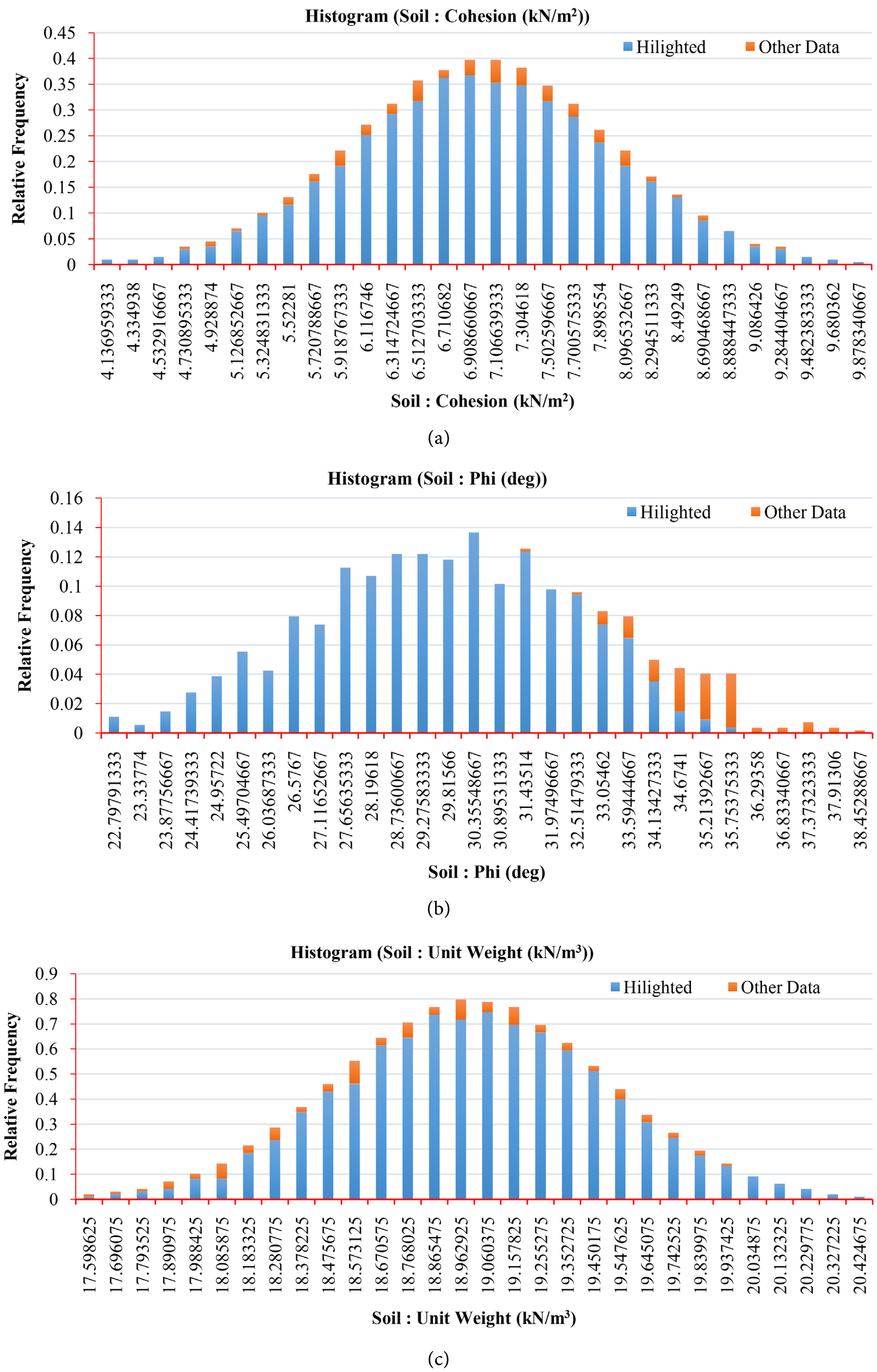
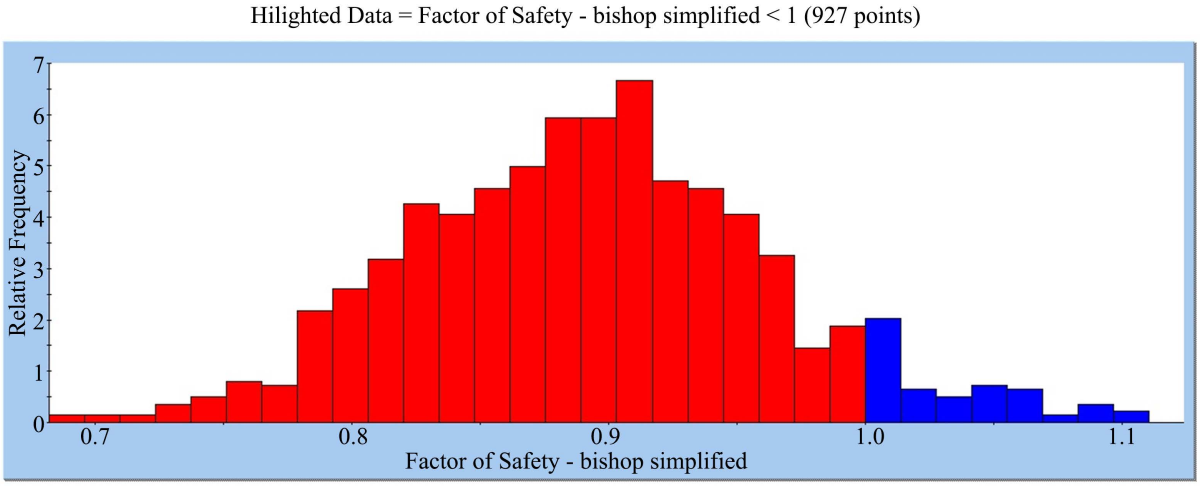
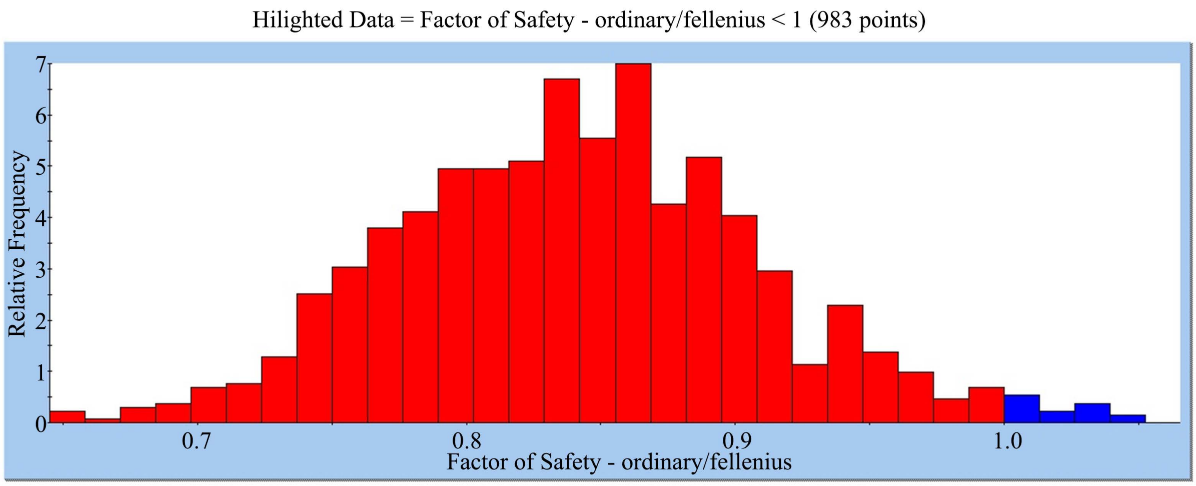


Figure 4. Probabilistic distribution by using Latin hypercube method (a) Cohesion, (b) Friction and (c) Unit weight.



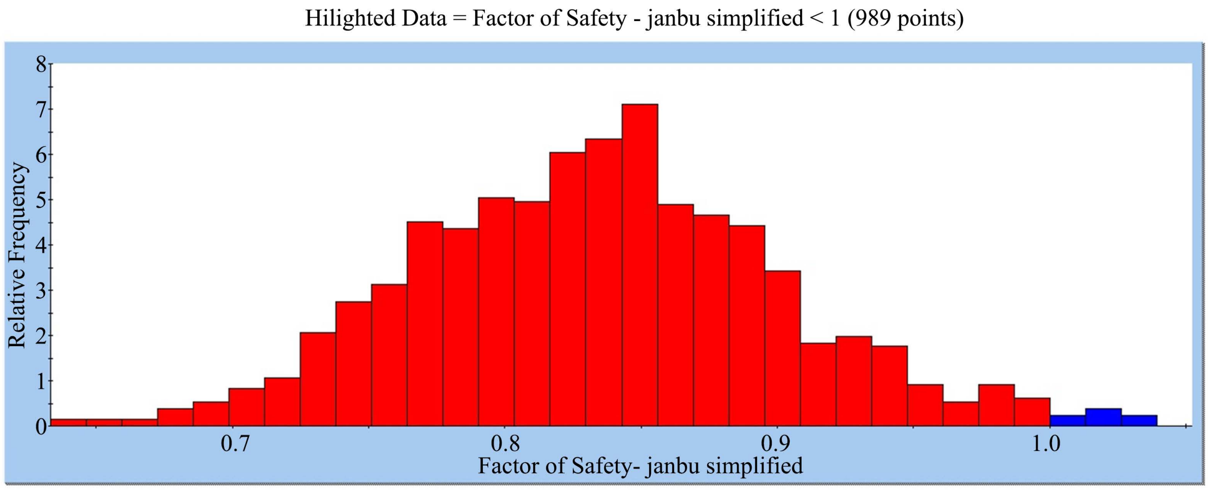
SAMPLED: mean = 0.8933 s.d. = 0.07017 min = 0.6924 max = 1.107 (PF = 92.700% RI = -1.52012, best fit = Gamma distribution)

(a)



SAMPLED: mean = 0.8415 s.d. = 0.0672 min = 0.6506 max = 1.045 (PF = 98.300% RI = -2.35790, best fit = Gamma distribution)

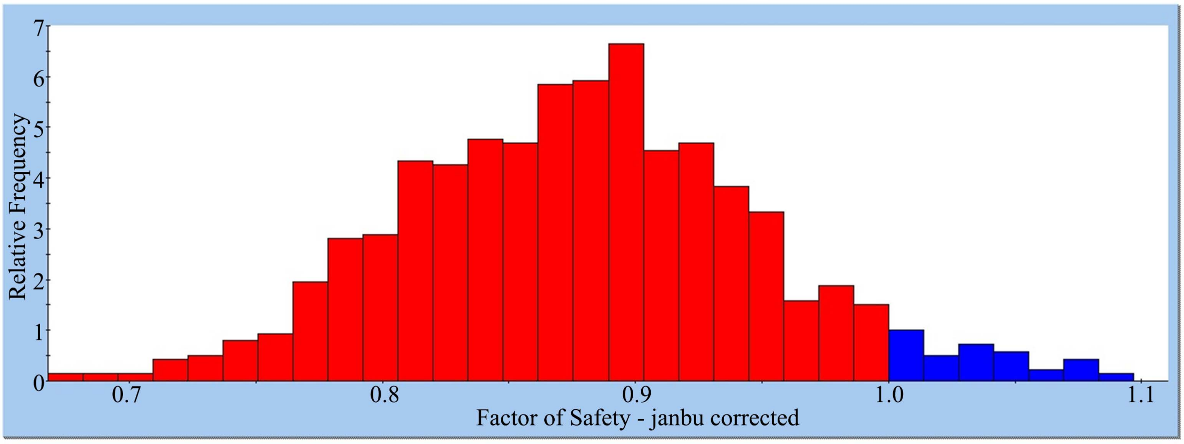
(b)



SAMPLED: mean = 0.8341 s.d. = 0.06702 min = 0.6449 max = 1.038 (PF = 98.900% RI = -2.47574, best fit = Gamma distribution)

(c)

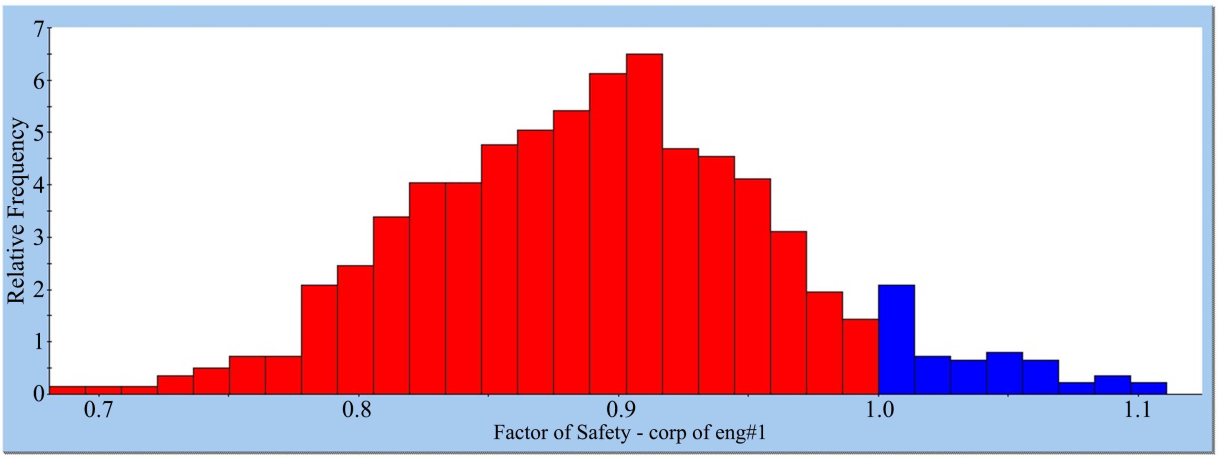
Hilighted Data = Factor of Safety - janbu corrected < 1 (950 points)



SAMPLED: mean = 0.8789 s.d. = 0.07063 min = 0.6782 max = 1.093 (PF = 95.000% RI = -1.71406, best fit = Gamma distribution)

(d)

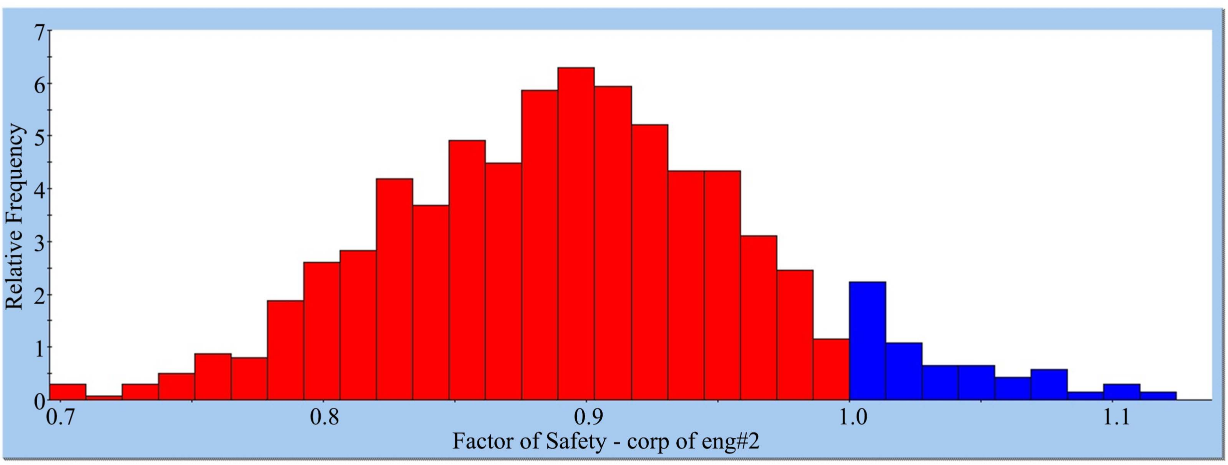
Hilighted Data = Factor of Safety - corp of eng#1 < 1 (921 points)



SAMPLED: mean = 0.894 s.d. = 0.07109 min = 0.6939 max = 1.11 (PF = 92.100% RI = -1.49159, best fit = Gamma distribution)

(e)

Hilighted Data = Factor of Safety - corp of eng#2 < 1 (914 points)



SAMPL ED: mean = 0.8965 s.d. = 0.07133 min = 0.6977 max = 1.112 (PF = 91.400% RI = -1.45029, best fit = Gamma distribution)

(f)

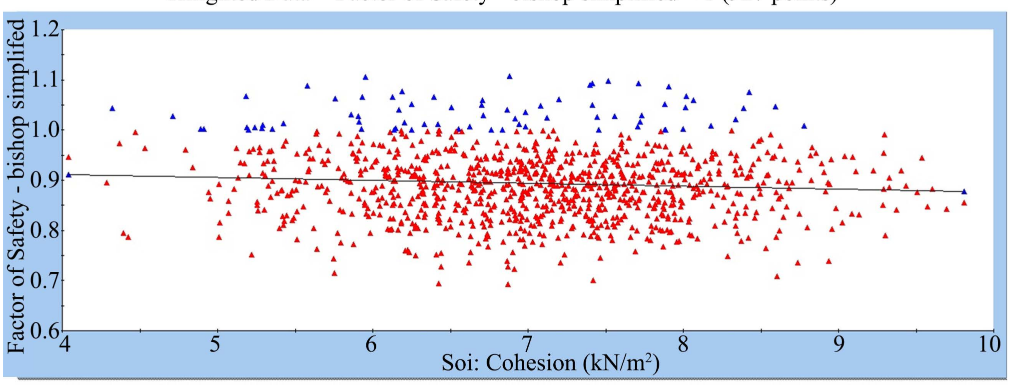
Hilighted Data = Factor of Safety - gle/morgenstern-price < 1 (941 points)

SAMPLED: mean = 0.889 s.d. = 0.07056 min = 0.6913 max = 1.102 (PF = 94.100% R = -1.57299, best fit = Gamma distribution)

(g)

Figure 5. Normal probabilistic distribution for different method of slope stability analysis (a) Bishop Simplified, (b) Ordinary/Fellenius, (c) Janbu Simplified, (d) Janbu Corrected, (e) Corp of Eng #1, (f) Corp of Eng #2 and (g) GLE/Morgenstern-price.

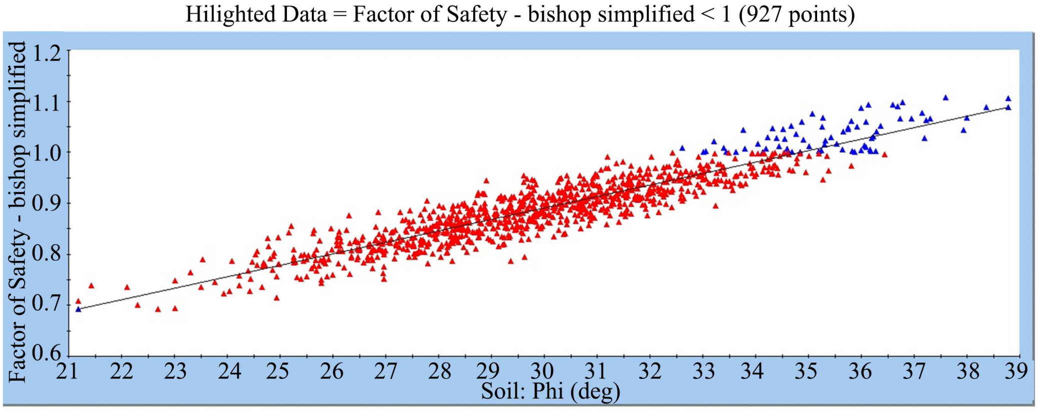
Hilighted Data = Factor of Safety - bishop simplified < 1 (927 points)



Correlation Coefficient = -0.0797721, alpha = 0.933466, beta = -0.00570361 (All Data)

(a)

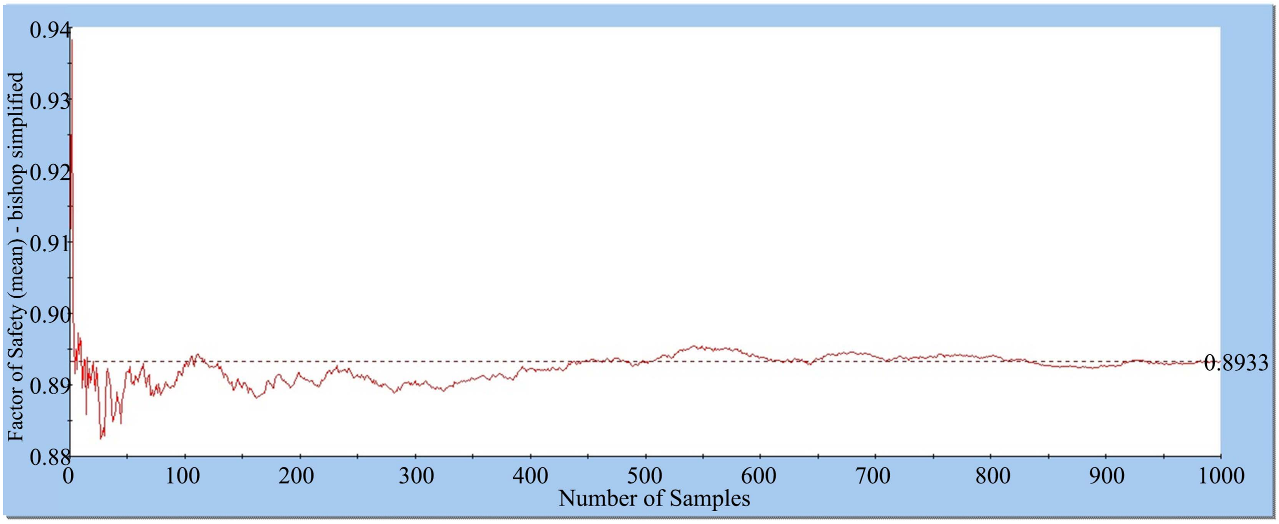
Hilighted Data = Factor of Safety - bishop simplified < 1 (927 points)



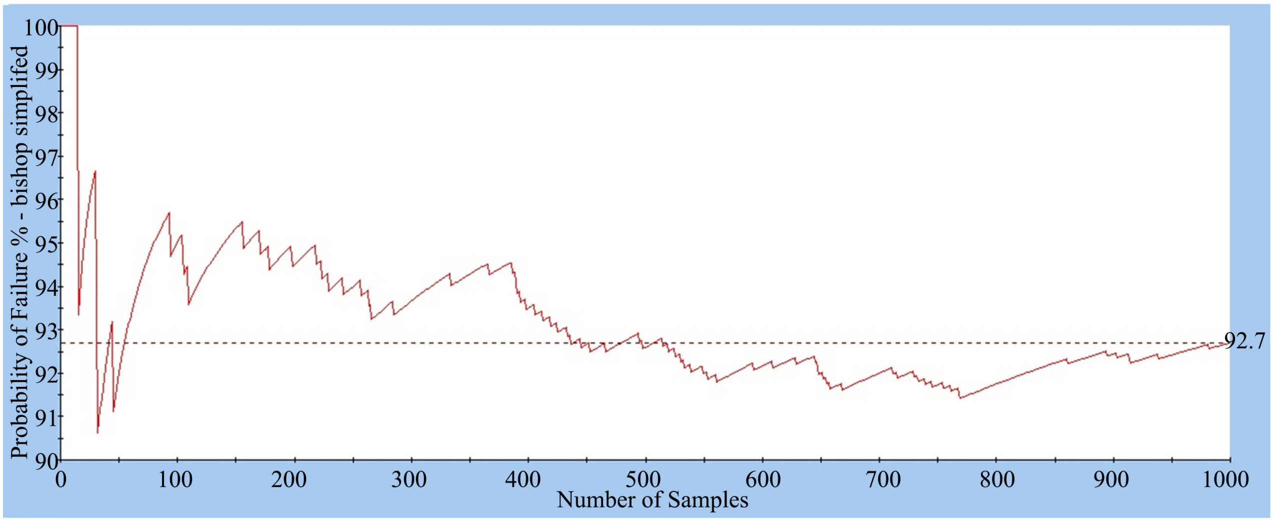
Correlation Coefficient = 0.922509, alpha = 0.214654, beta = 0.0225363 (All Data)

(b)

Figure 6. Scatter plot of bishop simplified method (a) Cohesion vs factor of safety, and (b) Phi vs factor of safety.



(a)



(b)

Figure 7. Convergence plot for the Bishop method: (a) mean safety factor and (b) probability of failure.

The slope's mesh geometry for FEM analysis is displayed in **Figure 8(a)** Meshing FEM approaches 0.82 as the critical SRF. (b) Deformation vectors are displayed in **Figure 8(b)**, which also indicates sufficient displacement to bring about a failure in the slope. The total displacement contours highlight the zone of failure. **Figure 8(c)** shows the contour of total displacement along with deformed mesh. The total displacement contours highlight the zone of failure. The total displacement by the analysis was 8.91 mtr. SSR analysis also provides a plot between maximum deformations and SRF (**Figure 9**). At a certain point, the slope failed, and the maximum displacement increased. The solution did not converge, indicating the point of non-convergence that defines the critical SRF. Critical SRF 0.82 is found here at a displacement of 8.91 meters.

According to both methods, the slope materials are more likely to fail. To prevent the slope from failing and causing significant damage to the area, this layer

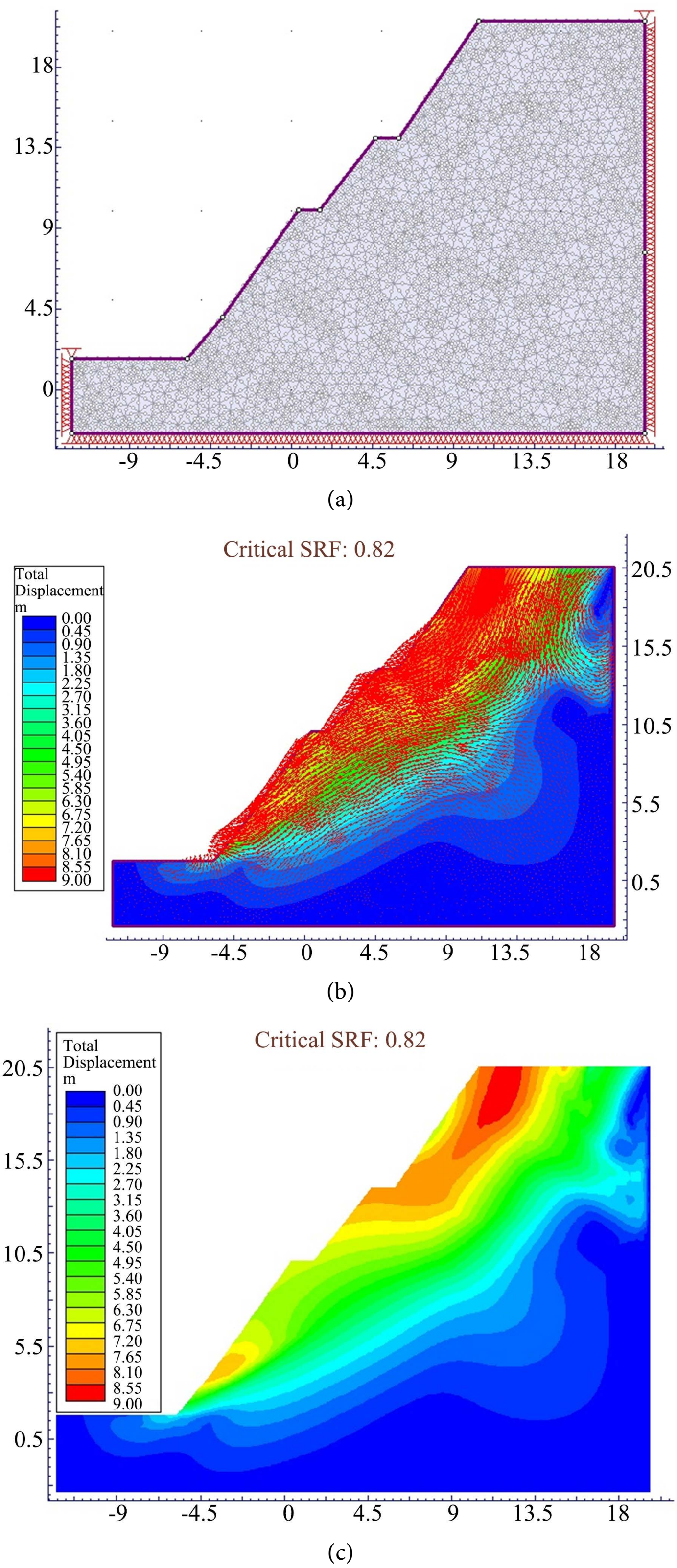


Figure 8. (a) Meshing FEM approaches 0.82 as the critical SRF. (b) Deformation vectors are displayed in (b), which also indicates sufficient displacement to bring about a failure in the slope. The total displacement contours highlight the zone of failure. (c) shows the contour of total displacement along with deformed mesh.

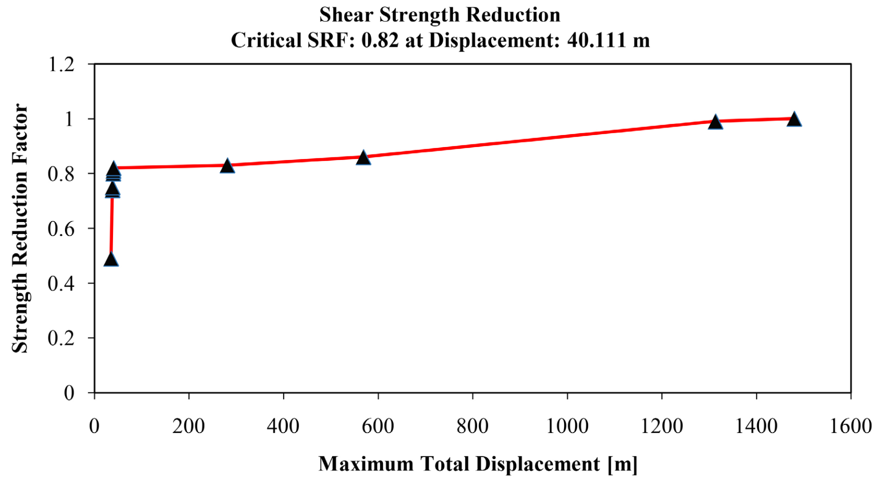


Figure 9. Plot between maximum deformations and SRF.

needed to be strengthened at the top. The tensional crack needs to be filled with material to consolidate the slope material and prevent any filtration or further widening.

6. Conclusions

The present study focuses on assessing the condition and stability of the slope in the Amalpata region, employing two distinct methods: Probabilistic Slope Stability Analysis (PSSA) and Finite Element Method (FEM). Both methods converge in indicating the failure of the slope, attributing it to the presence of weak and fragile material in a layer above the basement.

The slope is identified as critically stable, as evidenced by a factor of safety very close to unity, as determined by both deterministic and probabilistic methods. The use of PSSA, an advanced technique, introduces a probabilistic element by indicating a probability of failure ranging between 98.9% and 100%. On the other hand, FEM suggests slope failure based on a critical Safety Factor (SRF) of 0.82. One noteworthy observation is the higher displacement at the toe of the slope, suggesting that the movement is deep-seated and interconnected. This implies that reinforcing the toe of the slope is crucial to providing adequate support and improving overall stability, thereby preventing further damage. Strengthening measures should be implemented to address the identified weaknesses and mitigate the risk of slope failure.

This study highlights the serious dangers to the Amalpata region's communities and infrastructure. Devastating outcomes including landslides, property destruction, and fatalities can arise from slope collapse. Deep-seated movement is indicated by the increased displacement observed near the slope's toe, which raises the possibility of cascade failures and extensive damage. One of the most important mitigation strategies to improve stability and stop future degradation is to reinforce the slope's toe. In order to mitigate the identified vulnerabilities and lower the likelihood of slope collapse and protect lives and livelihoods in the area, strengthening measures must be put into place. This study also emphasizes how crucial sophisticated methods like FEM and PSSA are for evaluating slope stability and assisting with well-informed choices on risk reduction and infrastructure design.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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