Soil Strength Parameters Sensitivity Analysis of Tied-Back Urban Deep Excavation

Conference Paper · September 2024

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ABSTRACT
With the ongoing development of urban areas, excavation plays a vital role in building construction, requiring careful consideration of safety from a geotechnical standpoint. Tied-back walls serve as a cost-effective solution for supporting excavations. This study focuses on the geotechnical engineering and stability analysis of tied-back urban deep excavations. Previous research primarily utilized deterministic methods, overlooking soil strength's inherent uncertainties. In contrast, this study employs probabilistic analysis to account for uncertainties in cohesion and friction angle. The results underscore the significant impact of soil strength parameter variability on tied-back urban excavations, emphasizing the necessity of incorporating uncertainty of cohesion and friction angle into analysis and design.

RÉSUMÉ
Avec le développement continu des zones urbaines, l'excavation joue un rôle essentiel dans la construction de bâtiments, nécessitant une attention particulière à la sécurité d'un point de vue géotechnique. Les murs ancrés constituent une solution rentable pour soutenir les excavations. Cette étude se concentre sur l'ingénierie géotechnique et l'analyse de la stabilité des excavations profondes urbaines reliées. Les recherches antérieures utilisaient principalement des méthodes déterministes, ignorant les incertitudes inhérentes à la résistance du sol. En revanche, cette étude utilise une analyse probabiliste pour tenir compte des incertitudes liées à la cohésion et à l'angle de frottement. Les résultats soulignent l'impact significatif de la variabilité des paramètres de résistance du sol sur les excavations urbaines liées, soulignant la nécessité d'incorporer l'incertitude de la cohésion et de l'angle de frottement dans l'analyse de conception.

1 INTRODUCTION

The pile-anchor structure (PAS), combining stabilizing with piles and anchors, is a rapidly growing and promising technique in large-scale slope engineering. This method offers cost-effectiveness and high performance in reinforcing slopes and enhancing the stress distribution in stabilizing piles (Chen et al., 2016; Huang et al., 2020a; Huang et al., 2020b). Conventional methods for evaluating slope stability, often rely on principles like safety factor calculated by the Limit Equilibrium Method (LEM) deterministically. Traditionally, the majority of geotechnical projects have been designed using deterministic methods with no consideration given to the natural uncertainties of the soil during the design process (Alhajj Chehade et al., 2021; Villalobos & Villalobos, 2021). Certain geotechnical engineering uncertainties cannot be mitigated or eliminated, and they need to be appropriately addressed in the geotechnical design phase. With the rapid progress and enhancement of reliability theory, it has become extensively applied in geotechnical engineering (Bong & Son, 2018; Dastpak et al., 2021; Huang et al., 2023; Jiang et al., 2018; Su et al., 2018). Zhao et al. (2016) recommended incorporating reliability analysis techniques in geotechnical engineering to address uncertainties. In reliability analysis, safety is usually evaluated with a parameter called the Reliability Index (RI) or Probability of Failure (PF). Phoon and Kulhawy (1999) proposed ranges for the variability in shear strength of various soil types, including undrained cohesion, friction angle, and unit weight.

Javankhoshdel and Bathurst (2014) utilized LEM combined with Monte Carlo simulations to investigate how variations in soil strength impact PF in simple unreinforced slopes. In another study, Karthik, Manideep and Chavda (2022) investigated the impact of various soil parameters of a soil slope such as cohesion, internal friction angle, unit weight, Young's modulus, and Poisson's ratio, on displacements and RI. Cheng and He (2020) examined the soil slope reliability by considering varying cohesion and friction angles of the soil through the application of the Monte Carlo simulation. They computed RI for the friction angle and cohesion parameters across 5 distinct coefficients of variation (COV) (0.1, 0.2, 0.3, 0.4, and 0.5) and for 3 different slope ratios (1:1, 1:1.5, and 1:2). With escalating variability and uncertainty in the parameters, there is a decline in RI. When holding the COV at a constant value, the decrease in RI due to changes in the friction angle is more pronounced compared to the impact of alterations in cohesion. This highlights the heightened sensitivity of slope safety to variations in the friction angle.

In this paper, the inherent variability of soil strength parameters in an urban deep excavation stabilized by PAS is taken into account by employing a probability distribution model for random variables. The lognormal distribution along with the Response Surface Method (RSM) is utilized for probabilistic analysis. This analysis considers the variations in cohesion and internal friction angle across different COVs and examines their impact on RI. Moreover, the sensitivity analysis was conducted to find out which of the cohesion or the internal friction angle is more sensitive to the reliability of the excavation.

This study examines the impact of the correlation coefficient (ρ) between cohesion and internal friction angle on the RI, with both parameters treated as variables. Additionally, a comprehensive analysis is conducted to explore scenarios where soil strength parameters vary across different stages of excavation in urban projects. The research aims to provide geotechnical engineers with a holistic understanding of how uncertainties in soil strength parameters, affect the reliability of urban deep excavations stabilized with PAS.

2 NUMERICAL MODEL

An urban deep excavation stabilized by PAS located in Mashhad, Iran, was chosen as a case study using Slide2 software (Rocscience, 2024). Soil properties for the 8 soil layers of this project are displayed in Table 1. In this study, the soil behavior was modeled by adopting the Mohr-Coulomb shear failure criteria.

The excavation model, along with its successive stages and pertinent PAS parameters, is elucidated in Figure 1. Concrete piles, with a length of 28 meters and spaced 3 meters apart horizontally, with a shear strength of 1542 kN, have been implemented. The model encompasses dimensions of 150 m × 65 m. Excavation proceeds in stages: initial phase to 6 m, followed by two stages at 3 m intervals, four stages at 2.75 m intervals, and final stages at 2 m intervals, totaling 25 m depth. Adjacent to the excavation site, two-story residential buildings are situated at a distance of 23 meters, while the materials depot and transportation area also share this proximity. Furthermore, the surface of the numerical model bears two surcharge loads of 5 and 20 kN/m^2. Comprehensive evaluations were undertaken across 7 excavation stages using multi-scenario and the master scenario option in Slide2 software, yielding a total of 15 distinct scenarios for analysis.

Table 1. Soil characteristics of different layers.

Layer No.	Depth (m)	Cohesion (kPa)	Friction Angle (°)	Unit Weight (kN/m^3)
1	0 to 5	39.3	20	18
2	5 to 7	49.8	22.9	19.7
3	7 to 10	6	28.4	19.5
4	10 to 16	52.7	24.6	19.1
5	16 to 24	62.4	24.8	19.5
6	24 to 28	46.2	18.5	19.7
7	28 to 32	10.1	27.1	20.5
8	32 to 65	36.1	18.5	20.3

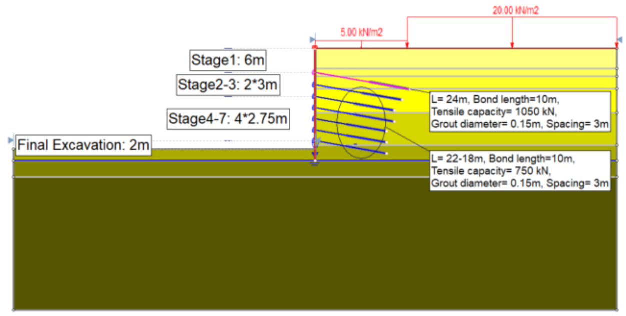

Figure 1. Numerical model with PAS parameters.

The lognormal probability distribution is chosen due to the prevalence of positive values in geotechnical engineering data. Moreover, the RSM is employed to develop precise simulations for reliability analysis without spatial variability. The third-ordered RSM equation is used to calculate the factor of safety (FS), PF, and RI accordingly. RSM can offer significant benefits in minimizing computational time through machine learning and effectively identifying failure surfaces. The RSM approach enables the estimation of the required number of simulations. In this investigation, a total of 10,000 RSM simulations were employed, which proved to be adequate.

3 DETERMINISTIC LIMIT EQUILIBRIUM METHOD (LEM)

In this study, the deterministic FS for excavation stages was obtained both before and after the anchorage for every stage. The GLE/Morgenstern-Price method (Morgenstern & Price, 1965) was used to calculate FS. FS values of each excavation stage before and after the corresponding anchorage are shown in Figure 2. As the excavation depth or stage number increases, FS consistently decreases, so that the first stage, which is 6 meters deep, has an FS of 3.521, while the final excavation (master scenario) has an FS of 1.327.

Moreover, after the execution of the corresponding anchor of stages, FS improves. For instance, in the initial stage, FS increases from 3.521 before anchorage to 3.874 after anchorage. Similarly, in the seventh stage, FS rises from 1.347 before anchorage to 1.396 after anchorage. It is evident that as the excavation depth increases, the impact of installing anchors at the same stage on enhancing FS diminishes. This is because as the excavation depth and the number of anchor rows implemented in earlier stages increase, the influence of the final row anchor on the overall excavation stability decreases.

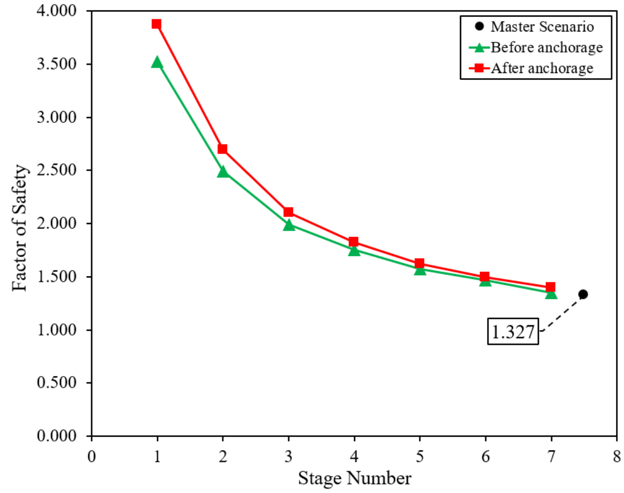

Figure 2. Variation of deterministic FS with various excavation stages.

4 RESULTS AND DISCUSSION

4.1 Influence of COV_C or COV_φ on RI

The impact of the variability in the cohesion and the friction angle of all layers on RI has been examined. In this research, COV_C and COV_φ are assumed to be 0.05 to 0.5. From Figure 3 and Figure 4, it is evident that RI decreases as the COV of the strength parameters (cohesion and internal friction angle of all 8 layers) increases. Moreover, as COV increases, the alteration in RI concerning cohesion demonstrates less pronounced significance compared to the change observed in RI for the internal friction angle. This suggests that variations in the internal friction angle exhibit greater sensitivity compared to cohesion. Notably, RI tends to exhibit a smoothing effect as COV increases.

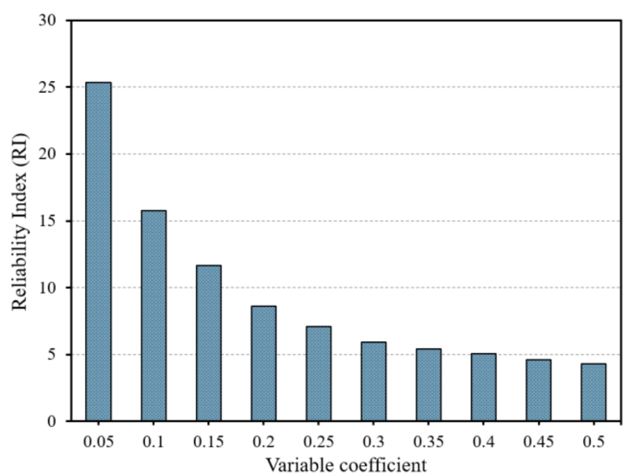

Figure 3. RI values versus different values of COV_C.

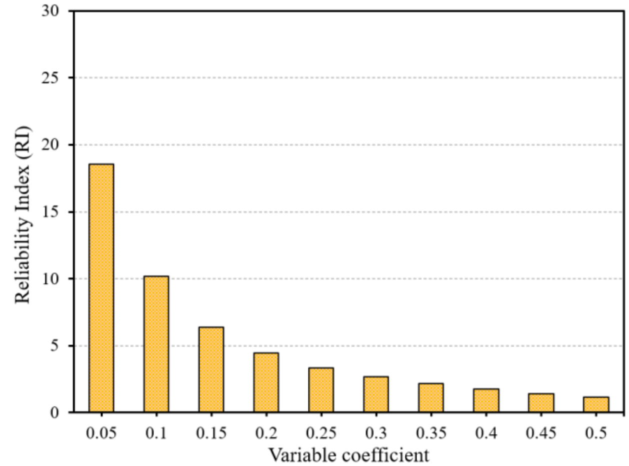

Figure 4. RI values versus different values of COV_φ.

To compute RI for different scenarios in this study, a particular value was selected for COV_C and COV_φ according to the maximum coefficients introduced in the study of Phoon and Kulhawy (1999). Therefore, the COV of soil cohesion and internal friction angle is assumed to be 50% and 20%, respectively, for all soil layers. Figure 5 and Figure 6 depict RI values, considering varying soil cohesion or internal friction angles, respectively, across all soil layers for both the master scenario and 7 stages of excavation (a total of 15 scenarios known as a multi-scenario option in Slide2) before and after anchorage. Similar to Figure 2, as the excavation depth progresses (with increasing stage numbers), RI consistently decreases. However, at a specific depth, RI value experiences an increase following the anchoring process.

As shown in Figure 5, RIs exhibit a slight change between stages 2 and 3 due to the variability in soil layer cohesion. According to Table 1, the third layer possesses relatively low cohesion compared to other layers. Consequently, its uncertainty has minimal impact on the overall RI. In contrast, Figure 6 reveals a significant alteration in RI between stages 2 and 3, attributed to the variability in the internal friction angle of the soil layers. Notably, the third layer has the highest internal friction angle, and its uncertainty significantly influences RI of the entire excavation.

By comparing Figures 5 and 6, it can be found that RIs for the master scenario are almost equal due to the 50% and 20% uncertainty of cohesion and friction angle of all layers, respectively. This underscores the high sensitivity of overall stability and RI to the internal friction angle parameter.

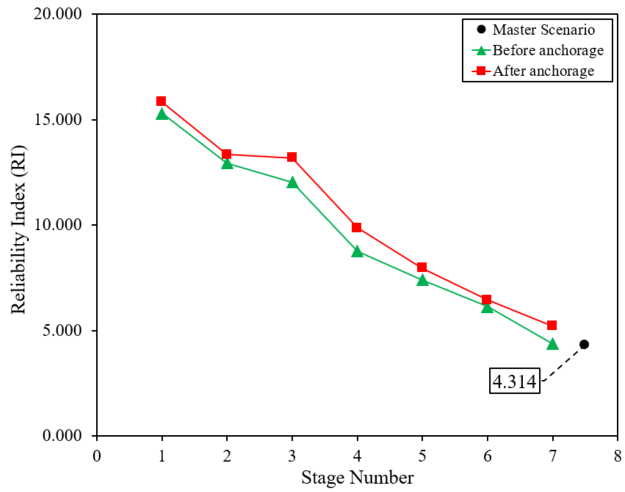

Figure 5. Variation of RI with excavation stages before and after anchorage due to cohesion variability of all layers with COV_C=0.5.

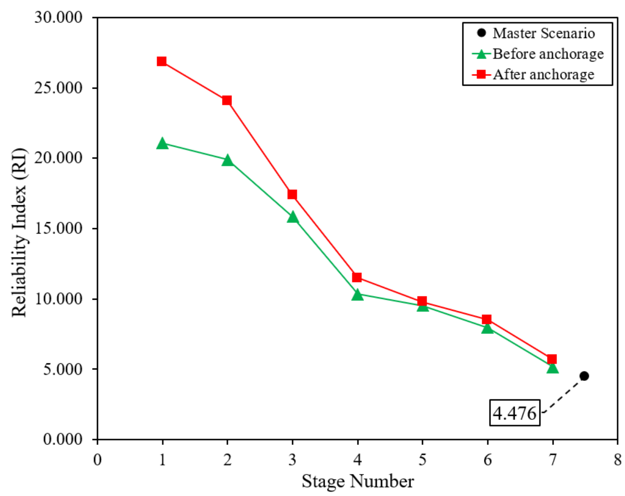

Figure 6. Variation of RI with excavation stages before and after anchorage due to internal friction angle variability of all layers with COV_φ=0.2.

4.2 Influence of Correlation Between Cohesion and Internal Friction Angle on RI

The correlation between shear strength parameters significantly influences RI. Hence, it is crucial to take into account the correlation among soil parameters. Previous studies indicate that there is a strong negative correlation between the cohesion and the internal friction angle of soils (Asadollahi et al., 2022; Li et al., 2015). The correlation coefficient (ρ) is utilized to indicate the degree of correlation between soil strength parameters. The correlation coefficient typically falls within the range of -0.5 to 0.

A positive correlation coefficient signifies a positive relationship between cohesion and friction angle, suggesting that higher cohesion values correspond to higher friction angle values. Conversely, a negative correlation coefficient indicates a negative relationship between soil parameters, meaning that higher cohesion values are associated with lower friction angle values.

Figure 7 demonstrates a decrease in RI of the master scenario (final excavation) as the correlation coefficient increases. Therefore, the correlation between cohesion and internal friction angle significantly impacts RI. For instance, when the correlation coefficient is -0.5, RI equals 3.961, while for correlation coefficients of 0 and 0.5, RI is 2.822 and 2.225, respectively. Moreover, as the correlation coefficient increases, the rate of decrease in RI value slows down. Typically, a negative correlation coefficient is used to correlate the cohesion and the internal friction angle of the soil because these variables have an inverse correlation. A correlation coefficient of -0.5 is a suitable and common value to use if more accurate data is not available.

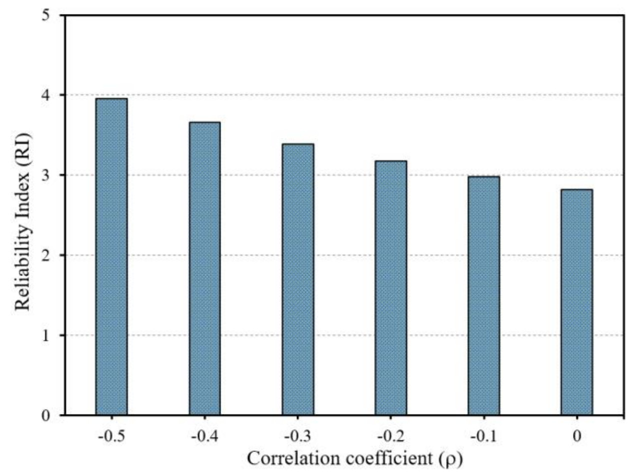

Figure 7. RI values versus correlation coefficient between cohesion and friction angle.

4.3 Effect of Both COV_C and COV_φ on RI

By considering a COV_C = 50% and COV_φ = 20%, along with a ρ = -0.5 between them, RI values for 15 scenarios were obtained both before and after anchorage, as illustrated in Figure 8. Similar to Figure 5 and Figure 6, RI steadily decreases as the excavation depth (stage number) increases, but it shows an increase in RI at a specific depth when the anchorage is applied.

When comparing Figure 8 to Figures 5 and 6, it can be seen that the RI value of the master scenario decreases from the values of 4.314 and 4.476 to 3.961 when both cohesion and friction angle are variable. Obviously, as the number of variables in the numerical model increases i.e., higher uncertainties, RI decreases.

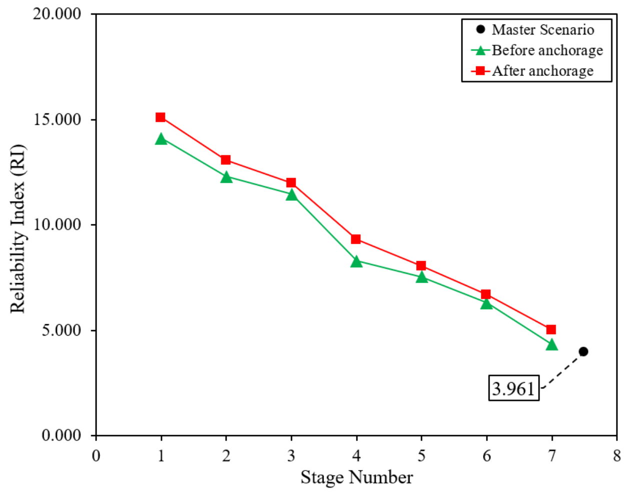

Figure 8. Variation of RI with excavation stages before and after anchorage when COVC = 50, COV_{φ}=50, and ρ = -0.5.

Figure 9 and Figure 10 depict the distribution histogram of FS and Cumulative Distribution Function (CDF) of this analysis, respectively. The FS values exhibit a wide distribution range, with the minimum being 0.961 and the maximum of 1.752. This variability in values underscores the significant influence of soil parameter variations on the FS. The average FS value is 1.282, accompanied by a standard deviation of 0.08. Overall, while the slope stability is generally acceptable based on the mean safety factor, the variability in safety factor values underscores the need for a comprehensive understanding of the soil parameters' influence on stability.

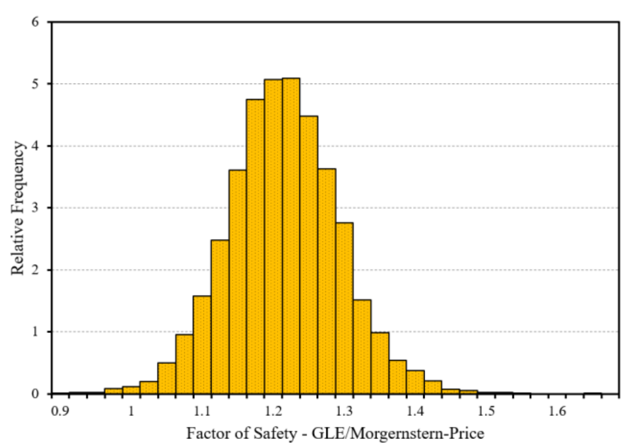

Figure 9. Distribution histogram of safety factors.

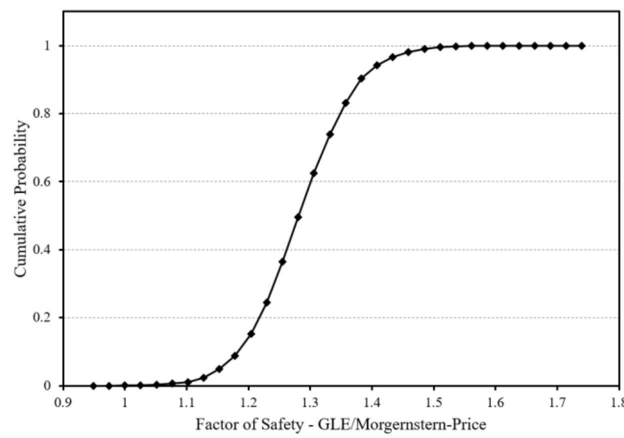

Figure 10. Cumulative Distribution Function (CDF) to FS.

5. CONCLUSION

This study reports the results of the sensitivity and probabilistic analysis of an urban deep excavation stabilized by a pile-anchor system (PAS) using the Response Surface Method (RSM) due to the uncertainty of cohesion and friction angle of soil layers with Limit Equilibrium Methods (LEM). There is a total of 15 scenarios in this study (7 excavation stages before and after anchorage plus the final excavation known as the master scenario), and the project land consists of 8 soil layers with different characteristics.

In this study, first, deterministic Factors of Safety (FS) of different scenarios were obtained through LEM. FS of the master scenario is equal to 1.327 and as the excavation depth or stage number increases, FS consistently reduces. Furthermore, when anchorage is applied at a specific depth, there is an increase in FS.

Traditional deterministic methods do not account for uncertainties. In this study, probabilistic methods and reliability analysis were employed to address the impact of uncertain soil strength parameters such as cohesion and internal friction angle on the Reliability Index (RI) was investigated. As the Coefficient of Variation (COV) or uncertainty in cohesion or internal friction angle increases, RI value decreases. Notably, the sensitivity of excavation stability and RI to the internal friction angle parameter is more pronounced than that of cohesion.

Then, according to Phoon and Kulhawy (1999), the COV for soil cohesion and internal friction angle was set at 50% and 20%, respectively, across all soil layers, and RI values were obtained for all 15 scenarios. The RI consistently decreased with increasing excavation depth, but following anchorage, there was an RI increase at a specific depth.

A negative correlation exists between cohesion and internal friction angle. The correlation significantly impacts RI. Increasing the correlation coefficient between cohesion and friction angle decreases RI value. For instance, at a correlation coefficient of -0.5, RI is 3.961, while for coefficients of 0 and 0.5, RI values are 2.822 and 2.225, respectively.

Finally, RI values were calculated for 15 different scenarios, both before and after the anchorage. These RI values were determined by taking into account a coefficient of variation of 0.5 for cohesion and 0.2 for the internal friction angle, along with a correlation coefficient of -0.5 between these parameters. RI value for the master scenario was reduced to 3.961 and the distribution histogram and Cumulative Frequency Distribution (CFD) of safety factors and this analysis were drawn. FS is concentrated within the range of 1.2 to 1.3, indicating acceptable stability of the slope.

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