https://doi.org/10.29227/IM-2025-01-02-012 Received: 30 Oct 2024, Accepted: 26 Feb 2025, Published: 01 Sep 2025

Slope stability at the Bau Trang area using deterministic, upper and lower bounds, and reliability analyses

DANG Van Phu[1], NGUYEN Thi Mai Suong[1], LE Xuan Bao[1], PHAM Ngoc Thinh[1,*]

[1] Thuyloi University, 175 Tay Son, Dong Da, Ha Noi, Vietnam
[*] *Corresponding emal: thinhtls@tlu.edu.vn*

Abstract: *The landslide at the sandhills in Bau Ba Lake in 2023 has significantly affected tourism activities in this area. Finding the exact causes and risk failure modes will help quickly come up with solutions to prevent possible landslides in the future. However, the analysis of slope stability is still done in the traditional way of deterministic analysis and has certain limitations. The question is whether or not only the deterministic analysis is enough to assess the slope stability thoroughly. If the slope stability is not analyzed fully and accurately, the solutions proposed will not be feasible and may not be effective in protecting the slope. In order to investigate slope stability in a general and accurate way, this study used the upper and lower bounds method and reliability analysis besides the deterministic analysis. In doing so, the study performed stability analysis for three cross sections, L1, L4, and L8, in the landslide area using the SLOPE/W module. In addition, scenarios of different lake water levels and live load from vehicles and visitors were also considered for analysis. The results show that in the deterministic analysis, the lake water level has a great influence on the stability of the slope, with relative differences in safety factors of around 30%. In the analysis using the lower bound analysis, the safety factor is quite low and smaller than that of the deterministic analysis by about 8%. In addition, the reliability analysis also shows that there are circular slip surfaces with safety factors smaller than those from the deterministic analysis. Another important result is that the slip surfaces with low safety factors from the deterministic analysis, the upper and lower bounds analysis, and the reliability analysis are different in shape and location. Noticeably, the lower bound analysis gives a slip surface that has the smallest safety factor. Thus, only the deterministic analysis might ignore this important issue. The results from this study will be the solid foundation for proposing appropriate solutions to reinforce and protect the sandhills in the Bau Trang area.*
Keywords: *slope stability; deterministic analyses; lower and upper bound; reliability analysis*

1. Introduction

Bau Trang tourist area, with a total area of 45 ha, has become an attractive destination in Vietnam since it was officially managed and developed for tourism in early 2012. The impressive growth in the number of tourists over the years, from 145,000 in 2016 to 183,000 in 2019, and despite the difficulties caused by the COVID-19 pandemic, Bau Trang still attracts tens of thousands of visitors each year [1]. This not only brings a large source of revenue to the local budget but also creates income for people and businesses participating in the tourism service supply chain in the area.

However, this area has significant potential risks of landslides that can cause economic and human damage. The landslide incident on May 3, 2023, at Bau Ba Lake (Fig. **1**) has caused great concern in public opinion, negatively affecting the environment, tourism image, and income of local people. In this situation, the People's Committee of Binh Thuan province has directed relevant agencies to conduct inspections and surveys of the actual landslide situation in order to find effective prevention measures [2].

Fig. 1. Landslide at Bau Ba Lake [2]

There are many causes of landslides in this area, such as steep slopes due to sand accumulation, lake waves that erode the foot of the sandhill, there may be underground seepage that causes erosion and loosening of the foot of the sandhill, the changes in the lake water level, the vibration effects of vehicles running in this area, or due to the surcharge load from vehicles and visitors approaching the lake shore. This paper will focus on analyzing the stability of the slope of the sandhill using the Bishop method with the circular slip hypothesis. This analysis takes into account fluctuations in the lake water level and the surcharge load from vehicles and visitors. The stability analysis is implemented using the SLOPE/W module of the Geostudio software.

In addition to the traditional stability analysis using deterministic analysis, this study also analyzed stability through the upper and lower bounds method and reliability analysis. The lower and upper bounds method has been applied to the slope stability by several researchers [3, 4]. Moreover, the reliability analysis of slope stability has been widely investigated by various researchers [5-8]. The soil layers in this area are sandy soil layers with loose grain properties, so if a landslide occurs, the landslide mass can develop continuously until reaching its equilibrium state. Therefore, determining the critical slip surfaces only through deterministic analysis has many limitations. In addition, because the soil parameters are spatially varied and become uncertain, the reliability analysis and the upper and lower bound can help determine the critical circular slip surface other than deterministic analysis. Thus, there will be a more complete analysis of the sliding stability of the slope in this area, which can be the basis for finding suitable solutions for slope stability reinforcement.

2. Case study and methodology

2.1 Case study

The calculated cross-sections include three cross-sections within the landslide area at the Bau Ba Lake, in which cross-section L4 passes through the middle of the landslide area, cross-sections L1 and L8 are located left and right next to the landslide area (solid red line in Fig. ***2***). The cross-sections are shown in Fig. **3**Fig**. 5** with three main soil layers and two interspersed soil layers. The parameters of the physical characteristics of these soil layers, which are soil unit weight, γ, effective friction angle, φ', and effective cohesion, c', are shown in Tab. **1**. Because all of the soil layers are sand and the long-term stability of slope is considered, the drained shear strengths of soil are used in this study.

https://doi.org/10.29227/IM-2025-01-02-012 Received: 30 Oct 2024, Accepted: 26 Feb 2025, Published: 01 Sep 2025

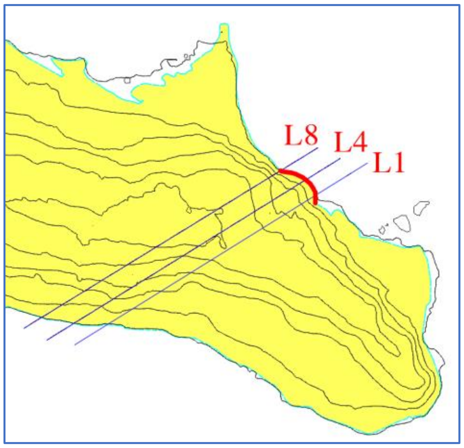


Fig. 2. Location of cross-sections L1, L4, and L8 in Bau Ba area

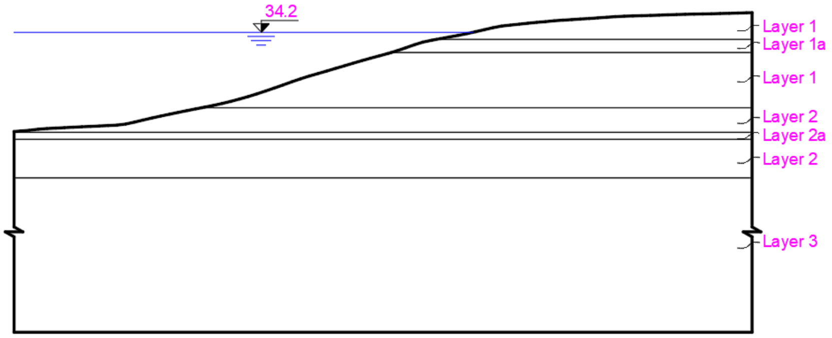


Fig. 3. Cross-section L1

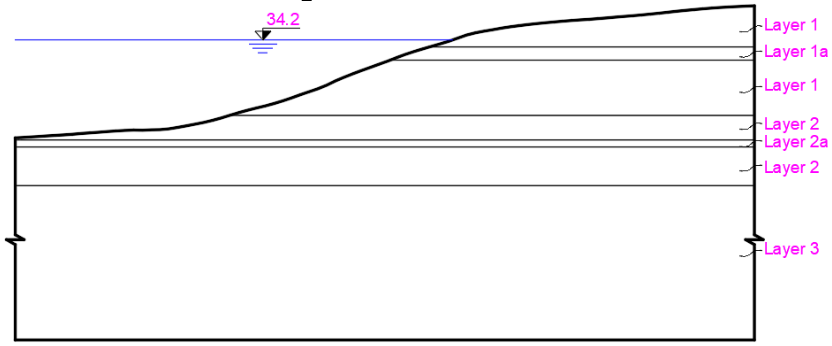


Fig. 4. Cross-section L4

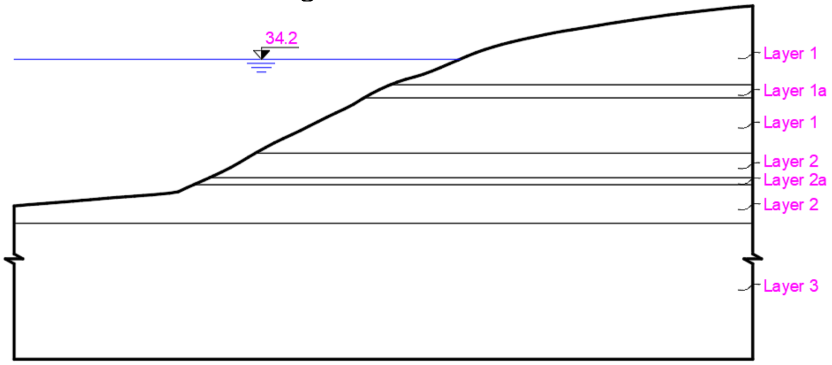


Fig. 5. Cross-section L8

Tab. 1. Parameters of soil layers

Soil layer	*γ* [kN/m³]	*φ'* [º]	*c'* [kPa]
1	19.9	24º56	1.4
1a	20.1	25º14	1.9
2	20.3	26º46	1.1
2a	19.9	26º45	1.8
3	20.5	28º56	1.2

In addition, to analyze stability according to the upper and lower bounds, the parameters for the soil layers are shown in Tab. **2**. Because the effective cohesion is quite small, the stability of the sandhill foot can be considered to be mainly governed by the effective friction angle of the sand layers when considering other parameters as unchanged. The difference between the lower bound and upper bound for the effective friction angle is about 6%, 7%, and 20% for soil layers 1, 2, and 3. In addition, the specific gravity of the soil layers also has a difference of about 10% for all three soil layers. The lens layers have a small thickness, so the value will be considered uniform.

Tab. 2. Upper, UB, and lower, LB, limit parameters of soil layers

Soil layer	*γ [kN/m³]*		*φ' [º]*		*c'* [kPa]	
	LB	UB	LB	UB	LB	UB
1	19.4	20.8	24º13	25º39	1.1	2.1
1a	20.1		25º14		1.9	
2	19.3	20.9	25º36	27º27	0.4	1.8
2a	19.9		26º45		1.8	
3	19.6	21.4	25º07	30º20	0.005	0.019

The statistical parameters for the physical properties of the soil layers are given in Where HCV is the highest conceivable value of the parameter, LCV is the lowest conceivable value of the parameter. These parameters are the values at the upper bound and lower bound listed in Tab. **2**.

Tab. 3. It can be seen that the variation of effective cohesion is quite significant, about 10% for layer 1 and 20% for layers 2 and 3. The variation of specific gravity and effective friction angle is quite small, about 1-3%. A sensitivity analysis was performed in this study to determine which parameters have a large influence on slope stability. In addition, the distribution characteristics of these parameters are assumed to be normally distributed. This is the common distribution form of soil mechanical properties.

Moreover, due to the limitations of observed data, the standard deviation of soil parameters is estimated as [9]:

$$\sigma = \frac{\left(HCV - LCV\right)}{6} \quad (1)$$

Where HCV is the highest conceivable value of the parameter, LCV is the lowest conceivable value of the parameter. These parameters are the values at the upper bound and lower bound listed in Tab. **2**.

Tab. 3. Statistical parameters of soil layers

Layer	*γ*			*φ'*			*c'*		
	μ [kN/m³]	σ [kN/m³]	Distribution	μ [º]	σ [º]	Distribution	μ [kPa]	σ [kPa]	Distribution
1	19.9	0.233	Normal	24º56	0.239	Normal	1.40	0.167	Normal
1a	20.1	-	-	25º14	-	-	1.90	-	-
2	20.3	0.267	Normal	26º46	0.308	Normal	1.10	0.233	Normal
2a	19.9	-	-	26º45	-	-	1.80	-	-

3	20.5	0.300	Normal	28°56	0.869	Normal	1.20	0.233	Normal

μ - mean value, σ – standard deviation

Live load due to vehicles and visitors

This is a tourist area with sightseeing activities of vehicles such as pickup trucks, off-road vehicles and pedestrians approaching the lake shore. Therefore, the load will affect the slope stability. With data collected from the tourist area, the pickup truck has a load capacity of about 2 tons and can carry a maximum of 8 people. The vehicle and person approach the lake shore about 2-3 m. According to TCVN 2737-2023 standard, the live load value calculated for vehicles and people is 10 kN/m^2 [10]. This live load is considered an evenly distributed force and is assigned about 3m from the edge of the lake. It extends within a range of about 5 m in this study.

Lake water level

To examine the influence of the reservoir water level on slope stability, several reservoir water level scenarios were proposed, assuming that the water level fluctuates around the measured value. The monitoring data in May 2024 showed that the reservoir water level was at an elevation of 34.2 m. The monitoring data for the entire year of 2023 showed that the reservoir water level fluctuated between the highest and lowest water levels by about 1 m. Therefore, in this study, water level scenarios at elevations of 32 m, 33 m, 34.2 m, and 36 m were considered to see how the influence of the reservoir water level in the dry and rainy seasons affects slope stability with water levels of 32 m and 36 m for extreme water level scenarios.

In addition, geological surveys show that the groundwater level in this area is approximately 34.7 m. This groundwater level is connected to a small lake about 100 m northeast of the landslide site. Therefore, this study also considers the influence of seepage on slope stability.

2.2 Methodology

2.2.1 Slope stability

In this study, the SLOPE/W module and Bishop method are used to analyze slope stability. Bishop's method is the limit equilibrium method. This method only considers the normal force without paying attention to the tangential force between the segments, and it only needs to satisfy the moment equilibrium equation [11]. Additionally, the Bishop method is often used due to its high accuracy and simplicity.

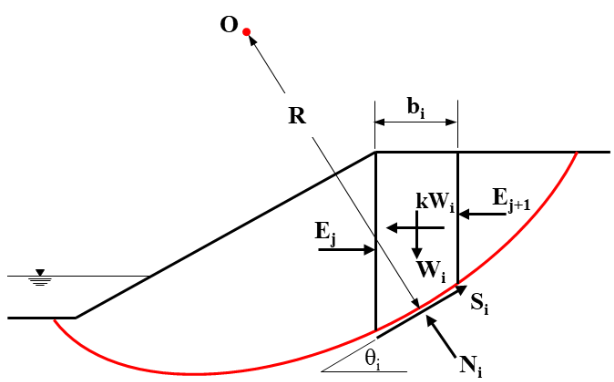


Fig. 6. Illustration of method of slice for circular slip surface

+ The general equation to calculate FS by Bishop's method [12]:

$$FS = \frac{\sum\left[c_i^{'} b_i \cos\theta_i + \left(W_i - u_i.b_i\right).\tan(\varphi_i^{'})m_i\right]}{\sum W_i.\sin\theta_i} \tag{2}$$

Where:

+ FS: Safety factor,
+ W_i: Self-weight of the segments and live load above the segment,
+ u_i: Pore water pressure,
+ b_i: Width of the segment,
+ $c_i^{'}$: Effective cohesion of soil at the segment base,
+ $\varphi_i^{'}$: Effective friction angle of soil at the segment base,
+ θ_i: Inclination angle at the segment base,
+ m_i is defined as follows:

$$m_i = \frac{1}{\cos\theta_i + \frac{\tan(\varphi_i^{'}).\sin\theta_i}{FS}} \tag{3}$$

Because m_i is a function of FS, the value of FS is calculated using the trial-error process.

2.2.2 Reliability analysis

The reliability analysis in this study uses the Latin Hypercube sampling technique. This method gives very high reliability and accuracy, similar to the Monte Carlo simulation method, especially when the reliability function is an implicit function when using the Bishop method. In addition, Latin Hypercube will solve the computational efficiency limitation encountered in the Monte Carlo simulation. The appropriate number of sampling points to give accurate results will be performed before applying to reliability analysis.

The reliability index is defined as follows:

$$\beta = \frac{(\mu - 1.0)}{\sigma} \tag{4}$$

Where μ and σ are the mean value and standard deviation of the realizations of the Monte Carlo or Latin Hypercube simulations.

3. Results and discussion

3.1 Slope stability analysis results

Fig. **7**Fig**. 9** show the safety factors for the cases without considering load and without considering seepage (NoLL-NoSeep), without considering load and considering seepage (NoLL-Seep), with considering load and without considering seepage (LL-NoSeep), with considering load and considering seepage (LL-Seep). In general, the water level has a significant influence on the stability of the sandhill, with the assumed water levels of 32 m, 33 m, 34.2 m, and 36 m for all three cross-sections L1, L4, and L8. It can be seen that the lower the lake water level, the more likely the sandhill foot will become unstable with a low safety factor. The safety factor can be reduced by about 30% for sections L4 and L1 when the lake water level is reduced from 36 m to 32 m while the remaining parameters are kept the same. The influence of the lake water level on the stability of the sandhill foot for section L8 is smaller, with a reduction in the safety factor of about 15%.

In addition, the live load from vehicles and visitors approaching the lake shore from a range of 3 m also has a significant impact on slope stability for all three cross-sections. The greatest impact is on cross-sections L1 and L4, with a reduction in the safety factor of about 10%. The reduction in the safety factor when considering the live load for cross-section L8 is about 3%.

Regarding the influence of considering seepage with the assumption that the groundwater level through the small lake in the Northeast has an elevation of about 34.7 m, the reduction of the largest safety factor for sections L1 and L4 is about 5%. In comparison, the influence on section L8 is about 2%. Therefore, it can be seen that the influence of seepage on the stability of the sandhill is smaller than the change in lake water level and live load in terms of slip surface analysis.

In general, the safety factors for the two cross-sections L1 and L4 are quite high. Especially cross-section L4, which is the cross-section reshaped after the landslide in 2023, has already reached its equilibrium state. However, this location has a history of frequent landslides, and this cross-section can be deposited by wind over time, so the sand is poorly consolidated. There is a possibility of landslides when the impact of lake waves weakens the sand foot. Therefore, measures need to be taken to protect the foot of the sandhill and prevent landslides from occurring.

The cross-section L8 passes through the edge of the landslide area and extends through the small lake next to Bau Ba. This section can be representative of the cross-section L4 before the landslide occurred. As shown in Fig. **9**, the cross-section L8 has very small safety factors for all the cases. In some unfavorable conditions, such as changes in groundwater levels and lake waves eroding the foot, the risk of landslides is very high. The minimum safety factor is 1.076 for the LL-Seep case at the lake water level scenario of 32 m.

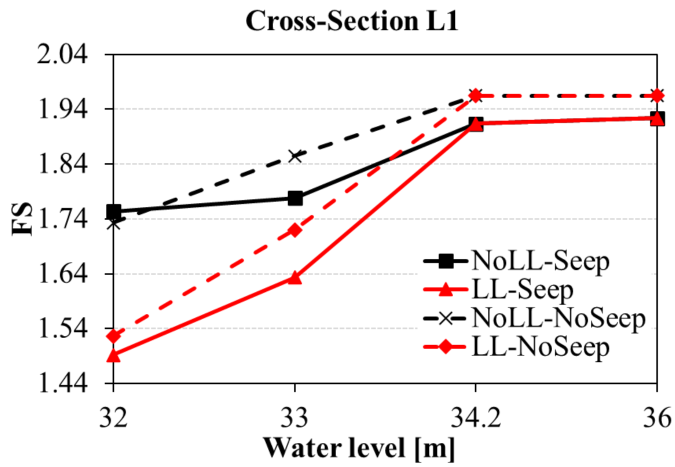


Fig. 7. Slope stability for cross-section L1

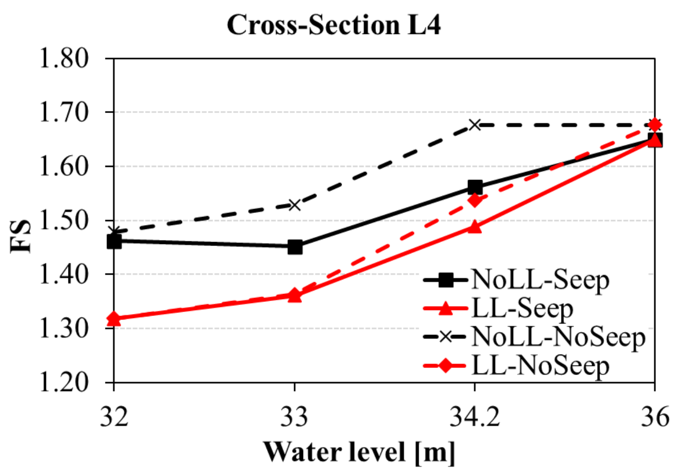


Fig. 8. Slope stability for cross-section L4

https://doi.org/10.29227/IM-2025-01-02-012 Received: 30 Oct 2024, Accepted: 26 Feb 2025, Published: 01 Sep 2025

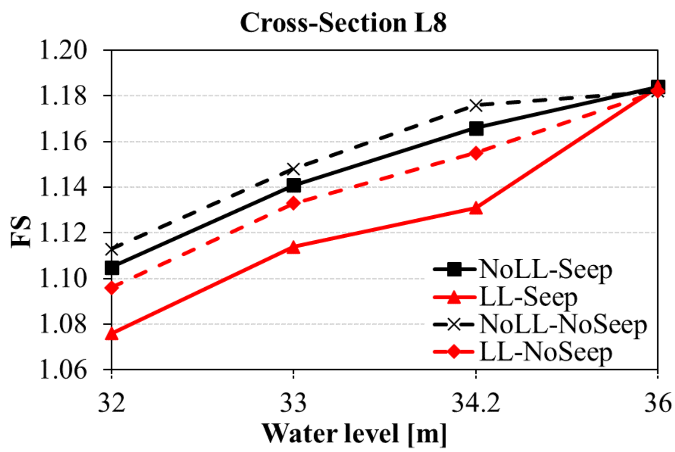
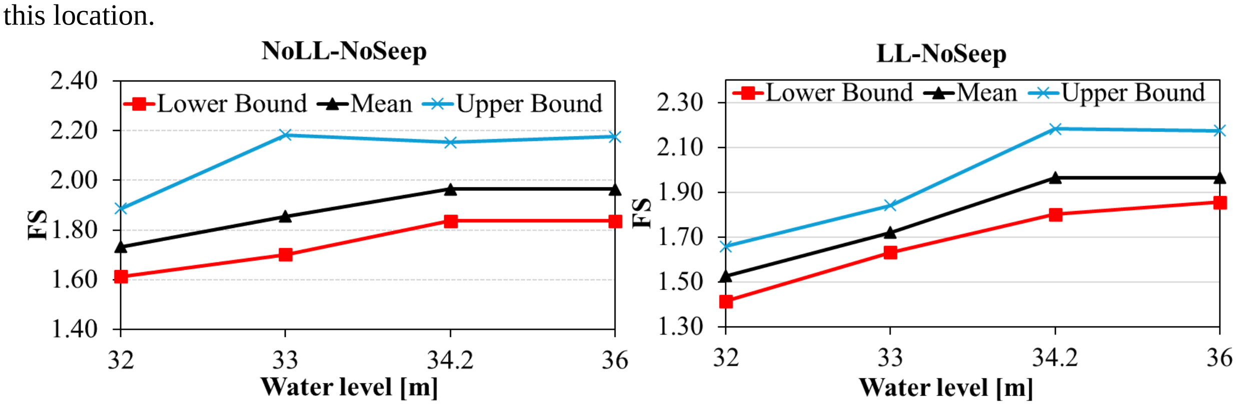


Fig. 9. Slope stability for cross-section L8

3.2 Lower and upper bounds analysis in slope stability

This section calculates the stability of the sandhill with the lower bound (LB) and upper bound (UB) of the soil parameters, as shown in Tab. **2**. The results from analyses with LB, UB, and mean values are shown in Fig. **10**Fig**. 12** for different calculation conditions. From the figures below, it can be seen that the safety factors from the lower bound analyses are quite small, about 8% lower than the mean value. Noticeably, the results obtained from the mean value are close to the lower bound for most of the calculation cases. In addition, the relative differences in the safety factors between the lower bound and the upper bound are about 20%.

The safety factor at the lower bound of the L1 and L4 lines is greater than 1.25, while the safety factor at the lower bound of the L8 section is less than 1.10. Typically, in the LL-Seep case with a lake water level scenario of 32 m, the safety factor is 1.00. Therefore, if the slip surface passes through locations with values close to the lower bound, a small safety factor may occur. If there are stimulating causes, such as lake waves eroding the sandhill or a larger live load, landslides will occur in this case. However, with the analyzed value, it can be seen that the safety factor has a very small margin, so the risk of instability is very high for this location.



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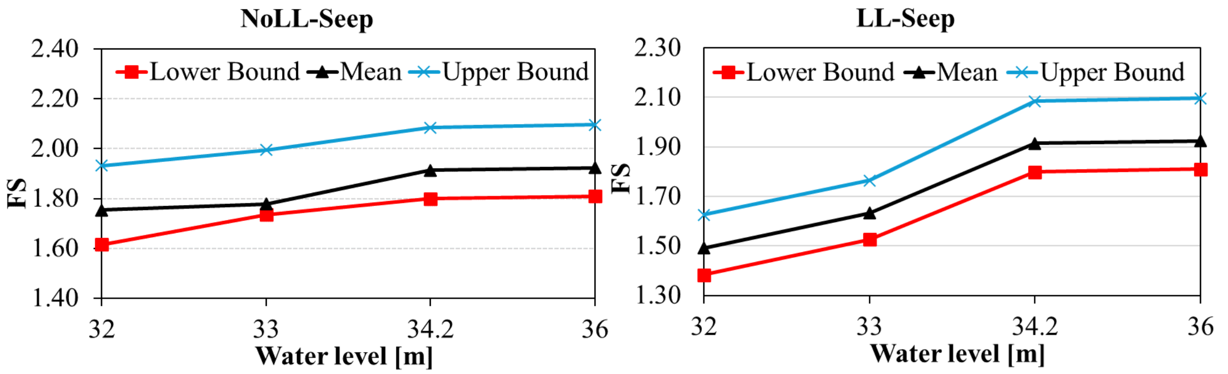


Fig. 10. Slope stability with lower and upper bounds for cross-section L1

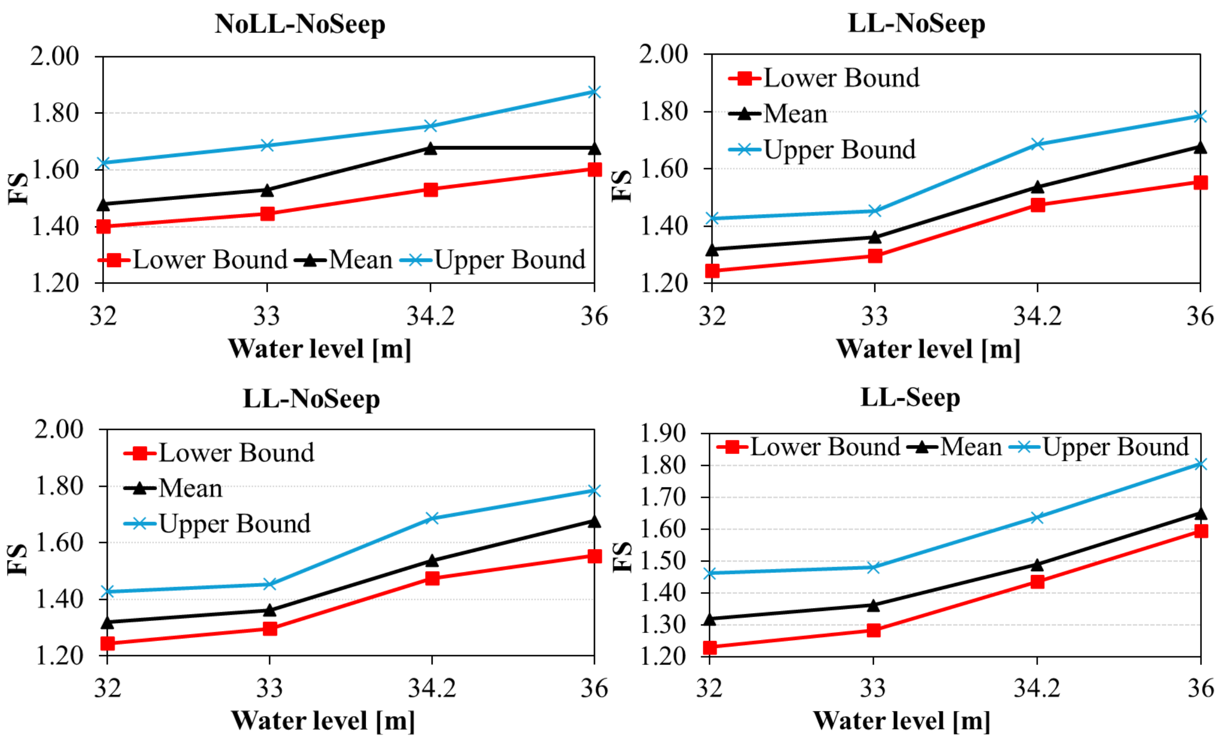
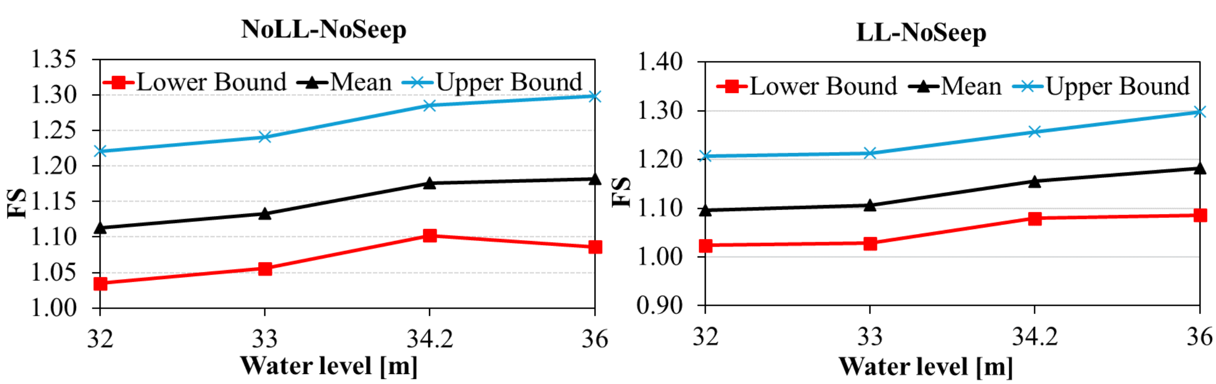


Fig. 11. Slope stability with lower and upper bounds for cross-section L4



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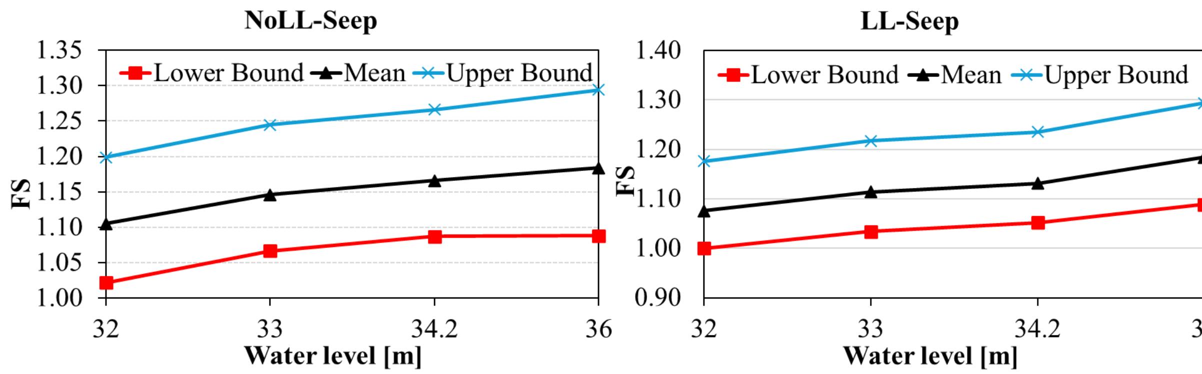


Fig. 12. Slope stability with lower and upper bounds for cross-section L8

From the analysis of the lower bound and upper bound in this section, it can be concluded that in the most unfavorable case, if the sliding arc passes through locations with soil mechanical values close to the lower bound, the safety factor will decrease significantly. Typically, the safety factor can decrease by about 10% compared to the values taken at the average value. Therefore, in actual design calculations, this influence must be taken into account.

3.3 Probabilistic Analysis

3.3.1 Sensitivity Analysis

The sensitivity analysis aims to identify the most predominant factors in slope reliability analysis. The cross-section L8 is used for this analysis. The results are presented in Fig. **13**. In general, the safety factor is most sensitive to the effective friction angle of the soil layer 1 in all the water level scenarios. At the water levels of 32 m and 33 m, the second predominant factor is the effective cohesion of soil layer 2, while the remaining factors seem to have no effect on the stability of the slope. At the water levels of 34,2 m and 36 m, the effective friction angle of soil layer 2 is the second predominant factor, while the remaining factors have a minor effect on slope stability. In addition, at low water levels, the factor safety is more sensitive to the effective friction angle than those at high water levels.

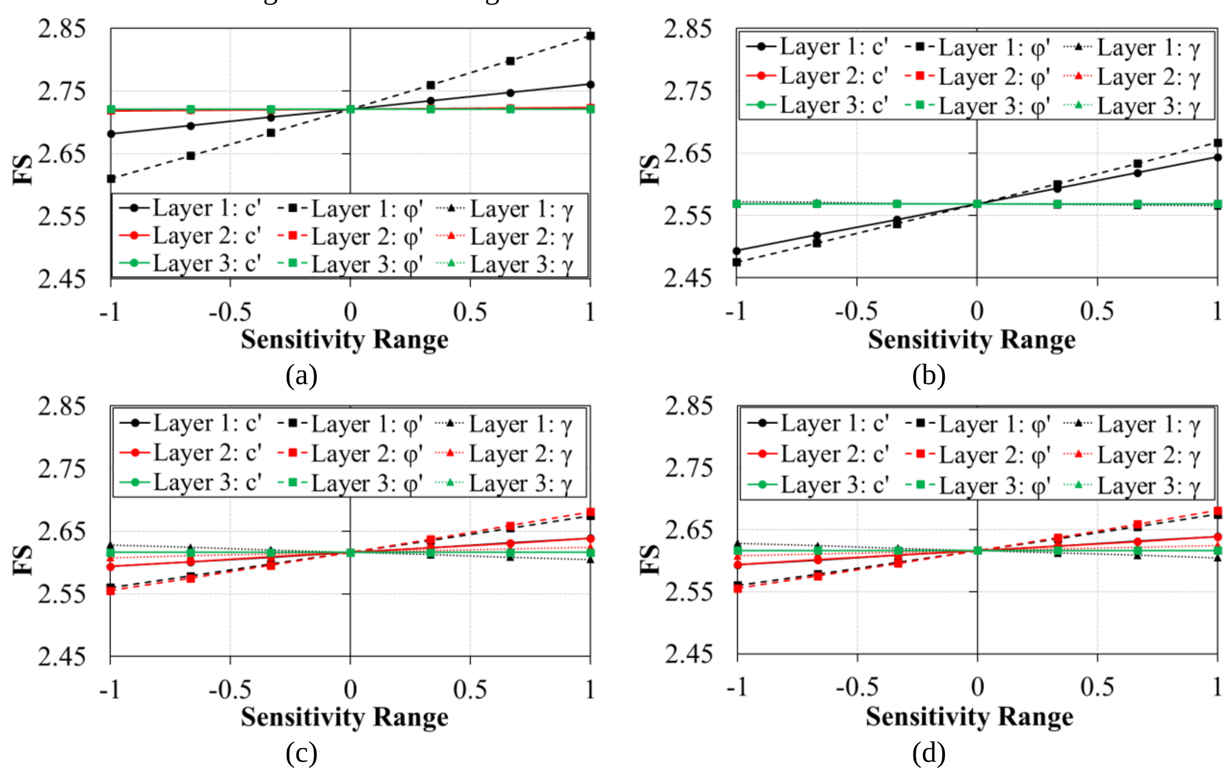


Fig. 13. Sensitivity analysis when water level is: (a) 32 m; (b) 33 m; (c) 34,2 m; (d) 36 m

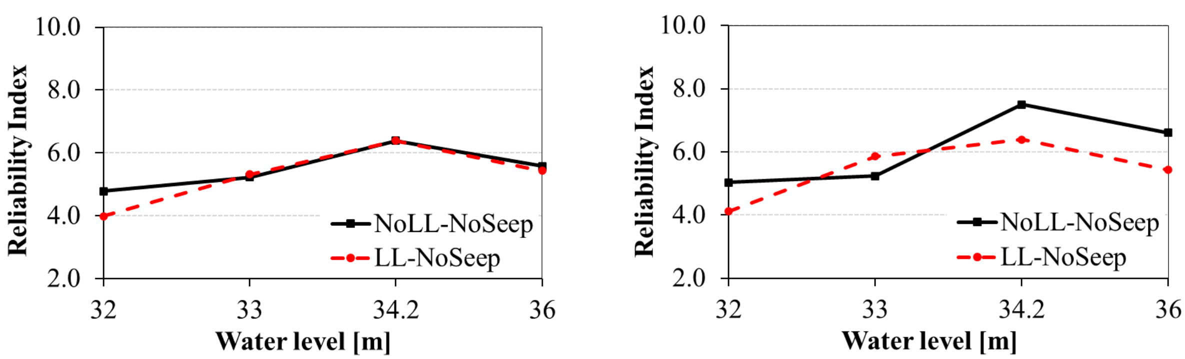
3.3.2 Reliability Analysis

Before starting the reliability analysis using the Latin Hypercube sampling technique, the number of realizations needs to be surveyed to achieve high computational efficiency while still obtaining accurate results. Tab. ***4*** shows the results of reliability analysis using Monte Carlo simulation with 100,000 samples and Latin Hypercube with 1,000 and 10,000 samples for cross-section L8 with NoLL-NoSeep condition and at the water level of 33m. The results show that the Latin Hypercube sampling technique with 1,000 sampling points still has high accuracy results. The difference is only 1% when taking the results obtained from the Monte Carlo simulation as accurate results. Thus, the Latin Hypercube sampling technique with 1,000 sampling points can be used for the reliability analysis.

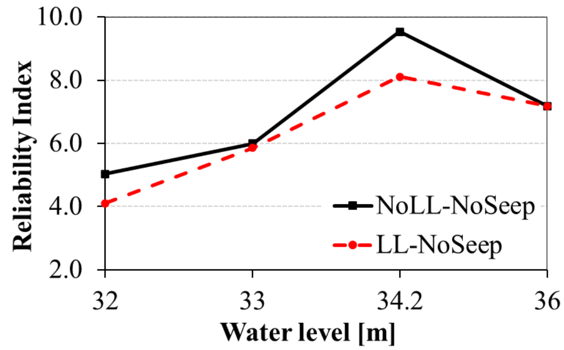
Tab. 4. Reliability analysis with different techniques

Method	Number of sampling points	β	Relative difference
MCS	100,000	5.2128	0.00%
Latin Hypercube	10,000	5.2316	0.36%
Latin Hypercube	1,000	5.2857	1.03%

The cross-section L8 is selected for the reliability analysis, which is the most vulnerable section with a high risk of landslides. The results of the reliability analysis are plotted in Fig. **14**. In general, the reliability index increases with the increase in the lake water level. However, the reliability index with the water level of 36 m is decreasing from the water level of 34.2 m. The reason is that the failure mode when the water level is 36 m is almost different, with the slip surface almost below the water level. There is a possibility of shallow and small slip surfaces. Moreover, as can be seen from the figure, the reliability index from the critical probabilistic slip surface (Fig. **14**a) is different from the critical deterministic slip surface (Fig. **14**b). Additionally, the reliability index from the critical deterministic slip surface is higher than the critical probabilistic slip surface. Moreover, there is a slip surface that has the minimum factor safety obtained from the reliability analysis, which is different from the critical probabilistic nor deterministic slip surface. However, this slip surface has a higher reliability index than the others (Fig. **14**c). This finding implies that the first collapse might not be from the critical deterministic slip or critical probabilistic slip surface.



(a) (b)



(c)

Fig. 14. Reliability analyses for (a) Critical probabilistic slip surface; (b) Minimum-FS slip surface in reliability analysis; (c) Critical deterministic slip surface

Figures 15-18 show the positions of the abovementioned slip surfaces. In general, the positions of the critical probabilistic slip surface, minimum-FS slip surface, and critical deterministic slip surface are different for different water levels and with or without considering live load. Moreover, as can be seen from these figures, the positions of the critical probabilistic slip surfaces (solid and dashed green lines) are almost different from those in different water levels. In addition, the positions of the slip surfaces that consider live load (dashed lines) are primarily distinct from those without considering live load (solid lines). Except for the case of the water level of 36 m, the positions of the slip surfaces with or without considering live load are identical for the critical probabilistic slip surface, minimum-FS slip surface, and critical deterministic slip surface, as illustrated by Figure 18. Thus, it can be stated that water level plays a significant role in slope stability and the position of the critical slip surfaces.

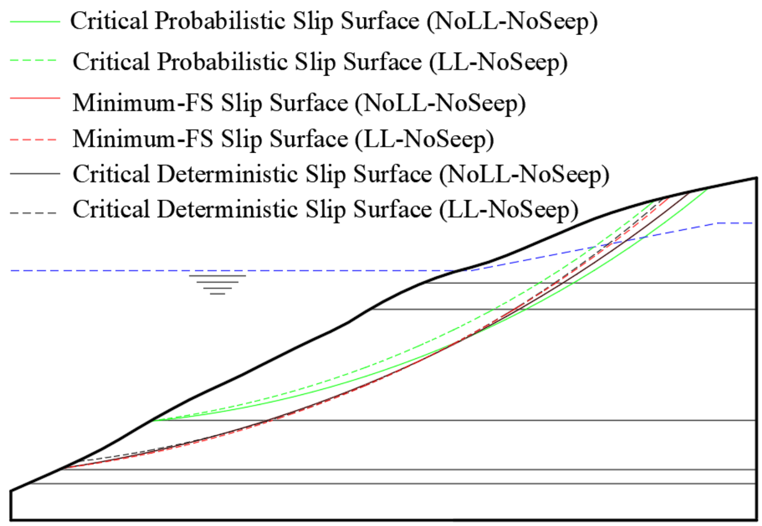


Fig. 15. Positions of the slip surfaces at the water level of 32 m at cross-section L8

https://doi.org/10.29227/IM-2025-01-02-012 Received: 30 Oct 2024, Accepted: 26 Feb 2025, Published: 01 Sep 2025

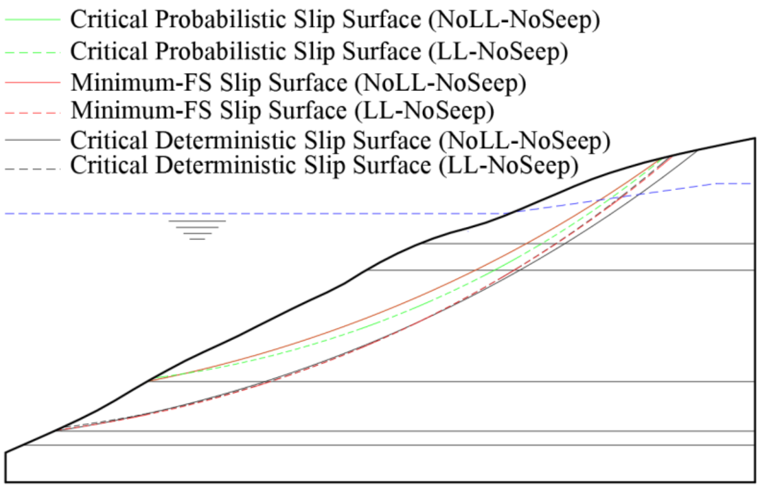


Fig. 16. Positions of the slip surfaces at the water level of 33 m at cross-section L8

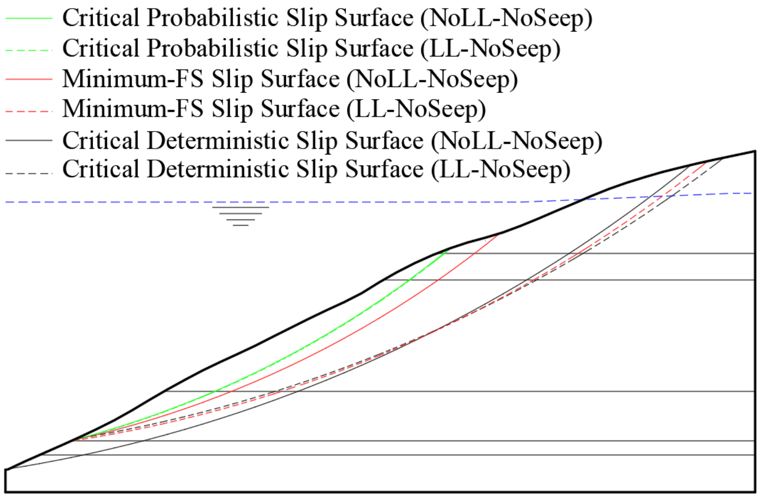


Fig. 17. Positions of the slip surfaces at the water level of 34.2 m at cross-section L8

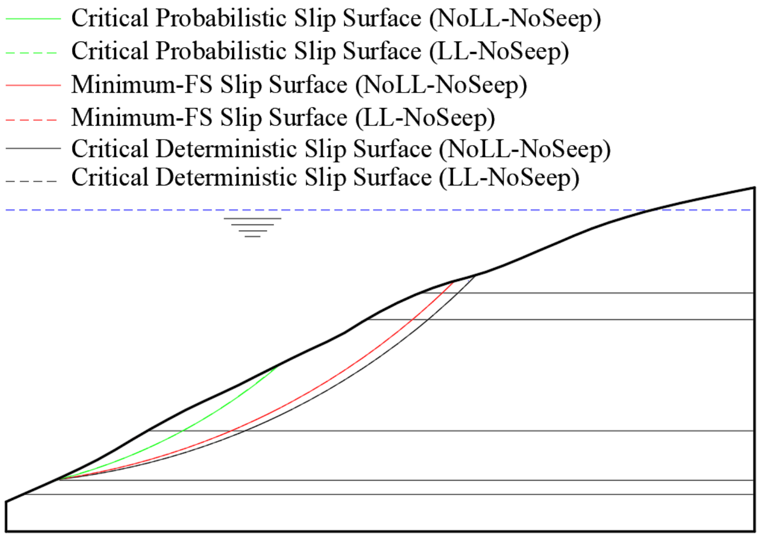


Fig. 18. Positions of the slip surfaces at the water level of 36 m at cross-section L8

Comparison between three methods

Fig. **19** shows the slip surfaces for the methods and calculation cases for the L8 section. It can be seen that the slip curves from the reliability analysis are completely different from the slip curves obtained from the deterministic analysis and the upper and lower bound analysis. These slip surfaces originate from above the lake water level. The critical slip surfaces in the reliability analysis are located below the lake water level. If the slip surfaces below the lake water level occur first, the sliding soil mass can develop and penetrate deep into the shore, creating a large landslide area. From the results obtained from the three methods, it can be said that the slip surface that has the smallest safety factor is from the lower bound analysis. Thus, if only the deterministic analysis is used, there will be shortcomings in providing solutions to prevent landslides. Therefore, reliability analysis and upper and lower bounds analysis are necessary to assess the stability of the slope comprehensively.

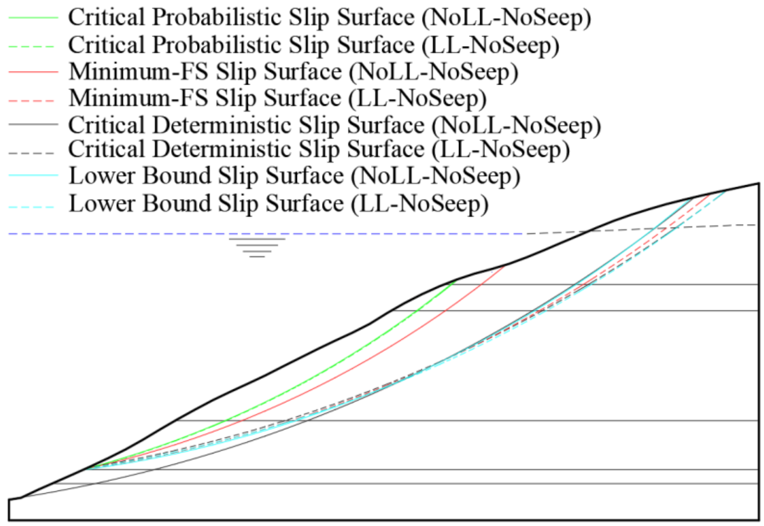


Fig. 19. Positions of the slip surfaces at the water level of 34.2 m for different methods at cross-section L8

4. Conclusion

From the results of this study, some conclusions can be drawn as follows:

1. In general, cross-section L8 is vulnerable to the landslide. Thus, solutions for protecting the slope should be implemented.

2. The lake water level significantly affects the stability of the slope. Specifically, the lower lake water level will be a more unstable slope.

3. The effects of seepage from the groundwater level outsideward to the lake and the live load have a smaller effect on slope stability compared to the lake water level. However, this can suddenly cause a landslide to occur, among other major causes.

4. The slip surface, which has a minimum factor of safety in the reliability analysis, is different from the critical deterministic and probabilistic slip surfaces.

5. The deterministic analysis is not enough for a full assessment of slope stability. It should be integrated with the upper bound and lower bound analyses, as well as reliability analyses, for a full understanding of the risk of the landslide. In doing so, the slope stability analysis will be a solid foundation for proposing solutions for reinforcing and protecting the slope.

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