STABILITY OF OPEN PIT LIGNITE EXCAVATIONS DURING FLOODING. COMPARISON OF A SIMPLIFIED ANALYTICAL TOOL WITH LIMIT EQUILIBRIUM COMPUTATIONAL ANALYSIS

STABILNOŚĆ WYROBISK KOPALŃ ODKRYWKOWYCH WĘGLA BRUNATNEGO PODCZAS ICH ZALEWANIA WODĄ. PORÓWNANIE UPROSZCZONEGO NARZĘDZIA ANALITYCZNEGO I ANALIZY METODĄ RÓWNOWAGI GRANICZNEJ

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A common practice for valorizing abandoned open-pit mines is flooding them to form pit lakes. Slope stability in post--coal areas is critical due to failure incidents reported in surface coal mines during operation and valorization. An analytical model was recently presented concerning evaluating the pit lake's slope stability in the presence of a weak zone. The present work compares that analytical model with a limit equilibrium computational approach for lignite mines' stability. Assumptions of each model are discussed, and identical geometries and geotechnical parameters are implemented. It is concluded that the Safety Factor and its evolution are very sensitive to the water regime and the lake's depth for the analytical model. On the other hand, the limit equilibrium analysis considering the same piezometric and lake levels proposes a drastically different SF evolution. Overall, the differences between the analytical and the limit equilibrium analysis might refer to different water conditions in practice and should be implemented with due caution.

Słowa kluczowe: *slope stability, lignite mines, weak zone, reclamation practices*

Powszechną praktyką rekultywacji byłych kopalń odkrywkowych jest zalewanie ich wodą w celu utworzenia zbiornika pokopalnianego. Stabilność zboczy na terenach poeksploatacyjnych jest parametrem krytycznym ze względu na przypadki zniszczeń występujące w kopalniach odkrywkowych podczas eksploatacji i rekultywacji. Ostatnio przedstawiony został model analityczny dotyczący oceny stateczności zboczy zbiornika poeksploatacyjnego przy obecności strefy osłabienia. W niniejszej pracy porównano ten model z obliczeniową metodą równowagi granicznej dla stateczności kopalń węgla brunatnego. Omówiono założenia każdego z modeli oraz wykorzystano identyczne geometrie i parametry geotechniczne. Stwierdzono, że w modelu analitycznym współczynnik bezpieczeństwa i jego zmiany są bardzo wrażliwe na reżim wodny i głębokość zbiornika. Z drugiej strony, analiza metodą równowagi granicznej, uwzględniająca te same poziomy wody w piezometrach i zbiorniku, wskazuje na radykalnie inny proces zmian współczynnika bezpieczeństwa. Ogólnie rzecz biorąc, różnice pomiędzy modelem analitycznym a metodą równowagi granicznej mogą w praktyce odnosić się do różnych warunków wodnych i powinny być wdrażane z należytą ostrożnością.

Keywords: *stabilność zboczy, kopalnie węgla brunatnego, strefa osłabienia, praktyki rekultywacyjne*

Introduction

During the last decades, coal has been the main mineral resource for producing energy for domestic and industrial purposes. Many surface mines have been created globally and on a European scale to exploit the coal deposits. These huge excavations are significantly affected by geotechnical issues, a critical one being slope stability (Zevgolis et al., 2019). Slope failures and subsequent landslides are critical as they disastrously impact human lives and infrastructure. A vital triggering factor of these phenomena is the presence of a sub-horizontal zone of low strength. This zone can be a layer or an interface between layers, named the weak zone. Several incidents of slope failures based on the above mechanism have been reported in many countries, such as Greece (Leonardos 2004), Turkey (Ural & Yuksel 2004), Poland (Bednarczyk 2017), the Czech Republic (Mencl 1977), and Australia (Ghadrdan et al. 2020).

While the transition to the post-coal era is in progress, many surface coal and lignite areas will be abandoned soon. Therefore, sustainable restoration measures are being planned. One of the most common reclamation practices is the formation of pit lakes when closed excavations are flooded with water to create a lake offered to the local societies, primarily for recreational purposes. The geotechnical assessment related to the slope stability of the flooding pit might be crucial, depending on each case. The water table's elevation during flooding affects slope safety by increasing the pore water pressures of the submerged soil layers. However, the increase of the water body inside the open pit also acts as a supporting force, and the pit lake's creation has been reported to improve slope stability as the lake height rises (e.g., Desjardins et al., 2020; Faur et al., 2020).

The present analysis investigates the impact of the pit lake's creation process on slope stability. Kavvadas et al. (2022) recently presented an analytical model to assess slope stability versus the pit lake's height. This work compares this analytical model with the limit equilibrium method (LEM) computational analysis as implemented in Slide2 (Rocscience, 2019). For this comparison, identical slope geometries, geotechnical parameters, and groundwater conditions were considered.

Methods of analysis

Analytical model: formulation and basic assumptions

Kavvadas et al. (2022), based on Kavvadas et al. (2020), developed a simplified analytical tool to calculate the evolution of the safety factor of surface lignite mining slopes after closure, considering the gradual rising of the water in the pit lakes. The analysis assumes that failure of lignite mining slopes occurs along a horizontal/sub-horizontal interface named the weak zone, close to the base of the slope, surface through a tension crack (Fig. 1). The SF is calculated as:

$$SF = \frac{c'_z L' + [(W+W_W)\cos\beta_z + (U_W - U_1)\sin\beta_z - U_2]\tan\varphi'_z}{(W+W_W)\sin\beta_z + (U_1 - U_W)\cos\beta_z} \quad (1)$$

where φ'$_z$ is the effective friction angle, c'$_z$ the effective cohesion, and β_z the inclination of the weak zone; W is the sliding mass' weight; U_1 is the horizontal water force along the tension crack; U_2 is the water force at the sub-horizontal slip surface (Fig. 1). Note that the angle β in Figure 1 indicates the total slope angle of the excavation since the benches' influence can be ignored (Mikroutsikos et al., 2021). The water forces U_1 and U_2 are calculated by integrating the water pressure distributions along the respective surfaces and are provided by:

$$U_1 = \frac{1}{2}\lambda_1 \gamma_W Y^2 \quad (2)$$

$$U_2 = \frac{1}{2}\gamma_W (H_W + \lambda_1 Y) L' \quad (3)$$

where Y is the depth of the sliding mass at the transition point, L' is the length of the sliding mass's base, from the toe of the slope to the transition point (Fig. 1), and the factor λ_1 (between 0 and 1) defines the height of the hydrostatic pressure in the tension crack.

In the presence of the lake's water, two additional forces, W_W and U_W, are acting at the toe of the slope vertically and horizontally, respectively:

$$U_W = \frac{1}{2}\gamma_W (H_W)^2 \quad (4)$$

$$W_W = \frac{U_W}{\tan\beta} \quad (5)$$

where H_W is the height of the lake's water depth.

Zevgolis et al. (2021) underlined that the rate of pit lake formation is critical to slope stability. The rapid filling of the pit lake is favorable because the stabilizing impact of the acting forces W_W and U_W prevail over the rising pore pressure inside the slope.

This work compares the above analytical model with limit equilibrium computational analysis. Thus, the main assumptions of the analytical model need to be clarified. Firstly, the overburden soil's strength is neglected since the failure occurs along the weak zone and reaches the ground surface through the tension crack. Furthermore, as underlined in Zevgolis et al. (2021), the forces U_1 and U_2 are crucial for the outcome of the analytical method. These water forces act against slope stability, and the factor λ_1 determines them. Notice that a critical assumption for the present model is the linear variation of pore water pressures acting on the base of the sliding mass leading to U_2. Finally, dry conditions inside the slope cannot be appropriately simulated with this analytical model; setting U_1=U_2=0 leads to an enormous SF, and if β_z=0° SF is infinite.

Limit equilibrium computational model: basic assumptions

The same stratigraphy as the previous model is assumed, with a weak zone crossing the slope from the toe to its left boundary (Fig. 2). The weak zone was simulated with a boundary condition named „Weak Layer" in Slide2 (Rocscience, 2022) employed for modeling very thin weak layers or interfaces with low strength. The advanced „cuckoo" search method for non-circular surfaces was used in this work, which does not demand the failure surface's location or shape, combined with Spencer's method for the Safety Factor calculation. The Mohr-Coulomb failure criterion was employed for the shear strength. The lake's water level (H_W) rise in the pit (leading to the lake's formation) was simulated with a horizontal phreatic water table being elevated from the bottom to the top of the excavation with a step of 10%. A horizontal-inclined water table similar to the analytical model was simulated (Fig. 2); the horizontal piezometric level reaches the crest, and then an inclined line connects this piezometric level with the lake level.

The groundwater regime is a crucial point of comparison for the two approaches. The analytical model uses the λ_1 coefficient (ranging from 0 to 1, with typical values from 0.5 to 0.9) to define U_1 and U_2, two water forces acting upon the two linear parts of the sliding surface as shown in Figure1. Similarly, in computational analysis the water table's level was determined by H'$_W$ which is associated with the piezometric level inside the sliding mass as shown in Figure 2. As a result, λ_1 and H'$_W$ quantify the same problem. The effect of

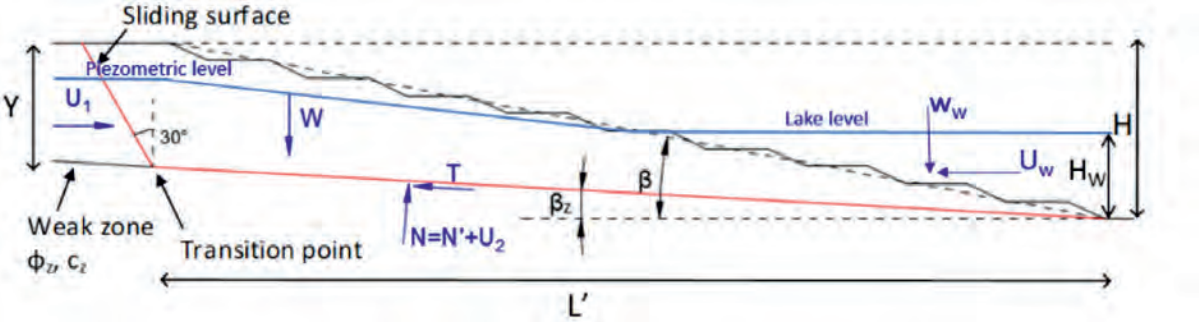

Fig. 1. Geometry and forces on a typical sliding mass (after Kavvadas et al. (2022))
Rys. 1. Geometria i siły dla masy ulegającej typowemu poślizgowi (wg Kavvadas et al. (2022))

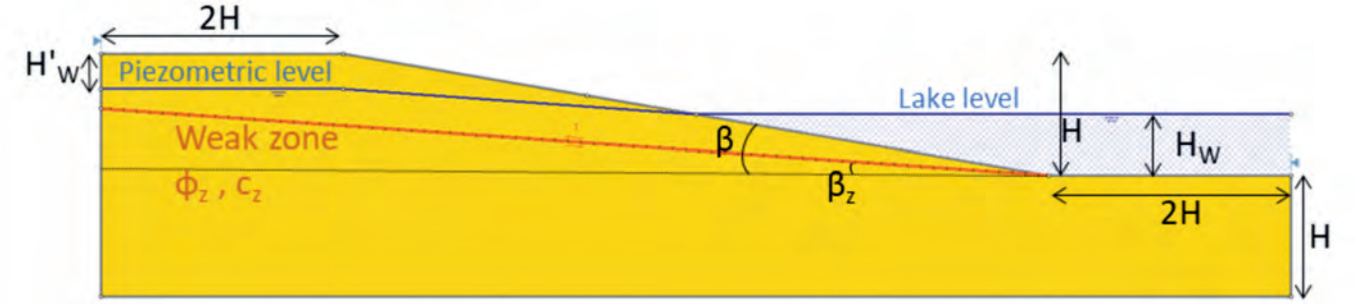

Fig. 2. Geometry and main parameters of the computational model with a horizontal-inclined water table
Rys. 2. Geometria i główne parametry modelu obliczeniowego z poziomym - nachylonym zwierciadłem wody

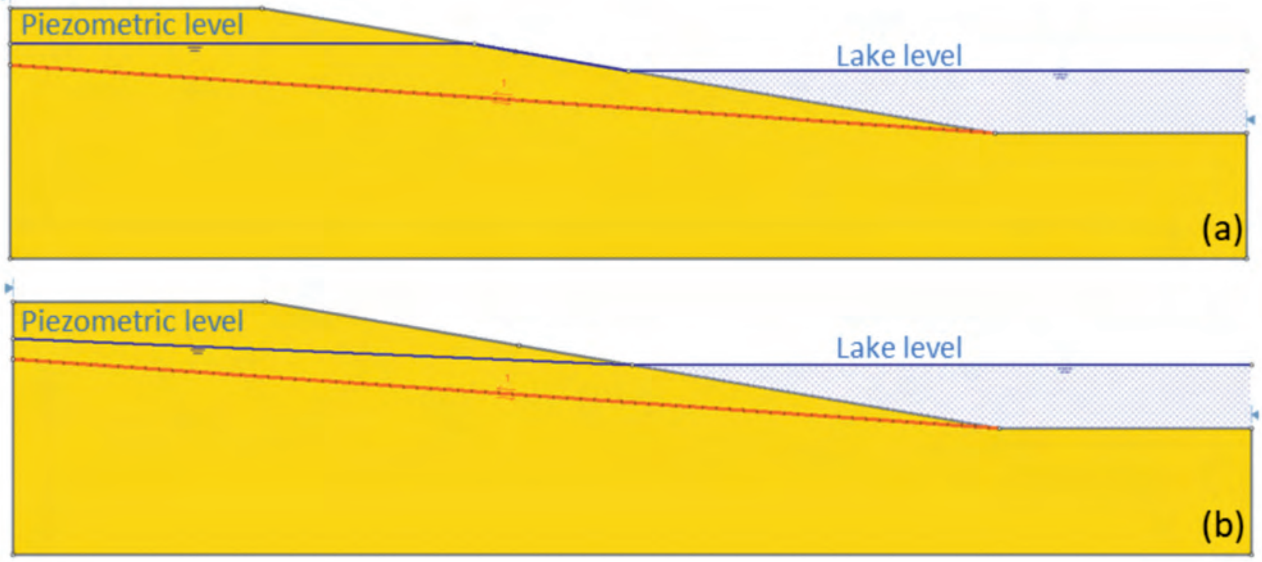

Fig. 3. (a) horizontal water table and (b) inclined water table
Rys. 3. (a) poziome zwierciadło wody i (b) nachylone zwierciadło wody

Tab. 1. Geometrical and geotechnical parameters implemented for the comparison
Tab. 1. Parametry geometryczne i geotechniczne wykorzystane do porównania

	Symbol	Analytical model	LEM model
Weak zone's effective friction angle	φ'_z (°)	22	22
Weak zone's effective cohesion	c'_z (kPa)	5	5
Soil's effective friction angle	φ' (°)	Tension crack	28
Soil's effective cohesion	c' (kPa)	Tension crack	185
Weak zone's unit weight	γ_z (kN/m^3)	17	17
Soil's unit weight	γ (kN/m^3)	-	20
Slope height	H (m)	200	200
Lake's water height	H_W (m)	0-200	0-200
Slope inclination	β (°)	10	10
Weak zone's inclination	β_z (°)	4	4

this simplified water table was further evaluated by employing a horizontal to the slope edge (named horizontal) (Fig. 3(a)) and an inclined from the model's left edge (named inclined) (Fig. 3(b)) water table.

Identical slope geometries and geotechnical parameters were studied to compare the two approaches (Tab. 1). The comparison was conducted for an inclined weak zone with β_z=4°, height and inclination of the slope H=200 m and β=10°, respectively. Both for the analytical and the LEM model, the soil's friction angle and cohesion were φ'=28° and c'=185kPa (Theocharis et al. 2021), while for the weak zone, φ'_z=22° and c'_z=5 kPa were considered.

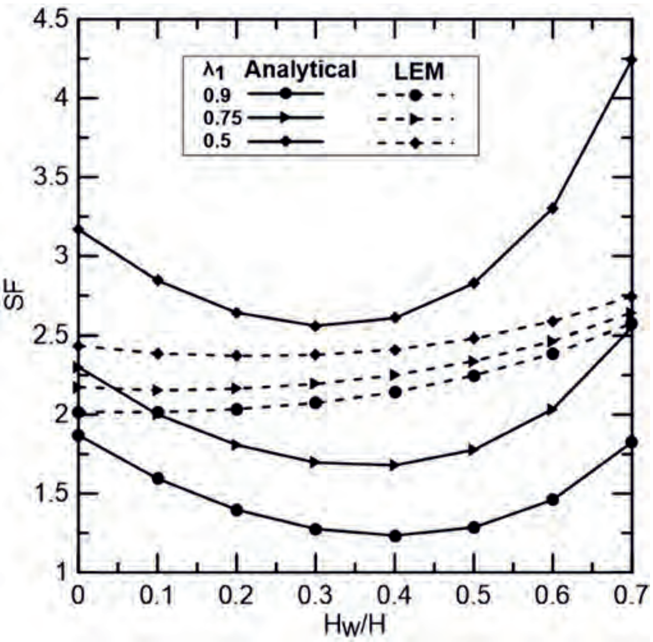

Fig. 4. Safety Factor (SF) with water filling ratio (H_W/H) for various λ_1, considering horizontal-inclined water table

Rys. 4. Współczynnik bezpieczeństwa (SF) ze współczynnikiem wypełniania wodą (H_W/H) dla różnych λ_1, przy uwzględnieniu poziomego-nachylonego zwierciadła wody

Results

Figure 4 presents SF with the water filling ratio (H_W/H) for the analytical and computational analyses, with solid and dotted curves, respectively, considering the horizontal-inclined water table (Fig. 2). Factor λ1 varied from 0.5 to 0.9, and it is used to characterize both approaches due to its relation with the H'_W. Specifically, H'_W is associated with λ_1 through Y (Fig. 1) as follows:

$$H'_W=(1-\lambda_1)Y \tag{6}$$

Increasing the water filling ratio from 0 to 0.35 leads to a gradual decrease of SF by approximately 15%. However, a further increase results in a rapid SF increase. The Safety Factor receives extreme values for a water filling ratio greater than 0.7 as the increase of the water body inside the open-pit acts as a supporting force and leads to increased SF. The factor λ_1 affects the SF tremendously regarding the analytical method; increasing λ_1 from 0.5 to 0.9 reduces the SF by approximately 43-55%. For instance, if the lake is half-filled (H_W/H =0.5), then the SF ranges from 2.8 (λ_1=0.5) to 1.3 (λ_1=0.9), closing the critical stability regime.

On the contrary, the factor λ_1 affects the SF tenuously in the LEM. In particular, from 0.5 to 0.9, the SF decreases up to 15% in the initial stages of water filling, while for H_W/H greater than 0.5, the changes are negligible. In the case of LEM, the SF practically does not decrease for the selected geometry and conditions, contrary to the analytical method; instead, the SF increases slowly. This difference is due to the different calculations of water forces in the analytical and the LEM model. For the analytical model, U_2 determines the changes in the SF at the initial stages (H_W/H<0.4, see eq. (3)); for the LEM, a very small difference in pore pressures inside and underneath the sliding mass takes place in these initial stages, leading to the very small differences observed. This difference is ultimately the critical one between the two methods.

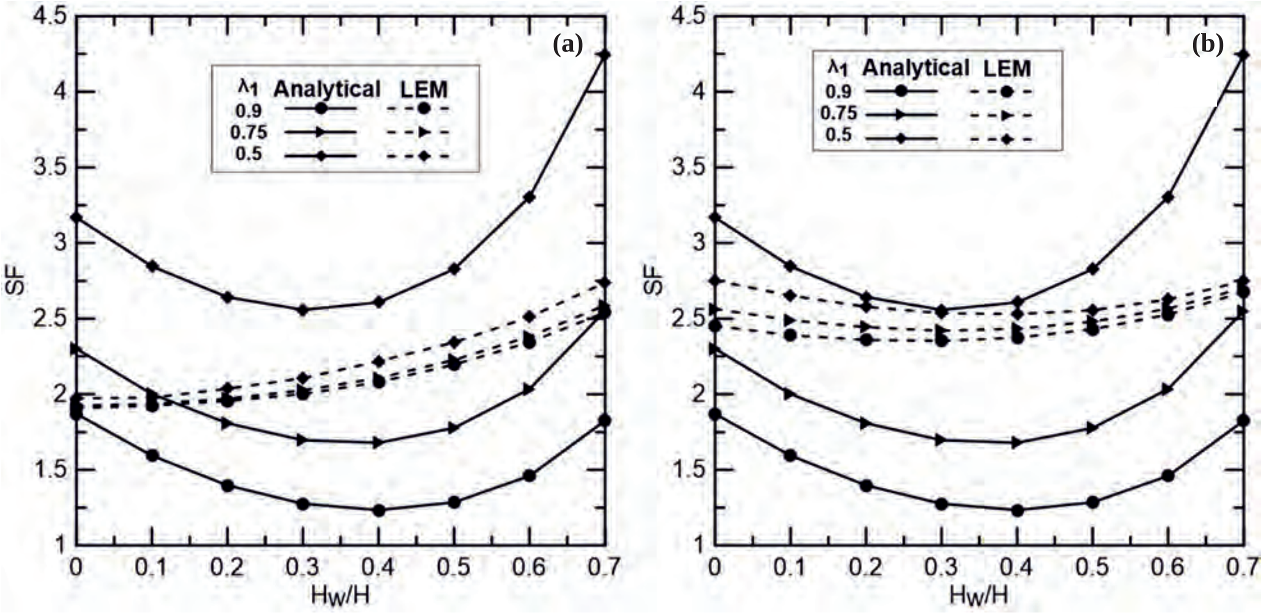

Fig. 5. Safety Factor (SF) with water filling ratio (H_W/H), for various λ_1, considering (a) horizontal and (b) inclined water table

Rys. 5. Współczynnik bezpieczeństwa (SF) wraz ze współczynnikiem wypełniania wodą (H_W/H), dla różnych wartości λ_1, przy uwzględnieniu (a) poziomego i (b) nachylonego zwierciadła wody

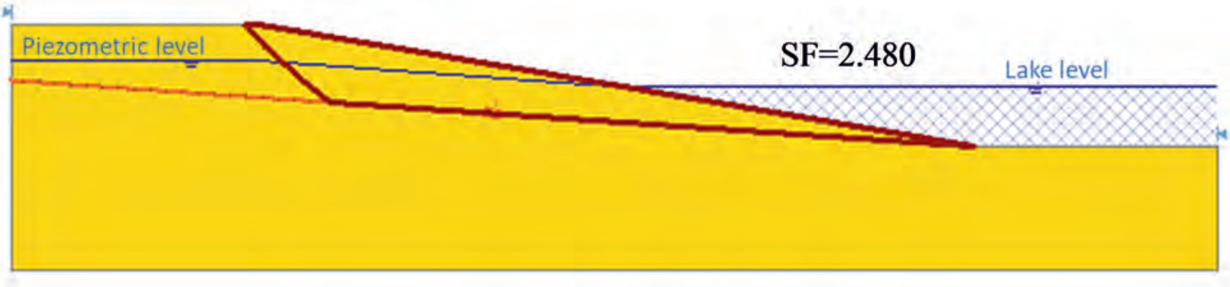

Fig.6. Failure surface with SF result for half-filled lake considering λ_1=0.5 (SF=2.480)
Rys. 6. Powierzchnia zniszczenia wraz z wynikowym współczynnikiem bezpieczeństwa dla wypełnionego do połowy zbiornika przy uwzględnieniu λ_1=0,5 (SF=2,480)

Figure 5(a) and Figure 5(b) present the same analytical results concerning a horizontal and an inclined water table in the LEM analysis; thus, only the LEM results change while the analytical results remain the same. Considering the horizontal water table, a slight increase of SF is observed during water filling, whereas in the inclined water table, the SF remains practically stable. In Limit Equilibrium analysis, the impact of λ_1 remains tenuous for all water table conditions.

Figure 6 illustrates a typical, non-circular failure surface for the slope with the horizontal-inclined water table and half-filled lake, which was calculated with LEM. Notice that the failure surface is similar to the predetermined of the analytical model since failure occurs along the weak zone.

Conclusions

Kavvadas et al. (2022) presented a practical and useful analytical model for lignite mines' slope stability in the presence of a weak zone with the impact of lake formation. The present study compared that analytical model and an LEM computational approach. Assumptions of each model were discussed, while identical geometries and geotechnical parameters were implemented. The water regime was simulated similarly for the two methods, and a tentative parametric study was conducted on the piezometric and lake levels.

The LEM does not demand any assumption regarding the failure surface's shape and location, as it arises naturally from the analysis. The analytical method is more sensitive to the changes in piezometric level and lake level, parameters hard to know precisely in real conditions. In the analytical model, the impact of water evolution, specifically the forces U_1, U_2, U_W, and W_W, is significant for slope stability since the SF changes rapidly as the pit-lake formation evolves. The SF decreases until the filling ratio reaches 35% because the force U_2 increases significantly, negatively affecting slope stability. On the contrary, in the computational model, the piezometric level's rise does not substantially impact SF; the pit-lake formation acts favorably from the initial stages of the water filling, and the SF slightly increases. Overall, the differences between the analytical and the limit equilibrium analysis might refer to different conditions and should be implemented in practice with due caution.

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