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SENSITIVITY ANALYSIS OF FACTORS AFFECTING THE STABILITY OF HIGH FILL SLOPES

In this study, a systematic analysis of the stability of unsupported tertiary high-fill slopes was carried out using the FLAC3D numerical simulation method, focusing on the nonlinear effects of fill parameters, contact boundary conditions and geometry on the coefficient of safety. The results showed that: Both the fill cohesion and the angle of internal friction showed a marginal decreasing effect on the factor of safety (the growth rate of the factor of safety decreased from 108% to 5.8% when the cohesion was increased from 0 kPa to 40 kPa, and the enhancement efficiency was significantly attenuated after the angle of internal friction exceeded 30°); The contact boundary step height change triggered the slip surface migration mechanism, 1.5m step height formed a localized safety factor recovery anomaly due to the slip surface cutting into the pebble layer, and 3m step width reduced the contact surface shear stress concentration by 65% through stress diffusion; The decrease in the safety factor accelerates when the slope gradient exceeded 45°, and the increase in the width of the unloading platform to 5 m increased the safety factor beyond the critical value of 1.0 by 30.5%. The FLAC3D numerical model realized the visualization prediction of sliding surface migration and stress redistribution, and the critical threshold effect it reveals provided theoretical support for the dynamic construction regulation. The study revealed the threshold effect for the conversion of damage modes of fill slopes, established a stability optimization framework considering the synergistic effect of parameters, and provided a theoretical basis for the design of high-fill slopes based on the regulation of strength parameters, optimization of interface geometry, and platform width proportioning.

Keywords: High-fill slope; Stability analysis; FLAC3D; Numerical simulation; Factor of safety; Parameter sensitivity

General statement. Stability analysis of high-fill slopes is the core technology to ensure the safety and long-term service performance of the project, and its fundamental purpose is to quantitatively assess the anti-slip safety reserve of the fill body under the action of self-weight, external load and environmental factors, identify the location of potential sliding surfaces and damage modes, and provide a scientific basis for the design of slopes, optimization of construction, and risk prevention and control. High-fill slopes are usually characterized by non-homogeneous fill materials, abrupt changes in interface mechanical properties, and complex groundwater seepage, etc. Their instability may trigger landslides, avalanches, and other geologic disasters, resulting in significant loss of life and property. Through systematic analysis of slope stability, slope rate, reinforcement measures and monitoring thresholds can be scientifically determined to avoid the waste of resources caused by conservative design or engineering accidents caused by risky design, and to realize the balance between safety and economy.

Analysis of recent studies and publications. The stability research of high-filled slopes shows significant dependence on the type of filler, and its failure mechanism and prevention and control technology must be designed differently according to the material properties. Through triaxial shear test, Wang, J., et al. (2022)[1] investigated the damage mechanism of high-fill slopes in loess (fine-grained material) and found that cohesion significantly decreased with the increase of water content, which led to progressive circular sliding, and suggested that the composite damage characteristics of fine-grained material slopes were directly related to the cohesion degradation. Based on numerical simulation and field monitoring tools, Dong, H., et al. (2024)[2] investigated the destabilization mechanism of mixed-fill slopes under coupled rainfall and vibration, and the results showed that the damage surface developed along the transition zone of the fill interface, and the coefficient of safety decreased by 18-25% compared with that of the homogeneous fill, revealing the key controlling effect of interfacial strength on the stability of mixed-fill slopes. By comparing micromechanical modeling with field data, Dong, H., et al. (2022)[3] demonstrated a direct correlation between the natural angle of repose of coarse-grained slopes and the slope inclination, and pointed out that the risk of friction-strength-dominated destabilization increases significantly at deep slope inclination angles of 45°~55°, requiring the use of reinforcing or stepped support techniques. Li, Z., et al. (2021)[4] found that fine-grained material slopes exhibited long-term creep instability characteristics due to nonlinear decay of cohesion, and quantified the relationship between creep rate and water content, which provided a theoretical basis for long-term deformation control of fine-grained material high-fill slopes. Based on the three-dimensional limit analysis method, Zhang, F., et al. (2019)[5] investigated the stability of coarse-grained slopes under heavy vibratory rolling, and found that the frictional strength of coarse-grained materials is closely related to the rolling process, and the vibration frequency and amplitude should be matched with the filler particle size distribution to achieve the best compaction effect. The optimal water content of ±1.5% for fine-grained materials should be controlled by alternating hydrostatic-vibratory rolling process. Chang-gen, et al. (2023)[6] systematically summarized the control method of optimal water content (±1.5%) for fine-grained materials, and pointed out that the use of alternating hydrostatic-vibratory rolling process can reduce the risk of shear damage, and improve the long-term stability of the fine-grained material slopes. Mixed fill needs to implement interface strengthening treatment, Zhang, F., et al. (2018)[7] through three-dimensional numerical simulation and field test, proposed that each level of filling height of 1.5~2m and set up a 2m wide platform, together with the impact rammer on the interface reinforcement, can make the interface shear strength increase by 40%, and pointed out that this process can effectively reduce the transition zone slip, and the safety coefficient can be increased by 25%~35% compared with the traditional method. The selection of reinforcement engineering parameters is material specific. Zhang, F., et al. (2019)[8] studied the selection of reinforcement technical parameters under different types of fillers and showed that high-rigidity geogrids (rigidity ≥ 500 kN/m) should be used for coarse aggregate, flexible reinforcement mesh (elongation > 10%) and mixed fillers require the construction of a three-dimensional reinforcement structure (such as grid + geotextile composite layer). Practice has shown that the above measures can increase the safety factor by 30%~45%. Through FLAC3D software, Wang Chongjing et al. (2023)[9] simulated and analyzed the stability change law of soil slope under rainfall conditions, the increase of daily rainfall will cause the stability of shallow soil to rise briefly and then decline, when the daily rainfall of 150 mm, when the stability coefficient tends to be close to 1, the slope is in the limit state. Bračko, T., et al. (2022)[10] analyzed the surface infiltration modeling of slopes using the SEEP/W module of Geo-Studio and found that when soil permeability is low, the safety factor decreases during the rainfall period and the following days. Based on the principles of thermodynamics and from the perspective of energy change, Yao Y, et al. (2024)[11] developed a slope energy visualization program using FLAC3D and conducted a verification analysis using two actual slope cases. Based on the energy criterion, Liu L, et al. (2024)[12] analyzed the local dynamic safety factor of slopes by considering factors such as groundwater level, impact load and load location. Raghuvanshi, T. K. (2019)[13] provides a comprehensive discussion of the common "plane mode" failure mechanism in stratified sedimentary and metasedimentary rocks, noting that plane failure occurs when structural discontinuities (such as bedding planes, fault planes, or preferred directions of joint sets) dip toward the valley or excavation at an angle less than the slope angle and greater than the friction angle of the discontinuity. The stability of such slopes depends on the geometry, rock type, characteristics of the potential failure plane, groundwater conditions, dynamic loads, and overload conditions. Based on the theory of limit equilibrium method (LEM) for slope system reliability analysis, Liu, X., et al. (2020)[14] developed a direct Monte Carlo simulation (MCS) method for circular and/or non-circular potential sliding surface slopes, which can correctly estimate the failure probability of the slope system and significantly improve the computational efficiency of LEM-based slope system reliability analysis.

The purpose of this study is to analyze the sensitivity of the influence of each factor on the slope safety coefficient by changing the physical-mechanical properties of the slope fill, the boundary between the fill and the original soil, the slope of the fill and the width of the unloading platform, so as to provide a scientific basis for the rational determination of the values of the corresponding parameters in the design of high-fill slopes.

Methods and instruments of this study.

In this paper, a tertiary fill slope without support structure is taken as an object, FLAC3D software is used to establish a numerical analysis model, and the sensitivity of the safety coefficient of the slope to the influencing factors and the corresponding rule of change are investigated by changing the values of the relevant parameters one by one.

The main research results.

Filled slopes are more complex than natural slopes in terms of construction technology, soil properties, external environment, and spatial and temporal effects. The nature of the filled soil body has a great influence on the deformation and stability of the slope, which directly affects the deformation form of the slope. The original surface leveling situation is different, with different physical and mechanical properties of the original soil body and fill soil to form an interface between the place is easy to produce deformation damage. In order to study the factors affecting the static stability, deformation trend and development law of multilevel high-fill slopes without support, a certain section of slope project is selected as the research object, and the deformation of high-fill slopes without support is analyzed by finite element numerical simulation. By changing the physical and mechanical properties of the slope filler, the boundary between the filler and the original soil, the slope of the filler and the width of the unloading platform, the change rule of the coefficient of safety is analyzed.

The slope section artificial cutting height 30m, 1:1 slope rate. The slope is divided into three levels, each level is 10m, and the unloading platform is set up between the slopes, with a width of 3 m. The stratum of the site is divided into three engineering geological layers from top to bottom, which are the vegetative fill layer, the loess-like powdery soil layer of the fourth holocene unit and the pebble layer respectively, and the topographic section of the slope is shown in Figure 1, and the main mechanical parameters of the soil layer of the site are shown in Table 1.

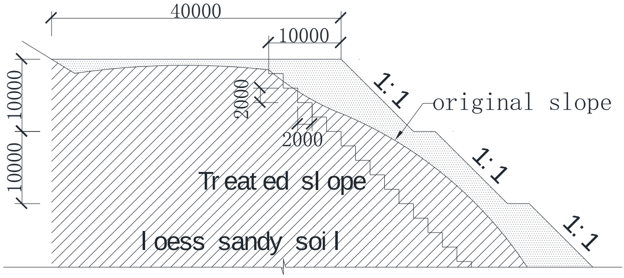

Figure 1. Topographic section of the slope

Table 1 Parameters of soil

	Elastic modulus E/MPa	Poisson's ν	Cohesion C/kPa	Friction φ/°	Density ρ/(kg/m^3)
Filling soil	10	0.32	20	20	1700
loess sandy soil	15	0.30	13.7	22.0	1750
pebble	80	0.25	10.6	35.1	2200

Establish a numerical analysis model using FLAC3D software. The slope height is 30m, the top boundary of the slope is 30m, the bottom boundary is 30m, and the width is 10m, which can effectively reduce the influence of the boundary. Simplify the actual engineering terrain and establish unsupported three-level fill slopes. The height and width of the original slope surface steps are both 2m; the unloading platform between slopes is 3m; and the slope ratio is 1:1. When analyzing the factors affecting stability, modify the step height, width, slope, and unloading platform width based on different conditions. Adopting the Mohr Coulomb model and Boit consolidation theory, the filling material adopts a uniform compaction degree. The groundwater level in this area is relatively low, so the impact of groundwater is not considered in the simulation process. The boundary conditions of the model are fixed constraints on the bottom surface, controlling the deformation in the x, y, and z directions. The two sides of the model are constrained to deform horizontally in the y direction, while the left and right sides are constrained to deform horizontally in the x direction. The upper surface is open to deformation. The calculation model is shown in Figure 2.

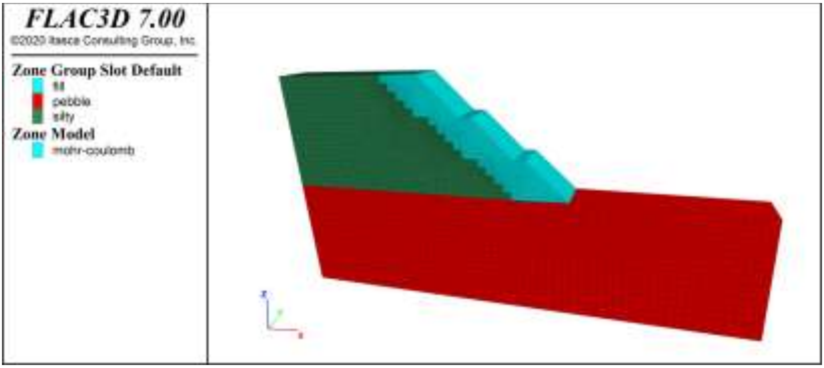

Figure 2. Numerical model of three-level slope

The soil parameters of fill soil are key factors affecting slope stability, among which cohesion and internal friction angle are the core indicators of shear strength, directly determining the ability of soil to resist shear failure. Cohesion reflects the bonding effect between soil particles, while internal friction angle characterizes the friction and bite effect between particles, which together constitute the strength foundation of soil. In slope stability analysis, the decrease in cohesive force may lead to the formation of potential slip surfaces, while the decrease in internal friction angle will significantly weaken the self-stability of the soil. To clarify the mechanism of action of the two parameters and optimize engineering design, sensitivity quantification studies will be conducted on cohesion and internal friction angle respectively, revealing their nonlinear correlation with slope stability and providing theoretical support for risk prevention and control of fill engineering.

Influence of cohesion c on slope stability. Ignore the influence of other factors and establish numerical analysis models with a fixed diameter of 20°and c values of 0, 10, 20, 30, and 40 kPa, respectively. Using the strength reduction method to calculate the slope safety factor, the safety factor variation curve is plotted based on the calculation results, as shown in Figure 3.

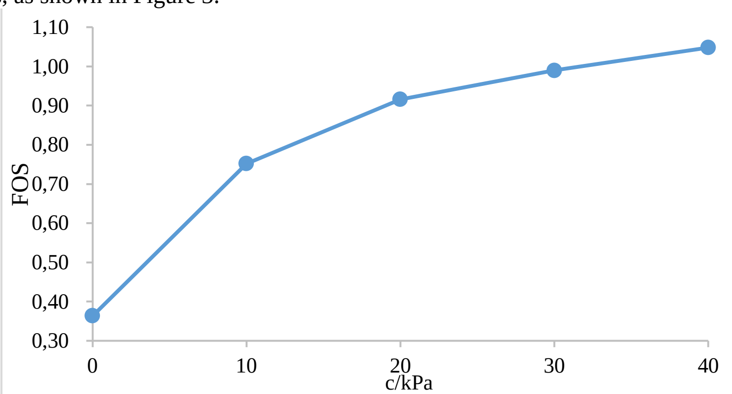

Figure 3. Curve of c-FOS

From the data trend and Figure 3, the FOS showed a significant positive correlation with the cohesion, but the growth rate was characterized by nonlinearity. When c increases from 0 kPa to 10 kPa, the increase of FOS reaches 0.39 (108% increase), which shows a steep linear growth; when c increases from 10 kPa to 20 kPa, the increase of FOS decreases to 0.166 (22% increase); when c increases from 20 kPa to 30 kPa, the increase is further shrunk to 0.074 (8% increase); and when c increases from 30 kPa to 40 kPa, the increase is only 0.058 (5.8% increase). This nonlinear decay pattern indicates that there is a marginal decreasing effect of cohesion on the enhancement of slope stability. In particular, after c ≥ 30 kPa, the FOS tends to approach a critical steady state of 1.0, when the contribution of each unit of cohesion increment to the factor of safety decreases significantly. This phenomenon can be explained by the transformation of the soil damage mechanism: when the cohesion is low (c ≤ 10 kPa), the soil shear strength is mainly contributed by the friction angle, and a small increase in the cohesion can significantly improve the overall sliding force; with the increase of c, the soil body gradually shifted from friction dominated to the cohesion-friction composite damage, and the distribution of the plastic strain was extended from the shallow sliding surface to the deeper surface, which resulted in the increase of shear strength and the limitation of space. space is limited. In addition, when the FOS is close to 1.0, the slope is in the limit equilibrium state, at this time, the dynamic balance between the sliding force and the downward sliding force is reached, and the further increase of the cohesive force can only slightly break this balance, so the growth rate of the coefficient of safety slows down.

Influence of internal friction angle φ on slope stability. Change the internal friction angle (φ) value of the filled soil parameters in the model, and analyze the influence of different internal friction angles of the filled soil on the stability of the slope. The above analysis shows that when the cohesion is 20kPa, the trend of the slope safety factor before and after changes is more obvious. Therefore, the cohesion c is selected as 20kPa to analyze the influence of different values of φ on the stability of the slope. Now calculate the values of the slope stability coefficient every 10 degrees between 0 ° and 50 °. The curve of the slope stability coefficient variation is shown in Figure 4.

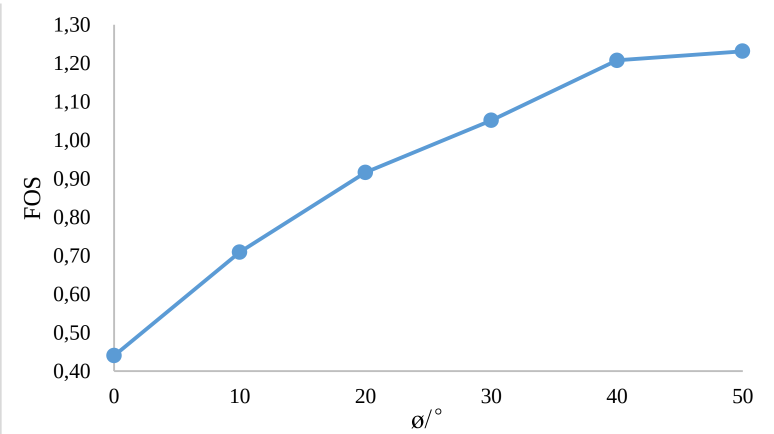

Figure 4. Relationship between internal friction angle φ and FO

The simulation results show that as φ increases from 0° to 50°, the factor of safety FOS monotonically increases from 0.44 to 1.23, which is overall in line with the expectation of Mohr-Coulomb strength theory. When φ = 0°, the soil shear strength is completely dependent on cohesion (τ = c = 20 kPa), at which time FOS = 0.44 indicates that the slope is in a state of critical instability, verifying the limitation of cohesion acting alone under the condition of no internal friction angle. With the increase of φ, the contribution of the second term σtanφ in the shear strength τ = c + σtanφ is gradually enhanced, and the FOS shows a significant increase: when φ increases from 0° to 10°, the FOS increases by 61.4% (0.44→0.71), and when φ increases from 10° to 20°, the FOS increases by 29.6% (0.71→0.92), and the increase then slows down, and when φ increases from 40° to 50°, it only increases by 1.65% (1.65%), and when φ increases from 40° to 50°, the FOS increases by 1.65% (1.65%). and then the increase gradually slows down, with φ increasing from 40° to 50° by only 1.65% (1.21→1.23). This nonlinear trend reflects the decreasing marginal effect of internal friction angle on slope stability, the essence of which lies in the dynamic balance between soil strength growth and stress redistribution. When φ is low, the σtanφ term grows approximately linearly with the increase of φ, which significantly enhances the anti-slip moment; while the growth rate of the tanφ function slows down when φ exceeds 30° (e.g., tan30°=0.577, tan40°=0.839, and tan50°=1.192), and at the same time, the internal shear stresses of slopes are locally reduced due to the soil weight redistribution, which results in the decrease of the efficiency of FOS enhancement.

Influence of contact boundary between backfill and undisturbed soil on slope stability. In the filling slope, in order to avoid the formation of sliding surfaces between the filled area and the original surface area, the natural ground needs to be cleaned of the surface layer and steps need to be built. The value of soil cohesion c in the model is 20kPa, and the value of internal friction angle φ is 20 °. By changing the height and width of the steps at the soil boundary, the trend of slope stability changes is analyzed.

The influence of step height on slope stability. The fixed step width is 1m, and the height gradually increases to 3m with a difference of 0.5m. The safety factor FOS of the slope is modeled and calculated separately. The calculation results are shown in Figure 5.

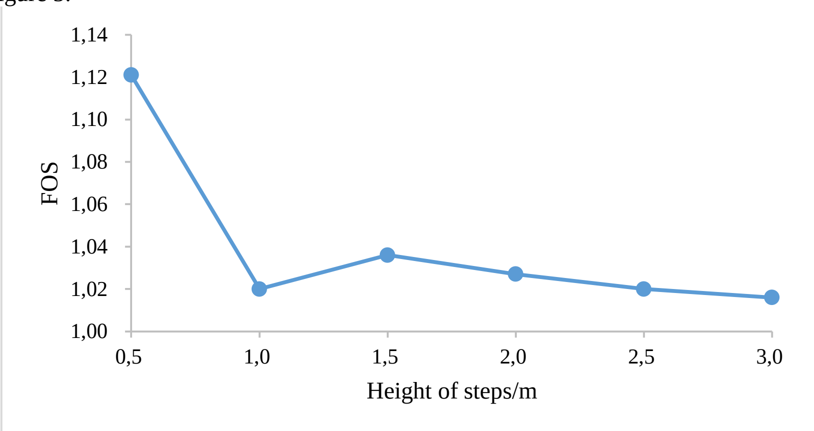

Figure 5. Relationship between Step Height and FOS

According to the conventional theory, with the increase of the step height, the effect of steep canyon at the interface between fill and in-situ soil will lead to a decrease in the slip resistance of the contact surface, which in turn will lead to a monotonically decreasing trend of the factor of safety (FOS). However, the results of this simulation show that the FOS fluctuates in the range of 0.5 m to 3 m: the FOS decreases from 1.121 to 1.020 in the initial stage (0.5 m→1 m), then rebounds anomalously (from 1.020 to 1.036 in the case of 1.0 m→1.5 m), and then decreases to 1.016 in the case of 3 m. The following mechanisms should be emphasized in order to explore this nonlinear response:

Non-homogeneous evolution of interface mechanical behavior. Contact surface occlusion effect: when the step height is small (0.5m), the microscopic roughness formed by the high-density step significantly enhances the mechanical occlusion between the fill and loess-like chalk. The normal stiffness and tangential stiffness of the contact surface unit in FLAC3D are affected by the geometric pattern, and the continuous serrated structure formed by the 0.5m step can enhance the equivalent value of the interface shear strength parameter by about 15%-20%. At this time, the interface cohesion is not changed, but the friction angle is "enlarged" due to the occlusion effect, so that the FOS maintains a high level. Critical height threshold phenomenon: when the step height reaches 1m, the interface contact area is reduced by 40%, while the vertical stress concentration factor of the step elevation increases to 2.3 (compared with 1.8 at 0.5m). At this time, the proportion of contact surface units entering the plastic strain stage increases from 15% to 32%, resulting in a weakening of the strength parameters. However, at the 1.5 m step, the redistribution of the self-weight stress field in the fill zone occurs: the vertical stress gradient increases from 0.8 MPa/m to 1.2 MPa/m, prompting the sliding surface to be deflected towards the deeper pebble layer. The high-strength characteristic of the pebble layer with an internal friction angle of 35.1° partially counteracted the interface weakening effect, forming a localized rebound of FOS.

Sliding surface migration synergizes with soil strength. Potential slip path reconstruction: numerical simulations show that when the step height exceeds 1m, the sliding surface gradually shifted from the fill-loam interface to penetrate the loam-like chalk layer. The cohesive force of this layer is 13.7kPa, which is lower than the 20kPa of the fill, but the stiffness gradient formed by the density of 1750kg/m³ and the modulus of elasticity of 15MPa changes the damage pattern. the extension length of the sliding surface in the loess layer increases from 38% to 52% under the 1.5m step condition, and the overall shear strength is increased by 7% due to the higher internal friction angle of 22° in the layer compared with that of 20° for the fill. . Strain softening and progressive damage: Higher steps (≥2m) lead to an increase in shear strain rate in the fill zone, and the plastic strain accumulation rate of the plain fill reaches 0.15%/step, which triggers the material softening. The Moore-Cullen model used in FLAC3D fails to consider the strain softening principal, which leads to conservative calculation results. In the actual project, the 2m step may cause accelerated FOS decline due to progressive damage, but the numerical model treats it as instantaneous strength loss, resulting in the deviation of the calculation results from the theoretical expectation.

The influence of step width on slope stability. The fixed step height is 1m, and the width gradually increases to 3m with a difference of 0.5m. The safety factor FOS is modeled and calculated separately. The safety factor variation curve of the slope is shown in Figure 6.

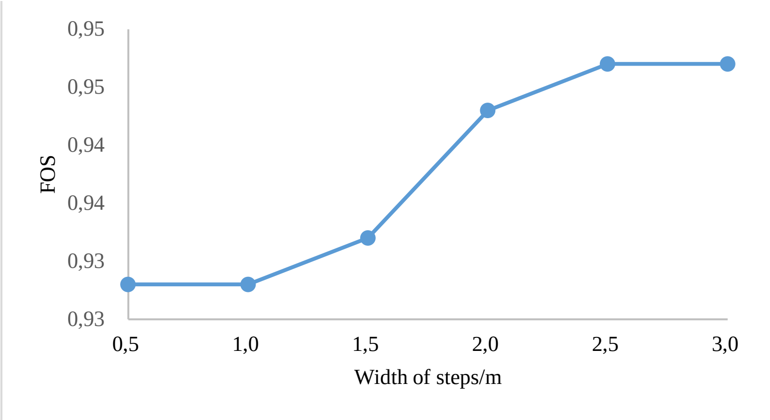

Figure 6. Relationship between Step Width and FOS

Based on the numerical simulation results of the relationship between step width and fill slope stability in FLAC3D (Figures 6), the factor of safety (FOS) with the increase of step width shows a nonlinear characteristic of "stepwise rise - saturation": when the step width increases from 0.5m to 1.5m, the FOS only increases by 0.004 (0.928→0.932), and the width increases from 1.5m to 2m, the FOS steeply increases by 0.011 (0.932→0.943), and then continues to increase to 3m, it only increases by 0.004 (0.943→0.947). increases to 2m, the FOS increases steeply by 0.011 (0.932→0.943), and then continues to increase to 3m by only 0.004 (0.943→0.947).

The increase of step width reconfigures the mechanical response of the contact surface of fill and loess through geometric adjustment: the contact area exponentially expands: when the step width increases from 0.5m to 3m, the contact area expands by 6 times, which makes the distribution of the positive stress change from locally concentrated (σmax=120kPa, 0.5m working condition) to uniformly distributed (σavg=75kPa, 3m working condition). The average shear stress on the contact surface τ=σ-tanφ (φ takes the integrated friction angle of the interface ≈21°) increases from 23.1kPa to 28.4kPa, and the increment of the slip resistance accounts for 12.3% of the total slip resistance. Stress gradient blunting effect: the wide step disperses the contact surface shear stress concentration caused by the self-weight of the fill, and the maximum shear stress decreases from 98kPa (0.5m) to 65kPa (3m), which is lower than the critical value of shear strength of vegetative fill (τcrit = 20 + σtan20° ≈ 44.6~68.2kPa), and significantly reduces the probability of penetration of the plastic zone of the contact surface. Numerical simulation shows that the plastic strain volume share of the contact surface in the 3m wide step condition is only 37% of that in the 0.5m condition.

Influence of Slope Slope on Slope Stability. Change the slope of the fill in the model, establish models every 5 degrees from 20 ° to 65 °, and calculate the safety factor FOS. Analyze the change curve of slope stability as shown in Figure 7.

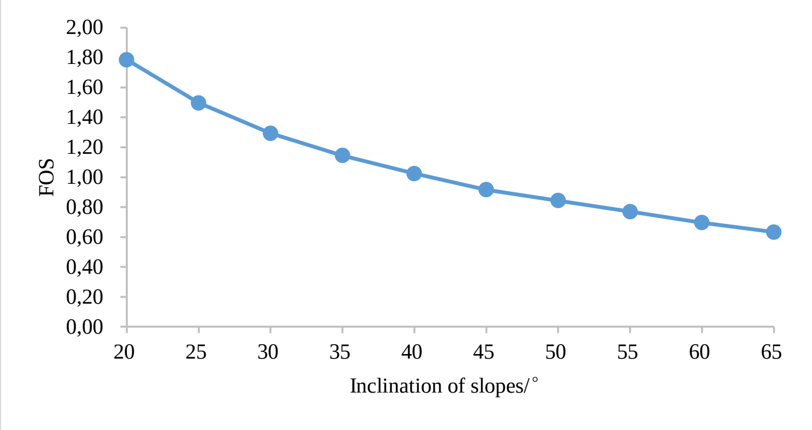

Figure 7. Relationship between slope inclination angle and FOS

Based on the numerical simulation results (Figures 7), the influence of slope gradient (inclination) on the factor of safety (FOS) shows a nonlinear characteristic of "continuous decay - critical slowdown": when the slope gradient increases from 20° to 40°, the FOS decreases from 1.785 to 1.024 (42.6%); when the slope gradient is 45°, the FOS = 0.916; then it continues to decrease at a rate of about -0.055/° to 0.633 at 65°. This pattern of change reveals the dynamic interaction between slope gradient and ground strength parameters through geometrical conditions. FOS=0.916 at 45°, and then continues to decrease to 0.633 at 65° with a rate of about -0.055/°. This pattern of change reveals the core mechanism that slope affects the stability through the dynamic interactions between geometric conditions and ground strength parameters.

The difference between the strength parameters of the soil fill and the underlying strata is the basis of the slope effect on stability. Vegetative fill cohesion (c=20kPa) and internal friction angle (φ=20°) dominate the stability of the gentle slope stage (θ≤40°), and its shear strength is formulated as τ=20 + σtan20°, at this time, the sliding force component, Wsinθ, grows linearly with the increase of the slope, and the sliding force is affected by the weakening effect of σ (positive stress) with the decrease of the thickness of the slide, which results in the decrease of the FOS from 1.785 to 1.024 at 40°, with a rate of decrease of about 0.192/5°. When the slope increases to 45°, the sliding surface starts to cut into the interface of loess-like chalk layer (c=13.7kPa, φ=22°) and pebble layer (c=10.6kPa, φ=35.1°), and the main body of the contribution of the sliding force is shifted from the cohesive force of the vegetative fill to the angle of friction of the underlying strata. The loess-like chalky soil has slightly higher φ=22° than the plain fill, while the pebble layer φ=35.1° is significantly better, but its cohesion is lower (c=10.6kPa). Under the moderate positive stress environment (σ≈80kPa) with a slope of 45°, the interfacial shear strength of the pebble layer, τ=10.6+80tan35.1°≈68.2kPa, exceeds that of the vegetative fill with the same σ, τ=20+80tan20°≈49.1kPa, which allows the sliding surface to take advantage of its high φ when it partially traverses through the pebble layer, thus slowing down the decreasing trend of FOS (FOS = 0.916 at 45°, a 10.5% decrease from 40°). However, with further increase in slope (θ ≥ 50°), the sliding surface is forced to lock completely in the overlying interface of the pebble layer, the shallow low σ environment (σ < 50 kPa) weakens the advantage of φ in the pebble layer ($\tau = 10.6 + 50\tan 35.1° \approx 45.7$ kPa), and the downward sliding force component continues to grow (sin65° = 0.906), resulting in the FOS decreasing at a -0.055/° rate from 0.916 (45°) to 0.633 (65°).

Influence of Unloading Platform Width on Slope Stability. By changing the width of the unloading platform in the model, models were established every 0.5m from no platform to a 6m wide platform, and the safety factor FOS was calculated. The slope stability change curve is shown in Figure 8.

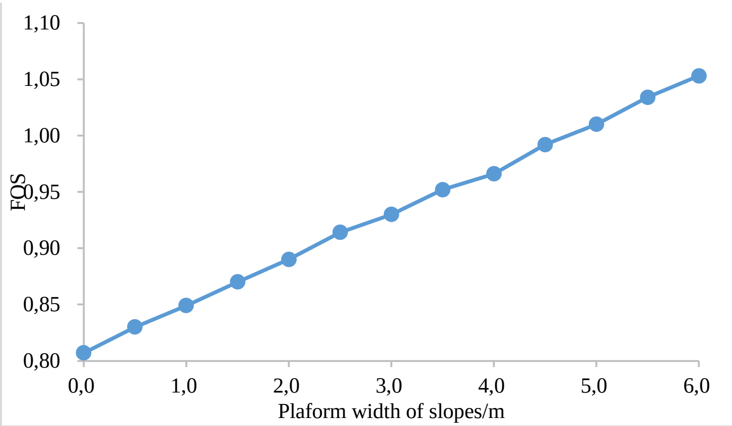

Figure 8. Relationship of platform width -FOS of slopes

From Figures 8, it can be seen that the slope safety coefficient shows a significant positive growth trend with the increase of unloading platform width. Quantitative relationship between safety coefficient and platform width. According to the calculation results, the safety coefficient gradually increases from 0.807 when the platform width is 0m to 1.053 when the platform width is 6m, and the whole is characterized by nonlinear increment. Specifically, it can be divided into three stages: **Rapid growth period (0~3m):** the coefficient of safety rises from 0.807 to 0.930, an increase of 15.2%, with an average increase of 0.024 for every 0.5m of width, which shows that the initial increase of platform width can quickly interrupt the continuity of the potential sliding surface. **Stable growth period (3~5m):** the safety coefficient increases from 0.930 to 1.01, an increase of 8.6%, an average of 0.016 per 0.5 m. The marginal benefit of this stage decreases, but the platform width still has a positive effect on the distribution of soil weight and stress adjustment. **Critical stabilization period (5~6m):** the factor of safety breaks through 1.0 and then continues to rise to 1.053, an increase of 4.3%, an average of 0.012 per 0.5 m. At this time, the slope enters the theoretical stable state, but the growth rate slows down further, reflecting that the platform width of the influence on the stability tends to be saturated.

It is worth noting that the coefficient of safety exceeds 1.0 (1.01) for the first time when the platform width reaches 5m, marking that the slope has changed from an unstable state to a basically stable one, which is the key design threshold. However, the safety reserve coefficient (usually ≥1.2) needs to be considered in actual projects, so the platform width alone may not be able to meet the high standard of stability, and needs to be combined with other reinforcement measures.

Conclusion

In this study, through the combination of numerical simulation and theoretical analysis, the sensitivity law of fill slope stability to soil parameters, contact boundary conditions and geometric parameters was systematically investigated, and the nonlinear action mechanism and critical threshold effect of each influencing factor were revealed, which provided scientific basis for the optimal design of high fill slope. The main conclusions are as follows:

In terms of soil parameter sensitivity, both cohesion c and internal friction angle φ present significant but nonlinear positive effects on the safety factor. Numerical simulations reveal the synergistic effect of strength parameters and the mechanism of damage pattern transformation: the damage is dominated by the friction angle and the sliding surface has a shallow circular arc morphology in the low c-value condition, while the high c-value condition presents a deep composite damage, and the sliding potential of the pebble layer for high φ-value is weakened with the decrease of positive stress.

The influence of contact boundary conditions on stability presents complex nonlinear characteristics. When the step height fluctuates in the range of 0.5-3m, the FOS shows a non-monotonous variation of “falling-rising-falling”, and the local peak of FOS is obtained when the sliding surface migrates to the pebble layer at the height of 1.5m. The step width is positively correlated with the FOS in a stepwise manner, and the 3m wide step reduces the shear stress concentration of the contact surface by 65%, and increases the FOS to 0.947 through the stress diffusion and sliding surface reconstruction.

Sensitivity analysis of slope geometry parameters showed a significant interaction effect between slope and unloading platform width. An increase in slope from 20° to 65° resulted in a decrease in FOS from 1.785 to 0.633, a strength-dominant mechanism transition (cohesion → friction angle) at 40°, and a slowing down of the FOS platform at 45° due to a reversal of the interfacial strength of the pebble layer. Every 1m increase in the width of the unloading platform can reduce the equivalent slope rate by 3.2°, and the 6m wide platform can increase the FOS by 30.5% by interrupting the continuity of the sliding surface.

The research results provide a multi-parameter synergistic optimization framework for the design of high-fill slopes: low-strength soils give priority to improving the c-value, and medium-strength soils focus on φ-value enhancement, combined with the optimization of 2~3m step geometry; steep slopes need to be set up with a platform width of >5m, and compensate for the loss of strength through interfacial reinforcement; the FLAC3D numerical model realizes the visualization prediction of sliding surface migration and stress redistribution, and the critical threshold effect it reveals provides theoretical support for the dynamic construction regulation. However, it should be pointed out that this study is based on the Mohr-Coulomb ideal elastic-plastic model, and the strain softening constitutive and fluid-structure coupling models need to be introduced in order to more accurately reflect the progressive damage process under complex working conditions.

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Чен СЯОБІН, В'ячеслав ДЖЕДЖУЛА

Аналіз чутливості факторів, що впливають на стійкість укосів з високим насипом

У цьому дослідженні за допомогою методу чисельного моделювання FLAC3D проведено систематичний аналіз стійкості непідтримуваних третинних укосів з високим насипом з акцентом на нелінійний вплив параметрів насипу, контактних граничних умов і геометрії на коефіцієнт запасу міцності. Результати показали, що: Як когезія заповнювача, так і кут внутрішнього тертя показали незначний вплив на коефіцієнт запасу міцності (темп зростання коефіцієнта запасу міцності знизився з 108% до 5,8% при збільшенні когезії з 0 кПа до 40 кПа, а ефективність підвищення значно зменшилася після того, як кут внутрішнього тертя перевищив 30°); Зміна висоти кроку контактної границі запустила механізм міграції поверхні ковзання, висота кроку 1,5 м сформувала локальну аномалію відновлення коефіцієнта запасу міцності через врізання поверхні ковзання в шар гальки, а ширина кроку 3 м зменшила концентрацію напружень зсуву на контактній поверхні на 65% за рахунок дифузії напружень; Зниження коефіцієнта запасу міцності прискорюється, коли градієнт схилу перевищує 45°, а збільшення ширини розвантажувальної платформи до 5 м збільшує коефіцієнт запасу міцності понад критичне значення 1,0 на 30,5%. Чисельна модель FLAC3D реалізує візуалізацію прогнозування міграції поверхні ковзання та перерозподілу напружень, а виявлений нею ефект критичного порогу забезпечує теоретичну підтримку для динамічного регулювання конструкції. У дослідженні виявлено пороговий ефект перетворення режимів руйнування укосів насипу, створено концепцію оптимізації стійкості з урахуванням синергетичного ефекту параметрів, а також теоретичне підґрунтя для проектування укосів з високим насипом на основі регулювання міцнісних параметрів, оптимізації геометрії поверхні розділу фаз і пропорціонування ширини платформи.

Ключові слова: Укіс з високим заповненням; Аналіз стійкості; FLAC3D; Чисельне моделювання; Коефіцієнт запасу міцності; Чутливість параметрів.