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Improved Stability Equations for Dry Homogeneous Slopes Considering Limiting Strength Conditions

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ABSTRACT: This study investigates the geometry of critical slip surfaces in dry homogeneous slopes and evaluates the applicability of existing regression-based stability equations under limiting strength conditions. A database was generated using the Morgenstern–Price method implemented in SLOPE/W, considering slope inclinations $\beta = 10^{o}$ - 85^{o}, friction angles $\varphi = 0^{o}$ - 40^{o}, stability numbers $N_s = c/\gamma H$, and foundation thickness ratios $d/H = 0 – 7.14$. The results show that slope inclination exerts the dominant control on failure geometry: increasing β generally produces shallower mechanisms. The influence of N_s depends strongly on the friction angle. For purely cohesive soils ($\varphi = 0°$), slip surface geometry remains nearly invariant with respect to N_s, whereas for frictional soils cohesion modifies failure depth through coupled interactions with slope geometry. The transition between shallow and deep failure mechanisms occurs near $\beta \approx 45°$ for $\varphi \geq 20^{o}$ and near $\beta \approx 60^{o}$ for purely cohesive slopes. Based on these observations, simplified stability equations are proposed for the limiting cases of purely frictional and purely cohesive slopes. The resulting formulations eliminate iterative slip-surface searches while preserving the governing mechanical trends of slope stability.

KEYWORDS: Slope Stability, Critical Slip Surface, Failure Mechanisms, Homogeneous Slopes.

1 INTRODUCTION AND BACKGROUND

Slope stability analysis is a fundamental problem in geotechnical engineering due to its direct implications for the safety of earth structures such as embankments, dams, and transportation infrastructure. The stability of a slope is commonly evaluated through the factor of safety (FS), defined as the ratio between available shear resistance and mobilized shear stresses along a potential failure surface (Bishop, 1955; Abramson et al., 2002). Among the available approaches, limit equilibrium methods (LEM) remain the most widely used because they provide reliable stability estimates with relatively low computational effort (Fredlund and Krahn, 1977; Duncan, 1996). However, these methods require iterative searches for the critical slip surface, which may become computationally demanding when numerous slope configurations must be analyzed.

To overcome this limitation, several regression-based stability equations have been proposed to estimate FS directly from soil parameters and slope geometry (Sah et al., 1994; Yang et al., 2004; Huang, 2018; Chien and Tsai, 2017; Sampa and Schorr, 2024). Although these formulations provide rapid estimates of slope stability, most were developed using datasets in which both cohesion and friction contribute simultaneously to shear strength, which may limit their applicability to the special cases of purely cohesive or purely frictional soils. In addition, the influence of foundation thickness and the geometric characteristics of the critical slip surface have not been systematically investigated.

Sah et al. (1994) proposed one of the earliest regression-based stability equations for slopes considering both circular and planar failure mechanisms and accounting for conditions with and without pore-water pressure. Their formulation was developed using linear regression applied to a dataset composed of 46 critical cases involving circular slip surfaces and 14 cases involving planar failures. The database included both stable and unstable slopes compiled from previously published studies.

For dry homogeneous slopes, the equation proposed by Sah et al. (1994) is expressed as

$$FS = \frac{2.27\, c'}{\gamma H \sin\, \beta} + 1.54 \frac{\tan \phi'}{\tan \beta} \tag{1}$$

where $c'$and ϕ' denote the effective cohesion and effective friction angle of the soil, respectively, H is the slope height, β is the slope inclination angle, and γ is the soil unit weight.

Yang et al. (2004) later proposed an alternative expression for estimating the factor of safety of dry homogeneous slopes. In developing their formulation, the authors adopted the same dataset compiled by Sah et al. (1994), although the analysis was restricted to cases involving circular failure surfaces. The resulting equation is expressed as

$$FS = \frac{(1.406 + 0.039 c' (\csc\, \beta)^2)}{H} + 1.25 \frac{\tan \phi'}{\tan \beta} + \frac{0.156}{\cos \phi'} + \frac{0.011}{\gamma \sin\, \beta} \tag{2}$$

This equation was obtained using a genetic algorithm, an optimization technique inspired by principles of natural selection and evolutionary processes.

Chien and Tsai (2017) developed a simplified procedure for estimating slope stability under seismic loading conditions. Based on extensive numerical simulations performed using the Morgenstern–Price method implemented in Slope/W, the authors proposed the following empirical expression for homogeneous slopes:

$$\frac{\tan \phi'}{FS} = -0.40 \tan \beta \ln \left[5.11 \left(\frac{c'}{\gamma H F S} \right) + 0.101 \right] \tag{3}$$

Since the factor of safety appears on both sides of the equation, the application of this formulation requires an iterative solution.

Huang (2018) proposed a set of stability equations applicable to different slope configurations, including a formulation specifically developed for dry homogeneous soils. The equation was derived based on the analytical solution presented by Michalowski and Nadukuru (2013) and is expressed as

$$FS = A_{est} \left(\frac{c'}{\gamma H \tan\, \phi'} \right)^{B_{est}} \tan\, \phi' + \frac{\tan \phi'}{\tan \beta} \tag{4}$$

where the parameters A_{est} and B_{est} are defined as

$$A_{est} = 10.50 e^{-0.009 \beta} \tag{5}$$

$$B_{est} = \begin{cases} 0.72 - 3.5 \times 10^{-5} \beta^2 + 0.0031 \beta, & 0 \leq \dfrac{c'}{\gamma H \tan\, \phi'} \leq 1 \\ 0.83 - 2.2 \times 10^{-5} \beta^2 + 0.0026 \beta, & 1 < \dfrac{c'}{\gamma H \tan\, \phi'} \leq 3 \end{cases} \tag{6}$$

More recently, Sampa and Schorr (2024) proposed a stability equation specifically developed for dry homogeneous slopes. The authors evaluated the stability of a large number of slope configurations using the Morgenstern–Price method implemented in Slope/W as the reference solution. Nonlinear regression techniques were then applied to derive the following dimensionless expression:

$$FS = N_1 + N_2 \left(\frac{c'}{\gamma H} \right)^{N_3} \tag{7}$$

where

$$N_1 = A\left(\frac{\tan\phi'}{\tan\beta}\right) \tag{8}$$

$$A = \begin{cases} 0.667 + 0.186(\cos\beta)^{-1{,}455}, & \beta > 45° \\ 1, & \beta \leq 45 \end{cases} \tag{9}$$

$$N_2 = 3.758167043 + 2.781\left(\frac{\tan\phi'}{\tan\beta}\right)^{0.41} \tag{10}$$

$$N_3 = 0.612 + 0.1238209944\left(\frac{\tan\phi'}{\tan\beta}\right)^{-0.226} \tag{11}$$

Despite the progress in regression-based stability equations, several limitations remain. Most formulations were calibrated using datasets in which both cohesion and friction contribute simultaneously to shear strength ($c > 0$ and $\phi > 0$), which may reduce their accuracy when applied to limiting conditions such as purely cohesive soils ($\phi = 0°$) or purely frictional soils ($c = 0$). In addition, existing equations generally neglect the influence of foundation soil thickness, implicitly assuming a fixed subsoil configuration. Variations in foundation thickness may affect not only the factor of safety but also the geometry of the critical slip surface, including the radius and position of the circle center.

Therefore, this study evaluates the performance of existing stability equations for dry homogeneous slopes, with particular emphasis on the limiting cases of purely cohesive (φ = 0º) and purely frictional (c = 0 kN/m²) soils. In addition, the influence of foundation thickness on both the factor of safety and the geometry of the critical slip surface is investigated. Based on these analyses, improved stability equations are proposed and the geometric characteristics of the governing failure mechanisms are interpreted.

2 REVIEW OF EXISTING STABILITY EQUATIONS

Recent comparative studies performed by Sampa and Schorr (2024) and Godoy (2024) evaluated the performance of the stability equations presented above against stability charts and limit equilibrium solutions obtained using the software Slope/W. The results indicated that the formulations proposed by Sampa and Schorr (2024), Huang (2018), and Chien and Tsai (2017) generally provide more accurate predictions of the factor of safety than earlier regression-based approaches.

One limitation of the formulation proposed by Chien and Tsai (2017) is the need for an iterative procedure to determine the factor of safety, since FS appears on both sides of the equation. This characteristic reduces the computational advantage typically sought in stability equations.

When compared with rigorous limit equilibrium solutions, the equations proposed by Sampa and Schorr (2024) and Huang (2018) show a high level of accuracy for slopes where both cohesion and friction contribute to shear strength ($c > 0$ and $\phi > 0$).

However, the regression procedure adopted by Sampa and Schorr (2024) was calibrated primarily using datasets in which both strength parameters were present simultaneously. As a consequence, the resulting equation was not specifically optimized for the limiting cases of purely cohesive or purely frictional soils.

This limitation becomes evident when the equation is applied to slopes composed of purely cohesive soils ($\phi = 0°$), where the predictive accuracy tends to decrease because the functional form of the regression model was not calibrated to represent this particular failure mechanism.

In contrast, when $c = 0$, both the equations of Huang (2018) and Sampa and Schorr (2024) tend to reduce to the classical expression associated with an infinite slope composed of cohesionless soil $FS = \tan\phi'/\tan\beta$.

In the formulation proposed by Sampa and Schorr (2024), this relationship is valid only for slopes with $\beta \leq 45°$. For steeper slopes, an empirical adjustment was introduced in order to improve the regression fit.

In the case of the formulation proposed by Huang (2018), the presence of $\tan \phi'$ in the denominator of the equation prevents the direct estimation of the factor of safety when $\phi = 0°$, making the equation inapplicable to purely cohesive soils.

Another important aspect is that the equations discussed above were derived assuming a fixed configuration of the soil foundation. In other words, the thickness of the underlying soil layer was not explicitly considered as a parameter in the regression models. As a consequence, the potential influence of the foundation thickness on the factor of safety and on the geometry of the critical slip surface was not systematically investigated.

In addition to affecting the magnitude of the factor of safety, variations in foundation thickness may influence the geometry of the failure mechanism, including the radius and position of the critical slip surface.

Considering these limitations, the present study aims to investigate the performance of existing stability equations in special cases involving purely cohesive soils ($\phi = 0$) and purely frictional soils ($c = 0$), evaluate the influence of foundation soil thickness on the factor of safety, and analyze the geometric characteristics of the critical slip surface, including the radius and the coordinates of the circle center.

Based on this analysis, improvements to existing stability equations for dry homogeneous slopes are proposed.

3 NUMERICAL METHODOLOGY AND DATABASE

The slope configuration analyzed in this study follows the reference model adopted by Sampa and Schorr (2024). The slope height was fixed at $H = 3.5$m, while the slope inclination angle βvaried from 10°to 85°, covering a wide range of practical slope geometries.

Three datasets of numerical simulations were generated to investigate different soil strength conditions and foundation configurations.

The first dataset considered purely frictional homogeneous slopes ($c' = 0$), with friction angles ϕ'ranging from 10°to 40°. These simulations were used to analyze the stability behavior of cohesionless slopes.

The second dataset considered purely cohesive homogeneous slopes ($\phi' = 0°$), with cohesion values c' varying from 0 to 80 kPa.

The third dataset considered general cohesive–frictional slopes in which both strength parameters were varied simultaneously ($0° \leq \phi' \leq 40°$ and $0 \leq c' \leq 80$kPa). In this dataset, six different foundation soil thicknesses (d) were analyzed, ranging from 0 to 25 m, in order to investigate the influence of the underlying soil layer on slope stability and on the geometry of the failure mechanism.

All analyses were performed under dry conditions, assuming a pore pressure ratio $r_u = 0$. The model domain was defined with sufficient dimensions to avoid any interaction between the stress field and the model boundaries.

The soil was modeled as a linear elastic–perfectly plastic material governed by the Mohr–Coulomb failure criterion. In the limit equilibrium analyses, the potential sliding mass was discretized into 30 vertical slices, and the factor of safety was computed using the Morgenstern–Price method, which satisfies both force and moment equilibrium. The critical slip surface was identified using the Entry–Exit search method, with 100 trial circles employed to locate the minimum factor of safety.

Due to space limitations, the regression plots used to derive the stability equations are not included in the following sections.

4. IMPROVED STABILITY EQUATIONS

4.1 Limiting Case: Homogeneous Frictional Slopes

For cohesionless slopes ($c' = 0$), the factor of safety depends only on the friction angle and the slope inclination. To simplify the formulation, the dimensionless parameter $M_{\phi,\beta}$ was introduced.

The factor of safety can be written as

$$FS = \mu M_{\phi,\beta} = \mu \frac{\tan \phi'}{\tan \beta} \tag{12}$$

where μ is a dimensionless correction factor accounting for deviations from the classical infinite-slope solution caused by the finite geometry of the slope.

The regression results indicate that for gentle slopes **($\beta \leq 40°$)**, the parameter $\mu \approx 1$, leading to $FS = M_{\phi,\beta}$, which corresponds to the classical solution for an infinite cohesionless slope. This result provides an important internal consistency check and agrees with the limiting behavior observed in the stability equations proposed by Sampa and Schorr (2024) and Huang (2018).

For steeper slopes ($\beta > 40°$), however, the regression analysis shows that the factor of safety deviates from the infinite-slope solution due to the influence of the finite slope geometry on the failure mechanism. In these cases, the correction factor μ becomes a function solely of the slope inclination, reflecting the progressive transition from shallow translational mechanisms to deeper rotational failure surfaces. The parameter μ can therefore be expressed as

$$\mu = \begin{cases} a_2 + b_2 \cos\beta + c_2(\cos\beta)^2 + d_2(\cos\beta)^3, & 40° < \beta \leq 60° \\ a_3 + b_3 \cos\beta + c_3(\cos\beta)^2 + d_3(\cos\beta)^3, & \beta > 60° \end{cases} \tag{13}$$

where the regression coefficients are a_2 = 2.002152342, b_2 = -4.758057634, c_2 = 7.613352378, d_2 = -4.059692958, a_3 =13.39301464, b_3 = -85.44227782, c_3 = 225.1972591 and d_3 = -207.6079677.

These results reflect the increasing influence of finite slope geometry on the stability of steep frictional slopes, indicating that the infinite-slope approximation may become less representative as the curvature of the critical slip surface increases.

4.2 Limiting Case: Homogeneous Cohesive Slopes

For purely cohesive slopes ($\phi' = 0°$), the factor of safety depends on the dimensionless stability number $N_s = c'/\gamma H$ and the slope inclination β.

The regression analysis reveals two distinct regimes when the quantity $FS/(N_s \tan\beta)$ is plotted as a function of $\cot\beta$, with the transition occurring near $\beta = 45°$. This behavior reflects the change in the geometry of the governing failure mechanism between shallow and deep rotational surfaces.

Based on the regression results, the factor of safety can be expressed as

$$FS = \begin{cases} \dfrac{N_{s,1} \tan\beta}{4.933886736 e^{-11.09661521 \cot\beta} + 0.6611077253 e^{-1.331 \cot\beta}} \rightarrow \beta > 45° \\ \dfrac{N_{s,1} \tan\beta}{0.4741524823 e^{-1.994883643 \cot\beta} + 0.1669134598 e^{-0.3733 \cot\beta}} \rightarrow \beta \leq 45° \end{cases} \tag{14}$$

The resulting formulation provides improved agreement with limit equilibrium solutions when compared with the equations proposed by Sampa and Schorr (2024) and Huang (2018), particularly for shallow slopes, where previous formulations tend to exhibit larger deviations.

4.3 Failure Mechanism Interpretation

The position of the critical slip surface depends on both the slope geometry and the **soil shear strength** parameters. In this study, two types of failure mechanisms were identified according to the position of the slip surface relative to the embankment layer (Fig. 1). A shallow failure mechanism (SFM) occurs when the slip surface remains confined within the embankment, whereas a deep failure mechanism (DFM) develops when the slip surface extends into the underlying foundation soil.

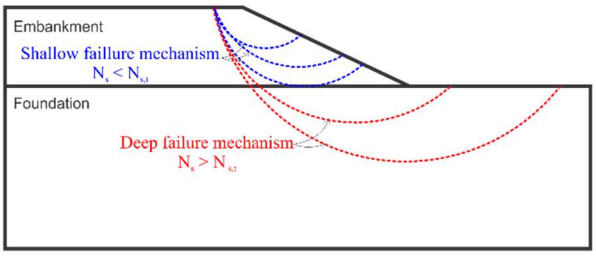


Figure 1. Representation of shallow and deep failure mechanisms in homogeneous slopes.

The analyses indicate that when the foundation thickness ratio d/H (foundation thickness divided by embankment height) exceeds approximately 0.5, the governing failure mechanism becomes essentially independent of the foundation thickness. Under these conditions, the transition between SFM and DFM is primarily controlled by the slope inclination β, the friction angle ϕ, and the stability number N_s.

Based on the regression results and the failure patterns illustrated in Figure 2, several characteristic trends were identified.

For a given friction angle, less steep slopes tend to develop deeper failure mechanisms as the stability number increases, indicating that greater cohesive resistance promotes the formation of deep rotational slip surfaces.

When $\phi = 0°$ (purely cohesive soil), the failure mechanism tends to be deep for steep slopes ($\beta > 60°$), largely independent of the value of N_s. For slopes with $\beta < 60°$, however, the governing mechanism depends on whether the stability number exceeds a transition value $N_{s,t}$ separating shallow and deep failure modes.

For soils with $\phi \geq 20°$, a similar behavior is observed, although the transition occurs at a lower slope inclination. In this case, the failure mechanism tends to be deep for $\beta > 45°$, whereas for $\beta < 45°$the type of failure mechanism depends on the relationship between $N_s$and the transition value $N_{s,t}$.

These observations suggest that the transition between shallow and deep failure mechanisms in homogeneous slopes is governed by the combined influence of slope inclination, friction angle, and stability number.

Additional analyses covering a wider range of slope inclinations and friction angles are required to derive an analytical expression for the transition stability number $N_{s,t}$. Such an expression would allow the boundary between shallow and deep failure mechanisms to be predicted directly from the governing parameters.

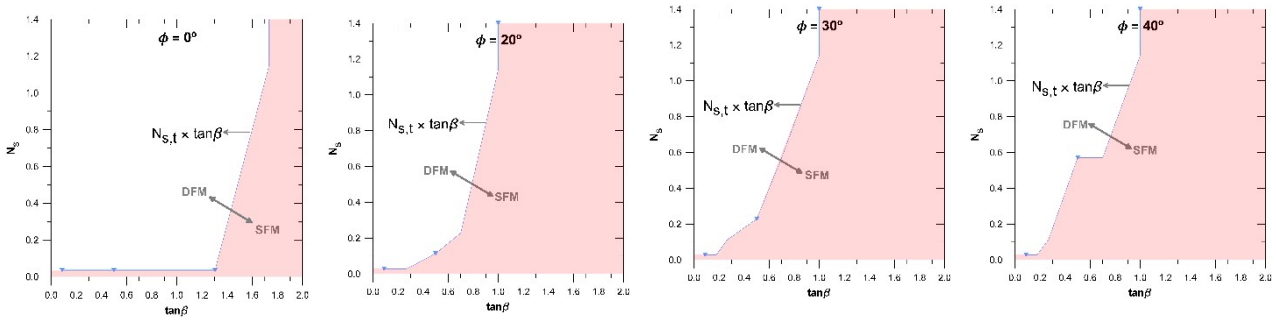


Figure 2. Classification of failure mechanisms based on the critical stability number, $N_{s,t}$.

5 GEOMETRIC CHARACTERISTICS OF CRITICAL SLIP SURFACE

In limit equilibrium analyses, the geometry of the critical circular slip surface is defined by three parameters: the radius R and the coordinates of the circle center (x_c, y_c). These parameters result from the equilibrium conditions governing the failure mechanism and therefore reflect the combined influence of slope geometry and soil shear strength.

For homogeneous slopes, the geometry of the failure surface is primarily controlled by the slope inclination β, the friction angle ϕ, and the stability number N_s.

The parametric analyses performed in this study generated a large dataset of critical slip surfaces obtained using the Morgenstern–Price method. The resulting values of R, x_c, and y_c exhibit systematic variations with these governing parameters, revealing consistent trends in the geometry of the failure mechanism.

5.1 Influence of Slope Inclination

Among the governing variables, slope inclination (β) exerts the strongest control on the geometry of the critical slip surface. For typical slope configurations, increasing β generally leads to shallower failure mechanisms, characterized by smaller radii (R), smaller horizontal coordinates x_c, and smaller vertical coordinates y_c.

This behavior reflects the increasing component of gravitational force acting parallel to the slope face, which promotes shallow rotational mechanisms. Conversely, gently inclined slopes tend to develop deeper failure surfaces that mobilize larger volumes of soil, resulting in larger values of R, x_c, and y_c.

For extremely steep slopes, the failure mechanism remains shallow and becomes largely independent of N_s and ϕ. The large values of R, x_c, and $y_c$observed in these cases arise because the circle center moves far from the slope, producing a large-radius arc that intersects the embankment near its face.

5.2 Influence of Stability Number

The influence of the stability number N_s on the geometry of the failure surface depends strongly on the friction angle.

For purely cohesive soils ($\phi = 0°$), the geometry of the critical slip surface is controlled almost entirely by the slope geometry. In this condition, variations in cohesion primarily scale the factor of safety, while the values of R, x_c, and y_c remain nearly unchanged.

When friction is present ($\phi > 0°$), the stability number begins to influence the depth of the failure mechanism. Increasing N_s modifies the balance between driving and resisting forces and may shift the position of the critical slip surface. However, the relationship is not strictly monotonic, since cohesion interacts with both slope inclination and frictional resistance in determining the optimal failure surface.

5.3 Influence of Friction Angle

The friction angle also influences the geometry of the failure mechanism, particularly when transitioning from purely cohesive to frictional soils.

Introducing friction into the soil strength generally allows the slip surface to extend deeper, since the additional shear resistance along the failure surface enables larger soil masses to remain stable. This effect is particularly pronounced when increasing ϕ from zero to moderate values.

For higher friction angles, however, the geometric response becomes more complex. The location of the critical slip surface depends on the interaction between frictional resistance, cohesion, and slope geometry, and the coordinates of the circle center may shift without producing proportional changes in the radius.

5.4 Combined Influence of Governing Parameters

The results indicate that the geometry of the critical slip surface results from the combined influence of slope inclination, friction angle, and stability number. While slope inclination primarily controls the overall depth of the failure mechanism, the parameters ϕ and N_s seem to modify the extent of the mobilized soil mass and the location of the rotation center.

These interactions explain the transition between shallow failure mechanisms (SFM) and deep failure mechanisms (DFM) identified in the numerical analyses. In dimensionless form, the geometry of the critical slip surface may therefore be expressed as

$$\frac{x_c}{H}, \frac{y_c}{H}, \frac{R}{H} = f(\beta, \phi, N_s) \tag{15}$$

indicating that the normalized position of the circle center and the radius of the slip surface depend only on the slope geometry and the dimensionless soil strength parameters.

6 CONCLUSIONS

This study investigated the geometry of critical slip surfaces in homogeneous slopes and evaluated the applicability of existing regression-based stability equations under limiting strength conditions using a numerical database generated with the Morgenstern–Price method. The main findings are below.

Slope inclination is the dominant geometric control: for $5° \leq \beta \leq 45°$, increasing β produces progressively shallower failure mechanisms characterized by smaller normalized radius R/H and smaller center coordinates $(x_c/H, y_c/H)$. For extremely steep slopes ($\beta \approx 85°$), the slip surface remains shallow while the circle center moves far from the slope, producing large-radius arcs intersecting the slope face.

The influence of the stability number depends on the friction angle: for purely cohesive soils ($\varphi = 0°$), variations in N_s mainly scale the factor of safety while the geometry of the critical slip surface remains essentially unchanged. When friction is present ($\varphi > 0°$), cohesion interacts with slope geometry and frictional resistance to modify the depth of the failure mechanism.

The friction angle governs the transition from cohesive to frictional behavior: increasing φ from zero to moderate values allows deeper slip surfaces to develop, whereas higher friction angles produce more complex geometric responses due to coupled interactions between friction, cohesion, and slope inclination.

Consistent transitions between shallow and deep failure mechanisms were identified: for $\varphi \geq 20°$, deep mechanisms occur for $\beta > 45°$, while for smaller inclinations the mechanism depends on whether N_s exceeds a transition value. For purely cohesive slopes, deep mechanisms occur for $\beta > 60°$.

A dimensionless representation captures the governing geometry: the normalized parameters R/H, x_c/H, and y_c/H can be expressed as functions of β, φ, and N_s, providing a consistent framework for describing critical slip surfaces.

Based on these findings, simplified stability equations were derived for purely frictional and purely cohesive slopes. These formulations allow direct estimation of the factor of safety without iterative slip-surface searches while preserving the governing failure mechanisms.

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