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MATHEMATICAL APPROACH FOR ESTIMATING THE STABILITY OF GEOTEXTILE-REINFORCED EMBANKMENTS DURING AN EARTHQUAKE

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Abstract: The Bishop's method gives a safety factor of circular slip surfaces in excellent agreement with those given by the reliable bi-dimensional slices analysis methods such as Spencer, Janbu or Morgenstern and Price methods. However, several significant disturbing factors are not considered by the simplified or rigorous Bishop's method on which depends a lot of commercial computer programs. This paper discusses a mathematical approach to take into account changeable values of cohesion and friction angle in the Mohr–Coulomb criterion in order to consider the reduction of intrinsic characteristics; adapt a new parameter (F_s) to take into account the behavior under seismic solicitations, introduce a force (r) to take into account the of infiltrated part of water. Finally stabilizing forces generated by the geotextile layers (Geo) are statically engaged in Boshop's polygon of forces. The result shows that the seismic factor gives the main disturbing force to the slope equilibrium; whereas the geotextile action gives the main stabilizing force. In other words, this modified Bishop's method is proposed to calculate cases for which the original method could not be used.

Keywords: *Bishop's method, geosynthetic, slope stability, rupture criterion, safety factor*

1. INTRODUCTION

Natural hazards are a natural phenomena that might have a negative effect on humans and the environment (Hamed et al. 2017a; 2017b; Dahoua et al. 2017a; 2017b;

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Mahdadi et al. 2018; Hamad et al. 2018a; 2018b; Besser et al. 2018). Geotechnical hazards encompass geological and meteorological phenomena such as earthquakes, floods, and landslides (Rouabhia et al. 2012; Demdoum et al. 2015; Mouici et al. 2017; Hamed et al. 2018; Dahoua et al. 2019). Most of Geotechnical hazards are related to natural conditions (Hadji et al. 2014a; Rais et al. 2017; Manchar et al. 2018; Tamani et al. 2019), although some may be due to human activities (Savenko et al. 2018; El Mekki et al. 2018). They might occur under morphlogical conditions include mudflow rock falls, slope wasting, and many more (Hadji et al. 2016; Anis et al. 2019; Karim et al. 2019). Because of its practical importance, the analysis of slope stability has received wide attention in geoscientific literature. Methods for the analysis of slopes could be empirical (Aydan et al. 2014), analytical (Souza and Nelson 2018); geomechanical (Zahri et al. 2016; 2017); and numerical procedure (Tschuchnigg et al. 2015). Despite the development of numerical calculation, limit-equilibrium methods based on the subdivision of the slipped mass into slices are still widely used to slope stability analysis (Hadji et al. 2014b; Gadri et al. 2015). These methods have the ability to accommodate complex geometrics and variable soil and water pressure conditions (Terzaghi and Peck 1967). They satisfying three principal equilibrium equations for each slice (Achour et al. 2017). As the original problem was statically indeterminate, some assumptions are made. Several methods of slices have been developed in the past such as Bishop; Janbu; Morgenstern and Price; Spencer... (Wright 1969). They vary in the statics used in deriving the safety factor and the assumptions employed to make the problem statically determinate.

Based on λ values (λ is a constant evaluated involving for the factor of safety), (Fredlund, and Krahn, 1977); the comparison between limit-equilibrium methods indicate that the Bishop's method satisfies overall moment equilibrium. Spencer's method has h equal to the tangent of the angle between the horizontal and the resultant interslice force. Janbu's factors of safety can be placed along the force equilibrium line to give an indication of an equivalent h value (Fig. 1a). Therefore the Bishop's method is the most favorable to undergo a mathematical approach calculating the safety factor for a natural slope, subjected to disturbing stresses, and an underground flow stabilized by the spreading of geotextile layers (Hadji et al. 2017a; 2017b).

2. METHODS

The fundamentals of the Bishop's method consist on the division of the sliding body about a circular slip surface of radius R, into n vertical slices (Fig. 1b). For the i-th slice, the width is b_i, the angle of base is α_i, the weight is W_i, the horizontal interslice forces are E_i and E_{i+1}, the vertical interslice forces are X_i and X_{i+1}, the normal force at the base is E_i, the shear resistance at the base is T_i, the pore water pressure at the base is u_i, the effective internal friction angle is φ_i and the cohesion is c_i. The safety factor along the slip surface is F.

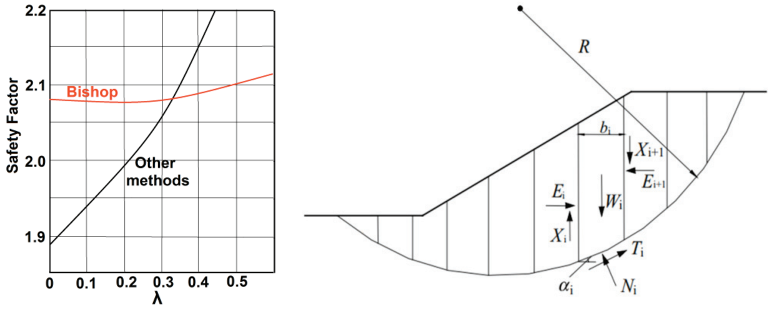

Fig. 1. a) safety factors comparison, b) sliding body and acting forces

The working method is to introduce variable values of c' and φ' in the Mohr–Coulomb failure criterion to take account of the reduction characteristics, a parameter (F_s) to take account of the effect of seismic loadings a force (r) to reflect the portion of water infiltrated and forces (G_{eo}) generated by incorporating geotextiles plies in the polygon Bishop forces.

2.1. INFLUENCE OF WATER FLOW

The cyclic variation of the interstitial pressure, will cause a significant decrease in intergranular forces, which can lead to a disturbance of the state of the stresses in the slope. Based on the general theory of aquifers, Richard's, and Depuit's equation (Rezzoug et al. 1994), two forces can be distinguished; the first is produced by the interstitial pressure, whereas the second is caused by the flow of seepage water.

The latter may be deciding in triggering a failure especially if the flow direction coincides with the slope dipping. However, the decrease in shear strength caused by the action of water along the sliding surface should not be neglected.

The ratio:

$$r_a = \frac{\Delta M_{\acute{e}}}{\Delta M_p} = \frac{\gamma_w}{\gamma'} \frac{\sin\alpha \sin(\theta + \alpha)}{\cos\theta} \tag{1}$$

with: $M_{\acute{e}}$ – motor moment due to the flow force and M_p moment due to weight.

According to Pilot, the ratio presents the action of the water flow versus to the own weight of the slice, this report is not negligible especially when γ values' and are close to γ_w (Khabiri et al. 2017).

Filliat proposed a flow-water distribution law in the slope connecting the shear resistance force to the normal effective, and the tangential stress (Dhaybi 2015).

$$\sigma = \Sigma \gamma_i \ell_i \cos^2\alpha (\lambda + \mu \tan \alpha) \tag{2}$$

with λ = compressibility.

In our approach we will introduce the force due to the flow of water (r) directly in the polygon of Bishop forces.

2.2. INFLUENCE OF THE SEISMIC SOLLICITATIONS

At the base of the slope, the shear stress due to the seism is given by its peak acceleration (a_h) (Swiss standards), multiplied by the reduction factor of Seed (r_d) (Seed and De Alba 1986).

$$\tau = 0.65 \frac{a_h}{g} \sigma_v r_d \tag{3}$$

In the body of the embankment it is rather expressed by the maximum acceleration (a_g) acting at the center of gravity of the slice (Houda et al. 2016).

$$\tau = 0.65 \frac{a_g}{g} \sigma_v . \tag{4}$$

The maximum acceleration ($a_{\max}$) is given by the sum of the spectral acceleration values (a_i) of each rethink spectrum (ω_i). These are calculated (after adjustment) from incidence speeds (v_s) (Ghahreman-Nejad and Kan 2017).

$$a_{\max} = [(1.60 x a_1)^2 + (1.06 x a_2)^2 + (0.86 x a_3)^2]^{0.5} \tag{5}$$

with

$$\omega_i = c^{st} \frac{v_s}{h} P = \frac{2\pi}{\omega} . \tag{6}$$

For the replacement of solicitations by forces. The horizontal force applied to the slice is the multiplication of the average acceleration by the mass of the slice. While the vertical force connects the vertical component of the seismic acceleration to the mass of the slice (Mestat 1998).

$$F_{horizontal} = a_{moy} m, \tag{7}$$

$$F^s_{vertical} = a_{vert} m \leftrightarrow F^s_{vertical} = 0.66 a_{horizontal} m. \tag{8}$$

2.3. THE GEOSYNTHETICS ACTION

Reinforcement by geosynthetic inclusions consists in creating a structure with improved properties, consisting of a soil that often has a tensile strength of zero, but which is resistant to compression, and a geotextile that has a better resistance to traction (Shukla 2002). The use of geosynthetic layers can significantly improve the equilibrium state of the slope. With a layered arrangement, it is only the tangential component (Geo) that contributes to the equilibrium. However its flexible behavior spreads its normal component.

3. MATHEMATICAL APPROACH

The method of Bishop (1955) has been widely used in slope stability analysis. It is regarded as a performing method of limit equilibrium for calculating the safety factors of circular slip surfaces (Hadji et al. 2013). In this method, the interslice forces are assumed to be horizontal, or the vertical interslice forces are neglected, the vertical force equilibrium and the moment equilibrium about the center of the circular slip surfaces are satisfied, but the horizontal force equilibrium is not considered (Fig. 2). Thus, the simplified Bishop method always gives safety factors in good agreement with those given by other rigorous methods of slices such as the Morgenstern-Price method (Morgenstern and Price 1965) and the Spencer method (Spencer 1967). In geological engineering calculations, the Bishop's method has been accepted as the accurate method of slices, although it does not satisfy all the limit equilibrium conditions (Duncan 1996).

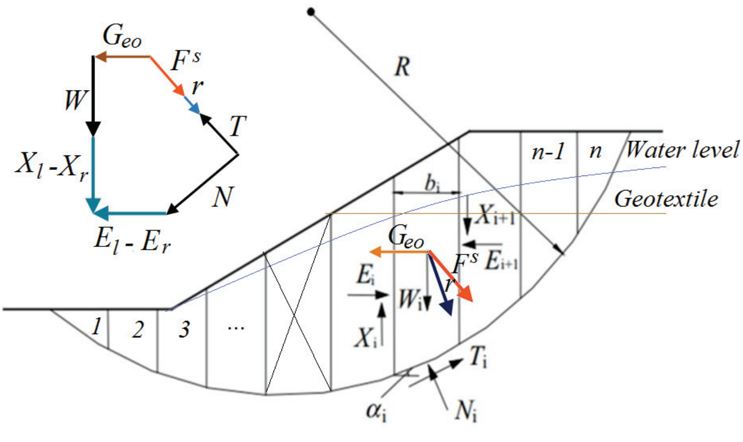

Fig. 2. a) sloped slice cutting, b) equilibrium of a slice, c) polygon of the forces

With: X_l, X_R, E_L, E_R – interslice forces; W – the weight, N – the normal force, S – the shear resistance, G_{eo} – tensile force of geotextiles, F^s – seismic forces, r – force due to flow.

$$S = 1/F(c'(w)\ell + N\tan\varphi'(w)). \tag{9}$$

The projection of forces on the vertical in the center of the slice:

$$(N + u_a\ell - \chi\ell s_e)\cos\alpha = W + (X_L - X_R) - S\sin\alpha + (F^s_{vert} + r\sin\theta). \tag{10}$$

With α – the angle of base of slice, θ – gradient of the piezometric level.
The replacement of the value of S from Eq. (9):

$$(N + u_a\ell - \chi\ell s_e)\cos\alpha$$
$$= W + (x_l - x_r) - \sin\alpha/F(c'(w)\ell + N'\tan\varphi'(w)) + (F^s_{vert} + r\sin\theta),$$
$$(N\cos\alpha) + (u_a\ell - \chi\ell s_e)\cos\alpha$$
$$= W + (x_L - x_R) - (c'(w)\ell/F)\sin\alpha - N\tan\varphi'(w)\sin\alpha/F) + (F^s_{vert} + r\sin\theta).$$

With $c'(w)$, $\varphi'(w)$: are residual characteristics due to material fatigue.

$$N(\cos\alpha + (\tan\varphi'(w)\sin\alpha)/F)$$
$$= W + (x_L - x_R) - \ell(u_a - \chi s_e)\cos\alpha - c'(w)\sin\alpha/F) + (F^s_{vert} + r\sin\theta).$$

$$N = \frac{(W + (x_L - x_R) - l(u_a - \chi s_e)\cos\alpha - c'(w)\sin\alpha / F) + (F^s_{vert} + \sin\theta)}{\left(\cos\alpha + \dfrac{\tan\varphi'(w)\sin\alpha}{F}\right)} \tag{11}$$

For clarity and simplification, Bishop allowed to neglect the interslice forces (with a small difference between them) and set the center of gravity of the slice to his half height. The moments relative to the slippery mass rotation center are:

$$WR_x = SR - F^s_{vert}R_x - F^s_{horiz}(R(\cos\alpha) - h/2)$$
$$- r\sin\theta R_x - r\cos\theta(R(\cos\alpha) - h/2) + G_{eo}(R(\cos\alpha) - h/2),$$

$$Wr\sin\alpha = R\tau\ell - F^s_{vert}R\sin\alpha - F^s_{horiz}(R(\cos\alpha) - h/2)$$
$$- ((r\sin\theta R\sin\alpha) + ((r\cos\theta - G_{eo})(R(\cos\alpha) - h/2))) \tag{12}$$

The introduction of Mohr–Coulomb criterion ($\tau = c' + \sigma\tan\varphi'$) in Eq. (12):

$$Wr\sin\alpha = R/F[(c'(w)\ell + N\tan\varphi'(w)\ell) - (\ell\tan\varphi'(w)(u_a - \chi s_e))]$$
$$- [(F^s_{vert} + r\sin\theta)(R\sin\alpha)] - [(F^s_{horiz} + r\cos\theta - G_{eo})(R(\cos\alpha) - h/2)]. \tag{13}$$

$$F = \frac{R[(c'(w)\ell + N\tan\varphi'(w)\ell) - (\ell\tan\varphi'(w)(u_a\sin\chi s_e))]}{WR\sin\alpha + [(F^s_{vert} + r\sin\theta)(R\sin\alpha)] + \left[(F^s_{horiz} + r\cos\theta - G_{eo})\left(R(\cos\alpha) - \dfrac{h}{2}\right)\right]}$$

$$F = \frac{[(c'(w)\ell + N\tan\varphi'(w)] - [\ell\tan\varphi'(w)(u_a \sin\chi s_e)]}{WR\sin\alpha + [(F^s_{vert} + r\sin\theta)(R\sin\alpha)] + \left[(F^s_{horiz} + r\cos\theta - G_{eo})\left(R(\cos\alpha) - \frac{h}{2}\right)\right]}. \tag{14}$$

By substituting the value of *N* taken from (11) in (14) and summing all slices:

$$\frac{1}{m\alpha}\frac{(\sec\alpha)}{\dfrac{(1+(\tan\varphi'(w)\tan\alpha)}{F}} \tag{15}$$

The use of the term: $\dfrac{1}{m\alpha}\dfrac{(\sec\alpha)}{\dfrac{(1+(\tan\varphi'(w)\tan\alpha)}{F}}$

$$F = \frac{(c'(w)\ell + N\tan\varphi'(w))(W - (\ell\cos\alpha(ua - \chi se))) + \left[\left(\left(\left(c'\dfrac{(w)\sin\alpha}{F}\right) + Fs_{vert} + r\sin\theta\right)(1/m_\alpha)\right) - \ell(ua - \chi se)\right]}{\Sigma W_1 \sin\alpha_i + [(Fs_{horiz} + r_i\cos\theta_i G_{eo})(\cos\alpha_i - (h_i/2R)) + (r_i\sin\theta_i + \Sigma Fs_{vert})(\sin\alpha_i)]} \tag{16}$$

Other simplifications and substitutions are possible, such as the replacement of the weight value by its formula exploiting the relative density.

4. RESULTS

The equation (16) is the result of the mathematical approach of Bishop's method. The appearance of forces due to seism, and flow simultaneously in the numerator and the denominator and traction due to geotextiles with a negative sign to the denominator (plays a positive role in favor of stability); characterizes the difference between the safety factor of our modified method and that of the simplified or the rigorous original Bishop's method Eqs. (17), (18);

$$F = \frac{\dfrac{\Sigma\{c'b + \tan\varphi'(W(1-ru))\}1}{m\alpha}}{\Sigma W\sin\alpha}, \tag{17}$$

$$F = \frac{\dfrac{\Sigma\{(c'b + \tan\varphi'(W(1-ru))) + (xl - xr)\}1}{m\alpha}}{\Sigma W\sin\alpha}. \tag{18}$$

With $\varphi' = \varphi K_\varphi$ and $ru = \dfrac{u}{\text{total vertical stress}}$

ru is the pore pressure ratio, *u* is the pore pressure value (kPa), K_φ is a reduction coefficient ≈ 0.8, and φ is the friction angle.

This makes it possible to draw a safety interval during embankment design. And take into consideration the different factors involved in the failure of a natural slope.

A numerical procedure to determine the location of the critical slip surface with the minimum value of safety factor is needed. By the machine programming of the modified mathematical equation of Bishop the procedure allow the definition of the slip surface corresponding to the convergence of safety factor to its lowest value.

5. CONCLUSIONS

The analytical aspects of slope stability can be viewed in terms of one factor of safety equation satisfying overall moment equilibrium and another satisfying overall force equilibrium for various *h* values. Then each method becomes a special case of the best-fit factor of safety lines. The mathematical approach developed in this study deals with the consideration of new parameters in limit equilibrium method. This makes it possible to better understand the mechanisms involved in the slope failures, and to draw a safety interval in the slopes exposed to the action of water, as well as the vibratory stresses. Instability appears directly related to earthquakes and water. The appearance of the term "G_{eo}" with a negative sign in the denominator of the equation proves the comfort exerted by the traction of geotextiles with respect to stability. This type of reinforcement allows to support larger loads and to resist more pronounced angles. The durability of structures, an improvement of the geotechnical performances of the ground while increasing the mechanical characteristics, and the possibility of construction in adverse environments, are also recorded.. Machine programming is essential for calculating the safety factor with actual field conditions, and for predicting stability by varying the forces for the set of predisposition and trigger factors. The slip surface intersect the ground surface only on the shear zone, the procedure needs several trials in which the boundary conditions of the intersection are sought methodically. The procedure can be applied to a slope including layared soil, pore pressure, seism or geotextiles. The Bishop's modified method gives accurate estimates the safety for rotational and symmetric sliding surfaces. It is therefore applicable to a wide range of practical problems, such as seism and seepage.

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