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METHODS OF GENERAL STABILITY CALCULATION FOR FLOOD EMBANKMENT BODY AND FOUNDATION

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The paper presents the methods of general stability calculations for the body and foundation of the flood embankment and their applicability.

Keywords: embankment stability, calculation of stability

1. INTRODUCTION

Many methods of calculating the stability of flood embankments have been invented. The most characteristic and universal method, based on assuming the possible slip on a circular arc surface, has been developed by the Swedish researcher Wolmar Fellenius. In hydro-engineering however, the more versatile Bishop method is recommended [Pisarczyk 2005]. As these methods are the most popular, they have been applied in computer software. In the paper the aforementioned methods are presented, as well as other less common ones [Borys and Mosiej 2003]. It should be emphasized that method selection depends on slope type.

2. FELLENIUS METHOD (SWEDISH CIRCLE METHOD)

This is the simplest method of all for the calculation of slope stability. The method assumes a slip on a circular arc surface (Fig. 1).

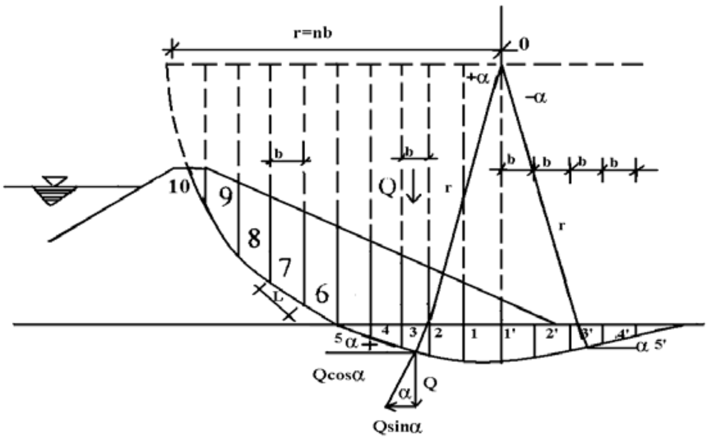

Fig. 1. Chart to calculate slope stability by Fellenius and Bishop method [Borys and Mosiej 2003].

Explanations: r - radius of slip arc surface, b – slice width, L - length of slice base, n – number of slices, 1-10 – slice number

The factor of safety F for a slip is derived by the following formula:

$$F = \frac{\sum_{i=1}^{n} [(Q_{sr} \cos \alpha_o) \cdot tg\phi' + c \cdot l_i]}{\sum_{i=1}^{n} (Q_{sr} \sin \alpha_i)} \qquad (1)$$

where:
Q_{sr} – weight of soil slice assuming that above the phreatic surface the soil unit weight is the same as the weight of undrained soil [y_n], while below the phreatic surface – unit weight of saturated soil (with water-filled pores) [y_{sr}],
α_i – angle of inclination of the tangent line to the slip surface assuming that above the phreatic surface the soil unit weight is the same as the weight of undrained soil [y_n], while below the phreatic surface – unit weight of saturated soil (with water-filled pores) [y_{sr}],
φ' – angle of soil internal friction in terms of effective stress,
c – soil cohesion,
l_i – base length of a slice,
n – number of slices.

External load forces add to the weight Q_{sr}, whereas side force moment adds to the numerator or to the denominator, depending on its sign. Hydrostatic lift forces are taken into account when calculating the slice weight. In the above formula the cohesion and angle of internal friction are related to a layer with slip surface. The minimum values of F assuming the limitation of the possible locations of the rotation centres are calculated for a net of assumed points. In order to determine a minimum value several calculations should be made assuming different rotation centres.

3. BISHOP'S METHOD – A SIMPLIFIED METHOD

This method differs from Fellenius method in that the stability factor appears on both sides of the equation, which imposes an iteration method of calculation. The following equation is applied:

$$N = \frac{\sum_{i=1}^{i=n}\left[(Q_{sr} - ub)tg\phi' + bc'\right]/m_\alpha}{\sum_{i=1}^{n}(Q_{sr}\sin\alpha)} \qquad (2)$$

where:
n – number of slices,
Q_{sr} – slice weight assuming that above the phreatic surface soil the unit weight is the same as that of undrained soil [y_n], while below the phreatic surface – unit weight of saturated soil (with water-filled pores) [y_{sr}],
u – water pressure in pores,
φ' – angle of soil internal friction,
c' – cohesion of soil,
b – width of a slice,
α – angle of tangent inclination in the centre of a slice base,
m_a – coefficient calculated according to a formula,

$$m_\alpha = \cos_\alpha(1 + \frac{tg\phi' tg\alpha_i}{F}) \qquad (3)$$

When m_a is close to nill, the equations become pointless, because factor $1/m_a$ heads to infinity. In practice it means that slip surfaces whose end part from the slope base is too inclined from the level, cannot be taken into account.

The Swedish circle method and Bishop's method can be applied to computer calculations of stability. They are used for the calculations of the stability of slopes made of cohesive soil.

4. JANBU'S METHOD

Similarly to Bishop's method, Janbu's method is an iteration procedure. Conditions of convergence and the initial value of F=1 are taken as previously. In Janbu's method the slip surface is non-circular. However, some points of the slip surface must be specified for calculations.

It is worth noting that Janbu's method does not apply the moment equilibrium but the force equilibrium method.

5. GRAPHIC METHOD

The graphic method can be used when computer iterative procedures cannot be applied and approximated calculations of stability are required. It is a graphical solution of Bishop's equation.

The graphic method assumes that the direction of the mutual interaction of neighbouring slices is parallel to the slope while in Bishop's method the direction is horizontal.

The method is based on the general solution of force projection equilibrium onto coordinate axes. In these calculations the shape of the slip surface is arbitrary, including also circular surfaces and planes. There are a few guidelines facilitating the slicing of the soil segment subject to failure:

- slicing as in Bishop's and Fellenius' methods in the case of circular surface (Fig.1),
- when the slip surface is a broken line, slicing should pass through the breakdown points, it can be additionally thickened by the separation of slices, bases of which pass through different types of soil, or the separation of slices in which slope breakdown occurs.

The graphic method consists of creating polygons of forces for subsequent slices. Forces of known values and directions vectors are as follows:

- intrinsic weight of a slice Q,
- water pressure in pores interacting with left PL and right PP side of a slice,
- water pressure in pores u, interacting with slice base perpendicular to slip surface.

Moreover, forces of an unknown value exist. On the other hand their direction of activites is known or can be assumed:

- soil response R' along failure surface in a direction deviated by an angle of internal friction φ' from a normal,
- interaction of slices EL and EP along planes separating the slices; generally it is assumed that the forces are parallel to the slope or are horizontal.

The graphic solution can be obtained by successive approximations, assuming different values of factor of safety. The researcher looks for such a value which completes a polygon of forces [Borys and Mosiej 2003].

6. METHOD OF BLOCK SLIDE

In this method failure surfaces consist of two or three intersecting planes [Borys and Mosiej 2003]. Calculating the stability is similar to the graphic method. The only difference is in considering blocks limited from the bottom by a plane failure surface instead of slices. The block method is applied when it is possible to determine one or two slip planes of a central block. Small blocks in the top segment of the slope soil, which are subject to failure are replaced by soil and water pressure, while small blocks in the bottom segment are replaced by soil reaction E_d and water pressure.

Pore-water pressure on a block base and on the side surfaces is calculated based on flownet elements. Approximately, values of pore pressure can be determined from the phreatic surface. However, the resulting values are lower than true factors of safety.

The factor of safety is calculated in the same way as in the graphic method, i.e. polygons of forces are drawn for assumed various factors of safety. A factor of safety corresponding to a given case is determined by interpolation.

7. BERER-MASŁOW'S METHOD

Berer-Masłow's method can be applied assuming that soil shall slide on an irregular surface (Fig. 2).

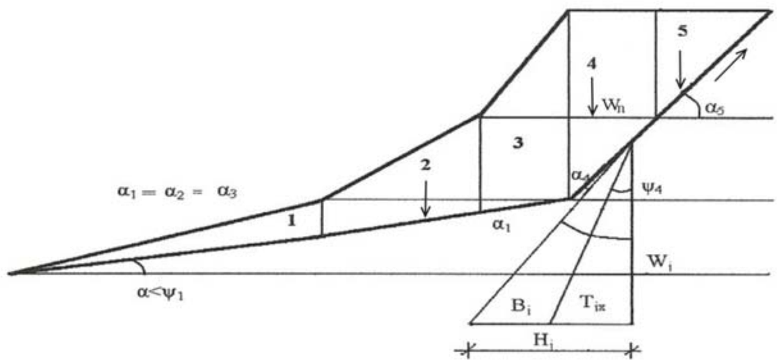

Fig. 2. Calculating chart as in Berer-Masłow method [Borys and Mosiej 2003]. Explanations: 1 - 5 separated slices, α_1 - α_5 - angles of slice inclination, other - as in formulae

In this method the factor of safety is determined as the volume of sums of horizontal projections of shear strength and reaction.

When the water flow pressure is not considered, the factor of safety F_P is calculated using the following formula:

$$F_p = \frac{\sum T_{ix}}{\sum(\pm H_i)} = \frac{\sum W_i\left[tg\alpha_i - tg(\alpha_i - \psi_i)\right]}{\sum(\pm W_i tg\alpha_i)} \tag{4}$$

where:
T_{ix} – projection of horizontal forces of shear force in a slice, invoked by friction and cohesion,
H – horizontal projection of failure force caused by weight of slice i,
W_i – weight of slice i (in the picture),
α_i – angle of failure plane inclination of a slice i,
ψ_i – replacement angle of friction in terms of shear σ_{ni};

$$\psi_i = arctg\left(tg\varphi_i + \frac{c_i}{\sigma_{ni}}\right) \tag{5}$$

where:
φ_i – angle of internal friction on failure plane of slice i,
c_i – cohesion on failure plane of slice i,
σ_{ni} – average normal shear on failure plane of slice i.

When the water flow pressure acts, the factor of safety F_p should be calculated from the following equation:

$$F_p = \frac{\sum W_i'\left[tg\alpha_i - tg(\alpha_i - \psi_i)\right]}{\sum\left(\pm W_i' tg\alpha_i\right) + \sum V_{wi}\gamma_w i\cos\alpha_{wi}} \tag{6}$$

where
W_i' – weight of slice i taking into account water uplift,
V_{wi} – volume of underwater part in slice i,
γ_w – specific gravity of water,
i_i – hydraulic drop in slice i,
α_{wi} – angle of inclination of down flow pressure [Borys and Mosiej 2003].

8. TAYLOR'S METHOD - COHESIVE SOILS

This method is used for the calculation of stability in uniform cohesive soils. It is based on introducing a notion of stability factor N expressed by the formula:

$$N = \frac{c}{F_{dop} \cdot \gamma \cdot H} \tag{3.1}$$

where:
c – cohesion,

F_{dop} – factor of safety,
γ – unit weight of soil,
H – slope height.

In this method so-called Taylor's nomograms are used, comparing stability factors N to angle of internal friction of slope soil, taking the readings of optimum inclination of designed slope.

9. NONVILLER'S METHOD

This method enables calculations assuming any failure surface. It takes into account interslice interactions, and applies the moment equilibrium method [Madej 1981].

10. MORGENSTERN-PRICE'S METHOD

It enables calculations for any failure surface. In the balance of single slices vertical and horizontal forces are taken into consideration; it applies conditions for the sum of moments and horizontal forces [Madej 1981].

11. BAKER-GARBER'S METHOD

It enables calculations for any failure surface. This method uses three conditions for equilibrium, which is the most precise and correct from the point of view of statistics.

12. SLOPE-SEAL METHOD

This method consists of the comparison of friction angles of the weakest layer where sealing screen inclination (Fig. 3) is expressed by the following relationship (stability factors F_p):

$$F_p = \frac{tg\varphi}{tg\beta} \tag{8}$$

where:
φ – lowest value of internal friction angle in contact place of elements applied to construction of a screen or screen with soil,
β – angle of slope inclination.

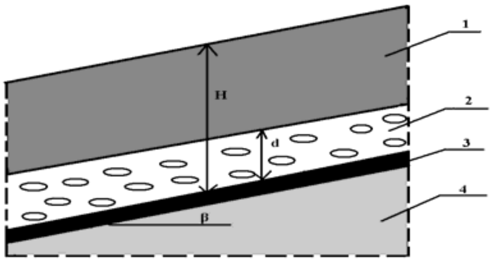

Fig. 3. Chart to calculate the stability of the covering layer [Borys and Mosiej 2003]. Explanations: 1 - covering layer, 2 -drainage layer, 3 - sealing screen, 4 -soil in slope body, β - angle of screen inclination, *H,d* - as in formulae

A more precise factor of safety F_P can be calculated by applying the equation

$$F_p = \frac{\left(WH\cos^2\beta - \gamma_w d\cos^2\beta\right)tg\varphi}{WH\sin\beta\cos\beta} \qquad (9)$$

where:
W – unit weight of soil in layer near surface,
γ_w – specific gravity of water,
β – angle of screen inclination,
H – thickness of soil surface layer,
d – density of drainage layer,
ϕ – angle of friction of the weakest layer.

In order to carry out a detailed analysis of the stability conditions of the covering layer, a block slide method or Berer-Masłow's method can be applied, assuming that the slide shall occur on a screen surface. In calculations it should be considered that soil cohesion on the failure surface c is nill, and the angle of internal friction is equal to the lowest found pressure angle where screen contacts soil, or each layer, creating the screen (e.g. geotextile, geomembrane).

13. SUMMARY AND CONCLUSIONS

As this paper shows, the stability of flood embankments can be calculated in many ways. In general, these methods differ insignificantly and it is difficult to select the only reliable one, or exclude others. However, it is not the selection of the method of calculation which is the most important factor while studying the stability of slopes. The most important is to construct a slope, to meet safety requirements and the basic condition of safety is slope stability. Depending on the safety factor value (F) the landslide formation can be regarded as: very unlikely ($F>1.5$), unlikely ($1.3<F\leq1.5$), likely ($1.0<F\leq1.3$) or very likely ($F<1.0$). The safety factor calculations are always encumbered with errors dependent on, but not limited to, the calculation method assumed. However, for a stable slope the value F should not be less than 1.3 and it is rather advisable to exceed 1.5.

In 2007, tests on the safety factor of flood banks located on the section of the Oder River in the Lubuskie Province were carried out. Using the method of calculating the stability of the soil layer that covers the sealing screen in waterfront slope of the flood bank, the safety factor was calculated for four sections of the flood bank, each sealed with different methods: PVC foil (geomembrane), PVC foil (geomembrane) placed onto body of the flood bank completed with protective screen C-LOC put into subsoil of the flood bank, bentomat (geotextiles) placed in the body of the flood bank, and bentomat (geotextiles) placed in the body of the flood bank completed with a silty partition set up in the subsoil of the flood bank. At the same time the geometry of the soil layers and the course of the slide surface, as well as the relevant parameters of the soil were taken into account.

The problem encountered during the calculations was that the sealing was only used in a part of the slope and the safety factor was to be determined for the whole slope. Therefore, the soil slide surface at the interface of the soil and the sealing screen was assumed, as it was recognised that the slide stops when the sealing ends. The force causing the soil to fall down was decreased by the braking force value.

The obtained results indicated that the safety factor was higher in each case than the required minimum. Although the best result, i.e. the highest guarantee of stability, was obtained in the sections of the flood banks where bentomat and silt partitions were installed.

The method used in the calculations is not rated among the most popular ones. However, it is the only one that considers the sealing used in the slope. As some values in the calculations are averages, the obtained results are not the most accurate. Nevertheless they represent a certain guarantee of slope safety with regard to landslides.

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