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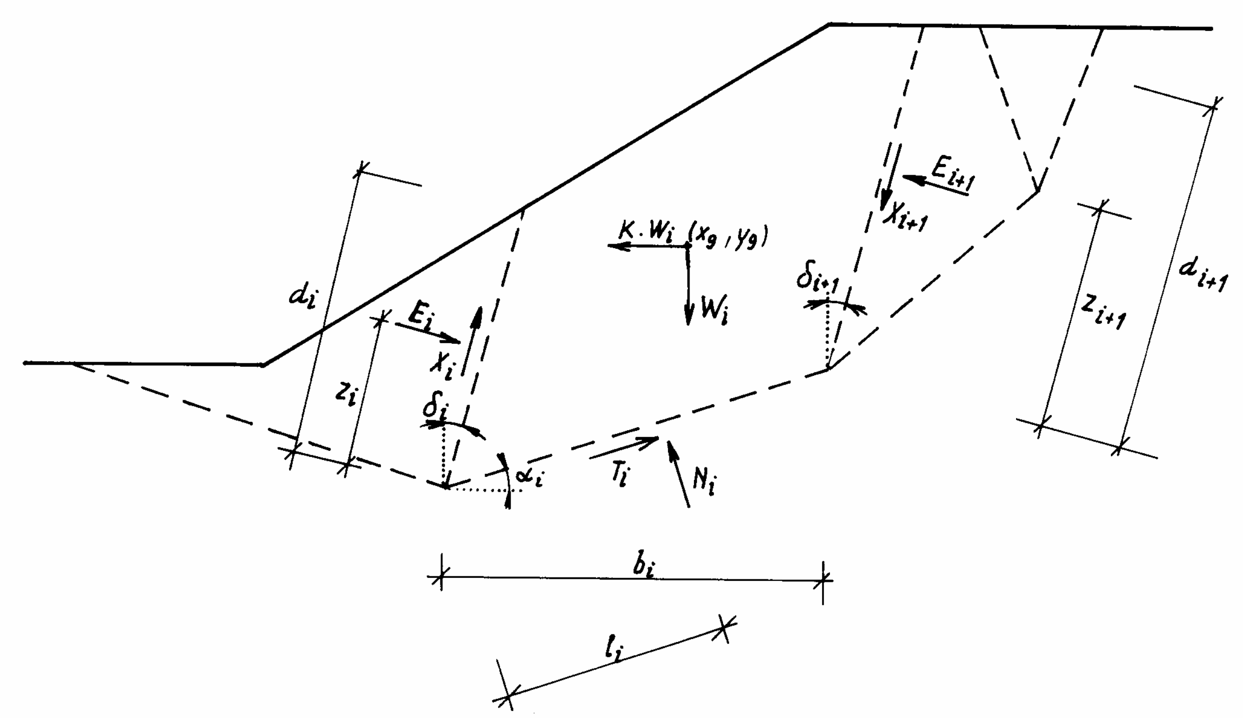
4. Stability problems

4.1 Program „Stability of slopes"

To analyze the stability of earth slopes the program assumes two slip surfaces – polygonal slip surface (due to S.K. Sarma) and circular slip surface (due to Petterson and Bishop).

4.1.1 Polygonal slip surface – the Sarma method

The Sarma method is a general strip method of limit equilibrium. The method is based on satisfying the equilibrium of forces and moments on individual strips. The strips are created by slicing the region above the slip surface using generally inclined planes. A static scheme of strips and corresponding forces are displayed in **Fig. 4.1**.



Obr. 4.1 Static scheme – the Sarma method

Here, E_i and X_i represent the normal and shear forces between strips. N_i and T_i are the normal and shear forces acting on individual sections of the slip surface. W_i is the strip weight and $K.W_i$ is a horizontal force, which serves in Sarma's method to reach the state of limit equilibrium. A generally inclined surcharge can be specified in each block. Such a surcharge enters the solution analysis together with a surcharge due to water having the water table above the terrain surface and with forced developed in anchors. All these forces are resolved into horizontal and vertical components and add up forces Fx_i and Fy_i.

A constant K, called the factor of horizontal acceleration, is introduced into the solution to brink all forces acting within strips into equilibrium. A certain relationship, which serves to compute the factor of safety F_S, exists between K and F_S. In general, the coefficient K assumes a zero value. A non-zero value of K can be used to simulate a load applied in the horizontal direction (e.g., to simulate an effect of earthquake).

4.1.1.1 Solution procedure

Analysis of limit equilibrium

The analysis of limit equilibrium handles *6n-1* unknowns, where *n* is the number of strips. The unknowns are:

- E_i - inter-strips forces,
- N_i - normal forces on slip surface,
- T_i - shear forces on slip surface,
- X_i - shear forces between strips,
- z_i - points of applications of forces,
- l_i - points of applications of forces,
- K - factor of horizontal acceleration.

To solve for *6n-1* unknowns we only have *5n-1* equations:

a) The force equation of equilibrium for each strip in the horizontal direction:

$$T_i \cos\alpha_i - N_i \sin\alpha_i = KW_i - Fx_i + X_{i+1}\sin\delta_{i+1} - X_i \sin\delta_i + E_{i+1}\cos\delta_{i+1} - E_i \cos\delta_i$$

b) The force equation of equilibrium for each strip in the vertical direction:

$$N_i \cos\alpha_i - T_i \sin\alpha_i = W_i - Fy_i + X_{i+1}\cos\delta_{i+1} - X_i \cos\delta_i - E_{i+1}\sin\delta_{i+1} + E_i \sin\delta_i$$

c) The moment equation of equilibrium for each strip:

$$N_i l_i - X_{i+1} b_i \sec\alpha_i \cos(\alpha_i + \delta_{i+1}) + E_{i+1}[z_{i+1} + b_1 \sec\alpha_i \sin(\alpha_i + \delta_{i+1})] - E_i z_i - W_i(xg_i - x_i) +$$
$$+ KW_i(yg - y_i) - Fx_i rx_i + Fy_i ry_i = 0$$

where r_{xi} and r_{yi} are arms of forces F_{xi} and F_{yi}.

d) The Mohr-Coulomb relations between shear and normal forces on a slip surface:

$$T_i = (N_i - U_i)\tan\varphi_i + c_i^{'} b_i \sec\alpha_i$$

$$X_i = (E_i - PW_i)\tan\overline{\varphi}_i^{'} + \overline{c}_i^{'} d_i$$

From above it is obvious that *n-1* unknowns must be estimated. A relatively small error is caused by estimating the points of applications of forces E_i. The problem thus becomes statically determined and solving the above system of equations provides the remaining unknowns. The main objective of this solution is to determine the factor of horizontal acceleration *K*.

Determination of safety factor F_S

The safety factor F_S is employed in the analysis to reduced parameters of soil *c* and $tg\varphi$. Performing the analysis of limit equilibrium results in a new value for the parameter of horizontal acceleration *K* associated with a given factor of safety F_S. This iteration process is repeated until the factor *K* reaches either zero or specified value.

4.1.1.2 Optimization of slip surface

Searching for the critical slip surface

The optimization of slip surface proceeds such that the algorithm changes locations of individual points of the predefined slip surface and monitors, which slip surface leads to the lowest factor of safety. In doing this, the end points are shifted along the terrain surface, while the internal points can move along the horizontal and vertical directions. The initial step is selected as one tenth of the smallest distance between adjacent points on the slip surface. After each iteration run, the step size is reduced into one half.

The location of points is gradually adjusted from the left to the right and the procedure is terminated when no point during the iteration run changed its position.

Note that the iteration process can be influenced by falling into a local minimum with respect to the factor of safety (this is attributed to the progress of motion of node points), and therefore the procedure might not always converged to the critical slip surface. In case of a complicated slope it is thus advisable to begin with more different slip surfaces. Starting points for the initial polygonal surface can be obtained from the results derived for a circular slip surface, see **Chapter 4.2.3**.

Inclining dividing planes

It is evident from **Fig. 4.1** that dividing planes do not have to be neither vertical nor mutually parallel. The first part of the optimization process, when individual points on the slip surface are moved, precedes assuming vertical dividing planes. The factor of safety can be further reduced by changing inclination of these planes. This is also performed in several runs. For each run the angle of inclination is fixed and is gradually reduced from run to run. This part of the optimization process is terminated when the change of inclination of planes is less than 1^o and during the last run the inclination of no plane was changed.

4.1.1.3 Earthquake

Generally the optimization assumes k_h equal to zero. This constant, however, can be assigned a non-zero value to simulate, e.g., earthquake effects. The assigned value represents the ratio of horizontal and gravitational acceleration. Increasing k_h leads to the reduction of the factor of safety. **Table 4.1** lists values of k_h that correspond to individual degrees of earthquake according to the M-C-S scale.

Degree M-C-S (MSK-64)	Horizontal acceleration [mm/s^2]	Factor of horizontal acceleration K
1	0,0 - 2,5	0,0 - 0.00025
2	2,5 - 5,0	0,00025 - 0.0005
3	5,0 - 10,0	0,0005 - 0.001
4	10,0 - 25,0	0,001 - 0.0025
5	25,0 - 50,0	0,0025 - 0.005
6	50,0 - 100,0	0,005 - 0.01
7	100,0 - 250,0	0,01 - 0.025
8	250,0 - 500,0	0,025 - 0.05
9	500,0 - 1000,0	0,05 - 0.1
10	1000,0 - 2500,0	0,1 - 0.25
11	2500,0 - 5000,0	0,25 - 0.5
12	> 5000,0	> 0.5

Tab. 4.1

The coefficient of vertical earthquake increases ($k_v>0$) or decreases ($k_v<0$) the bulk weight of soil, water in the soil and surcharges by multiplying the respective values by 1+kv. Recall that the coefficient k_v may receive both negative and positive values. Also note that applying a sufficiently high factor of horizontal acceleration may result in a slope lift ($k_v<0$) that is worth than its surcharge.

4.1.1.4 Influence of underground water

The influence of underground water, if present, appears in the equilibrium analysis in both directions, first when computing the self-weight of soil and then when computing the shear forces. To that end, the effective shear parameters of soil are considered. The programs allows the user to account for the presence of water in three different ways:

Ground water table

The ground water table is inputted as a polygon. The saturated bulk weight of soil γ_{sat} is assumed for the soil below the ground water table. The water also generates an uplift pressure. Above the ground water table the analysis employs the inputted bulk weight of soil γ.
The pore pressure in a given section is determined as hydrostatic pressure. For inclined water table the pore pressure computation takes into account the shape of the table curve.

The shear forces developed on a slip surface are provided by

$$T_i = (N_i - U_i)\tan\varphi_i' + \bar{c}_i' d_i$$

where:

U_i - pore pressure resultant on the i-th layer.

The shear force between strips is then given by

$$X_i = (E_i - PW_i)\tan\bar{\varphi}_i' + \bar{c}_i' d_i$$

where:

PW_i - pore pressure resultant on the i-th interface between strips.

Blocks for which the ground water table is found above the terrain are analyzed with the bulk weight of soil below water γ_{Su} ($\gamma_{Su} = \gamma_{sat}$ -10 kN/m^3). In that case the pore pressures U and PW are not computed.
When including the effect of earthquake in the analysis the equilibrium condition on a given block is extended by adding a weight of water below the terrain; as a vertical force multiplied by ($1+K_v$) where K_v is the coefficient of vertical acceleration and as a horizontal force multiplied by a value of the factor of horizontal acceleration K_h.
Blocks below the ground water table for which the ground water table is found below the terrain are analized with the bulk weight of water γ_{sat} and such a block is lifted by the pore pressure U. The horizontal component of pore pressure U is equilibrated by introducing a horizontal force of a magnitude $U*\sin\alpha$. When including the effect of earthquake this force is yet multiplied by ($1-K_h$) and is added to a horizontal load of a block Fx.

Pore pressure coefficients r_u

The pore pressure coefficient r_u gives the ratio between the pore and geostatic pressures. The bulk weight of soil in the soil body is assumed equal to the inputted value of γ regardless of coefficients r_u.

The values of coefficients r_u are specified using isolines, which connect points of the same r_u. Values between individual isolines are linearly interpolated. The shear forces are then provided in the following form

$$T_i = (N_i - G_i r_{u,i}) \tan \varphi_i^{'} + c_i^{'} b_i \sec \alpha_i$$

where:

G_i - resultant of geostatic pressure on the *i*-th segment of a slip surface,

$$X_i = (\overline{E}_i - GP_i \overline{r}_{u,i}) \tan \overline{\varphi}_i^{'} + \overline{c}_i^{'} d_i$$

where:

GP_i - resultant of geostatic pressure on the *i*-th interface between strips.

Pore pressure values

The underground water can be described directly by specifying the pore pressure values in a given cut taken through the soil body.

The bulk weight of soil in the soil body is assumed equal to the inputted value regardless of the inputted values of pore pressure.

The values of pore pressure are again specified using isolines, which connect points of the same pore pressure. Values between individual isolines are linearly interpolated. The resultants of pore pressure U_i and PW_i are then computed from the values of pore pressure obtained in specific points within the cut.

4.1.1.5 Influence of external loading

The analyzed slope can be loaded by generally inclined trapezoidal load applied on its surface. The vertical component of surcharge, when pointing in the direction of soil weight, is added to the weight of corresponding strip. This not only changes the value of weight but also changes location of the strip centroid. If the vertical component of surcharge acts in the opposite direction, then it is added to the force Fy_i. The horizontal component of surcharge is added to the force Fx_i. The centroid of loading is always assumed on the terrain surface.

4.1.1.6 Anchors

The anchor is determined by two points and a force. The first point is always placed on the terrain surface and the anchor force is directed into the soil body. The anchor force is resolved into vertical and horizontal components and these are added to forces F_x, and F_y, respectively. Two approaches are implemented to analyze an anchor:

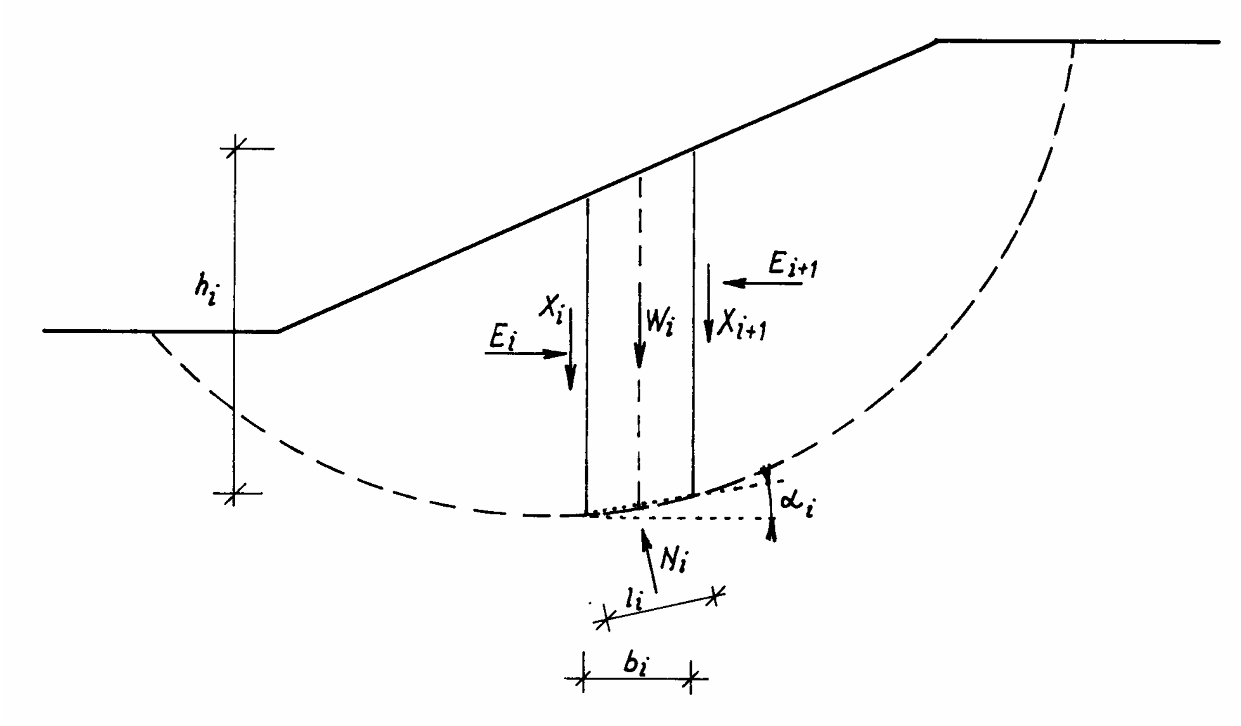
- Computing the anchor length – the procedure assumes an infinite length of anchor (all anchors are introduced in the analysis) and the required length of rigid links of anchors are determined (the distance between the anchor head and the intersection of anchor with the slip surface.
- Computing with pre-assigned lengths of anchors – the analysis accounts only for those anchor whose end point (center of the anchor root) is found behind the slip surface.

4.1.1.7 Foliation (slaty cleavage) of soils

Soils may have specified foliation. This means that under a certain angle (from the interval <*BegSlope*,*EndSlope*>) the soil experiences significantly different (usually worse) parameters (c and φ). If the inclination of a segment of the slip surface is found within the interval <*BegSlope*,*EndSlope*> then the modified parameters c and φ are used.

4.1.2 Circular slip surface (Bishop, Petterson)

The Bishop method is one of the classical strip methods of limit equilibrium. Its basic assumption is the circular slip surface. The method draws on satisfying the moment and force equilibrium conditions in the vertical direction. The planes diving the section into strips are always vertical. A static scheme of strips and corresponding forces are displayed in **Fig. 4.2**.



Obr. 4.2 Static scheme – the Bishop method

Here, X_i is the shear force between strips; N_i is the normal force on a segment of the slip surface. W_i is a weight of the i-th strip.

The Bishop method originates from the Petterson method at which the safety factor F_S is derived from the expression

$$F_s = \frac{1}{\sum_i W_i \sin\alpha_i} \sum_i [c_i l_i + (N_i - u_i l_i) \tan\varphi_i]$$

where:

u_i - pore pressure on the i-th strip,

c_i, φ_i - effective parameters of soil.

In addition, the Bishop method requires satisfaction of the horizontal force equilibrium condition.

The force equilibrium condition written in the horizontal direction provides

$$N_i - u_i l_i = \frac{W_i + (X_i - X_{i+1}) - l_i (u_i \cos\alpha_i + \frac{c_i}{F_s}\sin\alpha_i)}{\cos\alpha_i + \frac{\tan\varphi_i}{F_s}\sin\alpha_i}$$

Inserting the above equation into Petterson's equation gives more accurate expression for evaluation of the factor of safety F_S:

$$F_s = \frac{1}{\sum_i W_i \sin\alpha_i} \sum_i \{[c_i b_i + (W_i - u_i b_i + X_i - X_{i+1}) \tan\varphi_i] \frac{\sec\alpha_i}{1 + \frac{\tan\varphi_i \tan\alpha_i}{F_s}}$$

In the Bishop method the difference of forces $X_i - X_{i+1}$ is neglected since it has only a minor effect on the final result. The resulting expression then reads

$$F_s = \frac{1}{\sum_i W_i \sin\alpha_i} \sum_i \frac{c_i b_i + (W_i - u_i b_i) \tan\varphi_i}{\cos\alpha_i + \frac{\tan\varphi_i \sin\alpha_i}{F_s}}$$

4.1.2.1 Influence of underground water

The influence of underground water, if present, appears in the equilibrium analysis in both directions, first when computing the self-weight of soil and then when computing the shear forces. To that end, the effective shear parameters of soil are considered. The programs allows the user to account for the presence of water in three different ways:

Ground water table

The ground water table is inputted as a polygon. The saturated bulk weight of soil γ_{sat} is assumed for the soil below the ground water table. The water also generates an uplift pressure. Above the ground water table the analysis employs the inputted bulk weight of soil γ.
The pore pressure in a given section is determined as the hydrostatic pressure. For an inclined water table the pore pressure computation takes into account the shape of the table curve.

The shear forces developed on a slip surface are provided by

$$T_i = \frac{(N_i - U_i) tg \overline{\varphi}'_i}{F} + \frac{\overline{c}'_i l_i}{F}$$

where

T_i	- tangential components of forces on the slip forces [kN/m] and is inequilibrium with the mobilized shear resistant force,
N_i - U_i j	- effective component of normal loading on the slip surface [kN/m],
φ_i and c_i	- weighted averages of effective values of shear strength parameters,
F	- current value of the factor of safety.

Presence of water above the terrain appears in the analysis as a terrain surcharge. Its magnitude equals the magnitude of hydrostatic pressure and its direction is always normal to the terrain surface. This surcharge is resolved into horizontal and vertical components. The vertical component is added to the weight of soil W_i and the horizontal component to the component of the external surcharge Fx_i.

Pore pressure coefficients $\mathbf{r_u}$

The pore pressure coefficient r_u gives the ratio between the pore and geostatic pressures. The bulk weight of soil in the soil body is assumed equal to the inputted value of γ regardless of coefficients r_u.

The values of coefficients r_u are specified using isolines, which connect points of the same r_u. Values between individual isolines are linearly interpolated. The shear forces are then provided in the following form

$$T_i = (N_i - G_i r_{u,i}) \tan \varphi_i^{'} + c_i^{'} b_i \sec \alpha_i$$

where

G_i - the resultant of geostatic pressure on the i-th segment of a slip surface.

Pore pressure values

The underground water can be described directly by specifying the pore pressure values in a given cut taken through the soil body.

The bulk weight of soil in the soil body is assumed equal to the inputted value regardless of inputted values of pore pressure.

The values of pore pressure are again specified using isolines, which connect points of the same pore pressure. Values between individual isolines are linearly interpolated. The resultants of pore pressure U_i are then computed from the values of pore pressure obtained in specific points within the cut.

4.1.2.2 Implementation of anchor forces and water above the terrain surface into the analysis

The anchor forces act as an external loading per unit meter [kN/m] and enter the moment equation of equilibrium. These forces should contribute to a sufficient stability of the slope, providing there is no other, more suitable, way. Note, that the program does not check the magnitudes of forces in anchors. It is therefore the user responsibility to use realistic values.

The presence of water is simulated by a system of forces acting on the terrain surface and as a pore pressure on the slip surface derived from the location of water table. If we realize a rather simplified solution of the stability problem, in which satisfaction of equilibrium conditions is not absolutely correct, the influence of water reaching up to one half of the slope height is modeled with sufficient accuracy. In cases in which the height of flooding is higher than one half of the slope height this approach is not acceptable.

The factor of safety F_S is computed by iterating the expression introduced above.

4.1.2.3 Earthquake

This program enables to include effects of earthquake using two variables – the factor of horizontal acceleration k_h and the coefficient of vertical earthquake k_v.

The coefficient of vertical earthquake increases ($k_v>0$) or decreases ($k_v<0$) the bulk weight of soil, water in the soil and surcharges by multiplying the respective values by 1+kv. Recall that the coefficient k_v may receive both negative and positive values. Also note that applying a sufficiently high factor of horizontal acceleration may result in a slope lift ($k_v<0$) that is worth than its surcharge.

The coefficient of horizontal acceleration introduces into the solution an additional force having magnitude k_h*W_i, where W_i , and acts in the strip centroid. This force then contributes to active forces.

4.1.2.4 Optimization

The optimization procedure searches for the circular slip surface with the lowest factor of safety F_S. The circular surface is determined by three points: two points on the terrain surface and one point inside the soil body. Each point on terrain surface has one degree of freedom while the internal point has two degrees of freedom. The slip surface is determined by four independent parameters. To find the desired four parameters, the procedure employs a certain influence matrix (found from sensitivity analysis), which accelerates the iteration process. The critical slip surface corresponds to the one with the lowest factor of safety.
The present approach is usually not spoiled by falling into a local minimum. It is particularly useful in conjunction with the general (polygonal) slip surface. In such a case the results derived for the circular slip surface may serve as an input for the optimization process, which exploits the polygonal slip surface (the Sarma method).

4.2 Program „Reinforced slopes“

The program “Reinforced slopes” can be used to design and verify reinforced earth structures using the method of limit states. The program verifies stability of the structure on both the internal slip surface, which passes through the reinforcement, and external slip surface, which does not interfere with the reinforced region.
The required parameters that describe individual layers of a soil body are grouped into standard parameters such as bulk weight, angle of internal friction, cohesion and specific parameters related to the interaction with reinforcements, e.g., grain size, chemistry of the environment measured in pH. The design strength of reinforcement is automatically determined from inputted values, which characterize the reinforcement (material, instantaneous strength, life time, etc.) and the surrounding soil, see **Section 4.2.2**.

4.2.1 Methods of analysis

The basis for the stability analysis of reinforced slopes is the Jambu method (1973) modified to implement reinforcements. The method allows the internal stability analysis with the slip surfaces intersecting the reinforced region, **Fig. 4.3**, as well as the external stability analysis, when the slip surfaces is found out of the reinforced region, see **Fig. 4.4, 4.5**.

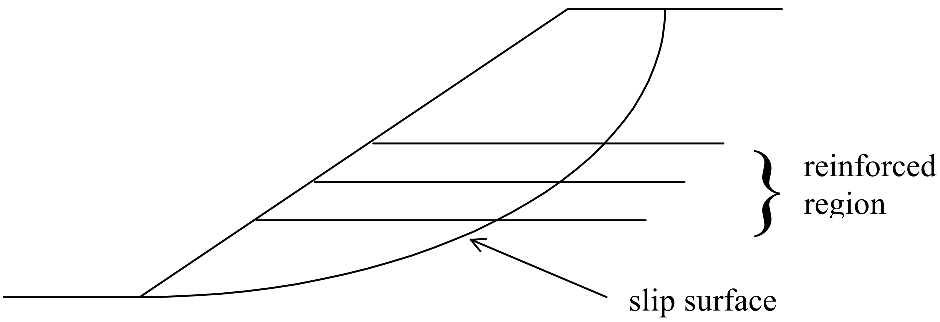


Fig. 4.3: The slip surface passes through the reinforced region – internal stability analysis

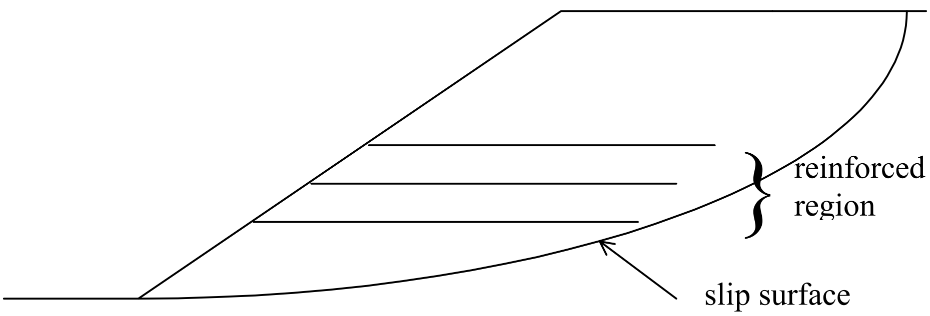


Fig. 4.4: The slip surface is located out of the reinforced region – external stability analysis

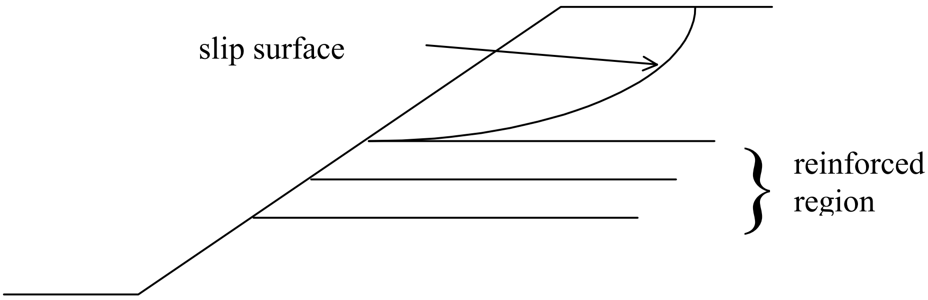


Fig. 4.5 The slip surface is located out of the reinforced region – external stability analysis

The verification of external stability also includes the verification of reinforcement against tearing the reinforcement apart and the verification of anchor length against pull out. In particular, the program checks utilization of the reinforcement and whether the maximum design strength Td, assigned to the reinforcement, was not exceeded.
To simplify the design analysis it is possible to begin with only a single reinforcement placed approximately in the middle of the slope. In the next step, you may adjust its design strength Td such that the stability condition is satisfied. Finally, you compute the required number of reinforcements having actual strength and repeat the analysis. This way you obtain the best approximation, which may be further modified.

4.2.1.1 Basic principles of the JANBU method

When computing the factor of safety the slope is first subdivided into vertical strips.

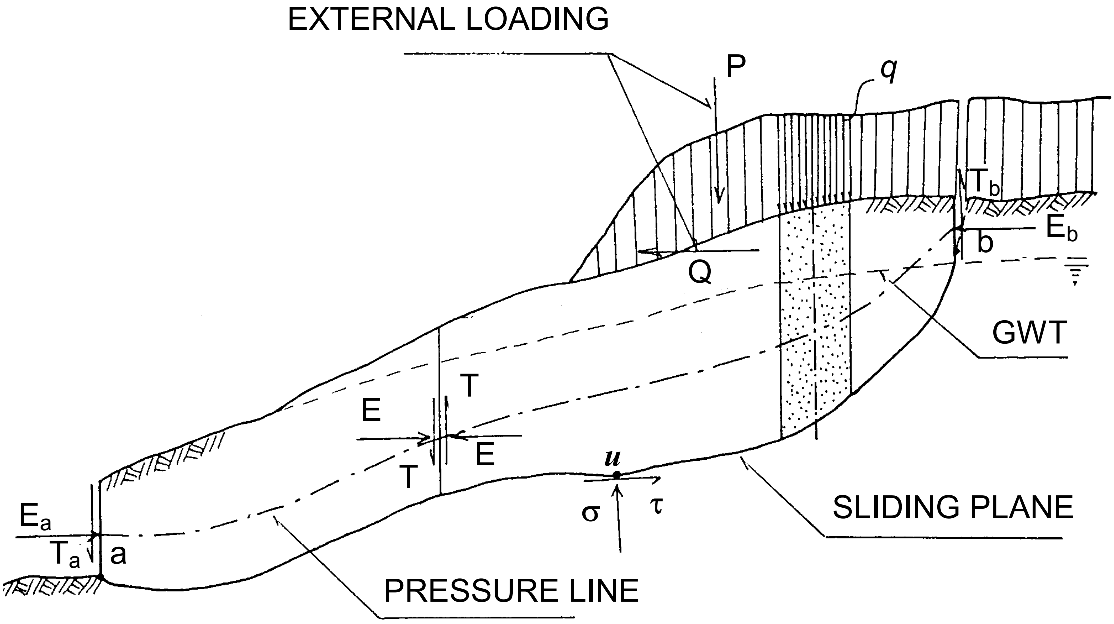


Fig. 4.6 General slope identifying basic terminology and notation

Individual forces acting upon each strip are displayed in **Fig. 4.7**. In particular, E_i and T_i represent the horizontal and vertical forces, respectively, acting between strips i-1 and i, ΔS_i and ΔN_i are the resultants of the shear and normal stresses acting on the slip surface of the *i*-th strip having length Δl_i. $W_{\gamma i}$ and q_i, are the self weight and surface surcharge of the *i*-th strip, respectively. u_i is the pore pressure at the point of application of force ΔN_i. α_i is the inclination angle of the *i*-th segment of slip surface and finally, ΔQ_i represents the surcharge caused by the reinforcement acting at heights Z_{Qi} and Z_{Qi+1}, respectively. Therefore, the reinforcement is introduced as a horizontal pre-stress of a given strip that is activated by a small deformation at the location of a potential slip surface. As an example we may consider a region of the slip surface of width equal to 10cm. Then the relative deformation equal to 3% corresponds to the slip of 3mm, which has essentially no impact on the overall earth structure.

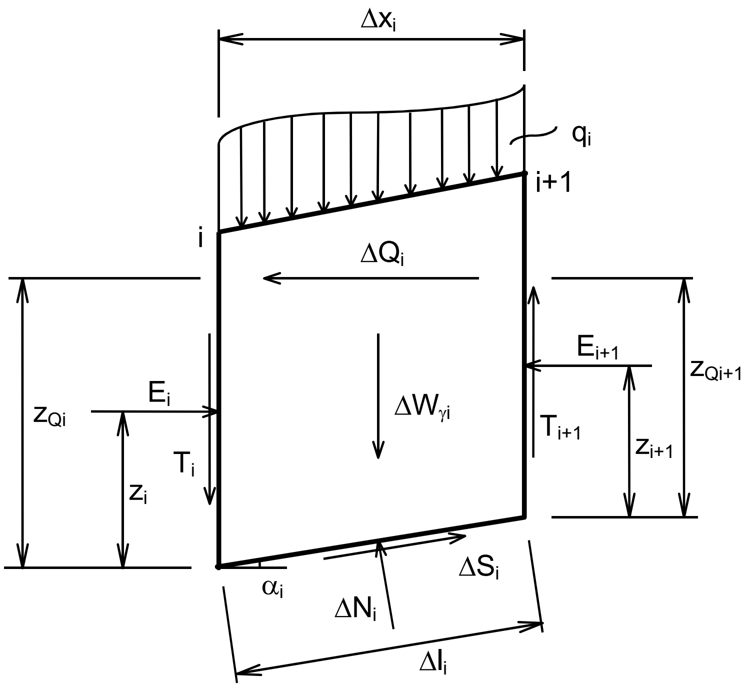


Fig. 4.7 Forces acting upon the ith strip and notation of all necessary geometrical variables.

Basic assumptions:

- known point of application z_i of horizontal forces acting between the i-1 and i strips (location of the pressure line – between 1/3 and 1/2 of the strip height),
- the stress resultant on the slip surface acts at the point where the resultant of vertical load intersects the strip base,
- the equilibrated shear stress on the slip surface is defined as a ratio between shear strength and the factor of safety: $\tau_i = \tau_{fi}/F$.

Thus the unknown quantities are the horizontal and vertical forces between adjacent strips, stresses within a strip of the selected slip surface and factor of safety of the entire slope. They are determined from the equilibrium conditions. Horizontal forces between strips, stresses within a strip and the overall factor of safety are derived from the force equilibrium conditions in the vertical and horizontal directions. Vertical forces between strips are found from the moment equation of equilibrium. The resulting factor of safety for the assumed slip surface follows from the iteration process. The Mohr-Coulomb failure condition is used to determine stresses on the slip surface. The equations of equilibrium thus read:

$$\tau_{fi} = c_{ef} + (\sigma_i - u_i) \cdot tg\varphi_{ef} \tag{1}$$

$$\sigma_i = \frac{T_i - T_{i+1} + W_i}{\Delta x_i} - \tau_i \cdot tg\alpha_i \tag{2}$$

$$E_i - E_{i+1} = \Delta Q_i + (T_i - T_{i+1} + W_i) \cdot tg\alpha_i - \tau_i \cdot \Delta x_i \cdot (1 + tg^2\alpha_i) \tag{3}$$

$$T_{i+1} = -E_{i+1} \cdot \left(\frac{z_{i+1} - z_i}{\Delta x_i} + tg\alpha_i \right) - \frac{E_{i+2} - E_i}{\Delta x_i + \Delta x_{i+1}} \cdot z_{i+1} - \frac{\Delta Q_i + \Delta Q_{i+1}}{\Delta x_i + \Delta x_{i+1}} \cdot z_{Qi+1} \qquad (4)$$

Using the relation $\tau_{fi} = \tau_i \cdot F$ and the summation of Eq. (3) over the whole analyzed region provides the factor of safety in the form

$$F = \frac{\sum_{i=1}^{n} \tau_{fi} \cdot \Delta x_i \cdot \left(1 + tg^2 \alpha_i\right)}{E_a - E_b + \sum_{i=1}^{n} \left[\Delta Q_i + \left(T_i - T_{i+1} + W_i\right) \cdot tg\alpha_i\right]} = \frac{\sum_{i=1}^{n} A_i}{E_a - E_b + \sum_{i=1}^{n} B_i} \qquad (5)$$

where E_a and E_b are horizontal forces at ends *a* and *b* of the examined region. Combining Eqs. (1) and (2) yields

$$\tau_{fi} = \frac{c_{ef} + \left(\frac{T_i - T_{i+1} + W_i}{\Delta x_i} - u_i \right) \cdot tg\varphi_{ef}}{1 + \frac{tg\varphi_{ef} \cdot tg\alpha_i}{F}} \qquad (6)$$

It is evident from Eq. (5) that searching for the factor of safety requires an iteration process. To start iteration it is necessary to select an initial factor of safety and specify vertical forces between strips. These are assumed equal to zero. Note that the actual iteration process is a combination of two processes. Each global iteration step begins with the determination of *F* in the internal iteration cycle for computed vertical forces acting between strips (assumed zero in the first step) using Eq. (5) with the factor of safety *F* on the right hand side found from the previous step. The internal iteration process is terminated when two successive iterations provide negligible change in *F*. This intermediate factor of safety is used to get:

- horizontal forces between strips with the help of Eqs. (3) and (5):

$$E_{i+1} = E_i - B_i + \frac{A_i}{F} \qquad (7)$$

- vertical forces between strips using Eq. (4).

After computing the vertical forces the computation returns back to the beginning of the global iteration process (computation of new *F*). The global iteration process is terminated when there is no significant change of F between two successive global iteration steps.

Introduction of ΔQ_i in the analysis

Reinforcements are represented in the analysis by forces ΔQ_i, which corresponds to the increments of activated force $Q = T_d$ in the reinforcement acting upon the *i*-th strip. The full mobilization of the reinforcement strength T_d (to ensure that the reinforcement will not be torn apart) on the expected slip surface and its linear increase from the slope edge (**Fig. 4.8**) is assumed. When the anchor length L_k is found insufficient the program allows mobilization of the reinforcement strength only up to the value guaranteed by the anchor length L_k. This prevents the reinforcement being pulled out from the region behind the slip surface. The degree of reinforcement utilization informs the user about the partial mobilization of the reinforcement. It follows, from the above results that the reinforcement is most effective when placed in the vicinity of the point of tangent to the slip surface, which is parallel to the slope inclination.

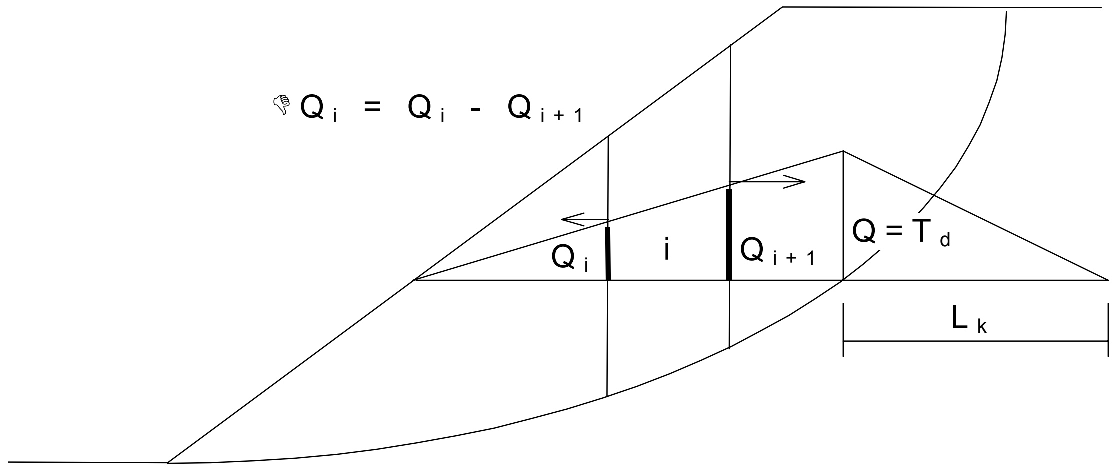


Fig. 4.8: Introduction of the reinforcement force into the analysis (tying the strips up)

The anchor length is found from the expression:

$$L_k = \frac{3.T_d}{2\sigma_z.k..tg\varphi}$$

where T_d is the design strength of the reinforcement,
k reduction of anchorage against pull out.,
σ_z geostatic stress at a given depth,
φ angle of internal friction of a surrounding soil.

4.2.2 Determination of the design material values

4.2.2.1 Design strength of soils

The program allows computation according to the limit states with the reduction of parameters of soils or using the classical theory with no reduction of the input data. It is the user responsibility to select the most suitable approach. The Eurocode 7 recommends the analysis according to the limit states with the following parameters:

$$\mathrm{tg}\ \phi_d = \mathrm{tg}\ \phi/1{,}25$$

$$c_d' = c'/1{,}6$$

Therefore you set, in the program mode „Setting“, $\gamma_{m,\phi}$ =1.2, $\gamma_{m,c}$ =1.6, reduce tangent ϕ. The recommended value of the factor of safety thus ranges from 1,2 to 1,3.

4.2.2.2 Design strength of reinforcements made from geosynthetic materials

The design strength T_d can be determined, e.g., by using the allowable value of relative deformation ε_d derived from the fast tensile test on a wide specimen and defined according to the importance of a structure (ε_d = 0,5 - 7 %). Such a value of T_d or the ratio T_d/T_f is then checked with regard to the creep deformation, i.e., it is checked whether an unsteady state creep may set in for a given level of stress or the resulting deformation due to sustain loading may exceed an allowable limit.
The following expression for the determination of the design strength of reinforcement is used in the program

$$T_d = \frac{1}{F_{tc}} \cdot \frac{1}{F_{comp}} \cdot \frac{1}{F_{env}} \cdot T_f$$

where:

T_f – is the maximum strength in tension at failure (EN-ISO 10319 test),

F_{tc} – is a partial factor of safety representing a risk of creep with respect to the life time of a structure,

---

F_{comp} – is a partial factor of safety representing a risk of damaging the reinforcement during soil compaction and it ranges from F_{comp} = 1,1 up to 1,5 depending on the type of soil and the material used for the reinforcement, the upper bound of 1,5 is assumed for sharp gravel and the reinforcement in form of woven or braided geotextile made from polyester; more accurate value is obtained by comparing the results of tensile experiment before and after compaction test,

F_{env} – is a partial factor of safety representing a risk of reducing the strength due to chemical resistance. When used in more aggressive environment it is necessary to proceed individually while taking into account tests of chemical resistance prENV 189029. For this reason it is not recommended to combine reinforcing of soils by reinforcements made from polyester with treating of soils by lime.

The design tensile strength T_d defined in such a way should keep the deformation of a soil body within acceptable limits. Nevertheless, it is necessary to check the value of relative deformation corresponding to $T_{d.}$

The following values of coefficients are used in the program:

Coefficient representing effect of time F_{tc}

t [years]	Fortrac	Stabilenka	PES	PP,PE
120	2,00	2,00	2,70	5,40
60(70)	1,70	1,70	2,25	4,50
7	1,50	1,50	1,50	3,00

Coefficient of chemistry of environment F_{env}

	Fortrac	Stabilenka	PES	PP,PE
Acid	1,10	1,10	1,10	1,10
Neutral	1,00	1,00	1,00	1,00
Alkaline	1,15	1,15	1,15	1,00

Coefficient of risk of damaging reinforcement F_{comp}

d50 [mm]	Fortrac - strength T_n		Stabilenka – strength T_n		PES		PP,PE	
	> 35 kN/m	< 35 kN/m	>300 kN/m	<300 kN/m	Geogrid	Geotext.	Geogrid	Geotext.
<0.006	1,05	1,10	1,10	1,10	1,10	1,10	1,10	1,10
0.006-2	1,05	1,10	1,10	1,17	1,17	1,22	1,10	1,10
2-20	1,10	1,15	1,14	1,35	1,22	1,28	1,20	1,25
20-60	1,10	1,20	1,14	1,35	1,33	1,40	1,30	1,30
2-60 sharp	1,30	1,30	1,40	1,40	1,35	1,50	1,30	1,30
>60	1,40	1,40	1,50	1,50	1,45	1,50	1,40	1,45

Various reinforcements producers have their products certified, i.e., some of the coefficients for creep, mechanical damage and environment are less severe. It is therefore left for users to decide what values of the design strength the reinforcement may attain. The design strength of reinforcement appears in the table when inputting the reinforcement. The actual value depends on the reinforcement material and the surrounding soil.

A risk of large elongations of reinforcements after their introduction into a soil structure can be assessed from plots showing a variation of deformation as a function of tensile stress for tests carried out at various velocities of the applied load. The results of experimental measurements performed over the last 20 to 30 years by some of the producers are now available and can be used to extrapolate the current results over a larger time span. It is evident from **Fig. 4.9** showing the results for polyester that for stresses below 40% of the tensile strength there is an insignificant difference in measured strain (less than 1%). This suggests that the initial instantaneous deformation will not substantially increase with time (no more than by 1%). On the other hand, when inspecting the results for polypropylene, **Fig. 4.10**, we notice a considerable increase in creep strain even for load levels at 20% of the tensile strength (from 5% to 6%).

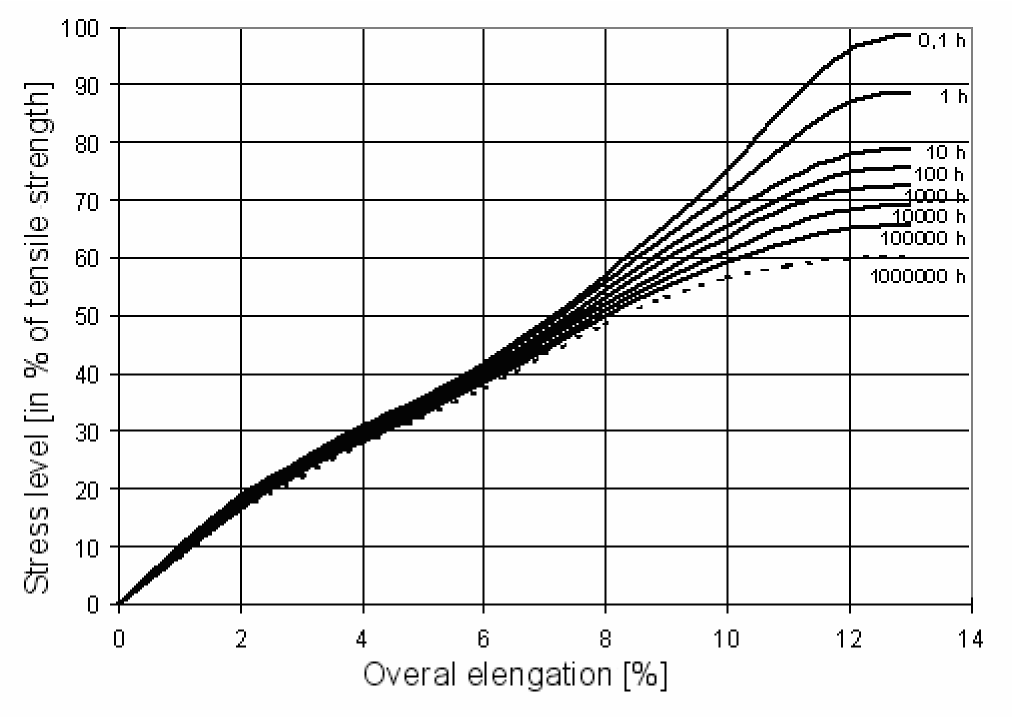


Fig.4.9 Tensile stress-strain relation – polyester, geogrid Fortrac

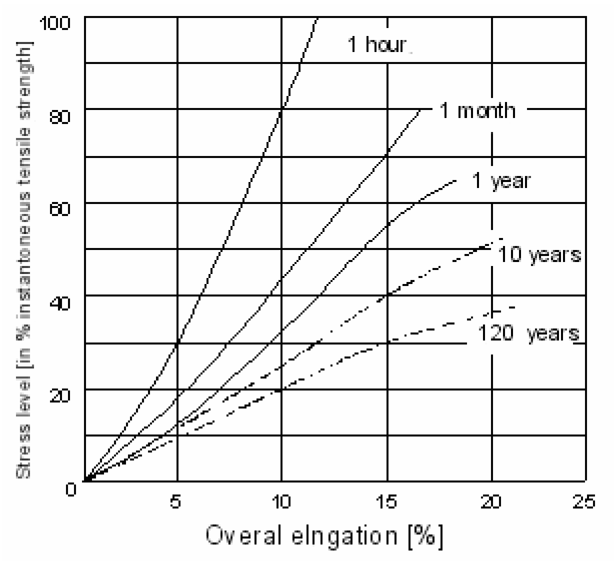


Fig.4.10 Tensile stress-strain relation – polypropylene, polyethylene,

4.3 Stability of rock slopes – program „Rock slope"

4.3.1 Introduction

The program „**ROCK SLOPE**" serves to analyze stability of both artificial rock slopes resulting from mankind activity (e.g., rock mass cuts for highways, motorways, railways, water overflows, open pits, etc.) and natural slopes resulting from natural erosive processes. The present geotechnical approach to the stability problems of rock slopes is based solely on numerical analysis. In particular, experimentally determined (both laboratory and in-situ measurements) parameters of rock mass are introduced into the numerical analysis to estimate the actual behavior of rock slopes as close as possible. When using the theoretical approach, the actual modeling should precede from simpler to more complicated analyses – e.g., stability analysis of a rock slope in discontinuous rock mass by determining a slip on a natural discontinuity while excluding the external loading. The factor of safety is determined by comparing passive forces (forces resisting the sliding of a rock mass) and active forces (forces leading to the failure of a rock mass).

The method of limit analysis is used to assess the rock slope stability. This method assumes that a sate of equilibrium of forces can develop on a potentially instable block of a rock mass. The method of limit analysis requires determination of shear strength on surfaces of discontinuity (slip surfaces, joints between blocks, etc.) The program „**ROCK SLOPE**" describes the shear strength using the Mohr-Coulomb friction law with a linear dependence of the shear stress on the normal stress as

$$\tau = c + \sigma_n \tan\varphi$$

where:

τ - shear strength,

σ_n - effective normal stress acting in the direction normal to a failure surface,

c - effective cohesion,

φ - effective angle of internal friction.

The most reliable estimates of shear parameters are provided by in-situ measurements. Experimental investigations, both in-situ and laboratory tests, suggest that for most joints in a rock mass the friction angle ranges from *27°* to *47°*. The program is applicable for all low rock slopes and for high slopes developed in a rock mass with high deformation modulus. In a rock mass with a lower deformation modulus the blocks must be separated by opened joints.

4.3.2 Failure modes

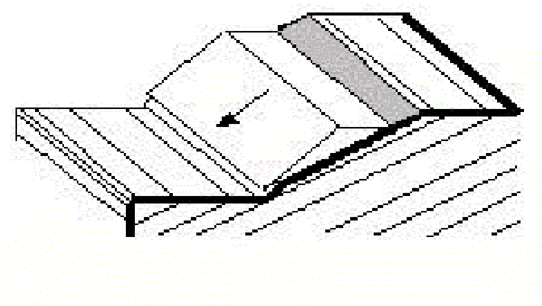
Determination of an actual slip surface for rock slopes is generally complicated. This is also why the stability analysis of rock slopes is carried out under a certain generalization of a real state from both the geometry of a given problem and material parameters of the rock mass points of view. The program **"ROCK SLOPE"** analyzes the following failure mechanisms (see **Fig. 4.11**):

shear failure along a plane slip surface,

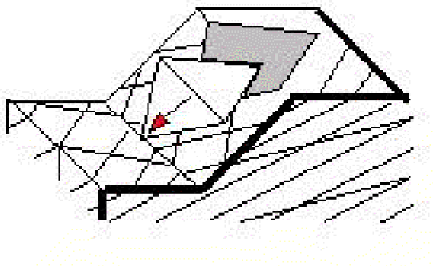
sliding of rock wedges,

overturning of rock blocks,

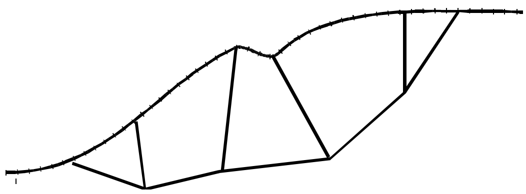
Other types of failure, e.g., due to swelling or shrinkage of rocks, thermal effects, weathering, residual stresses, seismic effects, must be analyzed from case to case using more sophisticated methods.



shear failure along plane slip surface



sliding of rock wedges



shear failure along polygonal slip surface

Fig. 4.11 Basic failure mechanisms of rock slopes

4.3.3 Definition of factor of safety

Stability of rock slopes is represented by the factor of safety index *F*. The factor of safety equals one when both passive and active forces are in equilibrium. In such a case the rock slope is stable. A certain safety, however, is required for most slopes. For example, walls of an excavation pit should have *F =1,1* up to *1,25*, rock cuts for roads should have *F =1,2* up to *1,5*, etc.

A rock mass is always loaded by two systems of forces – active and passive forces, **Fig. 4.12**. The active forces tend to move a rock mass while the passive forces resist the motion. If failure occurs, the rock mass starts to move along a slip surface. The motion is a combination of translation and rotation and it is always important to determine its direction and distinguish between the two types of motion, respectively. The factor of safety against the motion during failure is a measure of stability. In the following, the failure caused by translation a long a slip surface will be considered. Among the possible definitions of factor of safety the program adopts a concept of *F* in which *F* is defined as the ratio of the maximum shear resistance to available shear force:

$$F = \frac{S_{max}}{G_s - T_s} \qquad (1)$$

where

S_{max} - maximum shear resistance
G_s - tensile component of the block self-weight (**Fig. 4.12**)
T_s - tensile component of an anchor force

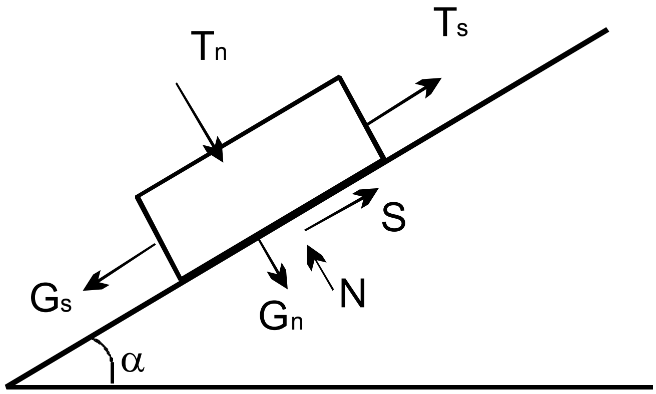


Fig. 4.12 Forces acting on the sliding block

4.3.4 Failure mechanism 1 – sliding along a single plane

When failure occurs along a plane surface (**Fig. 4.13**) the rock block slides down along a more or less plane or slightly undulating surface. The sliding therefore occurs most often along discontinuity surfaces present in the rock mass, such as joints, cracks, layered surfaces, interface between different rocks (changes in shear strength), contact surfaces, etc. For a failure mechanism to set in, however, the following conditions must be met:

- Direction of a discontinuity surface must not defer more than *±20°* from the direction of the slope edge.
- Heel of a slip surface must be found between the heel and edge of a rock mass.
- Inclination of a slip surface must be less than inclination of a rock slope and the discontinuity friction angle must not exceed its inclination.

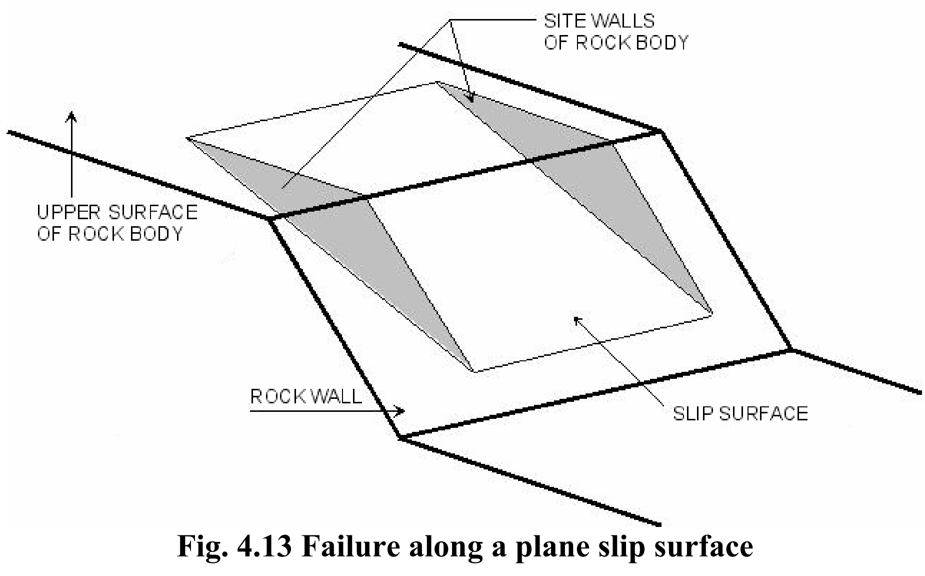


Fig. 4.13 Failure along a plane slip surface

The following governing equations serve, assuming only translation, to compute anchor forces stabilizing the rock mass that susceptible to failure, (**Fig. 4.14**),

- Two force equilibrium conditions

$$S + R \cdot \cos(\alpha + \beta) - G \cdot \sin\alpha = 0$$
$$N - R \cdot \sin(\alpha + \beta) - G \cdot \cos\alpha = 0 \qquad (2)$$

- Expression for the factor of safety

$$F = \frac{S_{max}}{S} \qquad (3)$$

- Mohr-Coulomb friction law

$$S_{max} = N \cdot tg\varphi + c \cdot F \qquad (4)$$

where:

c - cohesion along a slip surface

φ_j - friction angle along a slip surface

Using the above equations provides the resultant of all active forces R in the form (anchoring forces)[1]:

$$R = k_1 \left(1 - \frac{c \cdot F}{G} \cdot k_2\right) \cdot G \qquad (5)$$

where:

R - resultant of all active forces,

k_1, k_2 - coefficients depending on the inclination of a rock slope, deviation of an anchor force, friction angle and the factor of safety,

c - cohesion along a slip surface,

G - self-weight of a rock mass expected to slide.

The following parameters serve to determine stability of a rock block on a single slip surface:

- *cohesion along a slip surface (c)*
- *friction angle along a slip surface (φ)*

  If there is water floating along the slip surface the filling can be carried away and the slip surface can be further smoothed out which decreases the rock slope stability. The analysis in such a case adopts a reduced angle of internal friction and the surface is assumed permeable.

- *self-weight of a rock block*

  The weight of the sliding rock block is computed by the program after inputting the block geometry and the bulk weight of a given rock material. The self-weight of the rock block experiences both active and passive effects. Exclusively active or passive effects of the block weight occur only in exceptional cases (rock overhang, rock blocks resting on horizontal joints and bounded by vertical surfaces). The block weight depends on the density of individual minerals of rock solid face, rock porosity and water content. The degree of saturation has only a minor effect on the weight due to a low porosity and absorption and is not usually accounted for even in case of full saturation (for common rocks the weight of fully saturated rock increases no more than by 2%). If the rock block is found under the water then the uplift pressure is introduced as an independent force U

[1] Charles A. Kliche: Rock Slope Stability, ISMME, 2001

as oppose to soils in which the weight is reduced by the value corresponding to a volume of uplifted water (see further discussion).

- *overall external forces acting on a rock block*
  Anchors (surcharge) acting on the rock block can be prescribed.
- *water pressure acting on a slip surface (uplift) in kN (U)*
  The hydrostatic pressure acting on the slip surface can be prescribed as an external loading (uplift pressure). It can be reduced depending on the permeability along the slip surface. If an inclined ground water table in the rock mass is assumed (its gradient is directed to the wall face) then the horizontal component of the pressure acting on the rock mass must be added to the water pressure U_t acting on the joint of a given block (see further discussion).
- *horizontal water pressure in a tensile crack in kN (U_t)*
  It must be introduced into the analysis whenever a presence of water in the tensile crack is expected.
- *magnitude and deviation of a new anchor force or the required factor of safety for a given direction of the anchor force, respectively*

By selecting the mode “Analysis” the program enables determination of the factor of safety for a given rock slope (with the possibility of inputting new anchor forces) or to compute the required anchor force for a given factor of safety.

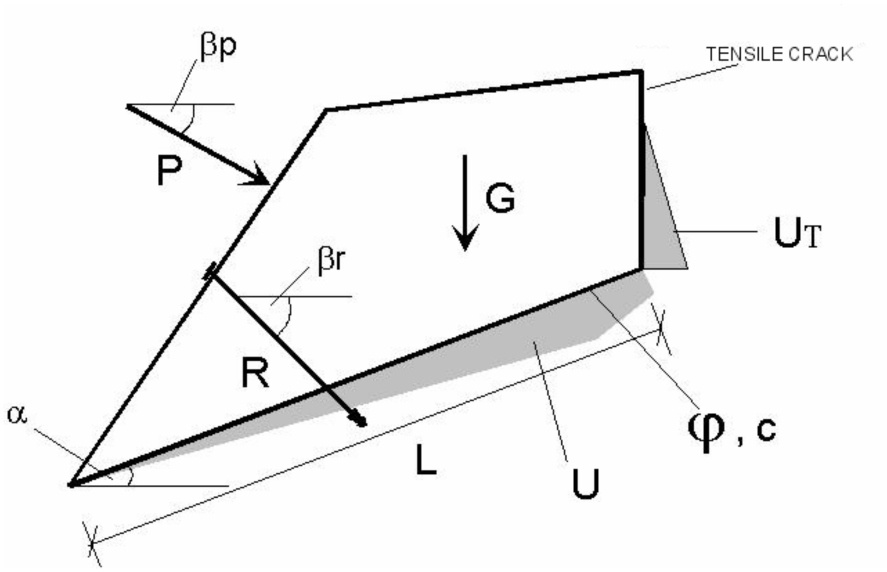


Fig. 4.14 Variables entering the stability analysis along a single slip surface

4.3.5 Failure mechanism 2 – sliding along a polygonal slip surface

Quite often the sliding of the rock mass takes place along polygonally-shaped surfaces after exceeding certain limit load (**Fig. 4.15**). These failure surfaces are usually formed by discontinuity planes that separate individual rock blocks. For a low level of stresses the rock blocks do not change their shape and the actual deformations within the rock mass are negligible. When exceeding strength of the rock material, failure within the sliding rock mass may occur manifested by separation of a part of the block (providing there is a suitable slip surface along which the separation may take place). Sliding of blocks along a polygonal slip surface is generally very complicated. However, a pure translation or rotation along the planes of segregation is often assumed.

Due to complexity of the general solution the program „**ROCK SLOPE**“ draws on the following assumptions:

- Only translation of rock blocks is assumed.
- Individual blocks slide along a polygonal slip surface formed by plane of slightly undulated surfaces.
- Individual blocks are separated by joints with known directions.
- Actual deformations within rock blocks are negligible.
- The Mohr-Coulomb failure criterion applies on a polygonal slip surface and joints between blocks.
- The same factor of safety is assumed for all joints and polygonal slip surface.
- All rock blocks are in contact (opening of joints between blocks cannot occur).
- Shear forces on a slip surface have the same sign.

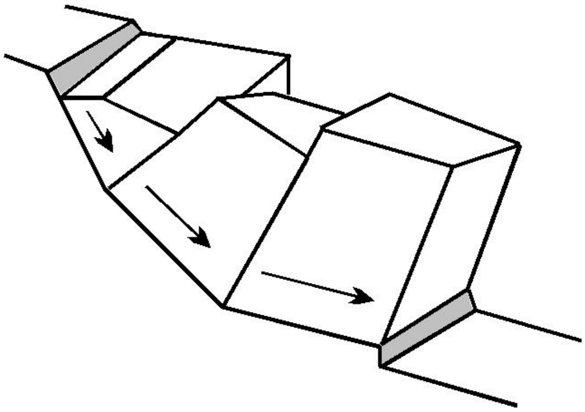


Fig. 4.15 Polygonal slip surface

Inputting properties of slip surfaces

- *cohesion along a polygonal slip surface (external sliding plane) c*
- *friction angle along a polygonal slip surface (external sliding plane)* φ_i

If there is water floating along the external slip surface the filling can be carried away and the slip surface can be further smoothed out which decreases the rock slope stability. The analysis in such a case adopts a reduced friction angle.

- *cohesion of joint between blocks (internal sliding plane)* c_j
- *friction angle of joints between blocks (internal sliding planes)* φ_j

Again, if there is water floating along the external slip surface the filling can be carried away and the slip surface can be further smoothed out which decreases the rock slope stability. The analysis in such a case adopts a reduced friction angle.

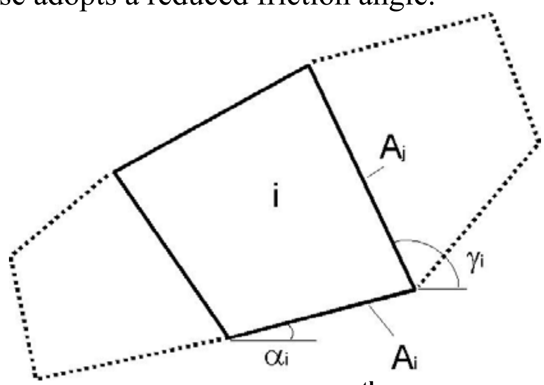


Fig. 4.16 Geometry of the ith element

Inputting forces

- *weight of a rock block*

As for a single plane, the weight of the sliding rock block is computed by the program from the block geometry and the bulk weight of a given rock material. The self-weight of the rock block experiences both active and passive effects. Exclusively active or passive effects of the block weight occur only in exceptional cases (rock overhang, rock blocks resting on horizontal joints and bounded by vertical surfaces). The block weight depends on the density of individual minerals of rock solid face, rock porosity and water content. The degree of saturation has only a minor effect on the weight due to a low porosity and absorption and is not usually accounted for even in case of full saturation (for common rocks the weight of fully saturated rock increases no more than by 2%). If the rock block is found under the water then the uplift pressure is introduced as an independent force *U* as oppose to soils in which the weight is reduced by the value corresponding to a volume of uplifted water (see further discussion).

- *overall external forces acting on a rock block*

Anchors (surcharge, the resultant of external forces) acting on the *i*-th rock block can be prescribed. The resultant of external forces includes all known forces acting on the block except the water pressure in the sliding plane and joint.

- *water pressure on a joint (internal sliding plane)* U'_i

It must be introduced into the analysis whenever a presence of water in the tensile crack is expected and is inputted as a lateral pressure. This value is increased by a horizontal component of hydrostatic pressure due to deviation of the ground water table.

- *water pressure on an external sliding plane (uplift pressure)* U_i

The hydrostatic pressure acting on the external sliding plane can be prescribed as an external loading (uplift pressure). It can be reduced depending on the permeability along the slip surface. If an inclined ground water table in the rock mass is assumed (its gradient is directed to the wall face) then the horizontal component of the pressure acting on the rock mass must be added to the water pressure U'_i acting on the joint of a given block.

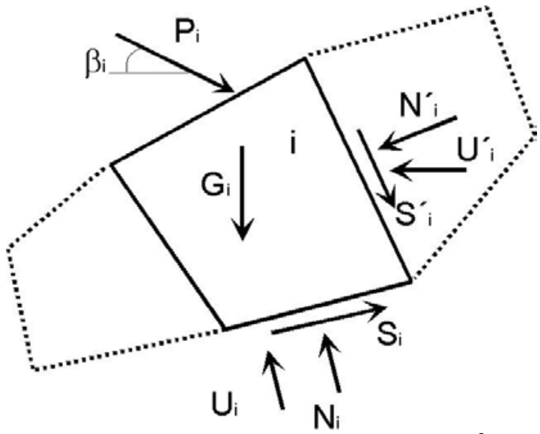


Fig. 4.17 External forces acting on the i^th element

Analysis

The solution analysis calls Eq. (5) for each block on the polygonal slip surface. In this case, however, the anchor force *R* is assumed as an unknown interaction force K_i between rock blocks (**Fig. 4.18**). Eq. (5) together with the system of forces acing on the *i*-th rock block according to **Fig. 4.17** provides the interaction force K_i in the form:

$$K_i = k_{1i}\left(1 - \frac{c_i \cdot A_i}{G_i + P_i^G + K_{i-1}^G} k_{2i}\right)\left(G_i + P_i^G + K_{i-1}^G\right) - \left(P_i^K + K_{i-1}^K\right) \qquad (6)$$

where:

- c_i - cohesion on a slip surface of the *i*-th rock block,
- G_i - weight of the *i*-th rock block,
- P_i^G - overall external force acting on the *i*-th block in the vertical direction,
- P_i^K - overall external force acting on the *i*-th block in the direction of force K_i,
- K_i^G - magnitude of interaction force of the *i*-th block in the vertical direction,
- K_i^K - magnitude of interaction force of the *i*-th block in the direction of force K_i,
- k_{1i} - coefficient depending on the inclination of a slip surface α, inclination of external loading β_i, stability of a rock slope and the friction angle φ_i,
- k_{2i} - coefficient depending on the inclination of a slip surface α, inclination of external loading β_i, stability of a rock slope and the friction angle φ_i.

Defining F of each block as the ratio of the maximum shear resistance to available shear force:

$$F_i = \frac{S_{\max,i}}{\left|S_i\right|} \qquad (7)$$

where

- $S_{max,i}$ - the maximum shear resistance on the ith block,
- S_i - the actual shear resistance developed on the ith block,

gives after combining Eqs. (6) and (7) implicit expression for the inclination of force K_i :

$$\tan\delta_i = \frac{1}{F_i}\left[\tan\varphi_i + \frac{c_i' \cdot A_i'}{R_i \cos\delta_i}\right] \qquad (8)$$

where:

- δ_i - inclination of force K_i of the *i*-th block,
- c_i - cohesion on the slip surface of the *i*-th block,
- A_i - sliding area of the *i*-th rock block,
- K_i - interaction force acting on the *i*-th block,
- φ_i - friction angle on the slip surface of the *i*-th block.

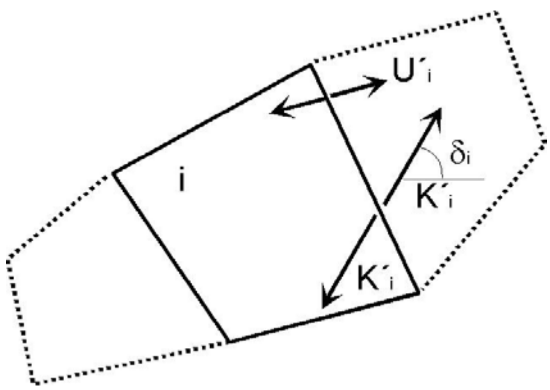


Fig. 4.18 Forces acting on planes between blocks (internal sliding planes)

4.3.6 **Failure mechanism 3 –** ***sliding along two planes***

The analysis assumes a rock mass wedged in between two planes forming a swale with a line of interaction inclined into the excavation, while the line of maximum slope of both planes must be directed towards the line of interaction (see **Fig. 4.19**).

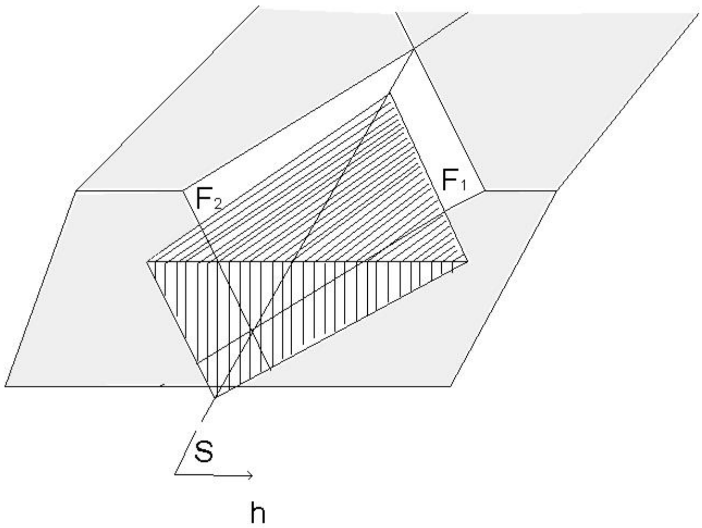


Fig. 4.19 Sliding of a rock wedge

Under the above assumptions the sliding of a rock wedge may occur in the direction of a line of interaction *S*. The stability problem of such a rock block can be solved by projecting its weight and other components of loading in the directions normal to the planes *F1* and *F2*, and in the direction of their interaction *S*. Projecting the resultant of loading V in respective directions gives a system of linear equations. However, the mathematical formulation of expressions entering this system of equations is, due to the way of imputing orientations of planes, rather complicated. When viewing the plane cuts of a rock wedge taken in the directions normal to the line of interaction *S* and a horizontal line *h*, (**Fig. 4.20**), the acting forces can be sorted into three groups:

- self-weight of a rock block
- reaction forces on a slip surface (N_1, N_2) and shear forces (S_1, S_2)
- resultant of external forces *R*

When limiting our attention to pure translation the governing equations become:

- Three force equations of equilibrium

$$S + R\cdot\cos(\alpha_S+\beta) - G\cdot\sin\alpha_S = 0$$
$$N_1\cdot\sin\omega_1 + N_2\sin\omega_2 - R\sin(\alpha_S+\beta) - G\cdot\cos\alpha_S = 0 \qquad (9)$$
$$N_1\cdot\cos\omega_1 - N_2\cos\omega_2 = 0$$

- Expression for the factor of safety

$$F = \frac{S_{max}}{S} \qquad (10)$$

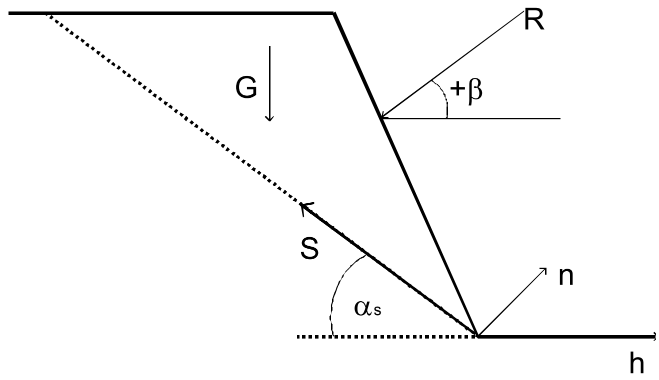
- Mohr-Coulomb friction law

$$S_{max} = S_{max1} + S_{max2} = (N_1+N_2)\cdot tg\varphi + c_1\cdot F_1 + c_2 F_2 \qquad (11)$$

After employing the above equations we arrive at the final expression for the stability of a rock wedge[2]:

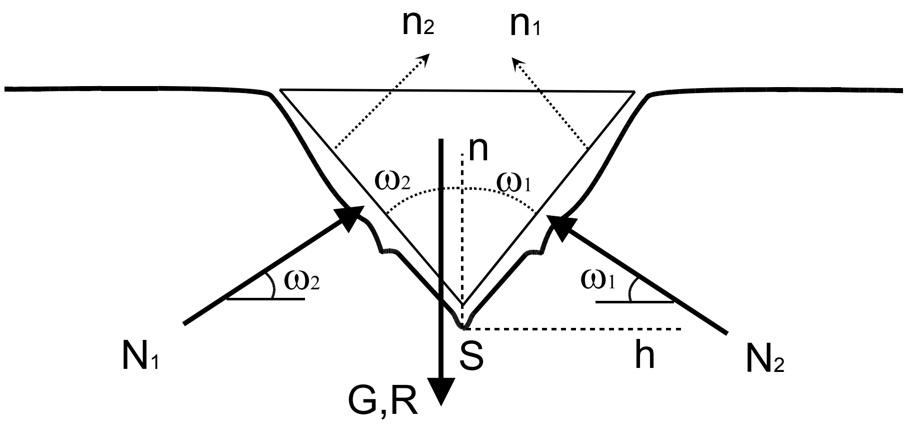
$$R = k_1^* \left(1 - \frac{c_1 F_1 + c_2 F_2}{G} k_2^* \right) G \qquad (12)$$

[2] Witke W: Verfahren zur Berechnung der Standsicherheit belasteter und unbelasteter Felsböschungen. Felsmechanik und Ingenieurgeologie.Supplementum II,1965



<u>Plane cut normal to *h*</u>

G weight of a rock wedge
R resultant of external forces
β inclination of the resultant external force from a horizontal line
n normal to the rock wall (rock wedge)
h horizontal line passing through the heel of a rock wall (rock wedge)
α_s inclination of the line of maximum slope of a rock wedge
S shear resistance



<u>Plane cut normal to the *S* axis</u>

G self-weight of a rock wedge
R resultant of external forces
N_1 normal force on the slip surface F_1
N_2 normal force on the slip surface F_2
n normal to the line of maximum slope of a rock wedge
n_1 normal to the slip surface F_1
n_2 normal to the slip surface F_2
h horizontal line passing through the heel of rock wall (rock wedge)
ω_1 inclination of the slip surface F_1 from a vertical direction
ω_2 inclination of the slip surface F_2 from a vertical direction

Fig. 4.20 Plane cuts through a rock wedge normal to the horizontal line *h* and the line of maximum slope *S*

The following parameters enter the solution procedure:

- *cohesion along a slip surface (c)*
- *friction angle along a slip surface (φ)*

  If there is water floating along the slip surface the filling can be carried away and the slip surface can be further smoothed out which decreases the rock slope stability. The analysis in such a case adopts a reduced angle of internal friction and the surface is assumed permeable.

- *self-weight of a rock block*

  The weight of the sliding rock block is computed by the program after inputting the block geometry and the bulk weight of a given rock material. The self-weight of the rock block experiences both active and passive effects. Exclusively active or passive effects of the block weight occur only in exceptional cases (rock overhang, rock blocks resting on horizontal joints and bounded by vertical surfaces). The block weight depends on the density of individual minerals of rock solid face, rock porosity and water content. The degree of saturation has only a minor effect on the weight due to a low porosity and absorption and is not usually accounted for even in case of full saturation (for common rocks the weight of fully saturated rock increases no more than by 2%). If the rock block is found under the water then the uplift pressure is introduced as an independent force U as oppose to soils in which the weight is reduced by the value corresponding to a volume of uplifted water.

- *overall external forces acting on a rock block*

  The overall anchor force (surcharge) acting on the rock block together with its inclination can be prescribed.

- *magnitude and deviation of a new anchor force or the required factor of safety for a given direction of the anchor force, respectively*

By selecting the mode “Analysis” the program enables determination of the factor of safety for a given rock slope (with the possibility of inputting new anchor forces) or to compute the required anchor force for a given factor of safety.