DEVELOPMENT OF A 3D MODEL FOR THE ASSESSMENT OF THE STABILITY OF THE SLOPES IN THE *MIZIA* QUARRY

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ABSTRACT. The main aspects of three-dimensional modelling for the assessment of the resistance of the slopes in open pit mines and quarries are reviewed in the article. Methods based on the boundary equilibrium and the mechanics of the continuous environment are analysed. An example is presented for the assessment of the stability of the slopes in the Mizia quarry based on a 3D model.

Keywords: open pit mining, slope stability

РАЗРАБОТВАНЕ НА 3D МОДЕЛ ЗА ОЦЕНКА НА УСТОЙЧИВОСТТА НА ОТКОСИТЕ В КАРИЕРА „МИЗИЯ“

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РЕЗЮМЕ. В статията са разгледани основните аспекти при триизмерното моделиране за оценка на устойчивостта на откосите в открити рудници и кариери. Анализирани са методите, основани на граничното равновесие и на механиката на непрекъсната среда. Представен е пример за оценка на устойчивостта на откосите в кариера „Мизия“ на базата на 3Dмодел.

Ключови думи: открит добив, оценка на устойчивостта

One of the important and increasingly developing areas in the field of slope stability assessment is the three-dimensional analysis, i.e. solving the so-called volume task.

Creating a 3D model is a widely used method for solving a number of practical engineering problems (for example, a numerical modelling of the strained distorted state of the object) as well as in solving a wide number of ecological and hydrogeological problems. Applying a 2D analysis for solving the planar task to estimate the stability of slopes remains one of the recent fundamental methods. Along with that, 2D modelling in this area has significantly changed in the past years. A large number of methods are developed for 3D analysis of slope stability based on the concepts of boundary equilibrium and the mechanics of continuous mediums. The first attempt to develop a three-dimensional method for estimating the slope stability dates back to the early 60's of the last century but 3D methods have been used more intensely during the past few years. A number of specialised software products are used that already have program modules for 3D modeling of slope stability, e.g. SoilVisionSystems, Inc. (Canada), TAGAsoft, Inc (USA), Itasca International, Inc. (USA), O.Hungr Geotechnical Research, Inc. (Canada), etc. It can be assumed that the popular companies like GEO-SLOPE Internatioanal, Inc. (Canada) and Rocsiense, Inc. (Canada) will soon develop similar products. Based on this information, a 3D innovation in slope stability assessment in the near future is coming.

Improving the analysis for slope stability assessment from 2D to 3D is a challenging task because of the additional dimension. Modelling the stability in three dimensions is undoubtedly the better and more perspective choice than the 2D models, and the advantages come from the volume analysis:

- In a 3D problem, the possible sliding surface is modelled (in conditions of continuous medium) as a segment of an elliptical surface, while the circular cylindrical surface in a 2D problem remains unchanged. In terms of mechanics, the problem in focus cannot be considered planar, so the 2D task could be solved appropriately in case of significant assumptions only.
- In solving the 2D problem for slope stability assessment, a large number of conditions that must be considered exist (for example, the homogeneity of the massif in the vertical profile and the topographical homogeneity of the slope in the direction of its incidence). But in practice, these factors significantly affect the stability (for example, tectonic leaps intersecting the slope at an angle or cutting the slope in parts when opening roads). These additional components can be taken into account only in 3D models.
- A significant advantage in 3D analysis for slope stability assessment is that these calculations make it possible to predict the development of a landslide or a deformation process not only in depth but also in plane. Besides, these can solve the problem with respect to the location of the most dangerous area of sink or loss of stability. The results are towards a more precise risk assessment with regards to the

spatial activation of a landslide process and for taking well-grounded constructive solutions for landslide prevention.

2D modelling of slope stability has basically used-up its long term potential. When solving the 2D problem, the main ideas and methods for slope stability assessment have been formed in their current state in the mid 60's of the last century and no significant scientific contributions are added nowadays. Only detailed analyses are added of the specifics of the earlier developed methods.

In most of the cases, the graphical presentation of the calculating work scheme for solving the 2D problem for slope stability assessment is significantly simplified and rarely corresponds to the real situation. Anyway, the practical solution of the 2D task is surprisingly successful. The main reasons for that are:

- In 1987, S. Cavounidis showed that the stability coefficient of a slope in 3D analysis was greater than the one in the planar problem. Thus, the 2D method is more conservative and contains significant reserves of stability.
- The mathematical realisation of 2D methods is much more developed in comparison with 3D modelling where there aren't important tools like probability analysis, analysis of the sensitivity, optimisation of the probable slope of sliding, etc.
- 3D methods of numerical analysis are less resistant than 2D calculations, especially when they are based on the consideration of force equilibrium conditions.
- 3D methods for slope stability assessment, as well as 2D models, require additional assumptions for achieving a static determination of the problem. There are several ways to do this: reduce the number of variables, increase the number of equations, or use them both. The introduction of additional assumptions in 3D methods depends on the specific area of application.

The best-known methods for spatial modelling of the slope stability are as follows:

Methods based on the boundary equilibrium theory

The Anagnosti method. In 1969, Anagnosti developed a 3D method for calculating the stability coefficient using potential surfaces with different shapes (Anagnosti, 1969). This method is actually an amplification of the 2D methods of Morgenstern-Price with the inclusion of additional equations for the equilibrium of a thin vertical plate. The main assumption concerns the distribution of the moving forces which satisfies all equilibrium conditions. The results show that the actual coefficient of stability increases more than 50%. Detailed investigations come to the conclusion that the calculated stability coefficients strongly depend on the assumptions concerning the moving forces between the plates. Anagnosti proves that all six equilibrium equations require four times more static assumptions than 2D calculations.

The Hovland method

The method which was developed by Hovland is based on the Fellenius method with additional assumptions in the third dimension (Hovland, 1977). Instead of plates, columns are used in this method. Here, all moving forces between the columns are ignored. The normal and tangential forces acting at the base of each column are obtained as a component of the weight of the column. Another assumption is that there is movement in only one direction and the equilibrium of the system is calculated for this direction.

The 3D stability coefficient is defined as the ratio of the total sum of the holding forces on the sliding surface and the total sum of the driving forces. The computational scheme of the Hovland method is presented in Figure 1.

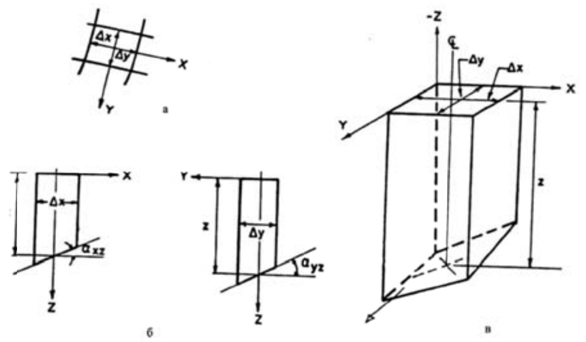

Fig. 1 The Hovland method
a) plan, b) profiles, c) 3D view of the column

It is assumed that the X and Y coordinates are perpendicular to each other in a horizontal plane, the Z coordinate is vertical, and the Y axis is along the side of the movement of the landslide (downstream). The column dimensions on a horizontal plane are determined by the Δx and Δy. Assuming that Δx и Δy are constant for all columns (the net is uniformly scaled), the stability coefficient can be calculated by the expression:

$$F = \frac{\sum x \sum y \left[cA_3 + W_3 \cos\left(DIP\right) tg\varphi \right]}{\sum x \sum y W_3 \sin \alpha_{yz}} \quad (1)$$

$$A_3 = \Delta x \Delta y \left[\frac{\sqrt{\left(1 - \sin^2 \alpha_{xz} \sin^2 \alpha_{yz}\right)}}{\cos \alpha_{xy} \cos \alpha_{yz}} \right] \quad (2)$$

$$\cos\left(DIP\right) = \frac{1}{\sqrt{\left(1 + tg^2 \alpha_{xz} + tg^2 \alpha_{yz}\right)}} \quad (3)$$

$$W_3 = yz \Delta x \Delta y \quad (4)$$

Hovland finds that any ratio between cohesion and the angle of internal friction of the mass may have its own critical surface of sinking and geometry. Studies also show that the ratio of the stability coefficient in the 2D and the 3D case is very sensitive to the strength of the scales, as well as to the shape of the sliding surface, but are relatively insensitive to the width. The results obtained show that the 3D stability coefficient is much higher than the 2D coefficient, excluding some situations where the 3D coefficient could be lower (for example, for unbound soils).

The Chen method and the modified Chen and Chameau method

Chen and Chameau (1983) perform complex studies on the influence of the 3D model on the slope stability using a wide range of different mass properties. They offer two methods for calculating the stability coefficient based on the Spencer method for the 3D model and depending on the nature of the landslide movement. The landslide surfaces are presented in Figure 2 and Figure 3.

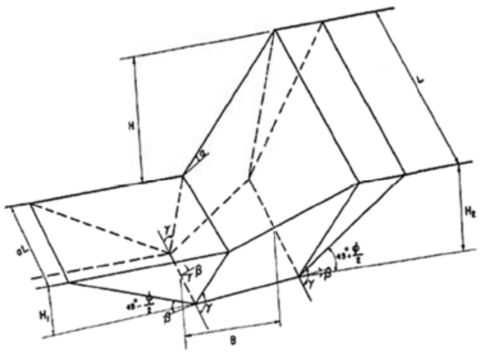

Fig 2 Calculation scheme for block shifting of a landslide body

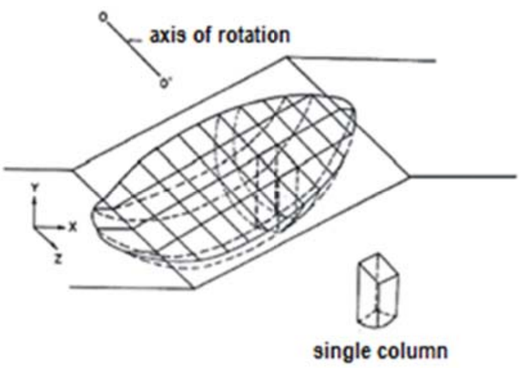

Fig 3 Calculation scheme with a landslide rotating body

Studying the block motion of the landslide in the 3D model, P. Chen makes the following conclusions:

- The 3D stability coefficient is always greater than the 2D coefficient;

- The 3D effect is greater for the slopes with connected masses;

- Staggering weak layers always give a smaller ratio of the stability coefficients obtained by the 3D and 2D models than those for sloping layers;

- In weak rocks, the 3D effect is more pronounced;

- When developing a wedge-shaped landslide, the ratio between the 3D and the 2D coefficient is usually less than one;

- Decreasing the surface slope of the landslide is the cause of a higher stability coefficient.

Based on the calculations for a rotating body, Chen concludes:

- The 3D effect is more significant when the landslide has a shorter length;

- For slanted slopes, the 3D effect is most significant for scales with a high coefficient of cohesion and a low internal friction angle;

- Pore pressure can cause significant three-dimensional effects.

In addition to the 3D modelling and slope analysis methods, there are also a number of methods based on 2D, such as the Hungr (1987) method (the Bishop method, the Yanbu simplified method), the Duncan method (1996), and others. In these methods, there is a tendency for higher values of the 3D stability coefficient.

Methods based on the mechanics of a continuous environment

Software products developed in recent years and based on the final difference method (FLAC3D, Itasca Consulting Group, Inc.) and the finite element method (PLAXIS3D) make it possible to solve the problem of slope stability with methods using the mechanics of non-continuous environments in three dimensional spaces.

An attempt of calculating a 3D slope stability coefficient has been made for the *Mizia* quarry by using the software product SVSlope 3D – SoilVisionSystems (Canada). Figure 4 presents the slope pattern used for the calculations. The properties of the mass are given in Table 1.

Table 1

Number	Density, kN/m^3	UCS,kPa	GSI	IRC	Distribance Factor
1	24.3	55000	25	9	0.7

UCS - Unconfined Compressive Strength
GSI - Geological Strength Index
IRC – Intact Rock Constant

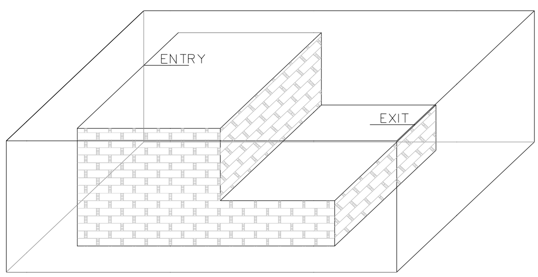

Fig.4 General overview of the model

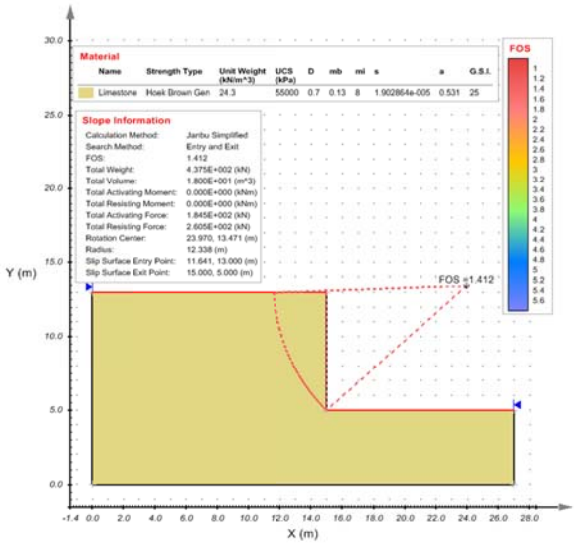

Fig.5 Results of estimating the 2D slope stability by the Bishop method

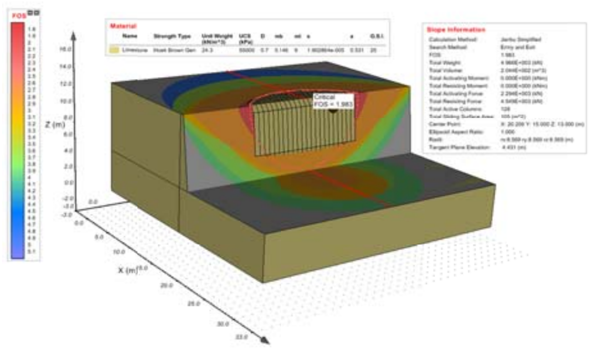

Fig.6 Results of the 3D model by the Janbu method

The following calculation methods were used for the modelling:

- The Yanbu method referring to the group of methods that satisfy the force equilibrium;

- The Bishop method referring to the group of methods that satisfy the moment equilibrium;

- The Spencer method referring to the group of methods satisfying the general equilibrium of moments and forces.

For searching the most dangerous sliding surfaces in the 3D model, the "entry and exit" algorithm is used. The results of the modelling are presented in Fig.5 and Fig 6.

A comparison between the results of 3D and 2D models is given in Table 2.

Table 2
Comparison of 3D and 2D computing results

Type	Estimation method		
	Spencer	Bishop	Yanbu
3D	2.866	1.969	1.893
2D	2.828	1.334	1.412
Ratio 3D/2D	1.01	1.48	1.34

Considering the obtained results, several important observations can be made:

1.The critical sliding surface obtained from the 3D model differs substantially from the sliding surface when solving the plane task.

2.The 3D stability coefficient is higher than the coefficient obtained by the 2D model.

Three-dimensional modelling based on boundary equilibrium methods has a number of significant constraints:

First, three-dimensional methods of analysis are less persistent than two-dimensional calculations. The analysis of the obtained results shows that the area of possible solution is not closed, and the result is significantly different from that obtained by the Entry and Exit method.

Secondly, it is necessary to mention that, in general, solving the slope stability task with the methods of the boundary equilibrium is statically undefined. In particular, using lamella methods, the task becomes statically determined for each element, but the need for accepting different assumptions arises.

Conclusions

Two-dimensional models based on the mechanics of the continuous medium imply conditions for flat stressed condition, which is not applicable for slopes with a complex structure and with a varying lithology and surface relief. The main methods of three-dimensional analysis of the slope stability are the methods of boundary equilibrium and the methods based on the mechanics of a continuous environment.

Several important conclusions can be drawn based on the results of the three-dimensional calculations of the slope stability:

- The values obtained for the slope coefficient by the 3D model are higher than those obtained in solving the planar task.

- When there is a transition from 2D modelling to 3D, it is necessary to take into account the following aspects:

1) The concept of describing the shape of the probable sliding surface is changed. In the 3D model, it is in the form of a segment of an elliptical surface. The circular-cylindrical sliding surface in the volume model can not be its analogue.

2) The forces at the boundary of the lamellae are distributed not in one but in two directions in the 3D modelling of slope stability and boundary equilibrium methods.

3) Three-dimensional methods of analysis are numerically less resistant than two-dimensional calculations.

Regardless of the limitations, it should be noted that in the near future, the implementation of the three-dimensional models in the quantitative assessment of slope stability will be applied in the Bulgarian specialised software products, too, and the methods for three-dimensional calculations will be introduced and updated in the normative documents.

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