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Numerical Methods in Analysis of Slope Stability

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Abstract-Slope stability is an important factor in a design and operation of an open pit mining, quarrying, civil engineering excavation projects and other geotechnical engineering. This paper presents capabilities of a limit equilibrium methods and a finite element method for analysis of slope stability problems in mining. It is described geometry of model, material input parameters, Mohr-Coulomb failure criterion, loading and boundary conditions required to adequately model of slope failure. Two models are analyzed with the finite element method, and the results are compared with outcomes from limit equilibrium method. First model is with 'middle' mesh density and second is with 'fine' mesh density. Also, it was analyzed model with and without pore pressure. Namely, it was assumed process of stabilization of slope slide with dewatering method. Comparison of obtained results will give us answer which method is most appropriate for process of making decisions as well as method for stabilization of slope in pit mines.

Keywords- *finite element method; limit equilibrium method; slope stability; failure criterion; decision making.*

I. INTRODUCTION

Slope stability analysis is an important area in geotechnical engineering. Failure surface is the most important in calculating of a minimum factor of safety (Fs) against sliding or shear failure. The factor of safety for slope stability analysis is usually defined as the ratio of the ultimate shear strength divided by the mobilized shear stress at incipient failure. In mining the design of stable slopes has significant impact on the economics of the open pit mine [2,5,8,9,12-14,16]. Monitoring of slope stability is essential to ensure that the risk to personnel, equipment, buildings and other infrastructure located close to the toe or crest of a man-made slope can be properly managed [10,14,17,19]. Slope stability analysis can be carried out by the limit equilibrium method (LEM), the boundary element method (BEM), the finite element method (FEM) or the finite volume method (FVM).

The limit equilibrium methods include the ordinary method of slices, Bishop's modified method, force equilibrium methods, Janbu's generalized procedure of Slices, Morgenstern and Price's method and Spencer's method. These methods, in general, require the soil/rock mass to be divided into slices. Limit equilibrium methods require a continuous surface passes the soil mass. Before the calculation of slope stability in these methods, some assumptions, for example, the side forces and their directions, have to be given out artificially in order to build the equations of equilibrium [5,8,9,12,13,21].

Recently years, finite element method (FEM) has been increasingly used in slope stability analysis because there is no assumption needs to be made in advance related to the shape or location of the failure surface, slice side forces and their directions. Advantages of this method are what can be applied with complex slope configurations, different types of materials, 2D/3D elements etc. The equilibrium of stresses, strains, displacements and the associated shear strengths in the soil or rock masses can be computed very accurately and fast. This method can give information about the deformations at surface of terrain and then we could be able to monitor progressive failure including overall shear failure [7,10,11,15,20,21].

This paper presents applicability of using ADINA (Automatic Dynamic Incremental Nonlinear Analysis) software (FEM) and SWASE software (LEM) in the analysis of slope stability. Two examples (drained and un-drained condition) are presented and compared to FEM and limit equilibrium method. The aim of this article is to give an insight on the possibilities for computer simulation of physical phenomena slope stability when it makes decisions regarding the selection of appropriate methods for calculation of slope stability factor and selection of the appropriate method of stabilization of slopes.

Hypothesis tested:

Value of the factor of safety obtained by the finite element method and limit equilibrium method do not differ greatly.

II. LITERATURE REVIEW

Early methods of slope stability analysis method have been using slices, i.e. solve the equations of stability. Dealt with this problem by a large number of authors starting with US Army corps of engineers with its engineer manual 2003, Petri and Stein 2012, Nuric et al. 2005, Goldscheider et al. 2010, Nutakor 2012, Martens et al. 2011 consider the different titles, all with the aim of ensuring undisturbed process exploitation of mineral materials. Separate chapters deal with the study and review of current knowledge concerning the calculation of slope stability using method of slices, then monitoring of slope stability in open pit, the impact of water (surface and subsurface) on slope stability, economic feasibility of designing mine in terms of determining the stability of slopes, with detail explained process of building slope in engineering (civil, mine, etc.) and methods of calculation factor of safety and methods for slope stabilization. With the rapid development of information technology (IT) and computer systems have been developed new options for slope stability estimation which could in less time and with greater accuracy provide solutions for a variety of models. For this reasons, the numerical methods for the calculation of slope stability (finite element, boundary element, finite volume, etc) have found a wide application in engineering. Application of numerical methods for the calculation of slope stability has dealt with the authors in their research work, such as: Stacey et al. 2003, Nutakor 2012, Delic et al. 2009, Singh 2011, Nuric et al. 2007 Stead et al. 2001. In order to efficiently apply these methods, implemented through software solutions to the computer, we need to be familiar with the theoretical background of these numerical methods. Many authors have contributed to this subject, such as: Hartmann F, Katz C 2007, Liu GR, Quek SS 2003, Zienkiewicz OC, Taylor RL 2000, Stead et al. 2001.

III. LOCATION OF PIT MINE DUBRAVE

Open pit mine of coal "Dubrave" (Fig. 1) taken middle part of Kreka South syncline.

Figure 1. Location of the pit mine Dubrave (taken from www.google.ba)

This space is limited Spreca River and right tributaries, streams rivers and streams Krivaja. Approved mineable field except the deposit covers and area provided outside of landfill covers an area of 220 ha. Coal bearing area about 185 hectares (the size of the main coal layer) has an irregular shape half-ellipse with the longer axis in the direction of east-west. In the general contour of the field of exploitation developed five lignite layers. For the exploitation of a certain depth are specified three layers, namely: the second layer of roof coal, the first layer of roof coal and the main coal layer. The depth of coal seams, according to the characteristic geologic profiles ranging from 16 m to 32 m, an average of 24 m. Foot wall and overlying coal seams consist of: clay, sands, a mixture of clay and sand and dust-and sand-clay material.

IV. RESEARCH DESIGN OF SLOPE STABILITY

A. Method and algorithm of estimation by finite element method

The applied algorithm can be defined through the following picture (Fig. 2).

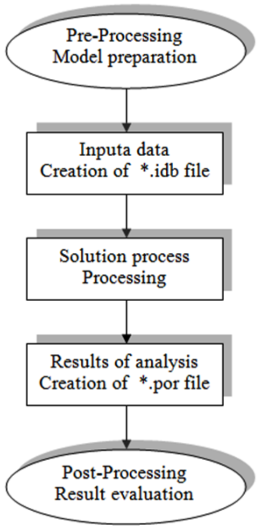

Figure 2. Algorithm applied estimation with software ADINA

The basic step is to develop a model of analysis according to the rules of modeling. Software ADINA offers a pre-processor to create graphical models in a simple way through the steps leading to the desired creation. It was made adequate preparations on the basis of the actual models as necessary simplification in geometry of the model. This is followed by the processing data with the finite element method on selected module, ADINA software. After that, it was started with post-processing, i.e. graphic presentation of estimation results [1]. Each of these three basic steps of the algorithm will be explained in detail below.

B. Procedures for pre-processing and processing of data

Pre-processing includes, as noted above, create a geometric model and input of material properties. In these calculations was used the main program ADINA finite element for high-nonlinear static analysis of body and structure. The plane strain defined by for all steps of analysis and all types of materials [1,10,11]. In the analysis have been used 2-D elements for plane strain shown in YZ plane. Elements typically used in the ADINA program are izo-parameter finite elements. For the calculation of matrix elements and vectors used numerical integration Gauss points. For geometrically nonlinear analysis, the position of the Gauss integration points are constantly changing as the element is subject to deformation and the reaction material and still gives you the integration points. Formulation of material models is given through the geotechnical Mohr-Coulomb's model material, which is used to define small and large displacements. In both cases, the assumed stresses are small. When used in the formulation of large displacement, as in this case, the Total Lagrangian's formulation is appropriate [1,4,6,10,11,20,21].

The failure surface of the Mohr-Coulomb's model can be presented as:

$$f=\frac{I_1}{3}\cdot\sin\varphi+\sqrt{J_2}\cdot\left[\cos\theta-\frac{1}{3}\cdot\sin\theta\cdot\sin\varphi\right] -C\cdot\cos\varphi \quad (1)$$

Where:
φ – the angle of internal friction,
C – cohesion.

$$I_1=(\sigma_1+\sigma_2+\sigma_3)=3\cdot\sigma_m \quad (2)$$

$$J_2=\frac{1}{2}\cdot\left(s_x^2+s_y^2+s_z^2\right)+\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2 \quad (3)$$

$$\theta=\frac{1}{3}\cdot\sin^{-1}\left(\frac{3\cdot\sqrt{3}\cdot J_3}{2\cdot J_2^{3/2}}\right) \quad (4)$$

For Mohr-Coulomb material model six material properties are required: Young's modulus *E*, friction angle φ, cohesion *C*, dilation angle ψ, Poisson's ratio ν and unit weight of soil γ. E and ν have a influence on the computed deformations, but they have insignificant influence on the predicted factor of safety in slope stability analysis. Dilation angle, ψ affects directly the volume change during soil yielding. If ψ = φ, the plasticity flow rule is known as associated, and if ψ ≠φ, the plasticity flow rule is known as no-associated. Required parameters are presented in Table 1.

TABLE I. GEO-MECHANIC PARAMETERS OF MATERIAL

Characteristic	**Material**		
	Sand	***Coal***	***Clay***
E (MN/m^2)	20000	20000	20000
C (kN/m^2)	3.2	16.3	4.2
γ (kN/m^3)	19	20.5	19.2
φ (°)	19	38	14
ν	0.3	0.3	0.3
ψ (°)	19	38	14

Very important influence on slope stability has size and location of the slope, surface water and ground water hydrology [2,5,7-16,21]. If material shear strength of the sliding surface can not resist the shear stresses slope will fails. For values factor of safety *Fs* greater than 1 - the slope is stable, for values lower that 1 - slope is instable. The factor of safety is calculated as:

$$Fs=\frac{\tau}{\tau_f} \quad (5)$$

Where τ is the shear strength of the slope material, which is calculated through Mohr-Coulomb criterion as:

$$\tau=C+\sigma_n\cdot\tan\varphi \quad (6)$$

And the shear stress on the sliding surface can be calculated as:

$$\tau_f=C_f+\sigma_n\cdot\tan\varphi_f \quad (7)$$

$$C_f=\frac{C}{srf}, \qquad \varphi_f=\tan^{-1}\left(\frac{\tan\varphi}{srf}\right) \quad (8)$$

Where:
srf – strength reduction factor.

If there is non-convergence within a user-specified number of iteration in finite element program then we can taken that number as indicator of slope failure. Non-convergence takes place at the same time as slope failure and with an increase in the displacements.

C. Processing of data

Data processing involves a series of steps which are explained below just a few, such as boundary conditions and applied load. The first class of boundary conditions defined by the boundary conditions involving the displacement nodal degrees of freedom in the previous shift was used. In this analysis is applied 'Mass proportional' load. Vector in the direction *i* of this load was calculated using the mass matrix of the entire system of finite elements and some acceleration as follows:

$${}^tR_i={}^tM\cdot d_i\cdot{}^ta_i \quad (9)$$

Where:
d - direction vector,
a - acceleration:

$${}^ta_i=magnituda\cdot f(t)\cdot A_i,\quad i=x,y,z.$$

Magnitude A is defined in function of loading and *f(t)* is time function.

Load proportional weight is usually used to load the model gravity and acceleration in uniform soil. Thus, the gravitational load vector acceleration of gravity during t_{az} =-g. The nonlinear static analysis is first calculated by linear response over the gravity loads only, and is taken into account if there are other loads, such as concentric load or load on the surface, etc. After the application of the load it is possible defined time function and time steps. The main purpose of the time function is to control the variation of load in time [1]. The text above is emphasized that this is a nonlinear static analysis, where the nonlinearity is reading trough the material properties, kinematic assumptions and use special features like for example option 'death/birth' elements. Solving the structural statically equation was carried out with a Full Newton's iteration, with a maximum of 15 iterations. The used algorithm can be given by the following equations:

$$
\begin{aligned}
&{}^{t+\Delta t}K^{(i-1)} \cdot \Delta U^{(i)} = {}^{t+\Delta t}R - {}^{t+\Delta t}F^{(i-1)} \\
&{}^{t+\Delta t}U^{(i)} = {}^{t+\Delta t}U^{(i-1)} + \beta^{(i)} \cdot \Delta U^{(i)}
\end{aligned}
\tag{10}
$$

Where:
${}^{t+\Delta t}K^{(i-1)}$ – tangent matrix of strength based on solution solved et the end of iteration (i-1) at time t+Δt,
$\Delta U^{(i)}$ – vector of incremental displacement in iteration (i),
$\beta^{(i)}$ – factor of acceleration,
${}^{t+\Delta t}F^{(i-1)}$ – consistent vector of force in node at appropriate stress in element with vector of displacement ${}^{t+\Delta t}U^{(i-1)}$,
${}^{t+\Delta t}R$ – vector applied outside loading at time t+Δt.

New matrix of strength always formed at start each new step of loading and each iteration step.

D. Method and algorithm of estimation by limit equilibrium method - The Wedge Method

The method assumes that the sliding mass is composed of three regions: the active wedge, the central block, and the passive wedge. The inclinations of the forces on the vertical boundaries between the zones are assumed. The Wedge Method fully satisfies equilibrium of forces in the vertical and horizontal directions and ignores moment equilibrium. The inter-slice force between the central block and the passive wedge is sometimes assumed to be horizontal. Inter-slice forces must be represented as total forces in the cases where mixed drained and un-drained shear strengths are used. Numerical solutions require an iterative procedure to compute the factor of safety. A factor of safety is first assumed; force equilibrium is then checked. If force equilibrium is not satisfied, a new factor of safety is assumed and the process is repeated until force equilibrium is satisfied to an acceptable degree. In the numerical solution for any force equilibrium method, the side force on the down-slope side of the slice is calculated using the following equation, derived from the equations of vertical and horizontal force equilibrium:

$$Z_{i+1} = Z_i + \frac{C_1 + C_2 + C_3 + C_4}{n_\alpha} \tag{11}$$

$$C_1 = W \cdot \left[\sin\alpha - \frac{tg\varphi' \cdot \cos\alpha}{F} \right] \tag{12}$$

$$C_2 = (U_i - U_{i+1}) \cdot \left[\cos\alpha + \frac{tg\varphi' \cdot \sin\alpha}{F} \right] \tag{13}$$

$$C_3 = P \cdot \left[\sin(\alpha - \beta) - \frac{tg\varphi' \cdot \cos(\alpha - \beta)}{F} \right] \tag{14}$$

$$C_4 = \frac{\Delta l}{F} \cdot [c' - u \cdot tg\varphi'] \tag{15}$$

$$n_\alpha = \cos(\alpha - \theta) + \frac{tg\varphi' \cdot \sin(\alpha - \theta)}{F} \tag{16}$$

The quantities Z_i and Z_{i+1} represent the forces on the upslope and down-slope sides of the slice, respectively, U_i and U_{i+1} represent the water pressure forces on the upslope and down-slope sides of the slice, and θ represents the inclination of the inter-slice forces. If the force on the down-slope side of the last slice is not zero, a new value is assumed for the factor of safety and the process is repeated. When the quantities, U_i and U_{i+1}, that represent water pressures on the sides of the slice are not zero, the inter-slice forces, Z_i and Z_{i+1}, represent forces in terms of effective stress. When total stresses are used, the quantities, U_i and U_{i+1}, are set to zero and the inter-slice forces then represent the total forces, including water pressures. The quantities, U_i and U_{i+1}, can also be set equal to zero for effective stress analyses and the side forces are then the total side forces [5,12].

V. Modelling and Calculation of Slope Stability

Computer simulations were performed for two specific examples (with underground water and without underground water) with ADINA finite element program and SWASE program as limit equilibrium method. Model has slope angle 30° and height of slope 33 m.

A. Modelling and calculation with finite element method

The parameters for FEM model include 2D finite element type, 15 maximum numbers of iterations and convergence factor 0.5, the searching method for 'srf' and using of ATS (automatic time stepping). The geometry of the slope presents in Fig. 3 for variant I of mesh density and for variant II of mesh density in Fig. 4.

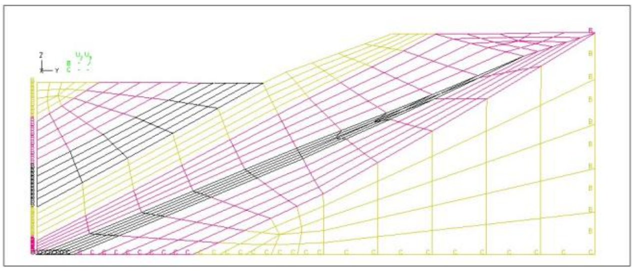

Figure 3. Geometry model of finite elements (I mesh density)

Gravity load is applied to the model and the strength reduction factor (*srf*) gradually increased until convergence could not be achieved. The boundary conditions used on line with fixed z and y translation (all fixity – c) and fixed y translation (b – fixity), what we can see in Fig. 3 and Fig. 4. The first mesh (Model I) uses 322 2D plane strain solid elements and 1357 nodes. The second mesh (Model II) has 1300 2D plane strain solid elements and 5361 nodes.

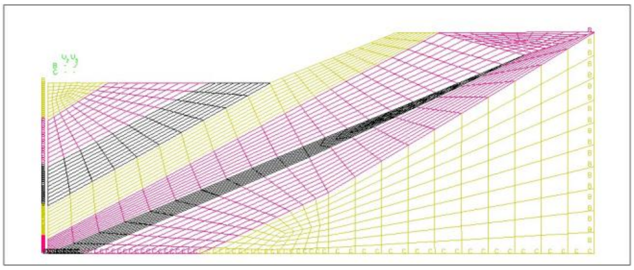

Figure 4. Geometry model of finite elements (II mesh density)

B. *Modelling and calculation with limit equilibrium method*

For limit equilibrium method it was necessary geometry of profile with all layers of materials and geo-mechanical parameters like friction angle φ, cohesion C, Poisson's ratio ν, unit weight of soil γ and reduction factor r_u for underground water. Sliding surface is assumed according to geometry model (contact layer of sand and layer of clay) and in-situ observation. For this method the soil mass have to be divided into tree blocks bottom, middle and top with characteristics of materials in these blocks.

VI. Results of numerical modelling and computer simulation

A. *Results of estimation with finite element method*

Results of plastic strain yy for mesh density type I and un-drained stage are presented in Fig. 5 as the bitmap.

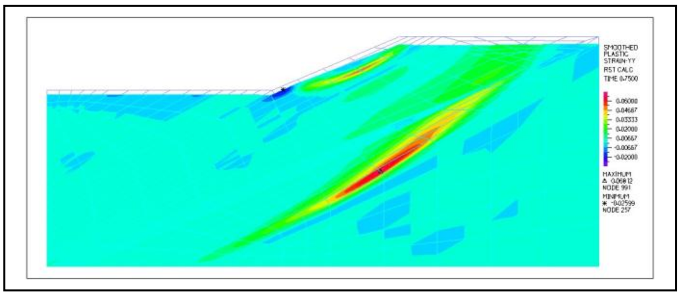

Figure 5. Deformed mesh and plastic strain-yy for model I with underground water

Results of plastic strain yy for mesh density type II and un-drained stage are presented in Fig. 6 as the contour map. Fig. 7 presents plastic strain yy for model without underground water and for mesh density type I. Fig. 8 presents plastic strain-yy for model without underground water and for mesh density type II.

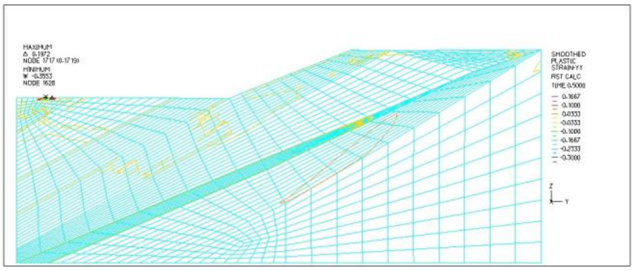

Figure 6. Plastic strain-yy for model II with underground water

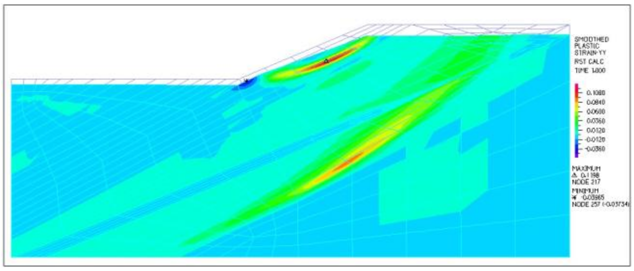

Figure 7. Deformed mesh and plastic strain-yy for model I without underground water

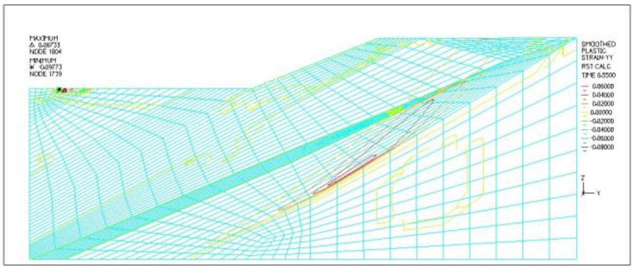

Figure 8. Plastic strain-yy for model II without underground water

Time of no-convergence for model I with underground water is presented in Fig. 9 with obtained Fs=0.9 and Fig. 10 presents time of no-convergence for model II with underground water with Fs=1.0.

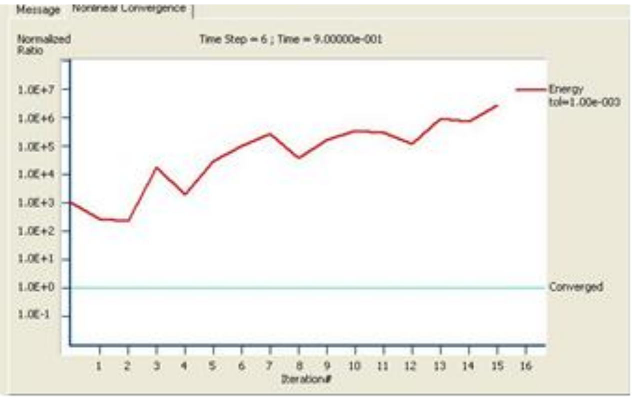

Figure 9. Time of no-convergence for model I with underground water (Time=0.9)

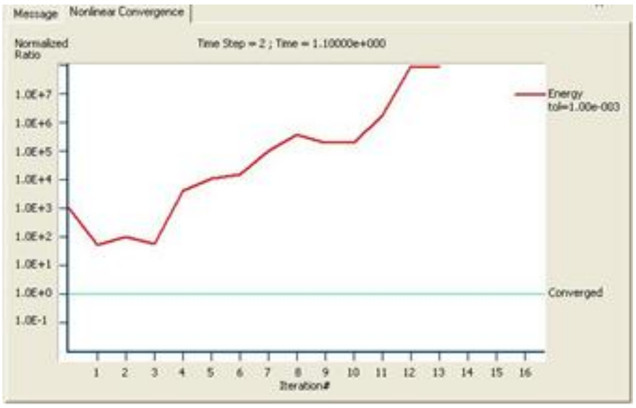

Figure 12. Time of no-convergence for model II without underground water (Time=0.88)

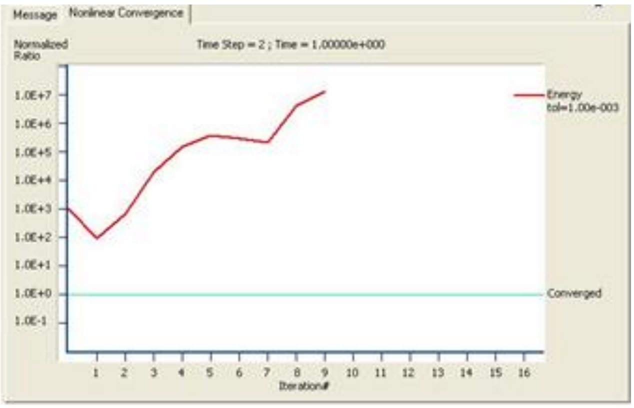

Figure 10. Time of no-convergence for model II with underground water (Time=1.0)

Time of no-convergence for model I without underground water is presented in Fig. 11 with obtained Fs=1.2 and Fig. 12 presents time of no-convergence for model II without underground water with Fs=0.88.

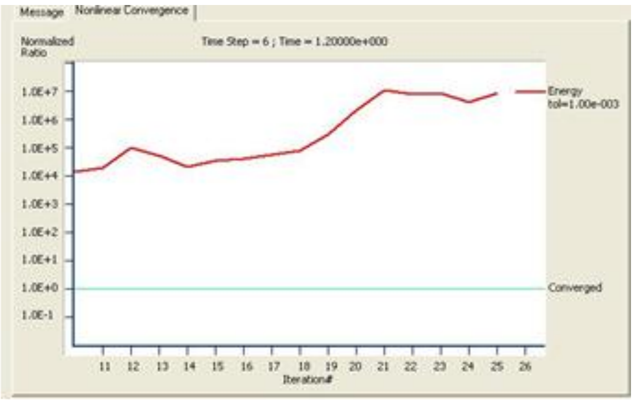

Figure 11. Time of no-convergence for model I without underground water (Time=1.2)

B. Results of estimation with limit equilibrium method

The factor of safety Fs=0.99 estimated by SWASE method is presented in Fig. 13 (for model with underground water) and Fig. 14 presents factor of safety Fs=1.14 for model without underground water. All results are presented in Table 2.

TABLE II. FACTOR OF SAFETY FOR ALL MODELS AND METHODS

	Model					
	Model I (FEM)		***Model II (FEM)***		***SWASE (LEM)***	
	A	***B***	***A***	***B***	***A***	***B***
Fs	0.9	1.2	1.0	1.1	0.99	1.14

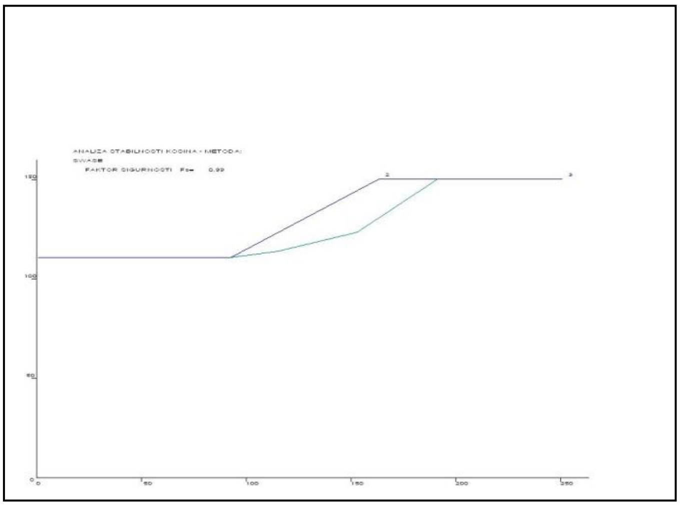

Figure 13. Factor of safety Fs=0.9 for model with ulderground water (SWASE method)

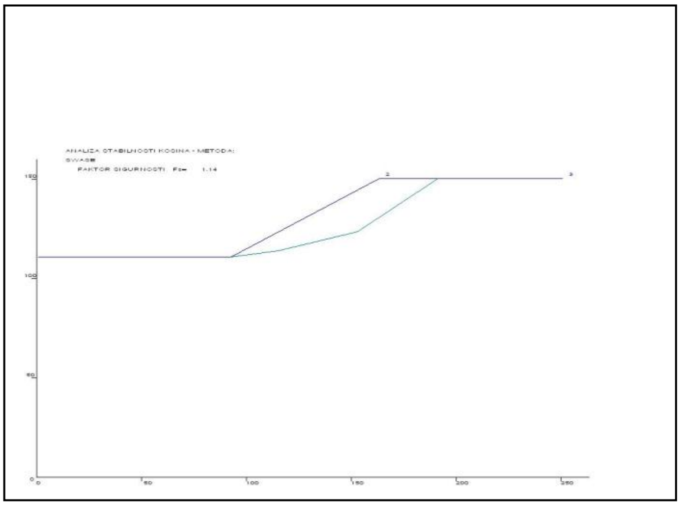

Figure 14. Factor of safety Fs=1.14 for model without uderground water (SWASE method)

VII. DISCUSSION OF RESULTS AND PROPOSED RECLAMATION

For understanding data from Table 2 it is necessary noted next: A is a variant with underground water and B is a variant without underground water. Model I is with variant I of mesh (medium) density and model II with variant II of mesh (fine) density. It is obviously that the factor of safety for Model I A Fs=0.9 is less for 11% then Model II A Fs=1.0, while the factors of safety for Model I B Fs=1.2 is bigger to 9% then Model II B Fs=1.1. Differs in the results for Model I and Model II shows that there are some deviations between ‘medium’ and ‘fine’ mesh density (maximal 11%). Also, differs in the results for Model A and Model B shows that there are some deviations because of existence of underground water.

SWASE method with underground water gave the factor of safety Fs=0.99 that is bigger then Model I A for 10% and less then Model II A for 1%. Also, SWASE method without underground water gave Fs=1.14 that is less then Model I B for 5.26% and bigger then Model II B for 3.64%.

Analyzing the results obtained with these two methods is obvious that the greater overlap in the values obtained with ‘finer’ finite element mesh. The influence of groundwater on slope stability was equally well simulated (with a small value of deviations) both finite element method and limit equilibrium method (similar results of investigation had Y.M. Cheng and C.K. Lau, 2008). Once again it should be noted that the finite element method can take a number of influential factors in the analysis, and thus increase the accuracy of prognostic value and thus affect correctly decision making in subsequent work processes.

VIII. CONCLUSIONS

In most applications, the primary purpose of slope stability analysis is to contribute to the safe and economic design of excavations, embankments, earth dams, and landfills. Slope stability evaluations are concerned with identifying critical geological, material, environmental, and economic parameters that will affect the project, as well as understanding the nature, magnitude, and frequency of potential slope problems. When dealing with slopes in general and slope stability analysis in particular, previous geological and geotechnical experience in an area is valuable.

Finite element method offers great advantages of over limit equilibrium methods because of possibility to use complex geometry of surface and layers, different types of materials, influences of water and other relevant factors. ADINA software is simple to use and give in output accurate results. Trough above mentioned example is presented all usefulness of ADINA software, which results (factor of safety) are compared with limit equilibrium method (SWASE). Model I compared to LEM method gave results which did not differ significantly but Model II gave to us more accurate results compared with SWASE method, because of ‘finer’ mesh density. Proposed hypothesis was discarded in case of ‘fine’ mesh density of finite element.

In this paper is presented only one corrective measurements, drainage (variant B). It is possible to make some more variants trough modelling like change in geometry (assuming some correction measurements, as decreasing of angle slope and decreasing of high of bench), changing time function and time step, different type of failure criterion, 3D modelling, etc. The stable/unstable slopes in a pit mine affect on all mining processes.

Effectiveness and productivity of a mine and the safety of people and equipment depends on their stability, because of that it's clear why they should be paid great attention to this field of research.

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