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THE THREE-DIMENSIONAL (3D) NUMERICAL STABILITY ANALYSIS OF HYTTEMALMEN OPEN-PIT

PRZESTRZENNA ANALIZA STATECZNOŚCI WYROBISKA ODKRYWKOWEGO KOPALNI HYTTEMALMEN W NORWEGII

The purpose of this paper was to perform the 3D numerical calculations allowing slope stability analysis of Hyttemalmen open pit (location Kirkenes, Finnmark Province, Norway). After a ramp rock slide, which took place in December 2010, as well as some other small-scale rock slope stability problems, it proved necessary to perform a serious stability analyses. The Hyttemalmen open pit was designed with a depth up to 100 m, a bench height of 24 m and a ramp width of 10 m. The rock formation in the iron mining district of Kirkenes is called the Bjornevaten Group. This is the most structurally complicated area connected with tectonic process such as folding, faults and metamorphosis. The Bjornevaten Group is a volcano-sedimentary sequence. Rock slope stability depends on the mechanical properties of the rock, hydro-geological conditions, slope topography, joint set systems and seismic activity. However, rock slope stability is mainly connected with joint sets. Joints, or general discontinuities, are regarded as weak planes within rock which have strength reducing consequences with regard to rock strength. Discontinuities within the rock mass lead to very low tensile strength. Several simulations were performed utilising the RocLab (2007) software to estimate the gneiss cohesion for slopes of different height. The RocLab code is dedicated to estimate rock mass strength using the Hoek-Brown failure criterion. Utilising both the GSI index and the Hoek-Brown strength criterion the equivalent Mohr-Coulomb parameters (cohesion and angle of internal friction) can be calculated. The results of 3D numerical calculations (with FLA3D code) show that it is necessary to redesign the slope-bench system in the Hyttemalmen open pit. Changing slope inclination for lower stages is recommended. The minimum factor of safety should be equal 1.3. At the final planned stage of excavation, the factor of safety drops to 1.06 with failure surface ranging through all of the slopes. In the case of a slope angle 70° for lower stages, FS = 1.26, which is not enough to provide slope stability. Another series of calculations were therefore performed taking water table lowering into consideration, which increases the global safety factor. It was finally evaluated, that for a water table level of 72 m the factor of safety equals 1.3, which is enough to assure global open-pit stability.

Keywords: Rockslide, slope stability analysis, numerical methods

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W artykule przedstawiono problematykę oceny warunków stateczności zboczy skalnych wyrobisk odkrywkowych na przykładzie kopalni rudy żelaza Hyttemalmen.

Kopalnia Hyttemalmen, zlokalizowana w północno wschodniej części Norwegii, powyżej północnego koła podbiegunowego, w rejonie miejscowości Kirkenes, prowincji Finnmark, prowadzi wydobycie rudy żelaza metodą odkrywkową przy zastosowaniu techniki strzałowej. Docelowo wyrobisko zostało zaprojektowane do głębokości 100 m ze skarpami o wysokości 24 m, z półkami o szerokości 10 m i kącie nachylenia 80 stopni. Jednostka geologiczna rejonu Kirkenes, w obrębie której eksploatację prowadzi kopalnia Hyttemalmen, nosi nazwę Bjornevaten Group. Jest to rejon geologiczny charakteryzujący się znacznym zaburzeniem strukturalnym, co jest efektem procesów tektonicznych, pofałdowań, zuskokowania oraz przeobrażeń metamorficznych. Utwory Bjornevatan Group to skały osadowo – metamorficzne, zapadające w kierunku z N-S na NW-SE. Bjornevatan Group składa się z sześciu formacji skalnych, a mianowicie: Gamvatn Formation, Fisketind Formation, Bjornefjellet Formation, Pesktind Conglomerate Formation, Hogfjellet Formation, Nosfjellet Formation.

Warunki geologiczne przedmiotowego rejonu, a także stosowana technika eksploatacji w połączeniu z warunkami klimatycznymi skutkuje wysokim stopniem spękania i naruszenia skał w rejonie wyrobiska odkrywkowego. Występujące nieciągłości cechuje duża zmienność rozstawu i przebiegu. Dodatkowo wyodrębnić można nieciągłości główne, których przebieg zarysowuje się wyraźnie na powierzchni odsłoniętych skał. Wpływ nieciągłości głównych na stateczność wyrobiska był przedmiotem analizy przeprowadzonej przez firmę Wardell Armstrong. Kopalnia śledzi ich przebieg wraz z postępującą eksploatacją. W artykule zaprezentowano stwierdzone główne nieciągłości występujące w obrębie wyrobiska odkrywkowego.

W kopalni Hyttemalmen warunki stateczności zboczy determinują mechaniczne właściwości utworów skalnych i systemu spękań, warunki hydrologiczne i atmosferyczne, nachylenie skarp oraz aktywność sejsmiczna wynikająca ze stosowania techniki strzałowej do urabiania złoża. Jednakże istotnym czynnikiem wpływającym na stateczność skarp będzie tu charakter systemów spękań. Spękania, lub ogólnie mówiąc nieciągłości są to płaszczyzny w obrębie utworów skalnych przyczyniające się do zmniejszenia ich wytrzymałości. Stopień redukcji właściwości masywu skalnego w odniesieniu do nieciągłości zależeć będzie od ich długości, rozwarcia, szorstkości, materiału wypełniającego, zwietrzenia oraz orientacji. System spękań utworów skalnych w kopalni Hyttemalmen powiązany jest z charakterem utworów skalnych należących do Bjornevatan Group, a mianowicie znacznego przeobrażenia na skutek procesów tektonicznych i metamorficznych. Dodatkowo eksploatacja prowadzona przy użyciu materiałów wybuchowych prowadzi do propagacji istniejących spękań, a także powstania nowych. Występujące spękania sprzyjają rozwojowi procesów wietrzenia. W warunkach kopalni Hyttemalmen dominuje wietrzenie mechaniczne, co jest efektem występujących tu warunków klimatycznych, a w tym okresowego zamarzania i rozmarzania oraz warunków hydrogeologicznych związanych z poziomem wód gruntowych i zawodnieniem spękań. Szczegółowy opis właściwości nieciągłości charakterystycznych dla rejonu kopalni Hyttemalmen omówiono w artykule.

Dla uwzględnienia charakteru wyrobiska odkrywkowego kopalni Hyttemalmen opracowano model przestrzenny uwzględniający aktualny stan eksploatacji. Do kalibracji modelu numerycznego wykorzystano zaobserwowane przejawy procesów osuwiskowych. Zatem dążono to określenia takich założeń, które pozwolą uzyskać jak najlepszą zgodność wyników z analiz numerycznych z rzeczywistymi warunkami występującymi w wyrobisku kopalni Hyttemalmen. W modelu numerycznym uwzględniono zwierciadło wód gruntowych oraz osłabienie ośrodka na skutek występujących spękań oraz niekorzystnego oddziaływania stosowanej techniki eksploatacji. Uwzględniono także poprawę właściwości mechanicznych skał otaczających (gnejsu) utwory złożowe wraz z rosnącą głębokością. Na podstawie programu RockLab określono wartości parametrów wytrzymałościowych warstwy gnejsu dla poszczególnych głębokości zakładając, że kąt tarcia nie ulega zmianie, a rośnie jedynie spójność. W ten sposób uwzględniono osłabienie warstw wierzchnich wyrobiska odkrywkowego na skutek wietrzenia i naruszenia robotami strzałowymi. Dla tak określonych parametrów skał otaczających i utworów złożowych przeprowadzono obliczenia numeryczne.

Analizy stateczności wykonane zostały w programie metody różnic skończonych FLAC 3D, w którym do określenia wartości wskaźnika stateczności stosuje metodę redukcji wytrzymałości na ścinanie. Rozwój procesów osuwiskowych odwzorowano poprzez zastosowanie zmodyfikowanej metody redukcji wytrzymałości na ścinanie. W artykule zaprezentowano założenia zastosowanej metodyki obliczeniowej.

Wyniki z obliczeń numerycznych odnoszono do zaobserwowanych przejawów ruchów osuwiskowych, które miały miejsce w obrębie analizowanego wyrobiska. W ten sposób weryfikowano przyjęte założenia, a szczególnie wprowadzone do modelu numerycznego właściwości wytrzymałościowo-odkształceniowe utworów skalnych. Dla parametrów zaprezentowanych w artykule uzyskano zgodność wyników z obliczeń

numerycznych z przejawami rzeczywistych ruchów osuwiskowych. Stwierdzono także, że przemodelowane zbocze wyrobiska odkrywkowego, na skutek procesów osuwiskowych charakteryzuje się zadawalającą wartością wskaźnika stateczności. Opracowany model numeryczny wyrobiska odkrywkowego kopalni Hyttemalmen posłużył do dalszych analiz przeprowadzonych dla docelowej geometrii. Analizy numeryczne pozwoliły ocenić stateczność projektowanego docelowego wyrobiska. Przeprowadzono także serię obliczeń numerycznych dla określenia optymalnego poziomu zwierciadła wód gruntowych i wpływu jego obniżenia na stateczność docelowego wyrobiska. W rezultacie przeprowadzone analizy numeryczne pozwoliły sformułować zalecenia odnośnie docelowej geometrii wyrobiska i poziomu zwierciadła wód gruntowych, zapewniających optymalne wykorzystanie złoża i bezpieczną jego eksploatację.

Słowa kluczowe: osuwisko skalne, analizy stateczności zboczy, obliczenia numeryczne

1. Introduction

Slope stability analyses are often performed with numerical methods. The most popular is the shear strength reduction method (SSR). This method is widely applied for two-dimensional (2D) and three-dimensional (3D) stability analyses (Cała, 2007a,b, 2013; Aringoli et al., 2008; Wei et al., 2009; Oh & Vanapalli, 2010; Li et al., 2011). A detailed discussion concerning the advantages and disadvantages of SSR over the limit equilibrium method (LEM) is provided by Cała (2007a).

The purpose of this paper was to perform the 3D numerical calculations allowing slope stability analysis of Hyttemalmen open pit (location Kirkenes, Finnmark Province, Norway). After a ramp rock slide, which took place in December 2010, as well as some other small-scale rock slope stability problems, it proved necessary to perform a serious stability analyses. A short technical visit to the Hyttemalmen open pit by Marek Cała and Michał Kowalski (Report, 2011) established four different reasons for the slope stability problems at the Hyttemalmen open pit, which were identified as:

1. Blasting using considerable amounts of explosives (40 up to 200 tones), influencing the opening and closing of joints, propagation of fractures and shear displacements among blocks. This has an impact on the stability of blocks prone to fall, possibly producing increased water flow and generally decreasing rock mass strength.
2. Water flow and freeze/thaw processes that affect mechanical or chemical suffusion, outflow of joint fillings and change of joint set system.
3. Joint condition which interacts with water flow and freeze/thaw process.
4. Joint system which interact with joint condition, water flow and the freeze/thaw process.

This can be presented on the fig. 1 as a matrix of interactions between all four factors of influence.

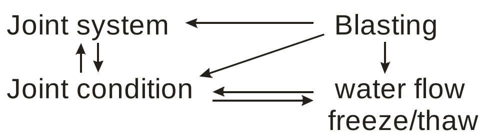

Fig. 1. Matrix of interaction among rock structure/blasting/water

A spatial character of Hyttemalmen open-pit (small size, concave slopes) forced to perform 3D numerical stability analyses (Cała et al., 2006; Cała, 2007a,b). A Finite Difference Code FLAC3D was utilized for this purpose. The 3D numerical slope stability analysis lead to corrections in slope design.

2. Hyttemalmen open-pit – geotechnical site characterisation

The Hyttemalmen open pit was designed with a depth up to 100 m, a bench height of 24 m and a ramp width of 10 m. The rock formation in the iron mining district of Kirkenes is called the Bjornevaten Group. This is the most structurally complicated area (Siedlecka et el., 1985) connected with tectonic process such as folding, faults and metamorphosis. The Bjornevaten Group is a volcano-sedimentary sequence. This formation consists of (SINTEF, 1990):

- metavolcanic (gneisses of quartz, biotite, hornblende),
- iron ore horizontal (meta-sediments),
- meta-rhyilite (thin bench, sporadic distribution),
- bjornevaten gneiss (mica-carrying, quartizeitic),
- bjornevaten conglomerate (polymictic, tectonised).

The rocks generally have a N-S to a NW-SE trend with a cat-northeast dip (Siedlecka et el., 1985). The group consists of six formations, namely: Gamvatn Formation, Fisketind Formation, Bjornefjellet Formation, Pesktind Conglomerate Formation, Hogfjellet Formation, Nosfjellet Formation.

Rock slope stability depends on the mechanical properties of the rock, hydro-geological conditions, slope topography, joint set systems and seismic activity. However, rock slope stability is mainly connected with joint sets. Joints, or general discontinuities, are regarded as weak planes within rock which have strength reducing consequences with regard to rock strength. Discontinuities within the rock mass lead to very low tensile strength. This means that every single point of discontinuance has a reducing effect on the stability of rock masses, so the potential of rock failures becomes prominent.

For the Hyttemalmen open-pit, Wardell Armstrong (2010), pointed out that failure through rock mass is unlikely. The most significant properties of rock in the Bjornevaten are given in table 1 (SINTEF, 1990; Berge & Li, 1968).

TABLE 1

Some properties of rock in he Bjornevaten Group

Rock	Bjornevaten gneiss	Hornblende gneiss	Iron ore
Specific weight [g/cm^3]	2.66	2,79	3.52
Axial point load strength, MPa	12.1	13.0	12.0
Diametric point load strength, MPa	8.4	14.0	-
Strength anisotropy (undesignated)	1.4	1.1	-
Uniaxial compressive strength, [MPa]	170	143	236
Elastic module, [GPa]	31	80	94
Poisson's Ratio	0.12	0.20	0.17

The Mohr-Coulomb criterion is the most common failure criterion described as a linear relationship between normal and shear stresses (or maximum and minimum principal stresses) at failure. The direct shear formulation of the criterion is provided by the following equation:

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

where c is the cohesive strength (kPa), and φ is the friction angle (degrees).

The maximum mobilized shear strength of the rock mass (SINTEF, 1990):

$\tau = 590\ \text{kPa} + \sigma_n \tan 29.5°$

For joints of plane slides the criteria gives the following result:

$\tau = 97\ \text{kPa} + \sigma_n \tan 27.8°$

The failure criteria for the equivalent friction (with effect of waving):

$\tau = 97\ \text{kPa} + \sigma_n \tan 36°$

However, for discontinuities, it's suggested following parameters:

$c = 0,\ \varphi = 36°$

The degree of significance of joints into slope stability depends in general on the following factors (Hoek, 2007):

- discontinuity length (persistence),
- separation (aperture),
- roughness,
- infilling (gouge),
- weathering,
- orientation.

The joint system at the Hyttemalmen open-pit is connected with the geological history of the Bjornevaten Group, which has strong folding and metamorphosis processes. Additionally, excavation work using explosives has caused secondary cracking which exposes rock to weathering, especially mechanical weathering (Freeze/Thaw action). Joint roughness in Hyttemalmen is, in most cases, Smooth Planar. The joint profiles in Hyttemalmen generally vary between Planar Rough and Planar Smooth. The joint alteration on PRO surfaces tend to be slightly altered walls with non-softening minerals (carbonates, sulphides, disintegrated rock etc.). Unaltered, surface staining only. PSM surfaces are generally unaltered with some surface staining.

Analysing stability of rock slope, the most important factor to consider is the relationship between the orientation of discontinuities and of the excavated face (Wyllie & Mah, 2005). Fig. 2 shows main joints from Wardell Armstrong Documentation (2010). Fig. 3 shows the results of geometrical field investigations which demonstrate the character of discontinuities along the exposed benches of the partially developed open pit.

The differences between Fig. 2 and Fig. 3 show how difficult it is to choose the main joint system. The Bjornevaten Group is a volcano-sedimentary sequence. This rock formation is the most structurally complicated area affected by the tectonic process. Rock slope stability in the Hyttemalmen open-pit is governed by joints. Additional, excavation work using explosives has caused secondary cracking, which exposes rock to weathering, especially of mechanical weathering (Freeze/Thaw action). The most important factor to be considered in the Hyttemalmen open-pit, is the relationship between the orientation of discontinuities and of the excavated face.

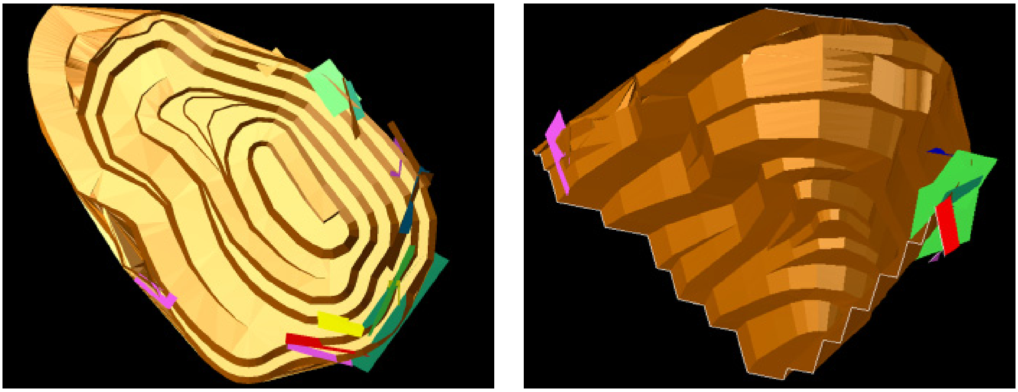

Fig. 2. Joints from Wardell Armstrong Documentation (2010)

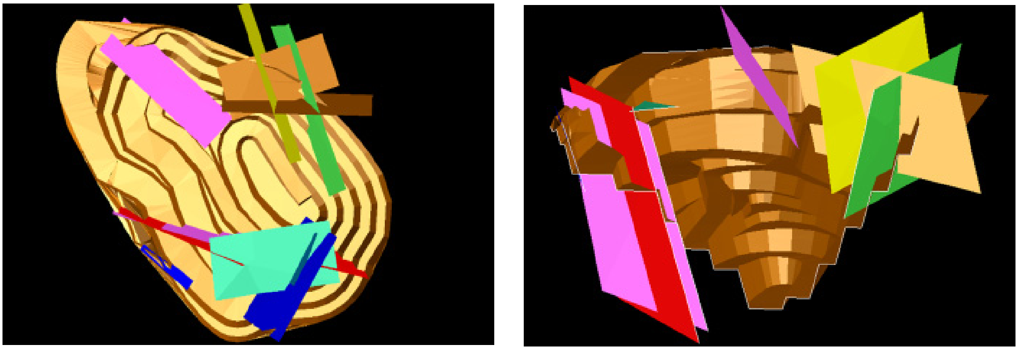

Fig. 3. Joints observed during the excavation

Joints should always be monitored after blasting operations, especially during the spring-summer seasons, when water may flow through joint system.

3. Slope stability analysis with 3D numerical calculations

All the 3D numerical calculations for the purpose of this report were performed with the Finite Difference Code FLAC 3D. The theoretical description of the code is introduced in code manuals (Flac3D, 2008a,b). FLAC3D is a numerical modelling code for the advanced geotechnical analysis of soil, rock, and structural support in three dimensions. FLAC3D is used in analysis, testing, and design by geotechnical, civil, and mining engineers. It is designed to accommodate any kind of geotechnical engineering project where continuum analysis is necessary. FLAC3D utilizes an explicit finite difference formulation that can model complex behaviours not readily suited to FEM codes, such as: problems that consist of several stages, large displacements and strains, non-linear material behaviour and unstable systems (even cases of yield/failure over large areas, or total collapse). The FLAC program uses the explicit, Lagrangian calculation scheme.

The full dynamic equations of motion are used, even when modelling systems that are essentially static. This enables FLAC to follow physically unstable processes without numerical distress. In fact, FLAC is most effective when applied to non linear or large-strain problems, or to situations in which physical instability may occur. This may lead to the identification of several other slip surfaces and provide the user with a full stability analysis of complex geology (or geometry) slope.

All slope stability analyses for the purpose of this report was performed with Shear Strength Reduction Technique (SSR) or Modified Shear Strength Reduction technique (MSSR).

For slopes, the factor of safety (*FS*) often is defined as the ratio of the actual shear strength to the minimum shear strength required to prevent failure. A logical way to compute the factor of safety with a finite element or finite difference program is to reduce the shear strength until collapse occurs. The factor of safety is the ratio of the rock's actual strength to the reduced shear strength at failure. To perform slope stability analysis with the shear strength reduction technique (SSR), simulations are run for a series of increasing trial factors of safety (FS_{trial}). Actual shear strength properties, cohesion (c) and friction angle (φ), are reduced for each trial according to the equations:

$$c_{trial} = \left(\frac{1}{FS_{trial}} \right) c$$

$$\varphi_{trial} = arctan \left(\frac{1}{FS_{trial}} \right) tan\, \varphi$$

If multiple materials and/or joints are present, the reduction is made simultaneously for all materials. The trial factor of safety is increased gradually until the slope fails. At failure, the factor of safety equals the trial factor of safety (i.e. $FS_{trial} = FS$). The detailed description of SSR technique may be found in Lorig & Varona (2000); Cała & Flisiak (2001); Cała (2007a).

The application of SSR for complex geology slopes is usually restricted to the weakest "link" estimation – the part of the slope with the lowest FS. However the Finite Difference Method code FLAC3D provides the opportunity to analyse several slip surfaces using the modified shear strength reduction technique – MSSR (Cała & Flisiak, 2003; Cała et al., 2004).

The water level, was assumed to be 83 m a.s.l. The friction angle for gneiss was assumed as constant, irrespective of depth. The cohesion of the gneiss was, however, assumed to be depth dependant. This can be explained by the metamorphic nature of the gneiss and three-axial stress field in the rock on given depth.

Several simulations were performed utilising the RocLab (2007) software to estimate the gneiss cohesion for slopes of different height. The RocLab code is dedicated to estimate rock mass strength using the Hoek-Brown failure criterion. Utilising both the GSI index and the Hoek-Brown strength criterion the equivalent Mohr-Coulomb parameters (cohesion and angle of internal friction) can be calculated. The GSI index for gneiss in the Hyttemalmen open pit was assumed to be 20, considering field observations. The disturbance factor was assumed to be 1.0 due to poor blasting. Bulk modulus (K) and shear modulus (G) were assumed to be constant and equal respectively K = 1000 MPa, G = 300 MPa. Back analysis of ramp rockslide proved necessary to calibrate the numerical model and also to obtain the correct rock properties. The final mechanical properties assumed for numerical calculations are given in table 2.

TABLE 2

Mechanical properties of gneiss for Hyttemalmen open pit.

Rock	Cohesion, kPa	Friction, deg
Gneiss 1, depth 0÷10 m	67	36
Gneiss 2, depth 10÷30 m	134	
Gneiss 3, depth 30÷50 m	184	
Gneiss 4, depth 50÷70 m	227	
Gneiss 5, depth 70÷90 m	265	
Gneiss 6, depth 90÷110 m	300	
Gneiss 7, depth 110÷130 m	333	

All of the nodes at the bottom surface of the model were fixed. For all four walls of the model, the only displacements in the perpendicular direction to each wall were fixed. Including above conditions into a numerical model, the failure mode of the ramp was simulated. Fig. 4 shows the mas of velocity for the $FS = 1$, the light blue color shows the actual range of the rockslide.

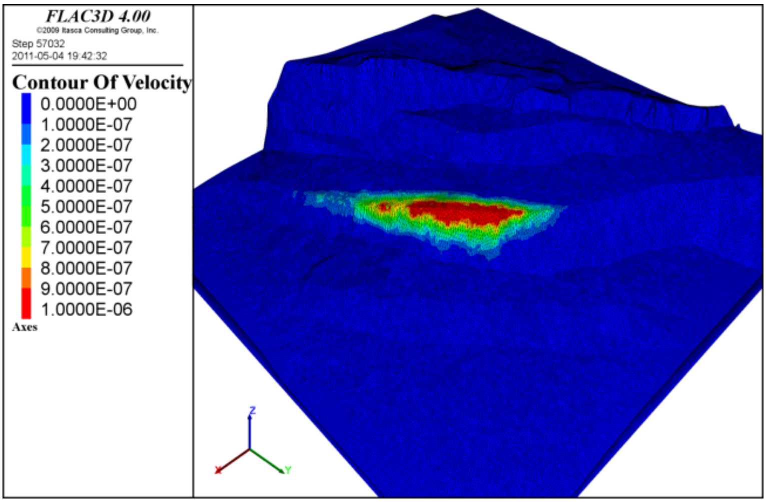

Fig. 4. Rockslide range for the ramp, $FS = 1.00$

Figure 5 shows the geometry of the entire open-pit (with water table) for the state after the ramp rockslide (state for March 2011). The SSR calculations for this state provided the $FS = 1.36$. That amounts to a stable situation, because generally, the minimum factor of safety should be equal to 1.3, which is widely accepted in open pit mining all over the world.

However two or three (depending on open-pit side) deeper levels were planned for further excavation. The final state of the open pit may be observed in figures 2 and 3 (the golden color). Here FS value is equal 1.06. Figure 6 shows the contours of velocity vectors and the failure of the entire open-pit wall, which can be easily observed.

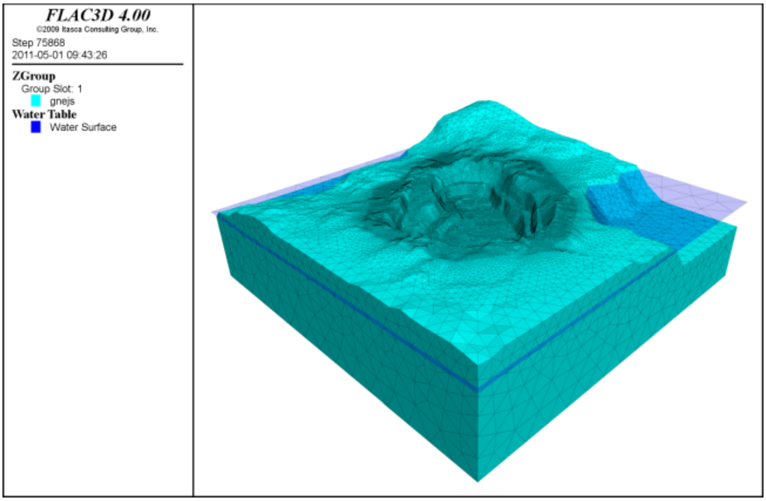

Fig. 5. Geometry of open pit for state after rockslide, March 2011

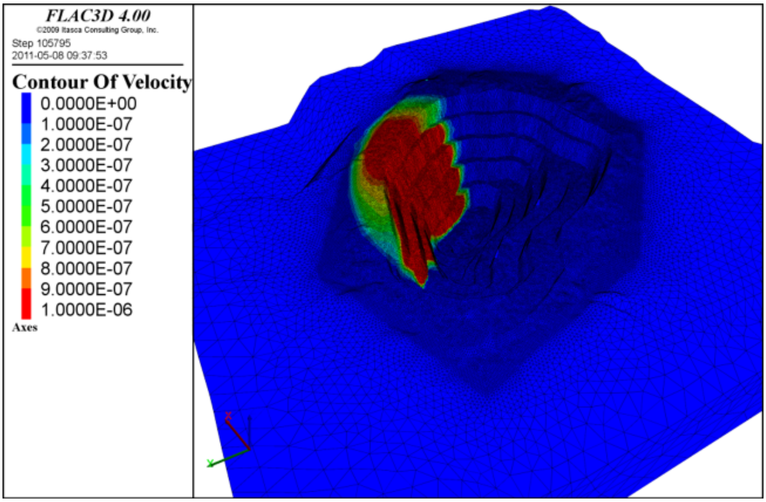

Fig. 6. Rockslide range for final state, *FS* = 1.06, unsafe situation

This is considered to be a minor *FS* value, therefore such an excavation option should not be executed. The normal level of inclination for the Hyttemalmen open-pit level is 80°. It was however proved that for such a slope, global open-pit stability cannot be assured. The change of slope geometry seemed to be unavoidable. The Hyttemalmen open-pit is in a very poor state due to blasting damage, water inflow and the freeze/thaw processes. These seriously reduced the rock mass and joint strength. That's why, two options were analysed to establish whether it's enough to optimise this geometry for the lower stages – decreasing the inclination to 60° and 70° respectively.

Assuming a slope angle of 60° for the lower stages, FS for such a proposition is equal 1.30, which is enough to provide slope stability (Fig. 7). The failure surface ranges of the upper level of the open pit suggests that geometry change improves stability and is satisfactory for providing the necessary safety level.

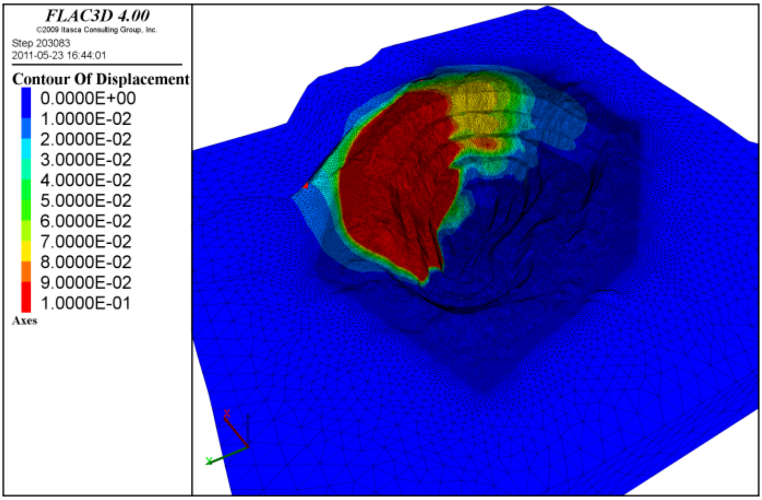

Fig. 7. Rockslide range for final state, slope inclination 60°,
FS = 1.30 safe situation

Unfortunately, a slope inclination of 60° degrees could not be obtained due to technological reasons. The drilling machines (derricks) for blasting holes can only bore with maximal (vertical) inclination of 70°. Other considered options for drilling were discarded. Due to this, the 70° slope inclination of the lower slopes were deeply studied. Unfortunately, *FS* for such a proposition is equal 1.26, what is not enough to provide slope stability. The failure surface ranges through all levels of the open pit, which would suggest that geometry change improves stability, but not satisfactory enough to provide the necessary level of safety.

The 70° slope angle option for the lower stages is however much easier and better to realize. In the meantime, (April-May 2011) a new system of dewatering was applied in the Hyttemalmen open-pit, which allowed for a serious increase in pumping capacity.

This allowed for the following series of calculations to be performed. The object of the analyses was to estimate, what the water level for the option of slope angle 70° for lower stages should be in order to obtain a factor of safety value equal 1.3. therefore, lowering the water table through dewatering improves global slope stability. After a few calculations for different water levels, it was evaluated that for a water table at the level of 72 m, the factor of safety equals 1.3 (Fig. 8). The failure surface is slightly different than in the case of fig. 6, but the safety factor of 1.3 assures the necessary stability level.

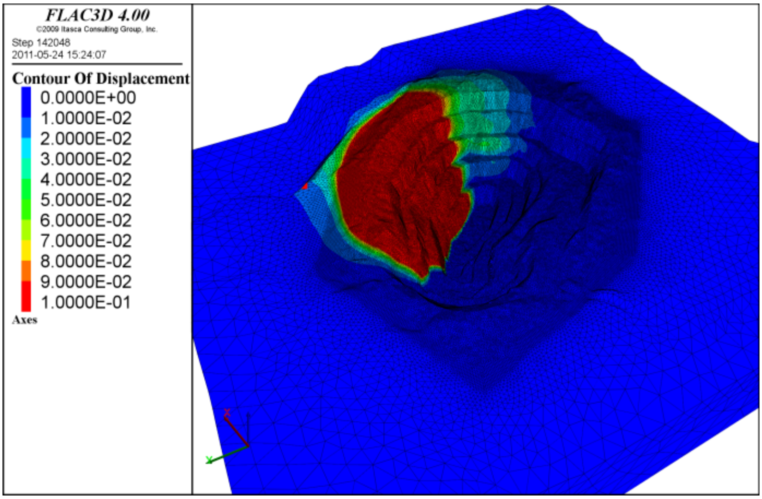

Fig. 8. Rockslide range for final state, slope inclination 70°, water level at 72 m a.s.l, *FS* = 1.30 safe situation

4. Summary

The results of 3D numerical calculations show that it is necessary to redesign the slope-bench system in the Hyttemalmen open pit. Changing slope inclination for lower stages is recommended. The minimum factor of safety should be equal 1.3, which is widely accepted in open pit mining.

At the final planned stage of excavation, the factor of safety drops to 1.06 with failure surface ranging through all of the slopes (Fig. 6). Options for decreasing the inclination of lower slopes to 60° or 70° degrees are not fully satisfactory. In the case of a 60° inclination, safe FS ranges equal a value of 1.3. This option is however not technologically executable due to the limitations of drilling equipment. In the case of a slope angle 70° for lower stages, *FS* = 1.26, which is not enough to provide slope stability. Another series of calculations were therefore performed taking water table lowering into consideration, which increases the global safety factor. It was finally evaluated, that for a water table level of 72 m the factor of safety equals 1.3, which is enough to assure global open-pit stability.

The application of three-dimensional numerical calculations provided optimal open pit excavation. This geometry is a balance between safety and economy and can only be estimated with 3D simulations. 2D calculations do not take the concave configuration of the open-pit into consideration.

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