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EVALUATION OF OPEN PIT SLOPE DEFORMATION USING NOVEL NUMERICAL MODELING SOFTWARE SLOPE MODEL

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN MINERÍA

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EVALUACIÓN DE DEFORMACIÓN DE UNA MINA A CIELO ABIERTO CON EL INNOVADOR SOFTWARE DE MODELAMINETO NUMERICO SLOPE MODEL

A medida que las minas a cielo abierto crecen y se profundizan la estabilidad de sus taludes toma un papel importante y crítico, es por eso que la estimación previa del comportamiento de la roca en cada una de las etapas de la construcción de la mina es crucial para asegurar la estabilidad en el largo plazo. Una correcta estimación permite diseños más empinados, y una mejora en la ratio de remoción estéril/mineral, lo que debería reflejarse en el mejoramiento del VAN del proyecto.

El objetivo de esta tesis es validar el nuevo software Slope Model, para el análisis de estabilidad de taludes, mediante la comparación de este con el software ya validado 3DEC. El fin del proyecto es mejorar el conocimiento respecto el comportamiento de macizos rocosos fracturados.

En la actualidad existen diferentes programas de modelamiento numérico para la estimación del comportamiento de taludes mineros, los cuales van desde el método de equilibrio límite (LE) hasta enfoques matemáticos analíticos más complejos.

La elección de usar un método u otro depende de varios factores como son el nivel de detalle que se le quiere dar a la zona a estudiar, las propiedades de las rocas y la cantidad de discontinuidades presentes. Los métodos utilizados más comunes son los continuos, discontinuos e híbridos. En el marco de los modelos discontinuos se observó que los softwares actuales no son capaces de reproducir la creación y propagación de nuevas fracturas mediante la rotura de roca intacta, hecho que si ocurre en la realidad. Por este motivo se eligió el nuevo software Slope Model (SM), de la empresa ITASCA, el cual sí reproduce dichos fenómenos, muy importantes para el estudio geotécnico del área analizada.

Siendo SM un software en desarrollo, los resultados fueron comparados con un modelamiento usando el software 3DEC.

En la presente tesis se llevó a cabo la representación simplificada de un talud de una mina ubicada en Chile. Utilizando los mismos parámetros de entrada, los resultados de SM representan correctamente los principales desplazamientos, habiendo diferencias en la magnitud de los valores. Los factores de seguridad obtenidos en SM son levemente menores que en 3DEC, lo que concuerda con la teoría ya que SM tiene la capacidad de representar

la rotura de roca intacta y propagación de fracturas, resultando en una menor resistencia de la roca.

ABSTRACT OF THE THESIS TO OPT TO
THE DEGREE OF: Master in Mining
BY: Iván Pedemonte Aguilar
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EVALUATION OF OPEN PIT SLOPE DEFORMATION WITH THE NOVEL NUMERICAL MODELING SOFTWARE SLOPE MODEL

As open pit mines become larger and deeper their slope's stability plays a critical operational role. For this reason, the estimation of rock mass behaviour at each stage of the open pit construction must be undertaken to ensure safe operation as steeper slope designs are implemented to improve the waste/mineral ratio and, thus, the project's NPV.

The objective of this thesis is to validate the new software Slope Model (SM) for slope stability analysis, through the comparison with the validated software 3DEC. The goal of the project is to enhance the knowledge in relation to fractured rock mases.

Currently, there are several numerical modelling software used to attempt to predict the rock slope behavior ranging from the Limit Equilibrium Method (LEM), to complex analytical and mathematical methods.

The selection of one method over another depends on various factors including the rock properties and the number and relevance of discontinuities on the area under study. The most commonly used methods are the continuous, discontinuous and hybrid. In any of these cases, the current software is not able to reproduce the creation and propagation of new fractures through intact rock breakage, which occurs during mining operation. For this reason, the numerical modelling was undertaken using a novel software Slope Model (SM), which reproduces the creation and the propagation of new fractures as mining activities progress.

As SM is still a software under development, the outcomes of the simulations were compared with the results obtained using 3DEC simulations.

The study shows that the factors of safety obtained using SM were smaller than the ones produced by 3DEC, which agrees with the theory as SM has the capability of representing the intact rock breakage and fractures propagation, resulting in a lower rock mass resistance.

DEDICATION

for my Mother

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1. Introduction

Slope stability in open pit mining is one of the most critical factors in the mine's life due to the potentially high impact on the mine operation in the event of slope failure, which may lead to fatal accidents, equipment losses, production delays and even the end of the operations.

The implementation of adequate slope designs, which can ensure long-term slope stability, are paramount for safe open pit operations. However, since rock masses resistive properties decrease over time, real-time monitoring is highly recommended to verify that the implemented design is performing as expected over the long term.

To extend the life of an open pit mine, some operations around the world, such as, Chuquicamata operated by Codelco or Palabora operated by Rio Tinto, have decided to change their mining method from open pit to block caving operations. These decisions were mainly made due to the decrease of valuable mineral grades and the increase in operational costs as the open pit became deeper, the hauling distances longer and stripping ratios higher, among other factors. Such a change in the mining method involves high economical investments related with new equipment acquisition and underground mine design, preparation and development.

An alternative to the transition to underground mining is to extend open pit mine life by increasing the slope angle, which would reduce the stripping ratio and increase the amount of profitable ore, reducing costs and increasing incomes. In both cases, extensive stability assessments have to be undertaken to safeguard the operation, especially, under a more aggressive design.

Currently, there are two main acceptance criteria being used when analysing the stability of a slope: Factor of Safety (FoS) and Probability of Failure (PoF). As it is not possible to precisely determine the rock mass resistance properties, the use of an exact empirical method for the calculation of the FoS and PoF would not be possible. The estimated values are highly influenced by designer's experience and assumptions made with regards to rock properties and fracture networks or tensional state, which results in the FoS being unique for every case (Kanda 2016).

It is also not possible to eliminate all the uncertainties involved in rock mechanics problems; thus, it is paramount to identify the sources of these uncertainties and incorporate them in the proposed design. The uncertainty level can be reduced if the quantity and quality of data used as input in the analysis is of high standard.

Although installation of monitoring devices is the most common source of new information related to slopes' performance, there are also other ways to enhance the representability of the information. For example, the usage of numerical models to forecast the performance of a design, which makes it possible to evaluate the stability of the area under different conditions more precisely. For instance, the application of Monte Carlo analysis leads to better understanding of the effects of the variation of various parameters (Jing 2003).

Currently, there are many modelling software well known in the mining industry (Bobet et al. 2009), such as 3DEC, FLAC, FLAC3D or PFC, which enable the analysis of the slope stability, but none of them is capable of representing the development and propagation of new fractures along the rock mass. Therefore, it was proposed to use the software Slope Model, which simulates the creation, propagation and closure of new and pre-existing fractures. This characteristic represents a significant step change in rock mass modelling (Damjanac et al. 2010).

Since the Slope Model software is not yet field validated, therefore, the creation of the models based on real case scenarios is a necessary step towards its validation as a new tool.

2. Motivation

Empirical failure criteria, experienced based design procedures and observational approaches are still widely used methods in rock engineering. However, there have been significant advances in the development and usage of numerical modelling methods in the assessment of rock behaviour; although, there are still important issues, such as, fracture propagation or groundwater pressure and flow evolution, which are poorly or not represented (Nikolić 2016).

One of the most important factors in rock mechanics is the rock mass fracturing and rock mass anisotropy. These factors have a high impact on the rock mass behaviour and, consequently, on the results of the studies involving rock mass performance, subjected to open pit mining. The characterization and representation of the rock mass fractures plays an important role in understanding the rock mass nature.

Since it is not possible to represent all the fractures and structures within a rock mass, uncertainty and variability are incorporated into any rock slope stability assessment. The origin of the data and their significance has to be well understood to allow for a correct representation of the real behavior through a numerical model as they have high influence on the level of uncertainty and variability of the parameters.

In Slope Model, the lattice method has the potential to represent rock mass fractures and behaviour by allowing the creation of new fracturing within the intact rock, incorporating additional level of understanding of rock mass behaviour as compare to the evaluation made using discrete rock masses (3DEC or PFC). It is believed that this characteristic would better represents the rock mass than its closest alternative 3DEC, which uses plasticity laws to deal with fractures (Itasca 2011).

This feature could also allow the reduction in the level of uncertainty associated with the slope design. This could lead to the implementation of more aggressive designs without compromising safety while reducing the waste extraction, increasing the ore recovery and improving the project's economic results.

This thesis aimed to:

1) Create a numerical representation of a selected area within an open pit mine using the Slope Model software,
2) Evaluate the slope's behaviour and assess the slope´s stability using the Slope Model, and
3) Compare the results obtained using Slope Model analysis with the outcome of numerical modelling conducted using 3DEC over the same representative area.

3. Objectives

3.1 General Objectives

The main objective of this thesis was to determine the applicability of the Slope Model numerical modelling software to represent the rock mass behaviour and compared this representation with the results obtained through the evaluation of rock mass behavior using the validated software 3DEC.

3.2 Specific Objectives

To achieve the main objectives, a series of specific objectives were performed, namely:

- Literature review of numerical modeling tools applicable to open pit slope stability problems.
- Geotechnical data gathering and analysis of its quality and relevance to the development of the model.
- Definition of intact rock types and their properties.
- Development of a representative Discrete Fracture Network (DFN) for the studied zone.
- Recreation and modelling of a representative section from the real slope using Slope Model and 3DEC.
- Analysis and comparison of results obtained from Slope Model and 3DEC.

4. Hypothesis

It was hypothesized that:

1. The application of the new geotechnical modelling software solution, Slope Model, would provide a better representation of the rock mass in comparison to the continuum and discontinuum numerical modelling tools used nowadays to assess slope stability, and

2. The Slope Model modelling tool will:

- Generate improved representations of the fractures present within the rock mass as compared to existing software
- Allow improved risk assessment due to the explicit representation of fractures and their evolution (creation, propagation and/or closure) within the rock mass.
- Enable optimization of slope designs with higher certainty.

5. Research Scope

The scope of this thesis is to compare the results of slope stability analysis representing the same slope section conducted using the software 3DEC and Slope Model (SM), where Slope Model is a software under development and, thus, providing validation of the Slope Model against the known modelling tool.

This study did not intend to:

1. Make an accurate representation of the entire open pit. Instead, it used a simplified representation of the selected area of the mine slope with two main rock types considered in the analysis.
2. Perform a full Discrete Fracture Network (DFN) site analysis; instead, a single DFN was created for the simulated zone.

6. Slope Model and 3DEC comparison, theoretical base and validation.

6.1. SM and 3DEC comparison

Both software, Slope Model and 3DEC, were created based on the distinct element method, which (1) allows finite displacements and rotations of discrete bodies, including complete detachment and (2) recognizes new contacts automatically as the calculation progresses.

While fulfilling the basic requirements, there are differences between 3DEC and Slope Model.

3DEC is a numerical modelling software and is the successor of its 2-dimension version UDEC (Itasca 2011), which simulates the response of discontinuous media (such as jointed rock masses) subjected to either static or dynamic loading. 3DEC treats the rock mass as an assemblage of rigid or deformable blocks. The continuous or discontinuous joints patterns can be generated explicitly or on a statistical basis, leading to a discrete fracture network (DFN) (Jakubowski et al. 2004. Damjanac et al. 2016).

3DEC represents the failure mechanisms of slip and opening of joints and intact-rock failure in tension simulating the new fractures through intact rock using the Laws of Plasticity, which may not produce a realistic representation of the actual fractures propagation.

Slope Model combines the behaviour of intact material with the joints network to numerically simulate rock mass properties, scale effects, anisotropy and brittleness, which cannot be calculated using empirical methods.

SM is based on a more recent approach to numerical modelling called Synthetic Rock Mass (SRM, Pierce et al., 2007), which has been developed based on the distinct element method. SRM is usually realized as a bonded-particle assembly representing brittle rock containing multiple joints, each one consisting of a planar array of bonds that obey a special model, namely the smooth joint model (SJM). The SJM allows slip and separation at particle contacts, while respecting the given joint orientation rather than local contact orientations. Overall failure of a synthetic rock mass depends on both fracture of intact material (bond breaks) as well as yield of joint segments.

Previous SRM models have used the general-purpose codes PFC2D and PFC3D (Itasca 2008a, b), which employ assemblies of circular/spherical particles bonded together (Ivars, 2009; Huaman, 2015). Much greater efficiency can be realized for brittle rock if a “lattice,” consisting of point masses (nodes) connected by springs, replaces the balls and contacts (respectively) of PFC3D (Figure 1.) (Damjanac et al., 2010). The springs, which connect the nodes and represent the rock contacts may break (creation of new micro-cracks), adjusting the strength of the rock mass to give the correct rock mass strength.

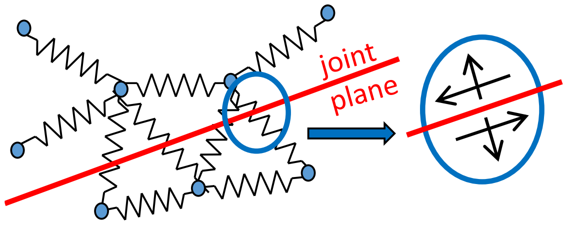

Figure 1. Joint plane through lattice (Itasca, 2011)

The lattice model still allows fracture through the breakage of springs along with joint slip, using a modified version of the SJM. The new 3D program, Slope Model (Itasca, 2010), described in this thesis, is based on such a lattice representation of brittle rock. Slope Model (SM) was designed to simulate rock masses, where overall failure mode is a combination of slip and opening of joints and tension failure of intact-rock bridges.

SM accepts a general DFN (discrete fracture network) consisting of multiple disk-shaped joints that are overlaid on the lattice springs. The DFN model aims to represent two main factors, the transmissivity of individual fractures and the fracture system geometry (Yu et al., 1999; Zimmerman and Bodvasson, 1996).

Fluid flow throughout the jointing network and the rock matrix also is modelled, with the resulting pressures being used to compute effective stresses (hence, failure conditions) on each joint element. Other aspects of fluid/mechanical coupling also are included in the influence of local stress or separation on aperture (hence, permeability) and the direct influence of deformation on fluid pressure. Thus, Slope Model can simulate the time-evolution of the field of pressures and flows due to mining activities, and the resulting influence on stability.

In summary, even though both 3DEC and SM can simulate 3D stability (or instability) of jointed rock masses with fluid interaction, SM allows the simulation of the development of new fractures through the intact rock as the model is being solved and deformation progresses. This feature is the main improvement of SM over existing geotechnical modelling software and has high impact on the analysis of large-scale slopes or slopes subjected to high horizontal stresses with low intact rock strength, where the induced stresses are sufficient to cause significant new fracturing and rock bridges failures.

The use of 3DEC simulations for comparison with SM simulations is justified as 3DEC is a validated DEM method suitable for application to resolve problems with large number of explicit structures dominant in the failure process.

6.2. SM and 3DEC theoretical base

The first step in the analysis is to define how numerical models define the contact detection and the interaction between points. According to literature (Itasca, 2016; R. Taghavi and M. Pierce, 2011; Potyondy, 2012), the contact detection and interaction between points are defined by key factors, such as, spatial searching strategies or interaction forces and stresses.

6.2.1. Contact detection

Contact detection is described as the process of identifying all possible interactions between discrete bodies. Efficiency and robust spatial-searching strategies are key factors for a proper contact detection method. Spatial searching alone may consume more than half of the total computational time for simulations involving rapidly moving objects [Williams et al. 1999].

In 3DEC, prior to contact analysis, the blocks have to be recognized as neighbours which leads to testing for contact: if there is no contact, the maximum gap between the blocks must be determined. Blocks separated by more than a set tolerance level may be ignored. If the distance is less than the tolerance and the blocks are not touching, a virtual contact is created. There is no load on this virtual contact, but it is still tracked at every step in the calculation. In this way, interaction forces act as soon as the blocks touch. The reason is that contact detection is not performed at every mechanical step and thus close points have more possibilities of contact. The contact-detection logic also provides a unit normal vector, which defines the plane along which sliding can occur. This unit normal vector should be updated depending on the direction of the blocks relative movement during the analysis. Extreme cases, such as vertex to vertex, should also be represented (see Figure 2).

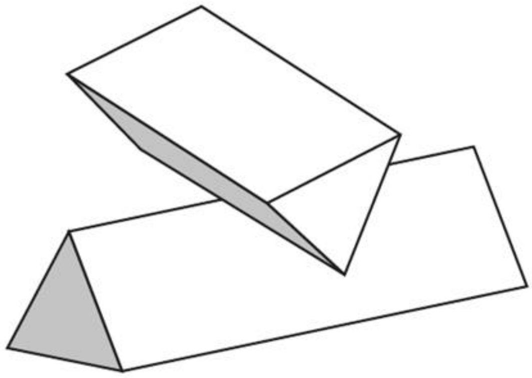

Figure 2. Extreme contact case: vertex to vertex (Taghavi 2011)

The contact type (vertex – edge, vertex – face, edge – edge, etc) has to be detected by the algorithms in order to use the appropriate physical law to represent the contact due to their variability.

In summary, the contact-detection logic must supply, with as little delay as possible, the contact type (if touching), the maximum gap (if not touching) and the unit normal vector.

In Slope Model, the location of contacts or nodes is obtained from the centroids of a packed assembly of spheres created by running the software PFC3D. The resulting array of centroids provides the Slope Model user a built-in data set, avoiding the need to run PFC3D when Slope Model is executed. PFC3D performs the contact detection as follows:

The model domain contains bodies, clumps and faceted walls. Bodies (called balls) are rigid assemblies of constituent pieces, which are used to define the body surfaces (Purvance et al., 2011). A ball is composed of one spherical piece (3D), a clump is composed of multiple spherical pieces, and a faceted wall is composed of multiple, triangular pieces in 3D. The contact model provides methods for delineating interactions between distinct pieces, where the pieces of one distinct body can only interact with the pieces of others. A contact model defines an interaction distance (r_i) within which piece interactions occur.

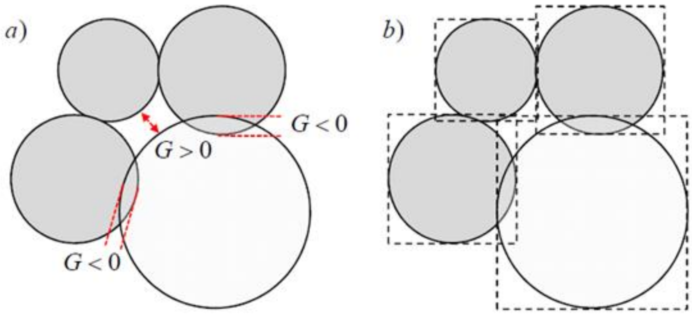

Figure 3. Clump of three gray pieces adjacent to a white ball with r_i=0. a) The gap G being grater and smaller than 0. b) Minimum piece extents are shown as dashed lines (Taghavi 2011).

The minimum distance between pieces of distinct bodies is the gap (G). G > 0 indicates that the pieces do not overlap; the body surfaces do not touch. Interaction occurs when G ≤ r_i for at least one pair of the constituent pieces (Figure 3a.). The process of contact detection uses spatial reasoning to identify all possible interactions. In contrast, contact resolution delineates the specific contact properties based on details of the bodies, their constituent pieces, and their physical/dynamic properties [Purvance et al. 2011].

Each piece is surrounded by a bounding box called an *extent,* which consists of a box aligned with the global coordinate system that contains the entire piece. Each side of the minimum extent touches the piece surface at least once (Figure 3b.). The extent used for the purposes of detecting interactions may be larger than the minimum extent and are not updated during each cycle.

Supposing the situation of different contact models existing for ball-ball, ball-clump, and clump-clump interactions, requires the piece extent dimensions to be enlarged in all directions by at least r_i/2, where r_i is the maximum of all possible interaction distances of contact models involving the particular body type. In case the enlarged extents of pieces belonging to distinct bodies overlap, the condition G ≤ r_i may be achieved and a possible interaction is detected.

Enlarging the extents does not allow for a new interaction to be detected prior to the cycle when G ≤ r_i. Detection prior to interaction may be desirable for the case of accurate contact-model evaluation. The user may choose to enlarge the piece extents further in each dimension by ε ∝ R, where R is the piece radius. Extent enlargement distance is represented by ε: ε>0 indicates that a piece extent is updated when the piece displaces ε/2 in any direction from the position when the current extent was created (Figure 4). The process of updating the extent and the underlying data structures used for proximity detection is termed remapping.

Prior to the first cycle of a simulation, all interactions are identified and the pieces involved in an interaction along with the contact properties are catalogued. During subsequent cycles, some pieces may translate sufficiently so that remapping is required. The remapping frequency depends on the specified enlargement parameters and piece velocities.

When G ≤ r_i, enlargement by ε does not guarantee that interactions will be detected prior to the cycle. PFC 5.0 may place kinematic constraints on the piece displacements to ensure that all possible interactions are detected prior to the cycle when G ≤ r_i. The extent expansion distance δ may depend on both the piece radius and the piece translational velocity. The value of δ is used to constrain the global time step; no piece translates more than their respective δ/2 distances [Purvance et al., 2011].

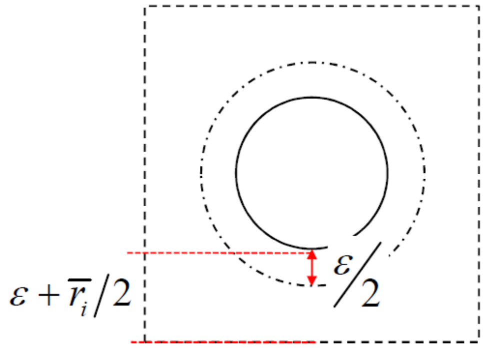

Figure 4. Ball with extent enlargement. The remapping tolerance of ε/2 is shown (Purvance et al., 2011)

6.2.2. Interaction between points

In the case of 3DEC, if a block face is in contact with the *common-plane* (c-p), it is automatically discretized into sub-contacts. The term c-p refers to a plane dividing two blocks, either touching or not. This plane is located in the middle of the smallest distance between two blocks (Figure 5).

For rigid blocks, the faces are triangulated to create the sub-contacts, which are generally created at the vertices of the block face. For deformable blocks, the triangular faces of tetrahedral zones at the block surface contain a number of internal surface nodes, each one has three independent degrees of freedom. In this case, a sub-contact is created for each node on the face.

The c-p logic is only applicable to convex blocks with planar faces. These conditions may be violated if large strains occur with deformable blocks. In practice, the program is used to model a rock mass, where displacements may be large but strains are usually quite small. In these circumstances, the logic will still work. However, in conditions, where block strains become large (for example greater than 1%), the scheme may need to be modified.

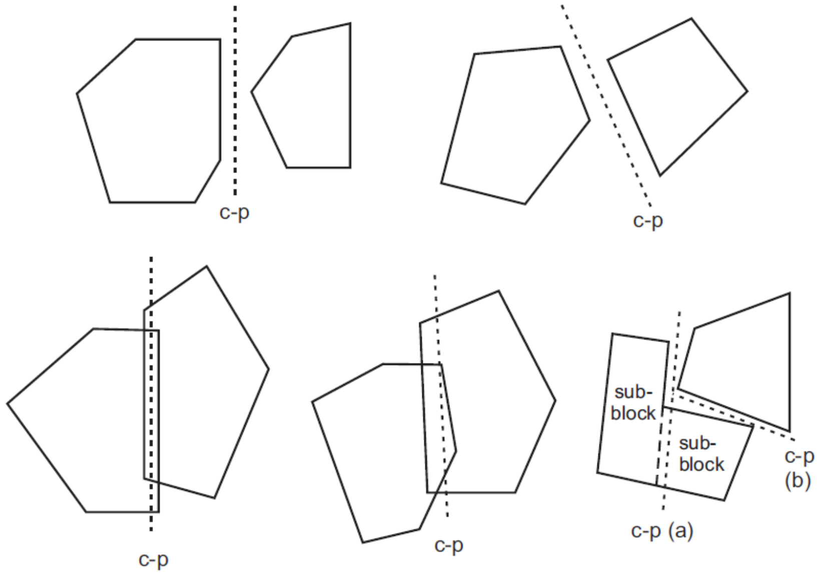

Figure 5. Common-plane between blocks (Purvance et al. 2011)

At present, 3DEC does not allow the use of rigid and deformable blocks to be evaluated at the same time neither for small-displacement and large-displacement relative motion between blocks. In the large displacements cases, a procedure incorporates an automatic relocation of each sub-contact, as the associated vertex crosses a face boundary in the other block. Sub-contact locations and weights are updated every 10 steps. Detection of new sub-contacts and sub-contact type changes are also performed with the same periodicity. This logic also prevents the user from abrupt deletion of a sub-contact whose associated vertex slides out of the other blocks' faces. The existing sub-contact forces are reallocated to ensure a smooth transition between neighbouring states, as in the two-dimensional code UDEC [User's guide. 3DEC, version 5.0].

In Slope Model, to simulate the behaviour of the contact between two rigid circular particles with locally flat notional surfaces the *flat-joint contact* is created (Figure 6).

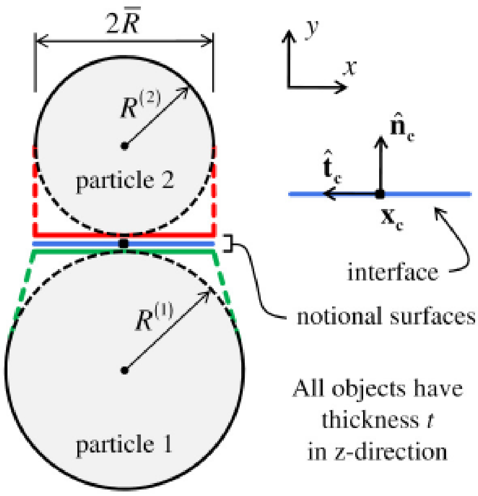

Figure 6. PFC flat-joint contact showing effective interface geometry (Potyondy, 2012)

The interface coincides with a middle surface that remains centred on the contact plane. The contact plane is defined by an origin (X_c) and unit normal and tangential vectors (n_c and t_c, respectively). The x_c is centred within the interpenetration volume of the two particles and n_c points from the centre of particle 1 to the centre of particle 2.

The interface mechanical behaviour is either frictional or bonded and may vary along the interface. In particular, the interface may evolve from a fully bonded state to a fully unbounded and frictional state. Some of the parameters defining a flat-joint contact are the number of segments in contact, the radius multiplier, normal and shear stiffness, friction coefficient, initial gap between segments, bonded or unbounded conditions and bond tensile strength, cohesion and friction angle (Potyondy, 2012).

6.3. SM validation

Detailed SM validation can be found in the Validation Examples report (ITASCA. 2011), where validation tests for mechanical, flow and coupled problems are presented. Table I summarises how different parameters affect the intact rock, the fractures and the rock mass. Those examples concluded that SM outcomes are consistent with the referenced solutions and that SM correctly simulates the mechanical, hydraulic and coupled (hydromechanical) processes that are of importance in the stability of large open pits.

Table I. Summary of validation tests performed with SM (SM validation examples)

	Mechanical		
	Intact rock	**Fracture**	**Rock mass**
Feature measured	Elasticity	Normal and shear stiffness	Stiffness
	Strength	Shear strength	Strength
	Inelastic deformation	Inelastic deformation	

<table>
<tr><td></td><th colspan="3">Fluid</th></tr>
<tr><td></td><th>Rock matrix</th><th>Fracture</th><th>Rock mass</th></tr>
<tr><td rowspan="4">Feature measured</td><td>Steady flow</td><td>Steady flow</td><td>Steady flow</td></tr>
<tr><td>Non-Steady flow</td><td>Non-Steady flow</td><td>Non-Steady flow</td></tr>
<tr><td rowspan="2">-</td><td rowspan="2">Unsaturated flow</td><td>Unsaturated flow</td></tr>
<tr><td>Flow exchange between matrix and fractures</td></tr>
<tr><td></td><th colspan="3">Hydromechanical</th></tr>
<tr><td rowspan="3">Feature measured</td><td>-</td><th>Fracture</th><th>Rock mass</th></tr>
<tr><td>-</td><td colspan="2">Effect of pore pressure on deformation and stability</td></tr>
<tr><td>-</td><td colspan="2">Effect on deformation on pore pressure</td></tr>
</table>

7. Research methodology

To achieve the planned objectives and to prove/disprove the hypotheses, the following methodology was applied:

1. Literature review of numerical modelling techniques. The review analyse rock mass behaviour for slope stability assessments in mining with special emphasis placed on discontinuum methods such as 3DEC.
2. Discussions with the geotechnical engineers from the mine site. Site selection for the study and gathering of data for numerical modelling was undertaken.
3. Description of the evaluated area and the creation of a 3D representation of the zone with a CAD software.
4. Definition of the input parameters and assumptions. Input parameters and assumption related to the rock density, boundary conditions, groundwater pore pressure, principal stresses orientation, joints sets orientation and their friction angle and cohesion, rock types and rock properties were made.
5. Numerical modelling. Numerical models were developed and simulations were made with Slope Model and 3DEC.
6. Interpretation of the results obtained through the simulations were completed. Results were related with the Factor of safety and points velocity and displacements.
7. Conclusions were drawn and recommendation towards further studies were provided.

8. Thesis outline

The thesis is divided into 4 parts related with the usage of numerical modelling tools for the representation of rock masses and their behaviour.

The first chapter is an introduction of the study, presenting the main and specific objectives, the hypothesis, the justification of the research, the scope of work, an introduction to the numerical models and their theoretical base, the methodology and thesis outline.

The second chapter of the thesis comprises an article presented to the World Mining Congress 2018 conference to be held in Kazakhstan in June 2018. It contains a brief literature review of numerical models, the explanation of the SM and 3DEC softwares, presentation of the area of study and the development of the models. The results of the simulations are also discussed.

The third chapter consists of an article submitted to the Journal of Rock Mechanics and Geotechnical Engineering of the Chinese Academy of Sciences. It contains a more extensive literature review, explanation of how the models were build, the slope stability analysis and its outcomes.

The fourth, and final chapter, summarizes the conclusions of the thesis and exposes the possible future ideas to be studied.

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10. Published articles

10.1. Article 1: Novel approach to numerical modelling of rock fractures using Slope Model

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Abstract

Correct representation of rock mass fracturing and its anisotropy are some of the most important factors in rock mechanics engineering studies. The variation of rock properties has a high impact on the rock mass behaviour and, consequently, on the overall slope performance in open pit mines. Even though there have been significant advances in numerical modelling approaches to better understand the behaviour of the rock mass in recent years, there are still areas, such as the fracture propagation in joined medium, which are not fully understood and cannot be examined with the well-known modelling software, such as, 3DEC or PFC. For example, 3DEC representation of the failure mechanisms of slip and opening of joints and intact-rock failure in tension is achieved by simulating the new fractures through intact rock using the Laws of Plasticity, which may not produce a realistic representation of the actual fractures propagation. Slope Model combines the behaviour of intact material with the joints network to numerically simulate rock mass properties, scale effects, anisotropy and brittleness, which cannot be calculated using empirical methods.

This paper presents the outcomes of the numerical modelling of an open pit mine with the Slope Model software and a comparison with the results obtained using 3DEC models.

Keywords: numerical modelling, open pit, slope stability, rock mechanics, rock mass deformations.

Introduction

Rock masses are natural geological materials consisting of different interconnected minerals crossed by randomly distributed defects and structures. These characteristics result in highly variable resistive properties within the same rock mass, which makes the prediction of its behaviour a very challenging task. Nowadays, a wide spectrum of modelling techniques are available to address different rock mechanics problems, from experimental approaches, to analytical mathematical approaches (Nikolic et al, 2016; Cundall and Hart, 1985; Cundall, 1988).

Numerical modelling methods applied to slope stability analyses, have shown good results in representing certain failure mechanisms, such as, toppling or sliding. Information related with structures and fractures in the rock mass is required to identify the most likely failure mode; rock mass fracturing and anisotropy have a high impact on the rock mass behaviour and, consequently, on the results' representativeness of the studies involving rock mass resistive properties.

PFC, FLAC and 3DEC (Itasca 2008) are the most commonly used numerical modelling codes for slope stability analysis. These codes, however, are not capable of representing the propagation and development of new fractures along the rock mass. Therefore, it is proposed to use the novel software, Slope Model (SM) (Damjanac et al. 2010), to simulate existing fractures closure and propagation, and the creation of new fractures. An initial validation of the SM software was performed by Varun and Damjanac (2012). In this validation 52 tests were performed, such as, triaxial compression tests, planar and wedge sliding, toppling, effects of cracks, pore pressure and flow types on rock stiffness and deformation, among others.

In this paper, the stability of the slopes in a phase of a currently operating open pit mine is evaluated using the Slope Model (SM) software. The main focus of this work is to determine whether SM can provide consistent results in the representation of the slope stability by comparing the simulations using SM with the simulations of a 3DEC model.

Background

The rock masses are discontinuous, anisotropic, inhomogeneous, inelastic media that contains numerous randomly distributed zones of initiation of potential failure (Nikolic et al, 2016). Weaker zones can be defined by pre-existing cracks, cavities or natural defects among others. Thus, an exact representation of the rock mass, in terms of its behaviour, is difficult to achieve through simulations and modelling; therefore, simplification and assumptions must be made to enable the assessment of the rock mass properties and behaviour as accurately as possible.

The methods to solve geotechnical problems using numerical models include continuum, discontinuum and hybrids. Nikolic (2016), Jing (2003) and Bobet (2009) explain and compare the various numerical methods. The 3DEC software, a discontinuum Distinct Element Method (DEM), suits for problems in which discontinuities have a great influence on the rock mass behaviour, which is the case for the slope analysed for this work. The simulations obtained using a 3DEC model are used to validate the results of the evaluation undertaken using Slope Model (SM).

3DEC and Slope Model comparison

3DEC is a numerical modelling software and is the successor of its 2-dimension version UDEC (Itasca 2011), which simulates the response of discontinuous media (such as jointed rock masses) subjected to either static or dynamic loading. 3DEC treats the rock mass as an assemblage of rigid or deformable blocks. The continuous or discontinuous joints patterns can be generated explicitly or on a statistical basis, leading to a discrete fracture network (DFN) (Jakubowski et al. 2004) and (Damjanac et al. 2016).

Slope Model (Itasca, 2010) was designed to simulate rock masses, where overall failure mode is a combination of slip and opening of joints and tension failure of intact-rock bridges. The SM software is based on the PFC3D code, which is a Distinct Element code (DEM) that models an elastic/brittle rock as a bonded assembly of spherical particles (Ivars, 2009; Huaman, 2015). SM follows the Synthetic Rock Mass (SRM) method, which combines the Discrete Fracture Network (DFN) with the intact rock properties. The DFN model aims to represent two main factors, the transmissivity of individual fractures and the fracture system geometry (Yu et al., 1999; Zimmerman and Bodvasson, 1996).

SM reproduces the rock mass' fluid flow and mechanical deformation mechanisms based on a lattice representation of brittle rock. The lattice is created by the replacement of the particles or balls created within the code PFC3D with nodes as shown in Figure 1. (Damjanac et al., 2010). The springs, which connect the nodes and represent the rock contacts may break (creation of new micro-cracks), adjust the strength of the rock mass to give the correct rock mass strength.

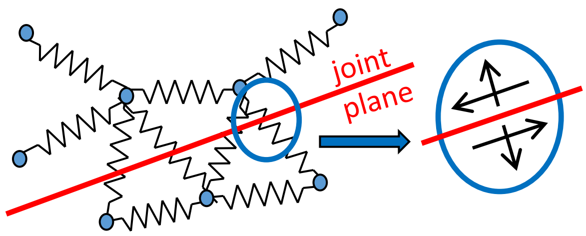

Figure 7. Joint plane through lattice (Itasca, 2011)

There are several differences between 3DEC and SM. Even though they both can simulate 3D stability of jointed rock masses with fluid interaction, SM allows the simulation of the development of new fractures through the intact rock as the model is being solved and deformation progresses. This feature is the main improvement of SM over existing geotechnical modelling software. This feature has high impact in the analysis of large-scale slopes or slopes subjected to high horizontal stresses with low intact rock strength, in which cases the induced stresses are sufficient to cause significant new fracturing and rock bridges failure.

The contact detection and interaction between points are defined by key factors, such as, spatial searching strategies or interaction forces and stresses (Itasca, 2016; R. Taghavi and M. Pierce, 2011; Potyondy, 2012). Detailed SM validation can be found in the Validation Examples report (ITASCA. 2011), where validation tests for mechanical, flow and coupled problems are presented. Those examples concluded that SM outcomes are consistent with the referenced solutions and that SM correctly simulates the mechanical, hydraulic and coupled processes that are of importance in the stability of large open pits.

The use of 3DEC simulations to be compared with SM simulations is justified as 3DEC is a validated DEM method suitable for problems with large number of explicit structures dominant in the failure process.

Case study

The validation of SM was conducted based on the data from a sector of a copper open pit mine located in Chile. The process started by the definition of a Discrete Fracture Network (DFN) representing all the major structures in the rock mass. The structural data comes from implicit or explicit information, detailed in this section.

The obtained data related with the discontinuities of the model consisted of a set of major structures with spacing greater than 15[m] and a set of minor structures with spacing lower than 0.35[m]. Major structures were used to create the DFN, and the minor structures were accounted implicitly by the GSI factor in 3DEC with the purpose of reducing the computational requirements. Major faults were included in the models as deterministic structures.

Figure 2 shows an overview of the models created with 3DEC (left) and SM (right). In both cases a 30[m] wide, 1,146[m] long and 800[m] high section was analysed. In Figure 2, primary (blue) and secondary (green) rock are differentiated in the 3DEC model, as well as its contact surface in the SM model. On the latter model a dark green and yellow surfaces delimitate the topographies after excavating the overburden material.

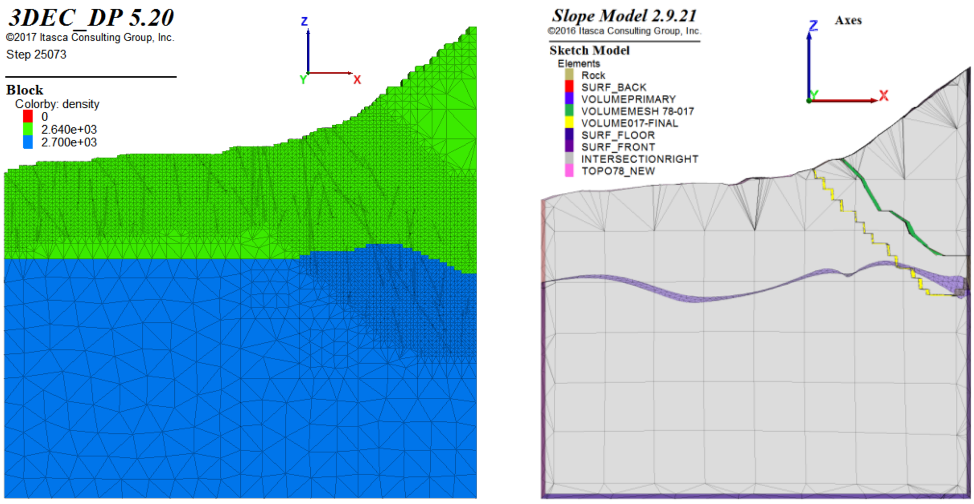

Figure 8. Models created with 3DEC (left) and Slope Model (right). Geometries are imported from a DXF file created with CAD software

The case study represents a 2D mine slope with competent rock properties. For this type of studies, limit equilibrium methods (LEM) are usually preferred as they are faster and simpler to create. On the other hand, LE methods, such as Slice, do not take into consideration the effect of all the discontinuities on the results and analyse only the initial and final slope stability state. 3DEC and Slope Model can simulate, to some degree, those effects, eventually achieving more realistic results, specially Slope Model which can simulate the propagation and interconnection of pre-existing and new discontinuities by breaking the rock bridges if stresses are great enough, resulting in a more detailed strength path.

Methodology

3DEC and SM aim to analyse the same parameters such as slope displacement, among others, and acceptability criteria's such as Factor of Safety. It is important to have in mind that the methodology to achieve the results are very different as each software has a specific way to solve the numerical models.

For the case of SM, the geometry of the studied area is directly imported from a DXF file (Figure 3.). In the DXF file, all the surfaces, volumes and discontinuities have to be defined in separate layers for their definition in SM. Discontinuities with the same properties can be in the same layer. The properties of friction, cohesion and stiffness of the joints, DFN and its properties, boundary and stress conditions, rock types, volumes to be excavated and model resolution, are then defined.

In 3DEC, the model and all the properties and parameters are introduced with the specific 3DEC code; the pit boundary surfaces of each step of the sequence are created using the same DXF files used in SM.

Once the models were created, excavations from the pre-mining surface to the actual pit and, then, to the final pit were simulated, according to a logical sequence, to match the final tensional state of the slope. Before the excavations begin, the models were solved until reaching a stable solution, to assure that the initial deformation and tensional state of the models were the same after settling down. The stresses were reset and the simulation of the excavations began.

For both models, the resolution was assumed to be 5 nodes between two neighbouring discontinuities; an Itasca recommended resolution to allow the rock mass to behave in a realistic manner between fractures. One of the most important factors for the creation of the DFN is the fracture frequency or P10 value. The P10 was assumed to be 0.066, which means 6.6 fractures every 100[m], which translates into a resolution of 3[m] (nodes separated 3[m]). The parameters for the statistical creation of the DFN discontinuities were: dip 83º, dip direction (DipDir) 151º, K factor (Fisher) 65 and disc diameter 79-81[m]. The latter parameters were obtained from a geotechnical structural report, except the disc diameters, which were assumed based on the size of the model.

The DFN and deterministic joints were created in 3DEC and imported into Slope Model, as the stochastic origin of the DFN will create a different distribution of fractures if it was created with SM. SM has its own tool for the creation of the DFN.

The rock matrix to fill the volumes between structures defined by the DFN was modelled as an isotropic linear elastic material. Two materials were represented in the model: the primary and the secondary Quartz-Monzonite Sericite. The input rock properties considered were: intact rock density, Hoek-Brown intact rock material constant (m_i), UCS (σ_{ci}), elastic modulusE_i), Poisson's ratio ν_i), GSI and D factor (Table I).

*Table II. Rock parameters. * GSI and D factor were only used in 3DEC*

GEOTECNICAL UNIT	Environment	$\rho[t/m^3]$	mi	σci [Mpa]	Ei [Gpa]	νi	GSI*	D*
QUARTZ-MONZONITE -SERICITE -QM QS-	Primary	2.7	20	160.89	57.27	0.29	45	0
	Secondary	2.64	19	80.74	38.28	0.24	55	0

Figure 9. DFN (black) and deterministic joints (red)

The D factor is considered 0 in 3DEC as SM cannot use this parameter.

The discontinuities were divided into two groups: stochastic and deterministic (Table II.). The former corresponds to the DFN discontinuities while the later were obtained from the mine's structural model. To save computational memory, the DFN was applied 200[m] below the surface with the 3[m] resolution between nodes. The rest of the model was set at a resolution of 900[m].

Table III. DFN and major faults properties

Joints	cohesion	Friction º	residual cohesion	residual friction	normal stiffnes	shear stiffnes	dilation angle	tensile strenght	residual tension
DFN	1.00E+05	25	0	25	2.00E+10	5.00E+09	5	0	0
Major Faults	7.50E+04	25	0	25	2.00E+10	5.00E+09	5	0	0

Comparison and analysis

The design of the slope, the rock properties and the discrete fracture network used resulted in a slope with a multi bench failure on the top of the pit, effect reproduced in 3DEC and Slope Model. The planar failure was caused by the slide of pre-existing structures and rock bridges breakage.

The units related with velocities and displacements shown in SM and 3DEC figures are, respectively, in meters per second and meters.

Both software represented the minor displacements caused by the deterministic joint "Falla8_S90-80E" (black line in Figure 4. and 5.), and a bigger planar slide created by the intersection of the previous joint with a daylight joint from the DFN (yellow line in Figure 4.), affecting 5 benches. Figures 4. and 5. represent the velocities in 3DEC and Slope Model, respectively.

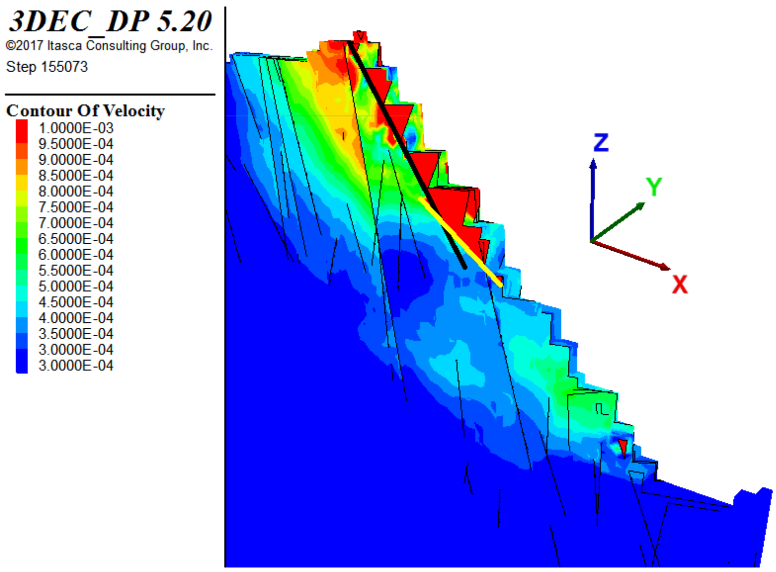

Figure 10. Total velocities in 3DEC

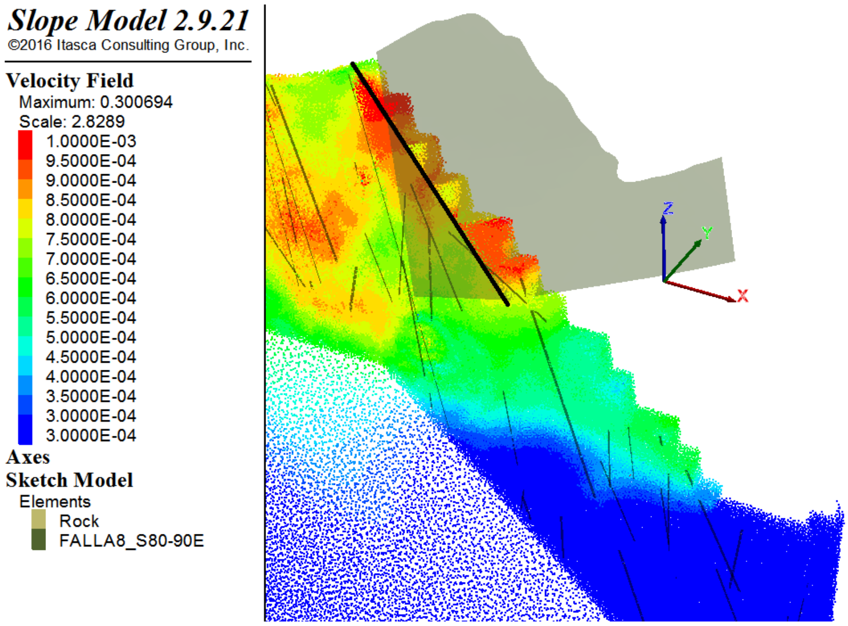

Figure 11. Total velocities in Slope Model

The Strength Reduction Factor (SRF) contour is calculated in both cases. This method consists of reducing the strength parameters by a certain factor until the model becomes unstable. To reach the smallest factor, which creates instability, the bracketing method is used. This factor is equivalent to the Factor of Safety (FoS). 3DEC uses a function (FISH) to compare the nodes velocity with a threshold value concluding in a SRF value for each node.

The SRF in 3DEC and SM showed a good correlation with their respective velocities being inversely proportional, with lower SRF in zones with higher velocities (Figure 6. and 7.). The resulting SRF or FoS contour from Slope Model had lower values than 3DEC as the latter does not take into consideration the breakage of intact rock and propagation of the existing fractures. This is represented in the Figure 8, which shows the micro-cracks due to the breakage of the rock bridges generated during the resolution of the model. The colour of the fractures indicates the broken percentage of a particular flat joint (33% in red, 66% in pink or 100% in blue), allowing to see where new cracks are initiating and propagating.

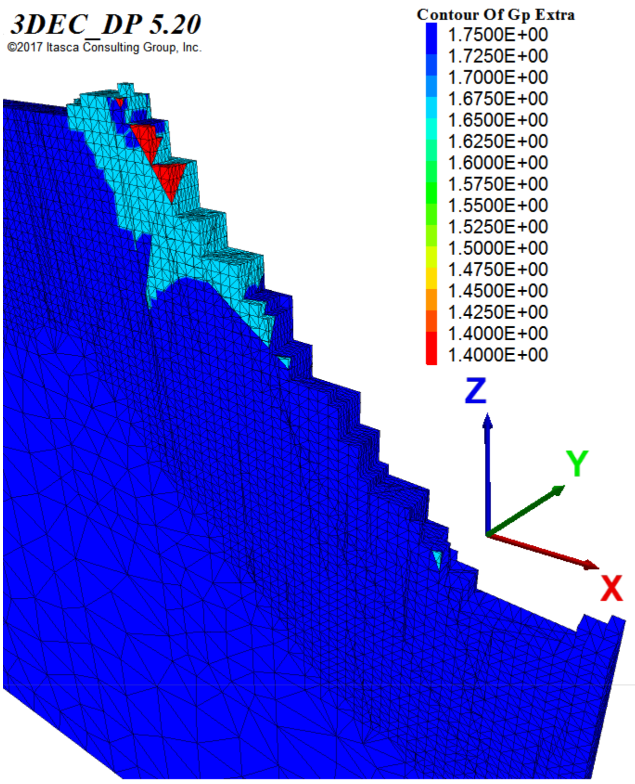

Figure 12. Factor of safety contours in 3DEC

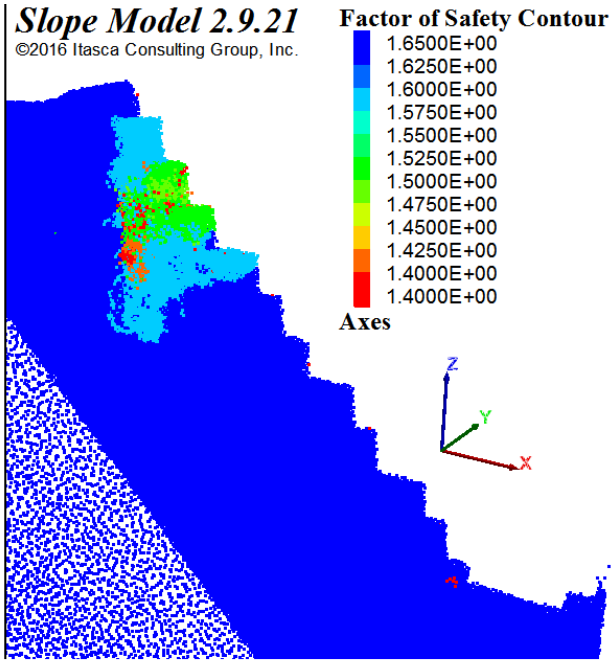

Figure 13. Factor of safety contours in Slope Model

The micro-cracks and displacements (Figure 8) simulated during the initial stabilization of the model are reset to cero before the excavations began. Micro-cracks generated in the interaction between the different resolution volumes are not taken in consideration. Figure 8 glimpses a concentration of micro-cracks at the toe of the pit as well as in the middle of the pit. Only few cracks are 100% broken, not being enough to create a bigger slide.

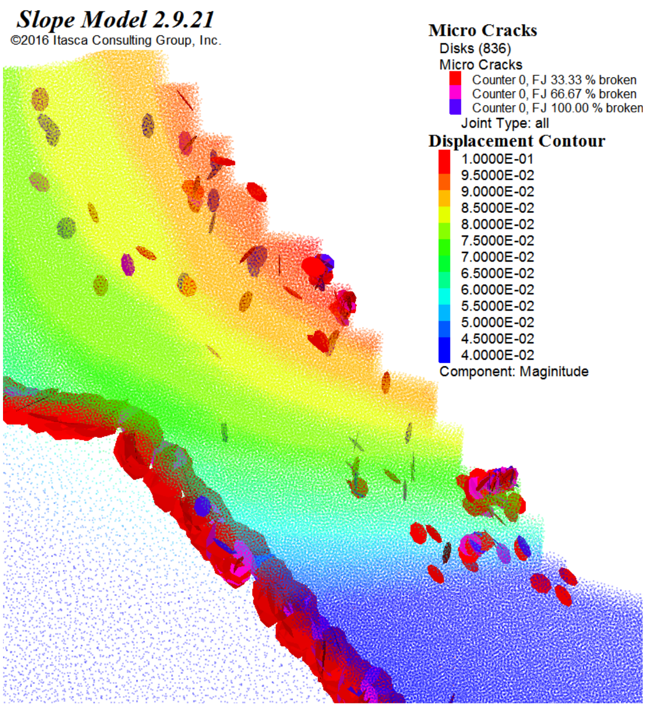

Figure 14. Micro cracks generated in Slope Model after model relaxation

Conclusions and recommendations

The SRF values obtained using the Slope Model modelling were between 1,25 and 1,6 while using 3DEC resulted in the values being 1.7. The lower values of SRF for SM are due to the breakage of the rock bridges between structures resulting in a lower resistance of the rock mass.

The visualization of micro cracks using SM gives extra information about the location of where tension cracks might initiate. The geometry and tensional state of this specific case are not sufficient to create a major slide even though the cracks show the areas where major fractures can initiate.

The analysis shows that special consideration needs to be given to the non-daylight joint “Falla8_S90-80E” as its location makes it very sensible to interactions with minor daylight faults, creating a larger failure surface, as occurred in the presented study. Therefore, intensive joint monitoring, such as drill hole sample analysis, should be made in this area to identify small faults, which can have a significant influence on the rock mass behaviour.

The study shows that Slope Model can represent the rock mass behaviour with more detail than 3DEC and it is suitable for slope stability analyses in fractured rock masses.

The results of this study should be validated against field data as the mining operation progresses and reaches the final pit. It is also recommended, that the analysis of real data using Slope Model modelling should be compared with the results obtained using conventional methods of analysis or well established numerical modelling software, such as, 3DEC.

Acknowledgement

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10.2. Article 2: Slope Model - An advanced numerical modelling approach for rock fractures representation in slope stability analysis

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Keywords: numerical modelling, open pit, slope stability, rock mechanics, rock mass deformations.

Abstract

For many years, empirical failure criteria, empirical designs procedures and observational approaches were widely used methods for rock engineering. Since numerical models started to be used, there have been significant advances in their usage for rock behaviour assessment; however, there are still important issues, such as fracture propagation or groundwater pressure and flow evolution, which are not fully represented during numerical modelling of rock mass behaviour.

While numerical modelling software aims to reproduce the rock mass behaviour as accurately as possible, there exists a margin of error, mainly due to the lack of knowledge of the physical behaviour of rock fractures and fractured rock masses.

One of the most important factors in rock mechanics engineering is the rock mass fracturing and its anisotropy. These factors have a high impact on the rock mass behaviour and, consequently, on the results of the studies involving rock mass strength. For that reason, the characterization and representation of the rock mass fractures plays an important role in representing the rock mass nature.

Although many codes can simulate 3D stability of jointed slopes with fluid interaction, the novel software Slope Model allows the creation and propagation of fractures through intact rock. It is believed that this characteristic of the Slope Model would provide more detail representation of the rock mass than the currently used 3DEC software, which uses plasticity laws to deal with fractures

In this article, an initial validation of the Slope Model software is undertaken. The slope stability analysis using Slope Model is compared with the results obtained using 3DEC. The study shows good correlation between Slope Model and 3DEC with lower values of FOS obtained with Slope Model pointing towards the breakage of the rock bridges between structures (new fracture creation) and thus lower resistance of the rock mass.

Introduction

Slope stability in open pit mines can be analysed by empirical methods, equilibrium methods and numerical methods. Numerical methods are able to examine the rock mass behaviour and interaction of rock mass with various factors, such as, ground water or major discontinuities.

The behaviour of the rock mass has been studied for many years yet it is still not fully understood mainly because the rock mass is Discontinuous, Inhomogeneous, Anisotropic and Not-Elastic (DIANE) medium [Harrison, et al 2000].

Simulations of slope stability using numerical modelling tools have shown good results in representing certain slope failure mechanisms, such as, toppling or sliding in well-defined environments.

Fractures, and especially their propagation method, have great influence on slope stability analysis [Sainsbury, 2012; Vyazmensky, 2008; Flores, 2005].

Numerical modelling based on linear elasticity allow to analyse only the initial and final states of the slope designs, regardless of the previous phases, which may cause high levels of uncertainty and present a risk of unsafe designs. Enhanced numerical modelling methods improve the understanding of the rock properties during all the excavation process, making possible to assess the stability in a better way [Jing, 2003].

Nowadays, the software used by the industry for slope stability analysis, such as FLAC/FLAC^{3D}, PFC/PFC^{3D} or UDEC/3DEC (Itasca 2008), is not capable of representing the propagation and development of new fractures within the rock mass. Therefore, it is proposed to use the new software Slope Model to simulate fracture closure as well as propagation and creation of new fractures [Damjanac et al. 2010].

Slope Model (SM) was developed by ITASCA and CSIRO for slope stability analysis with the application focusing on the competent joined rock masses, where failure results from joints opening and intact-rock failure in tension.

As of today, the SM software is not yet a validated tool and, therefore, the creation of models based on real case scenarios is a necessary step towards the validation of this tool.

Numerical simulations of the slope stability of open pit mine were undertaken using SM and 3DEC. The use of 3DEC was justified on the basis that it had been applied to rock mass analysis with large number of fractures dominant in the failure process. A case study shows close similarities between the results of SM and 3DEC in relation with the FOS, the displacements and the velocities.

Numerical modelling of joined rock masses

Many approximations and assumptions are made to represent the rock mass and to model its behaviour using various numerical methods, which are classified as continuous, discontinuous (or discrete) and hybrid systems [Jing, 2003; Mijo, 2016].

The main difference between the various models is the representation of contact between rock blocks or rock particles. For example, in continuous models, the contacts remain unchanged and cannot be torn open or broken into pieces. Discrete methods are continuously updated using contact mechanics principles and allow large displacements/movements of the fractures, including rotation and complete detachment [Jing, 2003; Bobet, 2009]. In the hybrids methods, born after concluding that the area closer to the excavations is usually more fractured than the rock mass located far behind the slope face, a combination of continuum and discontinuum methods are used simultaneously depending on the location of the area analysed [Lorig et. al, 1984].

Mijo et. al., (2016) compared the bases of different numerical methods (FLAC3D, PLAXIS, FRACMAN and 3DEC) and concluded that there is no generalized method, which would solve all rock mechanics problems but rather it is important to choose the method, which is most appropriate for the problem to solve.

Various methods had been studied with the purpose to solve engineering issues based on a discontinuous approach; consequently, many computer codes have been developed and applied, including RBM, SDEM, UDEC and 3DEC [Cundall, 1988; Cundall, 1974; Cundall and Marti, 1979; Cundall and Hart, 1985].

Numerical modelling – 3DEC

To-date, the most used code for discontinuous rock mass analysis is 3DEC, a three-dimensional numerical program based on the distinct element method (DEM) for discontinuum modeling. The base of 3DEC is it’s two-dimensional version, UDEC (Itasca 2011), which has been extensively tested over many years of application. 3DEC simulates the response of discontinuous media (such as a jointed rock masses) subjected to either static or dynamic loading. The discontinuous medium is represented as an assemblage of discrete blocks. The discontinuities are treated as boundary conditions between blocks; large displacements along discontinuities and rotations of blocks are allowed. Individual blocks can behave as either rigid or deformable material. 3DEC is based on a Lagrangian calculation scheme that is well-suited to model the large movements and deformations of a blocky system.

The advanced features of 3DEC, as compare to other modelling software, are the treatment of the rock mass, which is modelled as a 3D assemblage of rigid or deformable blocks while discontinuities are regarded as distinct boundary interactions between blocks. In addition, the continuous and discontinuous joint patterns can be generated on a statistical basis and an explicit in-time solution algorithm that accommodates both large displacement and rotation and permits time-domain calculations to be employed. More information about 3DEC functions and its applicability can be found in the 3DEC User's Guide Manual (2013) and Jakubowski (2004).

Numerical modelling - Slope Model (SM)

The new 3D program, Slope Model, developed as part of the Large Open Pit Project by CSIRO and Itasca, is a modelling software that allows the fluid flow and mechanical deformation to be reproduced. It encompasses the physical properties of the medium, unlike limit equilibrium methods or kinetic models.

SM has been designed to simulate rock masses in which overall failure mode is a combination of slip and opening of joints and intact-rock failure in tension. The joints within the rock mass are derived from a user-specified Discrete Fracture Network (DFN), where the fractures and joints can be introduced explicitly or stochastically into the model. The fluid flow throughout the joints network and the rock matrix can also be modelled, with the resulting pressures used to compute effective stresses for each joint element. Several aspects of fluid-rock interaction are represented, such as, effective stress (for sliding behaviour) and pressure response due to changes in rock geometry [DAMJANAC et al, 2010].

SM follows the Synthetic Rock Mass (SRM) method, based on the PFC3D code, and uses a lattice of springs and nodes to represent brittle rock. In comparison, a distinct element code (DEM) models an elastic/brittle rock as a bonded assembly of spherical particles [IVARS, 2009; HUAMAN, 2015].

The SRM approach is applied to specific case of rock slope stability in hard, fractured rock masses. It overcomes limitations of the conventional methodologies used for analysis of the slope stability when applied to fractured rock masses by representing correctly the physics of deformation of discontinuities and the fracture of the intact rock that forms the "rock bridges" between the pre-existing discontinuities [IVARS, 2009; HUAMAN, 2015].

In SM, the particles (or balls) and contacts of the DEC code are replaced by point masses and contacts are replaced by springs, creating the so-called lattice, as shown in Figure 1. Springs may break creating micro-cracks and their strength is adjusted to give the corresponding rock strength and to create an array of centroids. The resulting array of centroids is provided to the user of SM as a built-in data set, avoiding the need to run PFC3D when SM is executed [Damjanac et al. 2010].

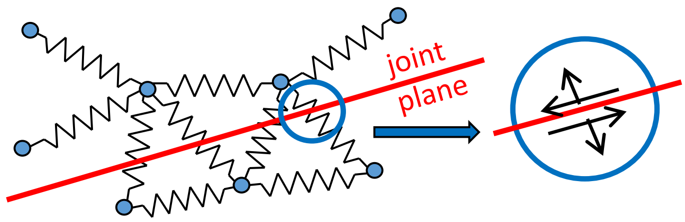

Figure 15. Joint plane through lattice

SM also includes a new coupled fluid-mechanical scheme to model the mechanisms associated with pressure changes in joints in response to mechanical deformation, called Mechanical Incompressible Fluid (MIF), which was proposed by Peter Cundall (2011). However, this feature is not put into practice in this study, as no fluid is incorporated to the model.

SM has a new contact formulation called the flat-joint model, developed by Potyondy (2012). It is aimed at capturing the effects of a clumped Bonded Particle Method (BPM) with a computationally more efficient method (Figure 2). The partial interface damage and continued moment-resisting ability of the flat-joint model allow the user to correctly match both the direct tensile and the unconfined compressive strengths of a hard rock.

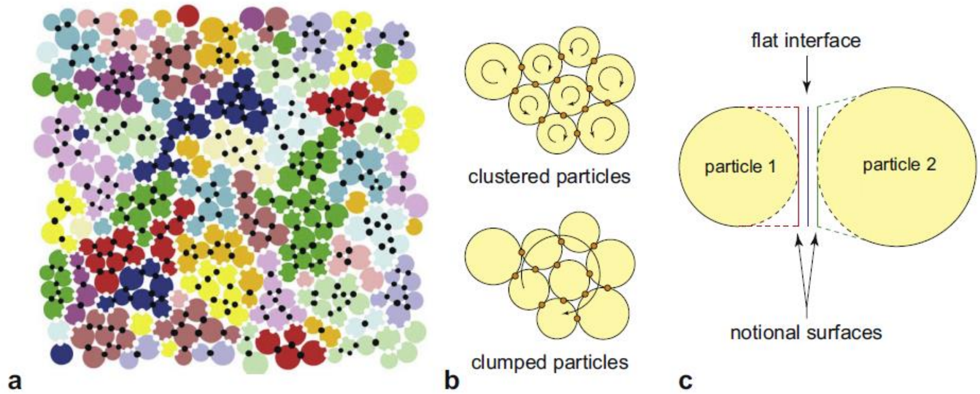

Figure 16. Proposed enhancements to the original BPM: a) particle clustering, b) clustered particles vs. clumped particles, c) effective interface geometry of the flat-joint contact model (Potyondy, 2012)

3DEC – Slope Model Comparison

SM and 3DEC are similar in representing the failure mechanisms of slip and opening on joints but SM has the added capability to simulate the fracture of intact rock, where 3DEC approximates the rock mass behaviour using plasticity laws [Damjanac et al. 2010].

In SM, a joint plane consists of springs that are intersected by the track of the plane. Each spring obeys the smooth joint model (SJM). Thus, the sliding block is actually represented as a network of nodes and springs bounded by sets of SJM springs (Figure 1). SM does not use continuous joint planes that are used in 3DEC code.

SM includes the new coupled fluid-mechanical scheme, Mechanical Incompressible Fluid (MIF), which models the mechanisms associated with pressure changes in joints in response to mechanical deformation.

While 3DEC can simulate the 3D stability of jointed slopes with fluid interaction, SM allows the development of new fractures through the intact rock during the simulation. This feature only becomes important for the analysis of slopes on a large scale or slopes subjected to high horizontal stresses and presenting low intact rock strength, in which case the induced stresses are sufficient to cause significant new fracturing.

Compared with 3DEC, SM has the advantage of having larger explicit time-steps to achieve numerical stability [DAMJANAC et al, 2010].

The SM software interface is friendly and intuitive, aimed to be used by non-expert professionals in numerical modelling. It allows to create simple benches. For complicated and realistic cases, geometries are imported in DXF from any CAD software able to save in this format. In comparison, 3DEC requires grater knowledge and expertise as it uses a specific code to create the models.

The contact detection and interaction between points within each software can be found in the 3DEC User's Guide (2013) and in Taghavi (2012) for SM.

Validation level

3DEC and other conventional numerical methods have been calibrated and validated through various application and comparison with field observations. SM is a new code that, as yet, must be carefully tested and validated before it is used in engineering practice.

For the calculation of the factor of safety (FoS), the computational methods employed in numerical analyses programs are: strength reduction method, limit analysis (upper- and lower bound solutions), and limit equilibrium method (LEM) (upper-bound solution) [Kanda M.J. 2016]. The method used in 3DEC and SM is the Strength Reduction Factor (SRF) technique, which progressively reduces the shear strength of the material to bring the slope to a state of limiting equilibrium [3DEC Manual, 2013]. The main advantages of SRF over LEM are the elimination of the assumption about the shape or location of the failure surface and obtaining the failure mechanism without the need of knowing the location of potential sliding sections. When using SRF analysis, the calculated Factor of Safety is generally higher than the one obtained with limit equilibrium methods.

The strength properties used to calculate the FoS can be obtained from Mohr-Coulomb failure criterion, ubiquitous-joint strength model or Hoek-Brown. The Hoek-Brown criterion was used in models with deformable blocks in this study [3DEC Manual, 2013].

Case study

The slope stability is evaluated based on a 30-meter wide section of a slope from a Chilean mine using Slope Model and 3DEC numerical modelling (Figure 3). This specific section was selected as it is in the vicinity of the crushing station located at the crest of the pit.

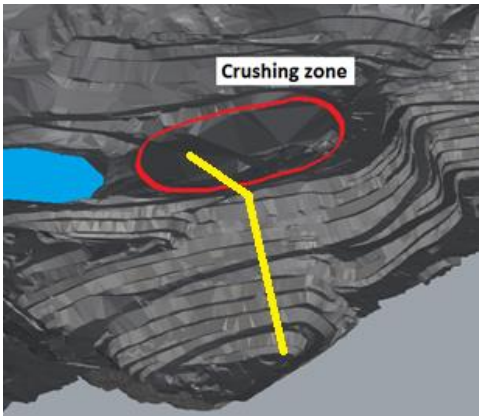

Figure 3. Pit section analyzed

The assumptions in the creation of the models are related with; rock properties, properties of the joints and faults, boundary conditions and failure criterion followed.

As the rock has been classified as competent, Limit Equilibrium method (LEM) could be used. However, the effect of the discontinuities is not taken into consideration in the LEM methods, which considers only the initial and the final states, not allowing for a comprehensive understanding of the mechanical behaviour.

Therefore, to achieve a more realistic outcome, both 3DEC and SM include the effects of the fractures. In the case of SM, rock bridges break if stresses are high enough, interconnecting the discontinuities and weakening the rock mass, resulting in a better representation of the rock behaviour. In 3DEC model, the effects of fracturing was analysed using the same geometry and input values as used in SM, except for the GSI value and the damage factor (D); the D factor in 3DEC was assumed to be 0 and the GSI value 55 and 45 for primary and secondary materials. The GSI and D were used only in 3DEC as SM uses only the intact rock properties during the analysis.

The statistical joints or Discrete Fracture Network (DFN) was created in 3DEC first and imported into SM. The pore pressure was not taken in consideration.

The appendix A describes in more detail the building of the models with both software.

Geotechnical Model

To estimate the rock mass strength, the Synthetic Rock Mass (SRM) model methodology is used in Slope Model, where the fractures and faults are represented explicitly. The SRM simulates slipping or opening of the pre-existing fractures, their propagation and internal damage of the matrix. This is represented using the bonded particle model (BPM) or, equivalently, the lattice model in SM. This method, instead of using empirical relations to account for scale effect on rock-mass properties, as occurs in 3DEC with Hoek & Brown, accounts for scale effects in a rigorous way. The main input parameters in SM are intact rock properties, explicit representation of the discrete fracture network (DFN) and the mechanical properties of fractures (Damjanac 2010).

Rock mass properties and In-Situ Stress

Due to its major presence, only the Sericite-Quartz-monzonite rock type was considered with its primary and secondary rock properties (Table I). The contact plane dividing both rock types is shown in figure 6. The rock matrix was modelled as an isotropic linear elastic material with the properties for each rock type as shown in Table I.

Table IV. Primary and secondary quartz-monzonite Sericite intact rock properties

GEOTECNICAL UNIT	ρ [t/m^3]	Mi	σci [MPa]	EI [GPa]	vl	Environment	GSI	D	mb	S	a
QUARTZ-MONZONITE - SERICITE -QM QS-	2.72	18.79	133.22	59.21	0.28	Primary	50-63	0.0 a 0.2	3.57	0.0065	0.504
								0.7 a 0.8	1.61	0.0017	
	2.63	25.01	91.45	43.23	0.26	Secondary	40-53	0.0 a 0.2	3.41	0.0023	0.507
								0.7 a 0.8	1.21	0.0004	
	a	σtm (MPa)	σcm (MPa)	E (GPa)	v	B (GPa)	G (GPa)	σ3 < 0.5 Mpa		σ3 > 0.5 Mpa	
								c (KPa)	φ (°)	c (KPa)	φ (°)
	0.504	0.24	34.1	22.2	0.23	13.7	9	-	-	1936	56
		0.14	22.6	9.1		5.6	3.7	647	61	-	-
	0.507	0.06	22.2	9.5	0.26	6.6	3.8	-	-	1404	53
		0.03	13.1	3.5		2.5	1.4	323	58	-	-

In order to estimate the stress tensor to be used in this study, the work of Galarce (2014) were used, in which the stress tensor's parameters were obtained from a Chilean database from different parts of the country and compared it with the results proposed by other authors (Mathews, 1981; Potvin, 1988; Mawdesley, 2001) providing consistent magnitudes and stress orientations. The slope analysed was not aligned with NS direction, thus, the stresses were rotated. The stress tensor and the rotations values for Chile, used in this study, are presented in Table II.

Table V. Stress tensor in Chile and stresses rotation

Chile			
	Gradient. [MPa/m]	*for 715m depth*	*39.92º rotation*
σ_{EW} [MPa]	0,021	15	13.467
σ_{NS} [MPa]	0,011	7.86	9.39
σ_{V} [MPa]	0,027	19.3	19.3

Boundary conditions and model resolution

In 3DEC and SM, the artificial boundaries are associated with the prescribed displacement, inhibiting the movements in either vertical or horizontal directions or both, depending on the surface. The boundaries were chosen as: fixed for the floor of the model, restricted to move only in the perpendicular direction of the four vertical surfaces of the model perimeter, and set free at the top surface (Figure 4).

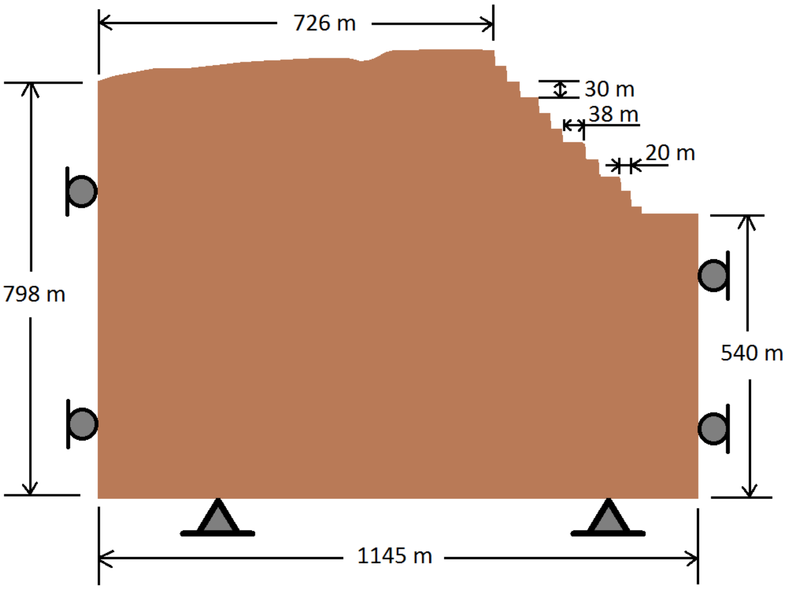

Figure 17. Final Pit geometry and boundary conditions

The resolution of the models, or average node spacing, was determined by the distance between structures. For proper representation of joints behaviour, at least 4-5 nodes have to be built between structures. In this model, the average distance between structures was 0.066 structures per meter (P10 value), which is 6.6 structures every 100 meters. In SM, the resolution 200 meters below the surface is 300cm, which is 3 meters between nodes and fulfils the requirements of 5 nodes between structures. In 3DEC, the resolution was also set for 200 meters below the surface and 3 meters between nodes.

Structural geology and Discrete Fracture Network

The stability behaviour of a mining slope is heavily influenced by the internal structures layout and their resistive properties. Its proper representation relies on the quantity and quality of the data on the studied area. In this manner, the DFN is defined as a representation of all the major and minor structures that the rock mass contains, coming either from explicit or implicit information (Yu et al, 1999; Zimmerman and Bodvasson, 1996). The transmissivity of individual fractures and the fracture system geometry are represented in the DFN model.

Apart from the DFN structures (Table III), the deterministic major faults were introduced manually in both software. The parameters used to create the DFN are shown in Table III.

Table VI. DFN parameters

Type	Set	Disc Ø [m]	Dip	DipDir	K [Fisher]	P10*	Spacing [m]
Joint sets	1	79 - 81	83	151	65	0.066	>15m
	2	79 - 81	87	332	239	0.066	>15m

P10 value is the average value of the number of fractures for each meter of scanline.

From the Dip and DipDir in Table III, it can be deduced that the joint sets are very similar, which causes the overlapping of many structures, creating small volumes and potential code errors. For that reason, only the set 1 of structures was used in calculations.

The fractures with less spacing than 15 meters were not included in the creation of the DFN, however, in the case of 3DEC, they were accounted implicitly in the GSI value. SM does not use the GSI value as it calculates the scale effects rigorously.

The faults´ properties are listed in Table IV.

Table VII. Faults´ properties

Structure type	Cohesion, c [kPa]	Friction angle, Ø [º]	Length [m]	Normal Stiffness [GPa/m]	Shear Stiffness [GPa/m]
Major faults	75	25	-	20	5
Minor faults	25	30	80	20	5
Joints (DFN)	100	25	15	20	5

Figures 5. and 6. show the two types of discontinuities in different colours in 3DEC and SM, respectively.

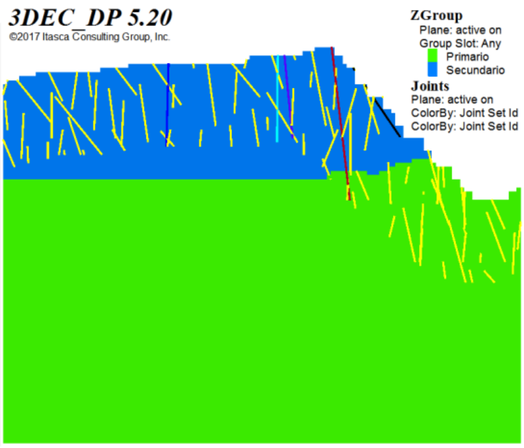

Figure 18. 3DEC model with DFN (yellow) and deterministic joints (major faults). Secondary material in blue and primary in green.

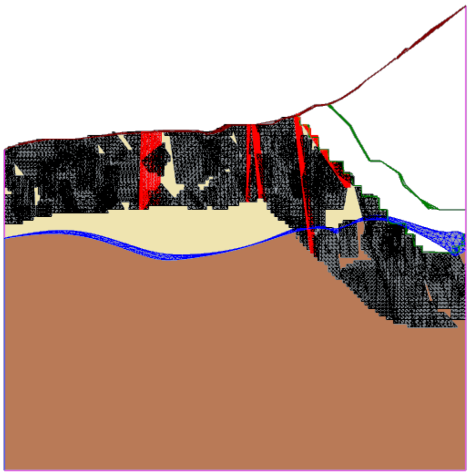

Figure 19. SM section view with deterministic joints in red and DFN in black

Methodology

The methodologies used for the creation of the models in 3DEC and SM varies even though they aimed to analyse the same parameters.

The study commenced with the creation of the 3D model using a CAD software. From the 3D model each software uses different parameters and define its properties. Subsequently, all the boundary conditions, initial tensional state, rock and structural discontinuities properties were defined.

The gravity value was added, causing the models to move downward until the equilibrium was reached. In both models, the excavation of the overburden material was made in two stages to recreate the relaxation of the ground and correctly represent the initial tensional state of the final pit. The equilibrium state was reached after applying gravity and after each excavation.

Monitoring points, represented as dots in Figure 7. and cubes in 3DEC (Figure 8.), were allocated in different parts of the model making it possible to plot variables, such as, displacements or velocities, in the X, Y or Z directions, allowing to see the trend in velocities to determine if the model was stable or unstable.

Modelling results comparison and analysis

The values obtained for relative displacements, velocities and Strength Reduction Factor (SRF) using SM and 3DEC were compared. Note that SRF is equal the Factor of Safety (FoS). The units related with velocities and displacements shown in the SM and 3DEC figures are in meters per second and meters respectively.

Figure 7 shows the displacements of the indicated points in the Z direction for SM. It can be deduced that the points stabilize at the end of each sequence (3 sequences of 4 seconds each). Three displacement disturbances can be seen between 0 and 2 seconds, 4 and 6 seconds and 8 and 10 seconds. The initial sequence corresponds to the settlement of the model due to the gravity; once displacements were stabilized, node displacements were reset and the removal of the initial volume was performed. At this point, after model stabilization, the volume between the actual pit and the final pit was removed and the behaviour shown in Figure 7 was observed.

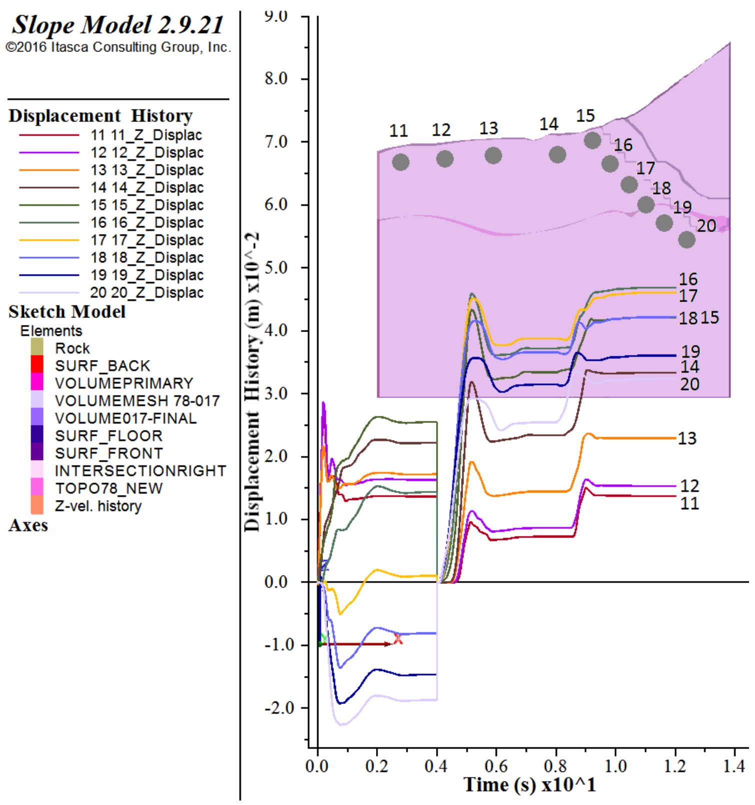

Figure 20. Monitoring points and displacements in Z direction using Slope Model

Figure 8 shows the displacement results computed using 3DEC after following the same process as used in SM (gravity effect, first excavation and second excavation). The results reflect the stability of the slope at various points. Figures 9 and 10 show planar sliding on the bench scale, not represented by the monitoring points in neither of the two cases. This fact is explained by considering that the joint creating the planar slide only affects a small volume near the bench surface and the monitoring point are not inside the moving areas.

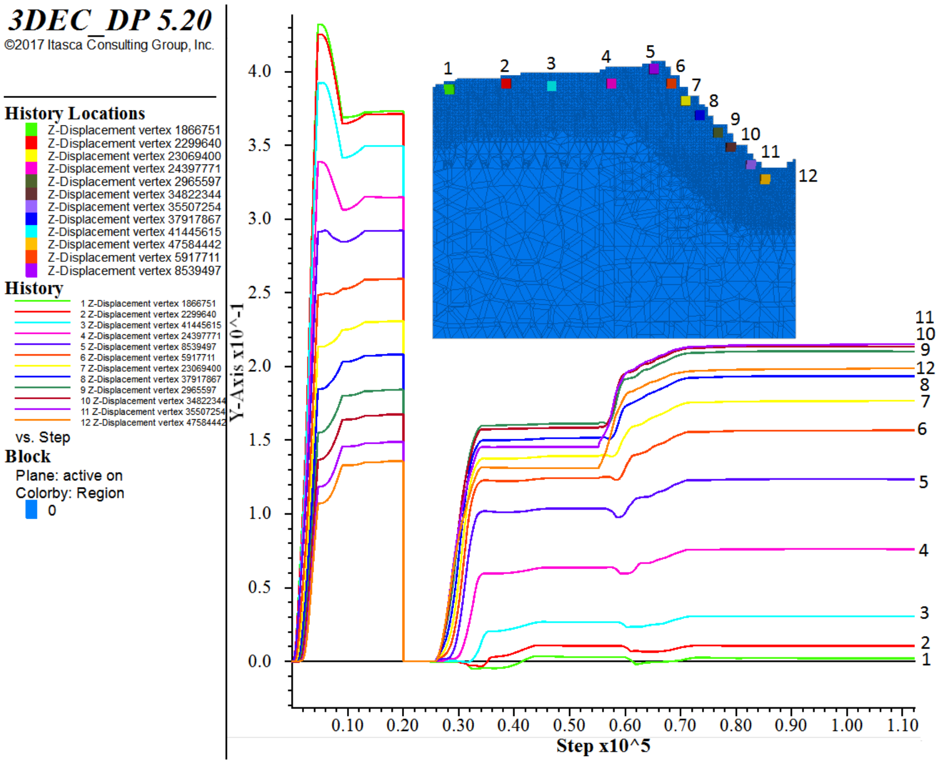

Figure 21. Monitoring points in 3DEC and Z direction displacements

The displacement and velocity fields in SM and the deterministic non-daylight joint called “Falla8_S80-90E” are represented in Figures 9 and 11 respectively. The mentioned non-daylight joint intersects with a daylight joint from the DFN (red line in figure 9.) creating a bigger planar sliding. This is represented in the 3DEC model as shown in Figures 10 and 12.

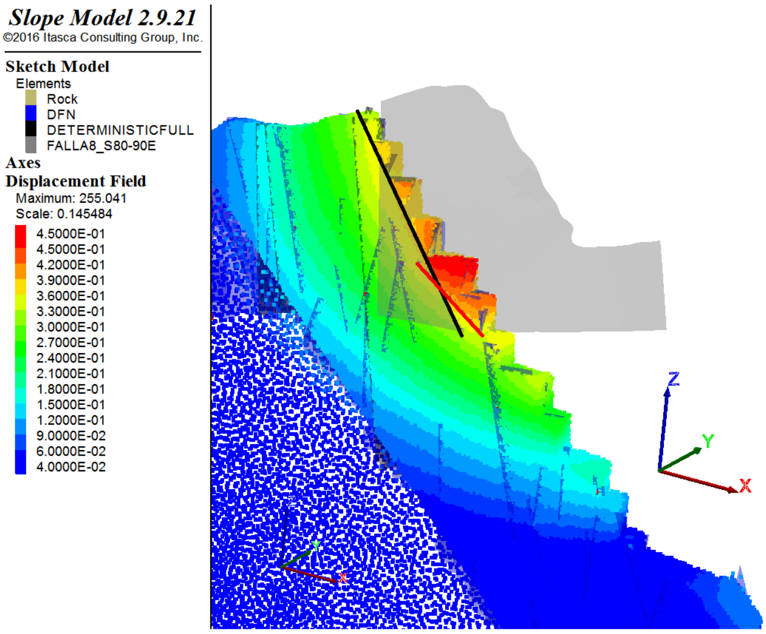

Figure 22. Displacement field and "Falla8_S80-90E" fault in SM

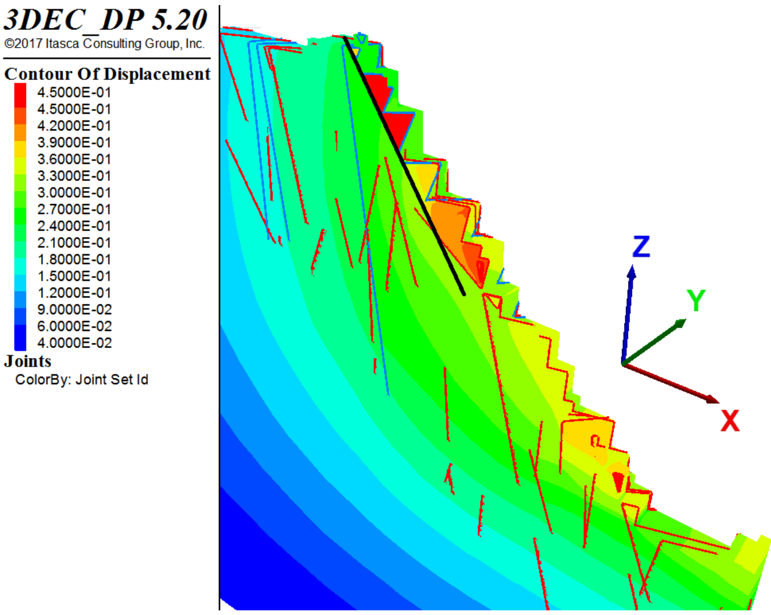

Figure 23. 3DEC model displacements and deterministic (blue) and stochastic (red) joints

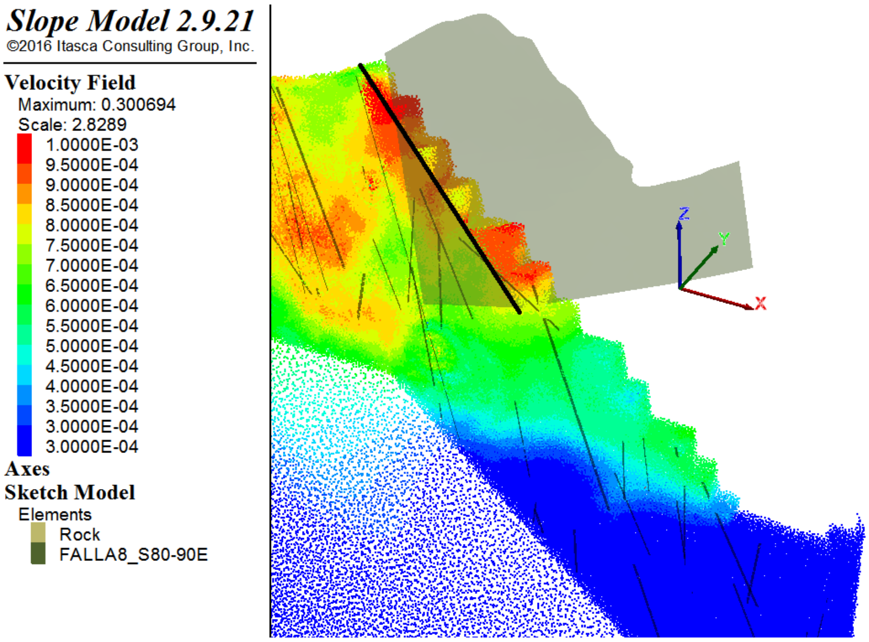

Figure 24. Velocity field and "Falla8_S80-90E" fault in SM

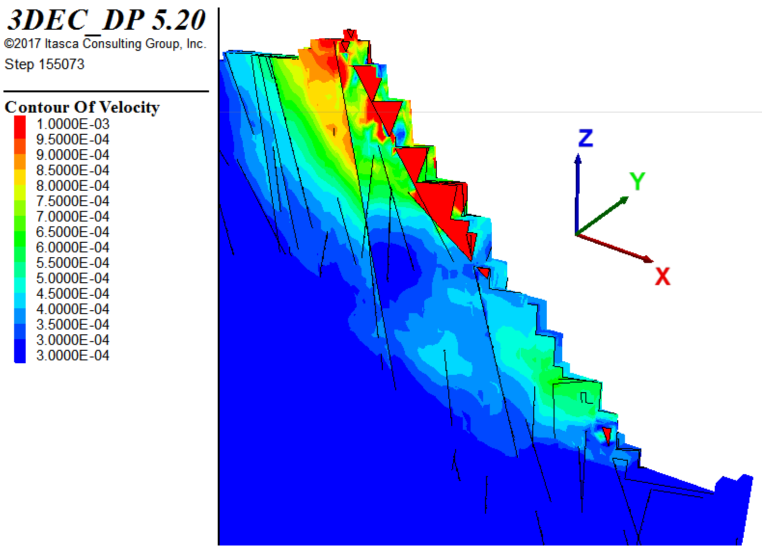

Figure 25. Contours of velocity in 3DEC

The Strength Reduction Factor (SRF), which resembles the Factor of Safety, was calculated using both software. The SRF method consists of reducing the strength parameters of the rock by a certain factor until limit equilibrium is reached. To reach the frontier factor between stability and instability, the bracketing method was used.

For the calculation of the FoS in 3DEC, the command “solve fos” can be used, even though it only gives a unique numerical value of the FoS without providing the FoS distribution. Therefore, a function (FISH) was created to compare the velocity of each node with a threshold value for each reduction, resulting in a contour of SRF as shown in Figure 13. The threshold value is the minimum velocity which decides if the point is stable or not

Figure 14. shows the FoS or SRF calculated with SM. The SRF contour of the two models presents good correlation between the allocation of the values and the values itself. The capability of SM in representing the breakage of intact rock and the propagation of the existing fractures results in a more detailed pattern and slightly smaller FoS values compared with 3DEC. The SRF contour of SM has good correlation with the micro-cracks from the line 2 in Figure 15.

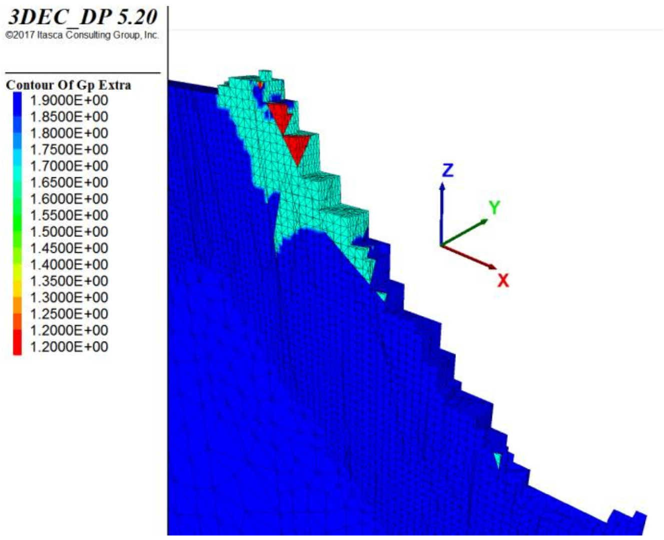

Figure 13. Factor of safety on 3DEC

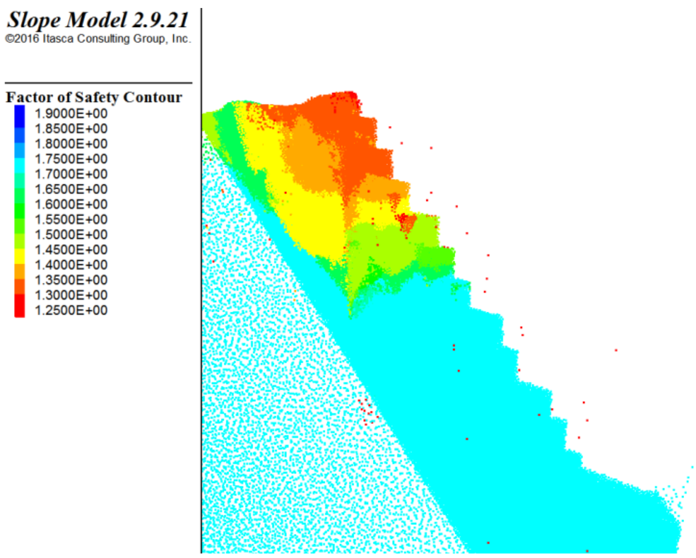

Figure 14. Factor of safety on SM

One of the capabilities of SM is to identify the tension cracks created during the calculation of the model, allowing to determine the matrix and rock bridges breakage. SM enables identification of where the cracks are initiated and the breakage percentage. Figure 15. shows the displacements and the micro-cracks determined using SM. All micro-cracks were created during the stabilization of the model. Subsequently, they were reset to 0 before the excavations began, which enable an identification of new micro-cracks.

Figure 15. shows a concentration of micro-cracks at the toe and in the middle of the pit. Their pattern may indicate 2 potential sliding planes marked as lines 1 (grey) and 2 (red). Only few micro-cracks are 100% broken (black), which will not be enough to create a bigger slide. The location where the fractures are initiating is shown in Figure 15.

The cracks dividing the model resolution were not considered.

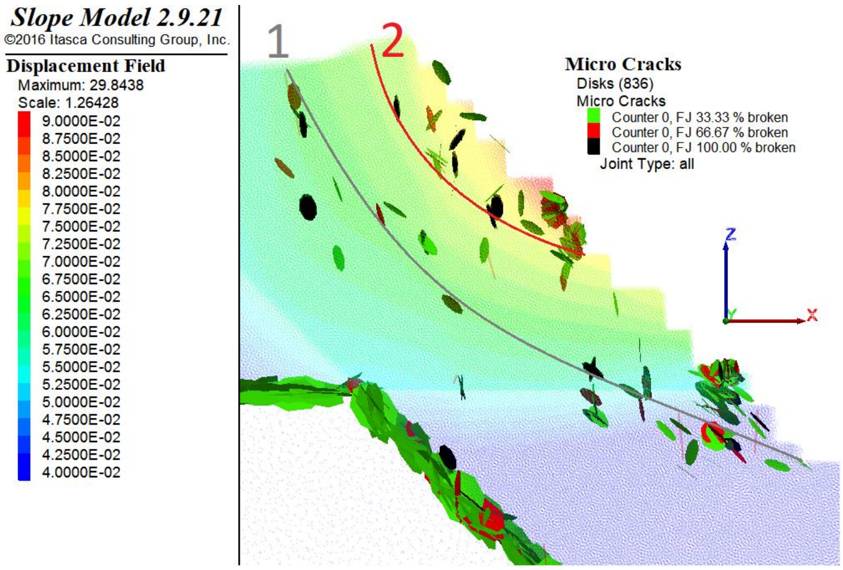

Figure 26. Micro cracks in SM

Conclusions and recommendations

After analysing the figures 13. and 14. strong correlation was found between the results obtained using the Slope Model and 3DEC numerical modelling methods. The small differences in velocity, displacement and SRF are caused by the method used in SM in representing the effect of the interaction between structures.

On the 6 top benches, the values of the SRF in SM were between 1,25 and 1,6 while in 3DEC were 1,7, not taking in consideration the lower values from the slides on the top benches. These results agree with the theory as the interaction and creation of new fractures represented by SM are expected to lower the rock competence. SM creates a more detailed contour, enabling to better identify the areas with higher potential of failure.

It is recommended to realize a joint monitoring study to identify the small joints on the benches near the intersection with the major non-daylight fault “Falla8_S90-80E”. Due to the similar orientation and closeness of the major fault to the bench face, there is a high potential for the creation of a bigger failure due to the interaction with a minor daylight joint, as occurred in this study.

The study shows that Slope Model performs well in slope stability analyses in fractured rock masses. It is recommended that the code is initially used together with some other conventional methods of analysis or software to compare both predictions until more field scale validation tests are performed.

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Appendix A: Creation of the models

The topographies to create the models were obtained from a Chilean mine, which includes the topography before mining operations began in 1978, the 2017 topography and the final pit surface.

The figure 16 represents the model created with the CAD software, where is possible to differentiate the excavated volumes from pre-mining to actual pit in grey and to final pit in green. In the same figure is possible to see the blue layer differentiating the primary and secondary materials.

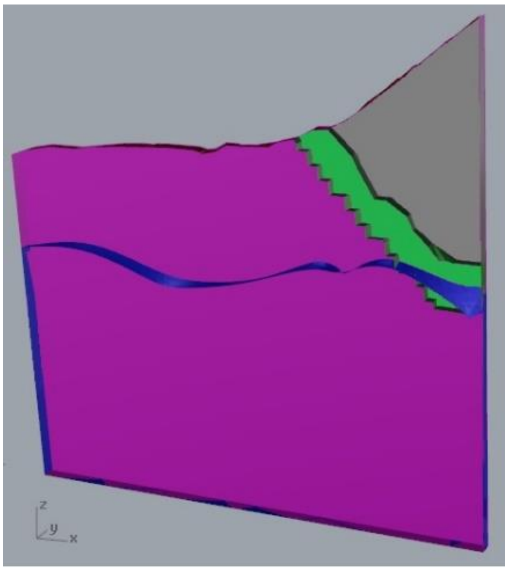

Figure 27. Pre-mining with volumes to be excavated, final pit and primary-secondary division layer

The analysed model is 30 meters wide, 1146 meters long and 800 meters height. The pit depth is 340 meters.

In both models the main joints and faults were introduced manually (figure 17.), and the stochastic joints or DFN were created in 3DEC and exported to Slope Model.

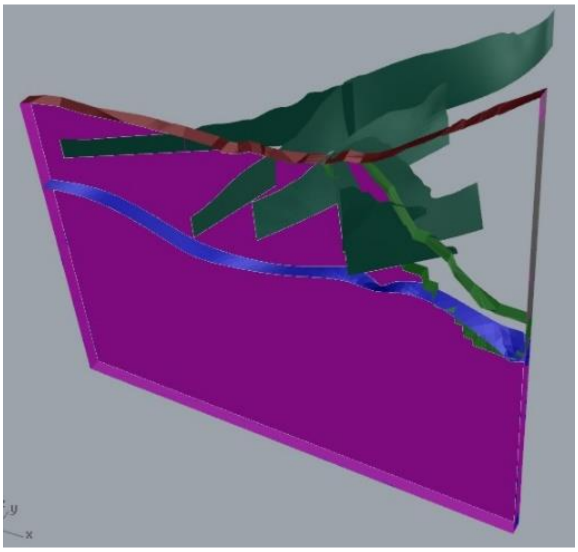

Figure 28. Deterministic joints in CAD software

A.1 Building the model with Slope Model

Previous to start working with Slope Model a 3D representation of the zone to study was made with a 3D CAD software. In the CAD model, every surface and volume, such as excavations and joints, was placed in different layers in order to define them accordingly in SM, as can be seen in the figure 18. under the tittle Sketch Model, Elements.

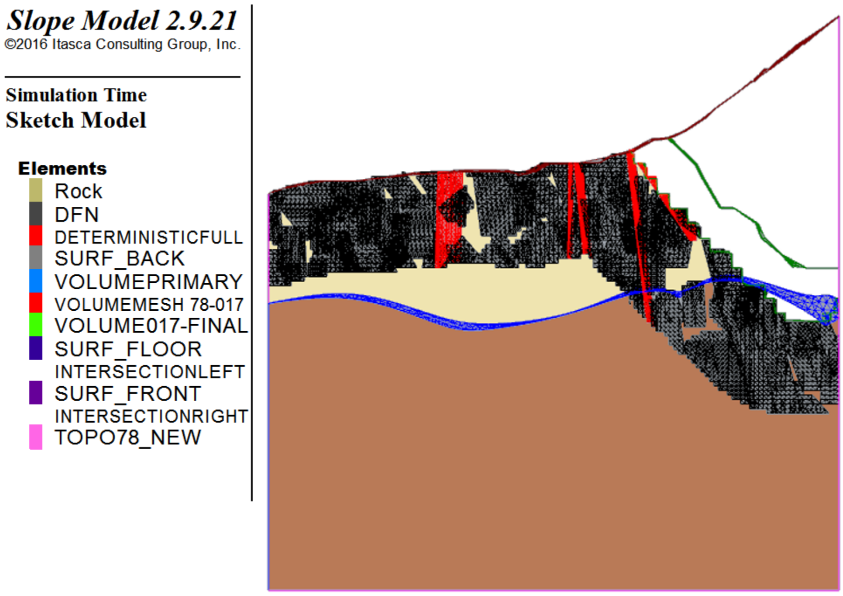

Figure 29. Model created with SM. Geometries DFN (black) and deterministic joints (red)

The CAD model should be watertight to avoid wrong allocation of springs and nodes. In this case the topography has two defined volumes which correspond to the excavations from the initial topography (1978) to the actual pit (2017) and to the final pit.

The DFN was created with 3DEC and exported to SM in DXF format. Is important to mention that SM uses Megapascals (MPa) as an input value for the cohesion of the joints.

For the calculation of the Strength Reduction Factor (SRF), which resembles the Factor of Safety (FoS), SM does the bracketing method between given values, creating a 3D map of the SRF on the studied area. The SRF distribution results and other details, are represented in section Modelling results comparison and analysis.

A.2 Building the model with 3DEC

To create the model, 3DEC has a specific Itasca code similar to the code used in other ITASCA software, such as, FLAC and UDEC.

The only external information used in 3DEC to create the model are the CAD surfaces, which were called to delimitate the three different surfaces boundaries and generate the excavation volumes, the rest of the model is defined using its specific code.

Before the excavations began, the model was run in elastic mode for the correct stress distribution without blocks displacements. Once the model was settled down, plastic model was set and the excavations started.

Figure 19. shows the primary and secondary rock and the area with higher resolution (200[m]) in which the joints and discontinuities were represented.

In order to create the same model in both software, the D factor in 3DEC is set to 0 as SM uses only the intact rock properties.

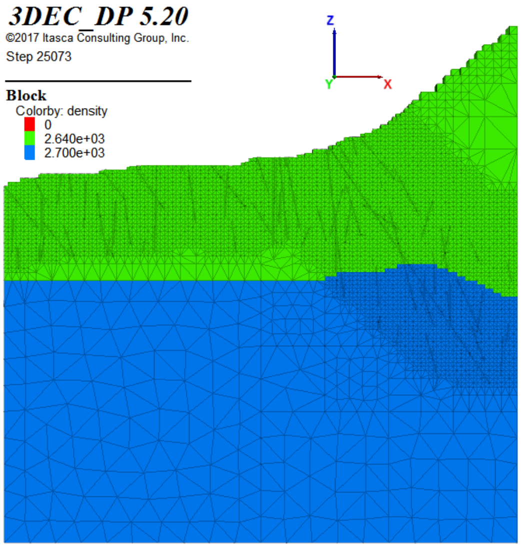

Figure 30. Model created with 3DEC grid. densification details and primary(green) and secondary(blue) rock

11. Conclusions

11.1. General conclusions

The present thesis gathers and analyses the results obtained after modelling a mine slope with the software Slope Model and 3DEC, both from the company ITASCA Consulting Group Inc.

The thesis consists of two articles, which were sent to be presented in a conference as a paper and published in a journal. Both articles started with a brief literature review of the chosen numerical modelling software and their main drawbacks, concluding that the fractured rock masses do not represented the reality in the best possible way, especially in terms of fracture propagation and intact rock breakage.

Slope Model (SM) was the software used in this study, which solves the problems related with fracture propagation and intact rock breakage. SM is a software under development, for that reason is necessary to compare their results with a validated software, which in this case was 3DEC.

Subsequently, a mine slope was represented with the same geometry in SM and 3DEC. In-put parameters where slightly different as both software do not require the same parameters, even though both models are considered identical.

Models followed the same process to achieve final results, which consisted in achieving equilibrium before initiate the excavations. Once reached, velocities, displacements and tensions were reset, to subsequently start the two excavations. When the final pit was reached, monitoring points were allocated near the surface and the models were run until stabilization.

Finally, the results were analysed, showing bench scale displacements caused by sliding of pre-existing structures and rock bridges breakage. Such mechanisms were represented in a very similar way by both software, which is represented on the displacements and velocities observed.

The strength reduction factor (SRF) was calculated with both software, obtaining high correlation between them. The results agree with the theory showing slightly lower values in SM than 3DEC, as SM is able to represent the creation of new fractures and their interaction, leading to a lower rock competence.

Due to the type of failure observed is recommended to perform a monitoring study to identify small structures near the intersection of the major fault “Falla8_S90-80E” with the surface. Its non-daylight and semi-parallel orientation with respect to the open pit design results in a high potential of intersection with a minor daylight joint, causing a greater displacement. The described event might occur, as indicated in this study, as the major fault intersects with a minor stochastic joint, eventually allowing for a 5 benches slide.

The present study concludes that Slope Model correctly represents the fractured rock mass behaviour and is recommended to be used in this type of environment. Although, as there are just few real scale validation tests, it is necessary to use a conventional and validated method to be able to compare both predictions.

11.2. Future work

The knowledge acquired during the realization of this thesis led to some ideas to perform future works. As the software SM is still under development, newer versions may incorporate new tools, which could open the possibility of other type of analysis, even though, the recommendations for future works are based on the version 2.9.21.

The first idea is to create a bigger representation of the studied area, modelling a wider section of the slope to achieve a closer representation of the reality. This idea requires equipment with high computational memory and the availability of time to run the models for some days or weeks.

Another possible study is to perform a statistical analysis modelling the same slope with many different Discrete Fracture Network (DFN) in order to reflect the intrinsic variability of fracturing properties along the site. The resulting Factor of Safety or Strength Reduction Factor from each calculation should led to a Gauss curve and the most representative DFN could be used.

Finally, is recommended to do a comparison study between the real monitoring information and the results of the models. However, at this point, the monitoring information is not yet available as the final pit has not been reached.