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Effects of geometrical and geomechanical properties on slope stability of open-pit mines using 2D and 3D finite difference methods

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Abstract

Slope stability analysis is one of the most important problems in mining and geotechnical engineering. Ignoring the importance of these problems can lead to significant losses. Selecting an appropriate method to analyze the slope stability requires a proper understanding of how different factors influence the outputs of the analyses. This paper evaluates the effects of considering the real geometry, changes in the mesh size, and steepness of the slope, as the dimensional effects, and changes in the geomechanical parameters, as the media effects on the global slope stability of an open-pit mine using finite difference methods with a strength reduction technique. The case study is the Tectonic Block I in the old pit (steep slope) and the redesigned new pit (gentle slope) of the Choghart iron mine. In the first step, a series of 2D and 3D slope stability analyses are performed and compared in terms of safety and potential failure surface. The results obtained show that by considering the real geometry of the slope, the FOS_{3D}/FOS_{2D} ratio (3D-effect) is more than 1 in the all cases. The 3D-effect in the new pit is smaller than that in the old one. In the next step, sensitivity analysis of the cohesion and the friction angle is performed for the 2D and 3D analyses. The results obtained show that the sensitivity of the analyses in terms of the 3D-effect to the change in the friction angle, especially in a low-friction angle, is more significant than that to the change in the cohesion.

Keywords: *Finite Difference Method, Two and Three Dimensional, Slope Stability, Open-Pit Mine, 3D-Effect.*

1. Introduction

Slope stability analysis is one of the most important problems in mining and geotechnical engineering. Ignoring the importance of these problems can lead to significant losses in terms of personnel and equipment safety, time, production, and capital. Therefore, the slope stability should be analyzed with consideration of the various aspects of problem, sufficient precision, and using an appropriate method.

There are several methods available for slope stability analysis including the limit equilibrium method (LEM), finite element method (FEM), finite difference method (FDM), discrete element method (DEM), etc. All of these methods are capable of being implemented with 2D or 3D approaches. The output of the analyses may vary depending on the selected method and approach. Hence, there are several important factors involved in the output of the slope stability analyses, and due to the various circumstances, each factor can potentially cause significant changes in the results.

Anagnosti (1969) has presented the first 3D method of slope stability analysis to calculate the 3D safety factor (FOS_{3D}) for sliding masses with different shapes. The comparison between the conventional 2D analyses and this method revealed that FOS_{3D} could be 50% higher than FOS_{2D} [1].

Over the past few decades, many researchers have proposed/developed 3D methods of slope stability analysis based on LEM [2]. As mentioned earlier, the first 3D method for slope stability analysis was developed in 1969; however, the tendency to study the differences between the stability of real 3D slopes (with curvature) and 2D slopes started in the early 60s.

Jenike & Yen (1961) have studied the stability of axisymmetric slopes in rigid–perfectly plastic materials using limit theory analyses for different radii of curvature. The results obtained showed that as the radius of the slope increased, the calculated failure shape in the axial symmetry approached the failure shape obtained from the plane strain method [3].

Several researchers have also studied the effect of plan curvature on the stability of curved slopes. The results of these studies showed that the concave slopes were more stable than the straight slopes, and that the convex slopes were less stable than the straight slopes [4].

Lefebvre et al. (1973) have performed some 3D slope stability analyses for dams in valleys with the valley wall slopes of 1:1, 3:1, and 6:1. The comparison between the 2D and 3D analyses showed that ignoring the end effects had a significant effect on the FOS value [5].

Baligh and Azzouz (1975) have proposed a 3D method of stability analysis and developed a computer program to evaluate the end effects on the stability of cohesive soils. They found that neglecting the end effects could reduce the FOS value by 40% [6].

Chen (1981) has conducted a series of 2D and 3D slope stability analyses on slopes with translational failure mode using LEM and FEM, and compared all the results. Based on the results obtained, the FOS_{3D}/FOS_{2D} translational ratio is usually more than 1, and the 3D-effect in the cohesive slopes is more considerable than that in the cohesionless slopes [7].

Hoek and Bray (1981) have studied the differences between the 2D and 3D analyses considering the changes in the curvature radius in a concave slope. The results obtained showed that if the curvature radius was greater than the slope height, the results of the 2D and 3D analyses would be closer [3].

Chen and Chameau (1983) have proposed a general method of 3D slope stability analysis using LEM, and presented a finite element computer program in order to calculate the local safety factors for the selected failure surfaces and the mean safety factor for chosen failure mass. They found that in certain circumstances, FOS_{3D} for cohesionless soils could be less than FOS_{2D}. Moreover, other factors including the length of the failure mass, steepness of slope, and pore water pressure could also change the 3D-effect in the slope stability analyses [8].

Skempton (1985) has suggested a 3D correction factor to shear the strength calculated from a 2D back-analysis. Moreover, it has been reported that depending on the different circumstances and types of material, this correction factor can result in 5% increase (average) [9].

Cavoundis (1987) has used simple algebra to calculate the minimum safety factors for slope stability analyses. Cavoundis (1987) has stated that FOS_{3D} is always greater than FOS_{2D} for the same slope and the methods that give the FOS_{3D}/FOS_{2D} ratio with values less than 1, probably containing simplifying assumptions that neglect important aspects of the problem [10].

Xing (1988) has proposed a method of 3D stability analyses for concave and straight slopes using LEM. Based on the results obtained, the stability of concave slopes increases as the relative curvature radius of slope (curvature radius of slope crest to height of slope) decreases [4].

Leshchinsky and Huang (1992) have presented a 3D slope stability analysis method for symmetrical slip surfaces based on the variational limit equilibrium approach. The results obtained show that ignoring the end-effects could lead to an overestimation of the *in situ* strength obtained from the local analysis [11].

Lam and Fredlund (1993) have proposed a generalized model for 3D slope stability analysis using the method of columns. This model was capable of modelling the geometry of the slope, stratigraphy, potential slip surface, and pore-water pressure conditions. The model was used for an open-pit mining failure, and based on the results obtained, FOS_{3D} was significantly greater than FOS_{2D}. Lam and Fredlund (1993) have also stated that the 3D method provides a more realistic analyses than the conventional 2D analysis [12].

Stark & Eid (1998) have studied the application of 3D slope stability programs available in 1998, and presented a teqnique to overcome some limiations of those programs. They performed several 2D and 3D back-analyses and showed that the differences between the friction angles obtained from the 2D and 3D analyses could be as large as 30%. Stark & Eid (1998) have proposed that the 3D analyses are more suitable for complicated topography, shear strength conditions, and pore-water pressures [13].

Arellano & Stark (2000) have performed a parametric study to investigate the importance of 3D end-effects. The comparison between the 2D and 3D slope stability analyses showed that the FOS_{3D}/FOS_{2D} ratio increased with decrease in the W/H ratios (the slope width to the slope height). The FOS_{3D}/FOS_{2D} ratio also increases with decrease in the slope in inclination [14].

Chugh (2003) has studied the effect of various boundary conditions on the 2D and 3D slope stability analyses using LEM and FDM. Based on the results obtained, spatial variations in geometry, pore-water pressure, and material properties can lead to a significant 3D-effect [15].

Eid et al. (2006) have developed the 2D and 3D stability charts for slopes susceptible to translational failure mode, and suggested a method for quantifying and incorporating the end-effects in these kind of slopes. They conducted an extensive parametric study with respect to configurations of sliding mass, unit weight, and shear strength of the materials. The results obtained showed that regardless of the material properties and geometry of slope, FOS_{3D} was greater than FOS_{2D} in the critical cross-section of the sliding mass, and the 3D-effect increases as the W/H ratio decreases [16].

Griffiths & Marquez (2007) have performed some 3D slope stability analyses by elasto-plastic finite element, and validated the results obtained against the conventional 2D limit equilibrium analyses of a homogeneous slope. The results obtained demonstrated that by increasing the out-of-plane dimension, the FOS_{3D} converged to the FOS_{2D}. Moreover, the 3D analyses are more realistic and accurate, and provide a better understanding of the failure mechanisms [17].

Li et al. (2009) have used numerical finite element analyses to produce stability charts for the 3D homogeneous and inhomogeneous undrained slopes. In this research work, it was found that depending on the slope geometries, using a 2D method to analyze a 3D problem could lead to a significant difference in the safety factors. Based on the comparison between the 2D and 3D analyses, FOS_{3D} was greater than FOS_{2D} [18].

Zhang et al. (2013) have carried out a comprehensive research work on the effects of complex geometries on the 3D slope stability using the elasto-plastic finite difference method with the strength reduction technique. In this work, various 3D shapes of slope including curving slope surfaces, turning corners, turning arcs, and turning forms were presented and compared in terms of the FOS, shear slip surface, and deformed mesh. The analyses results related to curving slope surfaces showed that curvature of slopes, either concave or convex, made slopes more stable; also the influence of a steep curved slope on the stability was more significant than the gentle slopes [19].

Saeed et al. (2015) have performed some stability analyses on the walls of an open-pit mine using the 2D and 3D district element codes (DECs). In these analyses, the difference between the FOS_{2D} and FOS_{3D} safety factors was calculated with respect to the changes of the groundwater table. The results of these analyses revealed that the safety factors obtained from the 2D slope stability analyses were not necessarily more conservative than the 3D slope stability analyses [20].

Wines (2016) has studied the differences between the 2D and 3D slope stability analyses in an open-pit mine, and have shown that the slope geometry can have a significant effect on the pit wall stability. Based on the results obtained, the concave slopes are more stable than the straight slopes, and considering an ideal geometry with isotropic and homogeneous rock mass, the convex slopes are also more stable than the straight slopes; however, in reality, the stability of the concave slopes is less than the others [21].

Based on the previous research works, some of the important factors controlling the differences between the different analyses can be divided as follow:

- **The selected method.** E.g. LEM, FEM, FDM, DEM, and so on.
- **Dimensional effects.** E.g. 2D or 3D approaches, slope geometry and curvature, slope steepness, mesh size, scale of problem.
- **Media effects.** E.g. groundwater conditions, geomechanical properties of the rock mass, isotropy/anisotropy, homogeneity/ heterogeneity, joint density.
- **Initial conditions.** E.g. boundary conditions and *in situ* stresses.

According to the conditions of the problem in practice (e.g. importance of the problem, available data, available equipment), the factors mentioned above may be considered to provide a more realistic model or be ignored to simplify the model.

The purpose of this work was to evaluate some of the various aspects of the differences between 2D and 3D analyses (3D-effect) in the slope stability analyses of a large open-pit mine. The research works conducted in the subject of 3D-effect on the slope stability of open-pit mines are less than that in the other geotechnical problems; while geometric complexities, uncertainty of strength properties, and various economic aspects involved in the large open-pit mines increase the importance of 3D-effects in such problems. The main objective of this work was to provide a general overview of the 3D-effect in a situation with the scale and characteristics of a large open mine.

Regarding the aim of this work, assessment of 2D and 3D slope stability analyses for an open-pit mine case (Choghart iron mine, Tectonic Block I) was conducted using a finite difference method with a strength reduction technique. In the following, some of the important factors that may influence the stability of an open-pit wall are discussed and assessed.

2. 2D and 3D analyses

Distribution of the stress and displacement fields in the physical problems are generally three dimensional. Therefore, for a thorough examination of the stress-strain fields, 3D analyses are more efficient and provide more realistic results. However, in some cases, 3D analysis is not necessary; these include problems that can be implemented with consideration of simplification assumptions in 2D analyses [22].

In the recent years, many large open-pit mines have been designed to reach depths of over 1000 m. An increase in the depth of open-pit mines leads to an increase in the amount of production and dumping, and consequently, the height of the mine walls, tailing dumps, and leach pads will increase. Moving towards larger, deeper, and steeper mines has increased the sensitivity of the slope stability analyses and requires more advanced analyses and design methods [22].

It is impossible (and unnecessary) to take an account of all the properties, mechanical behaviors, and geometric details of a rock mass into a model. In addition, due to the complexity and uncertainty inherent in the behavior of the rock mass, it is difficult to understand the detailed behavior of the rock masses; therefore, in an appropriate modeling, the real problem must be simplified according to the existing limitations and available tools for analysis [3].

Slope stability analyses are mostly performed by 2D methods, whereas in reality, all problems are 3D, and using 2D analyses can make inappropriate assumptions and ignore the effects of the more realistic 3D analysis [17]. There are several reasons for this:

First, in most cases, 2D slope stability analyses provide a more conservative estimates (a smaller FOS) than 3D analyses [13, 17, 20, 23, 24]. Lefebvre (1973) has stated that these conservative estimates are due to ignoring the end effects in 2D analyses [5], and according to Griffiths and Marquez (2007), the result will be conservative only when the most pessimistic cross-section in the 3D analysis is selected for 2D analysis [16]. However, conservative results of 2D analyses cannot be generally accepted because it is possible that a combination of properties and unusual geometry lead to a more critical 3D mechanism [8, 17].

Secondly, the 2D slope stability analyses in comparison with the 3D are easier to perform, require less precision to perform, and converge to a specific FOS [25], whereas the inputting data and interpretation of output in 3D slope stability analyses are more difficult and more complicated [23].

On the other hand, 3D analyses have advantages in terms of using more realistic geometry, boundary conditions, groundwater conditions, *in situ* stress conditions, etc. Considering all of these aspects in the analysis increases the accuracy of the results, and provides a better understanding of the problem conditions and the potential failure mechanism. These are the main reasons for the difference between the 2D and 3D analyses [17, 21, 25]. Thus 3D analyses of slope stability demonstrate their importance in situations where choosing a 2D plain strain method for analyses is difficult or the nature of the slope is complicated (changing geometry and slip surface in different directions, heterogeneity of the material properties, additional local loads on slope, etc.) or for back-calculation of the shear strength of a failed slope [21, 24].

In general, the slope stability problems can be divided into two groups [21, 22]:

3D analyses are not necessary, and 2D analyses can provide a reasonable display of problem; these include problems that are suitable for considering simplification assumptions (plane strain, plane stress, and axisymmetric model); some examples of this group include slope stability of high walls with low curvature, stability analysis of tunnel section with distance from the working face, longwall panels, cross-section of shafts, and similar problems.

2D analyses are unable to display the 3D nature of problems and obtain unrealistic results; in these cases, assessment of the stress-strain conditions by 3D analyses is more efficient, accurate, and realistic. There are some cases in geotechnical mining problems that necessarily have to be modeled in 3D, and 2D assumptions cannot be applied to them; for instance, areas near the entrance of the tunnels and stopes, tunnels working face, mining stopes, pits with irregular geometry, and high curvature.

3. Geometry effect

Several research works [3, 4, 19, 21, 26-36] show that the geometry of slopes has a significant effect on the stability. The most effective parameters used in the design and stability analysis of a slope are scale, angle, and curvature. In 2D analyses, plain strain assumption ignores the horizontal curvature of slopes, and assumes that slopes have an infinitely long surface (infinite radius of curvature in crown and toe). Moreover, it is possible to model vertical curvature and several efforts [32, 37-42] have been made in investigating this type of curvature; but the main focus of this work was on horizontally concave curvatures. Obviously, a vast majority of the natural and excavated slopes are not infinite in the plane, and have complicated configurations that may be concave or convex; particularly in open-pit mines, where the curvature of pit walls can affect the stable angle of the slope [3, 19]. Any form of curvature can be modeled in 3D analyses but in natural and excavated slopes (especially in open-pit mines), a horizontal curvature is more common. The general types of the slope curvature in three dimensions are shown in Figure 1.

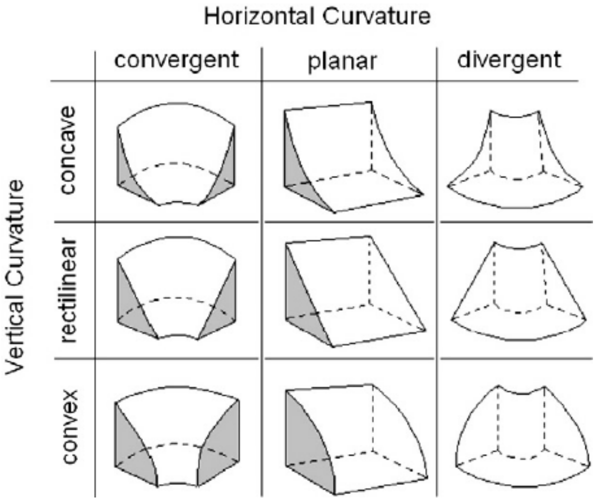

Figure 1. Dividing the slopes according to the curvature change in horizontal and vertical directions [43].

It is known that the slope curvature affects the slope stability. Several studies have been carried out to evaluate the effect of curvature on the slope stability. The analyses conducted on this subject have shown that the concave slopes are more stable than the straight slopes [3, 4, 19, 21, 26-36]; and Wines (2016) have stated that this is according to an additional maintenance caused by confinement provided by a concave slope. Also the stability of a convex slope is more than a straight slope in the analyses; although, due to the lack of confinement and beneficial effects of the side resistance in convex slopes, especially where the potential failures are structurally controlled, the stability of convex slopes is often less than that of straight slopes [21].

The effect of convex curvature on stability is less than the concave curvature, and therefore, the difference between 2D and 3D analyses has often been introduced for concave geometries [19]. Hoek and Bray (1981) have stated that when the radius of curvature of a concave slope is less than the height, the slope angle can be 10 degrees steeper than the angle suggested from the conventional stability analysis (2D plane strain) but since the presence of discontinuities in the rock mass can neutralize the beneficial effects of curvature, the designers are reluctant to take advantage of this positive effects. However, for the massive rock slopes or slopes with slightly jointed rock masses and relatively short persistence, the positive effects of the concave curvature slope should not be neglected; especially in open-pit mines, where the economic benefits of reducing the angle of pit walls could be considerable [3].

To compare the 2D and 3D FOS, usually, the ratio of the curvature radius to the slope height is taken into account. By reducing the ratio of the curvature radius to the height, due to increase in the lateral pressure, the stability of slope will increase. In other words, the increase in the curvature radius decreases the stable angle of slope, and the larger curvature radius will reduce the difference between the 2D and 3D results [3, 4].

Concave geometry is the most common form in the open-pit mines; for a narrow long pit, the walls at the ends of the pit, and in a circular pit, almost all walls are concave. There could be a convex geometry in natural or excavated slopes; convex geometries often exist due to reasons like complex distribution of mineral, ramp switchbacks, and a new cutback into the existing walls [21].

4. Mesh effect

Selecting an appropriate mesh size and geometry is an important decision in modeling the process of slope stability analyses. This decision can lead to underestimate or overestimate the outputs. In the numerical analyses, the accuracy of the results depends on the number of nodes that are used to represent the physical system. The mesh geometry has a limited effect on the safety factor obtained; however, the predicted failure surface is highly dependent on the mesh geometry, and using an inappropriate shape (e.g. slender elements) can lead to wrong conclusions [44, 45].

In general, finer meshes (more zones per unit length) lead to more accurate results. However, other factors such as the memory and processing power of the available equipment and the required analysis time must be considered in selecting the minimum mesh size. Moreover, the aspect ratio (ratio of length to width of an element) also affects the accuracy of the results. In the FLAC software (Fast Lagrangian Analysis of Continua), squared shape elements (unit aspect ratio) will result in more accurate and consistent safety factors and potential failure surfaces [44, 46].

The recommended average size of each element is usually introduced as one-tenth of the slope height (H), and H/32 or less for an accurate determination of the stress condition within vicinity of the slopes [19, 47].

5. Effects of strength parameter

Numerical analysis and the solutions it provides depend on the data. Usually, the collected data, especially the strength parameters of rock masses, are associated with some errors, and changing the problem conditions can also increase the uncertainty of the data. Hence, the results obtained from numerical analysis are not definite enough to provide a reliable assessment. In order to gain a better understanding of the problem conditions, it is better to examine the degree of dependence between the results and the data. In this way, there is not only one definitive answer. By considering a range of circumstances and responses, any changes in the circumstances and possible subsequent risks have already been taken into account.

The previous research works have shown that changing the strength parameters of the rock mass such as the cohesion and friction angles can change the three-dimensional effect (3D-effect). The most pronounced 3D-effect is for cohesive materials, and this effect is more significant for cohesive materials than for cohesionless materials. For materials with low cohesion, there is almost no 3D-effect, and under particular circumstances, FOS_{3D} may be slightly less than FOS_{2D} [8, 48].

The effect of the friction angle on the 3D-effect is opposite to the cohesion; with increase in the friction angle, the curvature effect (also FOS_{3D}) decreases. This could be due to reduction in the confining effect by increasing the friction angle in the curved slopes [3, 21].

6. Selected methods used in analyses

Since there are various methods available for conducting analyses, one of the decisions that must be taken is to choose an appropriate approach to perform the analysis based on the conditions of the problem. Before the new technology era, the stability analyses were performed graphically or by using classical hand calculations. Today, engineers have a lot more options to use analysis methods including stereographic and kinematic analysis, limit analysis, limit equilibrium analysis (e.g. analytical techniques and LEM software), numerical analysis, etc. [49].

The limit equilibrium methods are known as the conventional approach for the slope stability analysis. Most of the slope stability analyses in the past were conducted by 2D LEMs, and most of the 3D LEMs are the direct extension of the 2D methods [2]; these methods are simple and fast but compared to the numerical methods (e.g. finite element, finite difference, discrete element) are less accurate [50]. LEMs have some limitations on the use of detailed conditions of the problem and prediction of the shape and location of the potential failure; hence, due to the capability of numerical modeling to reduce the limit equilibrium method constraints, numerical approaches provide a powerful alternative to LEMs in evaluating the slope stability problems. At the present time, numerical modeling along with the shear strength reduction (SSR) techniques is an acceptable and common approach among researchers and geotechnical engineers, especially when the problem includes complex geometry, material anisotropy, non-linear behavior, *in situ* stress, etc., numerical methods achieve better estimates of the problem. However, numerical methods require time and sufficient knowledge to perform [50-53].

Since the theoretical principles of various methods are different, each method often produces different results for a similar slope [21]. For a simple homogenous slope, safety factors calculated from SSR are usually the same as the results obtained from LEM but in various research works [8, 51, 52], it has been seen that in slopes with a complex geometry and geology, the FOS obtained from SSR numerical calculations is significantly lower than LEM, and the value of this factor in the finite element method has been slightly higher than FDM.

7. Case study

The Choghart iron mine (55°28′2″E, 31°42′00″N) is located 10 Km from Northern East of Bafgh City and 120 Km of Southern East of Yazd City in the margin of Iran Central Desert in the Bafq mining district. According to the primary geological and tectonic studies, and based on the major faults in the region, the rock mass of the Choghart iron mine is divided into four Tectonic blocks (Figure 2). In the current work, the focus was on the Tectonic Block I.

Analyses were carried out on two pits (Figure 3); in the old pit (the steep slope), there were some local instabilities. Due to the instabilities in the old pit, this pit has been redesigned, and right now, the mining operation is performing according to the newly designed pit (the gentle slope) (Figures 3(b) and 4). There have been no failures in the new pit so far, which indicates the global stability of the walls in the new design; however, the economic justification for the new plan is still debatable.

The main reason for choosing this case study was that in this case, the old pit was designed based on 2D slope stability analysis, and in those analyses, the pit wall was stable. Previous analyses were made without considering dimensional effects on 2D analyses. On the other hand, the Tectonic Block I is located in an area of a pit that has the most radius of curvature. For these reasons, this case study helps to better understand the dimensional effects on the slope stability analyses. In addition, due to the low angle of the new pit and the relatively high angle of the old pit, we can compare these two types of slopes with each other. For comparative purposes, from now on, the new pit will be referred to as the "gentle slope", and the old pit will be referred to as the "steep slope" in the context. In this work, we assessed the dimensional effects in the steep and the gentle, and evaluated the various factors affecting the results. The purposes of these evaluations were to obtain a general overview of the differences in the results between different scenarios of the slope stability analyses and identification of more critical factors.

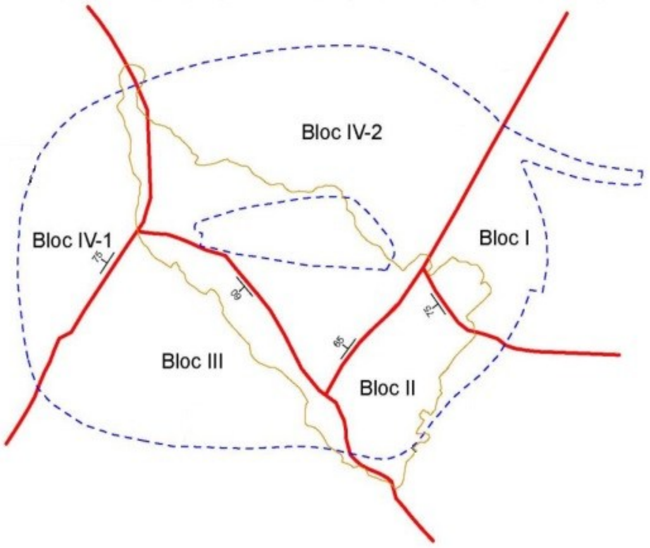

Figure 2. Tectonic blocks of Choghart Mine Pit [54].

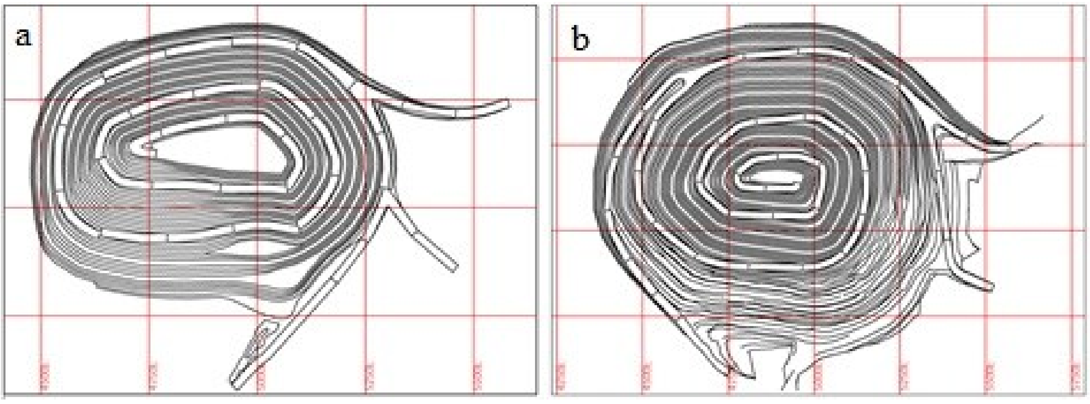

Figure 3. a) Old pit, b) New pit [54].

Figure 4. Satellite image of the current pit (new pit) [55].

8. Slope stability analysis and results

In this work, the slope stability analysis of the Choghart iron ore Tectonic Block I was performed on the old and newly designed pits. For the purpose of numerical modeling of the Block I, the following assumptions were considered:

- There is no groundwater condition. The presence of the groundwater is definitely affecting the stability of the mine walls but due to the lack of groundwater information in the previous reports, this factor has been neglected.
- The effect of excavation is not considered. A number of models were implemented by taking into account the effect of excavation but due to the negligible differences in the results in this case study, this factor was also omitted.
- Model conditions are static.
- Using the equivalent media and the rock mass properties instead of intact rock properties in calculations.
- The Mohr Coulomb model was selected as the behavioral model in these analyses.

In order to analyze the slope stability, the 2D software FLAC SLOPE and the 3D software FLAC3D were used; these softwares are based upon the finite difference method, and they use the strength reduction technique to determine the safety factor. In this research work, a series of 2D and 3D analyses with considering the mesh size effect, real geometry and curvature, steepness of slope (in interaction with other factors), and change in the strength parameters (friction angle and cohesion) was conducted in terms of the safety factor and the potential failure surface. The geometric boundaries of the model were selected in order to comply the geometric principles of modeling, and for this reason, the AB section areas and Block I volumes were not equal in the old and new pits.

In the first step, several 2D and 3D analyses were conducted to evaluate the mesh size effect on FOS. The range of mesh size in 2D was 3*3-40*40 m^2, and the range of mesh size in 3D was 5*5*5-40*40*40 m^3 for both pits. These analyses were performed on the east-west section (section AB) in the Tectonic block 1 (Figure 5) in both pits. Geometrically, Block 1 is a concave slope. Table 1 shows the geomechanical parameters of rock mass of Block I. The geometric characteristics of AB section and Block I are shown in Tables 2 and 3, respectively.

The safety factors obtained from the analyses of AB section in the old and the new pits are presented in Table 4. By reducing the mesh size (increasing the element density), FOS decreases in both cases. The difference between the results of 3*3 and 40*40 mesh size is 0.281 in the steep and 0.148 in the gentle. These differences indicate that the sensitivity of a steep slope to the mesh size is greater than a gentle slope. By changing the mesh size, it can be seen that FOS_{2D} does not change much in a specific range; the size of each element in this range is about 0.01 to 0.03 percent of the slope area for the both pits. Therefore, for a thorough examination of the steep slopes, finer meshes should be used.

Figure 6 shows the 2D constructed models and their results. In the coarse meshes, the surface of the potential failure cannot be seen well, and the strain contours are large. In the extra fine meshes, due to the focus of calculations on the details of slope and benches, overall surface of potential failure cannot be seen well either, and the strain contours near the benches are irregular. The surface of the potential failure in the range mentioned before can be seen well in both pits. This range (0.01 to 0.03 percent of the slope area) can be used as a criterion to select the appropriate mesh size for analyzing the overall slope stability and determining FOS_{2D}.

The results of the 3D analysis of Block I in the old and new pits are presented in Table 5. Similar to the 2D analyses, by reducing the mesh size, FOS decreases in both pits but the gradient of the changes for the 3D analysis is more than that for the 2D analyses. In these analyses, with reduction in the mesh size as much as possible, FOS_{2D} converges to a certain number; this number is about 1.1 for the steep and about 1.5 for the gentle. These ratios are derived from the averaging of the values obtained from all the analyzed meshes with the lowest standard deviation.

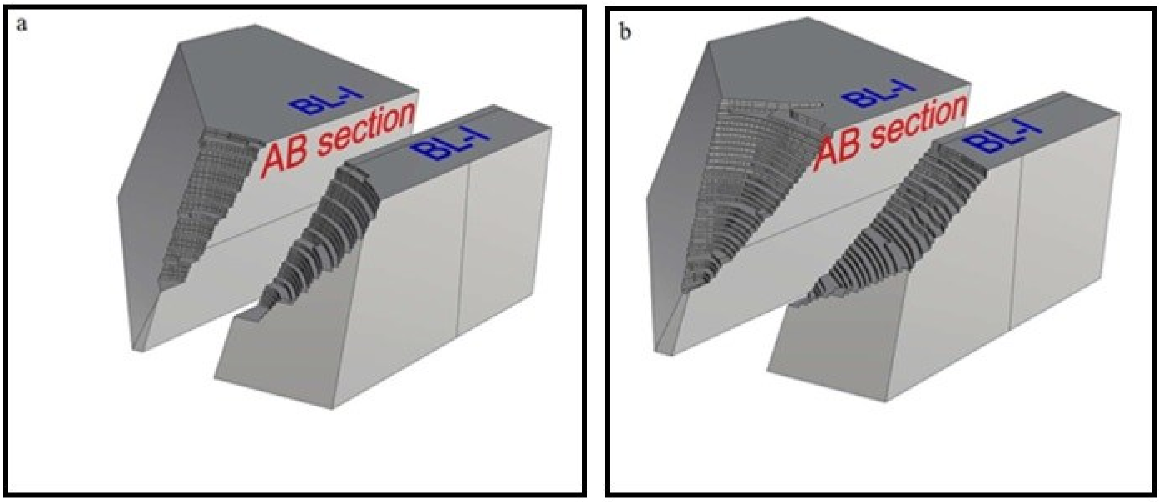

Figure 5. Geometric model of Block I and AB section in a) steep slope b) gentle slope.

Table 1. Geomechanical parameters of Block I.

Density (kg/m^3)	Cohesion (kPa)	Friction angle (°)	Bulk modulus (kPa)	Shear modulus (kPa)
2700	169	35	9.33E+06	5.60E+06

Table 2. Geometrical characteristics of AB section.

AB section	Height (m)	Width (m)	Angle of slope (°)	Area of AB section (m^2)
Old pit	500	750	36	$274*10^3$
New pit	500	1100	51	$404*10^3$

Table 3. Geometrical characteristics of Block I.

Block I	Radius of curvature (m)	Angle of slope (°)	Volume (m^3)
Old pit	180	36	$324*10^6$
New pit	330	51	$648*10^6$

Table 4. Results of 2D analyses by considering various mesh size.

Old pit's AB section		New pit's AB section	
Mesh dimensions (m*m)	**FOS**	**Mesh dimensions (m*m)**	**FOS**
3*3	0.78	3*3	1.22
4*4	0.81	4*4	1.23
5*5	0.85	5*5	1.25
6*6	0.85	6*6	1.26
7*7	0.87	7*7	1.27
8*8	0.87	8*8	1.28
9*9	0.90	9*9	1.28
10*10	0.90	10*10	1.28
20*20	0.94	20*20	1.31
30*30	1.01	30*30	1.34
40*40	1.06	40*40	1.36

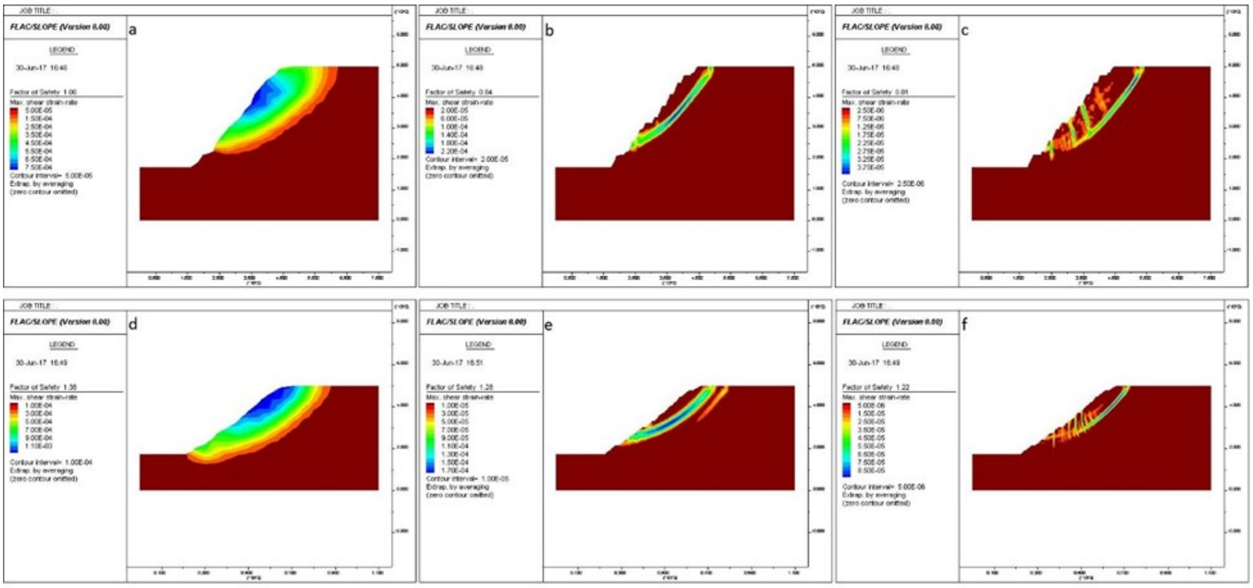

Figure 6. Safety factor and potential failure surface in 2D analyses a) coarse mesh, b) fine mesh c) extra fine mesh in the old pit, d) coarse mesh, e) fine mesh, and f) extra fine mesh in the new pit.

Regarding the safety factors obtained from the 2D and 3D analyses, the FOS_{3D}/FOS_{2D} ratio is about 1.29 in the steep slope and about 1.17 in the gentle. The height of Block I is 500 m, and the curvature radius is 180 m in the old pit' Block I and 330 m in the new pit's Block I. Thus due to the larger curvature radius and smaller angle of slope in the gentle slope, the 2D and 3D results in this pit are closer. Figure 7 shows the 3D constructed models and their obtained safety factor. The number of benches involved in the surface of potential fracture in the 3D analyses is less than the 2D analyses.

Table 5. Results of 3D analyses by considering various mesh sizes.

Old pit's Block I		New pit's Block I	
Mesh dimensions (m*m*m)	**FOS**	**Mesh dimensions (m*m*m)**	**FOS**
5*5*5	1.08	5*5*5	1.47
6*6*6	1.1	6*6*6	1.48
7*7*7	1.12	7*7*7	1.49
8*8*8	1.13	8*8*8	1.49
9*9*9	1.14	9*9*9	1.5
10*10*10	1.15	10*10*10	1.51
20*20*20	1.23	20*20*20	1.55
30*30*30	1.31	30*30*30	1.66
40*40*40	1.4	40*40*40	1.71

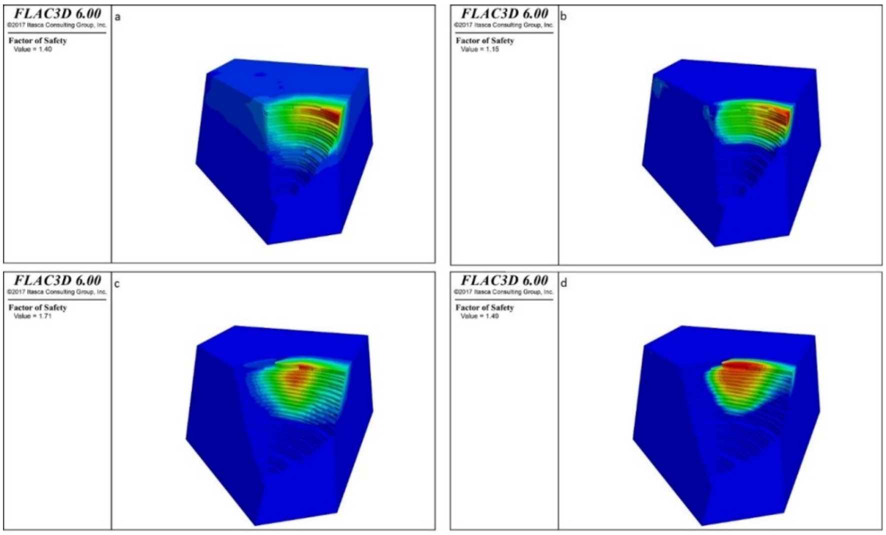

Figure 7. Safety factor and potential failure surface in 3D analyses a) coarse mesh, b) fine mesh in the old pit, c) coarse mesh, and d) fine mesh in the new pit.

Figure 8 shows the diagrams of the safety factor changes to the element size changes in the 2D and 3D analyses. By selecting a large element size, due to the increased 3D effect caused by mesh size increase, the FOS_{3D} value of the steep slope will be higher than the FOS_{2D} value of the gentle; this result could cause confusion and mistakes in detecting stable/unstable slopes. In order to avoid mistakes in detecting the stability or instability of the slopes with different steepness in different analyses, we have to set different safety levels for the 2D and 3D analyses. In this work and according to the guidelines [26], safety factors of 1.2-1.3 were chosen for 2D analyses and safety factors of 1.5-1.6 were chosen for 3D analyses. With these safety levels, all results of the 2D and 3D analyses (all considered mesh sizes) in the steep slope will be under their respective safety levels, and will be identified as unstable slopes. The diagram of the changes in FOS_{3D}/FOS_{2D} to the change of the element size is shown in Figure 9. In the fine and extra fine meshes, the amount of changes is small but in the coarse meshes, the 3D-effect starts to increase slightly; this increase in the gentle slope is more than the steep slope.

One of the important factors involved in selecting an appropriate element size is the processing power of the available equipment. For the study purposes, most of the analyses in this work were performed using a computer with a high processing power; but normally, these computers are not available for all engineers. Therefore, the appropriate element size should be selected according to the importance of the problem and the available equipment. Due to the large scale of this problem and the calculated run-times, an element size of 10 m (in both the 2D and 3D analyses) is suggested for the problems with a similar scale. In this element size, the run-times of the analyses and the accuracy of the results were acceptable.

In the next step, sensitivity analysis of the cohesion and the friction angle was performed for the 2D and 3D analyses. In each analysis, the amount of the friction angle and the cohesion were changed (±40%) and FOS recorded. Changes in FOS_{2D} and FOS_{3D} to the change of the friction angle are presented in Figure 10. Based on the results obtained, increasing the friction angle increases FOS in all cases. The amount of changes for the 2D and 3D analyses of the steep slope and 3D analysis of the gentle slope is similar (about 0.8). In the 2D analysis of the gentle slope, the amount of the changes is approximately 1.5 times the rest (about 1.2); this indicates that the sensitivity of FOS_{2D} in the gentle slope to the change of the friction angle is more than the others. The gradient of the changes of FOS in the 3D analysis in the gentle slope is non-uniform, and for the rest is uniform. Figure 11 shows the changes in FOS_{3D}/FOS_{2D} to the change of friction angle. As it can be seen, increasing the friction angle increases the FOS_{3D}/FOS_{2D} ratio in both the gentle and steep slopes. In other words, reducing the friction angle decreases the 3D-effect. The amount of 3D-effect reduction in the gentle slope is more considerable than the steep slope, and at the gentle slope with a high friction angle, the results of 2D and 3D analyses are much closer.

Figure 12 shows the changes in the FOS_{2D} and FOS_{3D} to the change of the cohesion. According to the results obtained, increasing the cohesion increases FOS in all cases. The gradient of the changes is uniform and almost the same for all analyses but the amount of changes in the 3D analyses are a little more than the 2D analyses. Hence, the sensitivity of the 3D analysis to the cohesion is greater than the 2D analysis. As shown in Figure 13, with increase in the cohesion, FOS_{3D}/FOS_{2D} increases in both types of slopes (gentle and steep). Figures 11 and 13 show the sensitivity of FOS_{3D}/FOS_{2D} to the change of their corresponding strength property. With increase in the cohesion and friction angle, all safety factors increase but the rate of changes in FOS_{2D} and FOS_{3D} for each property and in each slope is different. Therefore, based on these rates of changes for this case study, the 3D-effects for friction angle and cohesion are in reverse. In overall, the sensitivity of slopes to the changes in the friction angle is more considerable than the changes in the cohesion; particularly in the gentle slopes, an overestimation of the friction angle with using a 2D analysis (without considering a suitable 3D effect) will cause a great error in the results.

In the last step, the FDM results were compared with the limit equilibrium and finite element method using the Slide and Phase2 softwares. Among the methods of limit equilibrium approach, Janbu simplified is more conservative; hence, the safety factor of this method is used in the comparison. Table 6 shows the comparison of these results. In the unstable slope, the FDM results are more conservative than finite element and limit equilibrium (Janbu simplified); while on the stable slope, the finite element and limit equilibrium (Janbu simplified) methods are more conservative than FDM.

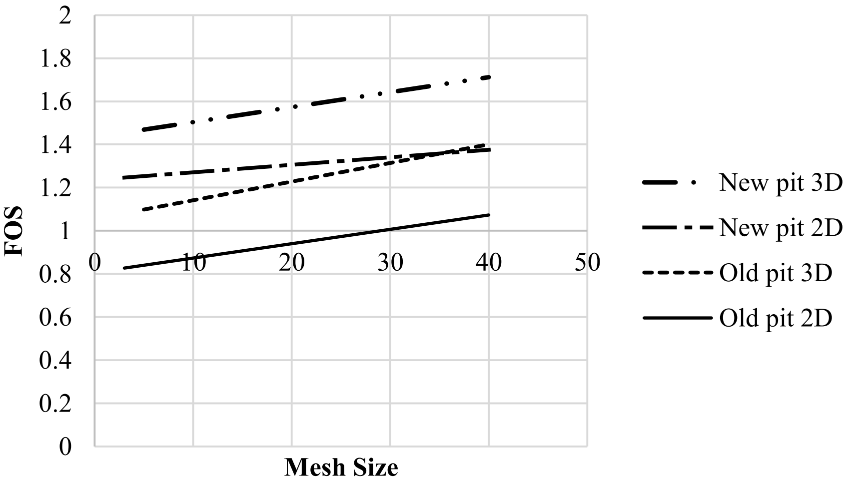

Figure 8. The safety factor changes relative to the element size changes.

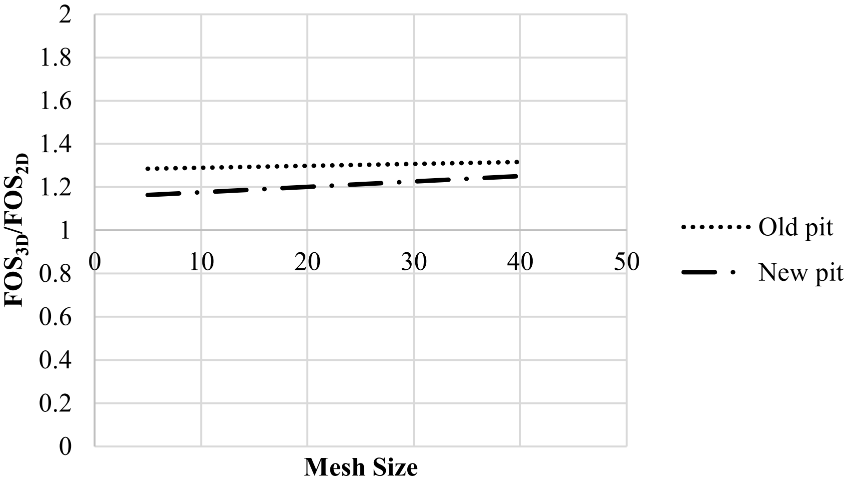

Figure 9. The changes in the FOS_{3D}/FOS_{2D} ratio to the change of the element size.

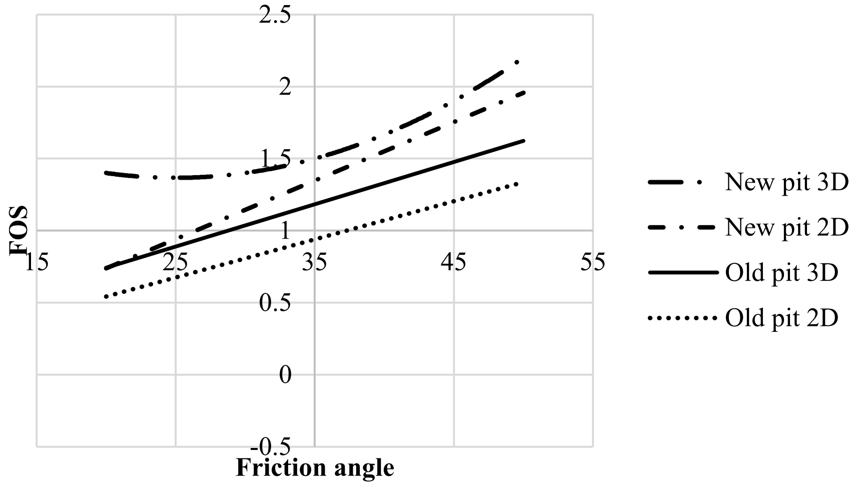

Figure 10. Sensitivity of FOS_{2D} and FOS_{3D} to the change of friction angle.

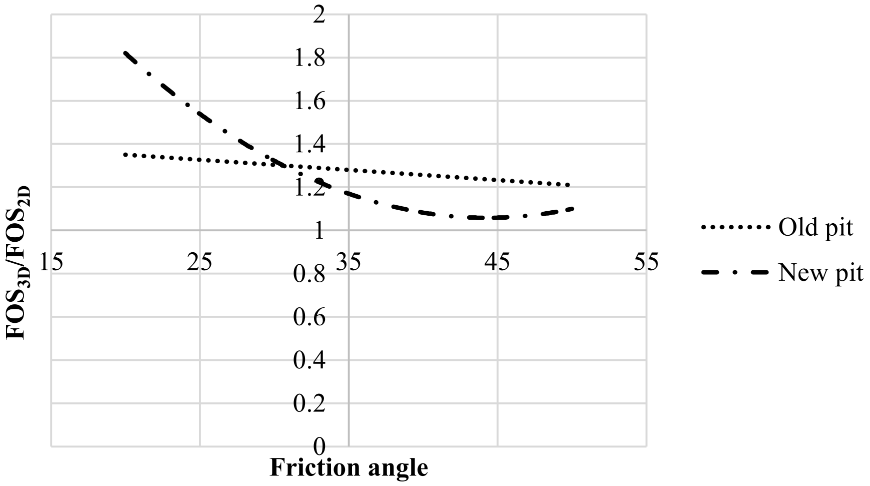

Figure 11. Sensitivity of FOS_{3D}/FOS_{2D} to the change of friction angle.

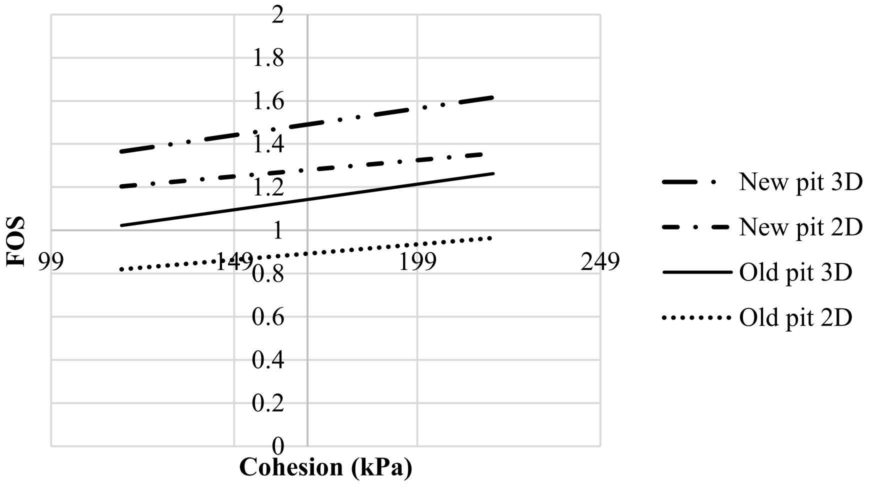

Figure 12. Sensitivity of FOS_{2D} and FOS_{3D} to the change of cohesion.

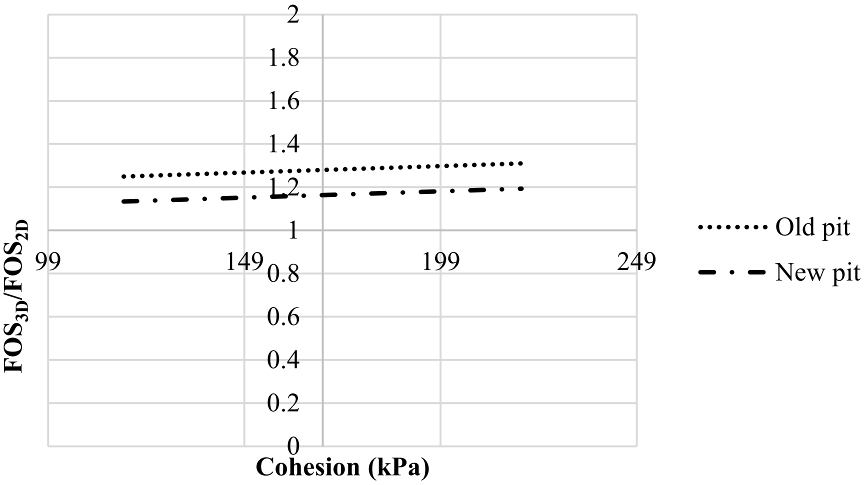

Figure 13. Sensitivity of FOS_{3D}/FOS_{2D} to the change of cohesion.

Table 6. Comparison between 3D FDM, 2D FDM, FEM, and LEM.

	FLAC3D	FLAC SLOPE	PHASE2	SLIDE
Old pit FOS	1.08	0.842	0.85	0.873
New pit FOS	1.49	1.27	1.27	1.216

9. Validation

In order to validate the analyses, the results obtained from this work were compared with the existing reports [54]. Figure 14 shows the failure in the old pit Tectonic Block I. As it can be seen, the location of the failure is exactly in agreement with the potential failure surface in the 3D analyses. Moreover, the displacements in the 3D analyses are close to the reported values. According to the results of the 3D analyses presented in this research work, it is expected that the new pit has an overall stability.

Figure 14. The failure in the old pit Tectonic Block I [54].

10. Conclusions

In this research work, the effects of the real geometry, element size, and change in the geomechanical parameters on the stability of the Tectonic Block I of Choghart iron ore were evaluated using a continuous finite difference method. After performing and comparing more than one hundred 2D and 3D analyses, the following results were obtained:

In both the 2D and 3D analyses, FOS decreased with decrease in the mesh size. The steep slope was more sensitive than the gentle slope to the change in the mesh size. Moreover, the rate of changes in FOS3D for the steep slope was more than that for the other cases. In the fine and extra fine meshes, the amount of changes in the FOS_{3D}/FOS_{2D} ratio was small but in the coarse meshes, this ratio started to increase. The FOS_{3D}/FOS_{2D} ratio was about 1.29 for the steep slope and about 1.17 for the gentle slope. The potential failure surfaces in the 3D analyses were smaller than those in the 2D analyses, and included fewer benches.

With increase in the friction angle, FOS in all cases increased. The 2D gentle slope was more sensitive than the other cases to the change in the friction angle. The rate of changes in FOS was non-uniform for the 3D gentle slope and was uniform for the other cases. Increasing the cohesion increased FOS in all cases. The rate of changes was uniform and similar for all analyses but the amount of changes in the 3D analyses was a little more than that in the 2D analyses. Increasing the friction angle reduced the 3D-effect in both the gentle and steep slopes. The amount of 3D-effect reduction in the gentle slope was more considerable than the steep slope, and at the gentle slope with a high friction angle, the results of the 2D and 3D analyses were much closer. Increasing the cohesion increased the 3D-effect in both the gentle and steep slopes. The sensitivity of the analyses to the change in the friction angle was greater than that to the change in the cohesion.

The difference in results between FDM, FEM, and LEM in a continuous 2D analyses was not significant, especially between FDM and FEM.

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تأثیر خصوصیات هندسی و ژئومکانیکی بر پایداری شیب معادن روباز با استفاده از روش‌های تفاضل محدود دوبعدی و سه‌بعدی

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چکیده:

تحلیل پایداری شیب یکی از مهم‌ترین مسائل موجود در مهندسی معدن و ژئوتکنیک است. نادیده گرفتن اهمیت این مسائل می‌تواند منجر به خسارت‌های قابل توجهی شود. انتخاب روش مناسب برای تحلیل پایداری شیب نیازمند یک درک صحیح از نحوه تأثیر عوامل مختلف بر روی نتایج تحلیل‌ها است. در این پژوهش، تأثیر در نظر گرفتن هندسه واقعی شیب، تغییر اندازه مش و تندی شیب به عنوان «اثرات ابعادی» و همچنین تأثیر تغییر پارامترهای ژئومکانیکی به عنوان «اثرات محیطی» بر روی پایداری سراسری شیب دیواره یک معدن روباز مورد ارزیابی قرار می‌گیرد. به این منظور، از روش‌های تفاضل محدود دوبعدی و سه‌بعدی برای تحلیل پایداری شیب دیواره بلوک تکتونیکی شماره ۱ معدن روباز سنگ آهن چغارت در پیت قدیمی (شیب تند) و پیت جدید (شیب ملایم) استفاده می‌شود. در مرحله اول، یک سری تحلیل پایداری شیب دوبعدی و سه‌بعدی انجام شد. در ادامه، نتایج به دست آمده از نظر ضریب ایمنی و سطح شکست احتمالی مورد مقایسه قرار گرفتند. این نتایج نشان می‌دهند که با در نظر گرفتن هندسه واقعی شیب، نسبت ضریب ایمنی دوبعدی (FOS_{2D}) به ضریب ایمنی سه‌بعدی (FOS_{3D}) در همه موارد بیشتر از یک می‌شود. مقدار این نسبت (اثر سه‌بعدی) در پیت جدید کم‌تر از مقدار آن در پیت قدیمی است. در مرحله بعدی، به منظور ارزیابی حساسیت پایداری شیب‌ها به تغییرات زاویه اصطکاک و چسبندگی، تعدادی تحلیل دوبعدی و سه‌بعدی اجرا شد. نتایج به دست آمده، حساسیت بالای نتایج تحلیل‌ها به تغییرات زاویه اصطکاک، به خصوص زوایای اصطکاک پایین را نشان می‌دهند. حساسیت اثر سه‌بعدی به تغییرات زاویه اصطکاک بسیار بیشتر از تغییرات چسبندگی است.

کلمات کلیدی: روش تفاضل محدود، دوبعدی و سه‌بعدی، پایداری شیب، معدن روباز، اثر سه‌بعدی.