

Integrated structural stability analysis for preliminary open pit design

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ABSTRACT

A design module has been developed for integrating slope stability analysis into the data management, ore reserve and pit optimisation processes of an open pit mine. The developed slope stability analysis tools were successfully implemented along the full projected pit model of a surface mine in Canada. Undertaken stability analyses included both kinematic and limit equilibrium stability analysis for bench and interramp design. The developed stability analysis modules employed geographical information systems (GIS) techniques to provide visualization tools and establish stability susceptibility zones along the pit. This approach facilitated the selection of acceptable slope design criteria for the pit. A case study was used to illustrate the developed methodology and tools. This approach led to an improved design for the optimised 3D pit configuration and can facilitate communication between the mine planning and geotechnical groups. This can contribute to a better understanding of the economic impact of the different slope and pit design scenarios. Given that open pit design is an iterative process, the opportunity of having design tools that can readily accommodate the use of updated data and explore different options provide tangible economic benefits.

KEYWORDS

Open pit design, Feasibility studies, Slope stability, Block modelling, Mining reserves, Kinematic analysis, Limit equilibrium analysis, Integrated pit design

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1 INTRODUCTION

Pre-feasibility and feasibility studies for open pit projects rely on a multitude of geological, economic, operational, and financial considerations. Ore reserve estimation relies on geoscientific data collection, model derivation and validation, estimation, and classification of resources. These data are an integral part of a comprehensive exploration program. Mine planning and the development of surface mine operations require the design, layout determination and excavation of stable pit slopes. This requires the input of mine planning, geotechnical and production personnel. The success of this process is dependent on these groups working well together. This is only feasible if there is increased communication between the different groups.

This paper provides an improved framework for the mine planning and geotechnical groups to work together by sharing data and facilitating slope stability analyses. The benefits of using

geotechnical databases to manage collected data as input for mine feasibility studies, initial slope design and ongoing slope optimisation have been documented in [1].

In the present work the authors provide a framework for integrating slope stability analysis into the data management, ore reserve estimation, pit optimisation and design processes. This approach relied on commercially available ore reserve and mine planning software to establish the optimised pit. The main contribution of the present work was the development and implementation of slope stability analysis tools that were successfully applied for the entire economically optimised 3D pit model. The stability analyses included both kinematic and limit equilibrium stability analyses for bench and interramp design. The developed stability analysis modules used geographical information systems (GIS) methods to provide visualization tools and stability susceptibility zoning along the pit. This approach facilitated the selection of the acceptable design for the pit. In the presented case study this has led to improved slope design for the optimised 3D pit configuration. This approach can contribute to improve communication between the planning and geotechnical groups and a better understanding of the economic impact of various pit design scenarios. Pit design is an iterative process and having design tools that can readily retrieve the necessary input from databases as data become available provides technical, operational, and financial advantages.

2 INTEGRATING BLOCK MODELLING AND SLOPE STABILITY

One of the first steps in the mine life-cycle is defining the orebody limits and resources. The success of any resource estimation is highly dependent on the quality of collected and assayed samples during exploration. The main sources of information at this stage are rock cores obtained through diamond drilling. Geostatistical techniques are consequently employed to establish the spatial variability of the geological resources, and block modelling is used to represent the spatial distribution of ore grades.

Block modelling is simply a subdivision of space into smaller blocks. The dimensions of the blocks are selected based on the employed diamond drilling pattern, the mining bench height, and the mine geology. Different techniques of varying complexity (e.g. inverse distance, ordinary kriging, or indicator kriging) are used to extrapolate ore grades within the blocks.

Once the resources block model has been constructed the optimal pit limits are identified based on economics considerations. An exploitation strategy is then developed based on the optimised pit. Optimisation is the process of maximizing the value of the pit based on a set of primary design parameters and assumptions at a given point in time. These include the geological models and metallurgical recovery which are all subject to an inherent degree of uncertainty associated with the sampling processes. The development of an exploitation strategy requires the investigation of different market scenarios and issues associated with supply and demand. Depending on the corporate philosophy, the design may want to minimise risk or can be risk neutral. Pit optimisation is critical in examining the economics of an open pit mine during the feasibility and production stages.

The most popular optimisation algorithm is the Lerchs–Grossman algorithm (LGA) [2]. LGA takes into account the influences of operating costs, product prices, slope geometry, etc. The LGA is used with varying revenue factors to develop a value based mining sequence strategy. This results in generated pit shells from revenue factors. Early pit shells are generated by high-grade blocks and low stripping ratio. The actual design has to also consider practical considerations such as haul road access, cut-off grades, stockpiling and processing, etc.

One way to maximize the use of block modelling functions and optimise the pit design process would be to fully integrate block modelling and slope stability analysis tools. This is a logical extension of current practice where mines already assign the rock type and grade to every block. This process can be further enhanced by defining, at every block location, the salient rock mass geotechnical properties, and in particular, the structural characteristics (fracture orientation, cohesion, angle of friction, etc.) that define the block area. Furthermore, it is possible to exploit the capacity of commercial software packages to store information on major structural features such as

faults, dykes or geological contacts. An integrated process would introduce this geotechnical database and its spatial representation into a full slope-stability analysis software package.

2.1 Slope stability analysis at the pre-feasibility and feasibility stages

A requirement during pre-feasibility and feasibility stages is to determine if the economically optimised pit slopes are stable. Based on operational requirements and on slope stability analysis results, ore-to-waste ratios (SR) are computed and preliminary pit layouts are designed. Quite often, there are limited geotechnical data available at these early stages to construct comprehensive geological and geotechnical models and provide reliable data for the stability analyses.

A comprehensive open pit slope stability analysis programme should investigate bench, interramp as well as global slope stability (Fig. 1). Bench stability is controlled mainly by local geological structure, whereas interramp stability is controlled by both local small scale and regional geological features such as faults and contacts. At the global slope level, stability is controlled by both the rock mass properties and large geological features.

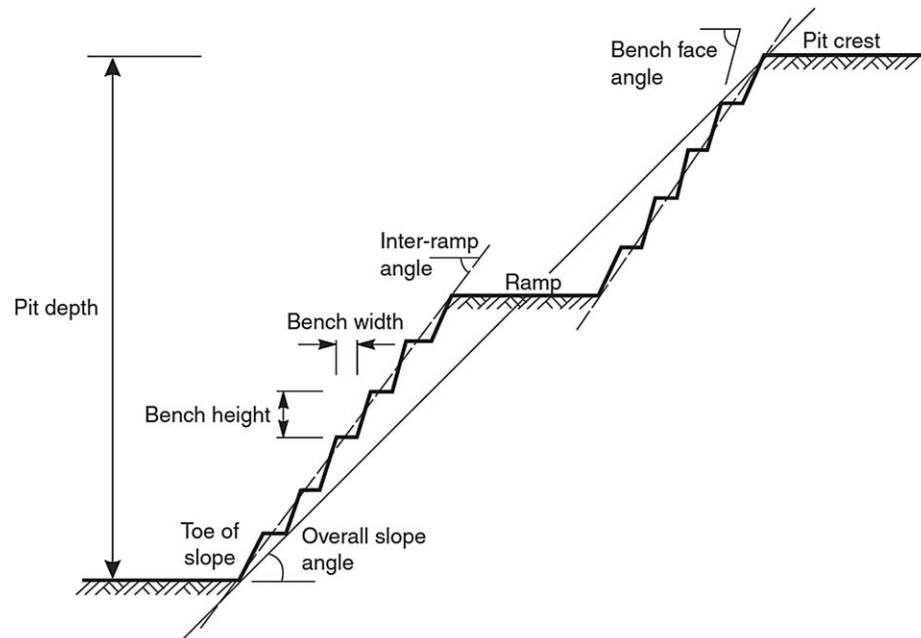


Fig. 1. Open pit slopes design scales, after [3].

In conventional design the pit is initially divided into different domains based on available information and some pre-defined criteria. These zones can be based on the lithology of the pit site, classification systems, etc. At the pre-feasibility stage and in the absence of rock face exposures the only available information is through diamond drilling. Core logging can be used to identify areas of similar rock quality and possibly the presence of major structures or zones of weakness. A kinematic stability analysis requires further information on the structural regime. This is possible if there are quality data from oriented drill cores. The use of oriented drill core data permits the construction of stereonet for different areas of the pit. This can be used, in connection with the lithology, to identify regions of similar structural characteristics. This information can then be used for slope stability analysis.

The stability of selected slopes in the different domains is determined for potential instability associated with planar, wedge and toppling failure modes. At the pre-feasibility stage this involves kinematic analyses and can produce preliminary slope design guidelines for the pit as illustrated in Fig. 2, after [4].

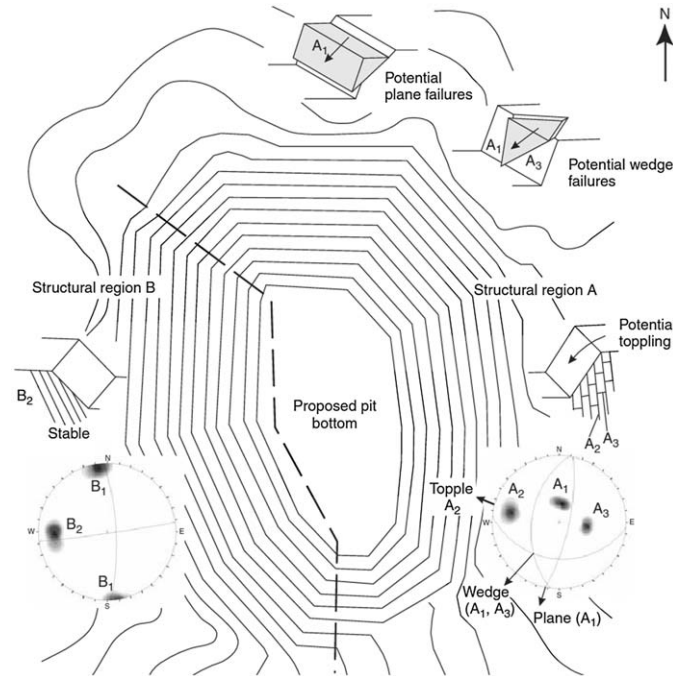


Fig. 2. Preliminary evaluation of slope stability of proposed open pit mine, after [4], reproduced from [3].

For design purposes it is convenient, for all potential failure mechanisms, to determine a factor of safety for every analysed slope. The factor of safety is usually determined using limit equilibrium techniques and is defined as

$$FS = \frac{\text{shear strength along the failure plane}}{\text{shear strength required for equilibrium}} \quad (1)$$

Stability analysis using limit equilibrium can be deterministic, sensitivity based or probabilistic. Deterministic approaches rely on the use of average values and do not take into consideration the variability and uncertainty in the employed input data. This can potentially result in misleading conclusions that, depending on the ground conditions can be either conservative or optimistic.

A more rational assessment of the associated risks with a particular slope design can be obtained by sensitivity analyses. This involves a series of calculations in which each significant input parameter is varied systematically over its maximum credible range in order to determine its influence upon the resulting factor of safety (FS). A range of possible outcomes for FS is thus obtained, enabling the identification of worst- and best-case scenarios in conjunction with the most probable results.

An even more sophisticated approach would be to assess a probability of failure for different modes of instability. This type of approach usually employs the Monte-Carlo method and uses random or pseudo-random numbers to sample from probability distributions defining selected properties of a rock mass. If sufficiently large numbers of samples are generated and used in the calculation, a distribution of FS values is generated and a probability of failure (PF) can be determined. Although the methodology for probabilistic slope stability techniques has long been understood [5], it is still not used on a routine basis in the pre-feasibility and feasibility stages of open pit mining projects.

2.2 Integrated slope stability and pit optimisation

Current slope stability analyses are limited in that they often use simplified pit geometries and often ignore the presence of pit infrastructure, such as a ramp. Quite often, only kinematic analyses are undertaken for selected locations along the pit. These stability analyses are not integrated in the mine optimisation and design process but are undertaken 'off-line'. Since the ore grades or other block model attributes are often reassessed and the pit dimensions changed during the feasibility studies, this implies that the stability of design slopes also has to be reevaluated to account for changes in slope configurations. This can be time consuming and requires good communication between the planning and geotechnical groups.

These limitations hinder the integration of the design process in surface mines. This paper uses a case study from a surface mine in Canada to demonstrate that these hindrances can be overcome. The developed stability analysis module was used to determine the stability of interramp slopes through kinematic and kinetic (FS and PF) methods. This has been implemented directly in a mine planning software package used to assess mineral resources and perform pit optimisation and mine design. The analyses focused on structurally controlled failure modes (planar, wedge and toppling) and did not investigate circular type failures associated with heavily fractured rock masses.

3 EXAMPLE APPLICATION OF AN INTEGRATED DESIGN

In order to illustrate the potential for an integrated design linking block models, optimised pits and accounting for slope stability considerations, the Gemcom Surpac (Gemcom software international inc., [6]) was used to model a metallic orebody in Canada. The pit size was 1200 by 1000 m at a depth of 300 m. The resulting ultimate pit was obtained using the Lerchs and Grossman [2] algorithm, taking into considerations available economic aspects.

During the feasibility and preliminary planning stages of an open pit mining project, the best possible representation of the final pit topography is obtained through block modelling. In this case study, the pit size was 1200 by 1000 m at a depth of 300 m and the pit surface was defined by 12 443 blocks or cells. All cells were defined by x, y, z coordinates and the structural and mechanical properties of the fracture sets that define the cells. These cells or blocks, located on the surface of the ultimate pit, were extracted from the entire block model and exported to a geographical information system (GIS) tool.

3.1 Input data

This case study investigated the potential for structurally controlled instabilities along the full pit area. The main sources of information for the stability analyses were available structural data from mapping and geomechanical data from core logging. The mine block model was used to construct a digital elevation model (DEM) for the pit with the orientations of all pit slopes determined using GIS techniques. As the topographical data information was in the raster format (data consisting of rows and columns of cells, with each cell storing pertinent values), GIS approaches were used to assess slope orientation on a cell-by-cell basis using The Mathworks' MATLAB platform [7]. In the MATLABGIS environment, slope orientation is defined by two parameters, slope and aspect. The slope (S) of a cell is the maximal inclination of a plane formed by the centre of a cell and the centre of its immediate neighbours. The aspect (A) of a cell identifies the steepest down slope direction from each cell to its neighbours. The use of slope and aspect is equivalent to dip and dip direction used in rock engineering to define fracture and slope orientation. Fig. 3a illustrates the pit topography in a 3D projection view, and Fig. 3b is a map view. All terrain elevation is with reference to sea level and is in metres. Higher terrain elevations are shown in brown, whereas lower elevation zones are in blue.

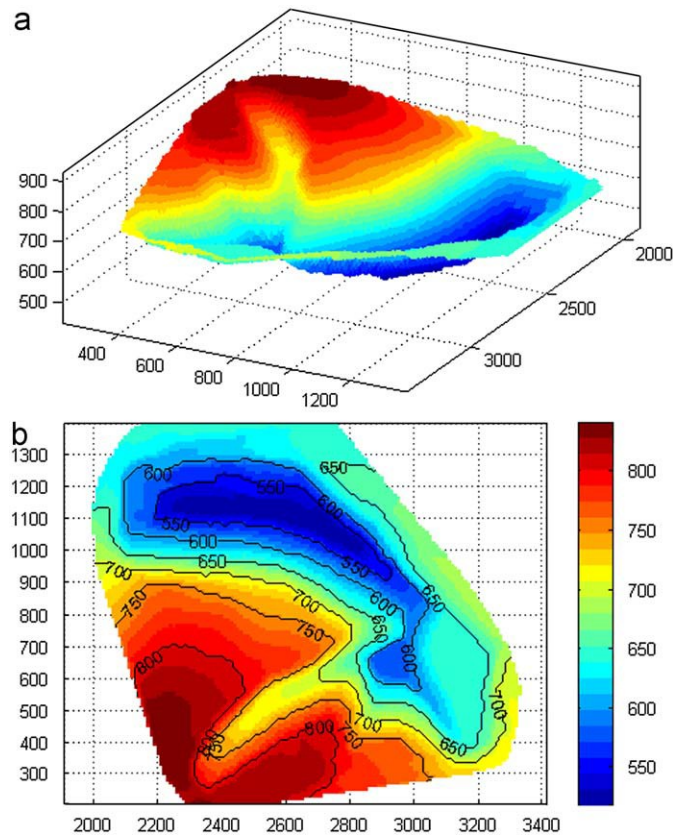


Fig. 3. Pit topography in (a) 3D projection view and (b) map view, terrain elevation above sea level (m).

A complete topographic analysis of the proposed open pit required the slope orientation of each cell of the DEM. This has been addressed in GIS stability analysis of natural slopes. Jaboyedoff et al. [8] analysed the stability of natural slopes using a coloured shaded relief map that combined both slope angle and slope aspect to visualise the results of a topographic analysis. This was accomplished by coding the slope orientation following the hue–saturation intensity (HSI) model. The implemented approach is similar to the work of Moellering and Kimerling [9].

The HSI model is defined by hue, saturation and intensity, Stevens [10]. Hues are simply the different colours. Colours are arranged in a circular pattern with the hue axis running from 0–360°. The colour sequence begins and ends with red and runs through green, blue and intermediary colours like greenish-blue, orange, purple, etc. Saturation refers to the depth or strength or vividness of a colour. It assigned values from 0%, no colour saturation, to 100%, the fullest saturation of a given hue at a given percentage of intensity. The level of illumination is quantified by intensity values that range from 0% in the absence of light, i.e. black, to full illumination, i.e. 100% illumination. Under full illumination, a colour of an HSI model is washed out and appears white.

The HSI model can be visualised and interpreted using stereonet. As illustrated in Fig. 4a, a given HSI value is defined by a unique trend and plunge combination. In this paper the HSI system was coded to represent the orientation of the normal vector to a slope plane. Fig. 4b shows two different representations of a slope plane oriented at a dip and dip direction of 60°/45°. The first approach plots the great circle of the plane on the stereonet, whereas the second plots the pole of the normal to that plane. In this example the pole is at a trend and plunge of 225°/30°. This plane is defined by a purple-blue colour located in the third (S–W) quadrant of Fig. 4a.

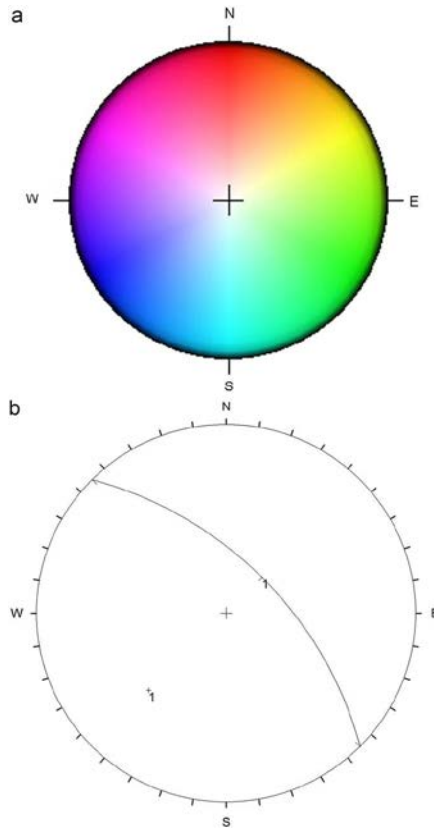


Fig. 4. (a) Stereographic projection of the HSI system; (b) great plane and pole representation of plane orientation on a stereonet.

In the developed stability module this approach was used to perform a topographic analysis of the open pit. The results are presented in Fig. 5a, with all cells assigned a colour based on their slope orientation. In this representation, flat surfaces are white and steeper slopes are identified by incrementally darker colours as illustrated using the constructed legend stereonet in Fig. 5b. Slope orientation was represented on a map using the pole vector convention; using the trend and plunge of the normal vector to a plane to represent slope orientation. Fig. 5b provides an interpretation legend of the colour code defining slope orientation and the direction of the mine North. This is important as the mine North does not coincide with the geographic North.

For the purposes of demonstrating the developed methodology, the ultimate pit was divided into two structural domains (401 and 402). All fracture sets were defined by mean dip and mean dip direction, Fisher's constant K , as well as the mechanical properties of the fractures, Table 1. Fisher's constant is a measure of the degree of clustering within the population [11]. An estimate, k , can be calculated from a sample of M unit vectors, for which the magnitude of the resultant vector is $|r_n|$. An unbiased estimate of K , when M is large, is provided by the following equation [12]:

$$k = \frac{M-2}{N-|r_n|} \quad (2)$$

At the feasibility stage data on the properties of fractures can be limited, but as more information becomes available the geotechnical database can be updated. The developed stability module can reanalyse the results as more data become available and the database is updated.

The two structural domains were incorporated into the block model, on a block by block basis, using Gemcom Surpac (Fig. 6). The mining bench height was 14 m, and the block dimensions were 10 by 10 by 14 m.

Table 1. Structural domains

Domain	Fracture set	Dip	Dip direction	Fisher's coefficient	φ	Cohesion	Density (t/m ³)
401	1	70	201	50	40	0	2.7
	2	3	194	75	40	0	2.7
	3	90	220	75	40	0	2.7
	4	86	183	75	40	0	2.7
	5	86	203	50	40	0	2.7
402	1	80	348	55	40	0	2.7
	2	84	10	100	40	0	2.7
	3	51	318	75	40	0	2.7
	4	22	262	75	40	0	2.7
	5	45	123	100	40	0	2.7
	6	26	201	75	40	0	2.7

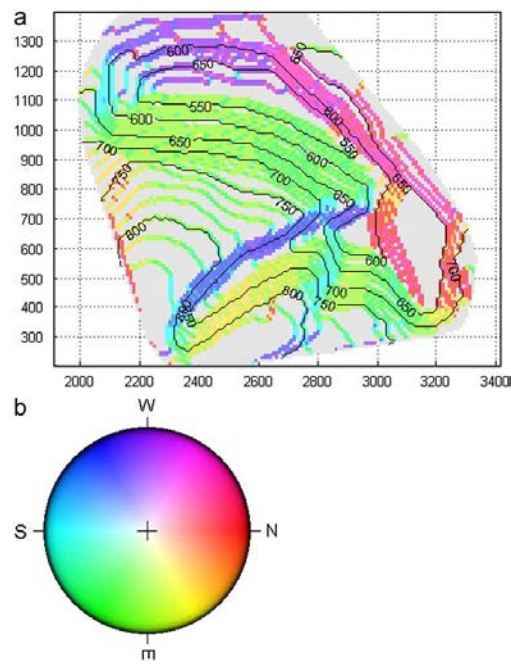


Fig. 5. (a) Map of slope orientation including 3D colour scheme; (b) slope orientation legend stereonet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

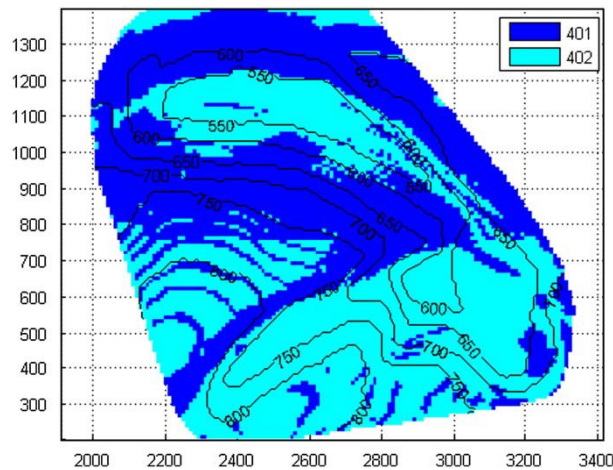


Fig. 6. Topography and structural domains extracted from the mine block model.

3.2 Kinematic analysis

At this stage of the integrated design, a 3D pit model was developed, the slope geometries were defined and the pit was divided into structural domains. The next step was the identification of pit areas susceptible to structural instability. A series of kinematic analyses were undertaken to investigate whether any given fracture–slope configuration was susceptible to planar, wedge or toppling failure modes. Although kinematic analyses are routine in preliminary stability work the significance of the present work lies in performing customised stability analyses considering the actual slope geometries at the pit scale and accounting for spatial variations of the rock mass conditions defining the different structural domains. This was achieved by performing kinematic stability analyses for every block model cell.

3.2.1 Implementing a GIS kinematic slope stability analysis

Kinematic feasibility conditions for rock slopes are summarized in several rock mechanics textbooks, for example [13]. The kinematic feasibility of plane instability requires that several conditions are satisfied: the dip of the slope must exceed the dip of the potential slide plane; the potential slip plane must daylight on the slope plane; the dip of the potential slip plane must be such that the strength of the plane is reached; the dip direction of the sliding plane should lie at approximately $\pm 20^\circ$ to the dip direction of the slope.

The kinematic feasibility for wedge instability requires that a wedge can slide along an intersection line between two geologic structures. The dip of the slope must exceed the dip of the line of intersection of the two fracture planes defining the potentially unstable wedge. For wedge failure to occur the line of intersection must daylight on the slope face. The dip of the line of intersection of the two fracture planes associated with the potentially unstable wedge must be such that the strengths of the two planes are reached.

The kinematic conditions for toppling are that one set of fracture planes dips into the slope at an angle that can result in interlayer slip, and that the direction of the slip planes is within 30° of the slope. Traditionally a kinematic analysis can be undertaken using stereonet or using trigonometric equations. Both approaches can be done manually or using computer software. The process is relatively quick for a single analysis, but can become time consuming when several slope–fracture configurations must be investigated. One efficient way to overcome these limitations is to use a GIS-based approach as proposed in this paper.

The developed slope stability module implemented a vector representation for kinematic analysis conditions in the MATLAB environment. The structural properties of fractures defining the blocks located on the surface of the pit and their respective slope orientations were already introduced or computed into MATLAB. Once the conditions for kinematically feasible planar conditions were implemented on a cell by cell basis in MATLAB it was possible to use the full pit geometry and material properties to establish the kinematic feasibility of planar failure.

Based on the digital elevation model, slope geometry and the mean values of the structural data, a series of kinematic analyses identified those cells susceptible to failure. All cells defined by a kinematically feasible failure were assigned a rating of one, and if stable they were assigned a rating of zero. The results of a plane failure kinematic analysis for the design pit are illustrated in Fig. 7a. The legend to the right of Fig. 7a indicates the probability of failure (PF). In the case of a deterministic kinematic analysis PF is either equal to 0 or 1. Using the proposed colour scheme this results in blue or red cell colouration.

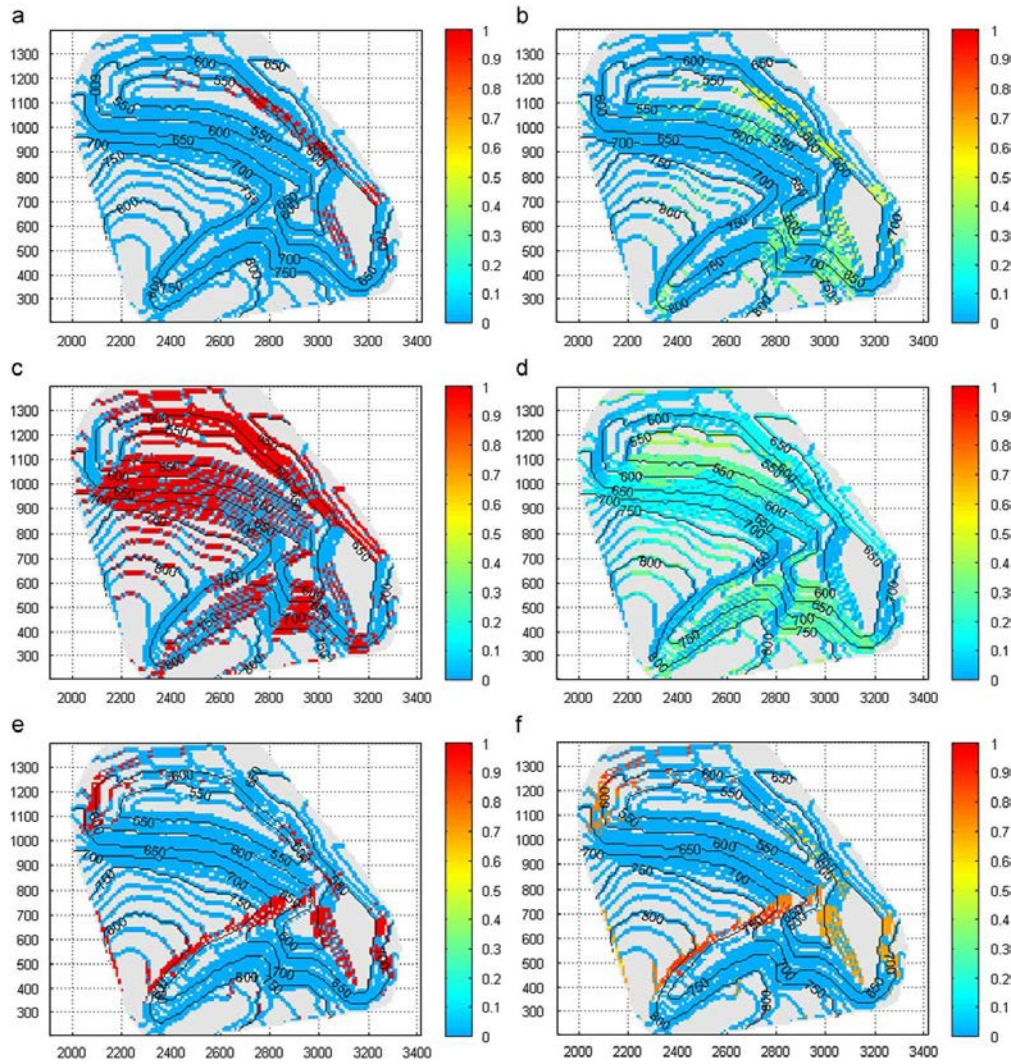


Fig. 7. Kinematic analysis of the rock slope: deterministic evaluation of planar, wedge and toppling instability A, C and E, and probabilistic evaluation of planar, wedge and toppling instability B, D and F. The legends indicate the colour coding associated with the probability for kinematic feasible instability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Even if only one fracture set in a cell was susceptible to planar failure, the cell is considered as unstable. In this case study example, slopes potentially susceptible to fail in planar mode were localized in the higher elevation areas. Only a few cells were unstable and the majority were associated with fracture set 5 in structural domain 402.

The GIS-based kinematic analysis was carried further to facilitate a kinematic probabilistic analysis. The structural data were retrieved from the GIS module and easily introduced in a kinematic analysis accounting for dip and dip direction variability for the major fracture sets defined in Table 1. The database and analyses can be updated as more data become available (for example, fracture mechanical properties). The Fisher statistical distribution was used to define the dip and dip direction input parameters. A Monte-Carlo sampling process approach was used to quantify the probability for planar kinematic feasible instability, P_k :

$$P_k = \frac{\text{Number of kinematically feasible samples}}{\text{Total number of samples}}$$

For example, in structural domain 402 all cells were defined by six fracture sets. For a given cell in this domain, 10,000 fractures were generated for each set. Their dip and dip direction were allowed to vary according to the corresponding Fisher probability density function (pdf). It was then possible to establish the kinematic feasibility P_k for every fracture set. This approach provided an insight into the influence of variability within a structural domain.

Fig. 7b shows the maximum P_k of any fracture set at a given cell location. This can be considered as the worst case scenario. Whereas Fig. 7a is a Boolean representation (potential for failure or potentially stable), Fig. 7b gives a more nuanced representation of areas in the pit that pose potential stability problems. The legend of Fig. 7b indicates the probability of failure (P_k), from 0 to 1, based on a kinematic analysis.

Determining if the necessary conditions for kinematic wedge instability are met is relatively more complex under a cellular or raster representation of space. This was overcome by representing the kinematic conditions presented at the beginning of this section in vector form according to the procedure outlined in [14]. The necessary conditions for wedge instability were coded in the MATLAB environment.

The results of the kinematic stability analysis for wedge type failure are presented in Figs. 7c (deterministic) and d (probabilistic). In structural domain 401 potential wedge instabilities are mostly associated with fracture set combinations 1–3 and 1–4, whereas in domain 402 wedge type failures are due to the combination of fracture sets 2–5.

It has been recognised that deterministic analyses can fail to capture the inherent variability of the geotechnical input data. Furthermore, defining a slope as stable or unstable using a Boolean criterion can influence the way the results of a slope stability analysis is interpreted. In this case study, the results of the deterministic analysis would suggest that the projected slope configuration is unstable requiring a revised design to less steep slopes to reduce the risk of slope failures. Using flatter slopes can potentially have important ramifications to the economics of the project.

The results of probabilistic analyses for wedge type failures are represented in Fig. 7d. The probability of failure along the pit area is mostly below 35%. This implies that the probability and magnitude of projected instabilities are less than suggested by the results of the deterministic analysis. Pit zones that are unstable as shown in Fig. 7c are subject to more nuanced interpretation in Fig. 7d.

The necessary conditions for kinematic toppling instability were also implemented under a GIS. The potential for deterministic and probabilistic toppling is illustrated in Figs. 7e and f. Toppling failures are only of concern in a limited area in the pit. It is interesting to note that the P_k is well above 70% for most of the unstable cells, indicating that if toppling is kinematically possible it will most likely be unstable.

3.3 Limit equilibrium analysis

Limit equilibrium analyses (LEA) are used to compute the factor of safety for a sliding mode for a given slope configuration. The factor of safety (FS) is defined as the ratio of shear strength to shear stress required for equilibrium of a slope. The structural and mechanical properties can be presented by a single design value (often an average) or by assigning a probability distribution function.

3.3.1 Implementing a GIS limit equilibrium slope stability analysis

In the GIS analysis, the resulting planar and tetrahedral wedge geometries were determined based on block theory [15]. Subsequently, all individual forces acting on a wedge were determined and the resulting active and passive force vectors for the wedge calculated. Once the sliding direction and

the normal forces acting on each wedge plane were determined, the resisting forces due to joint shear strength were calculated. This allowed the determination of the factor of safety for planar and tetrahedral wedge failure modes.

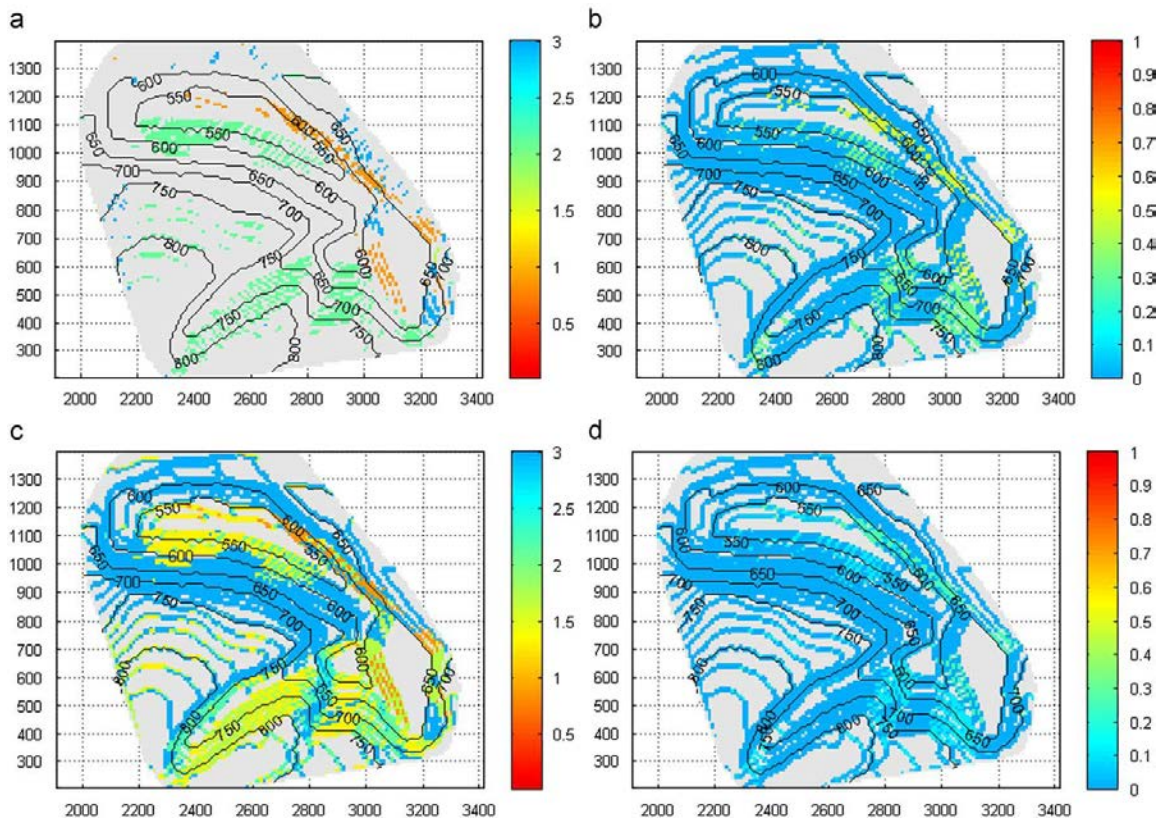


Fig. 8. Limit equilibrium analysis of the rock slope: deterministic evaluation of planar and wedge instability A and C (the legends indicate the colour coding associated with FS) and probabilistic evaluation of planar and wedge instability B and D (the legends indicate the colour coding associated with PF). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The results of the deterministic planar LEA are illustrated in Fig. 8a. The legend of Fig. 8a summarises the colour coding used for the FS. Very few slopes are susceptible to planar failure, i.e. a factor of safety < 1 . Cells, where no planar failure was possible, are coloured grey. A Monte-Carlo probabilistic approach was used to assess the probability of failure (PF). This is similar to the Pk computed in the kinematic analysis. The PF value defining the fracture set with the highest PF is plotted in Fig. 8b. The legend in Fig. 8b indicates the PF colour coding. The cells in grey are where no wedge failure was possible. In this case, the probability of planar failure, even for the most critical plane, is relatively low. In the structural domain 402, planar failure is more likely in the cells where fracture set 5 is present.

Based on the results of the deterministic wedge LEA, plotted in Fig. 8c, very few slopes were susceptible to wedge failure. This was somewhat surprising given the high number of unstable cells given by the deterministic kinematical analysis in Fig. 7c. This disparity is discussed in Section 4.1.

The results of the wedge probabilistic LEA, illustrated in Fig. 8d, suggest that the probability of wedge failure is relatively low. The majority of wedge failures are due to the fracture set combinations 2–5 in domain 402. From a design viewpoint, based on the results of the LEA, the actual interramp angle was acceptable.

3.3.2 Probabilistic slope design criteria

LEA techniques can be used to determine factors of safety (FS) and probabilities of failure (PF). These resulting FS and PF values can then be used to determine whether a particular mine slope design is acceptable. Hoek [16] suggested that for planar and wedge sliding along structural features, a factor of safety 41.3 is sufficient for ‘temporary’ slopes with minimal risk of damage, whereas a factor of safety 41.5 may be more appropriate for ‘permanent’ slopes with significant risk of damage. It was also suggested that a probability of failure of 10–15% may be acceptable for open pit mine slopes where the cost of clean up may be less than the cost of stabilisation.

More complex design guidelines have been proposed by several authors, including the ones from [5] reproduced in Table 2. For various categories of slopes they suggest tentative acceptable values for a mean factor of safety and the probabilities $P(F < 1.0)$ and $P(F < 1.5)$. These are values ranging between 0 and 1.0, indicating the probabilities that a factor of safety of a given slope will be 0.1 and 1.5. Table 3 illustrates how this information can be used to interpret the stability performance for a given rock slope, depending on design purpose and on whether the defined probabilistic design criteria are met.

Table 2. Probabilistic slope design criteria, after Priest and Brown [5].

Category of slope	Consequence of failure	Examples	Acceptable values		
			Minimum		Maximum
			Mean F	$P(F < 1.0)$	$P(F < 1.5)$
1	Not serious	Individual benches, small (height < 50 m) temporary slopes not adjacent to haulage roads	1.3	0.1	0.2
2	Moderately serious	Any slopes of permanent or semi-permanent nature	1.6	0.01	0.1
3	Very serious	Medium size (50–150 m) and high slopes (> 150 m height) carrying major haulage roads or underlying permanent mine installations	2.0	0.003	0.05

Table 3. Slope performance interpretation, after Priest and Brown [5].

Satisfaction of slope design criteria	Interpretation
Satisfies all three criteria	Stable slope
Exceeds minimum mean F but violates one or both probabilistic criteria	Operation of the slope presents a risk which may or may not be acceptable. The level of risk can be assessed by a comprehensive monitoring program
Falls below minimum mean F but satisfies both probabilistic criteria	Marginal slope. Minor modifications of slope geometry are required to raise the mean F to a satisfactory level
Falls below minimum mean F but does not satisfy both probabilistic criteria	Unstable slope. Major modifications of slope geometry are required. Rock improvement and slope monitoring may be necessary

The GIS approach proposed in this paper is particularly suited to multi-criteria design guidelines. It can easily be used to produce susceptibility maps identifying zones that do not meet any user defined design requirements. The potential of this approach is illustrated by applying the design guidelines proposed in [16] to evaluate the proposed slope design.

Fig. 9a presents a map of the pit where cells susceptible to wedge failure and having a mean FS 0.1.3 are colour coded red. This information can be used in combination with the PF map for wedge instabilities shown in Fig. 8d to conclude that only a limited area of the pit is potentially unstable. Temporary pit slopes of the optimised pit meet all design criteria. In selecting areas to place permanent mine infrastructure it would be usual to use a higher factor of safety threshold of 1.5. The revised susceptibility map for wedge type failure is illustrated in Fig. 9b. The pit area around the final ramp may be considered as ‘permanent’ slopes. Fig. 9b presents the location of the ramp, which is

characterized by two switch backs. Based on the available information the ramp is situated in an area that should not be susceptible to slope instability.

This case study illustrated the ease of implementing probabilistic design criteria to produce GIS-based susceptibility maps. It furthermore demonstrated an advantage of slope stability design along the actual pit layout. The proposed approach can be used with any slope design criteria and can provide a visual representation of different stability conditions along the pit. This provides an excellent tool for communications between the geotechnical, mine planning and eventually the production groups.

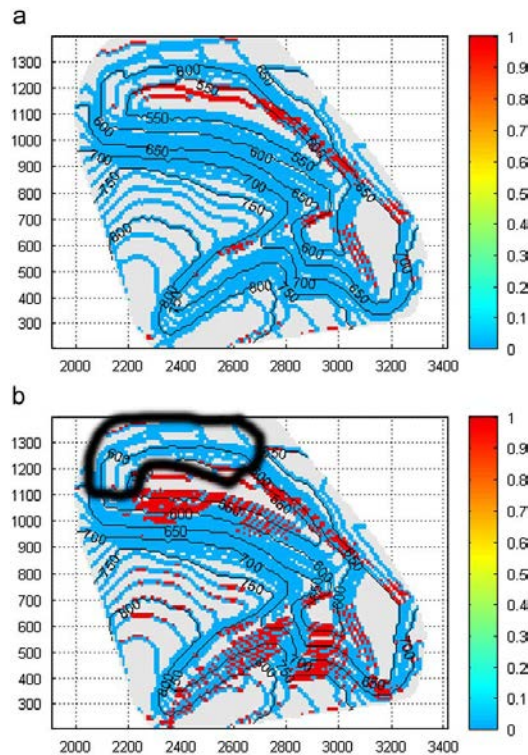


Fig. 9. LEA based on the probabilistic criteria proposed in [16]. (a) The deterministic LEA for wedge instability using a threshold $FS = 1.3$; (b) the deterministic LEA for wedge instability using a threshold $FS = 1.5$.

4 DISCUSSION

This paper has demonstrated an integrated design approach for preliminary pit design. The presented methodology allowed the evaluation of slope stability by both kinematic and LEA for all defined slopes of the optimised pit. This is significant because quite often initial pit design does not involve comprehensive slope stability analyses. This is often justified by claiming that data quality and quantity do not justify the time and expense and that the use of simplified assumptions make sophisticated analyses not justified.

4.1 Kinematic versus limit equilibrium analysis

At the preliminary stages of pit slope design, stability investigations rely on kinematic analyses. As demonstrated in Section 3, substantially different results were obtained using LEA and kinematic analyses for wedge type instabilities. The discrepancy between the approaches is illustrated in Fig. 10. Fig. 10a is a spatial representation of cells (in red) susceptible to wedge instabilities based on a kinematic analysis, whereas Fig. 10b identifies cells (in red) having a factor of safety ≤ 1 and therefore deemed unstable. The results of these two types of analyses are quite different and would result in

different design strategies. Based on the results of the kinematic analysis the obvious strategy would be to flatten the slopes. This would have important cost ramifications and a direct impact on the financial viability of the pit. On the other hand, the LEA results would suggest that the proposed design slopes were acceptable.

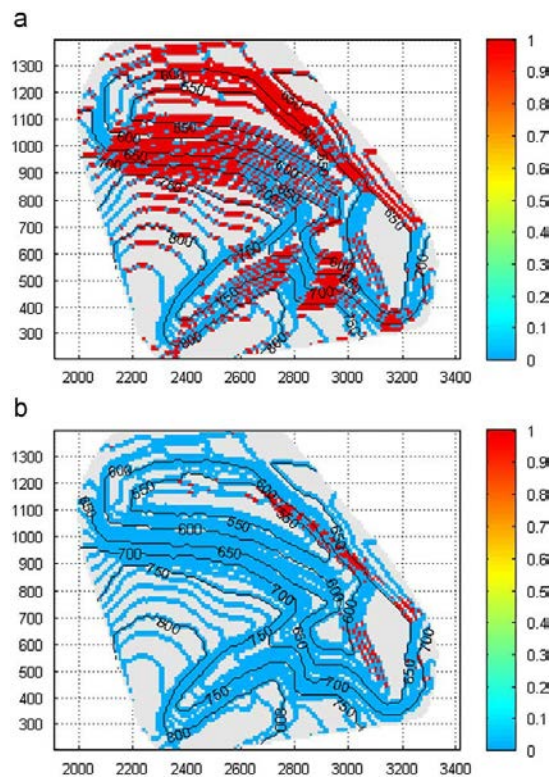


Fig. 10. (a) Kinematic analysis of the rock slope for wedge instability; (b) LEA of the rock slope for wedge instability. Legend presents the probability of failure (PF).

The potential discrepancy between kinematic and limit equilibrium analyses of wedge type failures has been recognised in the past for individual slopes. The GIS analyses in this paper have highlighted the significance and implications of these differences when they are superimposed on the design pit. Failing to account for this discrepancy would necessitate excessive design changes along a very large area.

Hudson and Harrison [13] attributed differences between LEA and kinematic analyses of wedge type failures to the wedge geometry, or 'how upright and how sharp the wedge is'. In all, four types of wedges were identified: thin inclined, thin vertical, thick upright and thick inclined wedges. A wedge factor is thus determined based on (d), the sharpness of the wedge or included wedge angle, and by (b), the verticality of the wedge, which is measured with respect to a horizontal axis, Fig. 11a. The significance of the wedge geometry is illustrated in Fig. 11b, where a small included angle (d) and a high verticality angle (b) result in a high factor of safety for kinematically feasible wedges.

In this case study, the kinematically feasible wedges in domain 401 were formed by the intersection of fracture sets 1–3 and 1–4. These thin upright wedges had a high verticality angle and a small included wedge angle, resulting in factor of safety much higher than 1. The spatial distribution of these wedges may be derived by comparing Figs. 10a and b. To ignore the wedge factor by performing only a kinematical analysis results in conservative designs with potentially adverse impact on the economics of the open pit.

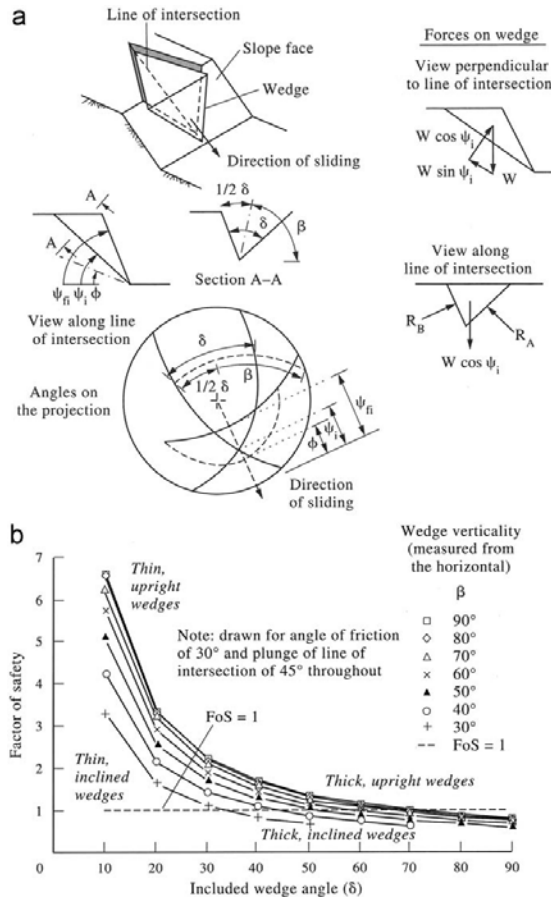


Fig. 11. (a) Wedge geometry definition and (b) simplified analysis of wedge failure demonstrating variation in factor of safety with included angle and wedge verticality, after [13].

4.2 Multiple design scenarios and changing economic conditions

The optimisation algorithms used in defining the ultimate pit for a given mining project are based on the maximization of the monetary output. This involves the choice of constraints such as mining and milling limits, ore contaminants limits, etc. In these algorithms, design slope angles are used as upper limits.

It is recognised that the final slope configurations will be dictated by stability considerations as well as other factors such as terrain topography, orebody geometry and grade distribution. In this case study it was observed that the terrain topography controlled slope geometry in region A of Fig. 12. In zone B, it was the ore-waste contact that was the deciding factor, whereas in zone C slope configuration was defined by the maximal stable slope angle. This case study shows it is incorrect to consider that for all areas of the pit, the slope geometry would only be controlled by the maximal stable slope angle. In doing so, the angle values (for interramp) used in the slope stability assessment may be too steep, which could result in a design that is too conservative.

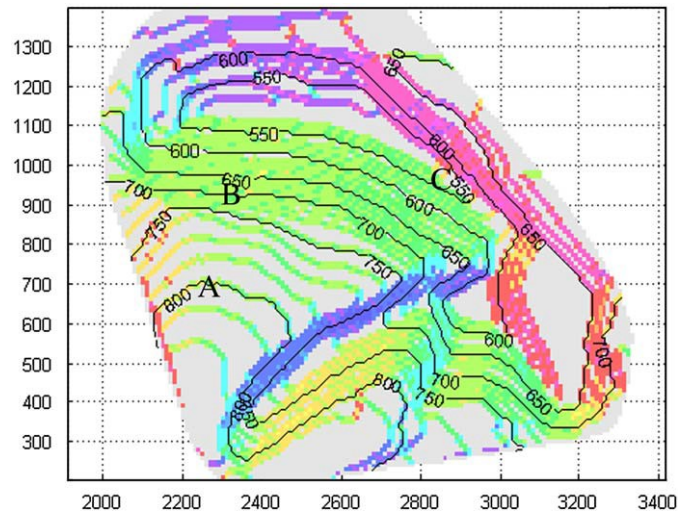


Fig. 12. Factors controlling the final pit slopes in the optimisation process: (a) natural terrain topography; (b) ore contact and (c) maximal slope angle constraint.

At the mine planning stage it is appropriate to evaluate multiple design scenarios. A case in point is the location of the ramp. Although several operational constraints will have a strong influence on the location of the ramp, the developed methodology can provide the level of stability risk associated with various options. In a fluctuating market environment, and to comply with long term company strategies, it is necessary to consider several optimisation exercises to explore different metal market prices. The developed integrated approach can provide immediate reassessment of slope stability for new pit layout. It can also quantify the impact of more aggressive slope design on the pit stability. Finally, since the approach features a direct link with the pit design tools, it provides an immediate and accurate insight into the economic implications of various scenarios.

5 CONCLUSIONS

This paper has addressed several practical issues in stability analysis of rock slopes during the feasibility stage of open pit design. An integrated approach was used to bring together block modelling and slope stability analytical tools. The proposed stability analysis is applicable along the full pit area and allows for stability investigations on all generated slopes in any proposed pit configuration. This example case study clearly demonstrated an effective mean of evaluating the actual planned slope orientations. The ease that the analyses can be revised as more data become available allows for thorough investigations of different optimised pits that can accommodate fluctuating financial and production data. This increased flexibility can contribute to better design and can respond to the needs of planning, geotechnical and production groups.

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