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Preliminary pit slope design using a simple analytical approach

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Abstract

Pit slope optimisation is a complex process as appropriate designs must be provided for different slope elements at batter, inter-ramp and overall slope scales. Maximum achievable parameters at just one scale do not always satisfy design stability criteria for the other slope scales. Therefore, the pit slope optimisation process often requires several iterations to reach an optimum result. However, a simple analytical approach can be useful for slope design in early stage studies or to develop a basis for initial pit shell design upon which further detailed pit slope optimisation analyses can be conducted.

Providing recommendations for preliminary slope angles requires an understanding of which scale of instability is the most critical one controlling the overall slope angle. In strong rock masses, achievable overall angle is usually controlled by limitations in batter–berm geometry. In weak rock masses, assessment of overall slope stability is a key factor in identifying optimum slope angle. For medium-strength rock masses, both scenarios may be applicable. This paper explains a simple analytical approach for identifying overall slope angle, based on a method of identifying collective shear strength properties within the rock mass constituting the overall slope and then using established design charts to determine appropriate slope angle. The approach has a key limitation: it requires that there should be no strong influence of structural fabric on rock mass shear strength in a directional manner (i.e. the rock mass must be isotropic); however, heterogeneous rock masses can be assessed if the properties of the lithologies or domains are not vastly dissimilar.

Some case studies are presented to illustrate the preliminary slope angle recommendations based on the simple analytical approach. The appropriateness of the resulting slope designs has been assessed using stability analyses.

Keywords: *simple analytical approach, early studies, preliminary slope angle, heterogeneous rock masses, collective shear strength, design charts, limit equilibrium method, finite element method*

1 Introduction

Pit slope optimisation is a complex process as appropriate designs must be provided for different slope elements at batter, inter-ramp, and overall slope scales. Maximum achievable parameters at just one scale do not always satisfy design stability criteria for the other slope scales. In addition, slope stability and appropriate design may depend on the exact location of slopes within the rock mass. Therefore, the pit slope optimisation process often requires several iterations to reach an optimum result based on both the resource geology model and appropriate slope angles. Providing recommendations for preliminary slope angles requires an understanding of which scale of instability is the most critical one controlling the overall slope angle.

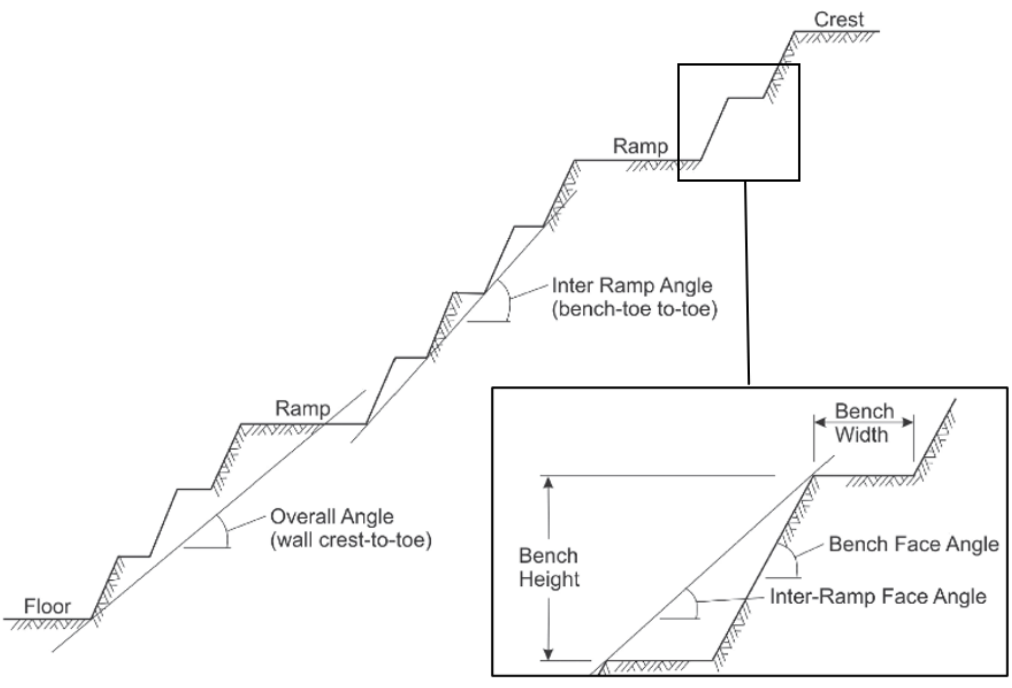
In strong, competent rock masses, achievable overall or inter-ramp slope angle is often limited by batter–berm geometry requirements which are defined either by kinematic stability assessments or by mining requirements. In medium-strength and weak rock masses, overall slope performance is usually a key factor in the determination of optimum slope angle.

At the preliminary design stage, assessment of the overall or inter-ramp slope angle can be carried out using design charts which have been based on analytical methods and can be useful tools for rapid design inputs prior to later detailed stability analyses. The slope angles obtained from the design charts should be compared with the slope angles generated by the required batter–berm geometry. The appropriate slope angle for each slope sector or domain within the pit is the minimum of the two scenarios, and this is provided to the mining engineers as an initial input for the pit shell creation. The use of design charts traditionally requires that the material forming the slope is homogenous, with uniform shear strength properties along the candidate failure surface. However, the simple analytical approach suggested in this paper is applicable in heterogeneous rock masses if lithologies are of similar geological types and/or have properties that are not vastly dissimilar. The same design charts can be used for identifying the overall slope angle, however, collective shear strength properties within the rock mass constituting the slope are first estimated. The simple analytical approach requires that the rock mass should be isotropic, with no strong influence of structural fabric on rock mass shear strength that can influence stability in a directional manner.

After the pit design is created, more sophisticated analyses are usually necessary for confirmation or further optimisation of the slope design in more advanced (pre-feasibility or feasibility) levels of study.

2 Synopsis of analytical approaches

It is a common approach for slope design that where the rock mass strength is expected to be the controlling factor for slope stability (i.e. weak or medium-strength rock masses), the design process should commence with analyses to establish suitable overall and inter-ramp slope angles (Read & Stacey 2009). In medium and strong rock masses, where persistent structures or structural fabric are expected to be a controlling factor, achievable overall angle is likely to be controlled by limitations in batter–berm geometry, and the design process should commence with assessments at this scale (Figure 1).



	Rock Mass Strength		
	Weak	Moderate	Strong
Slope Element			
Bench Face	Strength (structure)	Structure	Structure
IRA	Strength	Structure (strength)	Structure
Overall	Strength	Structure (strength)	Structure (strength)
Design approach	General Overall ↑↓ IRA ↑↓ Bench	By Sector Bench ↓ IRA ↓ Overall	By Sector Bench ↓ IRA ↓ Overall
	Major structures may impact Overall (and IRA)		

Figure 1 Slope design approach (modified after Read & Stacey 2009). Note: IRA = inter-ramp angle

At initial stages of pit optimisation, before pit designs are created, it is useful to estimate appropriate batter–berm and overall slope geometry using some simple approaches which help to understand the key limiting factor for achievable overall angle.

Overall slope angle by batter–berm geometry (α_r) can be estimated using Equation 1:

$$\alpha_r = arctg \frac{H}{\sum B_i + \sum h_i \, ctg\alpha} \tag{1}$$

where:

arctg = arctangent.

ctg = cotangent.

H = height of the overall slope.

h = batter height.

α = batter angle.

∑B = sum of all horizontal elements (berms, geotechnical berms, ramps).

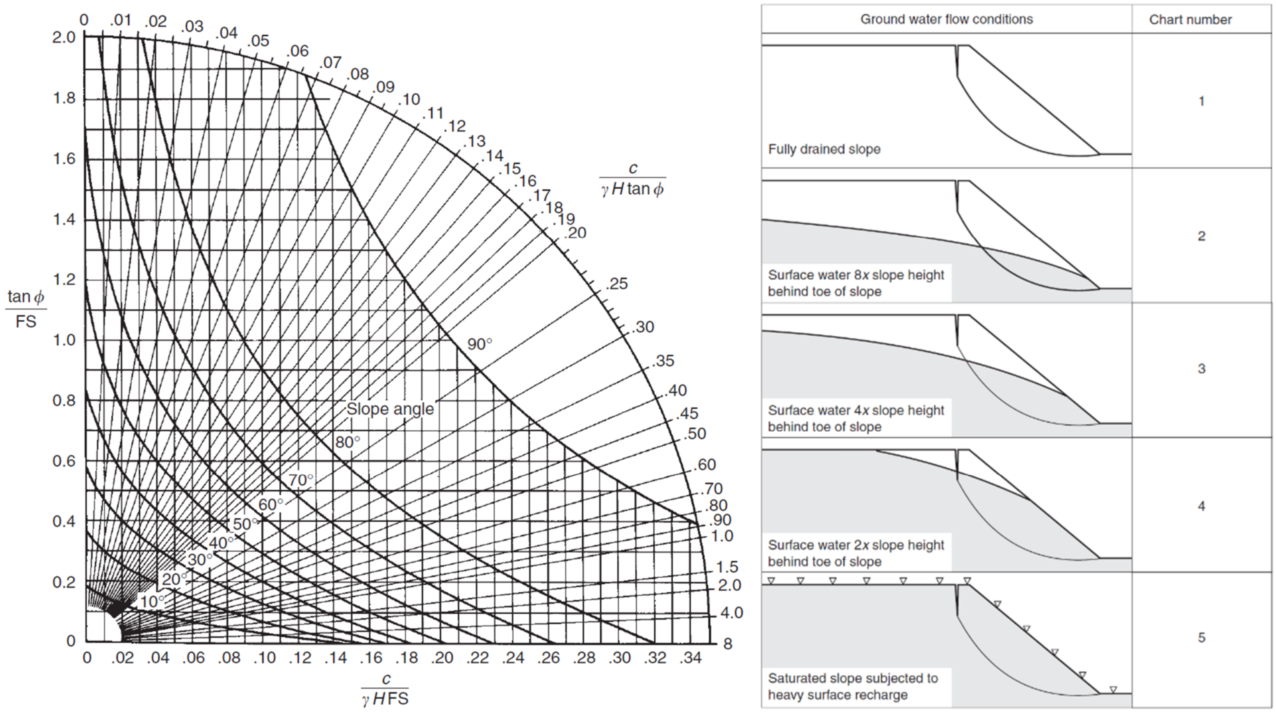
Stable overall slope angle can be assessed using some simple and quick approaches. In these methods, design charts have been developed from experience in actual pits, with several presenting or discussing the parameters from these pits (Hoek 1970; Sjöberg 2000; Haines & Terbrugge 1991).

In the analytical methods, design assessment is based on some simple and averaged inputs for which various stability charts have been developed. Usually these have been based on numerous analyses using limit equilibrium methods, and allow for the assessment of maximum slope parameters (height of slope and overall angle) or for identifying the Factor of Safety (FoS) for certain slope parameters. Some of these charts have been developed for different degrees of groundwater saturation. Among the various charts developed for the analytical methods (including Bishop & Morgenstern 1960; Gibson & Morgenstern 1962; Spencer 1967; Janbu 1968), the most widely used one has been developed by Hoek & Bray (1981), as shown in Figure 2. In order to use the charts to determine overall angle, the steps described by Hoek & Bray must be followed.

The use of the stability charts traditionally requires that slope conditions meet the following assumptions:

- The material forming the slope is homogenous, with uniform shear strength properties along the candidate failure surface.
- Failure occurs on a pseudo-circular rotational slide surface that passes through the toe of the slope.
- The location of the tension crack and the slide surface are such that the slope FoS is a minimum for the slope geometry and groundwater conditions considered etc.

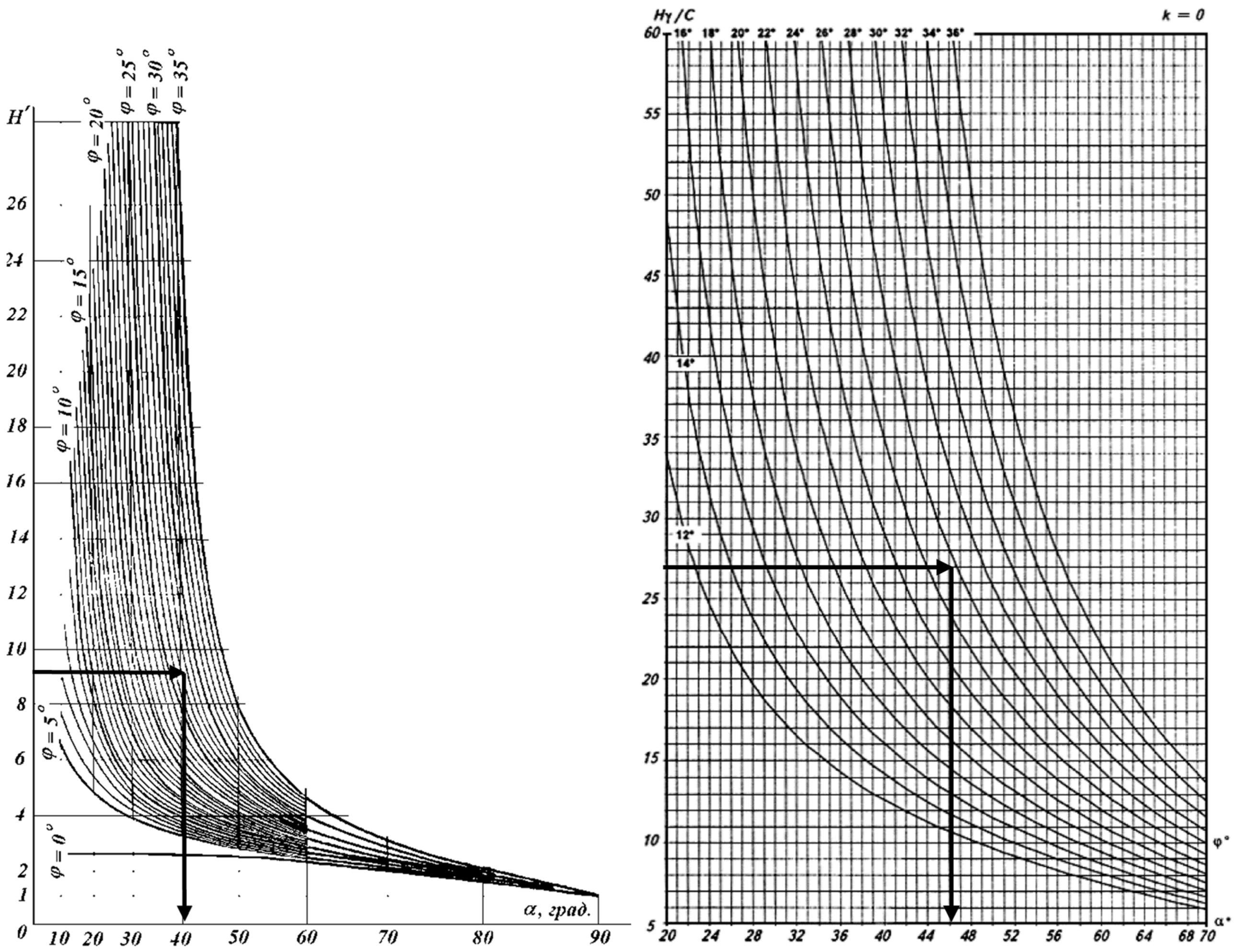
Based on these charts, some computational tools have been created for the determination of FoS and the location of the critical failure surface (Carranza-Torres & Hormazabal 2018).



(a) (b)

Figure 2 Slope stability charts (Hoek & Bray 1981): (a) Circular failure chart for a fully drained slope; (b) Groundwater conditions corresponded with charts

There are also analogy charts that are widely used in Russia and which were developed at the institute VNIMI (Research Institute of Mining Geomechanics & Mine Surveying) by Soviet Union scientists (Fisenko 1972; Fisenko & Pustovoitova 1998). These are based on an algebraic sum of forces method (Figure 3a) and a polygon of forces method (Figure 3b). Examples of the charts developed for these are shown in Figure 3, in this case representing drained slope conditions. Also, charts based on the polygon of forces method have been created for identification of appropriate slope design parameters for different saturated slope conditions with saturation factor (K)=0 (i.e. drained slope conditions, as shown in Figure 3b), 0.2, 0.5 and 0.8 (Fisenko & Pustovoitova 1998). Factor K represents saturation as a ratio of saturated slope interval to overall slope height, which is similar to the Hoek & Bray classification shown in Figure 2b.



(a) (b)

Figure 3 Slope stability charts for fully drained slope conditions: (a) Based on algebraic sum of forces method (Fisenko 1972); (b) Based on polygon of forces method (Fisenko & Pustovoitova 1998)

The key equations for using the charts are:

$$C_n = \frac{C}{n}, \qquad \varphi_n = arctg\frac{tg\varphi}{n} \tag{2}$$

$$H' = H / H_{90} \tag{3}$$

$$H_{90} = \frac{\sigma_0}{\gamma} = \frac{2 \cdot C_n}{\gamma} \cdot ctg\left(45° - \frac{\varphi_n}{2}\right) \tag{4}$$

$$H = \frac{H_{90}}{1 - \sqrt{tg\left(\frac{\alpha + \varphi_n}{2}\right) ctg\alpha}} \tag{5}$$

where:

C	=	cohesion.
φ	=	friction angle.
ctg	=	cotangent.
arctg	=	arctangent.
γ	=	unit weight.
n	=	FoS as a design acceptance criteria, C_n.
$φ_n$	=	cohesion and friction angle reduced by FoS.
H	=	height of the overall slope.
α	=	overall slope angle.
H_{90}	=	vertical tension crack.
$σ_0$	=	rock mass strength.

In order to use the charts to determine overall angle, the steps that should be followed are:

1. Decide upon the groundwater conditions which are believed to exist in the slope and choose the appropriate chart.
2. Select rock strength parameters (C – cohesion, φ – friction angle, γ – unit weight) applicable to the material forming the slope or determine weighted properties if several materials are present, as explained in Section 3.
3. Calculate strength parameters reduced by the FoS selected as the slope design acceptance criterion (C_n – cohesion, $φ_n$ – friction angle) using Equation 2.
4. For the algebraic sum of forces method (Figure 3a), calculate the value of the dimensionless parameter H' using Equations 3 and 4. For the polygon of forces method (Figure 3b), calculate (Hγ/C) and find this value on the vertical axis of the appropriate chart. Cohesion should be taken with FoS (C_n).
5. Follow the horizontal line from the value found in step 4 to its intersection with the appropriate friction angle (φ) presented by curves. Friction angle should be taken with FoS ($φ_n$).
6. Follow the vertical line and find the corresponding value of overall angle (α°) as shown by arrows in Figure 3.

Using computational tools based on such charts, it is possible to determine one of these parameters – overall angle, slope height or FoS, when other parameters are fixed. For the algebraic sum of forces method (Figure 3a) it is possible to use Equation 5 to determine the appropriate height of the overall slope (H) when other parameters are known.

The algebraic sum of forces method is a vertical slices method (Figure 4). In every vertical slice along the potential slip surface, all resisting and driving forces are estimated and then summed up for all blocks (*i*). FoS (*n*) is assessed as the ratio of resisting and driving forces (where P_i = weight of a single block, N_i and T_i = components of the block weight dependent on the slip surface angle (δ), l_i = length of the base of the block along the slip surface, $γ_B$ = water density, tg = tangent, sin = sinus, cos = cosine). Hydrostatic pressure is estimated in every block (D_i) as the weight of the water column on the slip surface. An assumption for this method is that resisting forces between vertical slices are not taken into account. This likely underestimates FoS and makes the design output somewhat conservative.

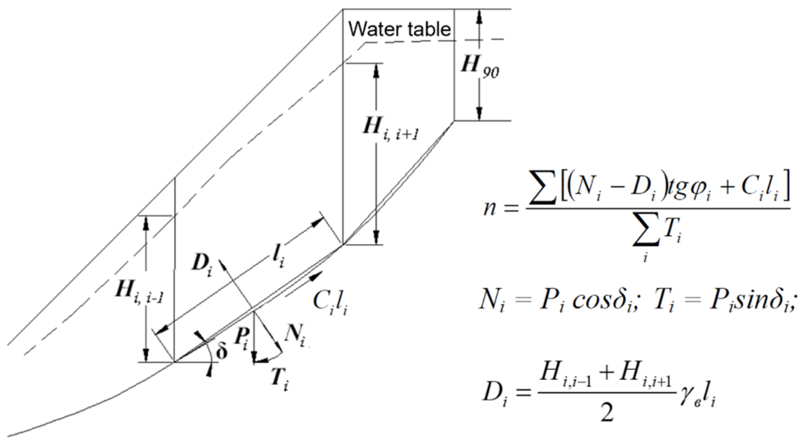


Figure 4 Algebraic sum of forces method (Fisenko 1972)

The polygon of forces method is a non-vertical slices method where for each separated slope sector a balance of forces is generated graphically, and an excess of forces (ΔF>0) or lack of forces (ΔF<0) is an output of this method that corresponds to FoS (Figure 5). A slip surface is created using geometric parameters (H_{90} = vertical tension crack; ω, ε, β = angles of slip surface inclination) and separated by non-vertical blocks. Geometric parameters of groundwater level are height of seepage (*H'*) and tilt angle (*j*). The forces for the blocks are the weight of a single block (P_i), hydrostatic pressure in every block (D_i), seismic load (*S*) if applicable, and reactions to block boundaries (R_i).

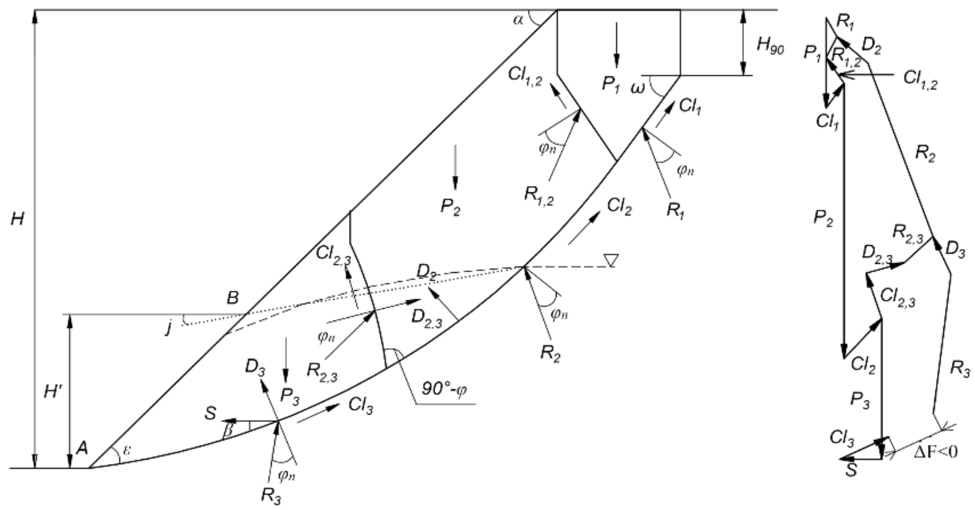


Figure 5 Polygon of forces method (Fisenko & Pustovoitova 1998)

A comparison of the slope parameters developed from the most widely used charts (Hoek & Bray 1981; Fisenko & Pustovoitova 1998) is presented in Figure 6, using the following set of inputs: friction angle φ = 40°, cohesion C = 1,000 kPa (the strength properties are recalculated using FoS = 1.3 as a design acceptance criteria into φ_n = 32.8° and C_n = 770 kPa), unit weight γ = 28 KN/m^3. Both drained and partially saturated slopes are considered.

From the comparison it can be seen that for drained slopes the achievable slope parameters identified using the two methods are very similar; however, for saturated conditions, the Hoek & Bray chart outputs are somewhat lower (more conservative).

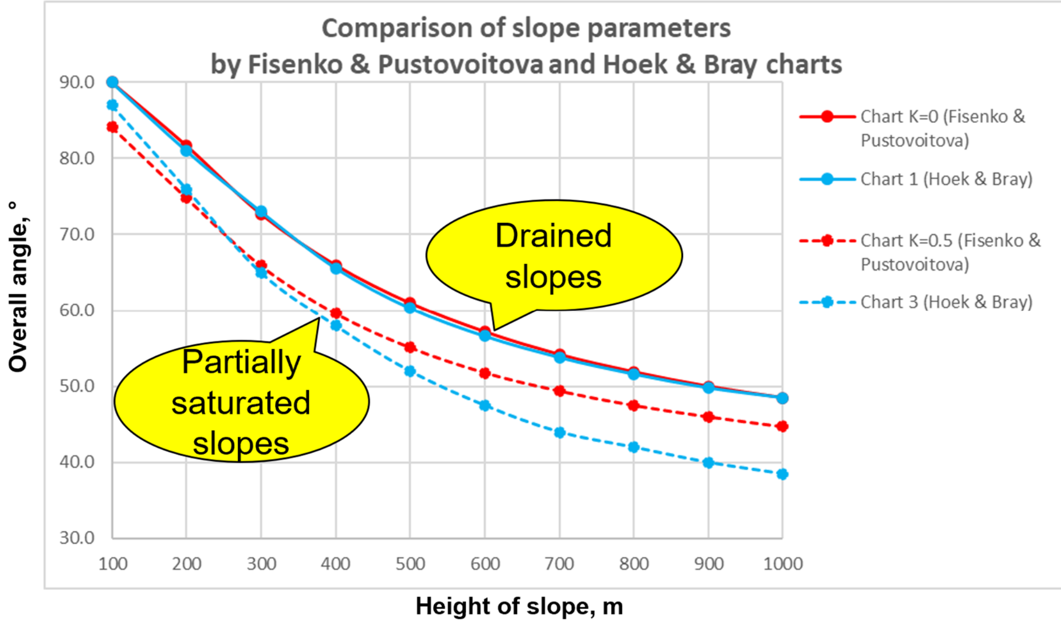


Figure 6 Comparison of charts for slope stability assessment by Fisenko & Pustovoitova (1998) and Hoek & Bray (1981)

The similar results indicate that the various design charts based on analytical methods that have been mentioned are equally useful in providing preliminary design recommendations.

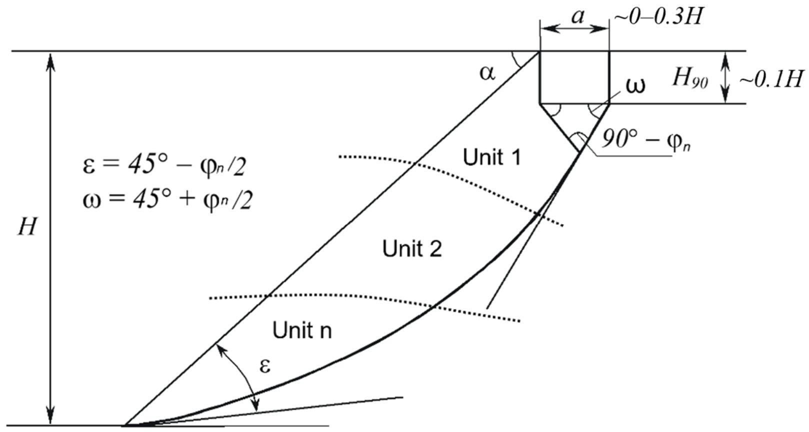
3 Simple analytical approach in heterogeneous rock masses

The simple analytical approach can be undertaken in heterogeneous rock masses. The same design charts as used for homogeneous slopes can be used for identifying the overall slope angle; however, collective shear strength properties within the rock mass constituting the slope must be estimated first. For this, weighted material properties along the assumed slip surface through the various rock types/domains are estimated (Fisenko 1972; Fisenko & Pustovoitova 1998; Rylnikova & Zoteev 2020).

The key assumptions and limitations in the simple analytical approach for heterogeneous rock masses are:

- Slopes can be in either weak or fractured rock masses; however, the rock mass must be isotropic, and a circular or near-circular slip surface should be expected as a failure mechanism. There should not be any explicit anisotropy that can affect the failure mechanism for this approach.
- The simple analysis identifies a planar pit slope profile; however, optimal slope profiles can be convex or concave. In reality, if rock properties differ significantly in a spatial sense, a global minimum FoS could present only in a local slope area related to the weakest unit, which would require a different slope angle.
- Analytical charts have originally been developed using the limit equilibrium stability analysis method. If complex failure mechanisms are expected, slope stability should be assessed by more sophisticated numerical models (finite element methods, 3D methods etc.).

The method of estimation of weighted properties of cohesion (C_w) and friction angle (φ_w) for the heterogeneous rock masses along the potential slip surface is performed as indicated in Figure 7. Friction angle (φ_w) is estimated using tangent (tg), arctangent (arctg) functions. Weighted rock unit weight (γ_w) is estimated for rock unit squares within the potential slip surface. The hypothetical slip surface is constructed using geometrical parameters (a, H_{90}, ω, ε) as shown in the figure. The selected design acceptance criterion (FoS) needs to be considered for strength properties (C_n, ϕ_n) in the determination of overall angle (α).



$$C_w = \frac{C_1 l_1 + C_2 l_2 + \ldots + C_n l_n}{l_1 + l_2 + \ldots + l_n}$$

$$tg\varphi_w = \frac{tg\varphi_1 l_1 + tg\varphi_2 l_2 + \ldots + tg\varphi_n l_n}{l_1 + l_2 + \ldots + l_n}$$

$$\gamma_w = \frac{\gamma_1 S_1 + \gamma_2 S_2 + \cdots + \gamma_n S_n}{S_1 + S_2 + \cdots + S_n}$$

$$C_n = \frac{C_w}{n} \qquad \varphi_n = arctg \frac{tg\varphi_w}{n}$$

Figure 7 Method of estimation of weighted properties along the potential slip surface

4 Examples of practical application

Preliminary slope design parameters for two open pit mines were determined using the proposed method; one section in the first pit and two sections in the second pit. These designs, and stability analysis checks carried out for each, are presented in the following subsections.

Figure 8a shows a pit in strong igneous rocks in Russia (Pit A). For most of the rock units, uniaxial compressive strength (UCS) varies from 66 to 130 MPa. The rock mass condition is very good: geological strength index (GSI) often exceeds 80, there is no significant anisotropy, and joint sets are developed in several orientations but are not highly persistent. Faults of different orders are the most important structures with regards to slope stability, most of which strike perpendicular to – and are therefore favourably orientated with regard to – the pit slopes.

Figure 8b shows a pit in strong igneous rocks in Kyrgyzstan (Pit B). For most of the rock units, UCS varies from 90 to 180 MPa. Rock mass conditions are of medium quality: GSI is often within the range of 45–65, there is no significant anisotropy, and joint sets are developed in several orientations. Faults are important structures with regards to slope stability and fault zones sometimes have widths in the order of a few tens of metres. It is often difficult at an early design stage to take into account the effects of faults because the position of the slopes relative to these faults may still not be well defined. Thus for preliminary slope design assessments, faults may have to be ignored and then assessed in further iterations after the initial pit design has been created.

(a) (b)

Figure 8 Photographs of slopes which illustrate the simple analytical approach: (a) Pit A; (b) Pit B

For each case, the following was carried out:

1. An assumed slip surface was constructed on a 2D section of the approximate pit slope profile (pit contour) . The proportions of the slip surface within each of the rock units were estimated.
2. The weighted properties along the assumed slip surface, assessed using the equations in Figure 7, were calculated.
3. Using the weighted properties, assessment of the overall slope angle (α) was undertaken for the design acceptance FoS using the design charts for the particular saturation conditions.
4. The overall slope angle was also generated using appropriate batter–berm geometry using Equation 1 and including pit ramps. The number of ramps included in the overall slope was estimated based on the intended ramp system for the pit.
5. The overall slope angles determined by the simple analytical approach and those generated by batter–berm and ramp geometry were compared to assess which presents the key control on overall slope angle. The minimum (shallower) of these two forms the basis for the recommended preliminary slope angle.
6. After the pit design was created based on the preliminary recommended slope angles, a detailed stability analysis was carried out using the limit equilibrium method (LEM) and finite element method (FEM).

4.1 Case 1 (Pit A)

The estimated proportions of the slip surface within each of the rock units in Pit A (Case 1) are shown in Figure 9.

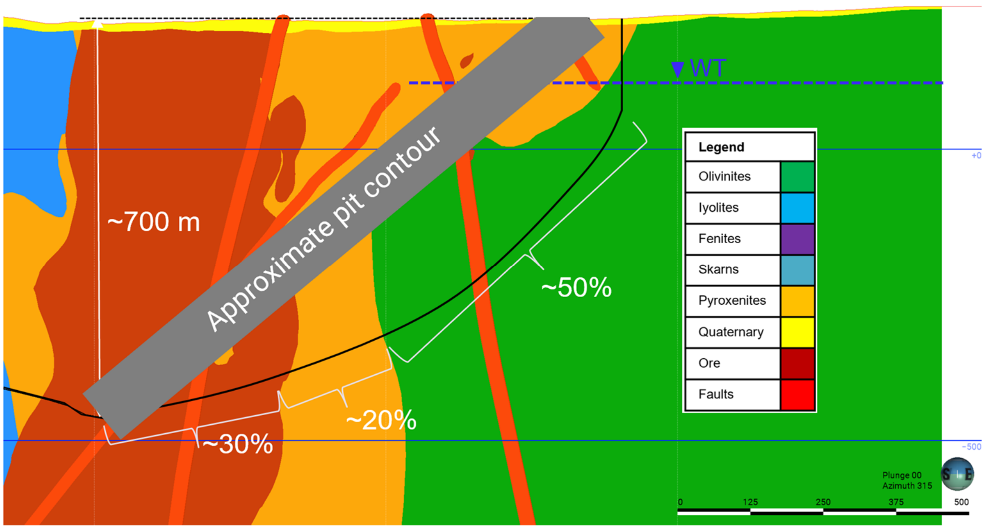


Figure 9 Rock units along the assumed slip surface of Case 1

The weighted properties calculated along the assumed slip surface are presented in Table 1.

Table 1 Calculation of weighted properties for Case 1

Lithologies	%	C (kPa)	φ (°)	γ (KN/m³)
Olivinites	50	1,270	26	32.0
Pyroxenites	20	1,740	31	32.2
Ore	30	1,790	29	38.2
Weighted properties	**100**	**1,520**	**28**	**33.9**

The overall angle was assessed for the design acceptance FoS of 1.3. Input data included: C_n = 1,169 kPa, ϕ_n = 22°, γ = 33.9 KN/m^3, slope height H = 700 m and saturation conditions K = 0.8. The overall angle (α) determined from design charts was 40°.

The batter–berm geometry design and other elements for Case 1 are listed in Table 2. Equation 6 shows the calculation of the overall slope angle from these geometries, which is 40°.

Table 2 Batter–berm geometry and other pit elements for Case 1

Batter–berm parameters	Number of batters	Batter height H (m)	Batter face angle α (°)	Berm width B (m)	Inter-ramp angle (°)
Upper stack	7	30	60	13	44.7
Middle stack	13	30	65	13	48
Lower stack	3	30	75	12	56.3
Overall slope height = 700 m					
Number of ramps = 5					
Width of ramps = 37 m					

$$\alpha_r = \text{arctg}\frac{700}{7\cdot13+13\cdot13+3\cdot12+5\cdot37+7\cdot30\cdot\text{ctg}(60)+13\cdot30\cdot\text{ctg}(65)+3\cdot30\cdot\text{ctg}(75)} = 40° \quad (6)$$

The suitable overall slope angles determined by the simple analytical approach and generated by batter–berm geometry are similar (α = 40°). Hence, the achievable overall angle is controlled by both overall slope stability and the batter–berm geometry, and 40° can be confidently recommended as the slope angle to be used for preliminary design and further stability and design optimisation assessments.

For a pit slope design created based on the preliminary recommended slope angle of 40°, stability analysis was undertaken using both Slide 2 LEM and RS_2 FEM software (Rocscience 2023), for comparison.

The results of the LEM stability analysis are shown in Figure 10: an overall slope with parameters H = 704 m and α = 40° has FoS = 1.30, which matches the design FoS of the simple analytical approach. However, local instability of the lower stack is identified.

The results of the FEM stability analysis for the same slope are shown in Figure 11. The FoS = 1.26, which is slightly lower than the LEM FoS result due to the presence of faults that dip steeply into the pit walls and which are not taken into account by the LEM. Therefore the results of the FEM are in this case deemed more reliable.

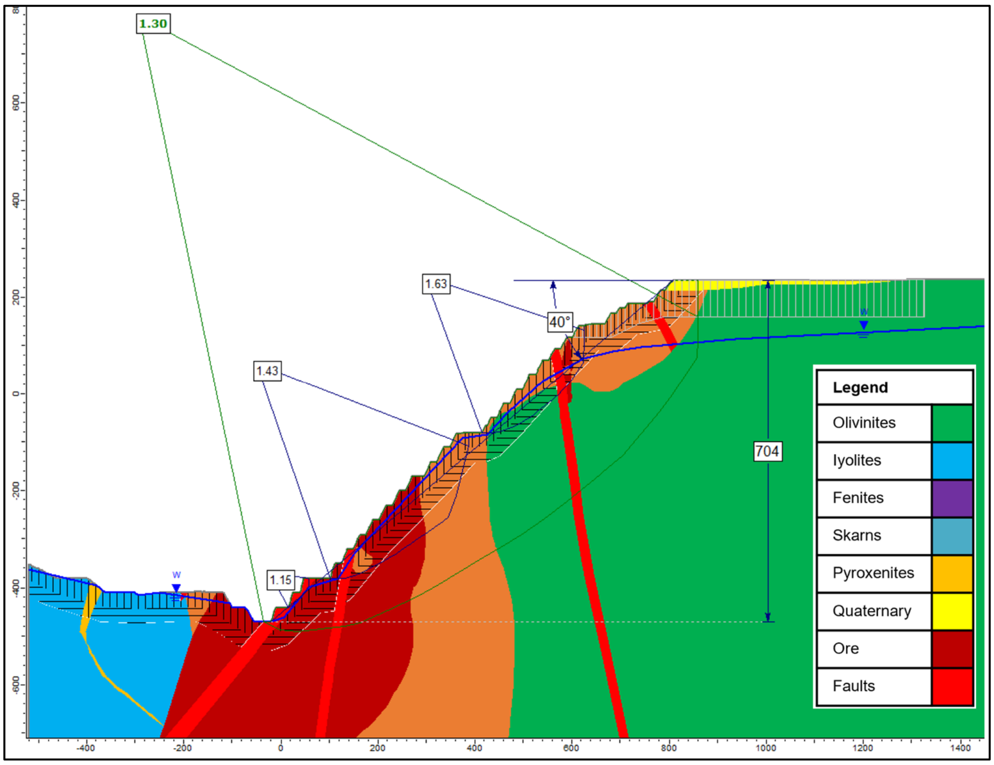


Figure 10 Results of Slide 2 stability analysis for the slope design determined using the simple analytical approach for Case 1

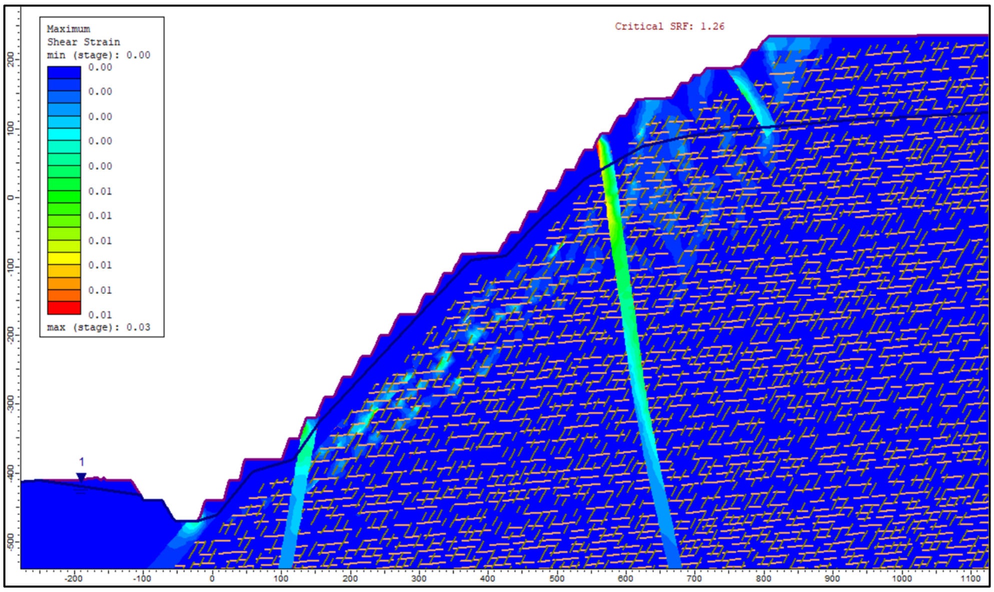


Figure 11 Results of RS 2 stability analysis for the slope design determined using the simple analytical approach for Case 1

4.2 Case 2 (Pit B)

The estimated proportions of the slip surface within each of the rock units in the first of the two selected sections in Pit B (Case 2) are shown in Figure 12.

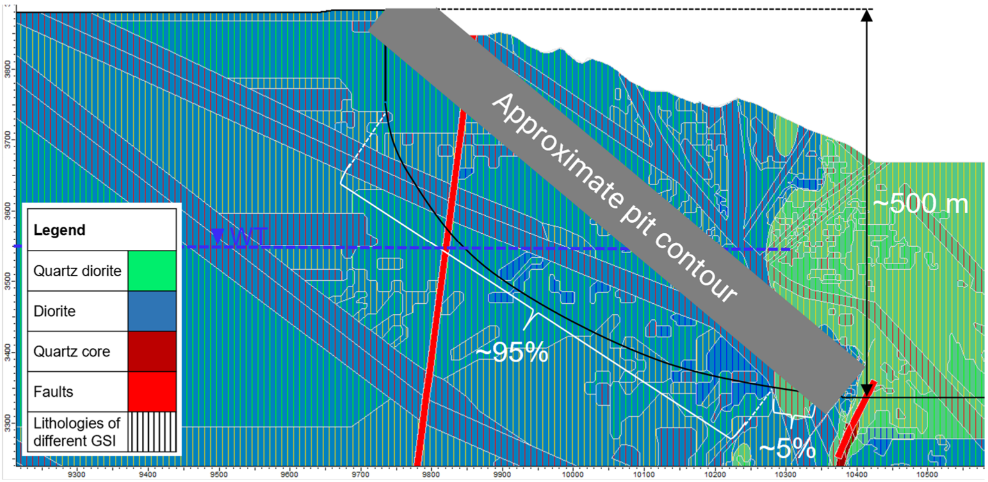


Figure 12 Rock units along the assumed slip surface of Case 2

The weighted properties calculated along the assumed slip surface are presented in Table 3.

Table 3 Calculation of weighted properties for Case 2

Lithologies	%	C (kPa)	φ (°)	γ (KN/m³)
Diorite	95	1,240	31	27.8
Quartz diorite	5	1,110	30	26.9
Weighted properties	**100**	**1,234**	**31**	**27.8**

The overall angle was assessed for the design acceptance FoS of 1.3. Input data included C_n = 949 kPa, ϕ_n = 25°, γ = 27.8 KN/m^3, H = 500 and saturation conditions K = 0.4. The overall angle (α) determined from design charts was 54°.

The batter–berm geometry design and other elements for Case 2 are listed in Table 4. Equation 7 shows the calculation of the overall slope angle from these geometries, which is 44°. The FoS for this angle of 44° estimated from design charts is 1.58.

Table 4 Batter–berm geometry and other pit elements of Case 2

Batter–berm parameters	Number of batters	Batter height H (m)	Batter face angle α (°)	Berm width B (m)	Inter-ramp angle (°)
All batters	21	24	65	13	44.8
Overall slope height = 500 m					
Number of geotechnical berms = 2					
Width of geotechnical berms = 20 m					

$$\alpha_r = \text{arctg}\frac{500}{21\cdot 13+2\cdot(20-13)+21\cdot 24\cdot \text{ctg}(65)} = 44° \quad (7)$$

The slope angle generated by batter–berm geometry (α = 44°) is significantly lower than the angle assessed from design charts (α = 54°). Hence the achievable overall angle is controlled by batter–berm geometry and α = 44° is a suitable recommendation for preliminary slope angle.

For a pit slope design created based on the preliminary recommended slope angle of 44°, stability analysis was undertaken using both LEM and FEM, for comparison.

The results of the LEM stability analysis are shown in Figure 13. For the overall slope with parameters H = 512 and a = 44°, the FoS = 1.72. This FoS compares reasonably with the FoS of 1.58 for α = 44° estimated from the design charts (both FoS are significantly greater than 1.3).

The results of the FEM stability analysis for the same slope are shown in Figure 14. The FoS = 1.60, which is slightly lower than the LEM FoS result because of the presence of faults that dip steeply into the pit walls and which are not taken into account by the LEM. Therefore, the results of the FEM are in this case deemed more reliable.

Further design analysis is not required for this case because the calculated FoS are greater than design acceptance criteria and there is no way of further steepening the slope angle because it is limited by batter–berm geometry.

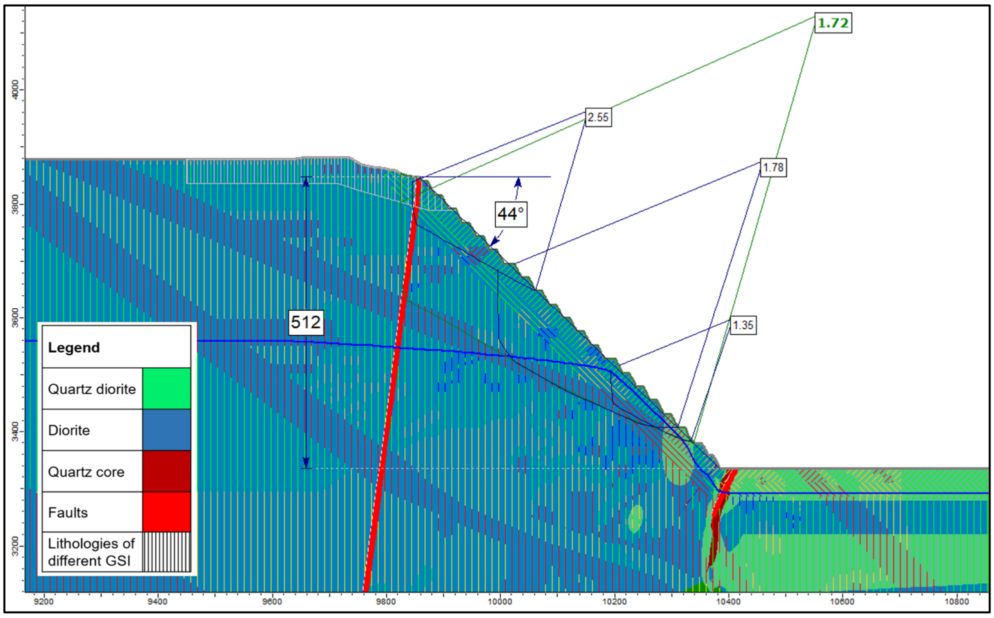


Figure 13 Results of Slide 2 stability analysis for the slope design determined using the simple analytical approach for Case 2

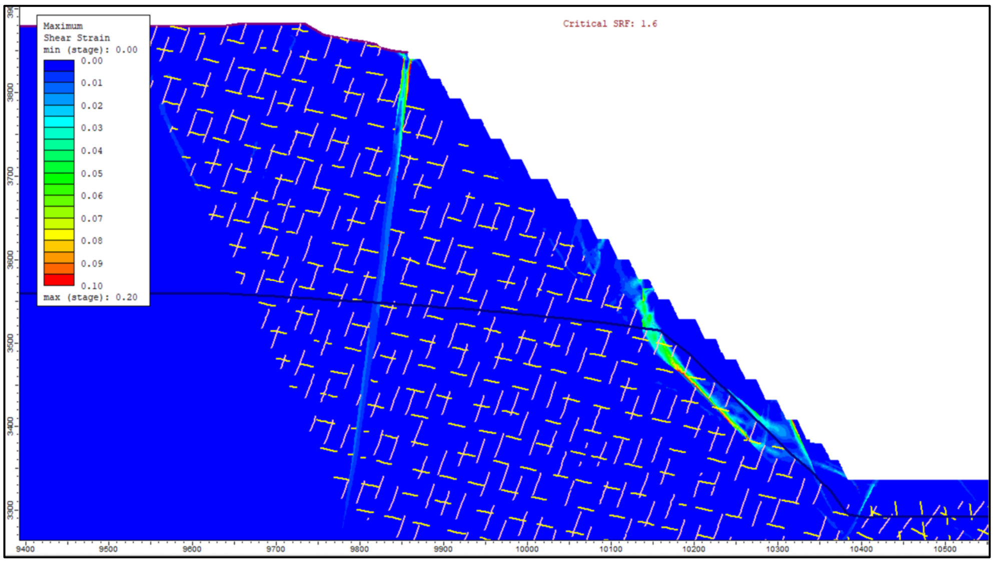


Figure 14 Results of RS 2 stability analysis for the slope design determined using the simple analytical approach for Case 2

4.4 Case 3 (Pit B)

The estimated proportions of the slip surface within each of the rock units in the second of two selected sections in Pit B (Case 3) is shown in Figure 15.

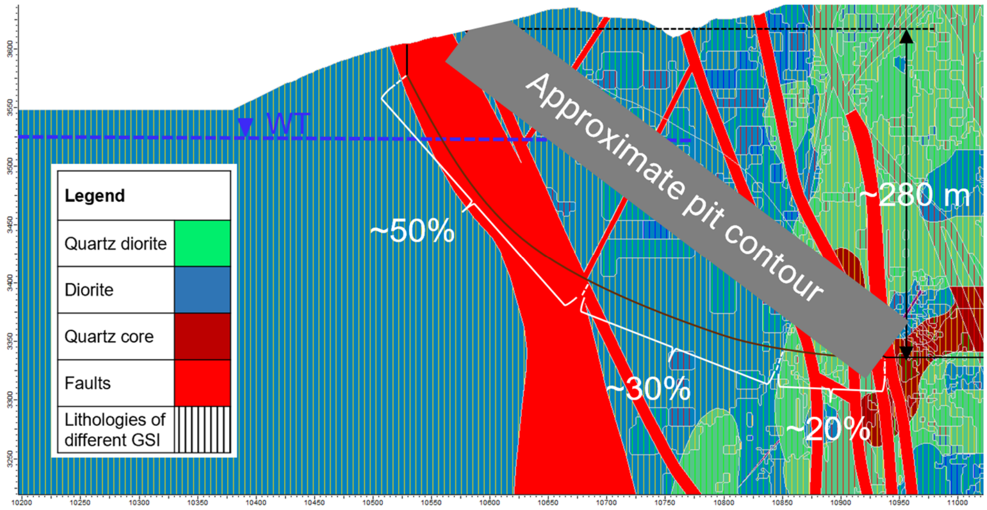


Figure 15 Rock units along the assumed slip surface of Case 3

Although a substantial fault zone is present (shown in red in Figure 15), this case has been confidently assessed using the simple analytical approach because the fault presents a substantial zone of weak material along the candidate failure plane and a circular slip surface is still expected in this case.

The weighted properties calculated along the assumed slip surface are presented in Table 5.

Table 5 Calculation of weighted properties for Case 3

Lithologies	%	C (kPa)	φ (°)	γ (KN/m^3)
Faults	50	50	20	26
Diorite	30	1,650	34	26.9
Faults	20	50	20	26
Weighted properties	**100**	**530**	**24**	**26.3**

The overall angle was assessed for the design acceptance FoS of 1.3. Input data included C_n = 408 kPa, ϕ_n = 19°, γ = 26.3 KN/m^3, H= 280 m and saturation conditions K = 0.7. The overall angle (α) determined from design charts was 37°.

The batter–berm geometry design and other elements for Case 3 are listed in Table 6. Equation 8 shows the calculation of the overall slope angle from these geometries, which is 41°. The related FoS for this angle of 41° estimated by design charts is 1.20.

Table 6 Batter–berm geometry and other pit elements of Case 3

Batter–berm parameters	Number of batters	Batter height H (m)	Batter face angle α (°)	Berm width B (m)	Inter-ramp angle (°)
All batters	12	24	60	13	41.8
Overall slope height = 280 m					
Number of geotechnical berms = 2					
Width of geotechnical berms = 20 m					

$$\alpha_r = \text{arctg}\frac{280}{12\cdot13+2\cdot(20-13)+12\cdot24\cdot\text{ctg}(60)} = 41° \quad (8)$$

The overall angle assessed by design charts (α = 37°) is lower than that generated by the batter–berm geometry (α = 41°). Hence achievable overall angle is controlled by the overall slope stability and α = 37° is a suitable recommendation for preliminary slope angle.

For a pit slope design created based on the preliminary recommended slope angle of 37°, stability analysis was undertaken using both LEM and FEM, for comparison.

The results of the LEM stability analysis are shown in Figure 16. For the overall slope with parameters H = 280 and a = 37°, the FoS = 1.31.

The results of the FEM stability analysis for the same slope are shown in Figure 17 and the FoS = 1.35. This FEM gives similar results to the LEM because of the similar failure mechanism as the slip surface passes along the wide fault zone and then through the competent diorite unit below.

Further design analysis is not required for this case because FoS results adhere to the design acceptance criteria.

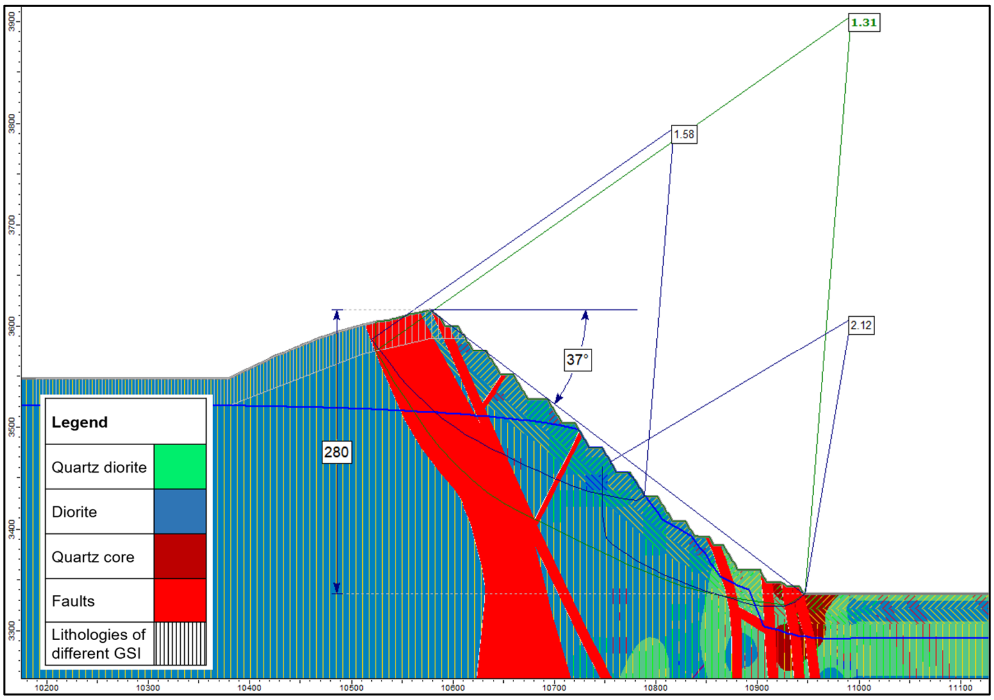


Figure 16 Results of Slide 2 stability analysis for the slope design determined using the simple analytical approach for Case 3

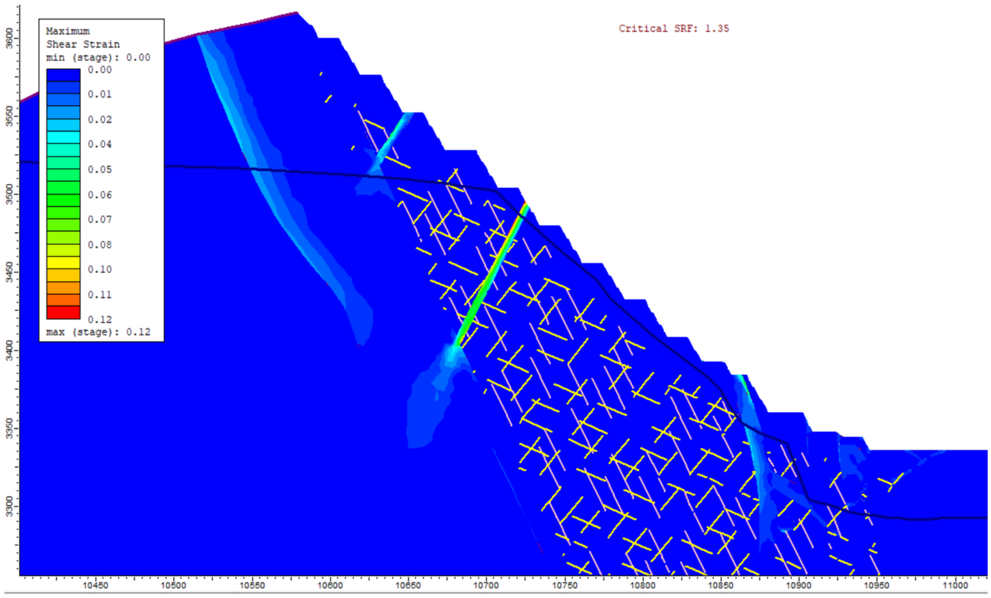


Figure 17 Results of RS 2 stability analysis for the slope design determined using the simple analytical approach for Case 3

5 Conclusion

A simple analytical approach is useful for quick assessment and confirmation of suitable slope angle parameters, either for slope design in early stage studies or to be used as a basis for initial pit design that is assessed by detailed stability analyses in more advanced studies.

The simple analytical approach presents the following advantages:

- It allows for the rapid assessment and provision of inputs to mining engineers, assisting them to create an initial pit shell based on preliminary slope angles and the resource geology model. Only once the locations of pit walls are known can further slope stability analyses be carried out.
- Design charts can be used not only for homogeneous rock masses but also, as described in this paper, for heterogeneous rock masses.
- It enables quick and easy comparison to determine the limiting factors for overall slope angle (either overall slope stability or batter–berm geometry). It is important to take this into account before confirming preliminary slope angle recommendations.

The approach must be used whille understanding its limitations, which are:

- It is not suitable for anisotropic rock masses and it must be used in scenarios where a circular or near-circular slip surface is expected as a failure mechanism.
- The stability of a slope can be controlled by faults which are unlikely to be suitably accounted for in the simple analytical approach. The numerical analytical software method utilised for design optimisation must allow for the effects of such features to be taken into account, depending on their nature and orientation (i.e. FEM or other numerical methods may be required instead of the LEM).
- Significant variations in rock mass conditions can result in locally less stable slope sections which will need to be individually optimised using detailed analyses.

The case study-worked examples presented have shown that the results of the simple analytical approach suggested in this paper can often match favourably with the results of subsequent stability analyses using the LEM. In spite of this, after the initial pit design is created, further pit slope optimisation analyses using detailed models and appropriate software are often required.

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