

# Analysis by Numerical Simulation of the Geotechnical Behavior of Mining Slopes under the Influence of the Variations of the Geometric and Mechanical Parameters of the Bench Using RocScience (Slide Module Version 6.020): Case of an Open-Pit Mine

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## Abstract

Better benches design enables to optimizes the risks of instabilities, to guarantee maximum of the ore recovery with minimum waste stripping. This requires detailed data on their geometric properties and the mechanical properties of the materials (soil and rock), thus defining the appropriate means for investigation, modeling and numerical calculations. The objective of this article is to study the geotechnical behavior of slopes and edges of a mining pit under the influence of variations in the geometric parameters of the bench and mechanical parameters of the ground in the case of open-pit mines. To do this, we used the stability calculation software well adapted to landslide problems, called RocScience (Slide module version 6.020). Four geometric models were tested in order to assess the slopes and the mining pit edges stability, in order to choose the best model for the application of the different parameter's variation. The stability calculations showed the influence of variations in the geometric parameters of the benches and the mechanical parameters of the soil on the factor of safety. The results of variations in favor of a decrease in the bench height, slope angle and an increase in the bench width show an increase in the factor of safety and vice versa. With the first three models, under static

conditions all the factors of safety are greater than or equal to 1.4, which shows a state of satisfactory long-term stability, whereas under Pseudo-static conditions, the factors of safety are all less than 1, which means that collapse is inevitable with these models. It can be seen that with a fourth model whose geometric characteristics, the factors of safety obtained are greater than 1.5 in static conditions and 1 in Pseudo-static conditions, which shows of the slopes and pit edges long-term stability. As for the variations in mechanical parameters, the factor of safety increases with the increase of the mechanical parameters in static and Pseudo-static conditions. The sandstone layer showed inevitable instabilities with values of the internal friction angle below  $40^\circ$  and internal cohesion below 65 KPa. Instabilities are observed in the limestone layer with internal friction angle values below  $35^\circ$  and internal cohesion below 120 KPa. The pegmatite showed a state of guaranteed stability in an interval of the internal friction angle ranging from  $30^\circ$  to  $35^\circ$  and internal cohesion ranging from 250 to 300 KPa outside which instabilities inevitably occur. The variation of the parameters showed a very low effect on the last two layers due to the high values of the different parameters.

## Keywords

Open-Pit Mine, Factor of Safety, Stability, Slope, Bench

## 1. Introduction

In rock massifs, many poorly defined parameters interact in complex ways, and safety calculation is a much less satisfactory process under these conditions (Hoek & Bray, 1981). The mechanisms causing ground instability are very varied and not linked to a single cause (Fassekh, 2012), so the assessment of the geotechnical behavior of mining slopes is probably the most difficult task of the geotechnical engineer (Abderrahmane & Abdelmadjid, 2014b). This difficulty may be due to several parameters, such as the rupture mechanism, the morphology of the terrain, the physical, mechanical and hydraulic properties, the speed of movements, and the non-linearity of the geomechanical behavior of the terrain (Abderrahmane & Abdelmadjid, 2014a). On the one hand, the failure curve along which the risk of sliding is highest, and on the other, the corresponding value of the safety coefficient FS are determined from stability calculations (Abramson, 1996; Zheng, Tham, & Liu, 2006; Zhang et al., 2024). The shear strength parameters of soils and the compressive strength parameters of rocks are very important and are often used in slope stability analyses (Abderrahmane & Abdelmadjid, 2014b). In an open-pit mine and in most software used, the main objective of slope stability analysis is to contribute to the safe and economical design of the pit (Abramson, 2001). However, the main objective of slope design is to identify the main parameters that influence of the slope stability considered (Mohamed, 2019), the specific state of the rock, discontinuities, groundwater, earthquake action related to blasting (shots), etc. (Mathe & Ferentinou, 2021). Once these parameters are defined,

an evaluation can be made to define a design criterion based on experience and judgment, focusing on maximizing overall slope angle and maximizing ore stripping (Mathe & Ferentinou, 2021). There are several evaluation methods, since many researchers have tried to develop and elaborate based on the analysis methods, and have solved this problem with different assumptions to simplify the calculations (Abderrahmane & Abdelmadjid, 2014a). The purpose of this article is to simulate the geotechnical behavior of mining slopes under the influence of variations in the geometric parameters of the benches and mechanical parameters of the ground using RocScience (Slide module version 6.020) for the assessment of landslide risks.

## 2. Choice of the Factor of Safety for Slope Stability Assessment

To have control over the risks of sliding, the choice minimum factor of safety (FS) adopted is greater than or equal to 1.5, therefore, the objective is to guarantee long-term stability.

Acceptability criteria are being developed to be used as a standard value to quantify and qualify the performance of slopes in open-pit mines. This performance can be described in terms of the factor of safety (FS) or probability of failure (PF). The factor of safety (FS) is the ratio of the ultimate shear strength to the shear stress mobilized at failure initiation (Cheng & Lau, 2008). However, the probability of failure (PF) is the probability that the factor of safety (FS) is equal to or less than 1 (Read & Stacey, 2009). The severity of the slope in question gives an inclination to the acceptance level, with critical slopes with vital installations such as ramps being designed according to higher factors of safety (FS) and lower failure probability factors (PF) (Mohamed, 2006; Read & Stacey, 2009; Yingren et al., 2009). The table below (Table 1) presents the typical standard acceptance criteria operated in open-pit mines.

**Table 1.** Typical acceptance criteria values for factor of safety (FS) and probability of failure (PF) (Read & Stacey, 2009).

Slope scale	Consequence of failure	FS (min) (static)	FS (min) (dynamic)	PF
Bench	Low-high b	1.10	0.067	25% - 50%
	Low	1.15 - 1.20	1.00	25%
Inter-ramps	Moderate	1.20	1.00	20%
	Top	1.20 - 1.30	1.10	10%
Overall a	Low	1.20 - 1.30	1.00	10% - 20%
	Moderate	1.30	1.05	10%
	Top	1.30 - 1.50	1.10	5%

a: Must meet all acceptance criteria. b: Semi-quantitative and semi-qualitative evaluation.

Depending on the type of landslide, the stability assessment is based on calculation methods developed by researchers to assess the state of equilibrium of the

slope based on the values of the factor of safety (FS) (Cerad, 2000; Mohamed, 2019) designated in **Table 2**.

**Table 2.** Slope equilibrium as a function of theoretical factor of safety (FS) values (Collin et al., 2010).

Factor of safety (FS)	State of the structure
$FS < 1$	Danger
$FS = 1$	Limit stability
$1 \leq FS \leq 1.25$	Questionable safety
$1.25 \leq FS \leq 1.40$	Satisfactory safety for minor structures, but questionable safety for open-pit quarries
$FS > 1.40$	Satisfactory safety

For mining design, the slope angle is defined according to the geomechanical characteristics of the rock (Protodiakonov, 1909; Terzaghi, 1946; Lauffer, 1958).

**Table 3** below shows standard values for bench angles.

**Table 3.** Slope angle and rock hardness.

Rock features	Hardness coefficient	Slope angle of the bench (°)
Extremely hard	15 - 20	75 - 85
Hard	8 - 14	65 - 76
Medium hardness	3 - 7	55 - 65
Soft	1 - 2	40 - 55
Furniture and plant	0.6 - 0.8	25 - 40

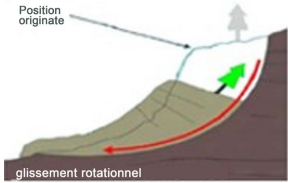
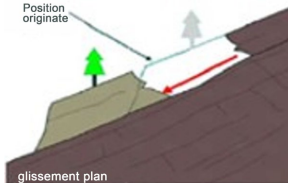
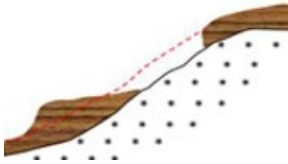
### 3. Analysis and Assessment of Slope Stability

Numerical modeling is a crucial step in any mining geotechnical study that determines the quality of diagnostic analyses or predictions of soil and rock behavior. A model not only represents a series of equations describing the physical or mechanical behavior of soils, but it is also a geometric representation of space, delimiting the layers or volumes occupied by each material.

In a mining pit, a typical analysis of the overall stability of a rock slope takes place at three scales: bench scale, inter-ramp scale and overall slope scale. It consists of studying the slopes stability by the kinematic approach of limit equilibrium analysis, and defining the “bearable” character of a load for a given structure based on accounting between the conditions imposed by the equilibrium on the one hand, and the resistance capacities of the constituent material(s) on the other hand (Houcemeddine, 2007). Incident prevention is done through the slope stability calculations (Cerad, 2000). The aim of this calculation is to determine the slope to give to a slope so that it presents a certain degree of safety against sliding (Houcemeddine, 2007; Luc, 2018; Abderrahmane, 2020). A wide variety of

procedures must be used to locate the critical circle, or non-circular critical slip surface. Locating the non-circular critical slip surface is more complex than locating the critical circular slip surface (Duncan, 1996). The determination of the type of landslide (circular, planar and wedge) depends on the form rupture shape, the number of families of discontinuities and their orientation (Goodman & Shi, 1985). Table 4 shows the different types of landslides.

**Table 4.** Main types of landslides on slopes, depending on the terrain involved (Campy & Macaire, 2003).

Types	Schematics	Land concerned	Internal reorganization	Average speeds
Circular sliding	 Position originate glissement rotationnel	Uncoherent rocks: Marls, Alluviums, Moraines	Quite low	A few centimeters to a few meters per day Discontinuous (seasonal)
Planar sliding	 Position originate glissement plan			
Corner sliding		Laterites	Quite strong	A few meters a day Discontinuous (seasonal)

The study of rock slope stability is based on different processes aimed to assess the state of overall slope stability. In a slope stability analysis, three steps are distinguished: the first step is to recognize the potential failure mechanism, the second step is to quantify the input parameters in order to obtain reliable input data, and consequently, a reliable assessment of slope stability (Harabinova & Panulinova, 2017), and finally the third step is the stability calculation and assessment (Nilsen, 2017).

The factor of safety is defined as the ratio of the total force available to resist sliding to the total force tending to induce sliding along any surface discontinuity (Hoek & Bray, 1881). The factor of safety is commonly used in slope design, and has already proven its effectiveness in its application to all types of geological conditions, both for rocks and soils. However, ranges of factors of safety exist for different types of engineered slopes, which facilitate the preparation of reasonably consistent designs. For open-pit mines, a factor of safety of between 1.2 and 1.4 is widely adopted (Cerad, 2000; Duncan & Christopher, 2005). In open-pit mines, slopes fail when the shear strength of the material on the sliding surface is insufficient to resist the actual shear stresses (Soren, Budi, & Sen, 2014).

## 4. Analysis Tools and Methods

### 4.1. Analysis Tool

In this article, we will mainly use the two-dimensional slope stability analysis software called RocScience (Slide module version 6.020). Slide is a 2D software that consists of performing a slope stability analysis using the limit equilibrium method (Harabinova & Panulinova, 2017), for non-circular and circular surfaces in soils and rocks. Deterministic or probabilistic methods are taken into account by Slide.

**Table 5** shows the data provided to the Slide software and the results obtained by the Slide software to perform a stability analysis.

**Table 5.** Data supplied to Slide software.

Slide data	Slide data
Measurement units	Safety factor before excavation
Breaking direction	Safety factor after excavation
Analysis methods	Breaking circles
Geotechnical parameters of the layers	Loads on the wafers
Slope geometry and layer boundaries	Shear strength as a function of slope length
Water table (if present)	Sensitivity diagrams

Along with other software, similar examples have been used in the soil and rock engineering literature to illustrate the above-mentioned approaches to rock slope design (Nilsen, 2000; Bedi & Harisson, 2013; Nomikos & Sofianos, 2014; Abderahmane & Abdelmadjid, 2014a; 2014b; Nilsen, 2017; Lahmili et al., 2018; Mathe & Ferentinou, 2021; Harish Kumar et al., 2020; Mezaini et al., 2021; Shannon, 2021).

This study will use a selected profile on the wall of a flank in the case of an open-pit mine, to illustrate the contribution of RocScience (Slide module version 6.020), the deterministic approach (limit equilibrium method) and the probabilistic approach through a simulation example. The behavior of the soil was studied with the Mohr Coulomb model which is a criterion accepted in most geotechnical models. It is expressed by the following equation:

$$\tau = C' + (\sigma - U) \tan \varphi' \quad \text{Équation (1)}$$

With,  $\tau$ : Shear stress;  $C'$ : Effective cohesion;  $\sigma$ : Total stress;  $U$ : Interstitial pressure;  $\varphi'$  Effective angle of internal friction.

### 4.2. Analysis Methods

For stability analysis, the choice can be made between limit equilibrium methods, discretization methods and probabilistic methods (Samir, 2008; Harabinova &

Panulinova, 2017). Melouka (2003) gave more details on these methods. Limit equilibrium methods can be quick and effective, in some cases, using software, charts and tables from Taylor, Bishop, Morgenstern, Spencer, etc. **Table 6** shows the different stability assessment methods.

**Table 6.** Methods for quantitative assessment of slope stability (Samir, 2008).

Limit equilibrium methods	Discretization methods
Culmann., 1886	Finite elements., 1967
Infinite slopes., 1910	Finite differences
Fellenius., 1927	Separate elements
Circle of friction., 1937	Boundary elements
Bishop., 1955	<b>Probabilistic methods</b>
Janbu, 1956	Monte Carlo simulation
Bishop and Morgenstern., 1960	Point evaluation
Morgenstern and Price., 1965	Statistical analysis
Logarithmic spiral line., 1969	
Sarma's method., 1973	
Perturbation., 1974	

In this paper, we will mainly use the deterministic limit equilibrium method (Bishop Simplified, Janbu Simplified, Spencer and GLE/Morgenstern-Price) to make this sensitivity analysis of the geometric parameters of the bench and the mechanical parameters of the layers in order to determine the most favorable conditions for stability, whose factor of safety is greater than or equal to 1.50. The conditions corresponding to the geometric and mechanical parameters at the sliding moment have a direct influence on the factor of safety in static and pseudo-static conditions (Fredj et al., 2017). In our case, all analyses were made using non-circular surfaces with the Automatic Search technique of the failure surface "Auto Refine Search".

### 4.3. Characteristics of the Study Model

In our simulation example, we initially considered the configuration of a stack of five benches of different thicknesses and natures. The bedrock is a granite ranging from fine to coarse grains intruded by pegmatites topped by limestones and sandstones that constitute the rocks of the mining wall. For the case studied, the slope design of these five benches is characterized by benches 20 m of height and 5 m of width, with a slope angle of  $76^\circ$ . The total height of the excavated area is 80 m with an overall edge angle of  $66^\circ$ . The profile below shows the lithological detail of the rock mass, limited with a window of 125 meters and 315 meters long (**Figure 1**). **Table 7** shows the physical-mechanical characteristics of the different layers in the case study.



## 5.2. Influence of Variations of Geometric Parameters of the Bench on the Factor of Safety

**Table 9** and **Table 10** show the results horizontal displacements on the factor of safety. The variation in geometric parameters concerned the slope angle ( $\alpha$ ), the bench height ( $HG$ ) and the overall edge angle ( $\beta$ ) as well as horizontal displacements.

**Table 9.** Interpretation results under the influence of geometric parameters.

Geometric parameters	Condition	Applied analysis methods			
		Factor of safety (FS)			
		Bishop Simplified	Janbu Simplified	Spencer	GLE/Morgenstern-Price
HG = 20 m $\alpha = 76^\circ$ $\beta = 66^\circ$	Static	1.41	1.39	1.40	1.40
	Pseudo-static	<b>0.76</b>	<b>0.70</b>	<b>0.74</b>	<b>0.75</b>
HG = 20 m $\alpha = 63^\circ$ $\beta = 55^\circ$	Static	1.696	1.633	1.682	1.680
	Pseudo-static	<b>0.887</b>	<b>0.793</b>	<b>0.870</b>	<b>0.863</b>
HG = 10 m $\alpha = 76^\circ$ $\beta = 50^\circ$	Static	1.667	1.617	1.675	1.668
	Pseudo-static	<b>0.889</b>	<b>0.795</b>	<b>0.867</b>	<b>0.851</b>
HG = 10 m $\alpha = 63^\circ$ $\beta = 43^\circ$	Static	1.913	1.829	1.924	1.922
	Pseudo-static	1.164	1.040	1.157	1.171

According to the results obtained in **Table 9**, the most stable model under different conditions is the last model, whose bench height is 10 m with a slope angle of  $63^\circ$  and an overall edge angle of  $43^\circ$ . According to [Read and Stacey \(2009\)](#), it is observed that with this model, all factors of safety are greater than 1.5 in static conditions, which shows a state of long-term stability of the mine slopes and edges ([Harabinova & Panulinova, 2017](#)). **Table 9** shows that under these conditions, pseudo-static stability is maintained because all safety factors are greater than 1. The Janbu Simplified method always gives the smallest factor of safety based on the results with different models and under different conditions.

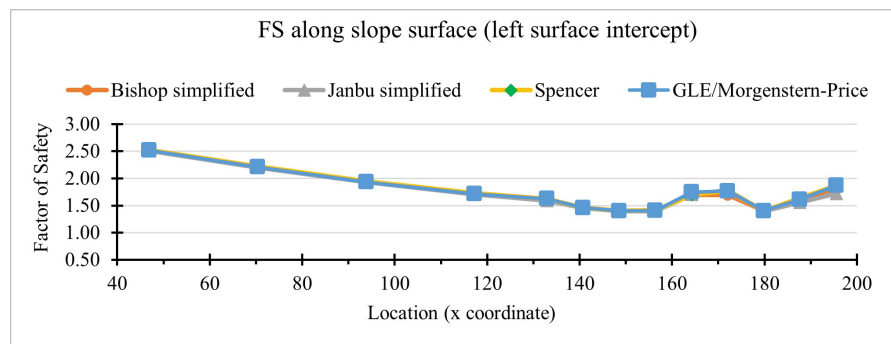
**Figure 2** shows that with the different numerical calculation methods a horizontal displacement on the X axis does not cause instability of the slopes and edges of the mine because all the factors of safety obtained are greater than 1. From X equal to 47 m to 149 m, there is a slight decrease in the factor of safety. **Table 10** and **Figure 2** show that from X equal to 164 m, the factor of safety increases before falling to X equal to 180 m and then resuming its increase at X equal to 188 m.

## 5.3. Influence of Variation of Mechanical Parameters (Cohesion and Internal Friction Angle) on the Factor of Safety (FS)

The influence of mechanical parameters ( $C$  and  $\varphi$ ) on the factor of safety was

**Table 10.** Influence of horizontal displacements on the factor of safety (FS).

Location (X coordinate)	Applied analysis methods			
	Factor of safety (FS)			
	Bishop Simplified	Janbu Simplified	Spencer	GLE/Morgenstern-Price
47	2.52	2.51	2.53	2.51
70	2.21	2.20	2.22	2.21
94	1.94	1.93	1.95	1.93
117	1.72	1.70	1.72	1.71
133	1.63	1.59	1.62	1.62
141	1.46	1.45	1.46	1.46
149	1.41	1.39	1.40	1.40
156	1.41	1.40	1.41	1.41
164	1.69	1.70	1.70	1.75
172	1.69	1.78	1.77	1.77
180	1.41	1.39	1.40	1.40
188	1.63	1.55	1.64	1.61
195	1.80	1.72	1.87	1.87



**Figure 2.** Diagram showing the variation in factor of safety (FS) under the effect of horizontal displacements.

studied first by varying the internal friction angle of the grains while fixing the value of cohesion and vice versa. Each layer was analyzed independently of the other and at the end, we made coupling of variation of cohesion and the internal friction angle of the grains. The results obtained are indicated in the tables and diagrams below.

**Table 11.** Influence of the angle of internal friction on the factor of safety in sandstone.

Sandstone	C = 73 KPa							
	Static condition [A], <b>Figure 3(a)</b>				Pseudo-static condition [B], <b>Figure 3(b)</b>			
	Phi (°)	FS- Bishop -Sim.	FS- Janbu -Sim.	FS- Spencer	FS- GLE/ M-Price	FS- Bishop -Sim.	FS- Janbu -Sim.	FS- Spencer
25	1.791	1.699	1.787	1.779	<b>0.949</b>	<b>0.865</b>	<b>0.955</b>	<b>0.921</b>
30	1.816	1.725	1.825	1.823	1.049	<b>0.962</b>	1.052	1.053

Continued

35	1.854	1.768	1.855	1.850	<b>0.945</b>	<b>0.863</b>	<b>0.940</b>	<b>0.932</b>
40	1.882	1.796	1.895	1.891	1.150	1.031	1.152	1.166
45	1.919	1.836	1.931	1.929	1.167	1.043	1.158	1.172
50	1.951	1.875	1.970	1.967	1.187	1.058	1.163	1.176
55	1.981	1.898	2.004	2.003	1.194	1.068	1.164	1.177
60	2.008	1.928	2.034	2.031	1.176	1.075	1.167	1.161

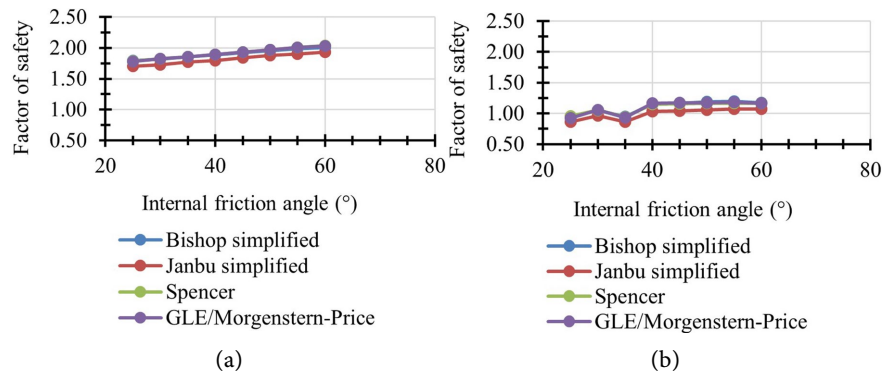


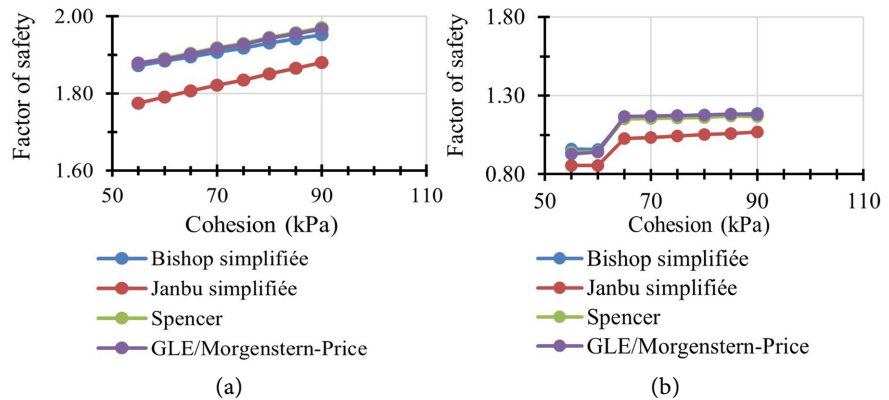
Figure 3. Influence of the internal friction angle on the factor of safety in sandstone.

Table 12. Influence of grain cohesion on the factor of safety in sandstone.

Sandstone	Phi = 44°							
	Static condition [A]. Figure 4(a)				Pseudo-static condition [B]. Figure 4(b)			
C (KPa)	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price
55	1.872	1.775	1.879	1.878	<b>0.959</b>	<b>0.857</b>	<b>0.938</b>	<b>0.928</b>
60	1.884	1.791	1.890	1.888	<b>0.957</b>	<b>0.857</b>	<b>0.945</b>	<b>0.940</b>
65	1.895	1.806	1.904	1.901	1.153	1.028	1.152	1.166
70	1.907	1.821	1.918	1.916	1.159	1.035	1.155	1.169
75	1.917	1.834	1.929	1.927	1.167	1.043	1.158	1.172
80	1.930	1.851	1.945	1.943	1.173	1.051	1.161	1.176
85	1.941	1.865	1.957	1.955	1.180	1.058	1.169	1.183
90	1.952	1.880	1.970	1.967	1.187	1.067	1.168	1.181

According to the results indicated in Table 11 and Table 12, the variation of the mechanical parameters (C and  $\phi$ ), does not cause instability in the sandstone layer under its own weight (static conditions). Figure 3(b) shows that on the other hand, in Pseudo-static conditions an internal friction angle of the grains ( $\phi$ ) less than 40° while maintaining the value of the internal cohesion of the grains at 73 KPa causes instability of the slopes and edges of the mine because the calculated factors of safety are less than 1. Similarly, Figure 4(b) shows that in Pseudo-static

conditions, an internal cohesion of the grains lower than 65 KPa causes instability of the slopes and edges of the mine.



**Figure 4.** Influence of grain cohesion on the factor of safety in sandstone.

**Table 13** and **Table 14** show that in static and Pseudo-static conditions, the factor of safety increases with increase of the mechanical parameters ( $C$  and  $\varphi$ ), in limestone. According to **Figure 5(b)**, it should be noted that instabilities are inevitable below a friction angle of less than  $45^\circ$ . Similarly, **Figure 6(b)** shows that instabilities are possible below an internal cohesion of grains lower than 120 KPa.

**Table 15** and **Table 16** show that in the pegmatite layer, the variation of mechanical parameters does not have enough effect on the factor of safety under static conditions. **Figure 7(b)** shows that under Pseudo-static conditions, this layer is stable within a range of values of the internal friction angle of the grains from  $30^\circ$  to  $35^\circ$ , outside of which an increase or decrease in this parameter will cause instabilities. Similarly, **Figure 8(b)** shows that outside an interval of internal cohesion of grains values ranging from 250 to 300 KPa, instabilities are inevitable with an increase or decrease in the parameter.

**Table 13.** Influence of the angle of internal friction on the factor of safety in limestone.

Limestone	C = 112 KPa							
	Static condition [A]. <b>Figure 5(a)</b>				Pseudo-static condition [B]. <b>Figure 5(b)</b>			
	Phi ( $^\circ$ )	FS- Bishop -Sim.	FS- Janbu -Sim.	FS- Spencer	FS- GLE/ M-Price	FS- Bishop -Sim.	FS- Janbu -Sim.	FS- Spencer
15	1.229	1.193	1.245	1.244	<b>0.614</b>	<b>0.560</b>	<b>0.613</b>	<b>0.609</b>
20	1.393	1.348	1.412	1.411	<b>0.703</b>	<b>0.637</b>	<b>0.698</b>	<b>0.699</b>
25	1.553	1.501	1.567	1.564	<b>0.787</b>	<b>0.706</b>	<b>0.787</b>	<b>0.783</b>
30	1.714	1.647	1.735	1.731	<b>0.883</b>	<b>0.787</b>	<b>0.869</b>	<b>0.864</b>
35	1.876	1.797	1.893	1.891	1.143	1.022	1.138	1.150
40	2.045	1.950	2.056	2.052	1.039	<b>0.936</b>	1.030	1.020
45	2.575	2.394	2.602	2.586	1.317	1.173	1.281	1.262
50	2.450	2.289	2.475	2.473	1.343	1.255	1.383	1.349

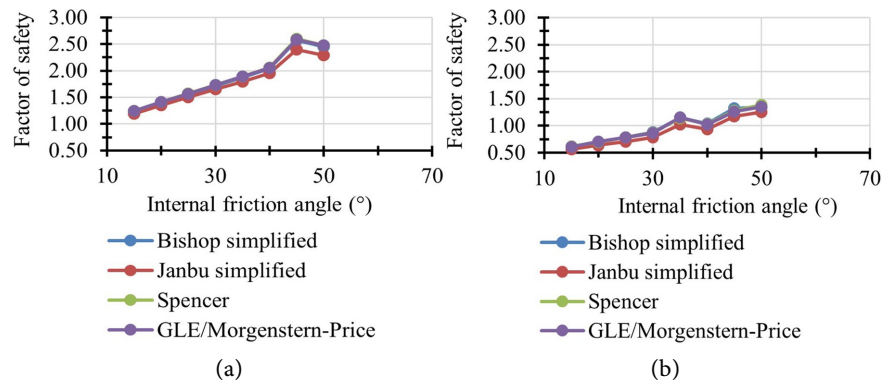


Figure 5. Influence of the angle of internal friction on the factor of safety in limestone.

Table 14. Influence of grain cohesion on the factor of safety in limestone.

Limestone	Phi = 36°							
	Static condition [A]. Figure 6(a)				Pseudo-static condition [B]. Figure 8(b)			
C (KPa)	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price
40	1.476	1.450	1.482	1.480	<b>0.729</b>	<b>0.657</b>	<b>0.752</b>	<b>0.721</b>
60	1.606	1.562	1.615	1.613	<b>0.809</b>	<b>0.724</b>	<b>0.795</b>	<b>0.792</b>
80	1.728	1.668	1.734	1.727	<b>0.878</b>	<b>0.784</b>	<b>0.866</b>	<b>0.864</b>
100	1.845	1.770	1.860	1.858	<b>0.936</b>	<b>0.840</b>	<b>0.931</b>	<b>0.924</b>
120	1.957	1.868	1.970	1.968	1.191	1.064	1.179	1.194
140	2.083	1.980	2.090	2.088	1.254	1.126	1.222	1.223
160	2.513	2.344	2.530	2.518	1.285	1.145	1.261	1.264
180	2.526	2.357	2.571	2.558	1.300	1.174	1.287	1.274

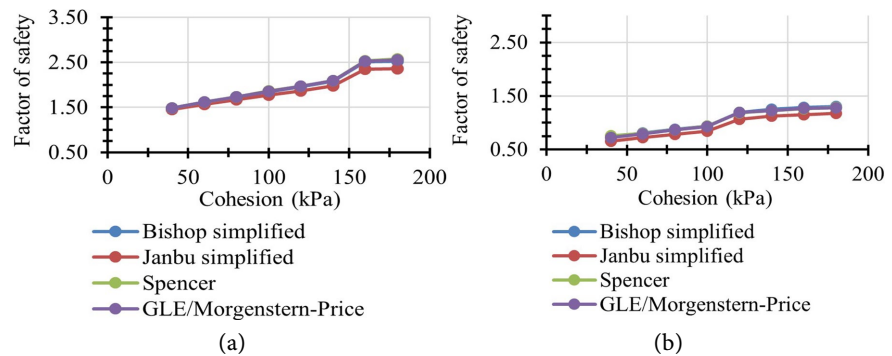


Figure 6. Influence of grain cohesion on the factor of safety in limestone.

Table 15. Influence of the angle of internal friction on the safety factor in pegmatite.

Pegmatite	C = 304.80 KPa							
	Static condition [A]. Figure 7(a)				Pseudo-static condition [B]. Figure 7(b)			
Phi (°)	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price
15	1.864	1.757	1.954	1.952	<b>0.920</b>	<b>0.831</b>	<b>0.940</b>	<b>0.932</b>

Continued

20	2.031	1.908	2.104	2.097	1.021	<b>0.914</b>	1.019	<b>0.998</b>
25	1.909	1.828	1.925	1.923	1.110	<b>0.988</b>	1.088	1.069
30	1.913	1.829	1.924	1.922	1.164	1.040	1.140	1.139
35	1.916	1.832	1.928	1.925	1.164	1.040	1.160	1.173
40	1.916	1.832	1.928	1.925	<b>0.974</b>	<b>0.874</b>	<b>0.965</b>	<b>0.962</b>
45	1.916	1.832	1.928	1.925	<b>0.984</b>	<b>0.880</b>	<b>0.964</b>	<b>0.958</b>
50	1.916	1.832	1.928	1.925	<b>0.984</b>	<b>0.879</b>	<b>0.965</b>	<b>0.957</b>

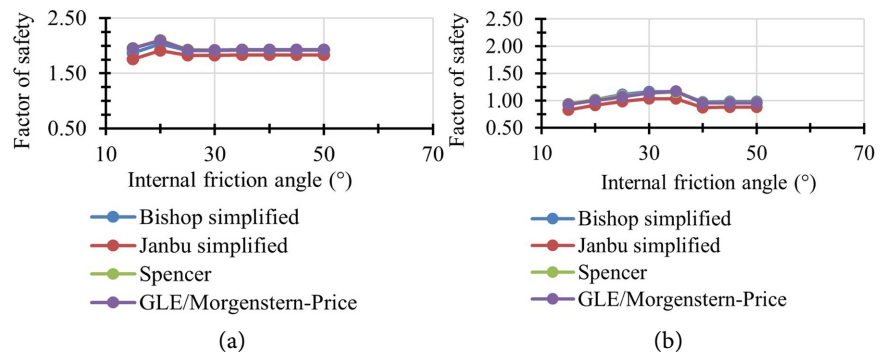


Figure 7. Influence of the angle of internal friction on the factor of safety in pegmatite.

Table 16. Influence of cohesion on the safety factor in pegmatite.

Pegmatite	Phi = 34°							
	Static condition [A]. Figure 8(a)				Pseudo-static condition [B]. Figure 8(b)			
C (KPa)	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price
150	1.915	1.801	1.953	1.945	<b>0.980</b>	<b>0.873</b>	<b>0.972</b>	<b>0.965</b>
200	2.088	1.958	2.112	2.108	1.065	<b>0.949</b>	1.048	1.047
250	1.913	1.829	1.924	1.922	1.141	1.022	1.113	1.119
300	1.913	1.829	1.924	1.922	1.164	1.040	1.155	1.169
350	1.916	1.832	1.928	1.925	<b>0.984</b>	<b>0.879</b>	<b>0.965</b>	<b>0.957</b>
400	1.916	1.832	1.928	1.925	<b>0.973</b>	<b>0.874</b>	<b>0.965</b>	<b>0.962</b>
450	1.909	1.828	1.925	1.923	<b>0.973</b>	<b>0.874</b>	<b>0.964</b>	<b>0.962</b>
500	1.926	1.842	1.926	1.926	<b>0.975</b>	<b>0.876</b>	<b>0.967</b>	<b>0.964</b>

Figure 9 and Figure 10 in the fine-grained granite layers, and Figure 11 and Figure 12 in the coarse-grained granite layers show that variation in mechanical parameters has an insignificant effect on the factor of safety under static and pseudo-static conditions. Table 17 and Table 18 show that with an internal grain friction angle of less than 40°, instabilities are unavoidable in the fine-grained granite. These results clearly show that the stability of these last two layers is

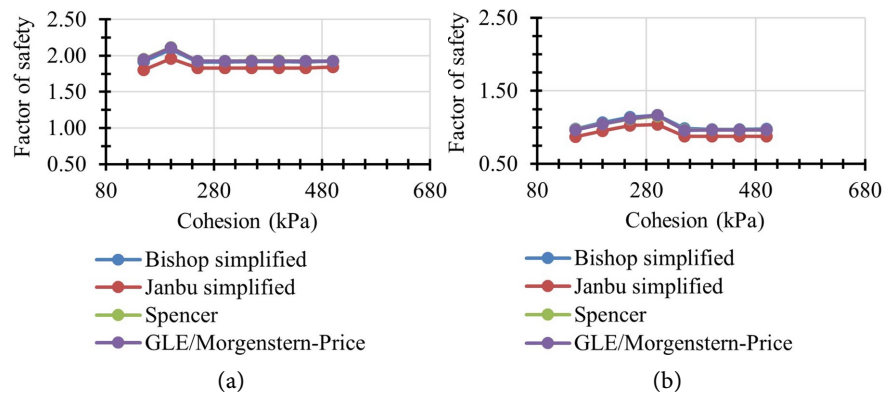


Figure 8. Influence of cohesion on the factor of safety in pegmatite.

higher than the stability of the first three layers. Table 19, Table 20, Figure 11 and Figure 12 show that the variation of the mechanical parameters in the coarse-grained granite layer has no effect on the factor of safety, therefore, the slopes and the edges of the mine.

Table 17. Influence of the angle of internal friction on the factor of safety in fine-grained granite.

Fine-grained granite	C = 430.90 KPa							
	Static condition [A]. Figure 9(a)				Pseudo-static condition [B]. Figure 9(b)			
Phi (°)	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price
35	2.337	2.166	2.348	2.330	<b>0.984</b>	<b>0.879</b>	<b>0.967</b>	<b>0.958</b>
40	1.909	1.828	1.925	1.923	1.164	1.040	1.157	1.171
45	1.909	1.828	1.925	1.923	1.164	1.040	1.157	1.171
50	1.909	1.828	1.925	1.923	1.164	1.040	1.157	1.171
55	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
60	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
65	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
70	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171

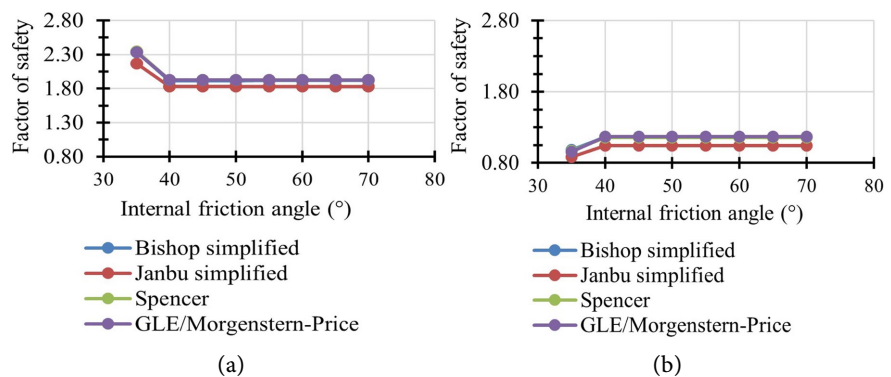
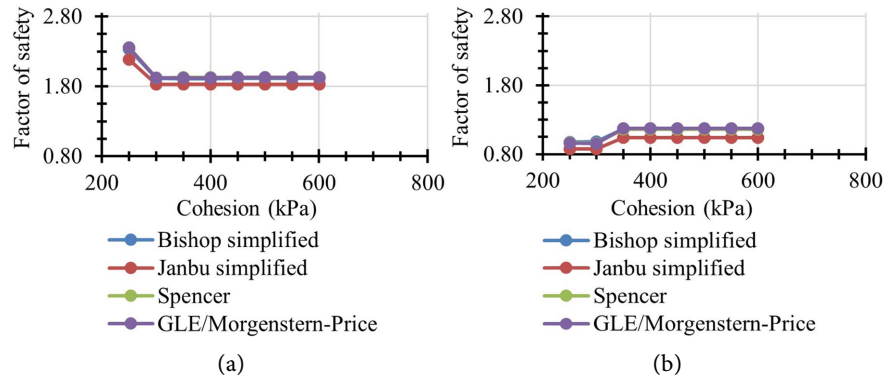


Figure 9. Influence of the angle of internal friction on the factor of safety in fine-grained granite.

**Table 18.** Influence of cohesion on the factor of safety in fine-grained granite.

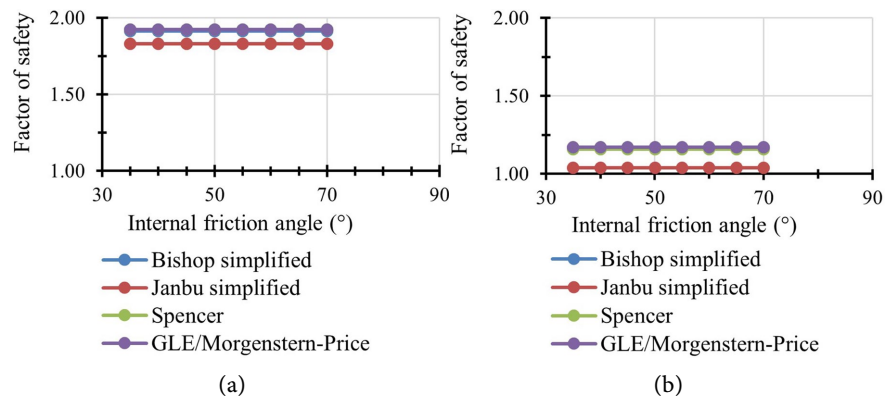
Fine-grained granite	Phi = 51.90°							
	Static condition [A]. <b>Figure 10(a)</b>				Pseudo-static condition [B]. <b>Figure 10(b)</b>			
C (KPa)	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price
250	2.330	2.183	2.354	2.351	0.975	0.875	0.967	0.963
300	1.913	1.829	1.924	1.922	0.981	0.875	0.963	0.955
350	1.909	1.828	1.925	1.923	1.164	1.040	1.157	1.171
400	1.909	1.828	1.925	1.923	1.164	1.040	1.157	1.171
450	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
500	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
550	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171
600	1.916	1.832	1.928	1.925	1.164	1.040	1.157	1.171



**Figure 10.** Influence of cohesion on the factor of safety in fine-grained granite.

**Table 19.** Influence of the angle of internal friction on the factor of safety in coarse-grained granite.

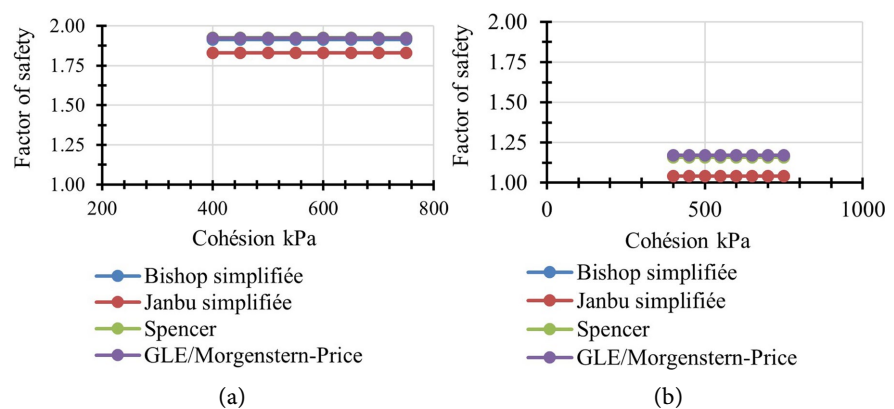
Coarse-grained granite	C = 553.40 KPa							
	Static condition [A]. <b>Figure 11(a)</b>				Pseudo-static condition [B]. <b>Figure 11(b)</b>			
Phi (°)	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop-Sim.	FS-Janbu-Sim.	FS-Spencer	FS-GLE/M-Price
35	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
40	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
45	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
50	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
55	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
60	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
65	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
70	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171



**Figure 11.** Influence of the angle of internal friction on the factor of safety in coarse-grained granite.

**Table 20.** Influence of cohesion on the factor of safety in coarse-grained granite.

Coarse-grained granite	Phi = 53.60°							
	Static condition [A]. <b>Figure 12(a)</b>				Pseudo-static condition [B]. <b>Figure 12(b)</b>			
C (KPa)	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price	FS-Bishop -Sim.	FS-Janbu -Sim.	FS-Spencer	FS-GLE/M-Price
200	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
300	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
400	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
500	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
600	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
700	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
800	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171
900	1.913	1.829	1.924	1.922	1.164	1.040	1.157	1.171



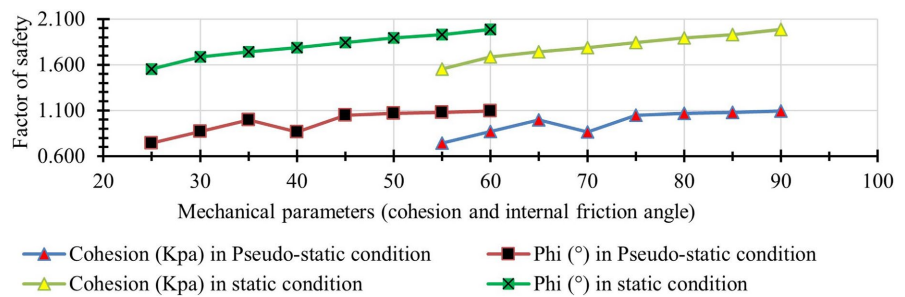
**Figure 12.** Influence of cohesion angle on the factor of safety in coarse-grained granite.

The influence of coupling mechanical parameters (C and  $\varphi$ ) on the factor of safety was studied by varying both the internal friction angle and the internal

cohesion of grains in each layer. Each layer was analyzed independently of the other in static and pseudo-static conditions. **Tables 21-25** and **Figures 13-17** show the results obtained. According to **Table 21** and **Figure 13**, and **Table 22** and **Figure 14**, in the sandstone and limestone layers, respectively, the results of safety factor calculations show that below a certain value of mechanical parameters, instabilities are unavoidable under the influence of a coupled variation in pseudo-static conditions.

**Table 21.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in sandstone.

Material: Sandstone		Analysis method: Janbu Simplified	
Cohesion (KPa)	Phi (°)	Factor of safety in static condition	Factor of safety in Pseudo-static condition
55	25	1.553	<b>0.742</b>
60	30	1.684	<b>0.871</b>
65	35	1.739	<b>0.995</b>
70	40	1.787	<b>0.864</b>
75	45	1.842	1.042
80	50	1.894	1.067
85	55	1.927	1.079
90	60	1.983	1.091



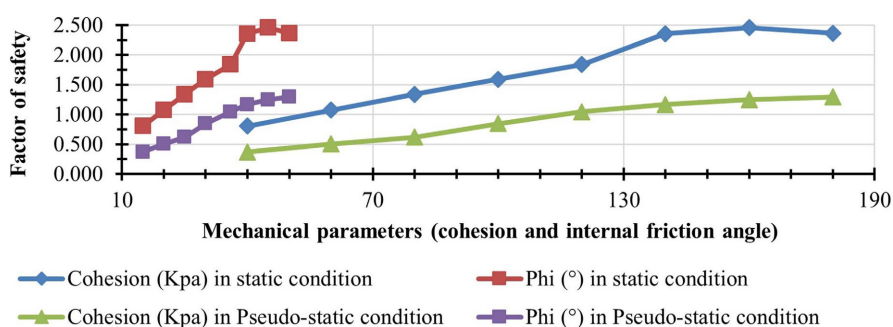
**Figure 13.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in sandstone.

**Table 22.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in limestone.

Material: Limestone		Analysis method: Janbu Simplified	
Cohesion (KPa)	Phi (°)	Factor of safety in static condition	Factor of safety in Pseudo-static condition
40	15	<b>0.805</b>	<b>0.371</b>
60	20	1.073	<b>0.502</b>
80	25	1.339	<b>0.616</b>

Continued

100	30	1.588	<b>0.847</b>
120	36	1.837	1.046
140	40	2.355	1.165
160	45	2.457	1.250
180	50	2.361	1.291

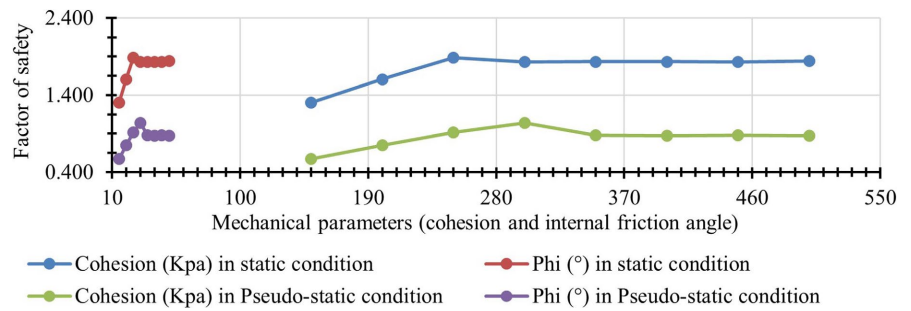


**Figure 14.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in limestone.

**Table 23** and **Figure 15** show that the pegmatite layer shows very high instability under the influence of coupled variation of mechanical parameters. **Table 24** and **Figure 16** that the effect of variation of mechanical parameters on the factor of safety is very limited in the fine-grained granite layer. On the other hand, **Table 25** and **Figure 17** show that the variation of the mechanical parameters has no effect on the factor of safety in the coarse-grained granite layer.

**Table 23.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in pegmatite.

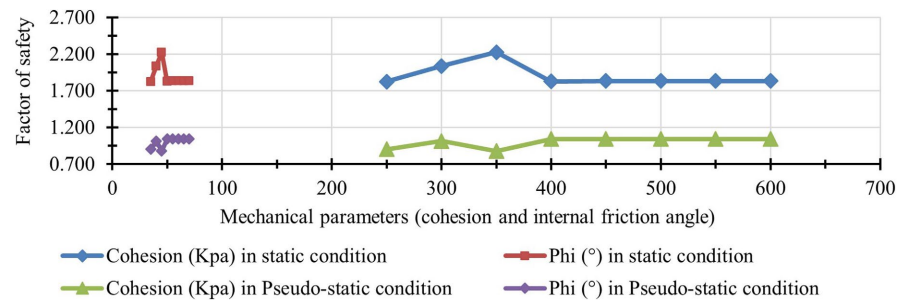
Material: Pegmatite		Analysis method: Janbu Simplified	
Cohesion (KPa)	Phi (°)	Factor of safety in static condition	Factor of safety in Pseudo-static condition
150	15	1.304	<b>0.572</b>
200	20	1.605	<b>0.750</b>
250	25	1.885	<b>0.916</b>
300	30	1.829	1.040
350	35	1.832	<b>0.879</b>
400	40	1.832	<b>0.874</b>
450	45	1.828	<b>0.876</b>
500	50	1.842	<b>0.874</b>



**Figure 15.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in pegmatite.

**Table 24.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in fine granite.

Material: Fine-grained granite		Analysis method: Janbu Simplified	
Cohesion (KPa)	Phi (°)	Factor of safety in static condition	Factor of safety in Pseudo-static condition
250	35	1.823	<b>0.901</b>
300	40	2.036	1.012
350	45	2.266	<b>0.875</b>
400	50	1.828	1.040
450	55	1.832	1.040
500	60	1.832	1.040
550	65	1.832	1.040
600	70	1.832	1.040



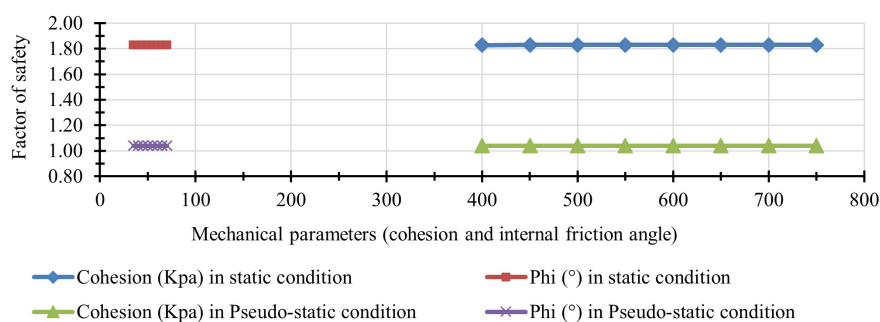
**Figure 16.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in fine-grained granite.

**Table 25.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in coarse-grained granite.

Material: Coarse-grained granite		Analysis method: Janbu Simplified	
Cohesion (KPa)	Phi (°)	Factor of safety in static condition	Factor of safety in Pseudo-static condition
400	35	1.828	1.040
450	40	1.829	1.040

## Continued

500	45	1.829	1.040
550	50	1.829	1.040
600	55	1.829	1.040
650	60	1.829	1.040
700	65	1.829	1.040
750	70	1.829	1.040



**Figure 17.** Coupling of grain internal friction angle variation and cohesion on the factor of safety in coarse-grained granite.

## 6. Conclusion

This work is part of a numerical simulation of the geotechnical behavior of the slopes and edges of the mine in the case of an open-pit mine. We used the deterministic finite element method and RocScience Slide stability analysis software, based on the “Mohr-Coulomb” behavior law. This analysis was carried out under the influence of the variation of the geometric parameters of the bench and the mechanical parameters of the layers subjected under evaluation and enabled us to assess the influence of variation in these parameters on the stability of the slopes and edges of the open-pit mine. These applications have been carried out on material properties and deterministic models without access to field data.

From the analysis of the results obtained through the different models under the influence of the variation geometric parameters, the most stable model has the following geometric characteristics of the bench: 10 m in height, 5 m in width, the slope angle  $63^\circ$  with a global edge angle  $43^\circ$ . This bench slope angle is in favor of materials which have a generally average hardness whose coefficient will probably be between 3 and 7. The factors of safety obtained with this model are greater than 1.5 in static conditions and greater than 1 in pseudo-static conditions. This shows that long-term stability is guaranteed in these conditions.

It is found that with the first three layers, instabilities are inevitable in certain intervals of internal cohesion value of grains and internal friction angle of grains. The variation of different mechanical parameters showed that the factor of safety increased with the increase of mechanical parameters in these first three layers. However, the variation of these parameters has no effect on the stability of the coarse-grained granite layer. It also showed that the higher the cohesion and internal friction angle of grains, the higher the stability of the layer is guaranteed

through a high factor of safety. The absence of field measurements in this work is justified by difficulties of access to the mines. The lack of validation of results by field data or physical models remains a limitation to the use of these applications in complex real-life problems. However, the results of numerical simulation must be validated by field measurements or tests on physical models. To validate a geotechnical stability model, it is necessary to account for the inherent variability and uncertainty of geological formations, as the physical and mechanical properties of formations vary from region to region according to climatic conditions.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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