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Back-analysis of a combined planar-extrusion failure in a mining slope

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Abstract

The present work analyses the failure of a slope in an ancient mining exploitation of plastic clays with a brown carbonated limestones overburden. The slope height is about 65 m, and a failure with a head displacement between 3 and 5 m was detected. Understanding the mechanisms that triggered the failure is crucial if the reopening of the exploitation is to be addressed in a future.

The back analysis was carried out using numerical models with FLAC 3D software. The results obtained have been compared considering two continuum constitutive models: Mohr Coulomb and ubiquitous joints. This comparation was made in terms of both geometry of mobilised block and magnitude and position of observed displacements. It was demonstrated that Mohr Coulomb model can´t adjust this type of problem, since an ubiquitous joints constitutive model allows obtaining accurate and realistic results.

Consequently, it is proved that the cause of the failure was the combination of two phenomena simultaneously: the liberation of the clays which, when deformed, promotes the failure of the upper materials; and the presence of a sub-vertical fault combined with a perpendicular family of discontinuities, which defines the geometry and magnitude of the failure.

It is also shown that a realistic adjust between modelling and reality can be obtained without resorting to discontinuous models, which are much more complex and computationally demanding. So, in a future mine design, the process could be optimised by approaching the problem in three phases: using the Mohr-Coulomb model in the earlier stages, the ubiquitous joint model for a fine-tuning and reserving the discontinuous models as a verification of the final design.

Keywords

Rock slope failure, forensic analysis, rock slope modelling, ubiquitous joints.

1 Introduction

The aim of this work is to establish a model that reproduces a complex failure that occurred in an ancient mining slope and that can subsequently be used to redesign the slope safely. The failure caused the displacement of a large rocky block with a headscarp of more than 3 m in height in the upper zone. A satellite photograph of the study area can be seen in Fig. 1 (a), where the geometry of the displaced block and its approximate dimensions can be appreciated in Fig. 1 (b). The total height of the slope is 65 m.

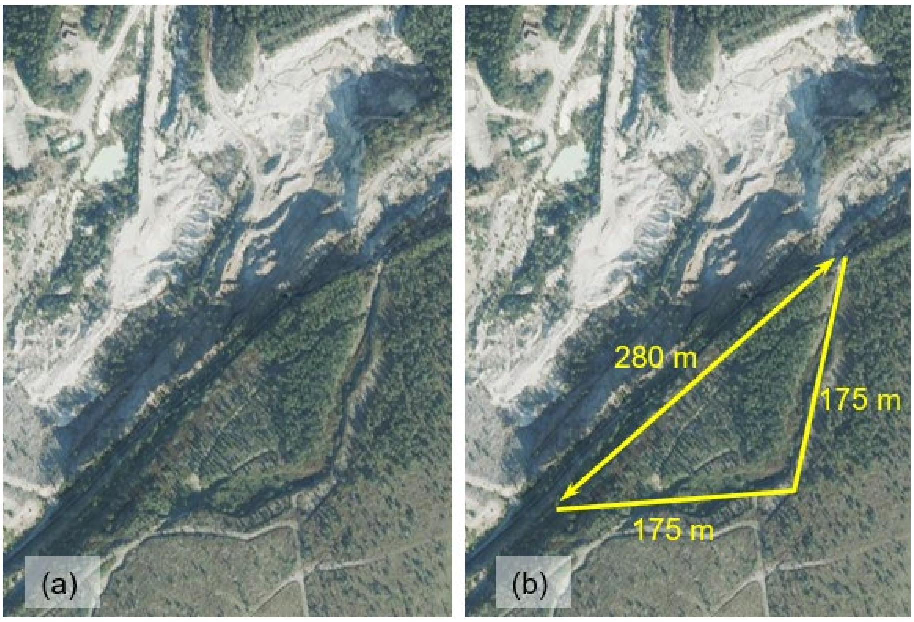

Fig. 1 Satellite photograph and block dimensions.

The appearance of the principal mobilised block can be seen in Fig. 2, where the height of the headscarp is represented in (a) and (b). Smaller secondary movements are linked to the main block (see Fig. 2 (c)).

Fig. 2 Appearance of the mobilised block.

To analyse the problems observed, a three-dimensional finite element model was developed with FLAC3D software (Itasca Consulting Group). FLAC3D is a three-dimensional explicit Lagrangian finite-volume program for engineering mechanics computation. To solve the interaction between a continuous model (as in the case of FLAC3D simulation) and a discontinuous problem (as in the case of block formation), a methodology similar to that described by Gao et al. (2021) and Li et al. (2019) was used. Prior numerical modelling, it was necessary to define a geotechnical model that considers the different materials involved, their geometry, discontinuities and stress-strain behaviours.

2 Geotechnical model: Materials description and properties

Prior to the development of the numerical simulations, it was necessary to define a geotechnical model that takes into account the different materials involved, their geometry, discontinuities and stress-strain behaviours.

2.1 Problem description

The original situation is represented in Fig. 3. There are three different materials:

- Brown carbonated sandstones: It´s the shallowest material, with a variable degree of carbonation influencing in actual properties of the rock mass.
- Greenish-grey clays: This is the material which is being extracted. It´s a very fine clay with various industrial applications. There are around 30-40 m of these clays at the base of the slope.
- Grey limestones acting as bedrock.

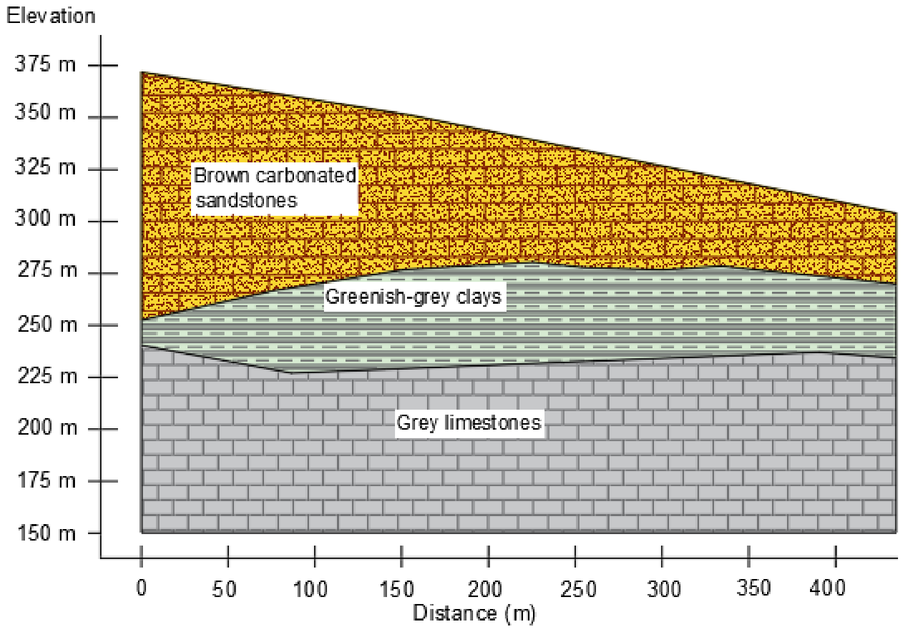

Fig. 3 Initial stage with original dips and materials geometry.

As a first step of exploitation, a slope in brown carbonated sandstones was excavated until it reached the contact with the clay level, releasing a working bench of around 70 m. This configuration is shown in Fig. 4. However, at the beginning of the clay excavation, the mentioned block was mobilized, and the whole slope was disturbed, as seen in Fig. 5.

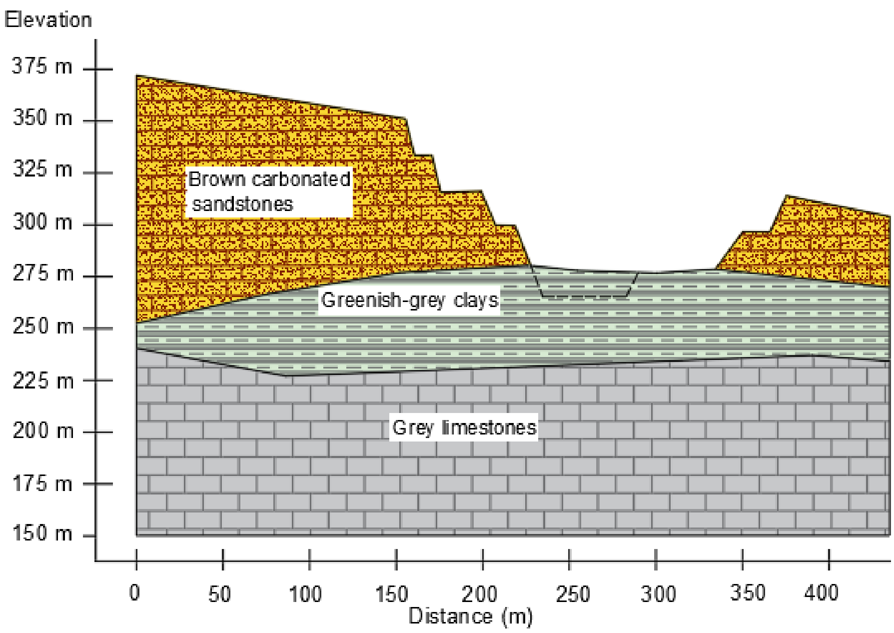

Fig. 4 First stages of exploitation, before the failure.

Although this seems a conventional rotational failure, the geometry of the failure head (see Fig. 1 and Fig. 2) suggests that it may be governed by some discontinuity planes. In fact, during the fieldwork, it was observed that the sandstone rock mass was affected by two conjugated families of vertical discontinuities (named J1 277/88 and J2 200/85). Stratification was identified as 285/40. It was also found that the block was laterally limited by a plane belonging to the 277/88 family, as can be seen in Fig. 6 (a). In the other extreme of the block, the failure is limited because a large rock fill (45 m height and 1.75 Mm^3) lies on the slope and acts as a wall, restricting displacements. This situation is showed in Fig. 6 (b). It is also possible that the characteristics of the clays located at the base may influence the process.

2.2 Materials properties

Due to the risk of accessing the mobilized block, three boreholes were drilled in the vicinity, extracting samples for subsequent laboratory testing. Lab properties are shown in Table 1.

Table 1 Lab properties for materials.

Materials	Density (t/m^3)	σ_t (MPa)	σ_c (MPa)	E (MPa)	ν	Cohesion (kPa)	Friction (º)
Sandstones	2.36	3.80	28.24	8642	0.32		
Clays	2.14		0.22	5.2		200	26
Limestone	2.65	4.35	75.83	17350	0.35		

Where σ_t Tensile strength
σ_c Uniaxial compressive strength
E Young´s Modulus
ν Poisson´s ratio

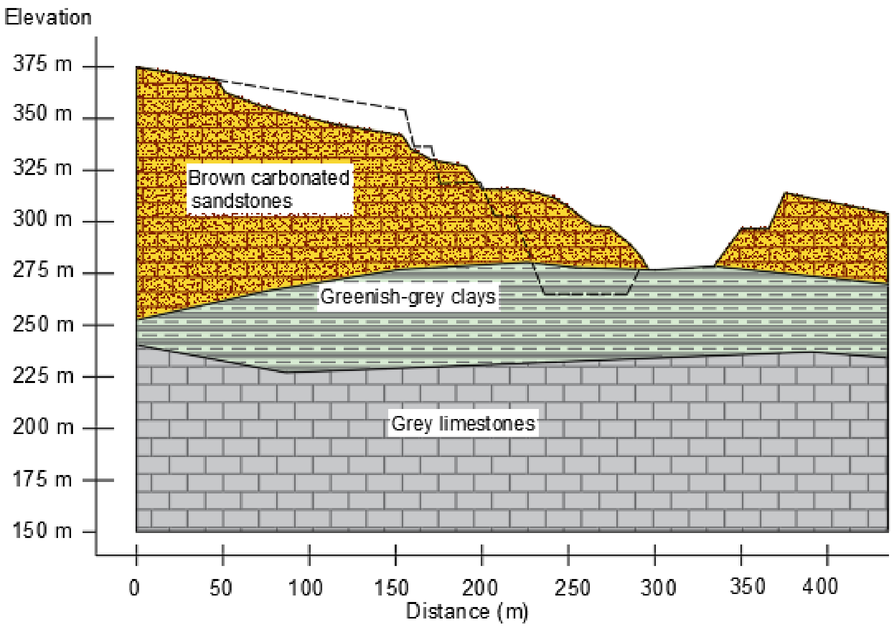

Fig. 5 Final profile after sliding.

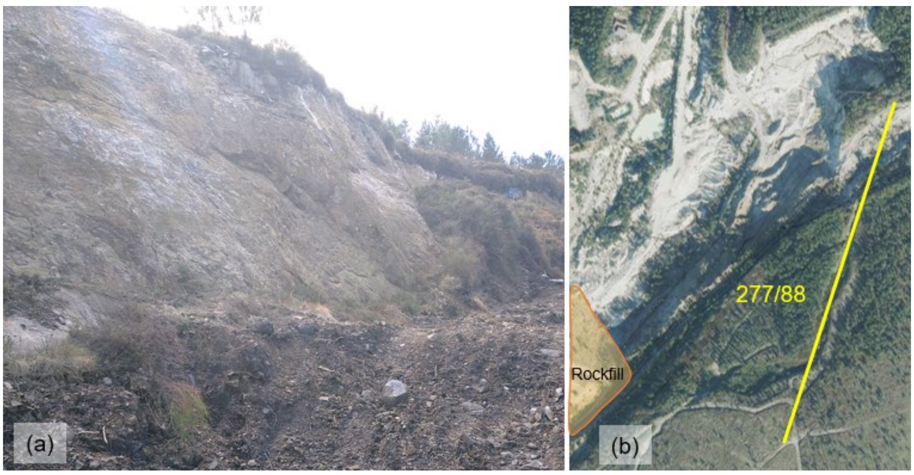

Fig. 6 Joint 277/88 limiting the mobilised block.

The families of discontinuities in the carbonate sandstones were also evaluated in the field, and the RMR (*Rock Mass Rating*) of this rock mass was rated as 35-40 (Bieniawski 1989). Bieniawski's criteria were followed to estimate the cohesion and friction of this rock mass. Considering the high degree of fracturing, the lower value of cohesion was taken within the range proposed by Bieniawski (200 to 300 kPa) and a medium-high value within the range of friction (25º to 35º). The Young's modulus of the sandstone rock mass was calculated using the formula of Galera et al. (2005): E (GPa) = 0.0876·RMR = 3.7 GPa. Finally, three direct shear strength tests were done with joints, with values ranging from 15 to 38 kPa and from 36º to 46º.

For the limestones, a RMR of 70 was estimated from the boreholes. As a summary, Table 2 presents the most significant properties of the three lithologies, which will be considered in subsequent modelling works. As no data is available on the Poisson's coefficient of clays the value of 0.3, recommended for medium clays in the Spanish Technical Building Code, has been considered.

Table 2 Material properties used in modelling works

Materials	**Density (t/m^3)**	**E (MPa)**	**ν**	**Cohesion (kPa)**	**Friction (º)**
Sandstones	2.36	3700	0.32	200	33
Clays	2.14	5.2	0.30	200	26
Limestone	2.65	6130	0.35	350	40

3 Back analysis modelling and discussion

To analyse this problem, a three-dimensional finite element model was developed with the FLAC3D software. For this purpose, the mobilised block was isolated on one of its faces and from there, the configuration of the rupture was analysed considering a continuous model. In this case, the influence of considering a purely continuous constitutive model (Mohr-Coulomb) or introducing a discontinuity effect through a model of ubiquitous joints was tested. In this way, fairly approximate and reliable results can be obtained without resorting to discontinuous elements modelling.

The simulation was developed by considering a plane belonging to J1 277/88 as a model boundary. So, the simulated block is shown in Fig. 7. The involved materials are represented in three different colours. Note that the modelled block has been extended in both sides of the OX direction to consider the toe of the slope and the head of the hill.

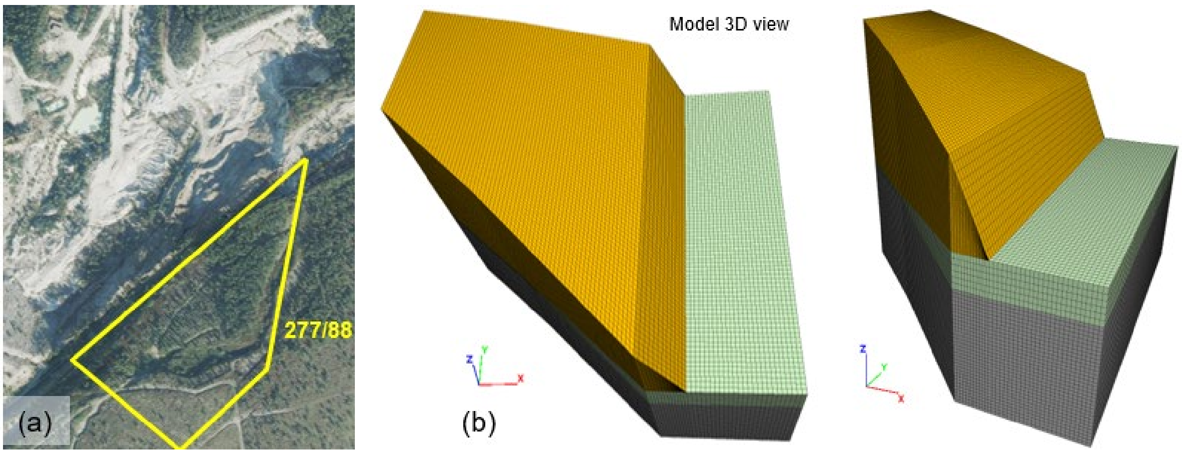

Fig. 7 Model geometry: (a) plant view; (b) model 3D view.

In the first step, all materials were considered as Mohr-Coulomb materials, with the properties of Table 2. Then, carbonated sandstones were considered as an ubiquitous joint material, in a way to represent the other conjugated family of joints J2 (200/85). The results of both are now exposed.

3.1 Mohr-Coulomb analysis

When Mohr-Coulomb analysis is made, the instability adopts a typical circular failure shape. This can be observed in Fig. 8 (a), which represents displacements along the OX direction (slope dip direction), including, in Fig. 8 (b) a cutting plane to visualize the displacements within the model in the next figures. Maximum values, around 2.5 m, are located in the base of the slope.

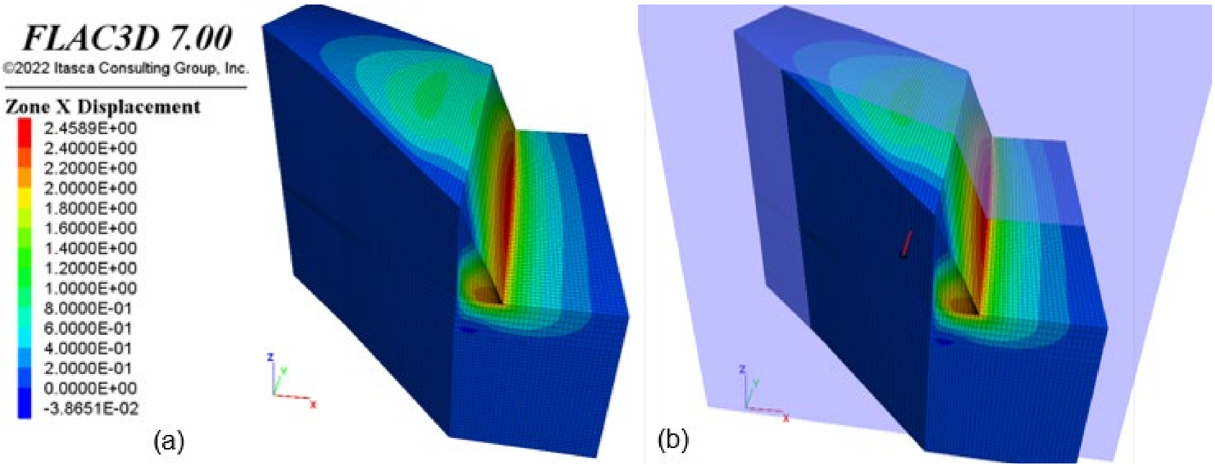

Fig. 8 Horizontal displacement (OX direction) and cutting plane.

Fig. 9 represents the magnitude of displacements and the plastic state in the model. This makes it possible to verify that the maximum scarp at the head of the landslide (corresponding a displacement up 2 m and marked with an arrow in Fig. 9 (a)) would be around 30 m above the slope head, which does not correspond to reality, since it reaches up to 100 m away. Moreover, the plastic state doesn´t show a real failure development.

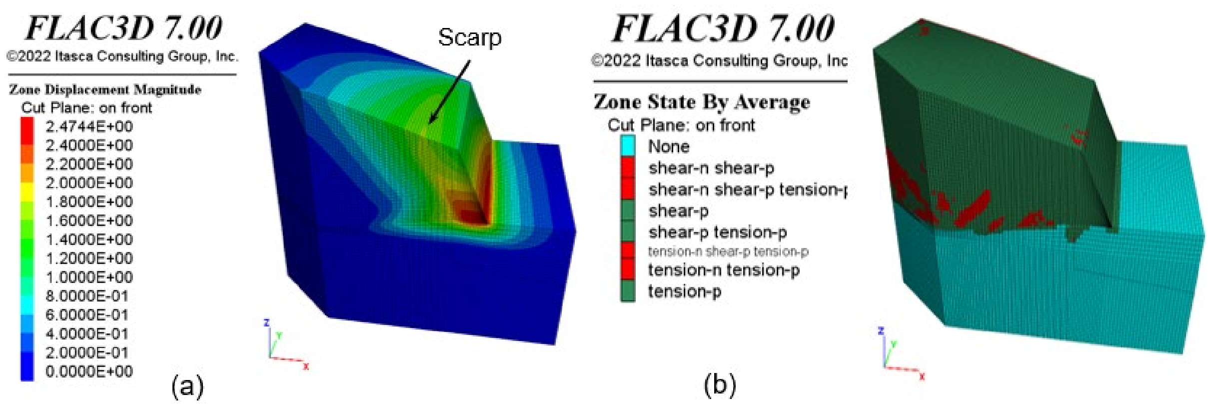

Fig. 9 Results with a Mohr-Coulomb constitutive model (with cutting plane): (a) displacements; (b) plastic state.

This situation changes when a bench of clays is excavated, but there is not a good agreement with real situation. As seen in Fig. 10, the plastic state reveals potential slope failures, reaching the top of the land but with a shape that is not coincident with the real one. Also, the scarp remains in the same position, too close to the top of the excavation slope.

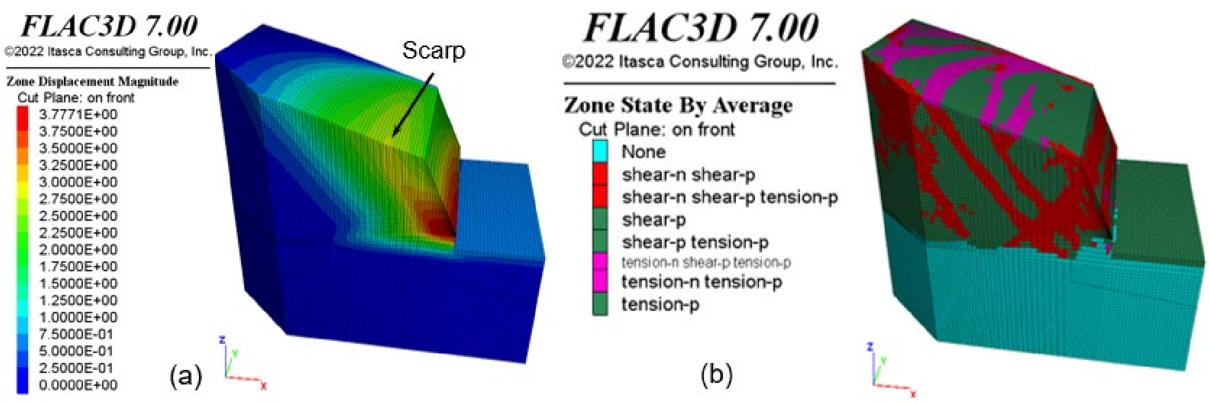

Fig. 10 Upper clays excavated (Mohr-Coulomb model): (a) displacements; (b) plastic state (both with cutting plane).

3.2 Ubiquitous joints analysis

In this case, a constitutive model of ubiquitous joints was considered for the sandstones, considering the J2 family. This represents the possibility that the 200/85 planes are homogeneously distributed in the material, allowing the occurrence of shear and/or tensile failure through them. The displacement magnitudes can be seen in Fig. 11. Clearly, the shape of the movements is similar to the one observed, with the mobilised block well defined.

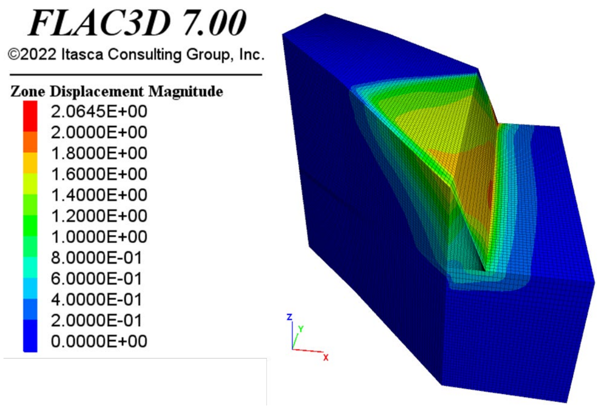

Fig. 11 Displacement magnitude with a ubiquitous joints constitutive model.

This idea is supported by Fig. 12, where the strain increments inside the ground and the plastic state are represented. In pink are marked the zones where failure is occurring through joints (either shear or tensile) and, in red, are marked the zones that are failing through the continuum. Therefore, according to this model, an incipient failure was already developing before excavating the clays.

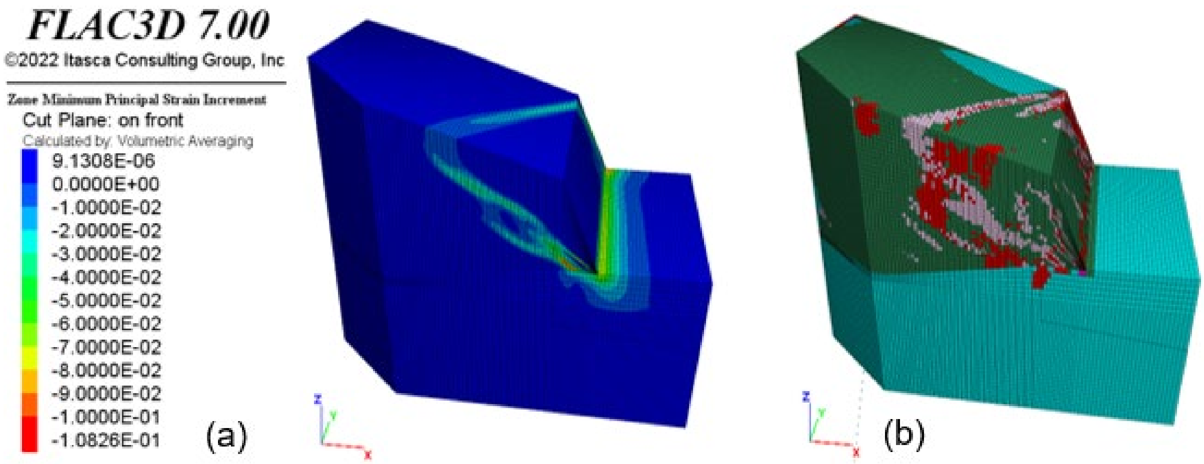

Fig. 12 Ubiquitous joints constitutive model: (a) strain increments; (b) plastic state.

When the upper level of clays is excavated, this incipient failure is magnified, as seen in Fig. 13, with a displacement of about 3 m around 100 m from the excavation slope. The strain increments and plastic state in the model (Fig. 14) show the geometry of failure and how new secondary blocks appear in a similar way as the real problem.

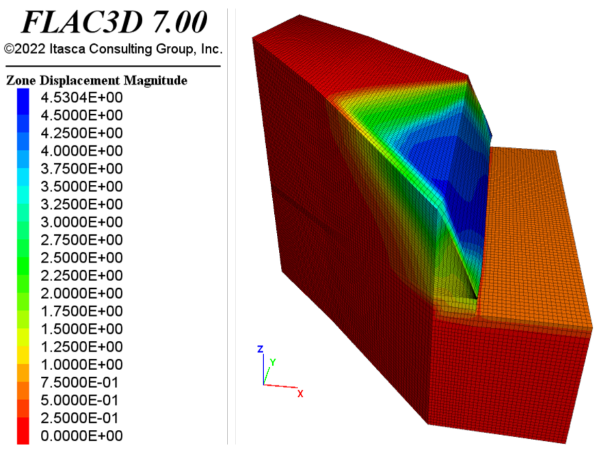

Fig. 13 Displacement magnitude when upper clays are excavated (ubiquitous joints model).

Therefore, although the Mohr-Coulomb model allows an approximation of the problem, the block model with ubiquitous joints is much more realistic. Its main drawback is the consumption of resources since it requires five times more computational time.

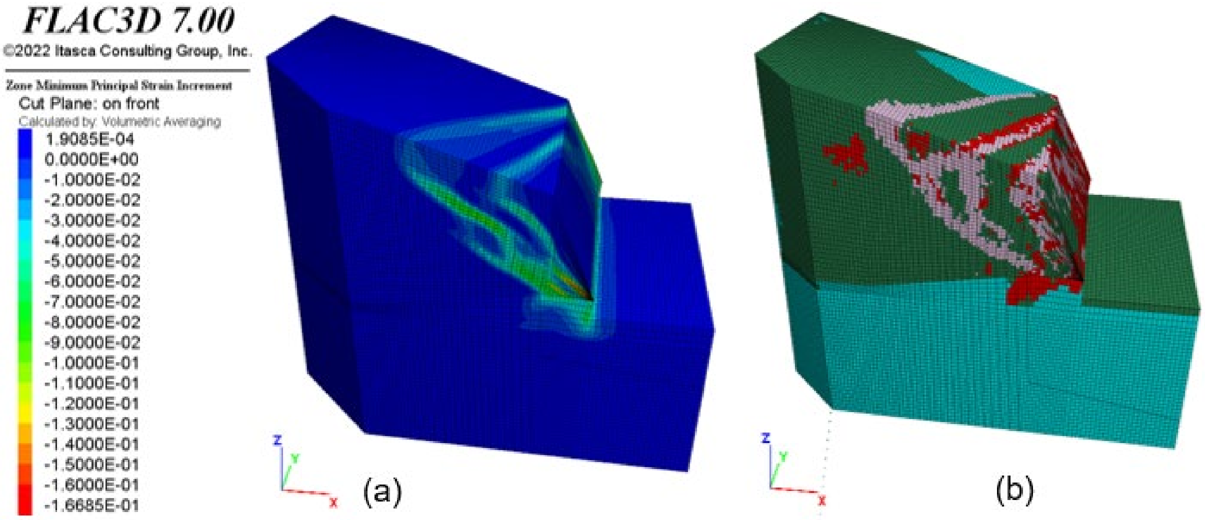

Fig. 14 Ubiquitous joints model when upper clays are excavated: (a) strain increments; (b) plastic state.

4 Conclusions

A back-analysis was carried out to determine the causes of the mobilization of a rocky block on the slope of an ancient mining operation. Computer modelling with FLAC 3D were developed for this purpose.

The results obtained have been compared when considering two different constitutive models (Mohr-Coulomb and ubiquitous joints). If Mohr-Coulomb constitutive model is used, the geometry of the sliding material is not similar to that observed in reality and the failure occurs just when the excavation of the clays begins. However, the ubiquitous joint model made it possible to reproduce the geometry and displacements of the mobilized block very accurately, without the need to resort to discontinuous elements modelling.

Based on results, it is highly probable that large displacements observed, more than 3 m, developed at the time when the excavation of the clays at the foot began because an incipient failure was latent before. Moreover, models showed that the problem resulted from a combination of two factors: the presence of two families of conjugate and sub-vertical joints and the deformability of the clays.

So, in a future mine design, Mohr-Coulomb models can be used in the first steps in approaching the problem, to optimize time resources. Fairly approximate and reliable results can be obtained with an ubiquitous joints model. Finally, discontinuous models could be used to verify the final solution.

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