A COMPLEX GEOTECHNICAL MODELLING OF AN OPEN PIT SLOPE. APPLICATION TO COBRE LAS CRUCES NORTH SLOPE

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Abstract

Cobre Las Cruces is a cooper open located in the Iberian Pyrite Belt (IPB), in the SW of Spain. Unlike deep shaft mining, open pit mines offer the advantage of easy access to the ore from the surface, nevertheless, Cobre Las Cruces mine is a particular case compared to other IPB mines due to the presence of around 150 metres of tertiary soft marls, known locally as the ´Guadalquivir Blue Marls´, before reaching the orebody.

These marls dip 3ºS and in its base is found a sandy formation that constitutes, jointly with the top part of the Paleozoic, the regional Niebla-Posadas aquifer. Below the marls and aquifer, the copper sulphide mineral is hosted by the rocks typical of the Palaeozoic within the IPB.

Experience gained since the beginning of excavations in 2006, has allowed to optimize the pit design in maintenance of slope stability, especially the pre-stripping of the marls, which has been a geotechnical challenge as these marls have low strength and poor deformational parameters. This has influenced the pit geometry, requiring an overall slope of 28° in marls, while in Paleozoic the general slope is 45°.

This paper describes a complex 2D modelling of the North slope of the pit, considering:

- A strain softening behaviour in the 150 m shallower marls.

- The existence of bedding planes in residual conditions developing progressive failure, due to some instabilities during the pre-stripping operations in 2009.

- The effect of pore-pressure dissipation considering a non coupled hydro-mechanical analysis.

The analysis carried out has been calibrated by monitoring using conventional topographical survey, conventional inclinometer and automated dynamic inclinometer measurements.

Introduction

Las Cruces mine is an open pit extracts copper sulphides from the volcano-sedimentary Palaeozoic deposit VMS deposit, typical of those present in other parts of the Iberian Pyrite Belt.

Las Cruces pit is 1600 metres long x 900 metres wide x 250 metres deep. Mineralization is embedded in volcanic and other metamorphic rocks. Prior to reaching the mineralization a pre-stripping of 150 metres of the tertiary marls known as “Guadalquivir Blue Marls” formation have been necessary.. These marls geotechnically behave as an over consolidated clay with weak bedding planes every 3-7 metres.

In 2015, work was concluded on the latest analysis of the northern slopes. The work comprised a finite difference two dimensional analysis of the mine´s least favourable slopes using the FLAC2D programming code. The use of FLAC 2D in slope pit mines a well known tool (Lorig et al, 2000). The use of FLAC in Cobre Las Cruces has been extensively reported in the last years (Cooper et al, 2014; Beale and Read, 2014).

The use of a number of differing techniques for slope evaluation purposes opened up the possibility of a comparative evaluation of the probable safety factor over and above the mines original analysis. The original analysis was a Limit Equilibrium Method (Slide of Rocscience) analysis which had confirmed stability but had been unable to explain certain kinematic instabilities and progressive failures that had been observed over the previous years. This raised initial concerns that warranted these further investigations and modelling.

Mine site geology

Prior to discussing the characteristics of the mine´s open pit and the slopes subject to analysis, it is appropriate to provide a more detailed understanding the mine´s geological context.

The mine´s ore body is buried under a marl unit of 150 metres of Miocene age sediments. The Guadalquivir “Blue marls” formation was deposited in the Guadalquivir basin in stable marine waters during the middle to upper Miocene. The marls are typically over consolidated as a result of greater depths of marls in the past which has subsequently eroded, They are fine grained clay sized in terms of particle size with massive and compact texture. Strength varies with depth from firm to extremely stiff. It is blue and grey coloured and brown orange coloured in more superficial zones that have been subject to weathering.

The marls are challenging geotechnically due to low strength and poor deformational parameters, requiring very little strain to provoke a rapid transition to residual resistance parameters. These marls have been extensively studied (Tsige et al, 1995), and the geotechnical problems related with their poor behaviour is well known in the last decades (Ayala, 1978). For these reasons, the pits operational slope angles are low, at 28°within the entire marl package.

The marl unit is also relatively impermeable (with k values of up to 10-10 m/s). One implication of this low permeability is that, without considering other drainage mechanisms, such as hydro-mechanical coupling, negligible pore pressure drop will be achieved during excavation when undertaking modelling.

The permeability values were obtained from several large scaled permeability tests. These values range from 10-9 to 10-11 m/s, from 7x10-7 to 1.5x10-8 m/s for the sands of the Niebla-Posadas aquifer and from 1.2x10-8 to 2.3x10-8 m/s for the top of the Paleozoic materials. Table I shows the vertical and horizontal permeability values assigned for the model.

The mine operation tries to decrease the water level around the pit, so in order to reach this objective a dewatering + re-injection drainage system has been implemented using 32 well points located at the perimeter of the pit. The water is pumped and conducted via pipework to injection boreholes located at a distance of 2 and 3 km from the pit.

Between the marls and the ore lies a regional sandstone aquifer ‘el Niebla-Posadas’ which is conserved around the mine by a water drainage and reinjection system, transferring water to injection wells at an appropriate distance from the mine. This ground water mange has been described by Baquero *et al* (2016).

While pore pressure drops will occur instantaneously in most rock masses during the excavation of a pit, a high permeability will quickly cancel this beneficial effect. More work is needed to define consolidation times in large pits, but preliminary analysis indicate that permeabilities lower than 10-8 m/s are required in order to maintain the pore pressure drops during the active life of an average pit (Galera *et al*, 2009a)
CHARACTERISTICS OF THE SLOPE ANALYZED

The slope in question is located on the north side and represented the mine´s worse case configuration. Furthermore, during excavation in 2010, a minor instability occurred between the newly formed haul road and the then slope toe affecting three benches, each of 10 metres height. This movement was detected by the inclinometers measuring its evolution avoiding any safety issues (Cooper et al, 2011).

Slumping developed at the toe of the instability at the excavation platform, while some tension cracks were mapped at the upper part of the instability. After analysing the slope stability, modifications to the upper haul road configuration were implemented, with marls removed from the head of the slope to improve stability. This was successful and the movement halted resulting in only minor cracks in the slope faces.

In Photo 1 and Figure 1 the location of the slope analyzed is shown. As it can be observed the section is located at the deepest part of the pit, between its bottom and the North Dump.

The bedding planes appear numerous and apparent at approximately 3 - 7m vertical intervals with an average dip of 3º to the South. The area of the mining pit subject to analysis was considered likely to be one of slopes with lowest safety factors due to a number of key factors:

1. Geometry – The geometry was considered the least favourable geometry at the mine with the area combining the deepest point in the mine at nearly 250 metres depth with the toe of the mine´s northern mineral storage zone at 100metres of distance from the slope crest, likely inducing additional pore pressures at depth which could potentially affect the slope safety factors.

2. Time scales – The area in question was located in the pit phase 1/2 area. This area of the pit was underdevelopment from 2007 with backfilling commencing adjacent to the marls in 2017. Over the same period the adjacent north dump mineral storage zone continued to grow to a height very close to final design levels. Thus these slopes would need to endure and remain stable for a minimum period of 10 years until commencement of pit marl backfilling operations.

3. Geology – The marls contain sedimentary bedding planes every six to seven metres depth. At least two of the bedding planes have shown potential for instability and indications of very low resistance, suggesting residual parameter behaviour. The strike of the slopes face runs exactly parallel to that of the bedding planes which are continues and manifest in a dip of 3degrees and dip direction of south-west. With high peak to residual ratios, this created a potentially severe disfavourability with reference to possible kinematic, structurally dominated, instability such as toppling or block failure.

4. Access and mineral transportation haul road – The mine´s principle haul road into the pit runs directly across these slopes. Although when possible a secondary auxiliary haul road has been in place since the marl stripping began, apart from the obvious safety issues, an instability on these slopes could have represent a significant risk for the company in terms of ability to extract and supply mineral to the mine´s mineral processing plant.

In Figure 2 the plane section analyzed is shown. In it all the levels distinguished in the marls can be seen from the weathered ones at the top to the aquifer and the Paleozoic tuffs at the bottom. Also the North Dump has been coundued in the analysis.

Geomechanical characteristics of the marls

The characteristics of the marl unit are well known (Galera *et al*, 2009b). Following their main geomechanical properties are summarized.

General resistance parameters

Evolution of the marl strength with the depth

The marls have been sectorized in order to take into consideration the evolution of the strength and deformability with depth. This evolution can be clearly observed in Figure 3.

In Table II the general strength parameters are shown.

Peak and residual resistance parameters were also determined

The combined cohesive and frictional elements of resistances indicated as much as a 500% fall in resistance post yield envelope with less than 3% deformation. These tests confirmed an extremely brittle material that would require intense vigilance during operations to control.

These values have been taken into account in the modelization to for the use of peak and residual strength parameters, as shown in Figure 4.

During the excavation phase the bedding planes appeared to play a prominent role in the marl behaviour, being a key aspect in the formation of localised displacements at the benches (Cooper et al, 2011).

The bedding planes appear numerous and apparent at approximately 3 - 7m vertical intervals with an average dip of 3º to the South.

The behaviour of these bedding planes has been intensively monitored at the benches and also at depth by 17 inclinometers. The vigilance plan includes 12 piezometers and 23 topographical prisms. Figure 5 shows the existing instrumentation around the NW slope of the pit.

Two dimensional finite difference analysis

The soil groups utilised in the analysis were exactly as described in the previous sections. In the FLAC2D implementation, the presence of planes of weakness within the Mohr-Coulomb model is taken into account due to the use of an ultra-fine mesh (as low as 0.5 metres by 0.5metres). These weakness planes have been included as an explicit zone which have been calibrated through the information analysis of inclinometers.

As is shown in the figure below, nineteen inclinometers have been installed in the open pit, and seven of them (INN-12, INN-13, IN-06, IN-12, IN-13, IN-16 and IN-94) have been taken into account for the section profile analysis. In Figure 6 the accumulate displacement registered at IN-16 is shown as an example.

Finally it is completed in agreement with the analysis results of accumulative displacement of inclinometers that three different weakness planes are identified which will be modelled as explicit weakness zones within strain-stress finite difference calculation. Weakness planes position are summarised in Table III.

The failure criteria of the weakness planes is defined with the inclusion of the ubiquitous-joint constitutive model and implemented in FLAC. In this case, yielding may occur in either the solid or along the weak plane or both.

Deformation at Las Cruces open pit is well known to happen as a combination of displacements potentially induced by the weakness planes together with the elastic deformation happening in the marls matrix as a consequence of stress relaxation due to open pit excavation.

Designated properties of the weakness planes have been calibrated in order to fit with prisms displacements registered at the different excavation stages at the open pit, and summarised in Table IV.

Initial pore pressure assigned to the model (which is different for each calculation stage) is based on the piezometers and cell pressure devices installed inside the pit and close to the section profile under consideration. Pore pressure assignation for each element in the mesh is done by a kriging interpolation from the cell pressure devices considered at the section profile.

Since this pore pressure assignation is different for each calculation stage, is therefore distinguished in FLAC 2D calculation stages, as can be seen in Figure 7.

As was already mentioned before, the selected modelling approach for the implementation of the hydro-mechanical analysis is an un-coupled strategy, which means that flow is prevented but mechanical response is allowed. Then pore pressures will be generated as a result of mechanical deformations.
Pore pressure distribution due to mechanical response of the model is shown in Figure 8.

Induced yielding at the final calculation stage shows that those are focused through zones with ubiquitous-joint constitutive model, acting as slipping zones which fits well with deformations identified with inclinometers as can be shown also in Figure 9.

Ubiquitous joint model implementation allows the possibility of fluency within either the solid part between planes of weakness or failure through the planes themselves. The transition into yield space along these residual planes can be clearly observed in the Figure 10 below representing the mines phase 4.

- Observations from two-dimensional finite difference analysis.

- The displacements obtained in the numerical model, coincide significantly with those that were measured before 2013 in the control instrumentation of the pit. (when the adjacent berm barrier dump of the mineral storage zone was constructed).

- All model planes of stratification presented relevant values of shear deformation increments, coincident with actual inclinometer displacement registers.

- The mechanical response of the model induces volumetric changes in the elements that generate small variations in pore pressure. The model records non-active plastifications (generated during the process of calculation) in the areas where higher values of the pore pressure and active in the foot of the global slope are assigned.

- During construction phase, the horizontal displacements in the pit increase slightly compared to the previous phase to around 450mm. This long term deformation corresponded directly with topographical observations of total pit wall movement over the years.

- The minimum safety factor obtained in the pit slope is 1.20, complying with the legal Spanish requirements of ITC 07.3.01.

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Table I. Permeability of the pre-striping materials

	Permeability k_H (m/s)	k_V (m/s)
Marls	1,15E-9	1,15E-10
Aquifer (Niebla-Posadas)	7,00E-7	7,00E-8
Paleozoic	2,00E-8	2,00E-8

Photo 1. Pit layout showing slope in question.

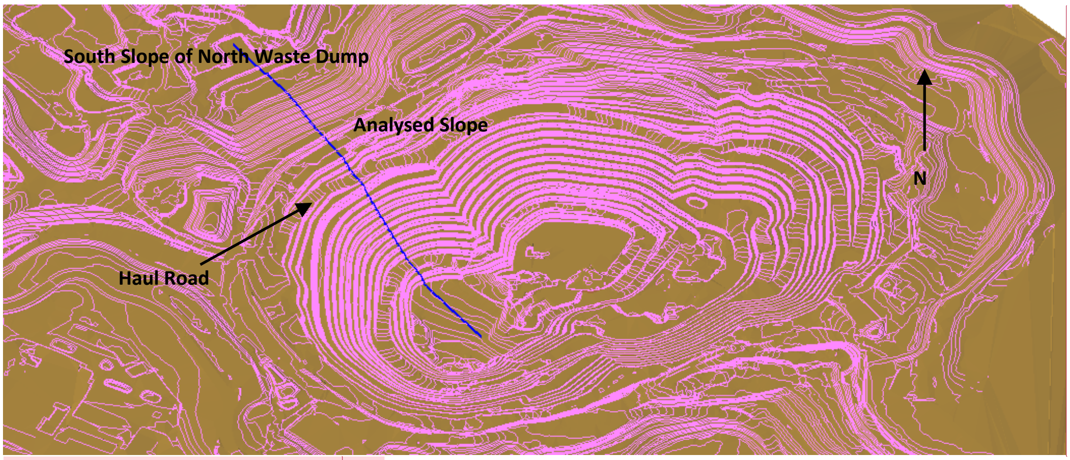

Figure 1. Section line for slope.[J1]

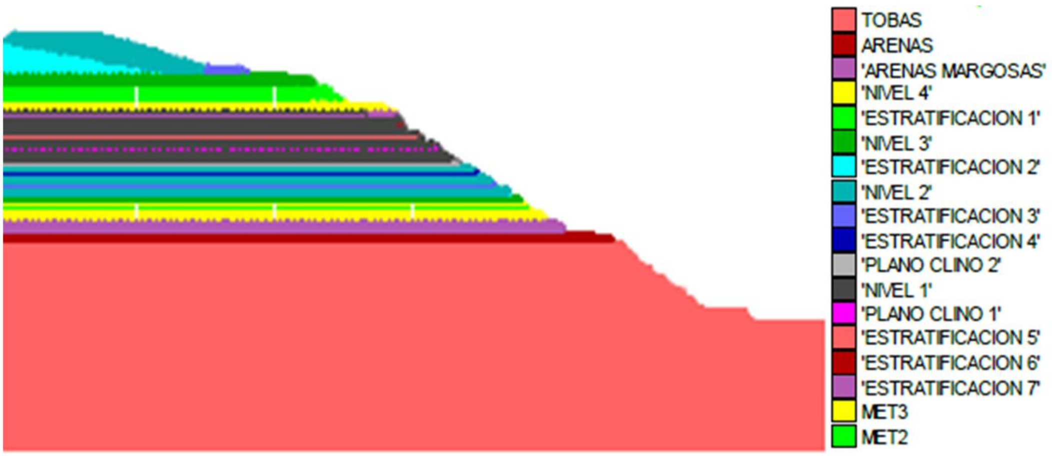

Figure 2. Complex lithology utilised in the various analyses.

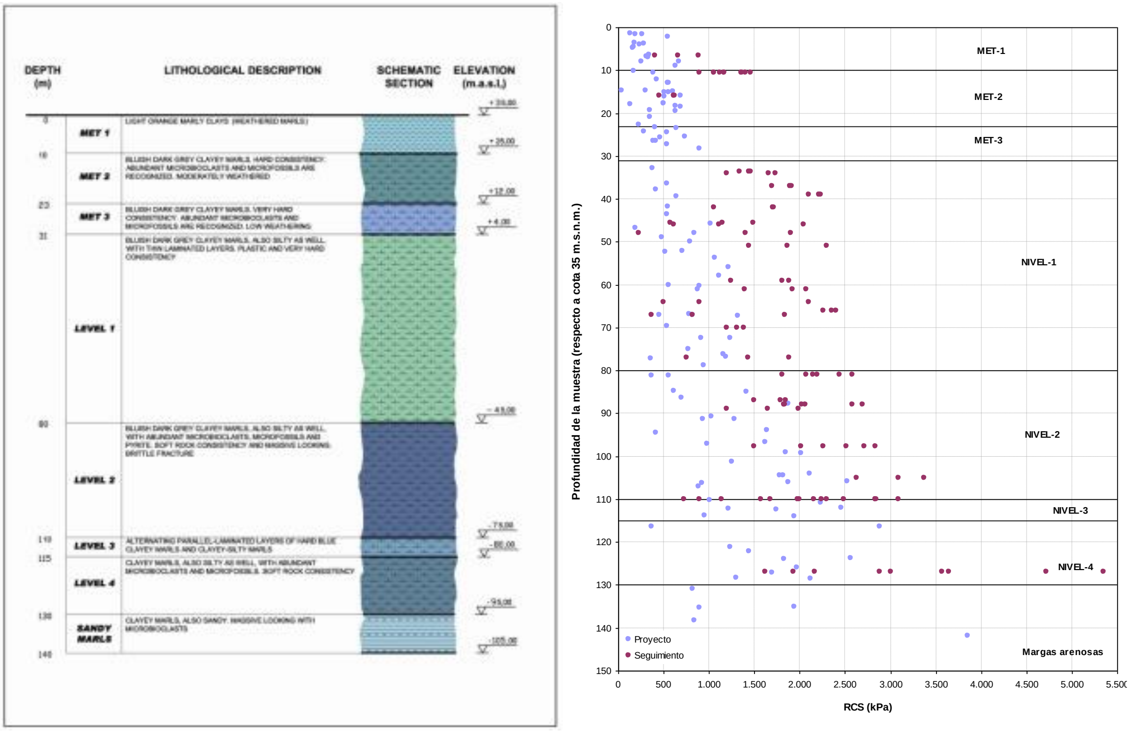

Figure 3. Evolution of the marl resistance with depth (Galera et al (2009b).

Table II. Laboratory determined resistance parameters.

Description	Horizon	Depth (m)	σ_{ci} (kp/cm^2)	m	s	c (kp/cm^2)	Φ (º)	γp (t/m^3)	γ (t/m^3)	ω (%)	PI (%)
Highly weathered marls	MET-1	0-10	3.5	2	1	1.10	22	2.714	1.415	30.3	34.3
Moderately weathered marls	MET-2	10-23	3.8	4	1	1.50	21	2.714	1.459	28.5	30.2
Slightly weathered marls	MET-3	23-31	3.8	4	0.07	1.50	21	2.714	1.496	27.1	30.8
Unweathered marls (low strength)	LEVEL-1	31-80	4.0	6	0.05	2.1	20	2.714	1.528	25.5	38.1
Unweathered marls (medium strength)	LEVEL-2	80-110	4.0	6	0.05	2.7	18	2.714	1.585	24.2	39.1
Unweathered marls (high strength)	LEVEL-4	115-130	6.0	6	0.01	2.8	18	2.714	1.579	24.2	38.5

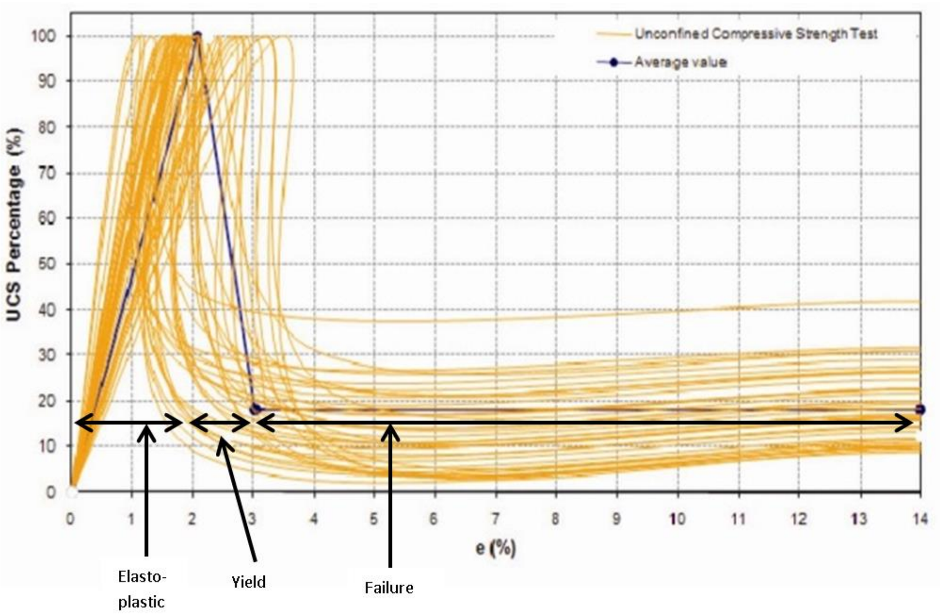

Figure 4. Resistance-deformational characteristics of marl unit.

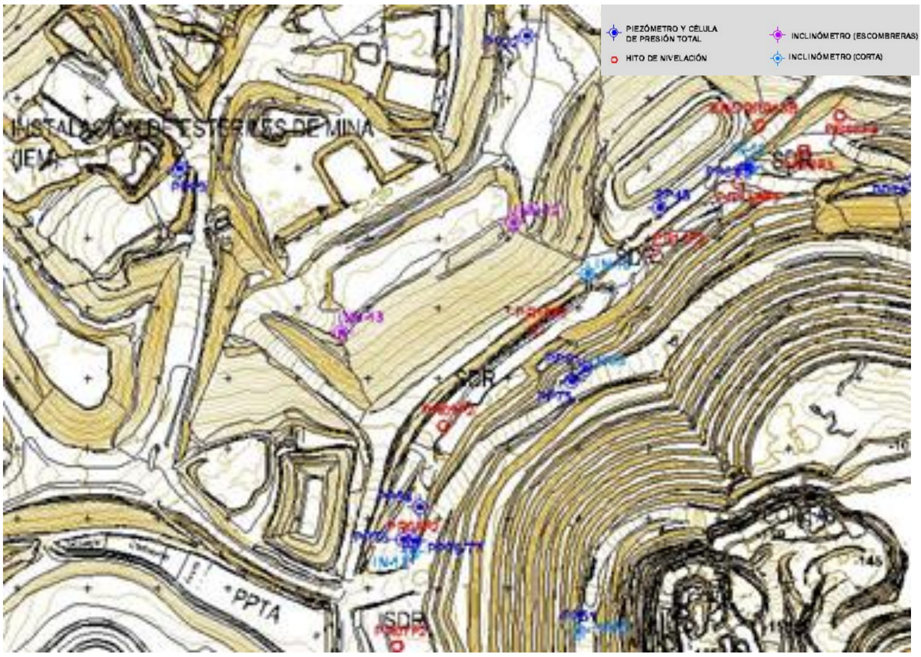

Figure 5. Instrumentation around the NW slope of the pit.

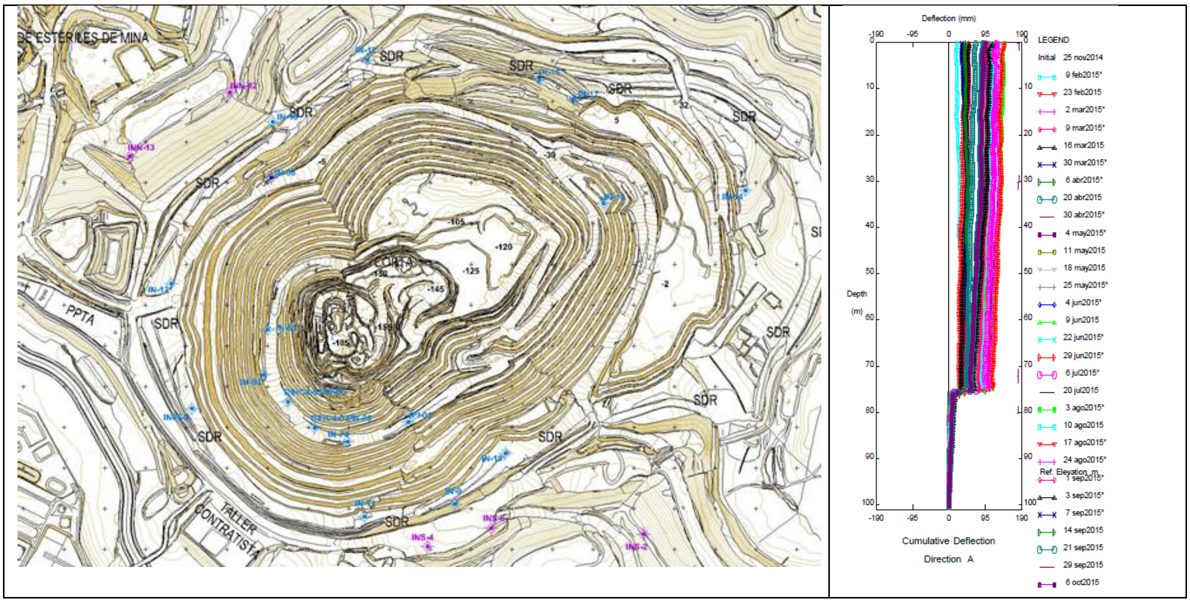

Figure 6. Installed inclinometers at CLC open pit mine and accumulate displacement registered at IN-16 inclinometer.

Table III. Weakness planes considered for the FLAC 2D analysis.

Inclinometer	Instalation Collar Height (amsl)	Weakness plane depth (m)	Weakness Plane height (amsl)
IN06	4	45	-41
IN06	4	87	-83
IN16	42	75	-33

Table IV. Weakness planes properties for ubiquitous joint constitutive model.

Inclinometer	C_j (MPa)	$Ø_j$(º)	σ_{tens}
IN06	0.1	22	0.24

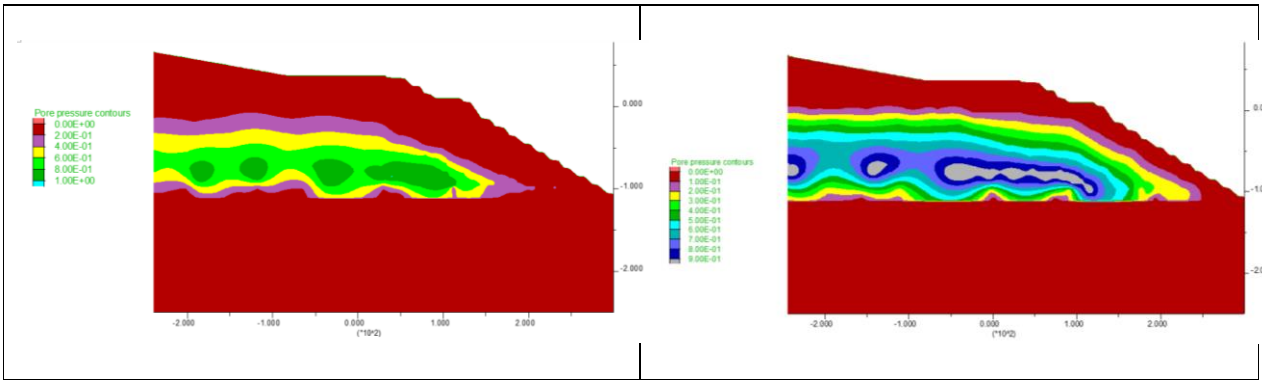

Figure 7. Pore pressure assignation for each calculation stage.

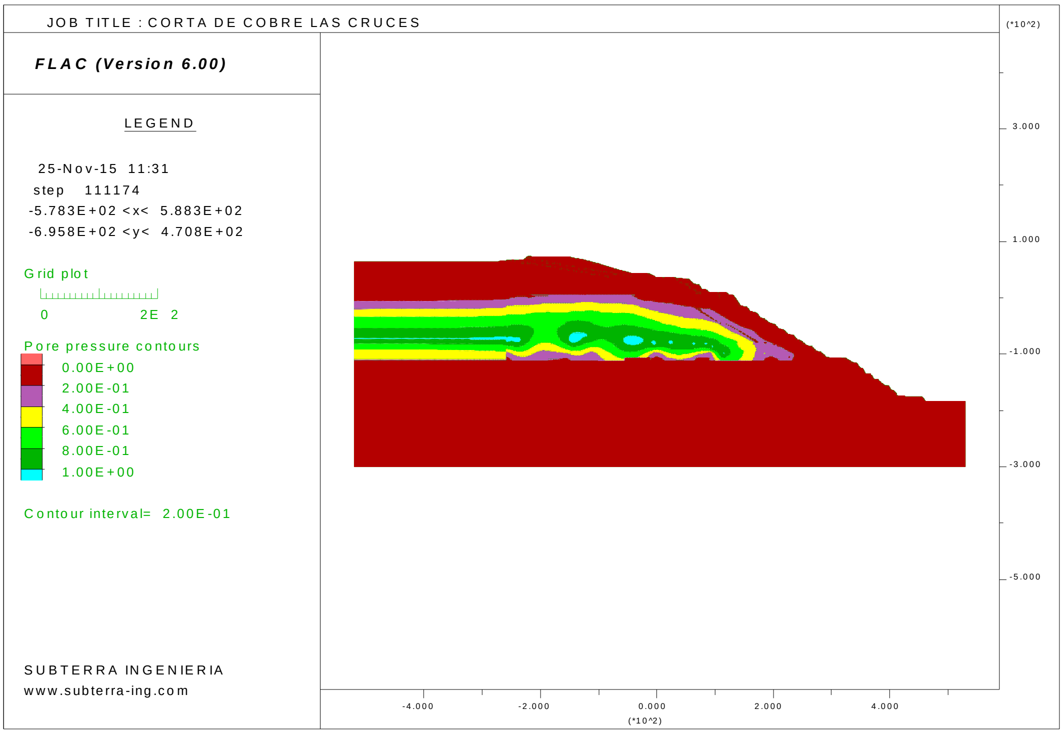

Figure 8. Pore pressure distribution response.

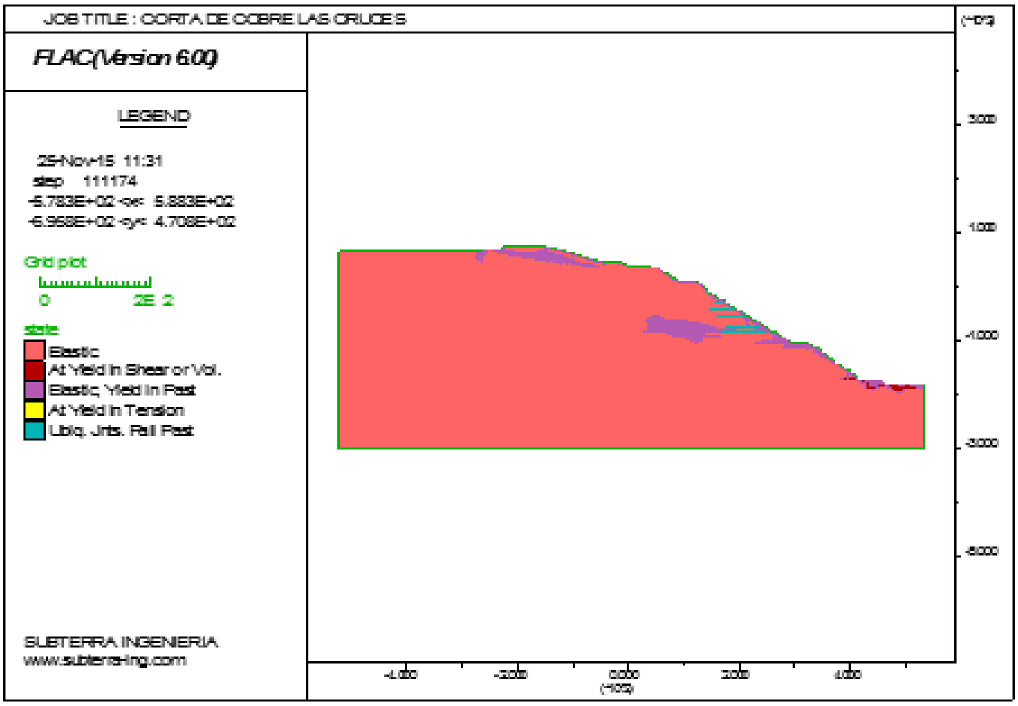

Figure 9. Yielding condition.

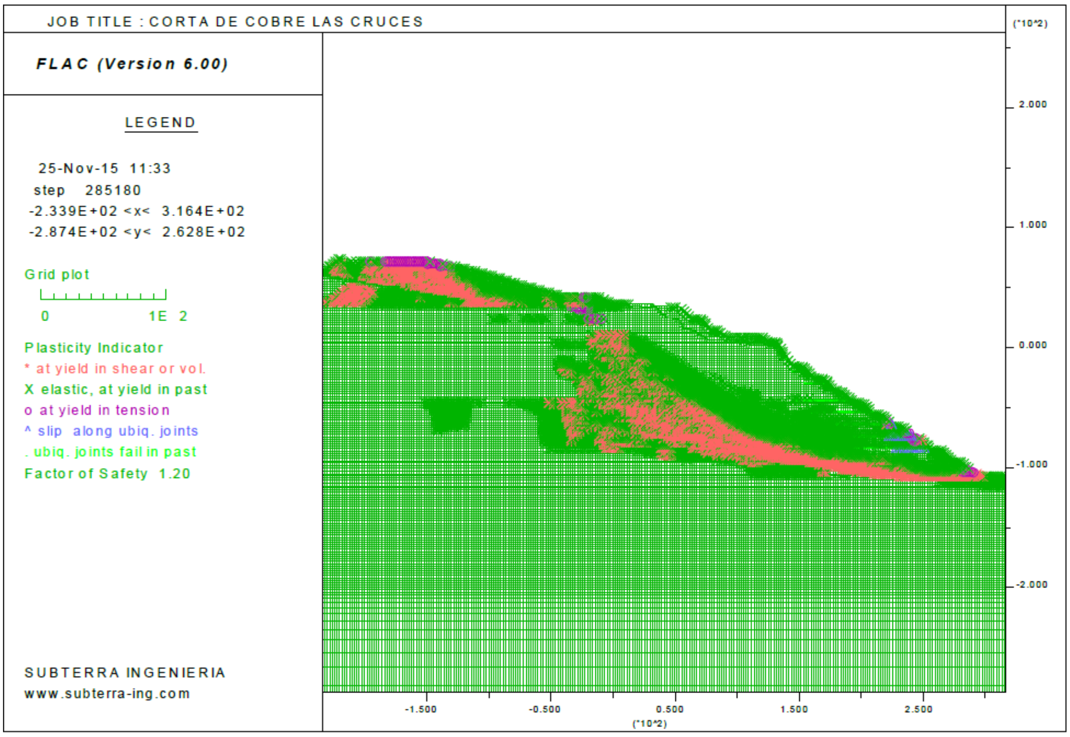

Figure 10. Commencement of yielding on a lower bedding plane.