Advanced 3D geotechnical modeling of Las Cruces Open pit

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Cobre Las Cruces is an open pit mine that extracts copper sulphides from the same volcano-sedimentary Paleozoic deposit as the mines of Rio Tinto, in the SW of Spain. The pit measures 1600 m long x 900 m wide x 250 m deep.

The ore is overlain by 150 metres of the tertiary marly formation which behaves as overconsolidated clay, locally known as "Guadalquivir Blue Marls". These marls are structured with bedding at approximately 5m vertical intervals with an average dip of 3º to the South. A detritical aquifer between the ore and the marls exists. The water table is located 30 m below the surface and pore pressure has been shown to play a dominant role on the slope stability, particularly in the marls benches.

Mineralization is embedded in volcanic and other metamorphic rocks, including some soft tuffs and clayey slates.

To provide accurate data for these calculations, a comprehensive geological and geomechanical characterization has been undertaken.

The geological work includes the elaboration of structural maps every 10 m (eg, every bench) based on the geological mapping of the existing pit as well as in the analysis of the borehole data that includes over 500 boreholes and 100,000m of cores.

The geomechanical works consist in the construction of RMR quality maps for each bench while the characterization is based on lab and in situ tests (dilatometer and borehole televiewer).

With all these characterization an advanced 3D model solved with FLAC has been undertaken. This work forms a decisive component of the pit optimization after the first seven years of exploitation of the ore body..

1 INTRODUCTION

Cobre Las Cruces is an open pit mine that extracts copper sulfhides from the same volcano-sedimentary paleozoic deposit as the Rio Tinto and Aznalcollar mines. The ore is overlain by 150 metres of the tertiary soft marls known as "Guadalquivir Blue Marls".

Below these marls there is a sandy formation that constitutes, jointly with the weathered top part of the Paleozoic, a regional aquifer known as "Niebla-Posadas". The water table is located 30 metres below the surface.

Finally the Paleozoic in which the mineralization is embedded, is constitute by slates, tuffs and porphyric rocks.

2 DESCRIPTION OF THE MINE

Cobre Las Cruces mine is located close to Seville, SW Spain. The mine is owned and operated by FIRST QUANTUM MINERALS LTD. Figure 1 includes the location of the mine as well as the actual layout of the mine showing its development as of December 2013.

The open pit measures are 1,600 m long x 900 m wide x 250 m deep. This mine is located in the pyritic belt of the Iberian Peninsula in the SW of Spain and it has an estimated reserve of more than 17 Mt grading at an average of 6.21% Cu. Mineralization is embedded in volcanic and metamorphic rocks, including massive pyrites and other copper sulphides.

Prior to reaching the mineralization a pre-stripping was required of around 120 to 150m of carbonated clay known locally as Guadalquivir Blue

Marls. These marls correspond to a marine Miocene formation that geotechnically behaves as a soil (overconsolidated clay) but in which bedding planes and other vertical joints play a major role, acting as a jointed and brittle rock mass. Furthermore they have low permeability. As a result their geotechnical behavior can be considered as challenging and problematic (Tsige et al., 1995 and Ayala, 1978).

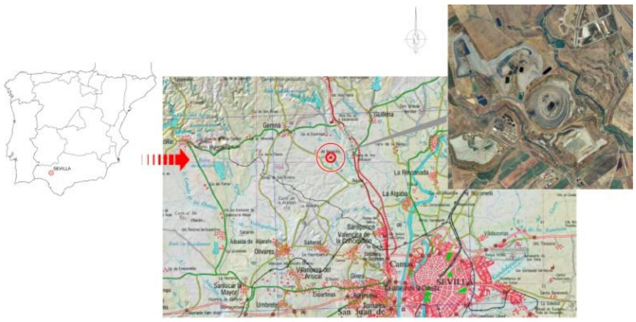


Figure 1. Location of CLC mines showing the actual layout (December, 2013)

For this reason, from the surface down to an elevation around -150 m, a general slope of 28 degrees has been used. This average slope is phased in benches of 10 m high and 60º inclination, except the first top two benches in which 45º of inclination was adopted.

3 GEOLOGICAL AND GEOTECHNICAL DATA

In respect to geo-mechanical characteristics, the following stratification (Galera et al., 2009) can be discerned:

a) WEATHERED MARLS: at surface highly altered by weathering and designated MET. Initially two levels were distinguished but finally three sections were established during the stripping operation: MET-1, highly weathered. Brownish coloured. It is 10 m thick; MET-2, down to 23 m depth. The marl is heavily weathered and presents vertical desiccation fractures spaced around one metre; and MET-3, down to 31 m depth. The marl is moderately weathered. The spacing of desiccation discontinuities is around 12 metres. The strength parameters at this level are similar to MET-2 level.

b) FRESH MARLS: After 31 m depth there are no visible signs of weathering with the marls now showing typical grey bluish colour. The following four levels can be distinguished: LEVEL1, "very weak marl", from 31 to 80 m depth. There are no desiccation fractures but several sub-vertical joint sets can be observed as well as horizontal bedding planes spaced at 5m intervals; LEVEL2, "weak marl" from 80 to 110 m. Its strength is characteristic of a weak rock type 0 to 0-1, showing fragile failures; LEVEL3, "weak marl", it presents the same characteristics of level 1 with a thickness raging from 5 to 10 m. Laterally it disappears between levels 2 and 3 showing strength and deformability properties similar to level above; LEVEL4, "strong marl". It has a strength characteristic of the weak rock type 0-1. There is an appreciable increase of the strength and stiffness of the marl; and SANDY MARLS, which lie just above the partially cemented SANDS (with negligible to 15 m thickness) of the "Niebla-Posadas" aquifer consisting of a final layer of sandy marls with an approximate thickness of 5 m.

Concerning the presence of discontinuities (Cooper et al., 2011) two layers can be discerned: from surface to 31 m depth in which desiccation fractures exists and there is no evidence of bedding, and from 31 m down to the aquifer, where regular bedding planes can be observed, every 5 m and occasional vertical joints. Figure 2 summarizes all the geotechnical horizons that can be observed in the marls while in the right hand side the evolution of the UCS values with depth is shown, Finally Table I present all the geomechanical parameters assigned to each horizon.

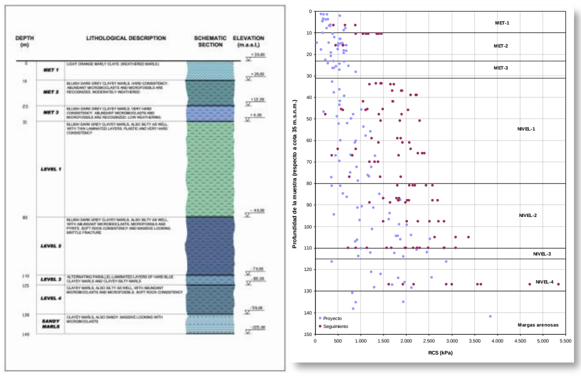


Figure 2. Lithological profile of the pre-stripping materials (Galera et al. 2009).

Below the marls and aquifer the mineralisation is hosted by the rocks typical of the Paleozoic within the Iberian Pyrite Belt. For the purposes of geotechnical evaluation the following lithologies were established: gossan, tuffs, slates and sulphides.

In addition to complementary geotechnical logging of key geological mineral resource boreholes, drilling of over 700 m of explicitly geotechnical boreholes was undertaken to achieve an improved characterisation of the surround host rocks. These boreholes were logged and analyzed in detail in order to characterize the materials. Figure 3 shows an example of the RMR histogram for the gossan highlighting the RMR statistical distribution for this lithology.

Table I. Geomechanical values for each geotechnical horizon of the marls

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

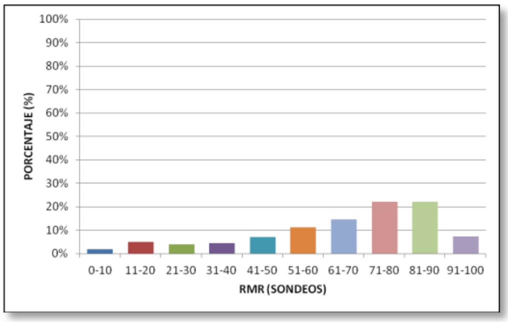
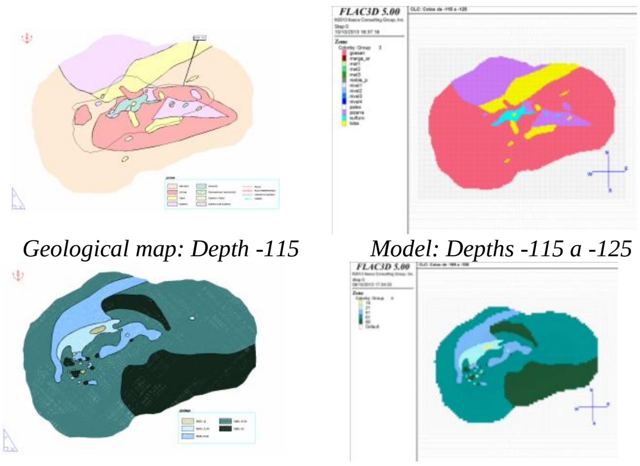


Figure 3. RMR statistical distribution for the Gossan (Top mineralization)

In the lithologies below -150 m, a general slope of 45 degrees has been adopted using benches of 10 m high and 75º inclination. In order to analyze the pit stability the lithology and RMR distribution has been defined every 10 m. Figure 4 shows an example for a given depth of the geological and RMR distribution maps on the left hand side while on the right hand side the model used is shown.



Geological map: Depth -115 *Model: Depths -115 a -125*

RMR distribution: Depth -185 *Model: Depths -165 to -185*

Figure 4. Example of the geological and RMR maps constructed every 10 m depth (for all benches)

The geomechanical parameters of the Paleozoic materials are shown at Table II.

These values for the rock mass have been directly assigned in the numerical model considering the intact rock values of each lithology and the RMR value at each element of the 3D model.

4 HYDROGEOLOGICAL DATA

The value of permeability has been derived from 12 large scaled permeability tests monitoring the water head in 55 piezometers during long-term pump tests. The values obtained for the marls ranges 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 III shows the vertical and horizontal permeability values assigned for the model.

Table III .- Hydrogeological parameters assigned in the model

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

The mine operation undertakes dewatering around the open pit of the Niebla-Posadas aquifer during the exploitation of the mine. To reach this objective a dewatering + re-injection drainage system has been implemented using 32 well points located externally and at the perimeter of the pit. There are also well points installed internally within the pit. To avoid a disturbance of the aquifer outside the pit, this water is pumped and conducted via pipework to injection boreholes located at a distance of 2 and 3 km from the pit. The flow rate involved in this dewatering-reinjection drainage system can be upto 150 l/s depending on the location of the water extraction well. The system operates in a close water circuit and will be active during the full exploitation life of the pit. Figure 5 shows the piezometers used in the analytical model. On the left hand side for the period 2006 – 2014 those that have been used to calibrate the model while on the right hand side the results estimated for the period 2015 – 2020 are represented.

Table II. Geomechanical values for each geotechnical group of the Paleozoic

Group	Intact Rock					Joints					
	ρ (kN/m^3)	Elastic		Plastic		Strike		Peak		Residual	
		Ei (MPa)	ν	σ_{ci} (MPa)	mi	Dip (º)	Dir (º)	Jc (kPa)	Jϕ (º)	Jc (kPa)	Jϕ (º)
Gossan	28,90	20.000	0,25	19,3	7,23	-	-	-	-	-	-
Tuffs	23,00	8.200	0,25	16,0	8,24	-	-	-	-	-	-
Slates	24,00	22.500	0,20	4,4	4,78	70	004	130	22	0	22
Suphides	44,00	80.000	0,20	115,0	12,85	-	-	-	-	-	-

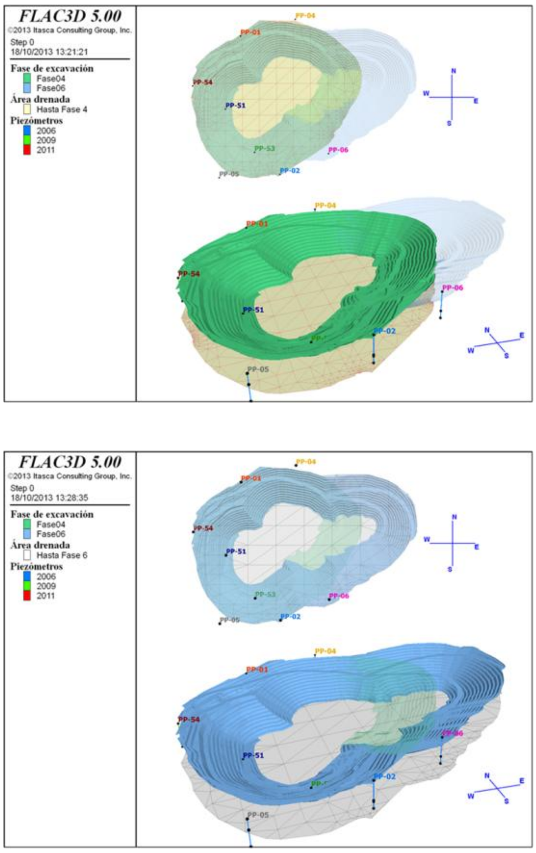


Figure 5. Drainage areas for the periods 2006-2014 and 2015-2020

5 RESULTS OF THE NUMERICAL MODELLING.

a) Model description

Herein the main results of the numerical modelling are summarized. FLAC 3D 5.0 code has been used calibrating the results for the excavation phases 1 and 2 (2006 to 2013) with an estimating for the excavation phases 3 to 6 (2014 to 2022), providing safety factors for the entire pit. The element size of the grid is 10x10x10m for the elements located close to the slopes while a size of 20x20x20 m has been used in the rest of the model.

The model simulates the excavation using an annual sequence, introducing the hydro-mechanical coupling for the following year (Galera *et al*, 2009) making a first step reaching an instantaneous mechanical equilibrium after excavation and readjusting the effective stresses considering flow with one-month intervals. Once the hydro-mechanical equilibrium is reached at each excavation phase, the safety factor is calculated.

In Figure 6 a general view of the model is given showing the coordinates of the model as well as the 6 phases considered representing the excavation sequences for the mine life between 2006 and 2022. To summarize therefore the period 2006–2013 was used to calibrate the model. The prognosis for the rest of the mine life will be used to adjust and optimize the pit design.

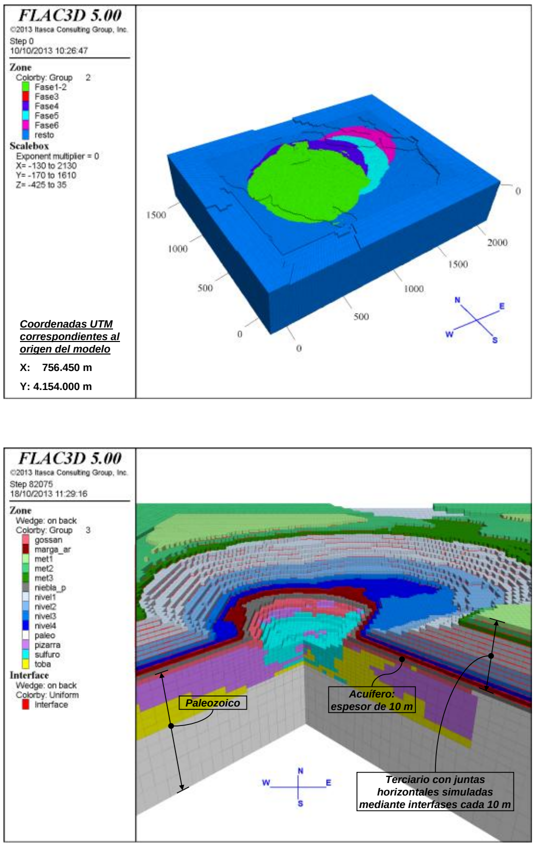


Figure 6. General aspect of the 3D model considering 6 excavation phases

To demonstrate these excavation phases, included in Figure 7 is the actual pit, as of 2013, as well as the final aspect anticipated in 2022 once the excavation of the target mineral is concluded.

The numerical model is constructed considering all the geological, geomechanical and hydrogeological data already described. The following constitutive models have been adopted (as shown in Figure 5):

- Marls: Mohr-Coulomb model with horizontal interphases every 10 m simulating bedding planes with c_J= 20 kPa y ϕ_J= 15º in order to take into account the relevant role displayed by the bedding planes in the behavior of these marls (Cooper *et al.*, 2011)
- Paleozoic: Hoek-Brown (2002) model considering D=0 for the peak values and D=0.7 for the residual strength and deformational parameters. The peak-residual transit is instantaneous once a plastic state is reached for a given element (brittle behavior). The shear strength of each element is quantified in terms of the cohesion and friction values tangent to the Hoek-Brown envelope for the σ_3' value at each element.

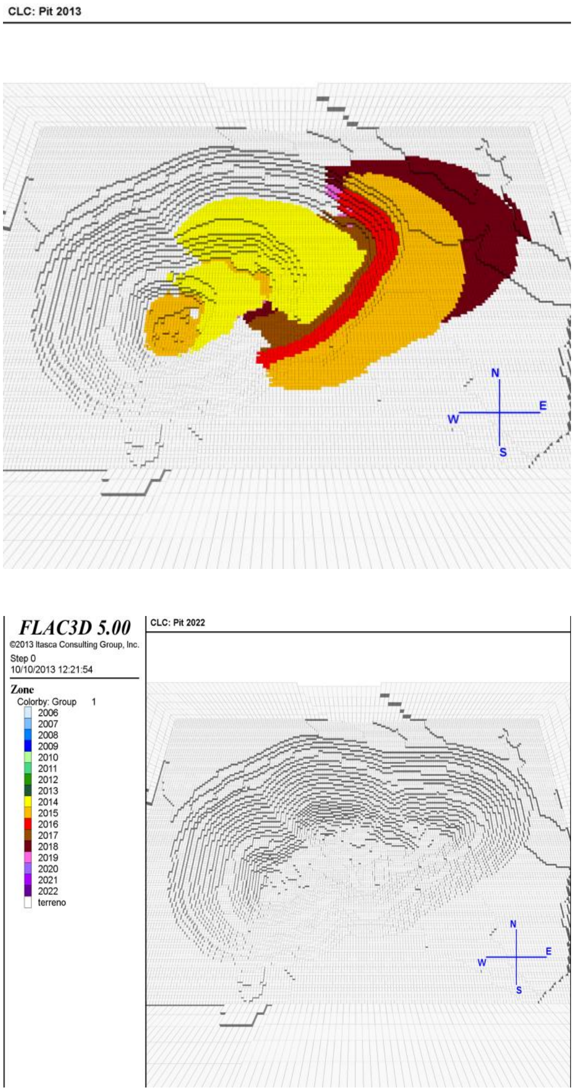


Figure 7. Pit model on 2013 and at its finalization in 2022

Additionally for the slates a "ubiquitous joint" model with peak-residual strength was introduced to simulating foliation. A typical dip and dip direction was assigned to these slates of 70/004.

b) Results

The results obtained are described considering pore-pressure estimations and the determined safety factor (FS).

Figure 8 show the precise data of the piezometer sensors used for calibration purposes.

Figure 9 shows the comparison between the values of the pore-pressures variations and those predicted by the model. As can be observed the comparison for piezometers PP01-93, PP02-82, PP05-44 and PP06-87 is excellent with differences less than 55 kPa, while reasonable results have been obtained for the rest of piezometers with differences lesser than 140 kPa (equivalent to just over one bench height), the exception being PP02-117 perhaps due to its close proximity to a pit extraction well.

Once the hydro-mechanical equilibrium is reached at each excavation phase, the safety factor has been calculated reducing the shear strength (Dawson et al., 1998).

Figure 10 show the results for the actual pit excavation state (2013).

The model provides sufficient precision to enable further analysis of potential localized instabilities such as the following, predicted for the period 2016 (shown in figure 11 below).

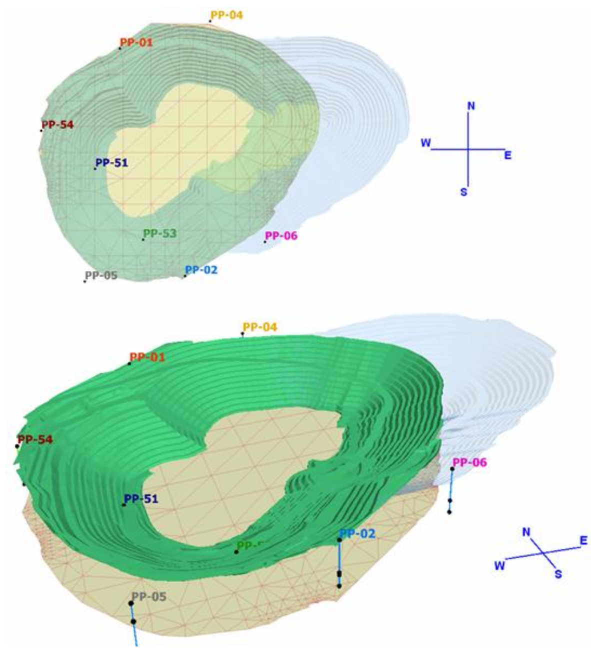


Figure 8. Location of the piezometers used for the calibration.

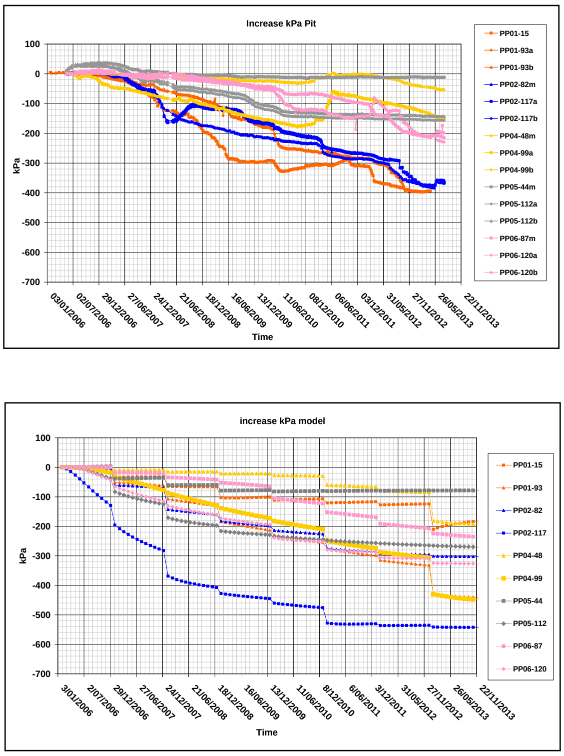


Figure 9. Comparison between the real pore pressures variations (left) and the results of the model (right)

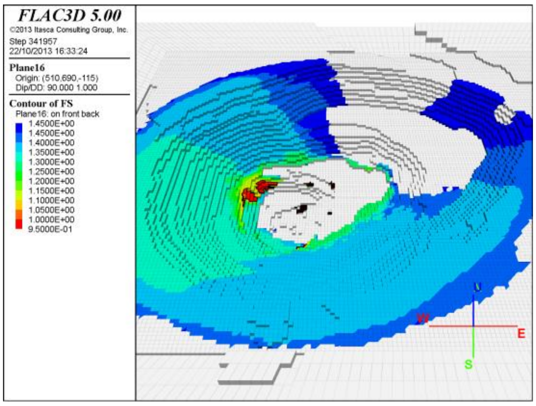


Figure 10. Safety factors obtained for the pit at the year 2013

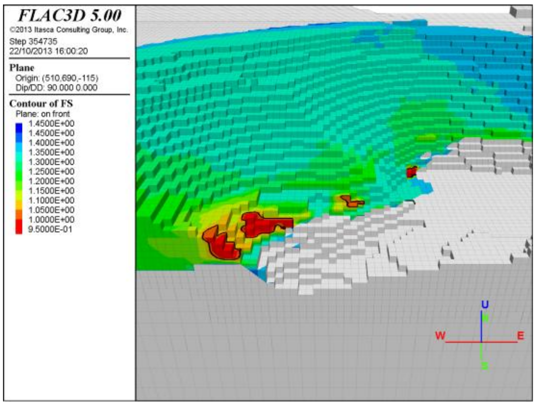


Figure 11. Safety factors for the year 2016

6 CONCLUSION

The characterization work in order to obtain representative strength and deformational values for marls and Paleozoic materials has enabled an accurate and relatively sophisticated calculation to be undertaken to analyze the safety factors of the CLC pit.

These calculations have been undertaken using FLAC 3D 5.0 code that provides an excellent tool to optimize the geometry and slopes of the pit, enabling advanced consideration of critical areas of the pit as well as potential instabilities where additional work may be required, the overall key aim being the safe extraction of mineral during the mine life.

7 AKNOWLEGMENTS

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