Coupled hydromechanical analysis of Cobre Las Cruces open pit

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Abstract

Cobre Las Cruces is an open pit mine that extracts copper sulfides from the same vulcano-sedimentary paleozoic deposit as Rio Tinto and Aznalcollar mines. At Las Cruces the ore is overlain by 150 meters of the tertiary Blue Marls formation which behaves as an overconsolidated clay .

The water table is located 30 meters below the surface and at the onset of the project there was a great concern about the pore pressure acting on the marls. This material is fairly impermeable (k=10-9 to 10-10 m/s) so a flow only analysis predicts a small pore pressure drop due to flow towards the pit. Aditionally drainage systems tend to be inneficient with so low permeabilities.

A coupled hydromechanic analysis predicts a significant pore pressure drop due to the volumetric expansion associated with the excavation of the pit. This lower pore pressure distribution allows for a more aggressive and economical slope design.

This paper compares the predicted pore pressure drop obtained from a FLAC3D numerical model and the actual piezometer readings.

INTRODUCTION

Cobre Las Cruces is an open pit mine that extracts copper sulfides from the same vulcano-sedimentary paleozoic deposit as Rio Tinto and Aznalcollar mines.

At Las Cruces site, the ore is overlain by 150 meters of the tertiary soft marls known as “Guadalquivir Blue Marls” formation which behaves as an overconsolidated clay.

Between these marls and the ore there is a sandy formation that constitutes a regional aquifer kown as “Niebla-Posadas”, that has a thickness ranging between 5 to 15 m. For this reason a perimetral drainage systems based on well points directly drilled to the aquifer has been constructed prior to the start of the pit excavation.

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DESCRIPTION OF THE MINE

The following section describes the main geological, geotechnical and hydrogeological data are.

Mine

Cobre Las Cruces mine is located in Gerena (close to Seville, SW Spain) and constitute the largest new mining project in Europe. The mine is owned by INMET and Leucadia, and operated by INMET.

Figure 1 includes the location of the mine as well as the actual lay out of the mine showing its development by the end of July 2009.

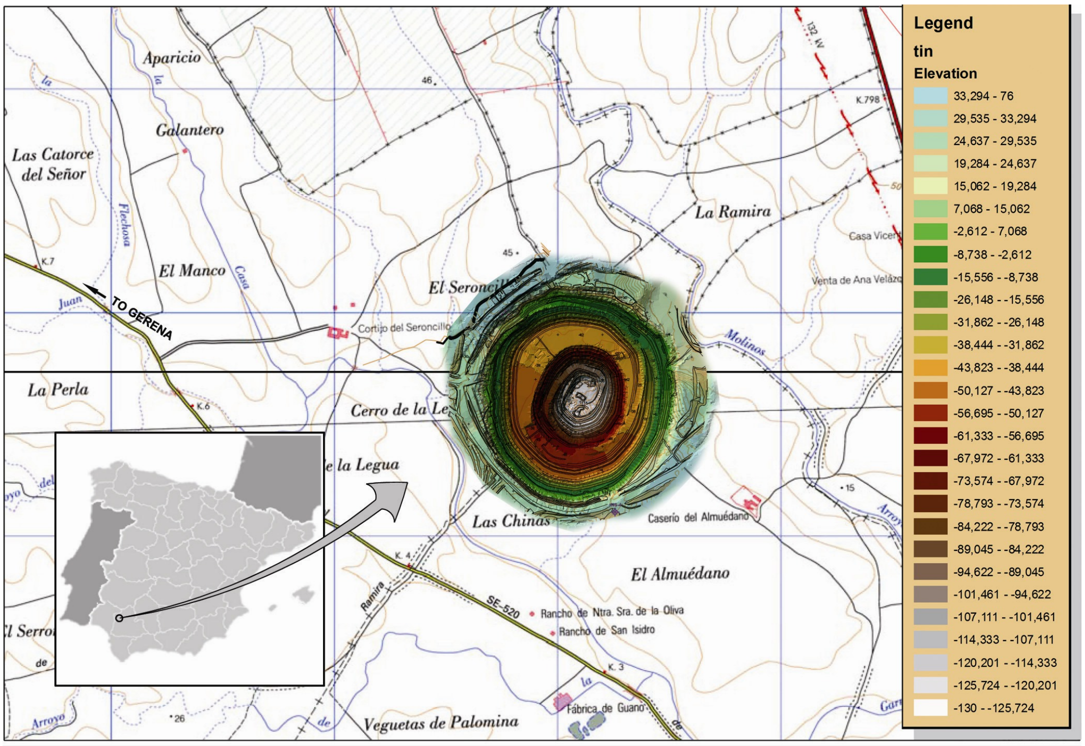


Figure 1 *- Location Map Showing the Digital Elevation Model of the Open Pit*

This mine is enclosed in the Faja Pirítica metalogenetic province at the SW of the Iberian Peninsula and it has an estimated reserve of 17.625 Mt. The average grade is the 6.21% Cu.

The exploitation consists basically of an open pit measuring 1600 m long x 900 m wide x 250 m deep. Also in the near future a small underground mine is foreseen. For this underground phase, the copper ore will be recovered using sublevel stopping and drift and fill methods.

Mineralization is embedded in volcanic and other metamorphic rocks, including massive pyrites and other cooper sulphides.

Prior to reach the mineralization it is necessary to do a pre-stripping of 120 to 150 m composed by carbonated clay, well known as Guadalquivir Blue Marls. This marls correspond to a marine Tertiary formation aged Miocene. From the geomechanical point of view, this marls constituted the more problematic lithology as they present a weak strength and low deformational parameters. Also they have low permeability as well as discontinuities. As a result they geotechnical behaviour can be considered very poor and problematic.

For this reason, from the surface down to an elevation of -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 2 benches in which 45º of inclination has been adopted.

Geology and geotechnics

Apparently the marls seem to be homogeneous but a detailed analysis as the one performed allow distinguishes with depth sections with different behaviour considering the mechanical point of view. According with the data include in this paper, the following levels can be established:

- WEATHERED MARLS: at surface very affected by weathering called MET. Initially two levels were distinguished but finally three sections have been established during its excavation:
    - MET-1, highly weathered. Brownish coloured. It has 10 m of thickness.
    - MET-2, down to 23 m depth. The marl is heavily weathered and presents vertical desiccation fractures spaced around one meter.
    - MET-3, down to 31 m depth. The marl is moderately weathered. The spacing of desiccation discontinuities is around a dozen of meters. The strength parameters of this level are similar to MET-2 level.

- FRESH MARLS: After 31 m depth there is no visible signs of weathering showing its typical grey bluish colour. The following four levels can be distinguish:

  - LEVEL1, "soft marl", it goes 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 5 m.
  - LEVEL2, "medium marl" it goes down to 110 m. Its strength is characteristic of a soft rock type 0 to 0-1, showing fragile failures.
  - LEVEL3, "soft 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 a soft rock type 0-1. There is an appreciable increase of the strength and stiffness of the marl.
  - SANDY MARL, just above the sands of the "Niebla-Posadas" aquifer there is a massive layer of sandy marls with an approximate thickness of 5 m.
  - SANDS, partially cemented with a thickness ranging from 0 to 15 m.
  - PALEOZOIC SUBSTRATE, constituted by volcano-sedimentary rocks.

Figure 2 summarizes all the geotechnical levels that can be observed in the tertiary formation while in Tables I and II are presented all the physical and geomechanical parameters assigned to each marl geotechnical horizon, respectively.

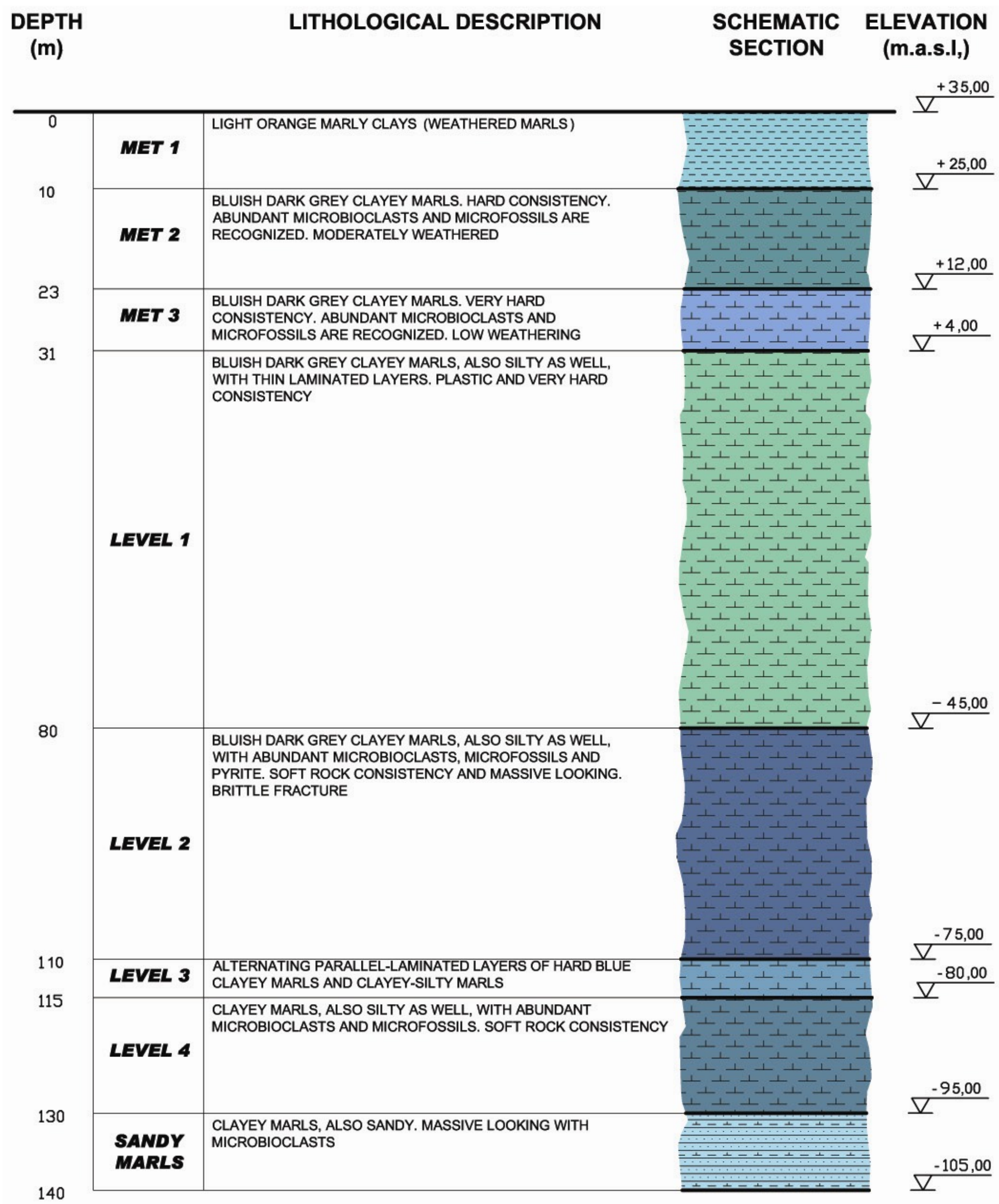


Figure 2 *- Lithological Schematic Section*

SECTION	DEPTH (m)	SPECIFIC WEIGHT OF SOLID PARTICLES (t/m^3)	DRY DENSITY (t/m^3)	MOISTURE CONTENT (%)	PLASTICITY INDEX (%)
MET-1	0-10	2,714	1,415	30,3	34,3
MET-2	10-23	2,714	1,459	28,5	30,2
MET-3	23-31	2,714	1,496	27,1	30,8
LEVEL-1	31-80	2,714	1,528	25,5	38,1
LEVEL-2	80-110	2,714	1,585	24,2	39,1
LEVEL-3	110-115	2,714	1,579	24,2	38,5
LEVEL-4	115-130	2,714	1,620	23,1	37,0
SANDY MARLS	130-140	2,714	1,622	25,7	35,3

Table I *- Main physical parameters for each section*

SECTION	DEPTH (m)	Σ_{CI} (kp/cm^2)	m	s	c (kp/cm^2)	Φ (º)	R^2 (Σ_1-Σ_3)	R^2 (Σ_N–T)	Nº UCS	Nº TRIAXIAL C T	Nº SHEAR T
MET-1	0-10	3,5	2	1	1,10	22	0,91	0,80	4	0	9
MET-2	10-23	3,8	4	1	1,50	21	0,21	0,73	7	5	18
MET-3	23-31	3,8	4	0,07	1,50	21	0,49	0,51	11	11	6
LEVEL-1	31-80	4,0	6	0,05	2,1	20	0,61	0,65	73	83	126
LEVEL-2	80-110	4,0	6	0,05	2,7	18	0,81	0,74	0	23	129
LEVEL-4	115-130	6,0	6	0,01	2,8	18	-	0,87	0	0	48

Table II *- Value of cohesion and friction angle for each geotechnical level and stress range*

Hydrogeology

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 sensors were located at the marls, aquifer and fractured top paleozoic materials.

The value of permeability 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.

Description of the water extraction/injection drainage system

The mine operation requires the dewatering around the open pit of the Niebla-Posadas aquifer located just above the ore, during the exploitation of the mine. To reach this objective a dewatering and re-injection drainage system has been developed and implemented using well points located externally and at the perimeter of the pit. Also some internal well points have been considered. The total number of dewatering well points is 32.

To avoid a disturbance of the aquifer outside the pit, this water is pumped and conducted to injection boreholes located at a distance between 2 and 3 km from the pit.

The flow rate involved in this dewatering-reinjection drainage system ranges between 100 and 150 l/s. The systems operates in a close water circuit and will be active while all the exploitation life of the pit.

PIEZOMETER MONITORING DATA

By the time of writing this paper the phase 1 of the open pit mine has been finished while the second phase, homothetic from the first one, has reached an advance of 50 %.

As part of the geotechnical monitoring system of the mine there is a piezometer net that actually consists, as it can be observed in Figure 3, of 14 piezometers located externally and at the perimeter of the pit as well as inside the excavation. The total number of functional vibrating wire sensors is 24 located at different depths between the aquifer and the water table.

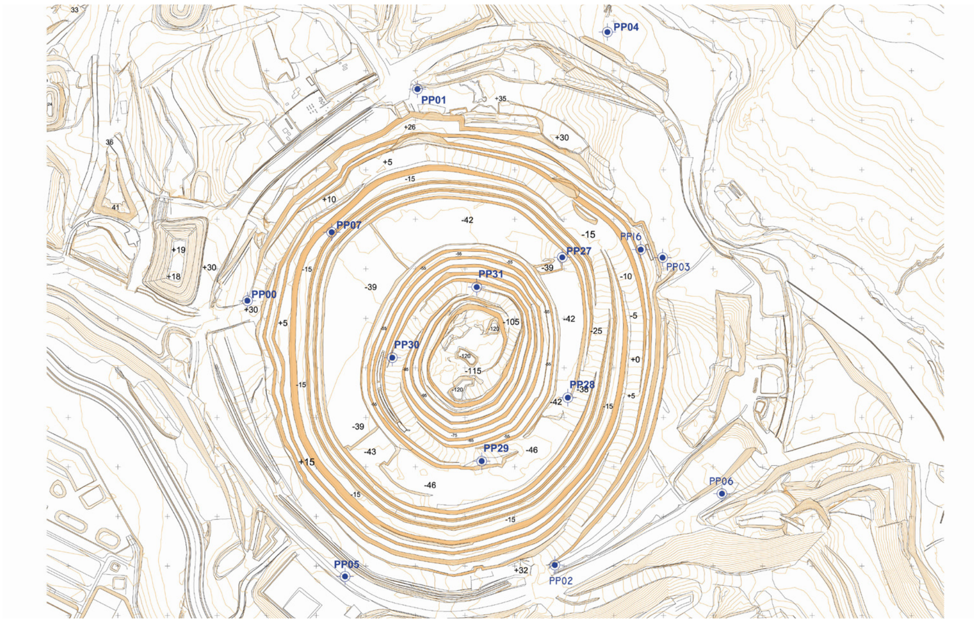


Figure 3 *- Piezometer monitoring net at the pit*

In Figures 4 a and 4b the evolution of the piezometer sensors since the beginning of the pit excavation is shown. As it can be observed the sensors located externanilly to the pit show a poor water head drop that ranges between 6.2 and 258.4 kPa. Only piezometer number 7, located internally to the excavation shows a higher pore pressure drop of 864 kPa.

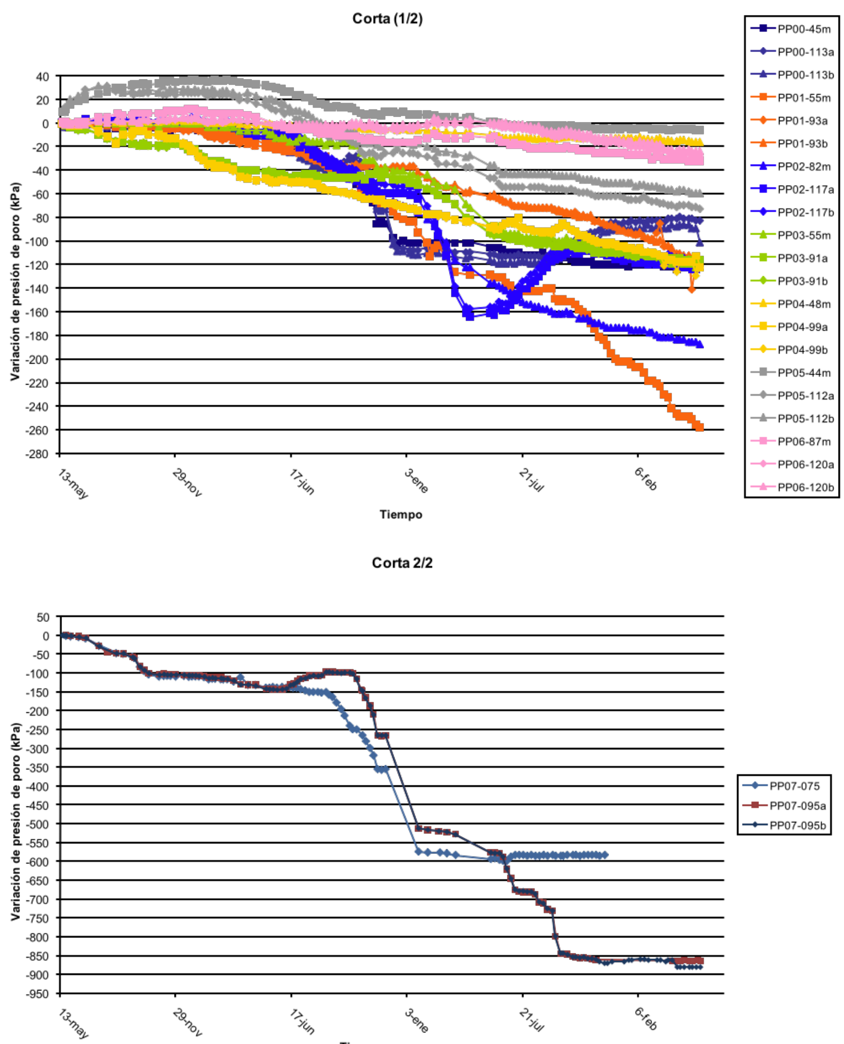


Figure 4a and 4b *- Evolution of the vibrating wire piezometer sensors*

The geology and excavation sequence (in 15 days increments) was imported into FLAC^{3D} (1) from the mine's database following an automated procedure described by Valera et al. (2). Figure 5 shows the model consisting in 150x160x25 10m cubes. For each time increment an instantaneous mechanical response is first calculated and then a coupled hydro-mechanical calculation is carried out for 15 days when the next excavation takes place.

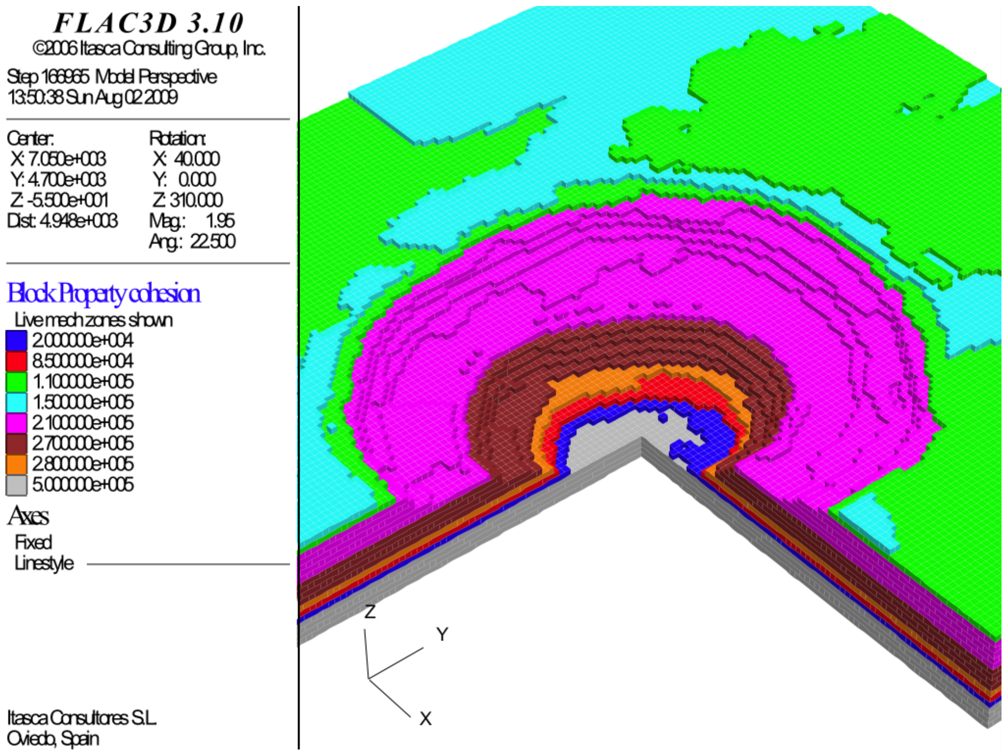


Figure 5 *- Piezometer monitoring net at the pit*

During the instantaneous mechanical response, the pore pressure drops according to Skempton's B coefficient (3):

$$B = \frac{\Delta pp}{\Delta\sigma} = \frac{\Delta pp}{\Delta pp + \Delta\sigma'} = \frac{K_w/n}{K_w/n + K}$$

where:
Δpp=pore pressure change
$\Delta\sigma$= change in mean total stress
$\Delta\sigma$'=change in effective stress
K_w=water bulk modulus (2GPa for pure water)
n=porosity
K=soil bulk modulus

The poroelastic response of a soft soil where K<<Kw/n is such that most of the change in total stress during unloading will be translated in a drop in pore pressure (figure 6)

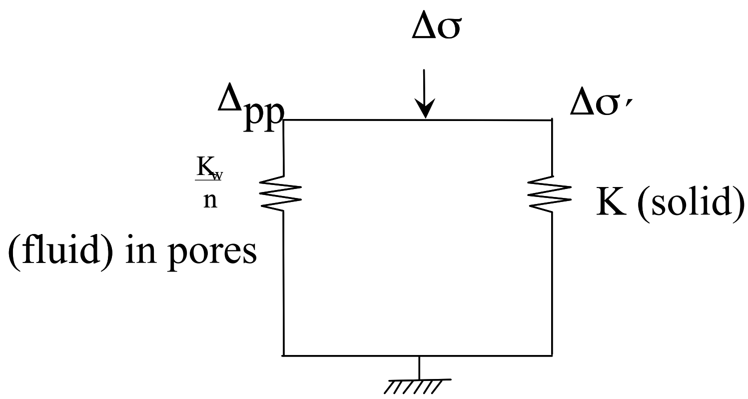


Figure 6 *- Poroelastic stress distribution*

During the flow calculation in between excavations, there is a slight increase of pore pressure but in this particular problem it is very small due to the low permeability of the blue marls. Figure 7 shows the pore pressure drop (expressed in meters of water head) at the time the pit reaches the lower aquifer. The calculated drop in the blue marls is up to 100 meters. This figure also explains why the piezometers located beyond the rim of the pit only record modest pore pressure drops (round 20 meters or 200 kPa) while inside the pit the pore pressure drop is more significant (up to 100 meters).

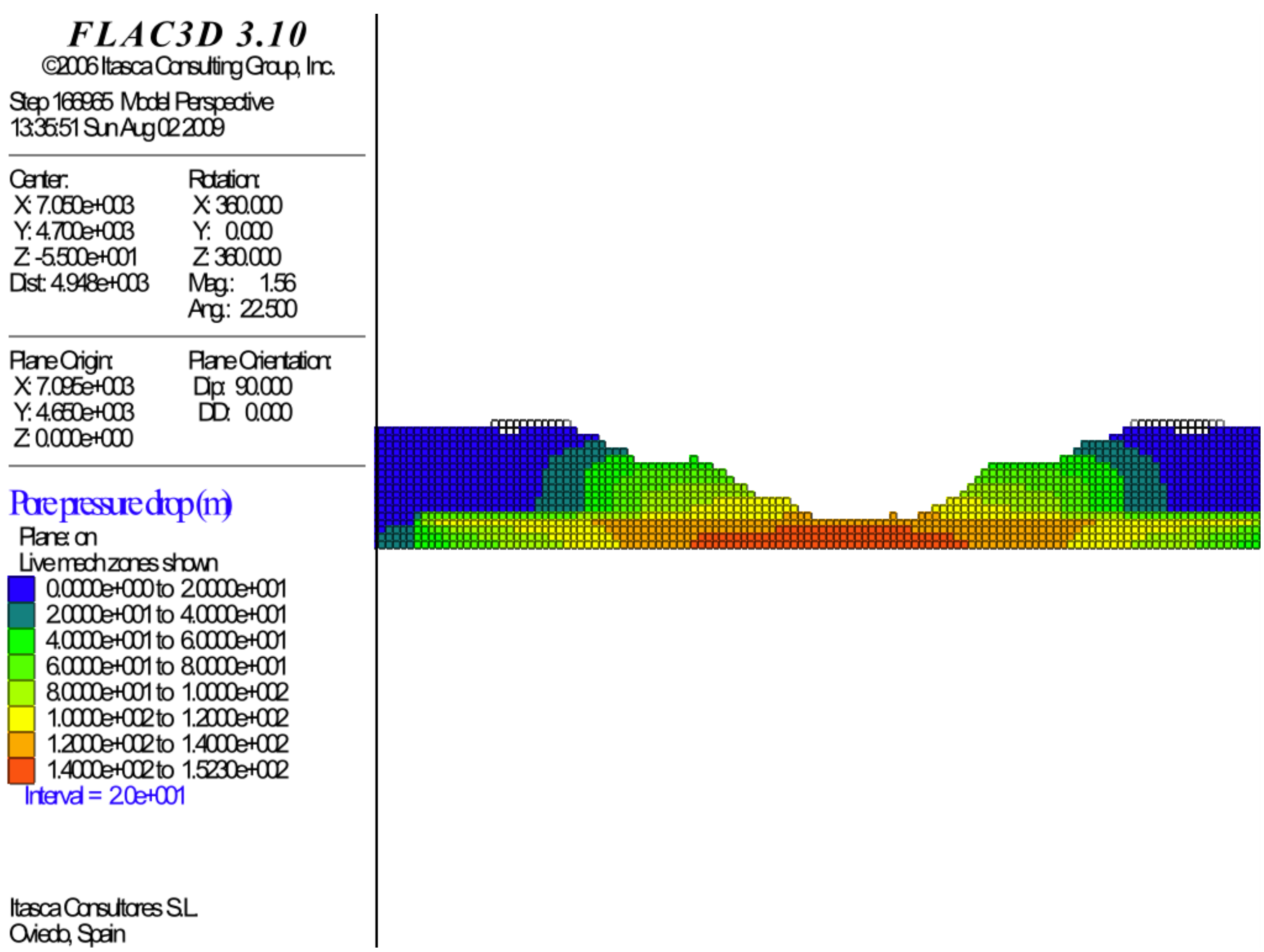
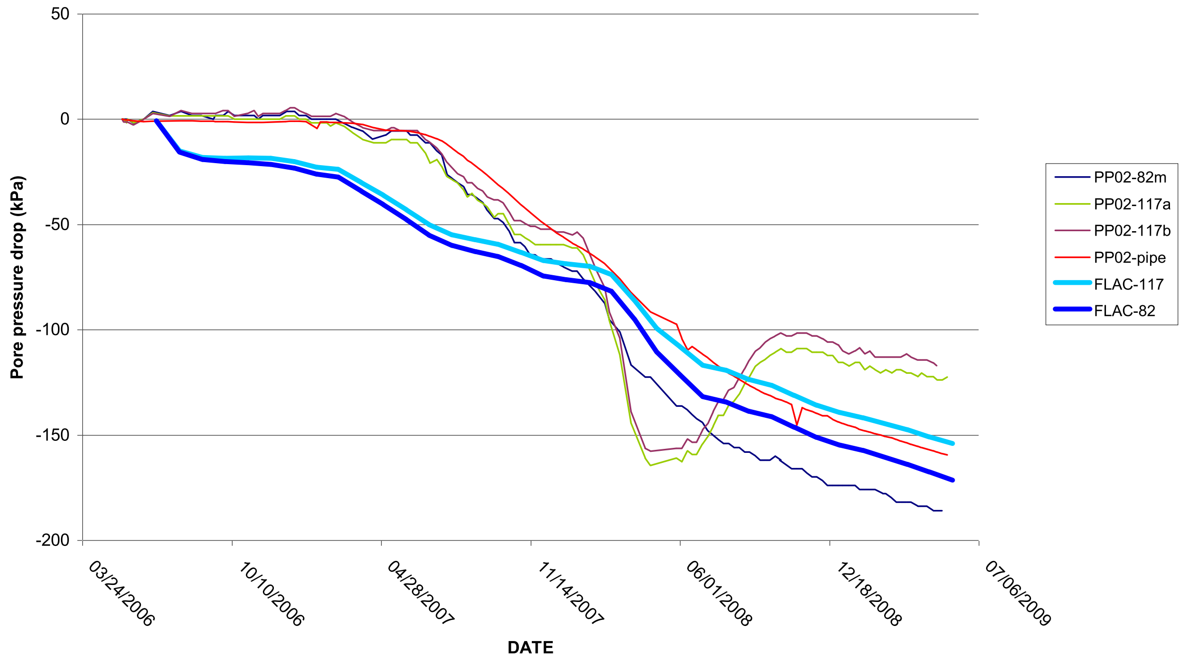


Figure 7 *- Pore pressure drop*

The match between calculated and measured pore pressure drops is quite good as seen in figure 8 a and b.



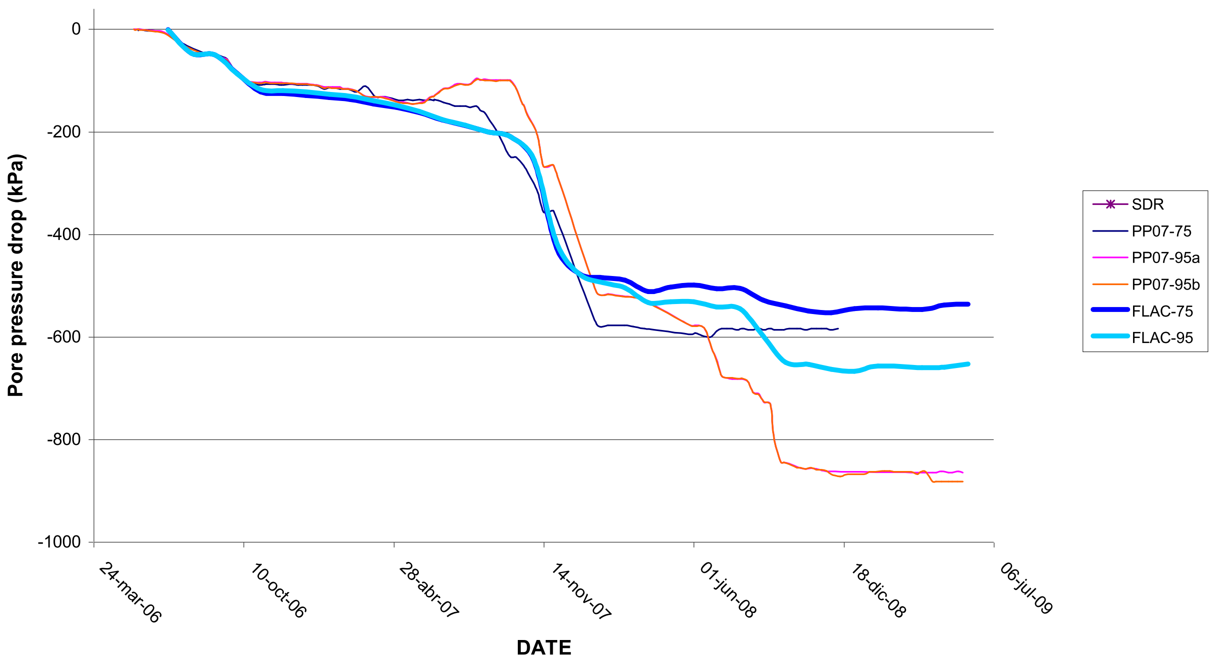


Figure 8a and 8b *- Evolution of the vibrating wire piezometer sensors PP02 and PP07 compared to FLAC calculation*

DISCUSSION

A classical soil mechanics approach, see Duncan (4) for example, would suggest an undrained "short term" total stress analysis with ϕ=0, and a "long term" effective stress analysis with a steady state pore pressure distribution. The method show here has the advantage that the stability can be calculated in terms of effective stresses at any point of the life of the mine which typically spans tens of years which is neither short term nor steady state. Besides as Lambe (5) states, an advantage of a coupled analysis is that it provides a rationale to interpret piezometers as part of the pit monitoring system.

While this paper shows the applicability of coupled analysis to soft rocks, marls with a Young's modulus of 100-200 MPa, it could also be applicable to stiffer rock masses with small porosity. Figure 9 shows the value of Skempton's B parameter as a function of the rock mass Young's modulus for porosities of 0.3 (typical of clays) and of 0.02 typical of the secondary porosity in granites. Solid lines represent pure water with a bulk modulus of 2GPa while the dotted lines represent gas dissolved in the water dropping the bulk modulus to 0.2 GPa. Rock masses in the order of 5-10 GPa Young's modulus may have a B coefficient greater than 0.8 as long as the porosity is small.

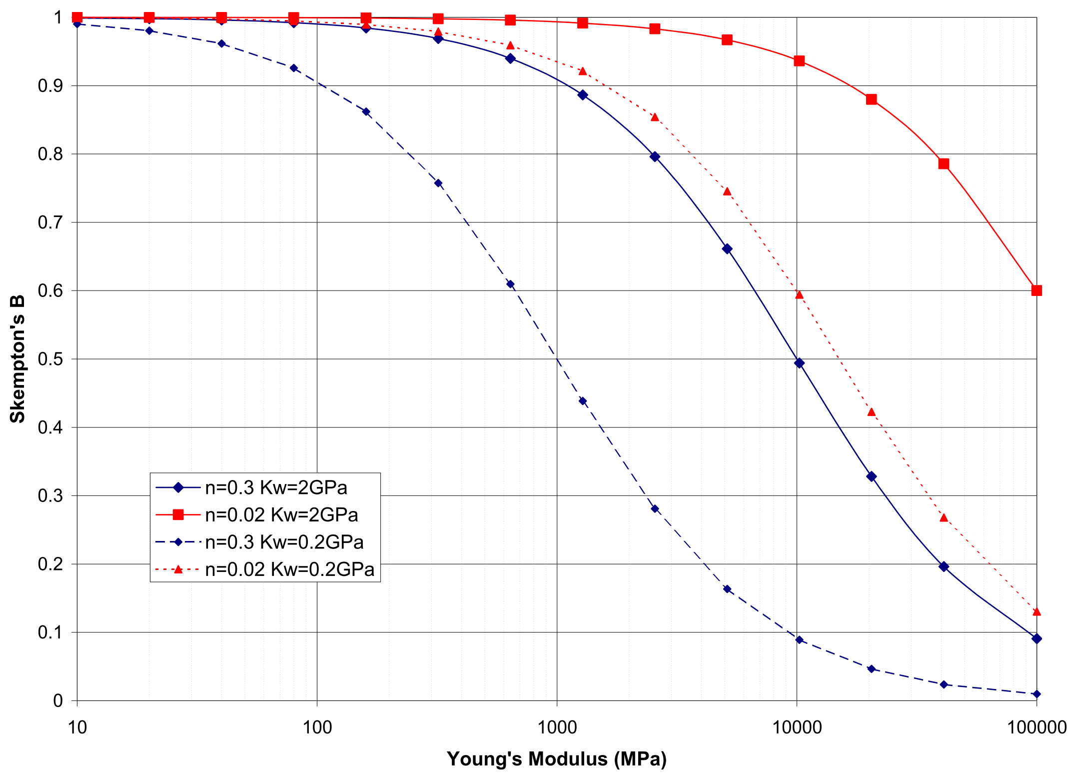


Figure 9 - *Pore pressure drop*

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.

AKNOWLEGMENTS

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