The role of bedding planes in Guadalquivir Blue Marls on the slope stability in Cobre Las Cruces open pit.

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Abstract

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. The ore is overlain by 150 metres of the tertiary marly formation which behaves as an overconsolidated clay (known as Guadalquivir Blue Marls). A detritical aquifer between the ore and the marls exists. The exploitation is in essence an open pit measuring 1600 m long x 900 m wide x 250 m deep. Mineralization is embedded in volcanic and other metamorphic rocks. Prior to reaching the mineralization a pre-stripping of 120 to 150 m in the soft clays has been undertaken.

The water table is located 30 metres below the surface and pore pressure has been shown to play a dominant role on the pit slope stability. As the clays are of very low permeability ($k=10^{-9}$ to 10^{-10} m/s), pore pressure drop due to the volumetric expansion associated with the excavation of the pit has been considered for the slope stability using precise coupled hydro-mechanical calculations, enabling a steeper and more economical slope design. The pore pressure dissipation is enhanced using contour pit well points.

To provide accurate data for these calculations, a comprehensive geomechanical characterization based on lab and in situ tests has been undertaken. During the excavation phase the bedding planes appeared to play a prominent role in the marl behavior, being a key aspect in the formation of localised displacements at the benches, especially at the contact horizon between the clays and the underlying aquifer. The bedding planes appear numerous and apparent at approximately 5m vertical intervals with an average dip of 3º to the South.

A general description of the role of bedding planes based on 17 inclinometers is provided in this paper. The paper also describes two different cases of localised displacements, both intensively monitored by 12 piezometers, 23 topographical prisms and 15 inclinometers, all within the open pit.

The first case concerned movement of 3 benches (of 10m height) located on the North slope of the pit. A back analysis, using the results of monitoring for calibration purposes, was completed. This analysis was solved using FLAC code considering a strain-softening constitutive model for the marls and interfaces for the bedding.

The second case, located on the South pit slope pertains to the marl/aquifer interface where a significant deformation pattern has been measured. The same mentioned methodology was adopted to undertake a stability assessment of this slope.

Keywords: Soft clays, geomechanical behavior, bedding.

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. At this site the ore does not outcrop but instead is overlain by 150 metres of the tertiary soft marls known as “Guadalquivir Blue Marls” formation which geotechnically behaves as a soil (overconsolidated clay) but in which the bedding planes and other vertical joints play a major role.

Between these marls and the ore 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 and at the onset of the project there was a concern regarding the pore pressure acting on the marls. These marls are relatively impermeable and so a flow only analysis predicts a small pore pressure drop due to flow towards the pit.

A general description of the role of bedding planes based on 17 inclinometers is given below. The paper also describes two different cases of localised displacements, both intensively monitored by 12 piezometers, 23 topographical prisms and 15 inclinometers, all within the open pit.

These two cases provide excellent examples for understanding the post-striping slopes behavior at Las Cruces pit.

2 DESCRIPTION OF THE MINE

In this section the main geological, geotechnical and hydrogeological data are described.

Mine

Cobre Las Cruces mine is located in Gerena (close to Seville, SW Spain). The mine is owned and operated by INMET. Figure 1 includes the location of the mine as well as the actual layout of the mine showing its development as of March 2011.

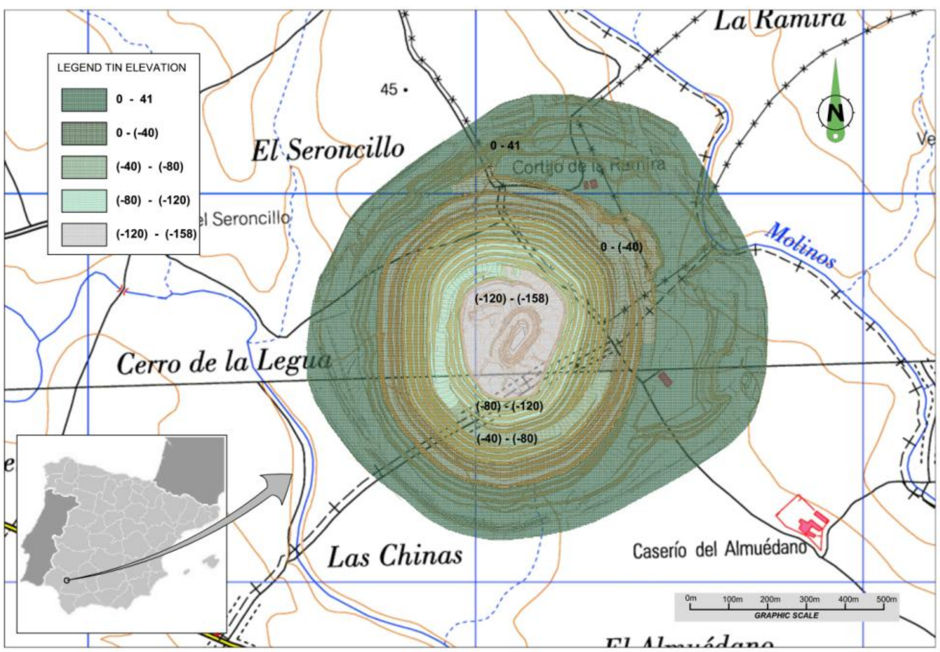


Figure 1. Location Map Showing the Digital Elevation Model of the Open Pit (March, 2011)

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.

This mine is located in the pyritic belt of the Iberian Peninsula in the South west of Spain and it has an estimated reserve of more than 17 Million tonnes. The average grade is the 6.21% Cu. Mineralization is embedded in volcanic and other metamorphic rocks, including massive pyrites and other copper sulphides.

Prior to reaching the mineralization it was necessary to undertake a pre-stripping of 120 to 150 m composed of carbonated clay, well known locally as Guadalquivir Blue Marls. These marls correspond to a marine Tertiary formation from the Miocene epoch. From a geomechanical point of view, these marls constituted the more problematic lithology as they are of weak strength and have low deformational parameters. Also they present bedding planes and other diagenetic vertical fractures, 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.

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.

Geological and geotechnical data

Visually the marls seem to be homogeneous but a detailed analysis as the one performed allows the distinction with depth sections of different behavior in consideration of geo-mechanical characteristics. The following stratification 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 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 metre.
- 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.
- 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 thickness ranging from 0 to 15 m.
- PALEOZOIC SUBSTRATE, constituting volcano-sedimentary rocks.

Concerning the presence of discontinuities two layers can be discerned:

- From surface to 31 m depth: weathered marls. Desiccation fractures and no evidence of bedding.
- From 31 m down to the aquifer: fresh marls. Regular bedding planes every 5 m and vertical joints.

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

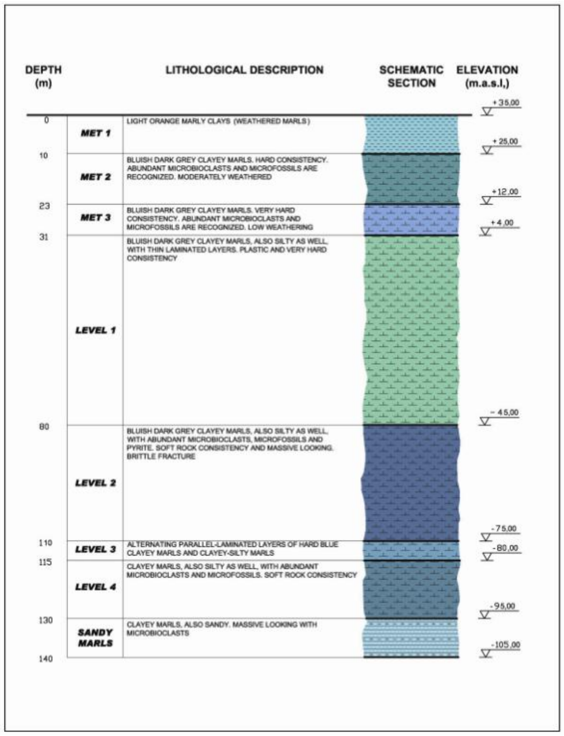


Figure 2. Lithological Schematic Section

Table I - Main physical parameters for each 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 II. Value of cohesion and friction angle for each geotechnical level and stress range

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–τ)	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

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 in the marls, aquifer and fractured top Paleozoic materials.

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.

The mine operation requires 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 there are internal well points installed. The total number of dewatering well points is 32.

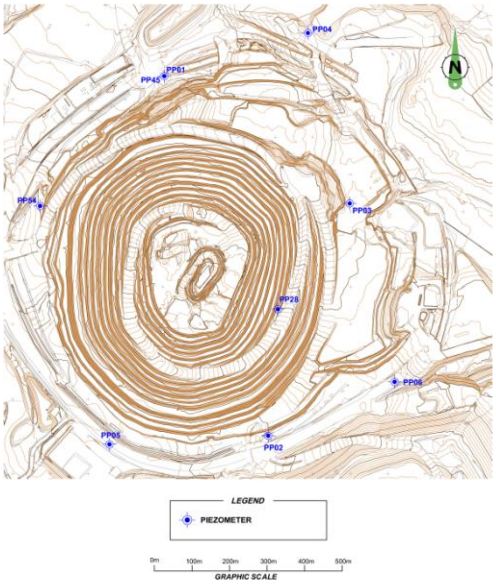
To avoid a disturbance of the aquifer outside the pit, this water is pumped and conducted to injection boreholes located at a distance of 2 and 3 km from the pit.

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

3 MONITORING DATA

By March 2011 the phase 1 of the open pit mine was finished while the second phase, homothetic to the first one, is reaching its end. Phase 3, in which the pit is extended towards the NE, has been started.

As part of the geotechnical monitoring system of the mine there is a piezometer net that actually consists, as can be observed in Figure 3, of 9 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 16 located at different depths between the aquifer and the water table.



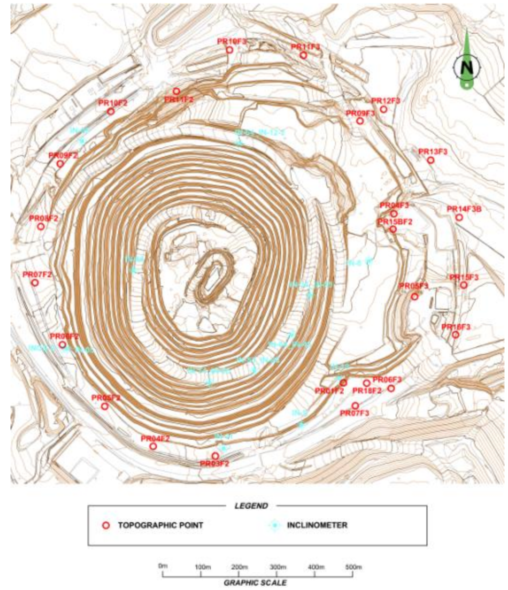


Figure 3. Piezometer monitoring net

Figure 4. Inclinometer and level monitoring net

Also there is an inclinometer net that consists, as can be observed in Figure 4, of 12 inclinometers located both at the perimeter of the pit as well as inside it. In addition, superficial deformations are monitored by means of 24 topographical prisms.

4 DESCRIPTION OF THE BEDDING PLANES

During the excavation phase the bedding planes appeared to play a prominent role in the marl behavior, being a key aspect in the formation of localised displacements at the benches.

The bedding planes appear numerous and apparent at approximately 5 m vertical intervals with an average dip of 3º to the South. Figure 5 shows in the left picture the general aspect of the marls in which the different grey tones highlight the bedding plane locations. In the picture on the right the existing displacement in one of those bedding planes can be clearly observed.

Figure 5. General aspect of the bedding in the marls and detail of one of those planes showing a milimetrical displacement.

Some of these bedding planes were carefully monitored, measuring the displacement between both sides of the plane. Systematically it has been proved that the displacement ranges between a few mm to cm, with an average of about 1 cm.

Also the response in the inclinometers clearly shows the same phenomena can be observed at Figure 6 in which two different inclinometers have been included. From this figure two main assumptions may be concluded:

- The bedding planes are present with an exceptional vertical regularity every 3 to 7 m with an average value of 5 m.
- The displacement at each bedding plane registered is about 5 mm.

Several correlations between the displacement measured at the inclinometers and in the slopes have been carried out. It can be concluded that the displacement on the surface slopes in which the bedding planes outcropped, is always higher than inside the rock mass at the inclinometers.

Also the total displacements measured at the topographical prisms located at the perimeter of the pit are systematically higher than the ones registered at the head of the inclinometers. Consequently the total displacement measured at the benches and at the head of the pit is a combination between the displacements at the bedding planes, an instantaneous and elastic deformation in the marl body, as a result of alivation of overburden, and the deformations that take place at the marl "bridges" between bedding planes.

5 CASES HISTORIES

The follow cases are examples in which the bedding planes can be seen to play a major role in the pit slope observed behavior.

CASE 1

The first case concerned movement of 3 benches, of 10 m height each, located on the North Slope of the pit. Figure 7 shows the location of this instability that was detected by the inclinometers measuring its evolution. The toe of the instability was detected at the existing platform between phases 1 and 2 of the pit excavation, at approximately -42 masl (metres above sea level). Finally the movement halted creating some cracks in the slopes.

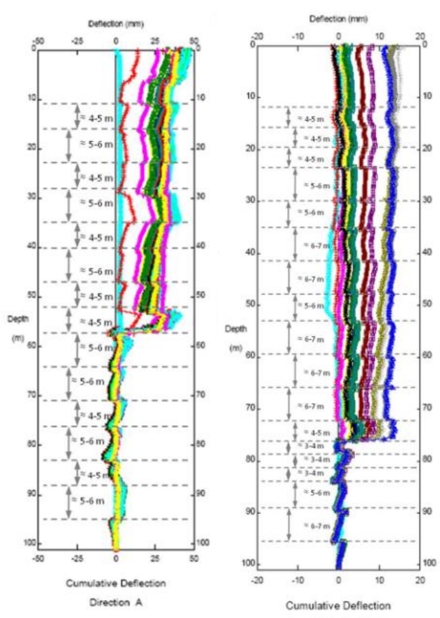


Figure 6. Bedding planes shown in two open pit inclinometers

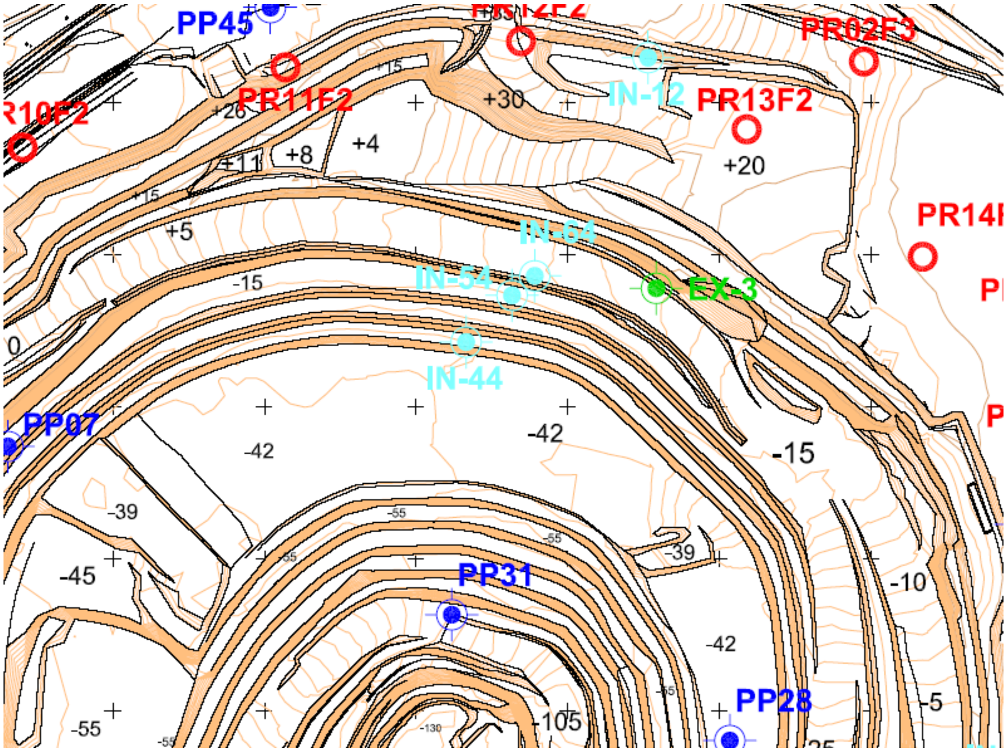


Figure 7. Location of the first case history, located at the North wall of the pit where inclinometers IN44, IN54 and IN64 were installed.

Movement was measured via the installation of the 3 inclinometers mentioned in Figure 7 and of a number of topographical and crack opening measurements. Figure 8 shows the aspect of the instability on the surface of the benches manifesting as a tension crack, while at the right hand side of figure 8, manifesting as a ground hump in the platform.

Figure 8. General views of the head and toe of the instability located at the North part of the pit.

A back analysis using the results of monitoring for calibration purposes was completed. This analysis was solved using finite difference FLAC code considering a strain softening constitutive model for the marls and specific interfaces for the bedding planes and, also, ubiquitous joints dipping 70º against the slope inclination.

The marls parameters utilised were those shown earlier. The shear parameters of the bedding planes were calibrated by successive approximations which provided decimetre displacements, greater than those observed in situ. Table III shows the parameters of the approximations undertaken.

The parameters finally assumed for bedding planes and ubiquitous joints was a cohesion of 0.02 MPa and a friction angle of 15º, according to the best fit monitoring measurements.

Figure 9a shows the FLAC 2D model used for this calibration and Figure 9b the shear strain at the bedding planes.

Table III. Parameters of the bedding planes/ubiquitous joints and displacements obtained for each approximation.

Bedding planes / ubiquitous joints SHEAR STRENGHT parameters		**Maximum shear strain increment (cm)**
c (MPa)	**Φ (º)**	
0.01	12	22
0.02	15	16

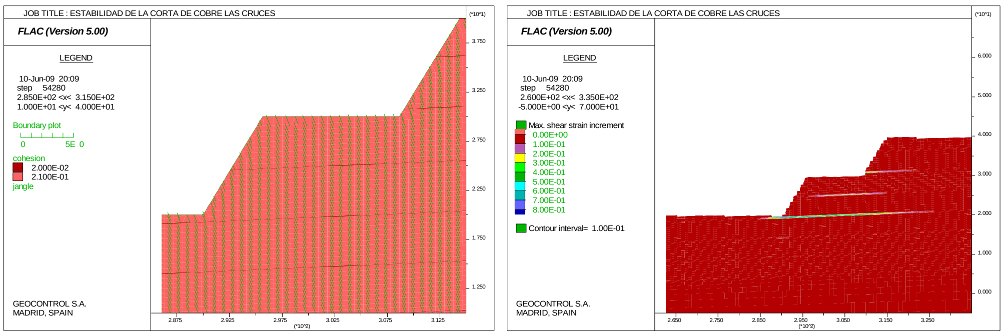


Figure (9a and 9b). FLAC 2D model and shear strain at the bedding planes.

The displacement measured at the inclinometer was 26 cm fitting reasonably well with the shear strain of 22 cm provided by the FLAC model. As the model showed finally the movement was stabilized before any major action was taken. The slope was monitored during several months until the velocities measured were negligible.

CASE 2

The second case, located on the South pit slope pertains to the marl/aquifer interface where a significant deformation pattern has been measured. The same mentioned methodology was adopted to undertake a stability assessment of this slope, based on the monitoring of the deformations by means of inclinometers.

Figure 10 shows the photographs from the top to the bottom of the marls, the aquifer (grey), gossan at the top of the Paleozoic, (light red) and the mineral at the base of the photo (dark grey).

Figure 10. General views of the interface between the marl and the aquifer.

The location of this second case history is shown in Figure 11. Figure 12 shows a profile of the section indicated in the plan view.

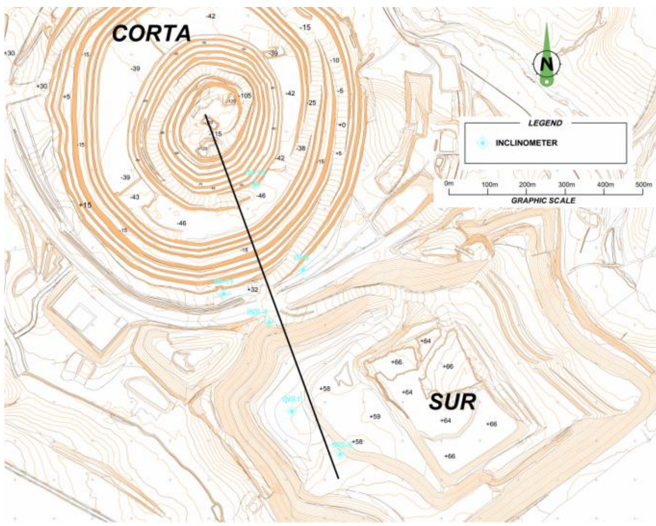


Figure 11. Location of the second case history, located at the South wall of the pit.

In this case the South Dump was also included in the analysis since the toe of the dump is located at a distance of 110 m from the perimeter of the pit border. Therefore it was consider that a potential failure could affect the dump itself. Figure 12 shows a NW-SE cross section in which all the marls levels above the aquifer have been distinguished as well as all the bedding plane mapped at the slopes and detected at six inclinometers located along the section.

This information permitted the evolution of the movement of the marl/aquifer interface to be charted. The charting of this movement indicated displacement magnitudes of a few centimetres with an ongoing velocity of a few mm each day.

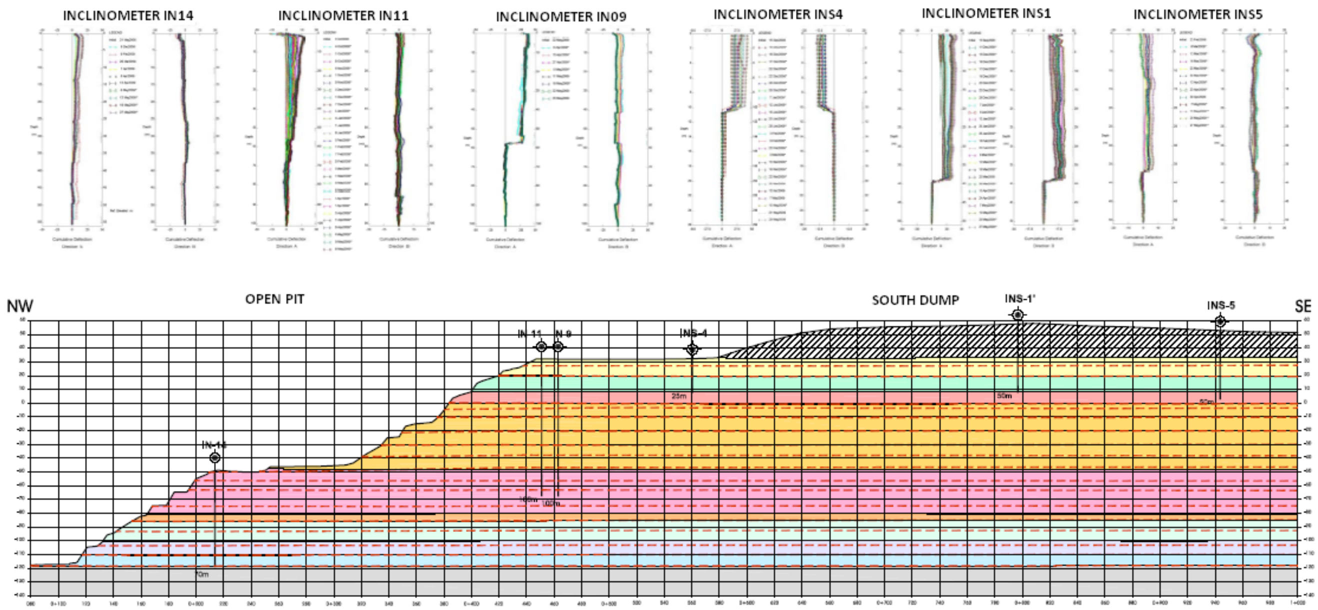


Figure 12. NW-SE Cross Section of the South wall of the pit including the South Dump

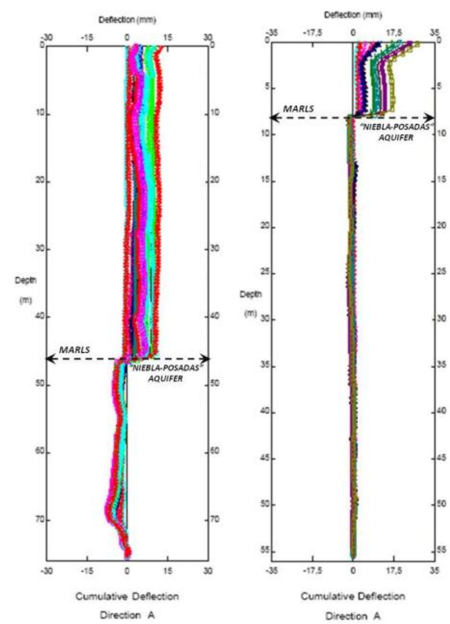


Figure 13. Behavior of the interface marl/aquifer, monitored at two different inclinometers.

As in Case 1, an analysis using finite difference FLAC code was undertaken, considering for the marls a Mohr-Coulomb constitutive model with strain softening, and representing real geological and geotechnical characteristic distributions. For the aquifer and Palaeozoic material simple Mohr Coulomb parameters were considered. Figures 14a and 14b show the calculus mesh and geological distribution of the model, respectively.

The detailed parameters utilised were those shown earlier (Table II) and the shear parameters of the bedding planes were the same as in Case 1.

As shown in Figure 15a, at the end of the excavation phase, the maximum horizontal displacement obtained reaches a value of 14 cm and it occurs in Level-1.

Finally, Figure 15b shows the shear-strain increments, which are greater at the aquifer level, as evidenced by the inclinometers (Figure 13).

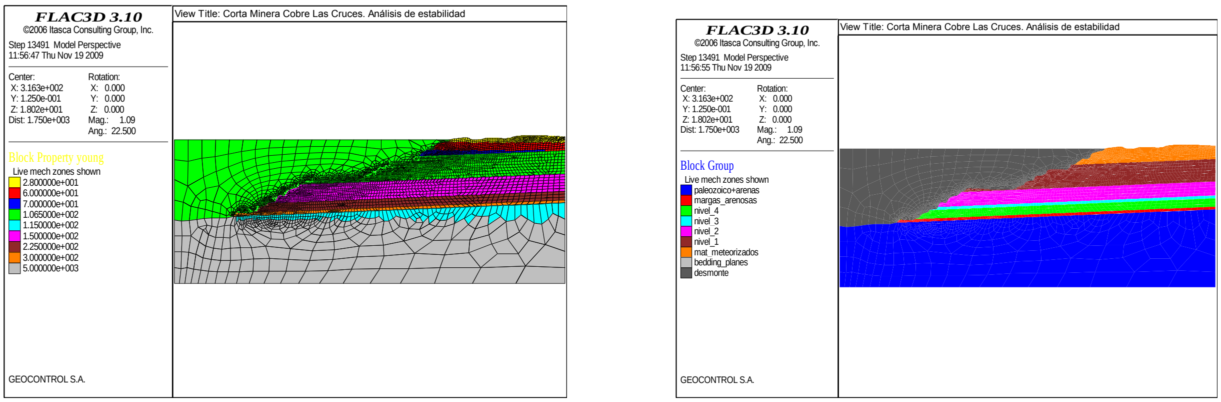


Figure 14a and 14 b.   Calculus mesh and lithological distribution used in the Case 2 analysis.

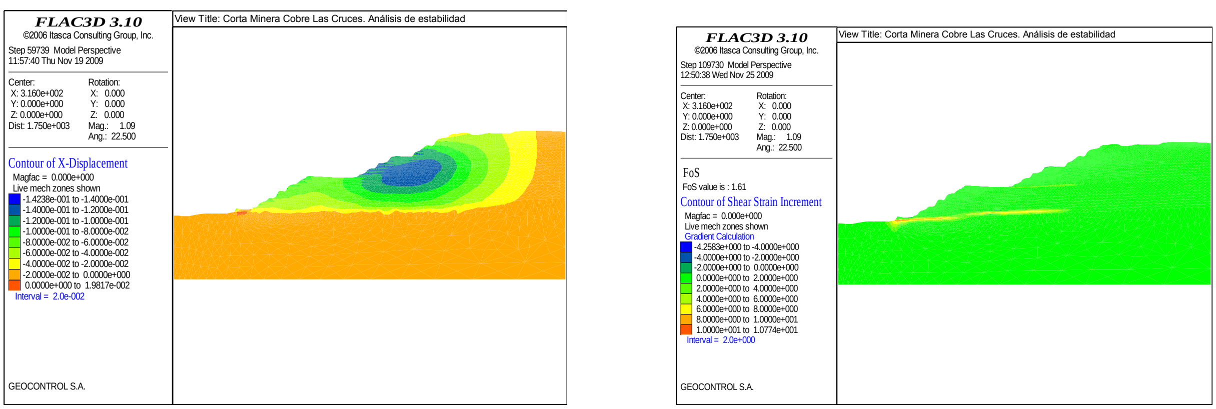


Figure 15a and 15b.   Horizontal displacements and shear strain increments obtained in Case 2.

6 CONCLUSIONS

The two cases analyzed provide excellent examples for understanding the post-striping slope behaviour at Las Cruces pit in which the bedding planes, as it has been shown, played a dominant role.

The slope monitoring, using inclinometrical and topographical measures, has proven very useful to chart slope behavior.

FLAC code is an effective tool in undertaking back analyses and providing reliable predictions of existing and future slope behavior.

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8 AKNOWLEGMENTS

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