# Stability considerations for slopes excavated in fine hard soils/soft rocks at Cobre Las Cruces, Sevilla, Spain

S. Cooper*, M.D. Rodriguez*, V. Pozo†, and J.M. Galera†
**Cobre Las Cruces-FIRST QUANTUM*
*†Subterra Ingeniería*

Cobre Las Cruces mine extracts copper ore from a VMS deposit located in the well-known Iberian Pyrite Belt (IPB). Cobre Las Cruces is distinguished geologically from other IPB mines by the overlying strata, consisting of around 150 m of Tertiary soft marls known locally as the 'Guadalquivir Blue Marls', followed by a regionally important aquifer (Niebla-posadas). Below the marls and aquifer, the sulphide mineralization is hosted by rocks typical of the Palaeozoic within the IPB, comprising gossan, tuffs, and slates.

This combination of a soft rock and, more competent, older (but still occasionally problematic) Palaeozoic strata provides a unique geological framework and substantial challenges in the maintenance of slope stability, and therefore operative safety, at the mine site. This paper describes the fundamental design, excavation, and monitoring measures implemented at the mine to maintain safe production.

## Introduction

As a modern Spanish mine, Cobre Las Cruces is committed to the use of best available technology and practices with the aim of guaranteeing the production of ore in a safe environment. From a practical perspective, this involves high-quality pit design, ongoing geotechnical mapping of exposed slopes to ensure conformity with design, and use of leading geotechnical surveillance technology to complement ongoing monitoring.

Figure 1 shows the layout of the pit at the beginning of 2015.

***Figure 1 – Actual layout of the pit (2015)***

## Mine description

Cobre Las Cruces is an open pit measuring 1600 m by 900 m (final pit shell) with a maximum depth of 250 m. The mine exploits a copper sulphide orebody in the same Palaeozoic volcanosedimentary sequence that hosts the Rio Tinto and Aznalcollar mines. The ore is overlain by 140–150 m of Tertiary soft marls, known as the 'Guadalquivir Blue Marls' (Oteo, 2000). Below these marls there is a sandy formation that constitutes, jointly with the weathered top part of the Palaeozoic sequence, a regional aquifer known as '*Niebla-Posadas*'. The water table is 30 m below the surface. The Palaeozoic, which hosts the mineralization, is comprised of slates, tuffs, and porphyric rocks.

To obtain access to the mineralization a pre-stripping excavation of the marls is required. These constitute a more problematic unit from a geotechnical point of view as they have low strength and poor deformational parameters. This has strongly influenced the original pit geometry, requiring an overall slope of 28° from the surface down to -150 m, while in the rest of the pit a general slope of 45° was adopted.

The marls are highly 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. Furthermore, between the marls and the ore there is the sandy regional aquifer '*Niebla-Posadas*'. For this reason a perimeter drainage systems based on well points directly drilled to the aquifer was constructed prior to the start of the pit excavation, to minimize environmental impacts.

## Geological and geotechnical characterization

Initial characterization of the rocks was by dedicated geotechnical drilling and laboratory testing. Use was also made of geological drilling undertaken to assess the orebody characteristics.

In addition to geotechnical logging of key mineral resource boreholes, more than 700 m of explicitly geotechnical drilling was undertaken improve the characterization of the host rocks. These boreholes were logged and analysed in detail. Figure 2 shows an example of the RMR histogram for the gossan, highlighting the RMR statistical distribution for this lithology.

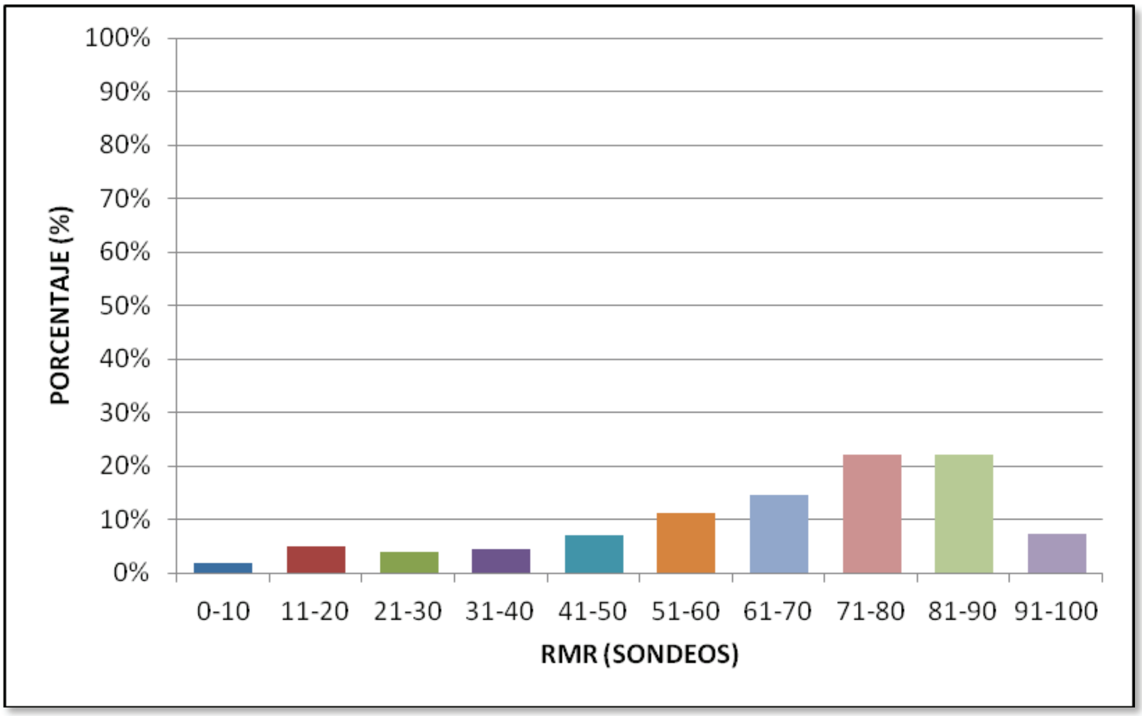


***Figure 2 – RMR statistical distribution for the gossan (leached component of mineralization)***

Table I shows the stratigraphy of the mine, indicating the typical thickness of each unit:

**Table I. Depth and thickness of variously lithologies within the mine pit**

| Lithological | Description | Designation | Typical depth (top, m) | Typical depth (base, m) | Thickness (m) |
|---|---|---|---|---|---|
| Weathered marls | Brown, highly weathered | MET1 | 0 | 10 | 10 |
| | Brown mottled blue, weathered | MET2 | 10 | 23 | 13 |
| | Blue mottled brown, moderately weathered | MET3 | 23 | 31 | 9 |
| Fresh marls | Blue, very weak, without observable weathering | LEVEL 1 | 31 | 80 | 49 |
| | Blue, weak, without observable weathering | LEVEL 2 | 80 | 110 | 30 |
| | Blue, weak, without observable weathering | LEVEL 3 | 110 | 120 | 10 |
| | Sandy marls, transition zone to aquifer | SANDY MARLS | 120 | 125 | 5 |
| Aquifer | Partially cemented sands | AQU | 125 | 140 | 15 |
| Gossan | Yellow reddish leached sulphide derived 'hard' rock | GOSSAN | 140 | 155 | |
| Sulphides | Massive or semi-massive sulphides, 'hard' rock | SULPHIDE | 155 | 250 | |
| Tuffs | Volcanic host rocks | TUFF | 140 | - | Surrounds orebody |
| Shales | Metamorphic host rock | SXM | 140 | - | Surrounds orebody |

Figure 3 shows the detailed stratigraphy of the Tertiary sequence that overlies the ore, as well as the change in UCS with depth. Table II shows the main geomechanical values of each horizon.

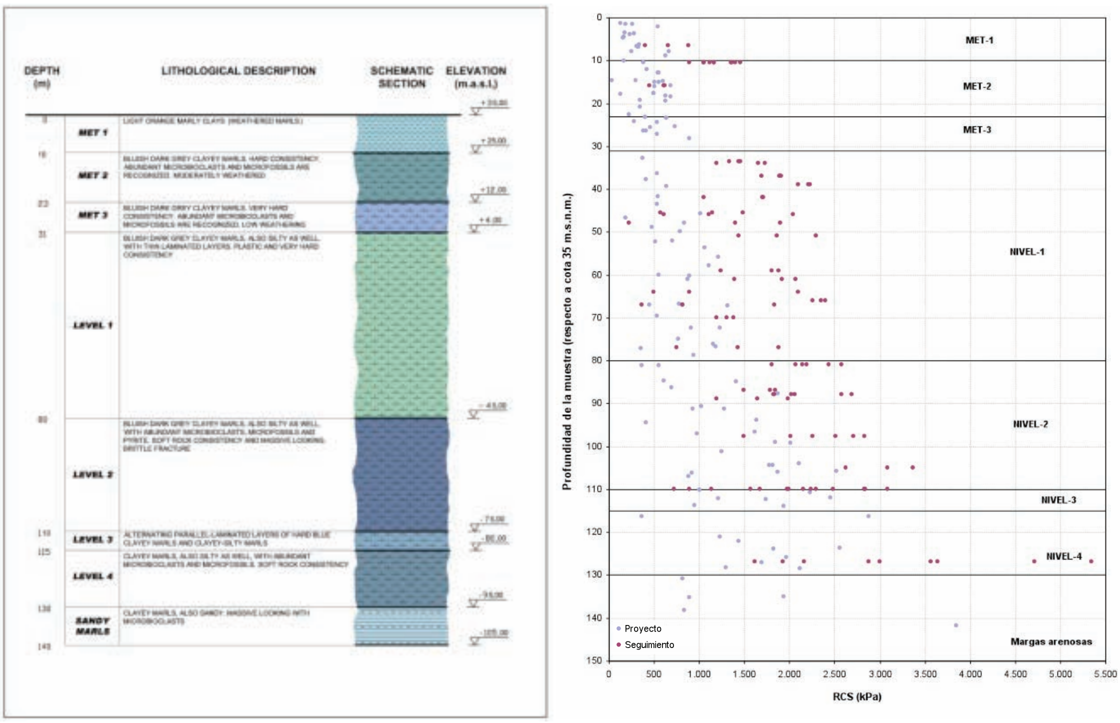


***Figure 3 – Lithological profile of the pre-stripping materials with compressive strengths (Galera et al., 2009a***

**Table II. Geomechanical values for each geotechnical horizon – Tertiary**

| Description | Horizon | Depth (m) | $\sigma_{ci}$ (kp/cm$^2$) | m | s | c (kp/cm$^2$) | $\Phi$ (º) | $\gamma p$ (t/m$^3$) | $\gamma$ (t/m$^3$) | $\omega$ (%) | 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 |

The mineralization is hosted by rocks typical of the Palaeozoic within the Iberian Pyrite Belt. For the purposes of geotechnical evaluation, the following lithologies were established: gossan, tuffs, slates, and sulphides. Geologically, these lithologies can be further sub-categorized with respect to their geochemistry. Table III includes strength and deformability values for each lithology.

**Table III. Geomechanical values for each geotechnical horizon – Paleozoic**

| Group | Intact rock | | | | | Joints | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\rho$ (kN/m$^3$) | Elastic | | Plastic | | Strike | | Peak | | Residual | |
| | | Ei (MPa) | $\nu$ | $\sigma_{ci}$ (MPa) | mi | Dip (º) | Dir (º) | Jc (kPa) | J$\phi$ (º) | Jc (kPa) | J$\phi$ (º) |
| GOSSAN | 28.90 | 20 000 | 0.25 | 19.3 | 7.23 | - | - | - | - | - | - |
| TUFFS | 23.00 | 8 200 | 0.25 | 16.0 | 8.24 | - | - | - | - | - | - |
| SHALES | 24.00 | 22 500 | 0.20 | 4.4 | 4.78 | 70 | 004 | 130 | 22 | 0 | 22 |
| SULPHIDES | 44.00 | 80 000 | 0.20 | 115.0 | 12.85 | - | - | - | - | - | - |

### Initial design (2003)

Using the geomechanical data from the site investigation based on boreholes and laboratory and *in-situ* testing, an initial design of the slopes was undertaken for the mine, comprising the utilization of final pit shell configurations to provide a geometry for a 2D limit-state analysis, applying the Rocscience commercial programme SLIDE and also FLAC2D finite element code. Figures 4 and 5 show typical analyses of the slope stability using 2D limit-state methods and stress-strain analyses solved by numerical methods.

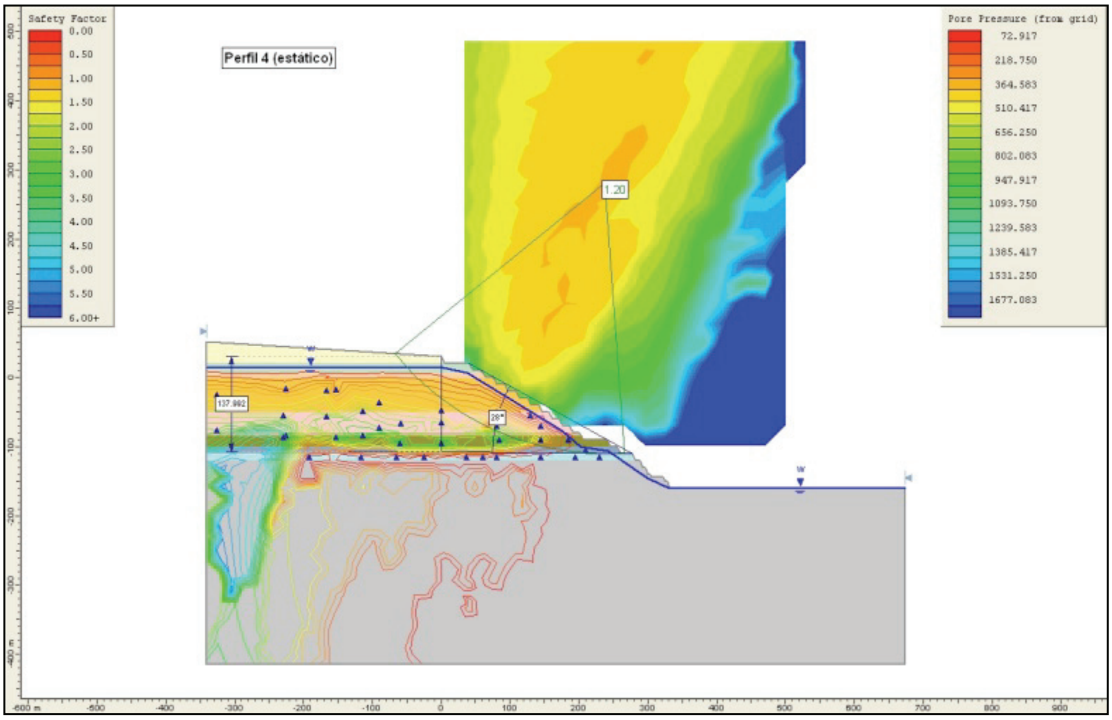


***Figure 4 – Stability analysis with pore pressure contours***

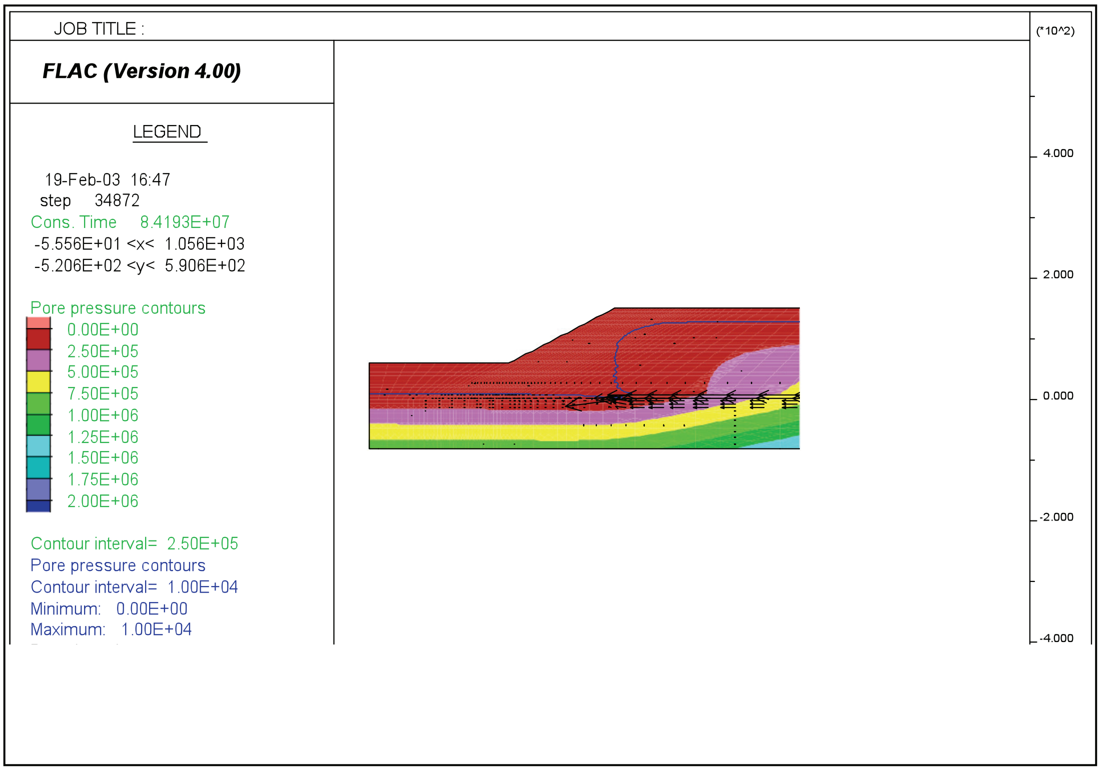


***Figure 5 – Pore pressure calculation in FLAC v4.00***

It should be emphasized that with this initial design, the mine operated successfully for three years, until a refinement exercise commenced in 2007. Figure 6 shows the aspect of the pit in late 2007, one year after the commencement of the pre-stripping operation.

***Figure 6 – Configuration of the pit in 2007***

Key points of the 2003 initial design include:

- Use of limit-state equilibrium analysis software to determine the minimum safety factor required to comply with legislative requirements
- Assumption of overlying homogenous marls subject to non-structural failure mechanisms
- Use of FLAC v4.00 to generate pore pressures associated with pre-strip pumping of the SDR system (system of drainage and reinjection)
- Strain softening characteristics incorporated into marl parameters.

## Pit monitoring

Intensive monitoring of the slopes was conducted from the very first stages of pre-stripping. The instrumentation implemented was based on two types of measurements: deformation (using inclinometers and topographical surveys) and pore pressure (using wire-vibrating piezometers).

### *Topographical monitoring (the geomoss surveillance system)*

Slope surface movement was monitored via a geomoss topographical system. An early version of the system was installed during the first stages of pre-stripping, enabling the movements to be catalogued and compared with determined velocity alert levels. These levels are shown in Table IV, while Figure 7 shows an example of the topographical prism survey of the perimeter and interior of the pit.

**Table IV. Established alert levels in the mine**

| Level | Displacement velocity | Likely cause | Action |
|---|---|---|---|
| Attention | 1 mm/d | Long-term decompression from pore-pressure dissipation | Visual inspection, increase local inclinometer measurement frequency |
| Alert | 3 mm/d | Short-term decompression from rapid principle stress rotation (localized pit stripping) / potential instability | As above, plus recheck design with local geometrics. Consider likely progress pattern and the necessity of cessation of activities in zone |
| Emergency | 10 mm/d | Instability | As above plus cessation of activities in zone |

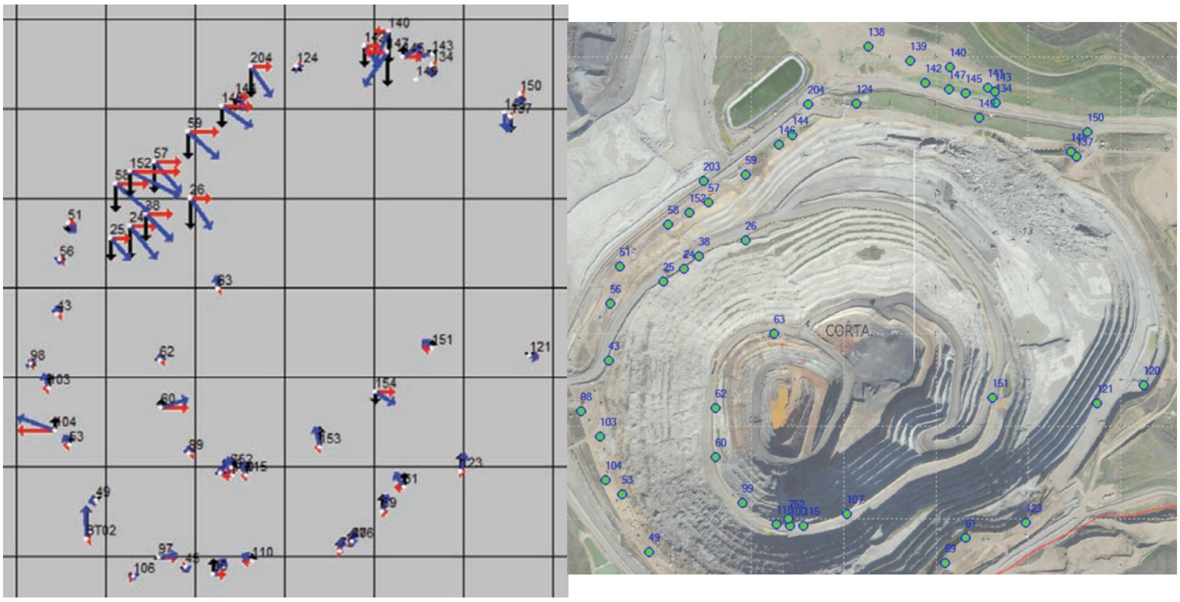


***Figure 7 – Example of daily pit prism displacement monitoring***

Over the years the system has been overhauled to increase reliability and measurement frequency (as high as one reading every 20 minutes of well over 100 prisms). In 2014 two further advanced systems were purchased. A scan from one of these is shown in Figure 8. The first of these systems was placed on the south side of phase 3 to reduce distances to prisms in newer phases and thereby increase precision. The most recently installed system represented a significant advance in the technology, enabling direct laser measurement of the slope surfaces (instead of installed prisms). This system, near analogous to a more expensive radar system, was installed within the Palaeozoic sequence to monitor slopes during an extraction of unanticipated high-grade ore in contact with problematic shales. The purchase of the system was justifiable, enabling the operations team to guarantee personnel safety while extracting substantial additional value.

*Figure 8 – Direct slope scanner showing areas of movement*

### *In-ground monitoring*

A matrix of piezometers and inclinometers has been installed over the mining facility (including pit and dumps). The number of instruments has increased proportionally with mine development from the early stages to the current contingency of 72 piezometers and over 50 inclinometers.

*Piezometers*

Piezometric levels are monitored to ensure pore pressure levels do not exceed those where the slope stability safety factors are considered to be adversely affected. Figure 9 shows an example of the ongoing monitoring of the pore pressure around the pit.

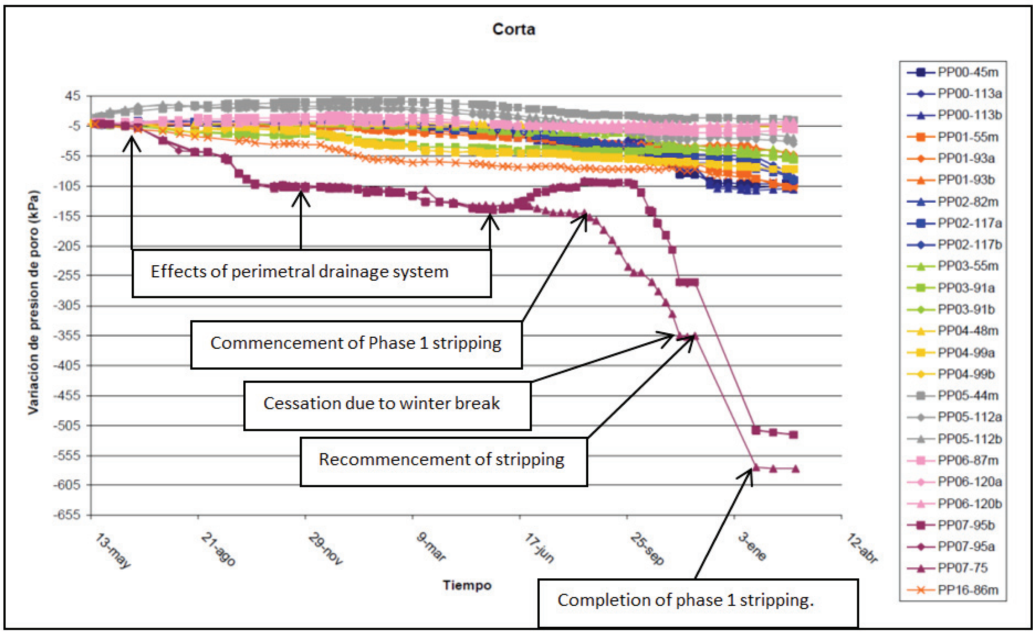


*Figure 9 – Ongoing piezometer monitoring during excavation showing clear relationship between pore pressures and stripping activities*

The information is also utilized to monitor effects of shutdown in sectors of the SDR system for maintenance purposes. The development of pore pressures due to increasing mining activities for over 10 years, as described in the section 'Geological and geotechnical characterization, provides invaluable information for checking and calibrating the estimated pore pressures generated by the hydrocoupling process utilized in FLAC3D.

*Conventional inclinometers*

Predominate use has been made of conventional inclinometer systems comprising continuous metal tubes installed to depths of up to 140 m. The distortions of these tubes are measured manually on a weekly or twice-weekly basis and compared with previous readings to calculate displacement velocities. Figure 10 shows a NW-SE cross-section of the pit incorporating the South dump, showing the displacements of bedding planes at depth.

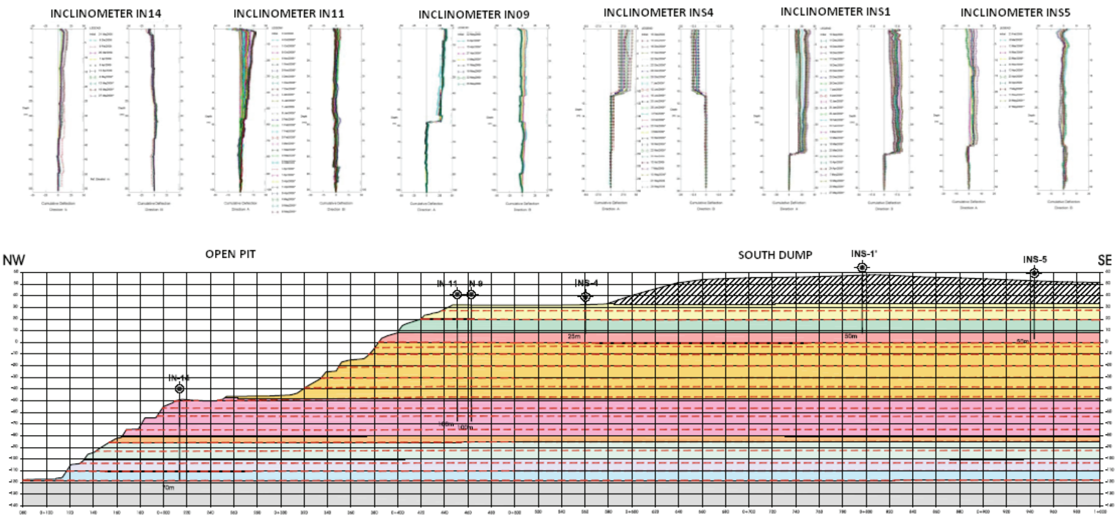


***Figure 10 – Cross-section of pit with key inclinometer locations, showing displacement in continuous bedding planes at depth***

*Real-time inclinometers*

As well as conventional inclinometers, in key areas of the pit, more technically advanced inclinometers were installed. These systems enable continuous information to be gathered, as well as displacement exceedance alerts to be sent directly to the geotechnical engineer's mobile phone (a functional tool that is also available for the topographical prism system). Figure 11 shows the cumulative displacements detected with a real-time inclinometer.

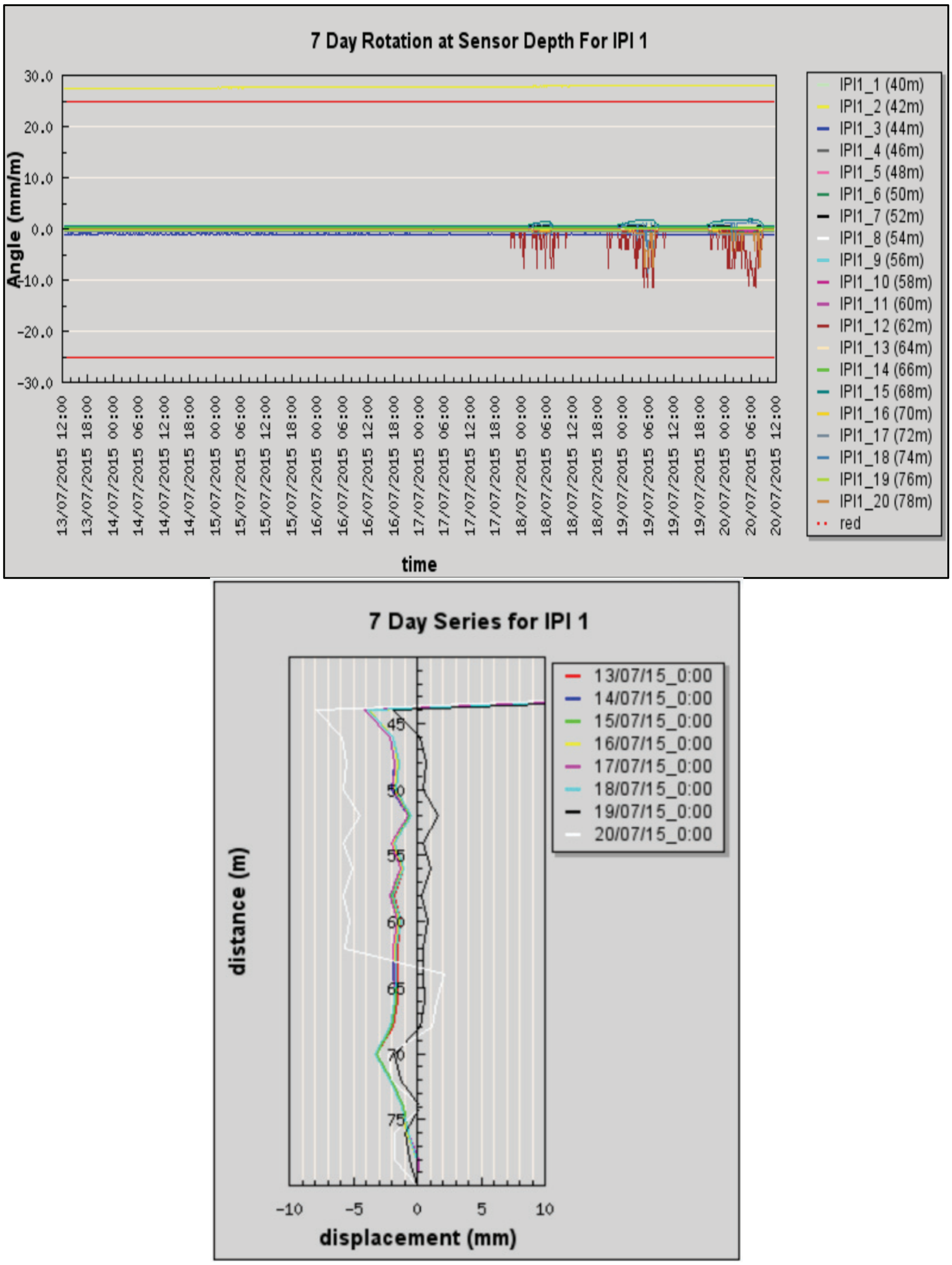


***Figure 11 – Cumulative movement per sensor and down the hole***

These inclinometers are more costly than the conventional system but provide far more information with respect to the evolution of movement and reaction of the substrata in response to mining activity in that particular area; for example, deepening of an adjacent excavation. Owing to the extra costs involved, the optimal form of implementation is to begin with a localized analysis of the slope in question, initially in conjunction with monitoring with conventional inclinometer systems to understand where instability is most likely to occur. Once this is firmly established, the zones with higher risk of instability can then be categorically targeted with real-time sensors. This has been the installation philosophy utilized at CLC.

### *Visual inspections and geotechnical mapping*

All the above monitoring is underpinned by solid field observations. These vary from simple but regular slope inspections undertaken to ensure short-term stability in an operative areas, through to complex geotechnical reconciliation cartography to determine the quality and condition of the blasting and excavation works in comparison. Figure 12 shows a typical geotechnical mapping of a mine bench using conventional methods as well as stereographical photo methods.

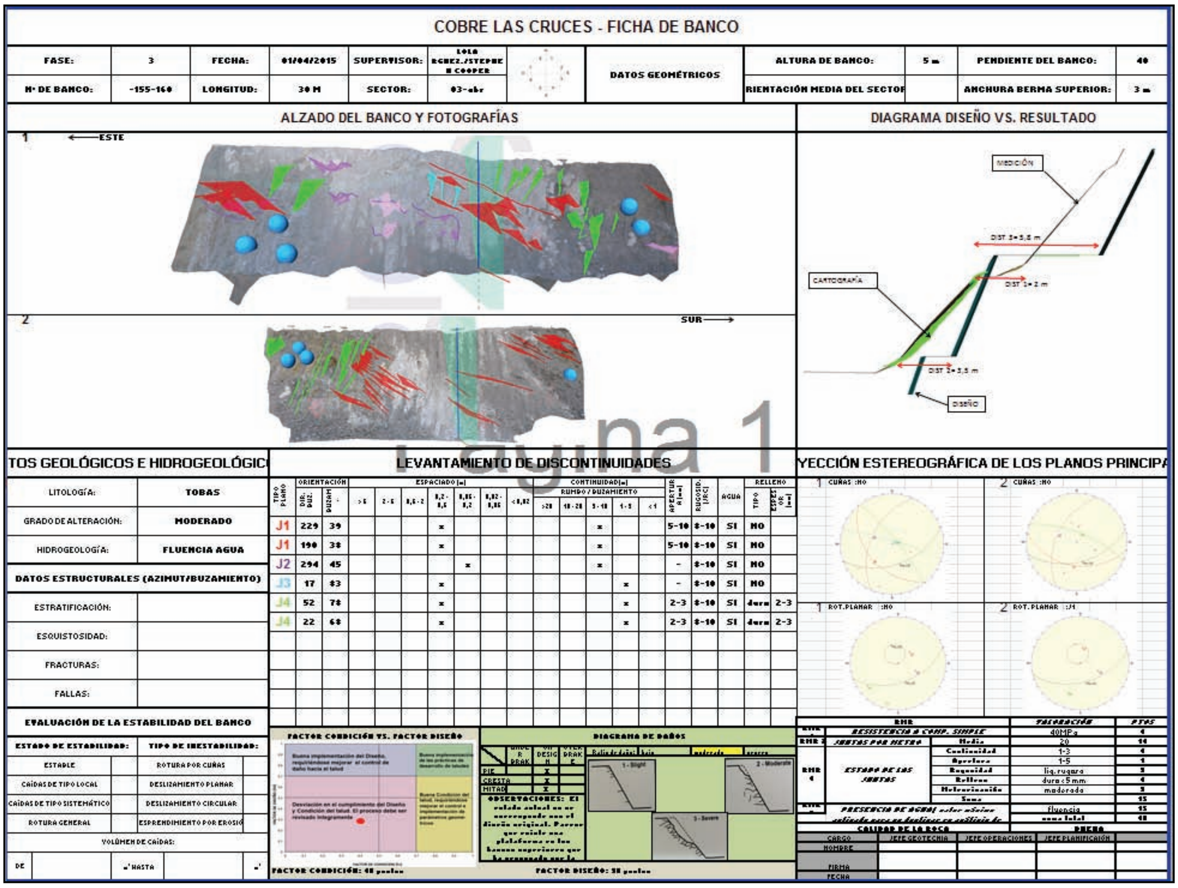


***Figure 12 – Formalized geotechnical cartography providing slope reconciliation following blast and excavation***

### Summary of design stages

Over the last 10 years during stripping and ore extraction, the initial geotechnical model and design has been modified and refined, culminating in additional investigations and geotechnical parameter characterization in 2012 during a pit optimization programme. This information was subsequently used to undertake a robust 3D finite difference stress-strain hydro-mechanically coupled analysis of the entire pit in 2014.

This evolution has been based in additional geomechanical data obtained from *in-situ* sampling as well as from observations of the behaviour of the slopes, including the results of the pit monitoring described previously.

Using FLAC3D, the hydrological complexities introduced by the pit decompression, low permeability of the overlying marls, and the use of a system of water extraction and reinjection put in place to obtain a drawdown on the water table were modelled successfully, improving overall stability and minimizing environmental effects.

This section describes key phases in the evolution of the design of the pit.

### *First design refinement (2007)*

During 2007 the first detailed 3D hydromechanical calibration of the pore pressure after the finalization of the pre-stripping of the marls was undertaken. The result of this work was described in Galera *et al*. (2009b). The 3D model used is shown in Figure 13, and the results of the pore pressure calibration for some of the existing piezometers in Figure 14.

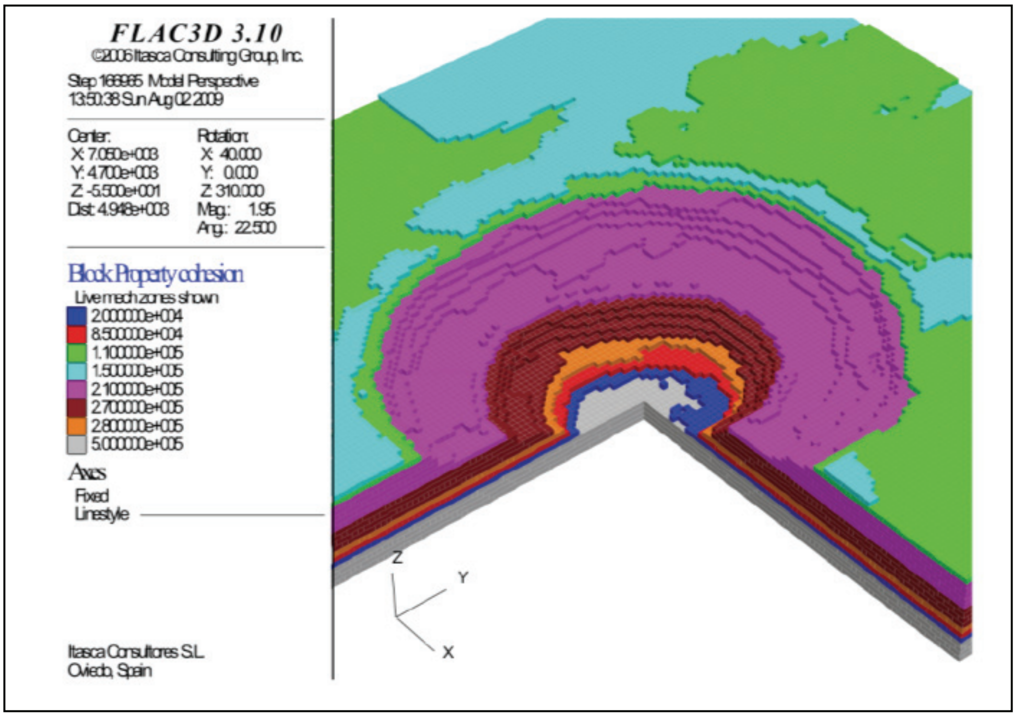


***Figure 13 – Initial FLAC3D pit analysis***

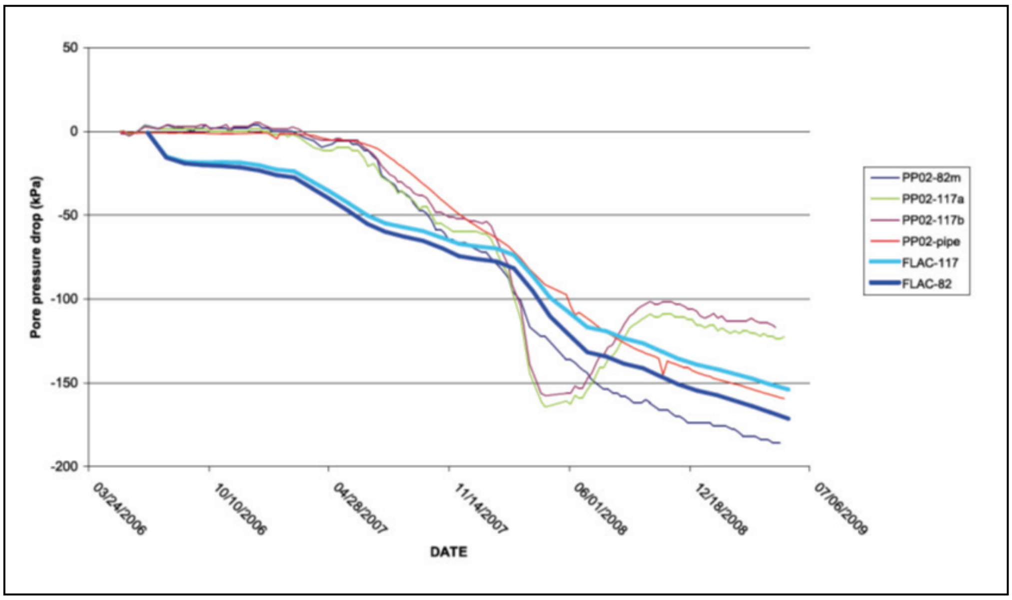


***Figure 14 – Pore pressure calibration***

Key points of 2007 design stage include:

- Axisymmetrical FLAC3D analysis undertaken to match pore pressures in design with those observed in vibrating wire piezometers during the initial phases of stripping (pore pressure calibration process)
- Coupling of pore pressures with SDR drainage activities, and incorporation of the significant pore pressure drop due to the volumetric expansion associated with the excavation of the pit in the pit design.

***Global pit optimization (2012)***

In 2012, during an operational optimization of the pit due to resource model modifications, the decision was made to complement the ongoing geological drilling with geotechnical drilling and a refinement of the geotechnical pit model. Re-analysis of the pit slope stability was undertaken using 2D limit state methods as shown in Figure 15. Figure 16 shows the pit at the end of 2012.

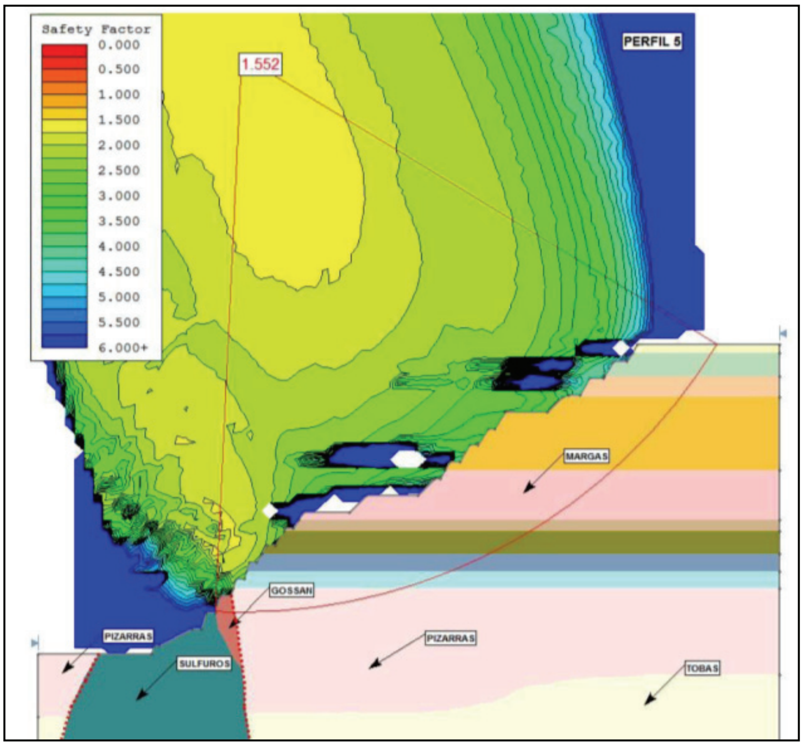


***Figure 15 – Example profile from 2012 analysis showing incorporation of Palaeozoic lithological variation***

***Figure 16 – Configuration of the pit in late 2012***

Substantial refinements were made in the following areas.

Modification of marl behaviour modelling, incorporating:

- Bedding planes and sub-vertical structures observed in geotechnical mapping of slopes during seven years of excavations (Figures 17 and 18). Over years of inclinometer monitoring, minor movements in the range of 100 to 200 mm had been observed in bedding planes, with decompression velocities of 0.1 to 0.3 mm/d being typical in newly opened excavation areas. Although few instabilities (at greater than at bench level) were associated with these bedding planes, previously instabilities in other mines (predominately at Aznalcollar) indicated that these bedding planes could be play a pivotal role in ground instability, and thus should be incorporated into the design. Analysis of bedding plane displacements observed with inclinometers was therefore included in the global analysis (Cooper *et al*., 2011)[1]
- Recognition of a significant transition in geotechnical resistance parameters between the upper and lower marls (with a transition zone at around 80 m depth (Blue Marls, level 1 to level 2). This transition was observed in laboratory testing and was also confirmed in the field, marking the depth at which blasting of the marls for excavation purposes became economically viable. This resulted in a recommendation for the slope angle to be increased from 28° to 31° at this depth
- Recognition of the disturbed condition of marl samples from drill-holes, and improvements in laboratory resistance tests on bulk extracted samples.

[1] The bedding planes in marls were observable both implicitly via movement within inclinometers and explicitly following geological mapping of the slopes. These bedding planes are generally observed to be closed without fill material and close to the horizontal (with dip direction around 3° to the south). In general, bedding planes can be observed every 5 to 6 m, some of which represent transition interfaces between the distinct marl bands.

***Figure 17 – Displacement observed in bedding plane***


*Figure 18 – Subvertical tectonic structures*

Improved analysis process for the Palaeozoic sequence, which was previously considered to be relatively intact and competent. Analysis included:

- Incorporation of geotechnical mapping
- Specific analysis of problematic footwall shales
- Variation in slope angle recommendations, depending on lithology and favourability/unfavourability of tectonic structures. The previous universal 45° slope recommendation was changed to between 32° and 51°, depending on the above factors.

### *Improvements in 2014*

Following minor modifications to tipping activities in dumps near the northern perimeter of the pit, and further modifications regarding ore extraction near the problematic footwall shales in the southern areas of the pit, a recommendation was accepted to utilize the information from the 2012 pit optimization exercise and incorporate this into a FLAC3D analysis of the pit, in order to ensure that these modifications were indeed negligible with respect to pit slope stability. Figures 19 and 20 show the north and south analyses of the pit in 3D.

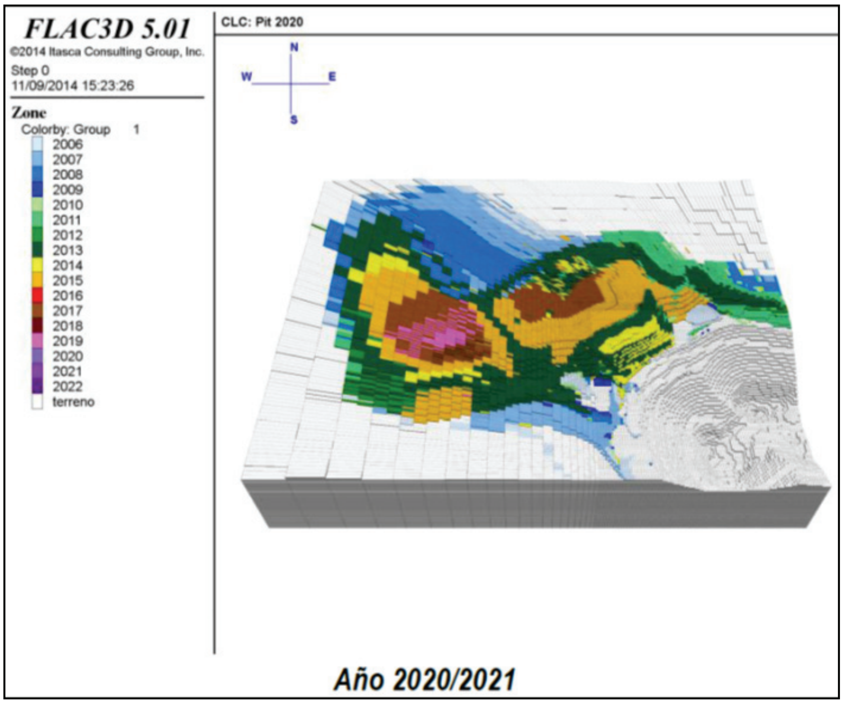


***Figure 19 – Analysis of the north side of the pit in FLAC 3D (Cooper at al., 2014)***

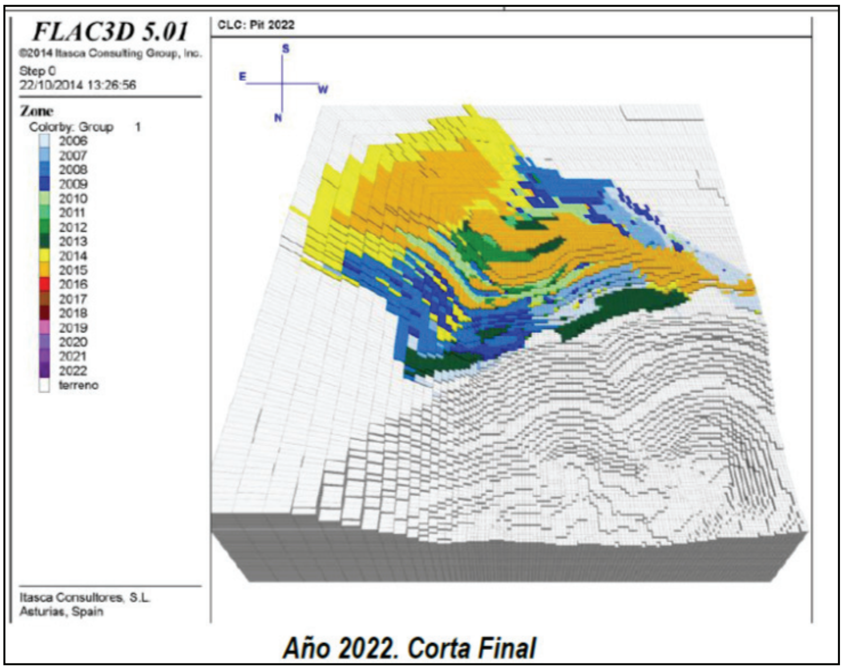


***Figure 20 – Analysis of the south side of the pit in FLAC 3D (Cooper at al., 2014)***

Key elements of the design were:

- Alignment of coordinate system with the geological block model for future data re-incorporation
- Division of the analysis into distinct zones (southern and northern) to reduce demand on processing power and reduce the duration of the analysis
- Reduction of analysis block size to 10 m × 10 m blocks within the pit. Enlargement of block size with increasing distance from pit
- Remapping of piezometric data up to 2014 to improve hydro-mechanical coupling

- Analysis of individual phases of pit within FLAC3D to arrive at final pit configuration.

***Improvements in 2015***

Information was ported into the Vulcan mine data visualization system to enable it to be used by the operation and planning teams during ongoing slope geometrical design, as shown in Figure 21.

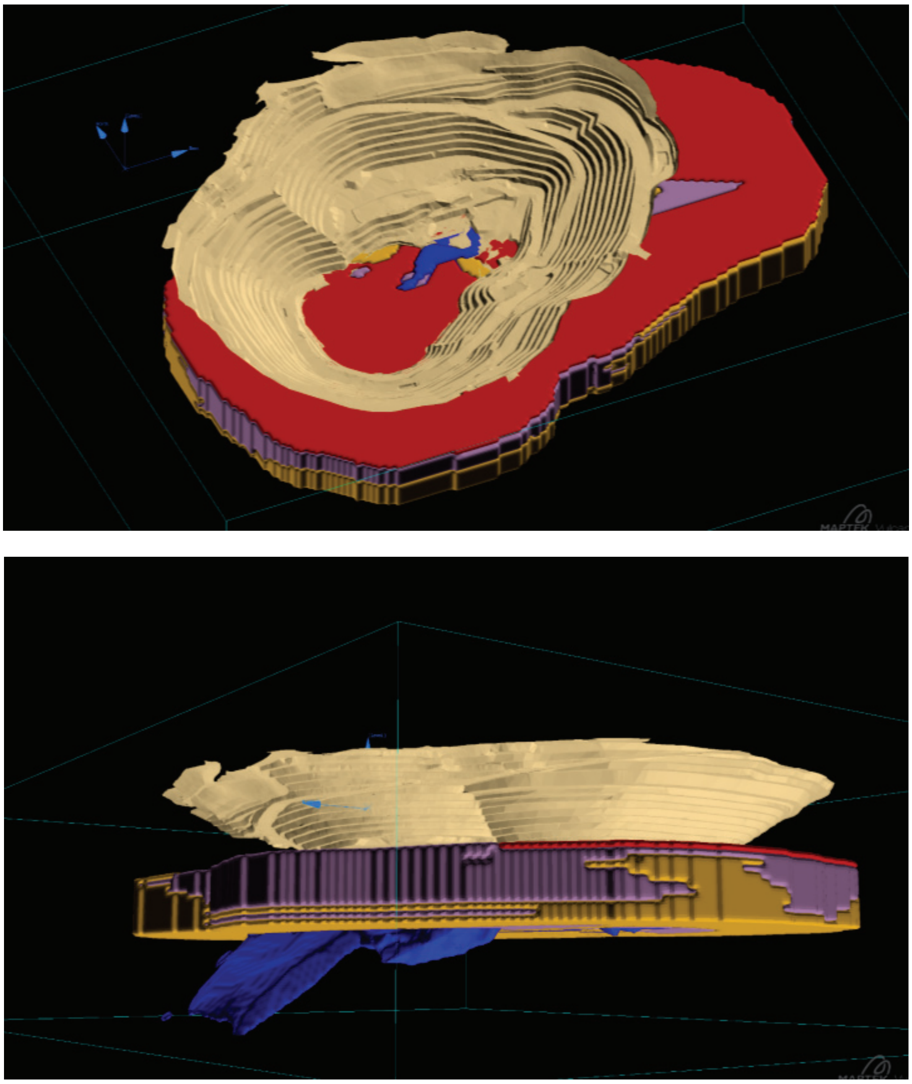

***Figure 21 – Screenshots of smoothed wireframe derived from final geotechnical block model***

Key aspects:
- Block modelling containing lithology and rock quality rating
- Refinement of 10 m × 10 m grid to 5 m × 5 m sub-blocks utilizing the Vulcan interpolation process.

**Excavation optimization**

During the various stages of excavation, the various operational activities were optimized in an attempt to best preserve the slope conditions. Highlighted amongst these are:
- Reduction in bank height from 20 m to 10 m. This led to a substantial improvement in bench-to-bench stability, especially in the initially highly weathered upper marls
- Rendering of benches impermeable utilizing plastic and topsoil emplacement
- Improvement of blasting practices, double-benching in separate 5 m stages, significantly reducing the energy imparted to slopes

- Optimization of blasting patterns in the Palaeozoic sequence, implementing wall blast procedure with modified blast patterns to improve bench preservation and reduce slope rock fragmentation
- Slope smoothing and bench-to-bench knitting to reduce wall promontories (pit bullnoses) between phases.

Figure 22 shows an analysis of the energy distribution of a test blast, while Figure 23 illustrates the berm preservation using the described optimization.

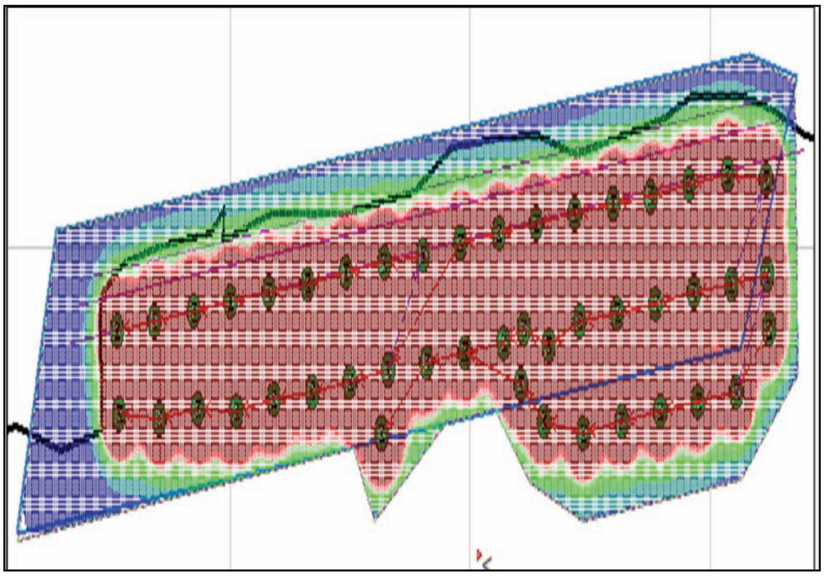

*Figure 22 – Energy distribution analysis of test blast at CLC (Rocha et al., 2012)*

*Figure 23 – Berm preservation via blast optimization in 2012*

## Conclusions

There is no panacea for maintaining stable slopes in an operating mine such as CLC. Although any activity can involve potential risks, the mine operates with a policy of ALARA (reduce the risk 'As Low As Reasonably Achievable') and an objective of zero harm. In order to achieve this objective, over the years more robust and refined designs have been implemented to determine where the predominate risks in the mine lie, and to what extent. Once the areas have been identified, critical monitoring systems have been put in place to manage the risk appropriately. In some circumstances, ore extraction has been possible only by increased local analysis, instrumentation, and monitoring.

It is not possible, either economically or technically, to implement all of these measures at the commencement of mining operations. Any pit design and monitoring plan needs to develop along with the mine's evolution, with increasing refinement in preparation for the mine's most critical periods (usually, but not always, when the mine is at its deepest configuration) and finally winding down, changing from new investment to ongoing maintenance later in the mine life, when preparing for closure and restoration.

## Bibliography

Cooper, S., Rodríguez M.D., Pozo, V., and Galera J.M. 2014. Advanced 3D geotechnical modeling of Las Cruces Open pit. *European Rock Mechanics Symposium (EUROCK 2014*), Vigo, Spain, 27-29 May 2014. International Society for Rock Mechanics.

Cooper, S., Pérez, C., Vega, L., Galera, J.M., and Pozo, V. 2011. The role of bedding planes on the slope stability in Cobre Las Cruces open pit. *International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering*, 18–21 September 2011, Vancouver. Canadian Rock Mechanics Association.

Galera, J.M., Checa, M., Pérez, C., and Pozo, V. 2009a. Enhanced characterization of a soft marl formation using in situ and lab tests, for the prestripping phase of Cobre Las Cruces open pit mine. *Slope Stability 2009 Conference*, Santiago de Chile, 9–11 November 2009.

Galera, J.M., Montero, J., Pérez, C., Vega, L., and Varona, P. 2009b. Coupled hydromechanical analysis of Cobre Las Cruces Open Pit. *Slope Stability 2009 Conference*, Santiago de Chile, 9–11 November 2009.

Rocha, M., Carrasco, I., Castilla, J., Cooper, S., and Rodríguez, M.D. 2012. Wall control by blasting optimization at "Las Cruces" open pit copper mine (Spain). *FRAGBLAST 10. 10th International Symposium on Rock Fragmentation by Blasting*, New Delhi, India, 26–29 November 2012. Singh, P.K. and Sinha, A. (eds). CRC Press, Boca Raton, Florida. pp. 715–724.

Tsige, M. 1999. Microfábrica y mineralogía de las arcillas azules del Guadalquivir y su relación con las propiedades geotécnicas. *Monografía* 67, Ministerio de Fomento, CEDEX; Madrid, Spain.

**The Author**