Geotechnical considerations for the evaluation of the stability of cohesive rock derived residues at Cobre Las Cruces mine, Sevilla, Spain

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Cobre Las Cruces is an open pit mine that extracts copper sulphides from the same volcanosedimentary Palaeozoic deposit as the mines of Rio Tinto, in the southwest of Spain.

The ore is overlain by around 150 m of the Tertiary marly formation which behaves as over-consolidated clay, locally known as 'Guadalquivir Blue Marls'. This material needs to be well managed by the construction of stable dump structures where the principal tipped material is this fine-grained cohesive rock derived residual.

The evaluation of stability of these types of structures is fundamentally different to that of more traditional spoil tips where simple scaling of the geometry is feasible due to the favourable geotechnical parameters. There have been a number of cases of dump failure due to the cohesive nature of both the tipped, and underlying natural material, where it can be definitively stated that if the structures had been free draining in nature, failure would not have occurred.

In the long term, the issue of dump slope stability is fundamental to sustainable mining, given that these residues are required to coexist within the local environment for many years after the life of mine (LOM) and, subsequently, the mine's eventual and inevitable closure. As a flagship mine, CLC has implemented Mining for Closure (MFC) sustainable mine practices.

Three essential aspects that should be included in any stability analysis of such materials are:

- The influence of compaction in the shear strength parameters of the spoil material
- The Skempton B-bar and pore pressure dissipation in the underlying natural founding material
- The development of progressive failures in pre-existing bedding planes.

At pre-design stage, several test dumps were constructed with a matrix of instrumentation to provide calibration information with respect to the limiting pore pressures and B-bar ratio. This calibration was undertaken using a coupled hydromechanical constitutive model, solved with FLAC 2D modelling software.

Following compaction using standard mining equipment, several trial pits were excavated to determine the evolution, with depth, of the modified Proctor value; the chosen method of evaluating compaction for these dumps. According to the results of these trial pits, a practical compaction specification was created, which resulted in alternate layers of shear strength with depth.

Several refinements of these analyses have been undertaken during the operative life of the mine, considering the specific geometry of each dump area and using limit equilibrium methods (SLIDE). The behaviour of these areas has been subject to ongoing evaluation via an intensive instrumentation programme that includes the installation and monitoring of inclinometers, piezometers, total pressure sensors, and topographical survey points. From these programmes of vigilance, limiting parameters have been established and incorporated into the management of each dump space, allowing stability to be assured and compliance with technical and legislative safety factors.

Introduction

Cobre Las Cruces (CLC) is an open pit mine located in Seville, Spain, extracting copper from the volcanosedimentary complex known as the Iberian Pyrite Belt. This is home to a family of polymetallic ore containing deposit,s including Rio Tinto and Aznalcollar.

The body of the massive sulphides associated with the deposit is found around 150 m below tertiary marls known regionally as 'Guadalquivir Blue Marls'. These sedimentary marls extend laterally along the banks of the Guadalquivir River with some of the greater thicknesses present within the zone of CLC´s mining installation.

Pseudo-horizontally (with a dip towards the south of around 3 degrees) positioned between the marls and the mineralization, the base of the Miocene formation is found, consisting of sands and fossiliferous sandstone which constitutes the Niebla–Posadas aquifer.

The management of all material resulting from the mining exploitation is regulated under the mine's Management Plan for Mining Waste, where the end placement of material is defined subject to strict environmental regulation.

Specifically at CLC two types of dumps are defined, in consideration of the potential contaminative effects of the waste stored, with respect to safety and the environment in the event that a breach of containment resulted in a release of such materials. The latter aspect is a key condition from a geotechnical point of view, necessitating pre-construction design of stable dumps, exhaustive supervision during construction, and ongoing monitoring and vigilance during and following completion of construction.

The management of the marls depends on their geomechanical characteristics, both in the natural *in-situ* condition as well as tipped. Aspects such as the control of pore pressure (induced by tipping activities), control over compaction of the tipping layers, and the exhaustive recording of structures and discontinuities with depth are necessary. With such information, revision of the initial design assumption is possible and can be used to refine those designs. This design philosophy has been in place since the commencement of mining operations, minimizing the possibility of both localized and large-scale instabilities.

Figure 1 – Location of CLC mines showing the actual layout (February, 2014)

Residues management at Cobre Las Cruces - general description

The orebody is exploited via an open pit, which will have a roughly elliptic final form with its long axis in an east- west direction, 1 600 m long x 900 m wide with maximum depth of 250 m. With a global angle in the marls of 28 degrees followed by 45 degrees in the Palaeozoic, the sum of extracted material is 17 625 000 t of ore, compared to 199 398 000 t of marls (a stripping rate of more than 1:11). This relatively high stripping ratio is made worthwhile by the substantially high grade of the orebody obtained (over 6.0% leachable copper content). Of the residual material stored within the dumps, three types can be distinguished: Inert residuals (marls), plant-treated material (tailings), and mineralogical materials (the storage facility for these materials, predominately gossan, tuffs, and shales, also provides an area for stockpiling and blending ore directly prior to feeding to the plant).

Typically, two design types have been established for the dumps: one for the inert marl dumps and a second, with much more strict construction criteria, for the non-inert residues, given the potential for contamination that the materials present. Figures 2 and 3 show profiles for each type of dump.

The dumps are constructed in layers with compaction grades that have been defined in terms of percentages of the optimum compaction obtained by the modified Proctor test. In the inert dumps (marls) the layers are of 5 m maximum thickness. Following initial testing, this form of depositing marls produces a ‘sandwich’ of high- and low-compacted material with 90% of optimum Proctor level in the upper 2.5 m and 65% in the lower 2.5 m. The material in these dumps is tipped directly over the natural ground, previously prepared by removal of the topsoil and alluvials and a process of scarification to provide interlock of the natural and tipped material.

The non-inert material containment dumps (whether tailings or mineral) are constructed with more demanding and restrictive compaction criteria. With respect to the surrounding containment berm, preparation begins with a foundation excavation of the area to depth where the competence of the subsoil is considered adequate (from previous analysis, this is determined to be with equivalent to 10 no. block counts of a standard heavy dynamic penetrometer test for 200 mm).

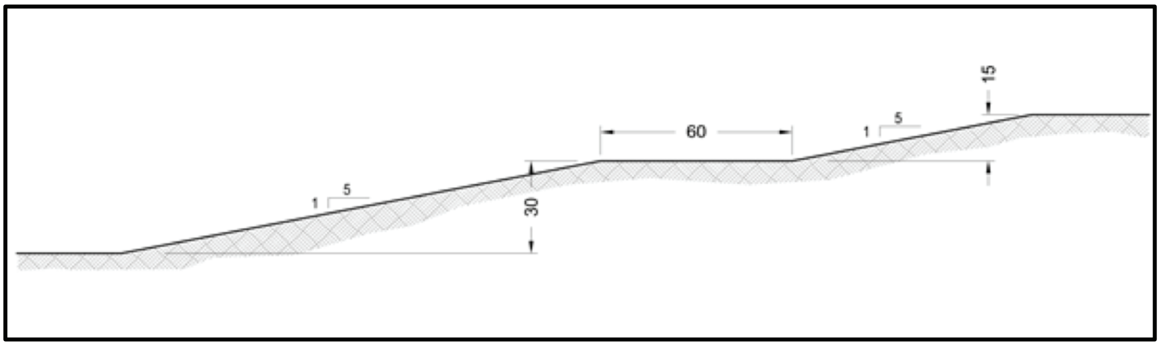


Figure 2 – Typical profile for a marl dump

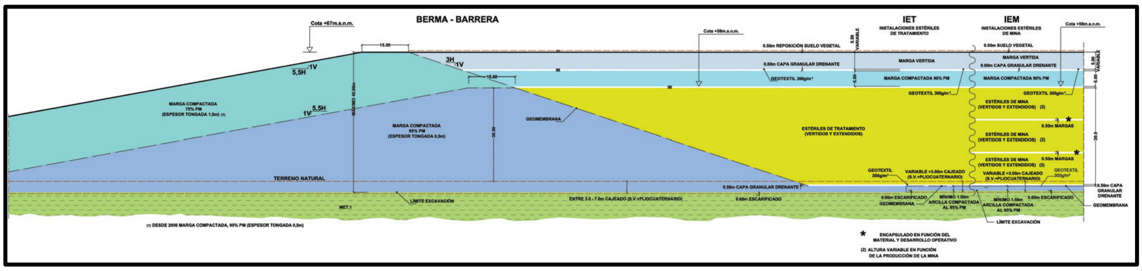


Figure 3 – Typical profile for a tailings or mineral residue containment facility

This level is then scarified to obtain interlocking as well as to dissipate the pore pressure induced in the first founding layer of the dump. Subsequent tipping of marls to build up the containment berm is undertaken in layers of 0.5 m with a required minimum compaction grade of 95% PM. In such way the nucleus of the denominated ’barrier berm’ is constructed, which acts to contain the internal residues produced by mineral treatment in the plant or from the mineral extraction process. The tailings facility and mineral storage facility at CLC are therefore fully distinct, but nonetheless constructed according to the same design. This barrier berm is final capped off with a free tipping of marls, to a Proctor level of 75%, as observed in Figure 3.

The low permeability of the marls is one of their more useful characteristics with respect to the environment. With a permeability of between 10^{-9} and 10^{-11} m/s, the natural state of this material, with nearly 150 m to the underlying aquifer, provides a perfect isolation of the facility from the external environment. Nonetheless, prior to tipping an additional plastic liner is put in place such that in the final configuration is obtained with an impermeable liner and an underlying drainage layer such that any remaining liquids may be collected and independently processed.

During the tipping operations, much importance is place on geotechnical vigilance, such that the tipping activities can be adjusted according to the responses observed within installed instrumentation in the area. This ’modus operandi’ for tipping has been successfully employed since the initial stages of construction of the dumps and is considered essential for the control of the evolution of pore pressure and reducing displacement (predominately horizontal in nature), which could direct effective friction angles for the marls from peak values to values closer to the residual.

Geological and geotechnical description of the marls

The marls, *a priori*, can be considered as a relatively homogeneous formation geologically. However, geotechnically and with further testing and investigation, they are observed to be moderately conditioned by numerous stratification planes as well as joint sets that are tectonic in origin, reducing homogeneity and finally dominating the geomechanical behaviour.

The marls are also well known to be of high plasticity and very low permeability, with high weathering observable at shallower depths. For these reasons, their behaviour geotechnically has been segregated into three subdivisions of alteration, followed by five further levels of non-altered, deeper, and more competent marls. These divisions have been established as a function of the geomechanical characteristics (Galera *et al.*, 2009):

- 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, 10 m thick
  - MET-2, down to 23 m depth. The marl is heavily weathered and presents vertical desiccation fractures spaced around 1 m
  - MET-3, down to 31 m depth. The marl is moderately weathered. The spacing of desiccation discontinuities is around 12 m. The strength parameters at this level are similar to MET-2 level
- 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 subvertical joint sets can be observed, as well as horizontal bedding planes spaced at 5 m 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’, presents the same characteristics as LEVEL1 with a thickness ranging from 5 to 10 m. Laterally it disappears between LEVELS 2 and 3, showing strength and deformability properties similar to LEVEL2
  - LEVEL4, ‘strong marl’, 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 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 4 summarizes all the geotechnical horizons that can be observed in the marls, together with the evolution of the UCS values with depth. Table I summarizes all the geomechanical parameters assigned to each horizon.

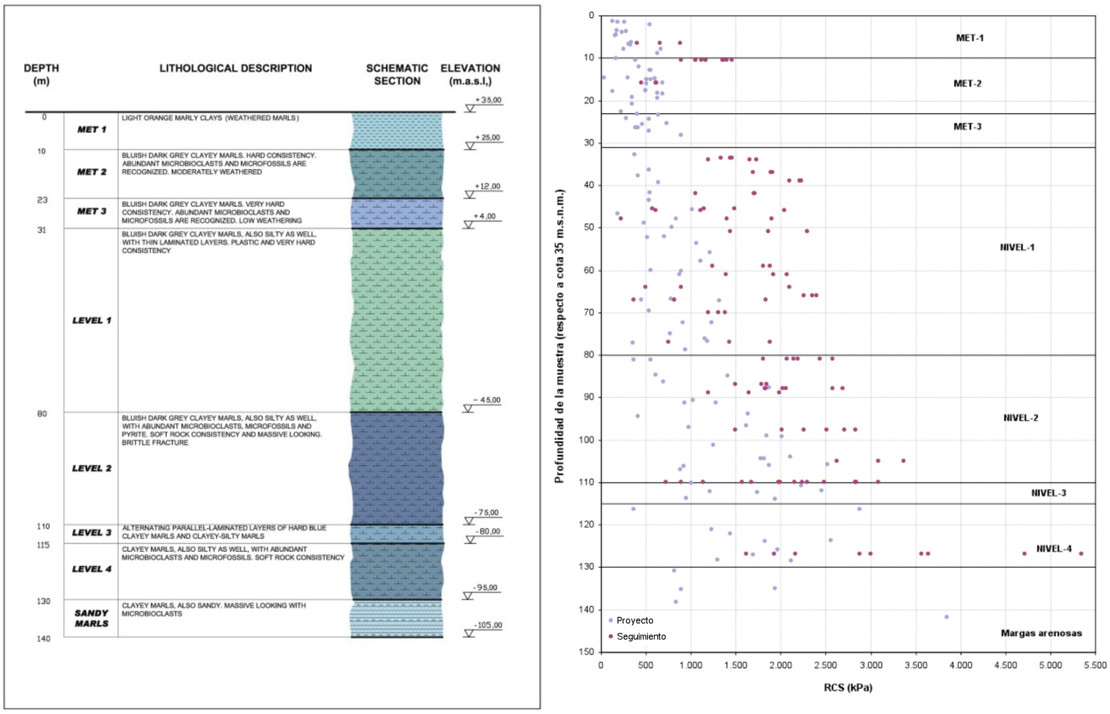


Figure 4 – Lithological profile of the pre-stripping materials (Galera et al., 2009

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

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 (%)
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

The bedding planes have played a key role when establishing the designs of residues containment structures. These planes present residual parameters, with negligible effective cohesion and friction angles in the range of 8 degrees (Cooper *et al.*, 2011). Once the planes were detected, a process of re-analysis was undertaken to incorporate and estimate the effect of their presence in the substrata. In some cases, such as the tailings facility barrier berm, the result of such analysis were used to justify the reduction of slope angles from 1:4 to 1:5.5, substantially increasing safety factors.

It is interesting to note that these same bedding planes were a determining factor in the breaching of the residues containment pond in an adjacent mine in Aznalcóllar in 1998, which resulted in significant damage to the environment in southeastern Andalucía. The tailings material at Cobre Las Cruces is in general manageable as a solid material and therefore is inherently a more competent material; nonetheless, the importance of including bedding planes in the stability analysis of the dumps at Cobre Las Cruces is paramount to ensuring accurate prediction of dump behaviour.

Dump founding strata - pore pressure dissipation

Given that the marls are described variously and in a mining context as soft rock/hard soil, one of the more problematic aspects of the marls is in relation to these bedding planes with the founding strata of the dumps.

There are well known and referenced cases of failures in these marls. That mentioned above, of Aznalcóllar dam, located only 10 km from Cobre Las Cruces Mine, comprised a 28 m high rockfill dyke, which failed catastrophically on 25 April 1998 and triggered an uncontrolled flow of acid pyritic tailings. This failure was described as a translational slide which carried with it the dyke itself (Alonso *et al*., 2010; Botin *et al*. 1999). Among various factors, the principal cause of the breach was considered to be the existence of bedding planes with residual shear strength and high values of pores pressure at the foundation of the dam.

For this reason, since the early stages of the CLC mine project, special attention was paid to the dump´s founding strata. At design stage, several test dumps were constructed with a matrix of instrumentation to provide calibration of the limiting pore pressure and B-bar ratio. This calibration was undertaken using a coupled hydromechanical constitutive model, solved with FLAC 2D modelling software.

The behaviour of these materials during excavation and tipping was predicted via the construction and monitoring of a pilot dump, formed with fill material derived from marls, free-tipped with layers of 9 m. Instrumentation was installed which provided valuable information in reference to the effects on pore pressure with tipping activities. Modelling of the pilot dump was undertaken utilizing FLAC2D, the objective being the calibration and validation of the values of pore pressure provided by the installed instrumentation, as well as to predict future evolution of both pore pressures and total pressure in the areas to be subject to dump installation.

During the loading process, maximum Skempton B-bar coefficients of B=0.83 were observed, being affected greatly by the construction process of the dump and in particular tipping rates.

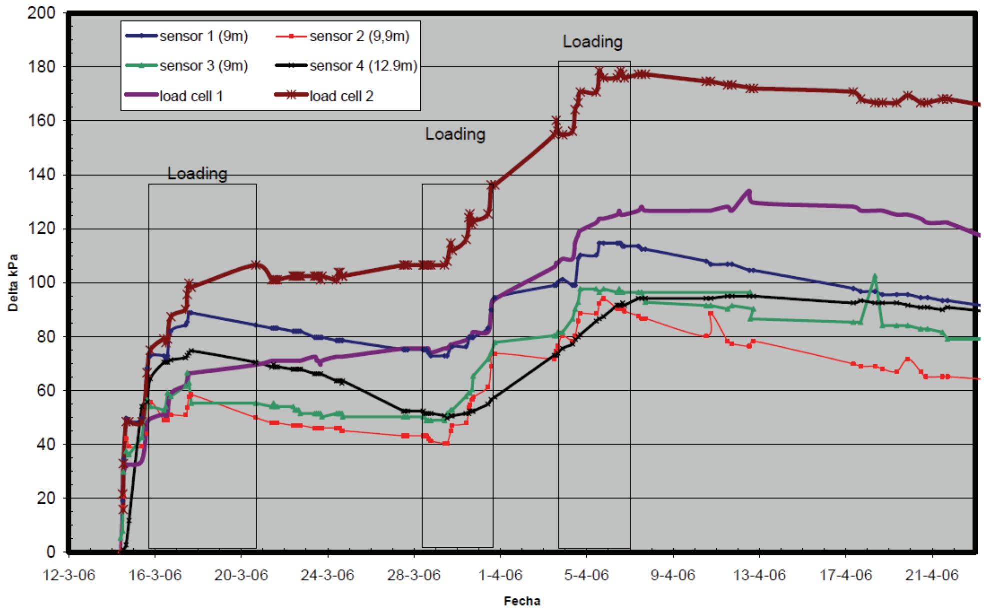


Figure 5 – The evolution of pore pressures recorded by monitoring sensors

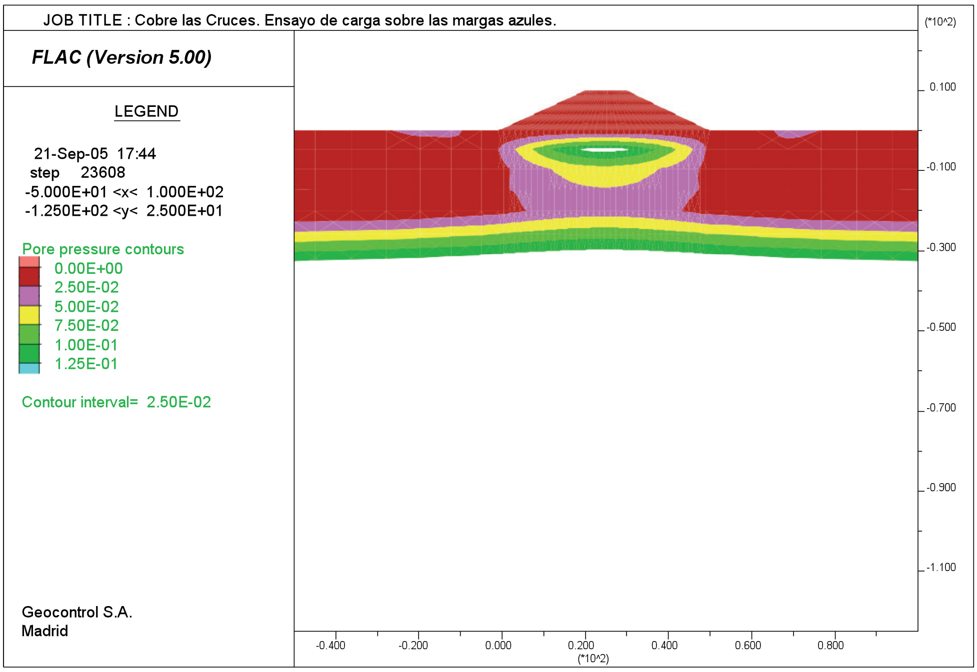


Figure 6 – Pore pressure after dump construction

Tipping marls - compaction and geomechanical behaviour

The designs of the dumps established tipping layer thicknesses defined effectively by compaction grades. The compaction is considered of great importance given that the sampling and testing of marls vial shear box and triaxial tests shows significant improvement in the resistive parameters with increased compaction. For obtaining strength parameters with respect the compacted marls, consolidated-undrained shear strength tests were carried out. An example of this test is given in Figure 7 for a compaction grade of 60% of Modified Proctor (MP). In Figure 8 this relation between friction angle, cohesion, and compaction grade can be seen.

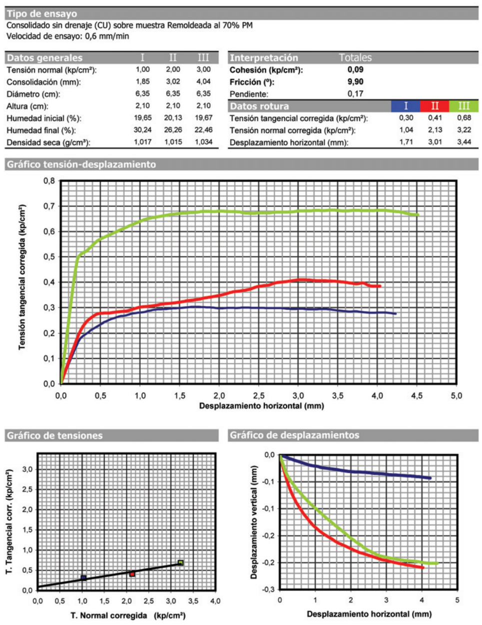


Figure 7 – Consolidated-undrained shear strength test in compacted marls

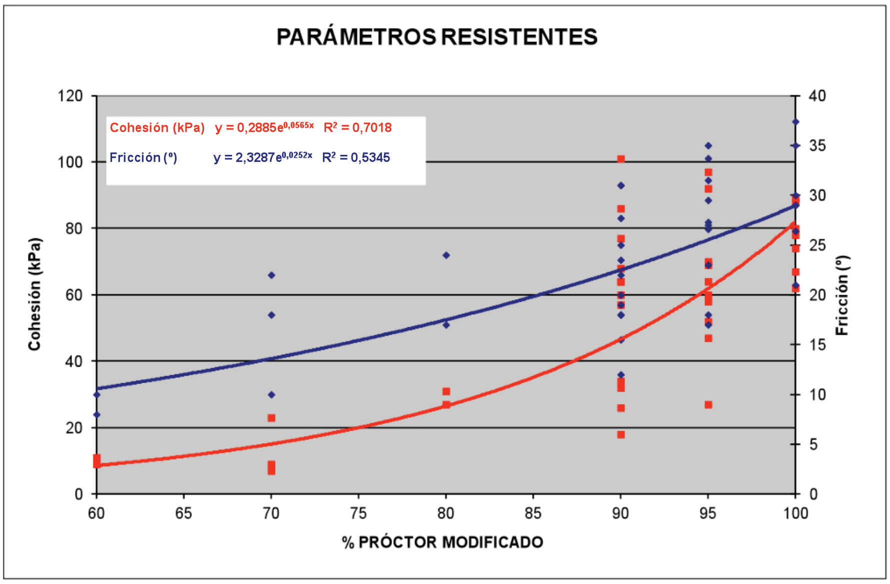


Figure 8 – Cohesion and friction angle relation to compaction.

As will be demonstrated, adequate compaction of tipped marls is an essential requirement for obtaining overall stability. At CLC this is achieved via a number of methods and equipment such as:

- Bulldozers: utilized for spreading out and levelling activities, as well as for compaction of the marls. At the mine both Komatsu 155 and Cat-D8 bulldozers are used
- Rollers: a sheep´s foot roller is utilized prevalently for the base layer to maximize interlocking of fill and natural material following a scarification process. The roller utilized at the mine is the CAT82.
- Dumpers: one should not underestimate the value of dumpers to achieve deeper compaction within tipping dumps during their tipping circuits. At CLC both Komatsu 785 and CAT-777 dumpers are used, with 100 t capacity. Although not relied upon directly in design, these provide an additional level of compaction.

During the construction of the actual dumps using standard mining equipment, several trial pits were excavated to determine the evolution, with depth, of the Modified Proctor value; the chosen method of evaluating compaction for these dumps. According to the results of these trial pits, a practical compaction specification was created which resulted in proven alternate layers of shear strength with depth.

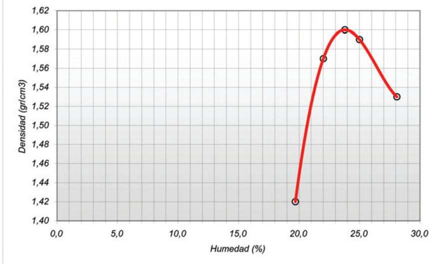
Figure 9 shows one of the trial pits to control the value of the compaction Proctor with depth.

Figure 9 – Trial pit for the evaluation of the compaction value in actual dumps

Figure 10 shows deposited marls with zones of high and low compaction with depth (90% MP in the upper 2.5 m and 65% MP in the lower 2.5 m).

The determination of the *in-situ* density and moisture is addressed through the use of a nuclear gauge in conjunction with the laboratory reference density (ρ_{dmax}) and moisture content from Modified Proctor test for each compaction grade. Figure 11 shows the laboratory reference density (ρ_{dmax}) and moisture content from Modified Proctor test for a grade of compaction of 65%.

Figure 10 – Details of a trial pit wall showing different levels of compaction



Ensayo de Apisonado (Próctor)

Tipo : *Modificado (UNE 103501)*

Procedencia ESC. SUR COTA 46

Referencia **9954559**

Datos del Molde

Molde (cm3)	2320
Maza (Kg)	4,531
Altura de Caída (cm)	45,7
Nº de Capas	5
Nº de Golpes/Capas	60

Material Grueso

Porcentaje	
Densidad (gr/cm3)	

Cuadro de Resultados

Punto	1	2	3	4
% Agua Añadido		3	6	9
Densidad (gr/cm3)	1,42	1,57	1,59	1,53
Humedad (%)	19,7	22,0	25,0	28,1

Densidad Máxima (gr/cm3)	**1,60**
Densidad Corregida (gr/cm3)	**1,60**

Humedad Optima (%)	**23,8**
Humedad Corregida (%)	**23,8**

Acreditación concedida en el Registro de Laboratorios de Ensayos Acreditados para el control de calidad de la construcción, con nº LE017-SE04 (BOJA)

AREAS DE ACREDITACIÓN

EHC: Área de control del hormigón y sus componentes.
VSG: Área de suelos, áridos mezclas bituminosas y materias constituyentes en viales.
VSF: Área de control de firmes flexibles y bituminosos en viales.
AFC: Área de control de los materiales de fábrica de piezas cerámicas.
AMC: Área de control de morteros para albañilería.
AFH: Área de control de los materiales de fábricas de piezas de hormigón.

Figura 11 – Laboratory reference density (ρ_{dmax}) and moisture content from Modified Proctor test for a grade of compaction of 65 %

Modelling of the dumps

Subsequent to the calibration of the behaviour of the founding materials, further evaluation of the shear strength of the tipping marls and the evolution of the degree of compaction with depth, several strain-stress analyses were carried out solved with FLAC 2D in order to further predict the behaviour of the dumps and to evaluate their stability.

Figures 12 and 13 show this modelling process with the lateral distribution of pore pressures during the different stages of construction of the south dump.

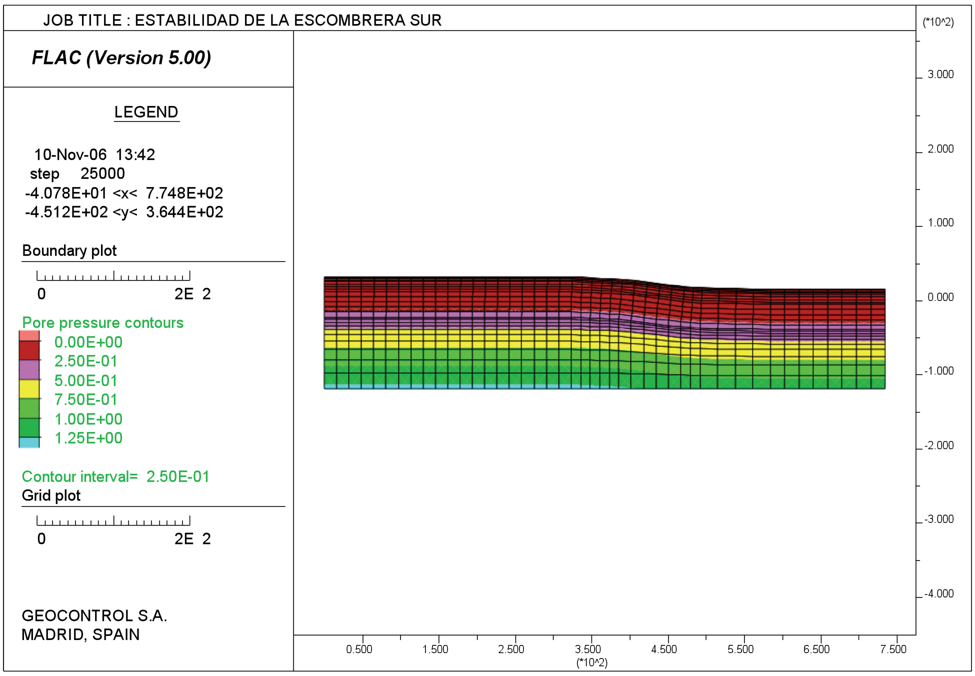


Figure 12 – Distribution of pore pressures in the natural marls (founding strata)

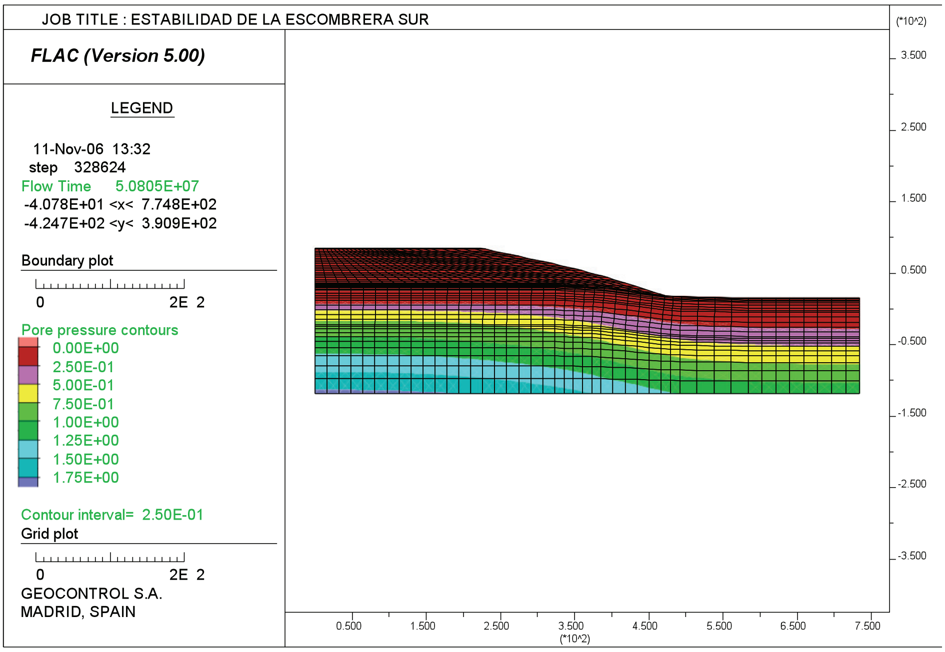


Figure 13 – Predicted distribution of pore pressures at the final stage of the construction of the south dump

In additional to the prediction of pore pressures, the use of FLAC 2D enabled an estimation of probable displacement during construction phases via the application of a elasto-plastic stress-strain model for the sub-strata, and the elastic method for the fill material obtaining a total settlement for a 45 m loosely compacted dump of 0.95 m (Figure 14).

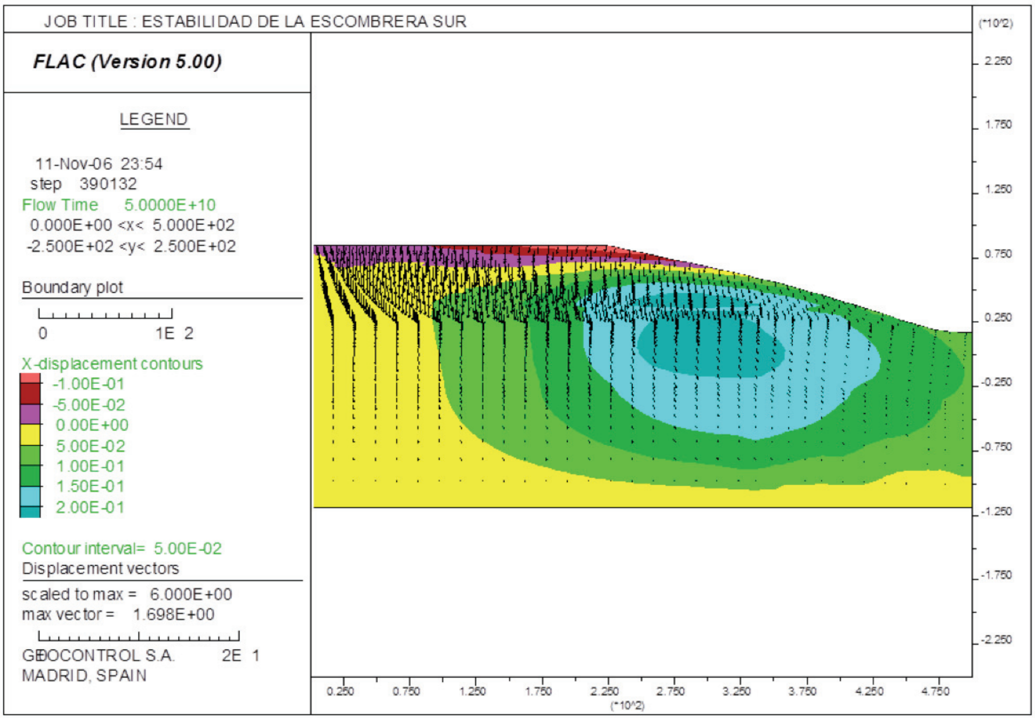


Figure 14 – Settlement obtained with the final dissipation of pore pressures in the south dump

This data permitted the categorization of orders of magnitude for pore pressure and horizontal displacement for a variety of mechanisms that could potentially be associated with the dumps, from ongoing anticipated consolidation through to those observable during a full global instability occurrence. This information was of tantamount important during the establishment of a vigilance plan for the dumps.

Vigilance and monitoring of the dumps

The dumps are subject to a vigilance system via geotechnical instrumentation comprising conventional inclinometers that monitor horizontal displacement at depth, surface prisms, and vibrating wire piezometers for the monitoring of interstitial pore pressure. The pore pressures were compared to total pressure sensors, placed at depth to obtain the critical pore pressure ratios. Figure 15 provides examples of inclinometers showing movement in a bedding plan with residual resistance characteristics can be observed. Figure 16 shows directly the response of pore pressure in the vibrating wire piezometers during tipping activities.

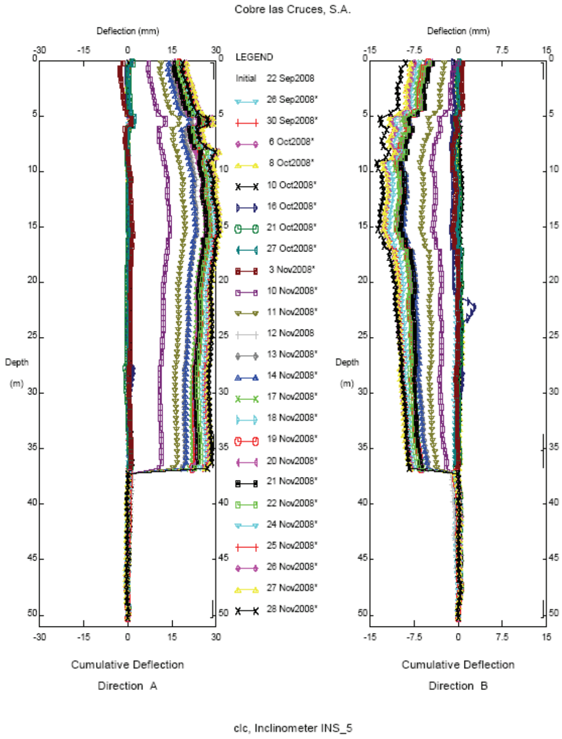


Figure 15 – Evolution of movement in inclinometer INS5 of the south marl dump

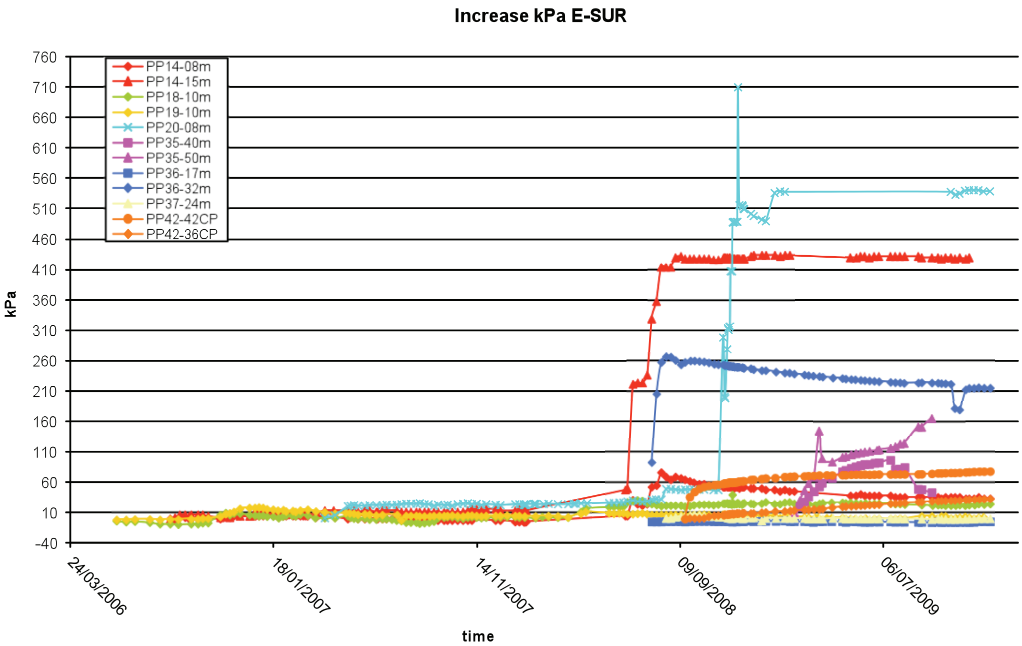


Figure 16 – Evolution de pore pressure in vibrating wire piezometers in the south marl dump

With the information from the aforementioned studies, 0 three alert levels of displacement were established for pore pressures, Bbar coefficients, and horizontal displacement velocities with the inclinometers. These levels were set within the mine's vigilance plan which defines the monitoring methodology, forms of vigilance, and required actions for those levels.

Differing levels are fixed depending on the dump type (inert or non-inert), as shown in Tables II and III respectively.

Table II. Established alert levels –inert dumps

Level	Displacement velocity	Likely cause	Action
Attention	1.5 mm/d	Long term decompression from pore-pressure dissipation	Visual inspection, increase local inclinometer measurement frequency.
Alert	3.5 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	15 mm/d	Instability.	As above plus cessation of activities in zone.

Table III. Established alert levels – non-inert dumps

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.

Supervision of tipping activities in the distinct tipping layers is undertaken via the formalization of tipping sheets, which include the following relevant information:

- Characteristics of the tipping substrata
- Geological mapping of the tipping substrata
- Topography of the tipped material
- Details of type of material tipped.

The control of the compaction is maintained by a control of the finished product method, with an objective of checking that each layer complies with the conditions of density and optimum moisture content. In this manner, a series of moisture content and density checks are undertaken *in situ* upon the compacted fill material (which will serve as the base of the next tipping layer). These results are checked against the corresponding compaction/density reference values obtained via laboratory testing to ensure compliance. Figure 17 shows the level of detailed compaction testing undertaken during the construction of the containment berm of the north dump, over the lifetime of that facility.

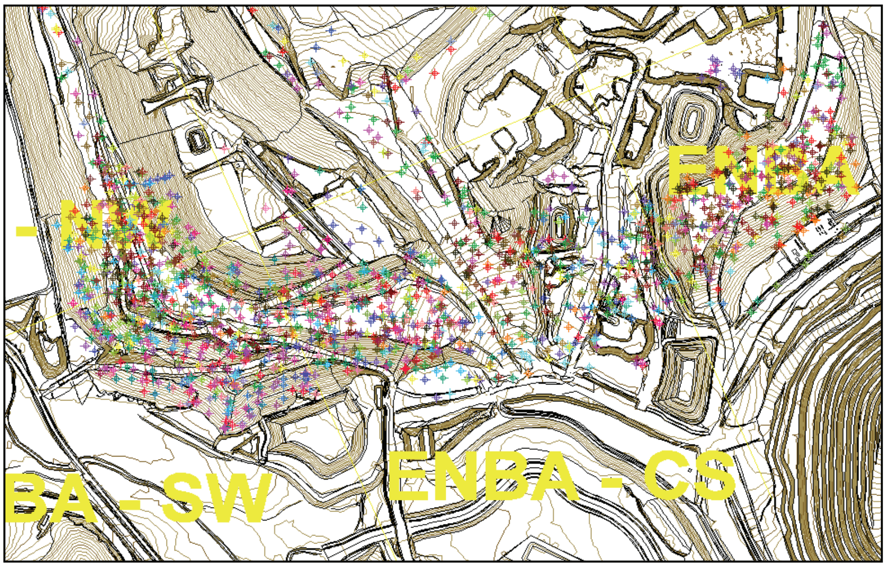


Figure 17 – Compaction tests undertaken in situ in the CLC north dump

It is considered that the compaction of a layer is acceptable when the *in-situ* compaction is greater than the characteristic value assumed within the dumps construction project geotechnical design.

For layers of 0.5 m undertaken in the barrier berms of the non-inert (north) dump, five *in-situ* tests should be undertaken for every 50 000 m^3 of tipped material (in surface areas defined as allotments). The plan dictates also at least one test along 500 m liner stretches, again determining both density and moisture content.

For layers greater than 1.0 m in thickness it is essential to guarantee that these tests correspond to the base of the layer. To achieve this, trial pits can be undertaken every 500000 m^3 of tipped material, in which tests should be undertaken, 25no (1.0 m), 15no. (2.0 m), 5no. (3.0 m) and 5no. (4.0 m) depth.

Conclusions

Over the life of the mine, Cobre Las Cruces will produce a quantity of inert stripping material over 10 times the quantity of mobilized mineral. The management of the material from one of the world's largest marl pits is critical to the mining operation. The marl's low permeability is an advantage from an environmental perspective. However, to design the mine's associated dumps, a robust understanding of and ongoing determination of interstitial pore pressure, both in the natural underlying and fill marls, is essential.

Exhaustive and prescriptive vigilance systems are a prime necessity to be able to proactively respond to any potential instability.

There is a history of severe problems recorded as a result of the undesirable or poorly understood behaviour of the Guadalquivir Blue Marls, such as that of the tailings pond of Aznalcollar in 1998. In the designs of these modern dumps, therefore, the key concepts highlighted within this article have been thoroughly investigated to provide a fuller understanding of their likely performance.

The management of the residue at Cobre Las Cruces is subject to a demanding legislation in reference to environmental matters. With these requirements in mind and the mine´s commitment to attain long-term, safe, sustainable mining activities, the dumps continue to be re-designed, constructed, checked, and monitored with the goal of providing an example of modern mining for the future.

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