Stability Analysis of the working face slope in a lignite open pit mine

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Abstract

The work presented in this paper was aimed to estimate pore pressure variation effects on the stability of bedding planes in working faces. This task involves the following phases:

- Geotechnical data acquisition of materials involved in a slope instability (open pit lignite mine in Spain), by means of in situ testing.

- Laboratory tests and geomechanical characterization of materials. Main strength parameters have been obtained from rock mass and soils.

- Modelling: Pore pressure dissipation: Using FLAC2D and PHASE a numerical model has the advantage that stability can be obtained in terms of effective stresses at any point of the life of the pit. This model will be also applied to spoil heaps materials after a proper calibration process; and the influence of bedding plane and joint condition: A stability assessment of the pit slopes, including a rigorous assessment of the influence of the joint locations, orientations, and mechanical properties, has been performed. The complex strain-softening behaviour of the constituent soft rock blocks as well as their interfaces will be considered using the FLAC2D and PHASE codes.

- Finally an evaluation of the results is done by calibrating numerical models with in situ data acquisition (inclinometer, piezometer).

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Keywords

Slope Stability, Modelling, FLAC2D, Pore pressure, Joint Condition, Saturated Marls

Introduction

This research activity has been carried out employing a case study concerning an open pit lignite mine in Teruel (Spain). The pit dimensions are around 2,5 km x 1,5 km, with a maximum depth of 205 m. The north slope has a total size of 750 m long.

Recent instability processes registered on the north slope (footwall of the coal seams) have led to a new exploitation plan avoiding this area.

As many other lignite deposits, Ariño basin presents a uniform stratification conformed by limestone, green marls and argillite from Cretaceus and sands-clays from Tertiary. As one of the potential trigger factors, the study of saturation of green marls has been tackled by means of 2D FEM simulations and shear strain analyses. Evolution of pore pressure within this material is undertaken employing Skempton B factor, representing the pore pressure variation with the excavation activity and induced changes in the phreatic level.

Geomechanical characterisation

Aiming to proceed to a strata characterization, materials involved have been divided into rock mass and soils, depending on its behaviour when testing them at geotechnical laboratory. This is a critical phase when modelling rock and soil materials (Galera *et al*, 2009), and results will be linked to strength properties assigned. The laboratory tests performed were the following:

- Unconfined compression strength.
- Unconfined compression strength with deformation measurement.
- Point load test.
- Brazilian test.
- Rock triaxial test.
- Shear strength test.
- Oedometer test.

The high degree of weathering and the jointing properties of some materials have added uncertainties to its characterization, due to the difficulty when performing samples for triaxial and direct shear tests.

Rock mass properties (limestone)

Rock mass is composed mostly by jointed limestone, acting as the basement of the coal sequence. Properties selected for further numerical analysis are detailed in the **Chart I**. Statistical approach is necessary to obtain the most representative parameters, given the amount of test performed and the variability of results obtained. Therefore, number of samples, maximum and minimum values, arithmetic average, standard deviation and variety coefficient have been employed to procure reliable data. In addition, intact rock properties have been transformed into rock mass properties employing formulation from RocLab software, and calculating the RMR index (45-55). Elastic modulus has been obtained by calibration of Hoek-Diederichs (2006) and Bieniawski-Galera (2005) formulation.

Soft rock properties (green marbles and clay-argillite)

Soft rock properties have been obtained by means of identification, direct shear (drained and undrained), triaxial (CU) and oedometer tests. The following chart shows the representative values obtained from laboratory test. See **Table I**.

Once the statistical analysis has been performed (Wroth, 1984), final strength properties of the materials involved are selected as input for numerical analysis.

Rockmass parameters used in the numerical simulations

Rockmass characterization process has led to a better comprehension of rock and soft rock behaviour, based also on previous experience and related investigations. Results for each lithology are shown in the **Chart III**.

Backanalysis of the instability in working face

The backanalysis performed was aimed to analyse the influence of hydraulic conditions within green marls as the triggering factor to produce landslides in the working faces of the exploitation (Alonso *et al.*, 2014).

First of all, the reconstruction of the original geometry was undertaken including bench height and IRA (Inter-Ramp Angle). One of the main restrictions associated to modelling of large slopes is the meshing process. Due to the low thickness and length of involved layers, first and second inter-ramp benches were taken into account for numerical analysis. **Figure 1** represents bench reconstruction of the pit slopes, and **Figure** 2 shows the line of the cross section analysed.

Unsaturated conditions analysis

Afterwards, first numerical analysis was conducted supposing dry conditions. Calculation results shows no relevant displacements nor shear strain increment within green marls **(Figure 3).** Since no relevant instrumentation is installed at the slope, the next calculation step will add phreatic surface, calibrating with real topography contours and compared with real design bench strings of north slope.

This will allow to take into consideration strain-softening constitutive model at green marls, based on shear direct test performed, considering post failure conditions (Cooper *et al, 2011*, Lupini *et al*, 1981).

Pore pressure and bedding plane effect on the slope stability

During the instantaneous mechanical response that takes place while excavation progresses, the pore pressure drops according to Skempton's B coefficient (Skempton and Hutchinson, *1969*). (see **Equation 1**). The poroelastic response of a soft rock or soil (green marls) where $K<<K_w/n$ (where K, Kw are the bulk modulus of the ground and water, respectively and n is porosity) is such that most of the change in total stress during unloading will be translated in a drop of pore pressure. In the period between excavations, there is a slight increase of pore pressure due to flow, but usually in the type of rock present within coal deposits this effect is not critical due to the low permeability of the rock mass. In the present investigation, the approach followed has been an undrained short term total stress analysis with a friction angle= 0, and a long term effective stress analysis with a steady state pore pressure distribution.

$$\Delta u = B\{\Delta\sigma 3 + A(\Delta\sigma 1 - \Delta\sigma 3)\} \quad (1)$$

This process has been reproduced in the model presented, through the removal of Tertiary material, leaving the working face and its benches as it has been stated above. Hereafter, water inflow has been introduced in the model by the application of the phreatic surface, lowered with every excavation stage until its final position. Therefore, green marls layer is considered to be under saturated conditions. This fact represents the real saturation process observed after rainfall events, which induces instability and slide processes on the north slope (**Figure 4**).

Mohr-Coulomb failure criterion (**Equation 2**) has been employed to modelling the increase of shear strain on the bottom surface of green marls, as the trigger factor of the instability (Barton, 1974).

In addition a joint between green marls and limestone bedrock has been implemented in the model aiming to represent the effect of the bedding plane within the sliding process.

$$\tau = c' + (\sigma - \mu)\, Tan\, \varphi' \quad (2)$$

A Shear Strength Reduction approach has been performed in order to obtain the safety factor of the slope during the process, including the joint strength properties and pore pressure effect on contact surface (0,05 MPa). Shear strain increment and volumetric strain evolution have been observed associated to the joint area and within the green marls layer (Brenner *et a*l. 1997). However, overall safety factor obtained was 1,77. See **Figure 5** and **Figure 6**

Conclusions

A backanalysis of a working face slope sliding has been tackled. It has included a complete rock mass and soil characterization and a numerical analysis to reproduce both drained and saturated conditions during the bench excavations.

Based on the findings from the back-analysis performed it can be concluded the effect of pore pressure increase and bedding plane presence in the stability of the slope within the green marls thin layer. When the effect of interstitial water is applied to the 2D model and the material becomes saturated, displacements, shear strain and volumetric strain evolves in the green marls layer leading to potentially instable scenarios (Leroueil, 2001). Despite this fact, overall safety factor obtained during numerical analysis where high, which shows some limitation in the employment of such factor for complex soil-rock masses.

Therefore, results of the research carried out encourages mine operators to an accurate monitoring of the hydraulic properties of cohesive materials present in working faces and slopes and a correct bedding plane identification and characterization.

Acknowledgments

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BULK DENSITY γ_a (g/cm³)	σ_{ci} (MPa)	E_i (MPa)	E_i / σ_{ci}	σ_{ti} (MPa)	mi
2,53	27,95	14.358	514	1,99	13,7

Chart I.- Intact rock properties

LIMESTONE PARAMETERS											HOEK-BROWN CRITERION			MOHR-COULOMB ADJUST		v (Karzulovic, 1999)
RMR	(γ_a) (g/cm³)	σ_c^i (MPa)	E_i (MPa)	RMR	GSI	σ_c^m (MPa)	Em (Mpa) HOEK-DIEDERICHS 2006	Em (Mpa) BIENIAWSKI-GALERA 2005	mi	D	mb	s	a	C (MPa)	Φ (°)	
RMR≥65				65	60	1,515	2881,39	5430,8			1,521	0,003	0,503	1,357	29,71	0,22
RMR 55-65				55	50	0,716	1540,35	4113,6			0,878	0,0007	0,506	1,090	25,29	0,25
RMR 45-55	2,53	27,95	14.358	45	40	0,328	836,07	3115,9	13,7	0,7	0,507	0,0002	0,511	0,863	21,08	0,27
RMR 35-45				35	30	0,140	516,36	2360,2			0,293	3,93e-5	0,522	0,657	17,10	0,29
RMR <35				25	20	0,051	380,88	1787,8			0,169	9,22e-6	0,544	0,461	13,25	0,32

Chart II.-Rock Mass properties

LITHOLOGY	BULK DENSITY (γ_a) (g/cm³)	DRY DENS (γ_s) (g/cm³)	HUMIDITY (%)	DIRECT SHEAR		OEDOMETER TEST		TRIAXIAL	
				C (kg/cm²)	Ø (°)	Pore Index (eo)	Edom. Modulus (kg/cm²)	σ_{ci} (kp/cm²)	σ_t (kp/cm²)
Green Marls	2,04	1,89	9,62	0,52	27,68	0,31	379,30		
Clay-Argillite	1.80	1.71	15.17	0.27	32.79			12,96	2,14

Table I.- Soft rock properties.

PROPERTIES		SANDY-CLAYS	CLAY-ARGILITE	GREEN MARLS	LIMESTONE
Unit Weight	(KN/m³)	20.0	17.5	20.4	25.3
Cohesion	KPa	0.2	0.57	0.52	1.0
Friction	(º)	37	30	28	40
Young Modulus	Mpa	300	300	30	700
Poisson Coefficient	-	0.3	0.33	0.33	0.23
Ko	-	1.0	1.0	1.0	1.0

Chart III.- Final properties adopted for numerical simulation.

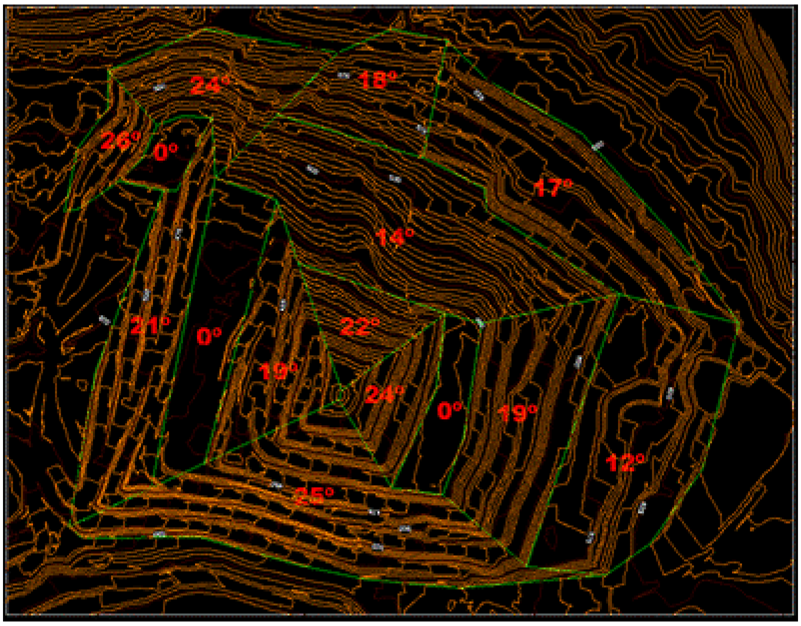

Figure 1.- Inter-Ramp definition. North slope is represented from bottom to top with 22, 14 and 18 degrees of Inter-Ramp Angle.

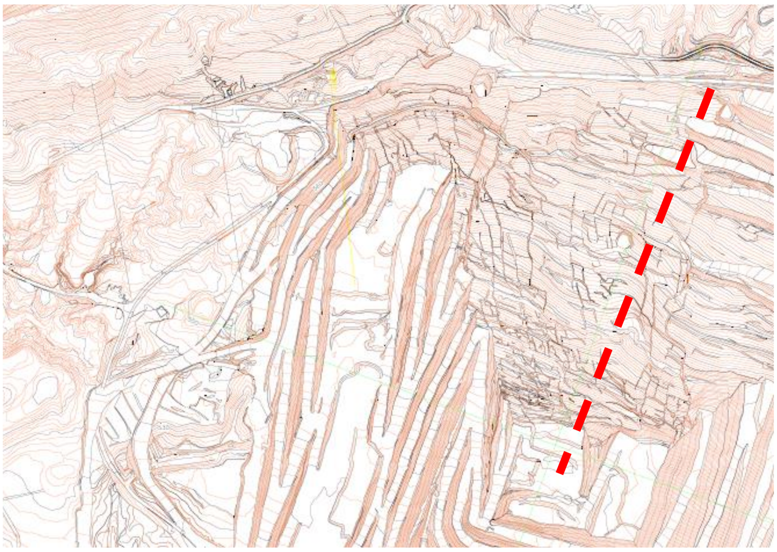

Figure 2.- Layout of the section analysed.

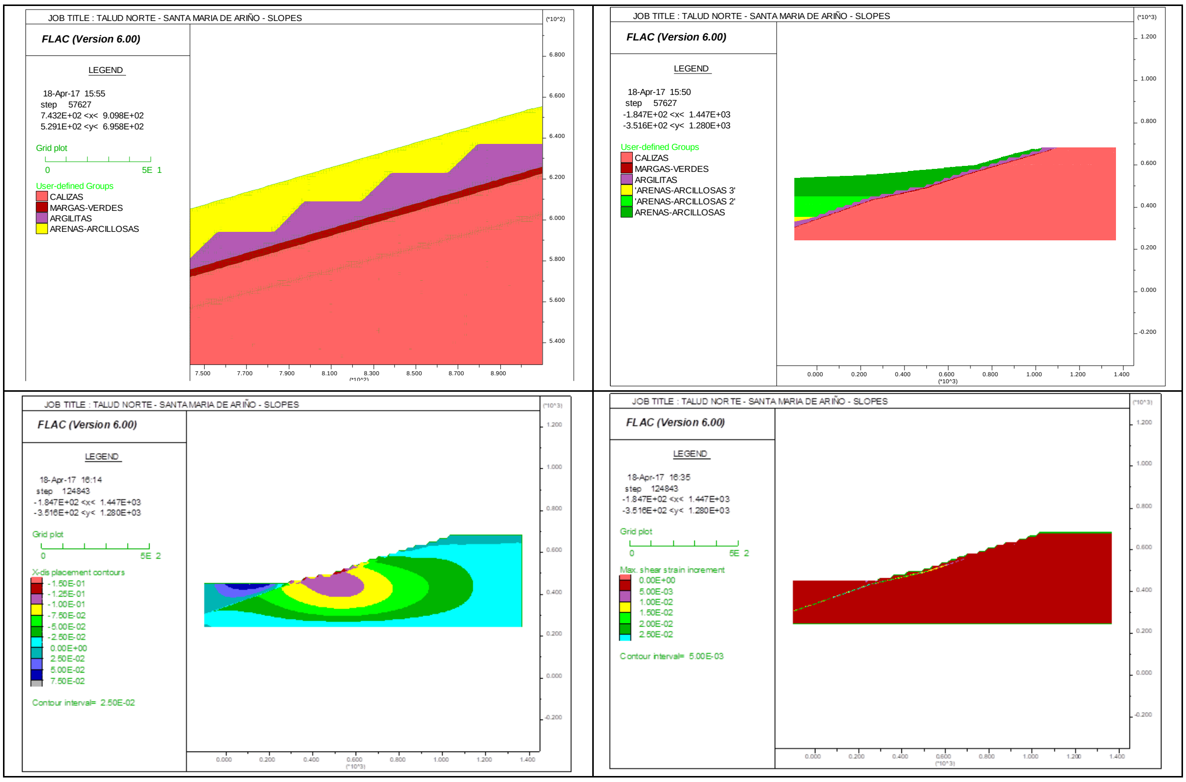

Figure 3.- Upper schemes show overall distribution of materials in north slope (right), and detail of Green marls, argillite and sand-clays (left). Lower schemes show shear strain increment associated to green marls layer (right), and horizontal displacements in the slope (left). Dry conditions are applied.

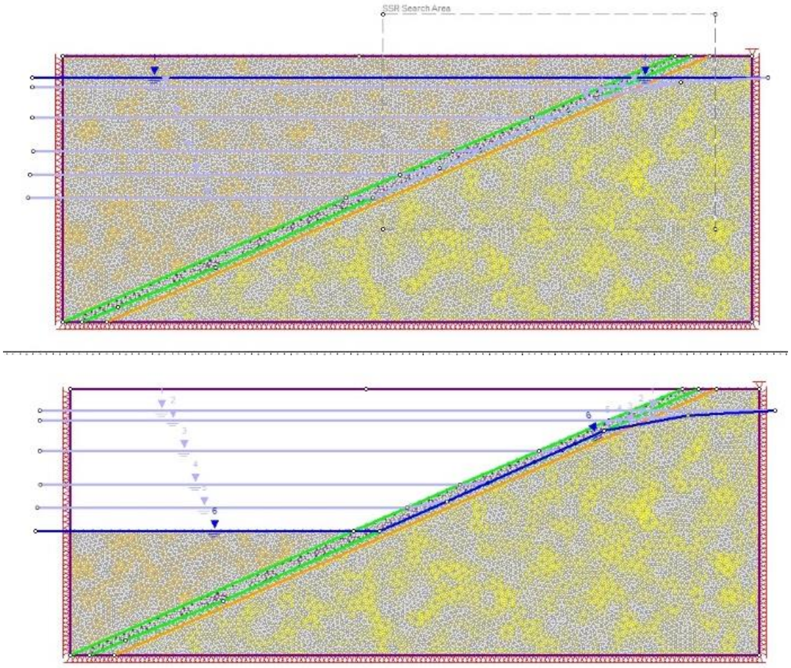

Figure 4.- Initial and final geometry of the model.

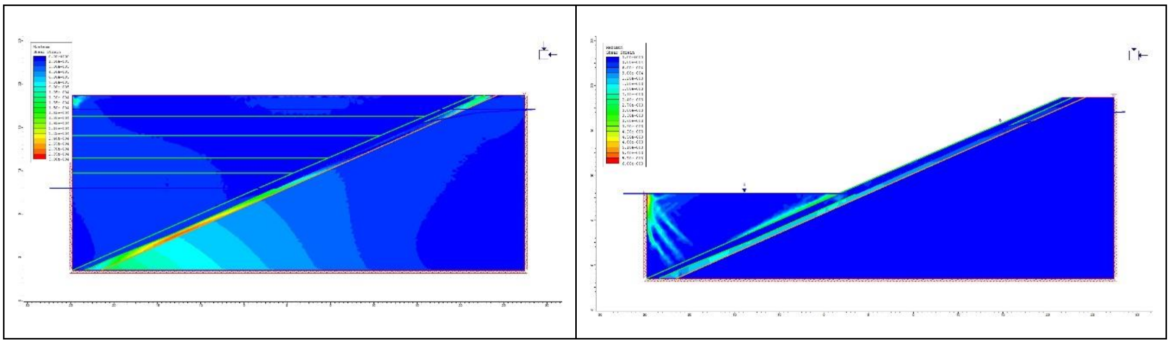

Figure 5.- Initial and final shear strain contours in saturated conditions as an indicator of incipient failure surface within green marls.

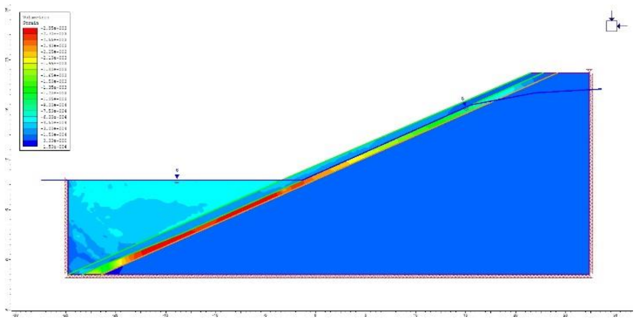

Figure 6.- Volumetric strain increase within green marls layer after excavation process in saturated conditions shows