Sandstone Intact Rock Strength - A focus on the comparison between uniaxial and triaxial laboratory tests in tunnelling design

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ABSTRACT: A complex hydropower project, with many underground structures, requires a lot of investigations and studies for a whole understanding of the rock mass behaviour. A recent large underground project in Andean Cordillera offers opportunity for a focus on the comparison between the laboratory data obtained from uniaxial and triaxial compressive tests on sandstone samples, with main reference to the Hoek-Brown failure criterion. These results drive the geomechanical characterization, with a direct consequence on the design, as the behaviour of the excavated rock masses strongly depends on the intact-rock proprieties. The knowledge of field geology based on site observations, surveys and investigations, is also fundamental for the interpretation of laboratory data. The availability of tens of confined compressive strength tests (→ σ_{ci}) on sandstone and their analysis through many rupture envelopes are of interest for a better understanding on the results of the laboratory data, possibly affected by different behaviour of the rock samples when tested through the unconfined compressive test (→ UCS). The sharp difference between the Hoek-Brown strength criterion parameter σ_{ci} and the UCS parameter is shown.

Keywords: Intact Rock Strength, UCS, Triaxial Tests (σ_{ci})

1 Introduction

The intact rock strength is a parameter that strongly influence the characterization of the rock mass with a direct consequence on tunnelling design.

Bewick et Al. (2015) and Kaiser (2016) focused on the conceptual difference between UCS and the Hoek-Brown parameter σ_{ci} derived by fitting in the main stresses plane the results of triaxial compressive tests. Moreover, the same Authors recommended the basic reference to σ_{ci} while indicating the Hoek-Brown failure envelope for the design.

The purpose of this paper is to take advantage of the large number of laboratory tests performed on the Cretaceous sandstones in the Andean Cordillera to analyse these rock parameters, possibly to individuate a rational procedure for assessing the most appropriate and representative design values of the intact rock strength.

2 Geological setting

The study area is in the central part of the Andean Cordillera, which is known as a double vergence chain controlled by the subduction of the Nazca Plate below the continental plate of South America. The convergence of these plates is the main responsible for the geodynamic setting and the tectonic structures of the site. Figure 1 shows a block-diagram view of the interpreted deep structures of the

Andes representative of the interest area, located in the eastern side of the chain, in the Sub-Andeans area between the Eastern Cordillera and the Amazonian plain.

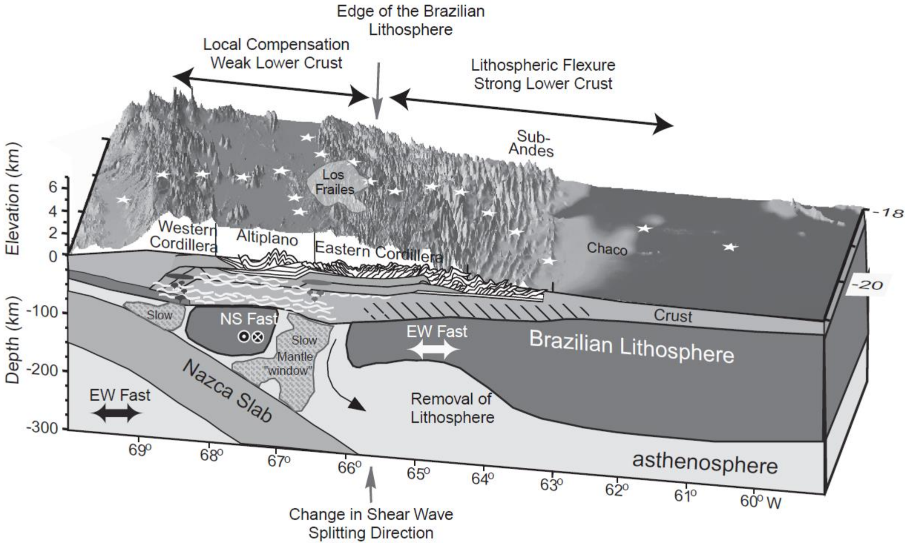

Figure 1. Regional scale interpretation of the crust and mantle structures in the Central Andes (McQuarrie et al., 2005)

The main works of the project are in a sedimentary sequence belonging to an asymmetric anticline, with the long side dipping toward SW. The bedrock is mostly covered by a thin layer of Quaternary deposits, mainly composed by coarse debris and alluvial cobbles. The tropical vegetation densely covers the whole area.

The bedrock sequence is composed by three geological formations tectonically stacked and separated by sliding planes with medium dipping. The direction of these plans is approximately parallel to the stratification and perpendicular to the longitudinal axis of the underground works. Figure 2 shows a 3D geological model of the project area.

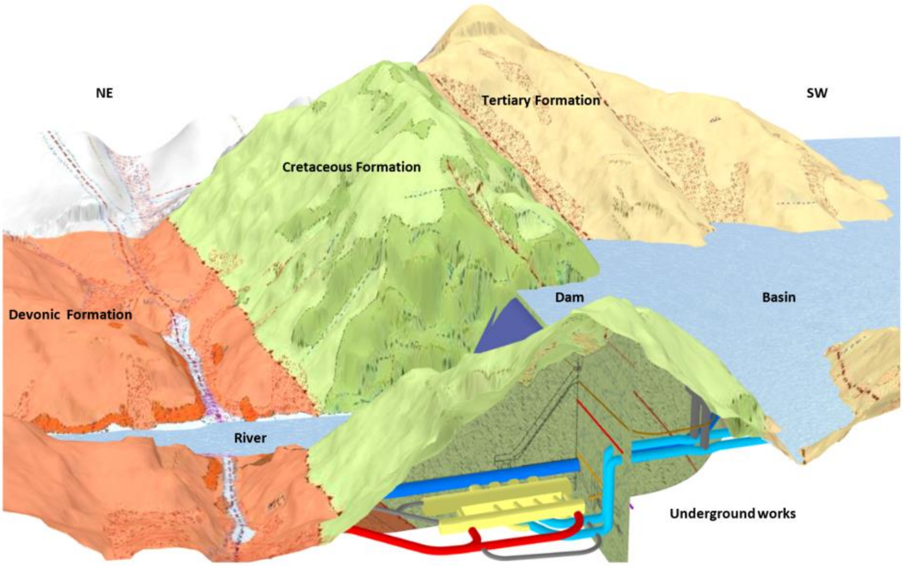

Figure 2. 3D geological model of the project area

Starting from upstream, at the top of the sequence outcrops the Tertiary Formation, with fractured sandstone interbedded to shales and claystone layers. The morphology is hilly with plain areas.

Moving downstream, in a mountain context, massive banks of quartzite-sandstone, belonging to the Cretaceous Formation, are exposed along the steep sides of the gorge (Figure 3); some high angle minor faults and master joints were detected during the geological survey.

Figure 3. The sandstone of Cretaceous Fm. outcropping along the riverbanks. Sandstone outcrop in massive banks; the original layering includes cross-bedding structure. Large collapsed blocks are locally piled on the edge of the river, fallen from the rocky slope

In this area there are the main underground works and external structures, therefore the Cretaceous sandstones were strongly investigated and tested during the two main investigation campaigns. Three major discontinuity-sets were measured in the sandstone rock masses (Table 1).

Table 1. Main discontinuity-sets measured in the sandstone Cretaceous Formation

Discontinuity set	Dip-Direction (-)	Dip (°)
Bedding (St)	SW	50 - 70
Joint set (Jn1)	E	20 - 50
Joint set (Jn2)	NNW	75 - 90

The fracturing degree, observed in the core samples and loggings (e.g. acoustic BHTV and optical OPTV tele-viewer images) from several vertical and inclined boreholes, is moderately low.

Moving further downstream, in the last part of the work, the Devonian Formation outcrops. It is an intensely folded sequence of sandstone alternated with shales, more fractured due to the proximity to a regional anticline axis which bends the described sedimentary sequence.

The tectonic discordance contact between Devonian and Cretaceous formations is marked by a pre-Cretaceous over thrust, while the tectonic contact between Cretaceous and Tertiary formations is given by low to medium-angle reverse fault.

3 Analysis of laboratory tests

By the analysis of the data obtained from the laboratory tests, some differences were observed between the sandstone samples (Cretaceous Fm.) collected in the boreholes located close to river area and those collected deeper inside the slope to investigate the cavern area. This condition even emerged from the analysis of the values of the unit weight (γ), where the higher values belong to the sandstones of the river area (Figure 4).

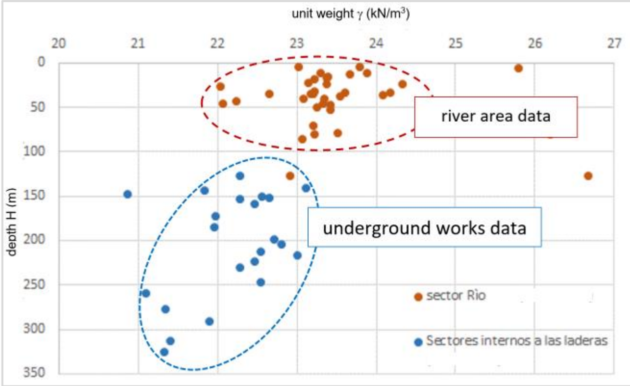

Figure 4. Cretaceous Fm.: unit weight (γ) vs depth (H), from different sectors

By the comparison of the results of the triaxial tests, the higher strength of the sandstones from the river area was also observed (Figure 5). The difference is related to the sedimentation process and the tectonic setting, since even by the comparison between the data from the samples collected at deeper levels on the two sides of the river (distance ~400m), a total similarity of the results was obtained. While the shallow sandstones of the river area showed a different behaviour (Figure 6).

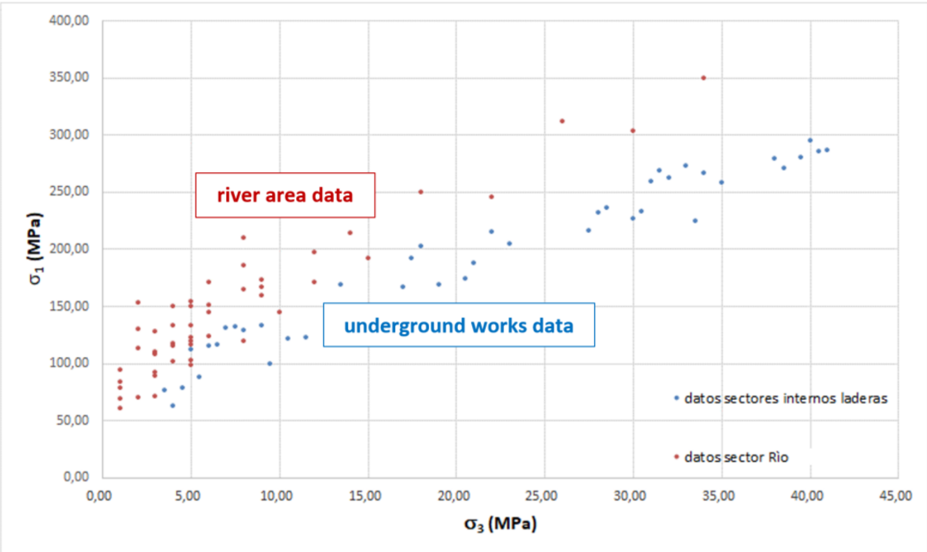

Figure 5. Cretaceous Fm.: triaxial test data, from different sectors

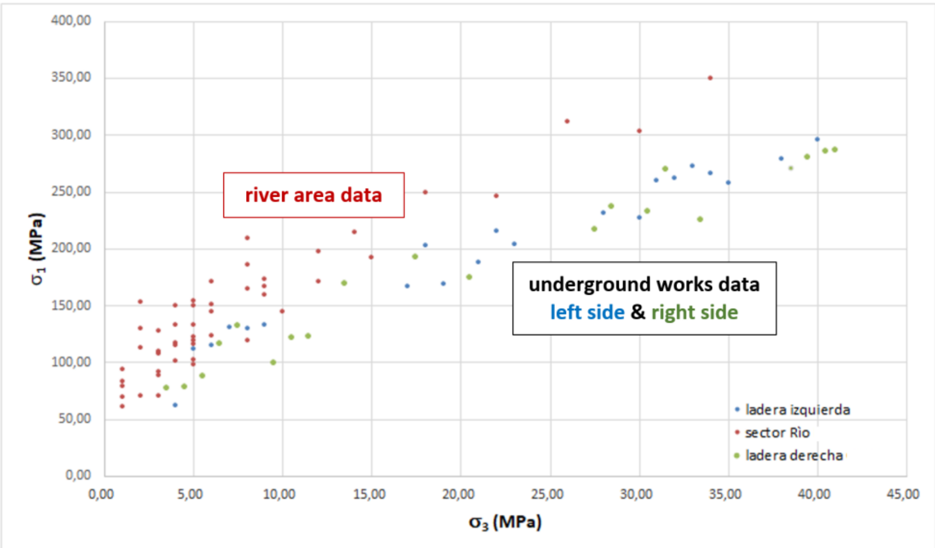

Figure 6. Cretaceous Fm.: triaxial test data, differentiation of left and right sides for deeper rock

The UCS data have a high range of variability (~10 to 65MPa, Figure 7), since many factors as the failure mechanism and testing procedure significantly affected the strength-values. Generally, the lower values, not representative, were associated to sampling disturbance and the partial rupture of the sample, while the higher ones to the shear-failure across the whole sample.

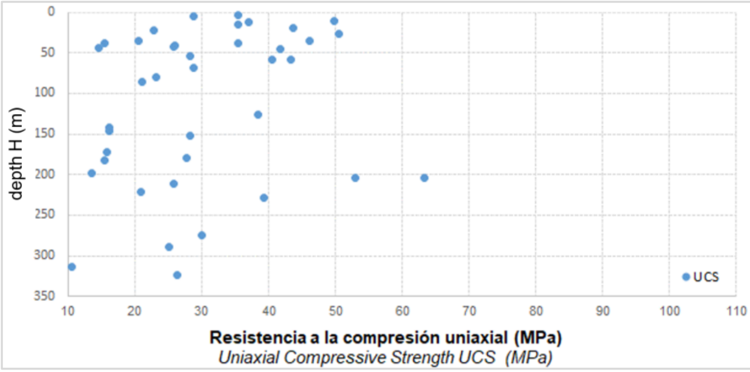

Figure 7. Cretaceous Fm.: Uniaxial Compressive Strength (UCS) vs depth (H)

From the comparison between the results of the compressive strength obtained with Uniaxial (→UCS) and the Triaxial (→ σ_{ci}) tests a clear difference was observed, by deriving in prevalence high values from the latter (UCS<<σ_{ci}). Furthermore, considering the different trends σ_1/σ_3 obtained from the samples collected in different sites (river area and underground structures), the triaxial data were analysed separately.

For the Cretaceous Formation 91 triaxial tests are available, 41 sandstone-samples were collected from the deeper levels (underground works) and 50 from the river area. According to the Hoek-Brown failure-criterion, the intact rock parameter "m_i" (material constant) and "σ_{ci}" (i.e. the resulting σ_1 value with σ_3=0) are thus calculated.

Different analyses (RocLab, by Rocscience) were performed, to define the representative values of the parameters.

For the river area, the 50 TX-tests have confinement values in the range $1<\sigma_3<34$MPa; different combinations of the value pairs of the main stresses (σ_1/σ_3), give values of m_i variables approximately between 14 and 24 and values of σ_{ci} variables from 70MPa to approximately 116MPa (Figure 8). The representative values of the parameters are:

- m_i 18 (14-22)
- σ_{ci} 90 (70-110) MPa.

For the underground work sectors, the 41 TX-tests have confinement values in the range $4<\sigma_3<41$MPa (Figure 9), by the combinations of the value pairs of the main stresses the representative parameters are:

- m_i 23±1 (22-24)
- σ_{ci} 65 (50-80) MPa.

The average σ_{ci} value, between 90MPa and 65MPa, is exactly the value obtained from the analysis of all the 91 TX-tests plus one sound and representative UCS value obtained from a reliable test with the shear-failure across the whole sample (Figure 10):

- m_i 18.5
- σ_{ci} 77.8 MPa.

The m_i values obtained from different combinations of triaxial test data is consistent with the range indicated in the Literature for sandstone rocks (m_i=17±4, Hoek-Brown failure criterion).

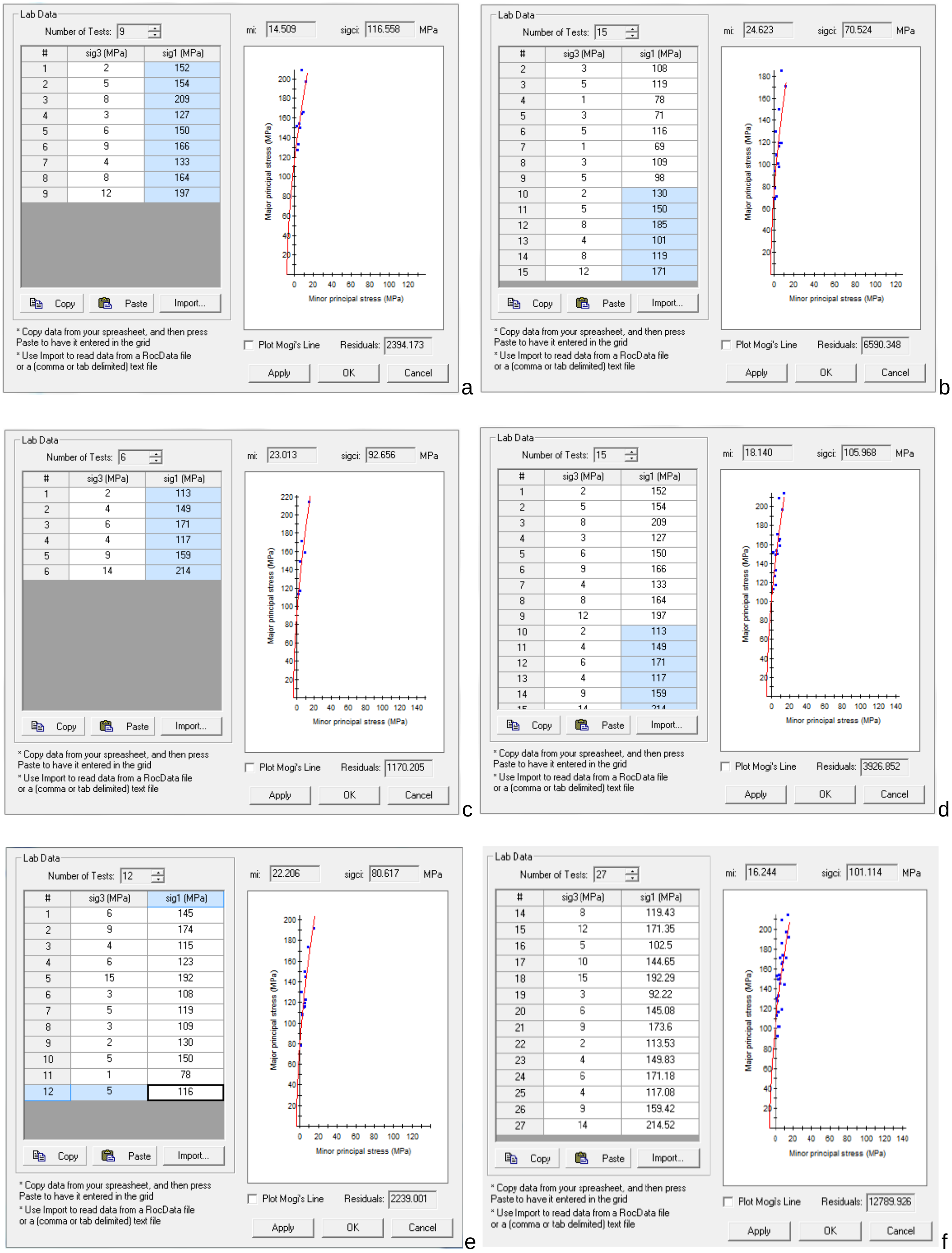

Figure 8. Cretaceous Fm., river area: combinations of value-pairs σ_1 / σ_3 to define the rupture envelope and the constants mi and σ_{ci} - (a-b-c-d) right river side; (e) left river side; (f) 27 triaxial tests (RocLab, Rocscience)

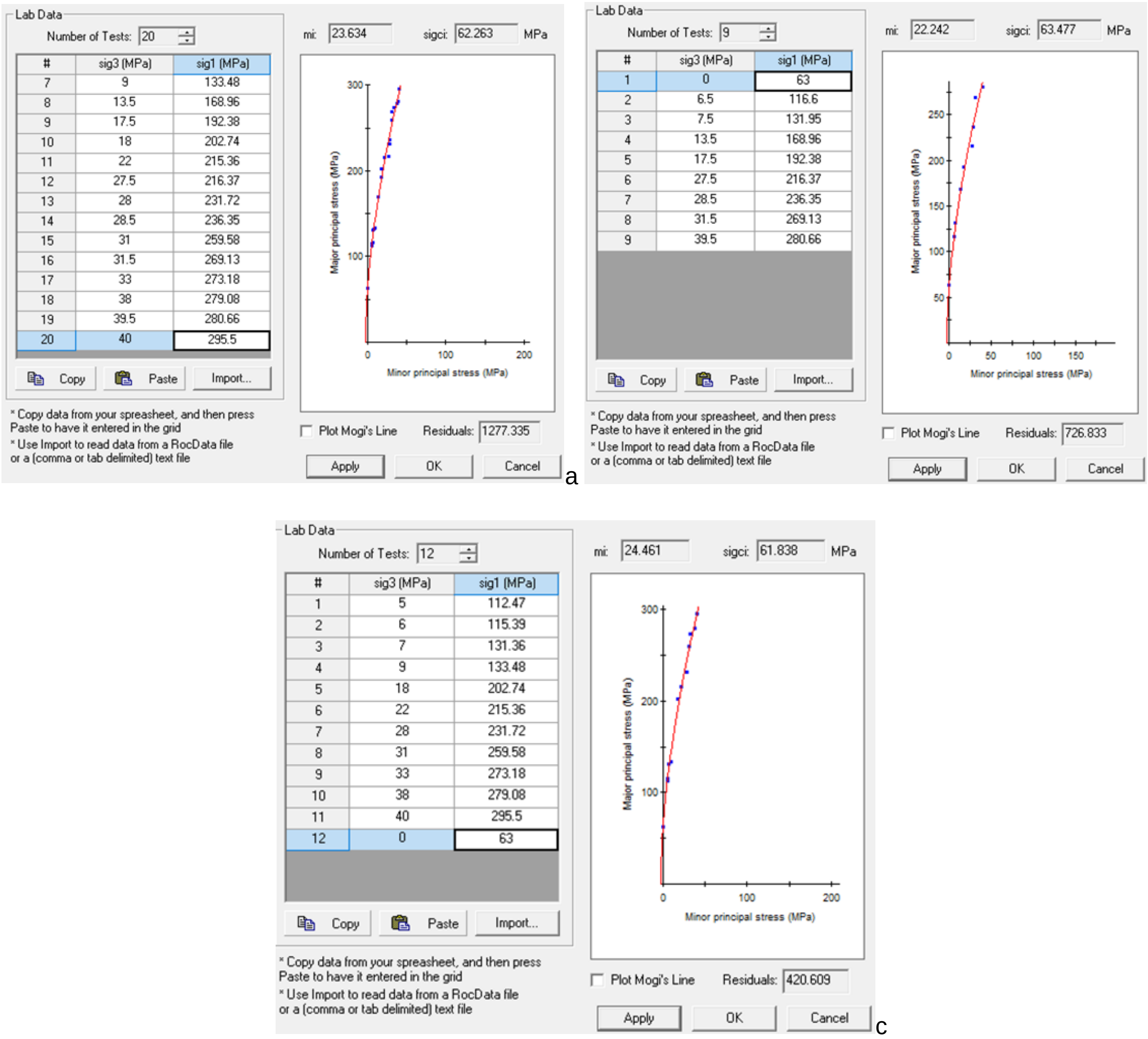

Figure 9. Cretaceous Fm. underground sectors: combinations of value-pairs σ_1 / σ_3 to define the rupture envelope and the constants m_i and σ_{ci} (RocLab, Rocscience)

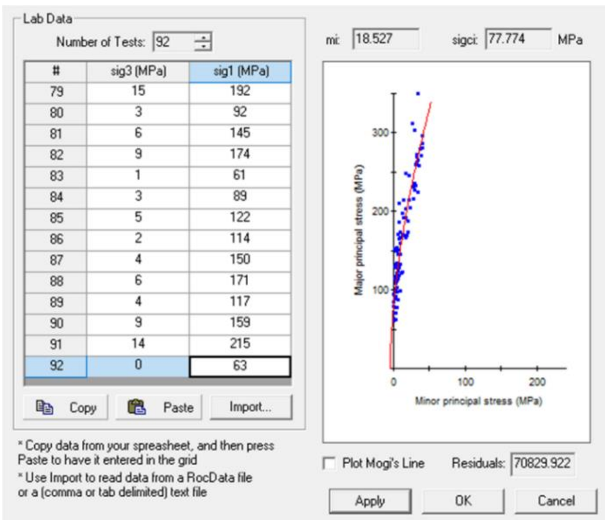

Figure 10. Cretaceous Fm.: envelope and constants m_i and σ_{ci} 91 triaxial data and 1 UCS (RocLab, Rocscience).

4 Conclusions

The difference between UCS and σ_{ci} derived from uniaxial and triaxial compressive strength tests, respectively, can have a significant impact in geomechanical modelling.

As indicated in the Literature, the values of uniaxial compressive strength resulting through the triaxial tests (σ_{ci}, confined test), are generally higher than those obtained through the uniaxial compressive tests (UCS, unconfined test). Therefore, as also remarked by Kaiser (2016), for characterizing the Hoek-Brown failure envelope, the value of σ_{ci} should be considered, in place of the UCS value.

For example, in the frame of the discussed data analysis, by the comparison between the values of the rock mass strengths (σ_c and σ_{cm}) resulting from three different sets of INPUT data (Table 2, from RocLab, by Rocscience) we observe that those obtained with UCS=30MPa without a Disturbance Factor (D=0), are close to those obtained applying the Disturbance Factor (D=1) with σ_{ci}=65MPa. This seems to confirm that the UCS-values are more affected by sampling disturbance, while the σ_{ci} values (from triaxial tests) are more representative of the undisturbed rock.

For the specific case analysed, the rock mass behaviours resulting as a function of the two different input data of the intact rock strength (UCS and σ_{ci}) are sharply different. From numerical analysis calculations it can be observed, for example, that considering the UCS as input the plastic zones induced by tunnel excavations extend for about hundred metres, while the reference to σ_{ci} provides a more realistic rock mass behaviour, showing the development of a few meters of plastic zone around the tunnels, as observed in similar cases.

Table 2. Comparison between rock mass strengths (σ_c σ_{cm}), from different INPUT data (σ_{ci}, UCS, m_i, D, GSI)

σ_{ci} (MPa)	UCS (MPa)	m_i (-)	D (-)	GSI	σ_c (MPa)	σ_{cm} (MPa)
65	-	23	0	70	12.2	25.8
			1		5.3	14.7
-	30		0		5.6	11.9

Disclosure statement

The Authors show the laboratory data and relevant analysis on behalf of the scientific community of engineering-geology, without mentioning the project for confidentially reasons. All the triaxial tests have been performed according to the requirements and supervision of the Authors.

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