A Model Benchmark Exercise for the 2D Analysis of a Tunnel Excavation in Rock

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ABSTRACT: The Hoek-Brown with softening model (HBS model) has been recently added to the PLAXIS material library. This was a good opportunity to experiment the PLAXIS software capabilities for underground excavation in rock where usually FLAC is often being used. An example related to a 2D excavation analysis of a tunnel in a rock mass is presented. Extensive elements of comparison are proposed with an identical analysis run in both PLAXIS 2D and FLAC 2D to analyse the possible differences due to the implementation specificities. Results obtained will be presented in terms of tunnel convergence, structural forces in shotcrete and axial forces in rock bolts for which very good agreement between both solutions is observed.

Keywords: Rock, FLAC, PLAXIS 2D, tunnel, finite element.

1 THE HBS ROCK MODEL FORMULATION IN PLAXIS

The elasto-plastic characteristics of the Hoek & Brown with softening (HBS) implemented in PLAXIS (2019) have been defined according to the yield surface proposed by Jiang and Zhao (2015) which represents a generalization of the Hoek & Brown criterion through the invariants associated with the stress tensor:

$$f = \frac{q^{1/a}}{\sigma_{ci}^{(1/a-1)}} + A(\theta)\frac{\mathrm{q}}{3}m_b - m_b p - s\sigma_{ci} \tag{1}$$

where p, q and θ represent the mean stress, the stress deviator and the Lode angle respectively. σ_{ci} represents the uniaxial compression strength and the function $A(\theta)$ is defined as follows:

$$A(\theta) = \cos\left\{\frac{1}{3}\arccos[\kappa\cos(3\theta)]\right\}\Big/\cos\left[\frac{1}{3}\arccos(\kappa)\right] \tag{2}$$

with -1 ≤ κ ≤ 0. The parameters m_b, s and a are dimensionless parameters which are determined through the empirical correlations proposed by Marinos et al., (2015) and Brown (2008) (i.e., the GSI system):

$$m_b = m.\exp\left(\frac{GSI-100}{28-14D}\right) \tag{3}$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right) \tag{4}$$

$$a = \frac{1}{2} + \frac{1}{6}\left[\exp\left(-\frac{GSI}{15}\right) - \exp\left(-\frac{20}{3}\right)\right] \tag{5}$$

where GSI represents the Geological Strength Index which is aimed to determine the quality of the rock mass from geological observations of joints, fractures, and discontinuities. Although the GSI classification enables to differentiate the initial yielding according to the spatial distribution of discontinuities, there is no specific reference to their rock-quality (i.e., the opening and the roughness of joints and fractures). For this purpose, a disturbance factor D has been introduced by Hoek et al. (2002) to calculate the material properties m_b, s and a.

The material degradation due to shearing is simulated by means of a softening rule in which a reduction of the hardening variables Γ_j is prescribed as a function of the equivalent plastic strain (i.e. cumulated value of deviatoric plastic strain), thus enabling to describe the material de-structuration due to shearing. Specifically, a hyperbolic decay of Γ_j is enforced to approach its residual value for large values of plastic strain accordingly with the softening rule proposed by Barnichon (1988) and Collin (2003).

2 BENCHMARK MODEL PRESENTATION

2.1 Problem description

The tunnel cross-section and profiles are provided in Figure 1. The studied tunnel section is constructed at a depth of 654 m in a uniform rock mass with unit weight γ_{rock} = 26.7 kN.m^{-3}. The initial stress ratio's are respectively equal to $K_{0,x}$ = 0.6 (in-plane horizontal) and $K_{0,z}$ = 0.8 (out-of-plane horizontal).

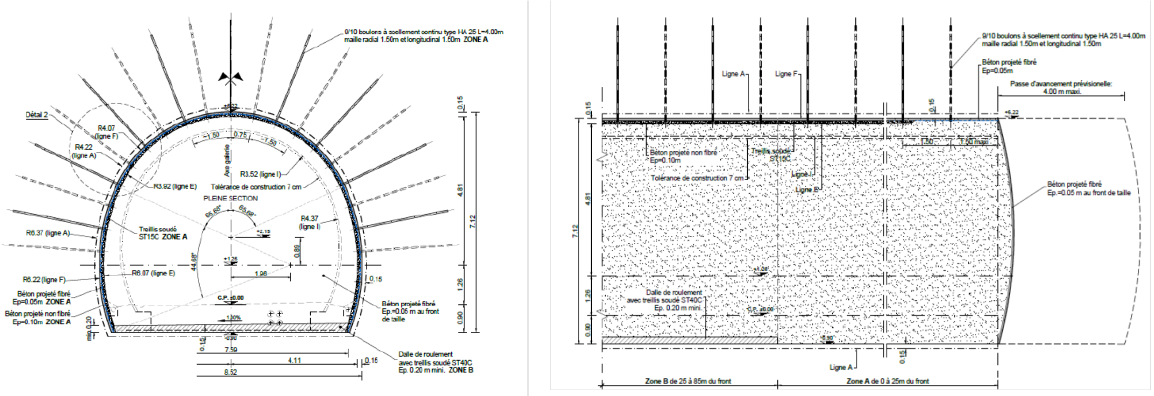


Figure 1. Tunnel drawings.

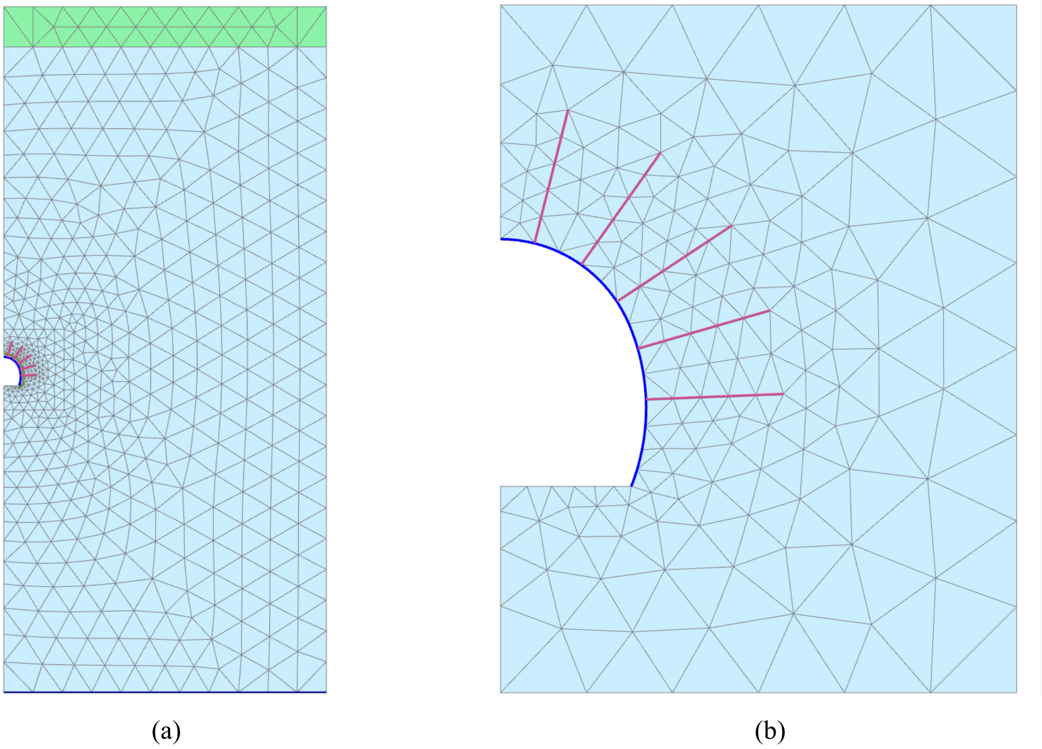
2.2 Finite element model presentation

We are presenting in this section the PLAXIS finite element model. An equivalent analysis model has also been built up in FLAC. The material properties for the rock are summarized in Table 1.

Table 1. HBS model parameter summary.

Material Name	Rock HBS
Unit weight γ	26.7 kN.m^{-3}
Young's modulus E	7.8E6 kPa
Poisson ratio ν	0.3
Yield criterion shape factor κ	-1
Intact compressive strength σ_{ci}	80E3 kPa
Tension cut-off parameter α	1
Initial Geological Strength Index GSI_{ini}	49
Dimensionless parameter of the intact rock m_i	18
Disturbance factor D	0.2
Residual Geological Strength Index GSI_{res}	49
Initial value of the dilatancy variable $m_{\psi i}$	0
Softening rate parameter B_{GSI}	0.025
Dilation rate parameter F_{ψ}	0.4
Fluidity parameter γ	5 day^{-1}

The geometry of the theoretical excavation is given in Figure 2. It is composed of a 3.8 m long vertical segment followed by two arcs of 6.22 m and 4.06 m radius respectively. A 0.1 m thick shotcrete layer is applied on the tunnel crown with $\gamma = 22$ kN.m^{-3}, $E = 7$ GPa and $\nu = 0.2$. Moreover, the rock is being reinforced by a series of 4 m long rock bolts spaced every 1.5 m (both radially and transversally). Rock bolt properties are summarized in Table 2.



(a) (b)

Figure 2. PLAXIS finite element model presentation.

Table 2. Rock bolt summary.

Material Name	Rock bolt
Cable diameter D_{cable}	0.025 m
Cable Young's modulus E_{cable}	2.E8 kPa
Cable tensile strength $f_{\text{t,cable}}$	5E5 kPa
Grout shear modulus G_{grout}	2E6 kPa
Grout cohesive strength c_{grout}	1500 kN.m^{-1}
Rockbolt spacing s	1.5 m
Drillhole diameter D_{drill}	0.038 m

In order not to have to physically model the entire overburden (and that would have required for the model to extend up to an elevation of 730 m vertically), a fictitious 10 m top layer was introduced at an elevation of 160 m with a unit weight of $\gamma_{\text{overb}} = 1522$ kN.m^{-3} equivalent to a 570 m thick overburden with $\gamma_{\text{rock}} = 26.7$ kN.m^{-3}.

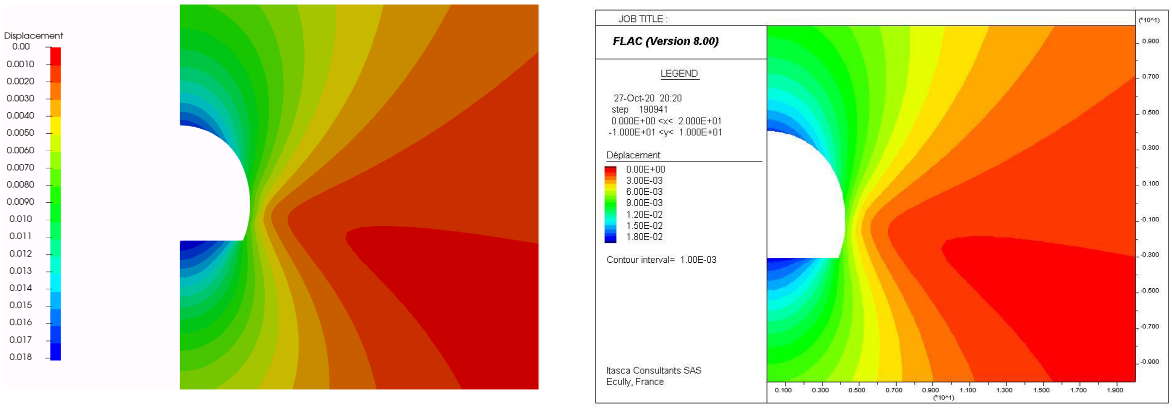
The analysis has been performed by considering the following 3 construction phases

- Initial stress definition: Initial field stresses are being initialized in the model
- Rock mass deconfinement: The level of deconfinement at the installation of the yielding sprayed concrete lining is taken equal to 0.75.
- Tunnel lining installation: The shotcrete lining along with yielding elements are wished in place

3 NUMERICAL ANALISIS RESULTS PRESENTATION AND COMPARISON

3.1 Displacement contour plots

We first start looking at the displacement contour plot which is presented in Figure 3. Comparison against FLAC is provided where PLAXIS results have been exported to ParaView to edit the coloring mapping and set it up identically to FLAC. One can see on Figure 3 that the results are in extremely close agreement.



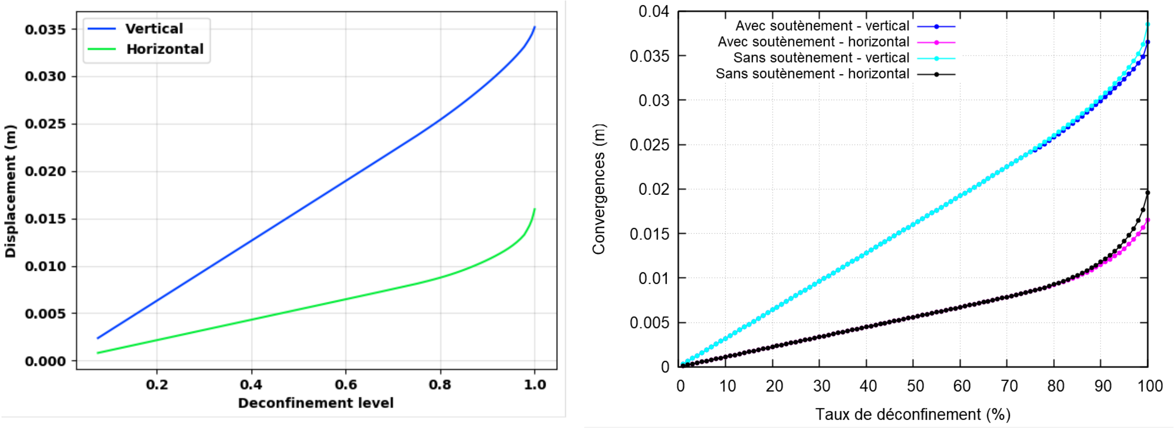
(a) PLAXIS (post-processed in ParaView)

(b) FLAC

Figure 3. Comparison of total displacement contour plots at the end of tunnel construction.

3.2 *Convergence-confinement curves*

Convergence can be evaluated based on the evolution of the vertical displacement u_Y at the tunnel crown and inversion as well as the evolution of the horizontal displacement u_X on the left side. A comparison with FLAC is provided in Figure 4 showing the perfect result matching between both numerical software packages.



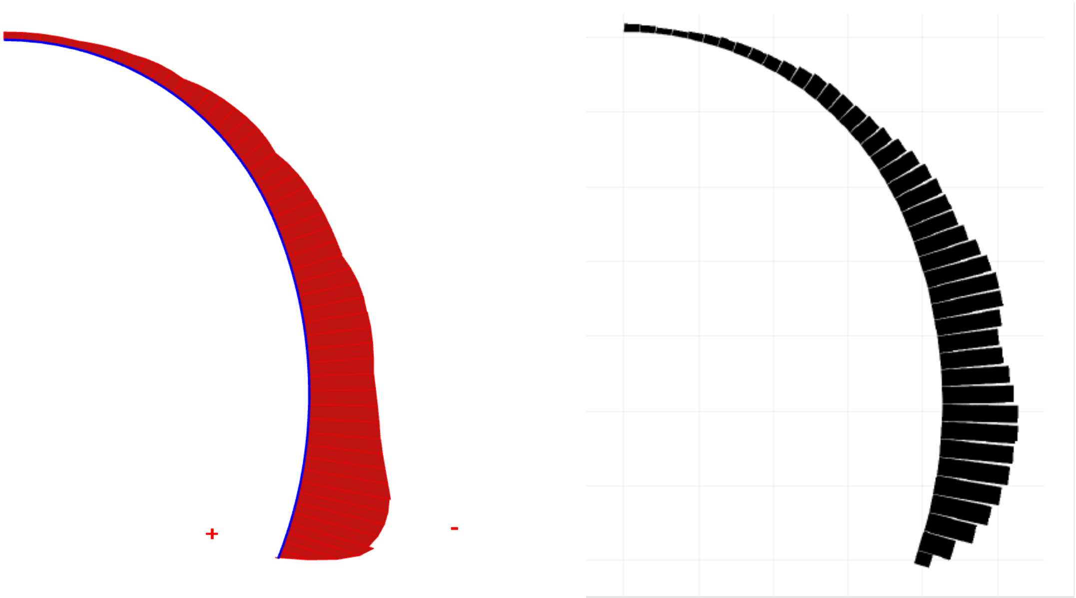
(a) PLAXIS (post-processed in ParaView)

(b) FLAC

Figure 4. Comparison of the convergence-confinement curves.

3.3 *Structural forces in shotcrete*

The normal forces that develop in the shotcrete lining are displayed in Figure 4a and compared against FLAC (see Figure 4b). Globally speaking, the results here are also in very good agreement, with a maximum force value slightly lower for PLAXIS (with N_{max} = 1530 kN) than for FLAC where N_{max} = 1660 kN (corresponding to 7.8% difference). Perhaps most important is the development of the normal force around the lowest tip of the shotcrete lining where PLAXIS provides larger values locally than FLAC.



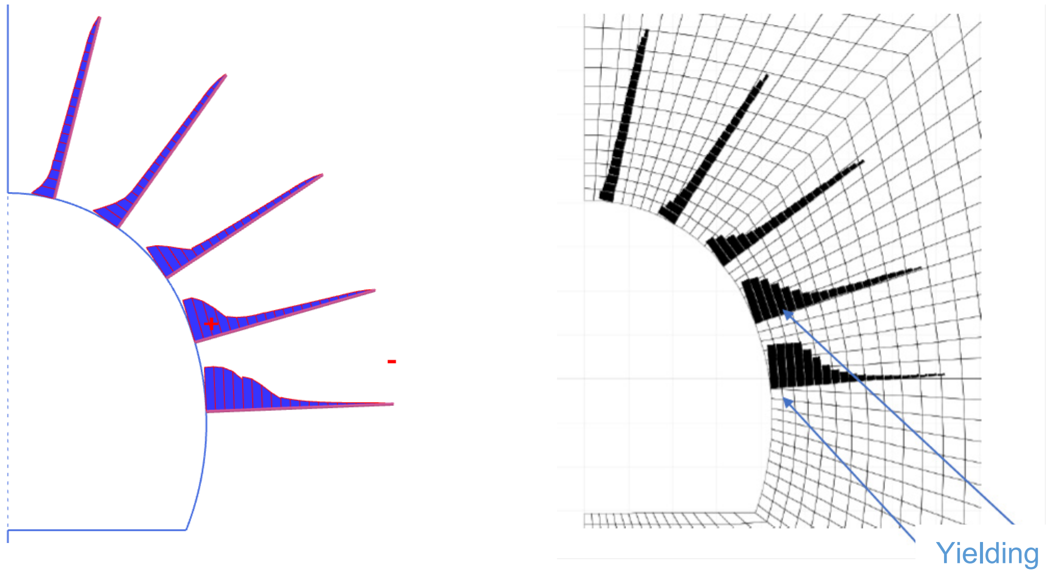
(a) PLAXIS (N_{max} = 1530 kN)

(b) FLAC (N_{max} = 1660 kN)

Figure 5. Comparison of normal forces in shotcrete.

3.4 *Axial forces in cable bolts*

Normal forces in cable bolts are displayed in Figure 6a and compared against FLAC (see Figure 6b). Note that the pile forces are output per meter length model and not per cable element. The axial force per cable bolt element can be retrieved by multiplying by the out-of-spacing spacing $L_s = 1.5$ m



(a) PLAXIS (b) FLAC

Figure 6. Comparison of normal forces in shotcrete.

4 CONCLUSIONS

The numerical analysis to a 2D excavation analysis of a tunnel in a rock mass is presented in this article. Extensive elements of comparison are proposed with an identical analysis run in both PLAXIS 2D and FLAC 2D in order to analyze the possible differences due to the implementation specificities. Results obtained will be presented in terms of tunnel convergence, structural forces in shotcrete and axial forces in rock bolts for which very good agreement between both solutions is observed. In this context, it can be concluded that the HBS rock model is perfectly adapted for the numerical analysis of underground excavation and tunnel support system in rock.

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