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On the Practical Use of Advanced Constitutive Laws in Finite Element Underground Structures Analysis

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Abstract

This article emphasizes the value of applying sophisticated constitutive soil models in numerical modeling as daily geotechnical practice. The capabilities of two different constitutive relations for the modeling of the second Heinenoord bored tunnel are compared. The hypoplastic model of Wolffersdorff for granular materials (Hypo) is a relatively simple model without recourse to yield surface or plastic potential based on rational mechanics, whereas the chosen elastoplastic model, the Hardening Soil Model (HSM) belongs to the non-associative plasticity with double hardening. A modification of the hypoplastic model with improved intergranular strain (IGS) was tested, leading to improve model behavior. Comparisons between numerical simulations and experimental values demonstrate the advantages of using the hypoplastic model with improved intergranular strain (IGS).

Keywords: tunneling, numerical modeling, interaction, hypoplasticity, HSM

Introduction

The term hypoplasticity appeared about 30 years ago as an alternative to elasto–plasticity for the description of the irreversible behavior of soils and has since then attracted the attention of many geotechnical scholars [1-3]. The theory is based on nonlinear tonsorial functions and is created without using Elasto-plastic theory ideas like yield surface, flow rule, and breakdown of deformation into elastic and plastic portions. Without the application of numerical methods, substantial progress in understanding the behavior of geomaterials would not have been possible [4-7]. The evolution of digital modeling, and soil behavior, in particular, is intimately tied to advances in the domain of numerical analysis [8,9], which employs several approaches such as the Finite Element Method, or the Finite Difference Method.
The contact of existing structures and tunnels is a complex process [9], with the behavior of the surrounding soil being one of the most important factors to consider [10].

Therefore, the choice of ground behavior model is a crucial task to better estimate the magnitude and distribution of deformations.
Different physical mechanisms, e.g., consolidation processes, creep or progressive failure, cause deformations with different displacement patterns. Likewise, different constitutive models provide varying responses concerning displacement behavior because of their mathematical formulations [11].
In this article, two constitutive models with improved levels of complexity are used to simulate the behavior of soil around the second Heinenoord tunnel. The first is a model with hardening (Hardening Soil Model, or HSM); the second is a hypoplastic model (HYPO) [6] with an evolution of this model taking into account the improvement of intergranular strain (IGS) [12].
The HSM model is available in the library of Plaxis software, while the second (HYPO) model is a subroutine, user-defined model [6].
Comparing the results of numerical simulations in this study to in-situ measurements in the second Heinenoord tunnel [13, 14] for settlements and horizontal displacements shows good adaptation and benefits of the use of the hypoplastic model with improved intergranular strain (IGS).

Soil Models

Hardening Soil Model (HSM)

The Hardening Soil Model (HSM) can be considered as an advanced model for soil behavior. This model is a derivative of the Duncan-Chang hyperbolic model. The stress-strain relationship, due to the primary loading, is assumed to be a hyperbolic curve in the HSM. The hyperbolic function, as given by [15], for the drained triaxial test can be formulated as:

$$\varepsilon_1 = \frac{q_a}{2E_{50}} \frac{q}{q_a - q} \quad pour\ q < q_f \tag{1}$$

where ε_1 is the axial strain, and q is the deviatoric stress. The ultimate deviatoric stress (q_f) is defined as:

$$q_f = \frac{6 \sin\varphi}{3 - \sin\varphi} (p + c.\cot\varphi) \tag{2}$$

where the quantity (q_a) is the asymptotic value of the shear strength, in which $q_a = \frac{q_f}{R_f}$. The R_f is the failure ratio.
Figure 1 illustrates a stress-strain representation by the HSM model. Three different stiffnesses are used to explain the soil behavior:
triaxial loading stiffness E_{50}, triaxial unloading stiffness E_{ur} and the oedometer loading stiffness E_{oed}.

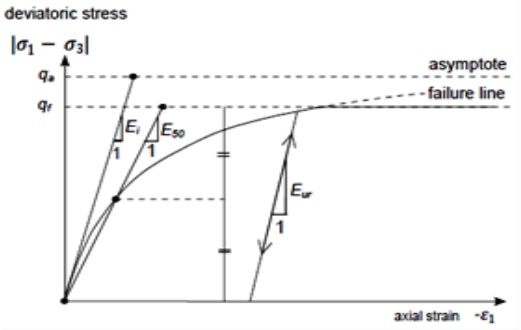


Figure 1: Hyperbolic stress–strain in HS model [16].

The expressions of these three modules are given by Equations 3, 4 and 5.

$$E_{oed} = E_{oed}^{ref} \left(\frac{\sigma}{p^{ref}}\right)^m \tag{3}$$

$$E_{50} = E_{50}^{ref} \left(\frac{c.\cos\varphi + \sigma_3.\sin f}{c.\cos f + p^{ref}.\sin f}\right)^m \tag{4}$$

$$E_{ur} = E_{ur}^{ref} \left(\frac{c.\cos\varphi + c.\cot\varphi}{\sigma^{ref} + c.\cot\varphi}\right)^m \tag{5}$$

where E_{50}^{ref} is a reference stiffness modulus corresponding to the reference stress p^{ref} (100 kN/m²). E_{ur}^{ref} is the reference modulus for unloading and reloading, which corresponds to the reference pressure pref. The reference oedometer modulus (E_{oed}^{ref}), is used to control the magnitude of the plastic volumetric strains that originate from the yield cap. In a similar manner to the triaxial moduli, the oedometer modulus (E_{oed}) obeys the stress dependency law.
More explanation of the Hardening-soil model is in [18, 16, 19].

Hypoplastic Model (HYPO)

The hypoplastic model (HYPO), developed by Kolymbas [20] in 1985, describes the stress-strain behavior of granular materials in rate form. It is derived from the stress rate, which is expressed as a function of the stress tensor and strain rate. Later, other researchers [21, 22, 23, 24...] added the void ratio as an additional state variable. This model's simplicity is a significant advantage, as is its ability to express inelastic deformation without the use of any additional concepts such as yield surface or plastic potential [25, 26, 27, 28, 29, 30].
Later, Niemunis and Herle [12] introduce the concept of intergranular strain, which allows for the accounting of small deformation.
This research is limited to sand applications using Von Wolffersdorff's constitutive law [31] with improved intergranular strain (IGS).

Constitutive Equation

The general form of the hypoplastic model is expressed by Equation 6:

$$\dot{T} = F(T, e, D) \tag{6}$$

where:
$\dot{T}$ is the stress rate.
T is the current Cauchy stress.
e is the void ratio.
D is the stretching tensor.
Equation 7 expresses Von Wolffersdorff's modified constitutive equation:

$$\dot{T} = f_b f_e \frac{1}{tr(\hat{T}^2)}\{F^2 D + a^2\, tr(\hat{T}D)\hat{T} + f_d a F(\hat{T} + \hat{T}^*)\|D\|\} \tag{7}$$

in which:

$$a = \frac{\sqrt{3}(3-sin\,\varphi_c)}{2\sqrt{2}\,sin\,\varphi_c} \tag{8}$$

The factor F is a function of $\hat{T}^*$

$$F = \sqrt{\frac{1}{8}tan^2\,\Psi + \frac{2-tan^2\,\Psi}{2+2tan\,\Psi cos3\,\theta}} - \frac{1}{2\sqrt{2}tan\,\Psi} \tag{9}$$

$$tan\,\Psi = \sqrt{3}\|\hat{T}^*\|;\ cos\,3\,\theta = -\sqrt{6}\frac{tr(\hat{T}^{*3})}{[tr(\hat{T}^{*2})]^{\frac{3}{2}}} \tag{10}$$

Herein, $\hat{T}^* = \hat{T} - \frac{1}{3}I$ is the deviatoric part of the stress ratio tensor $\hat{T}$.

I is the unit tensor and $\hat{T} = \frac{T}{tr\,T}$, $p_s = -tr\,\frac{T}{3}$

$$f_b = \left(\frac{e_i}{e_c}\right)^{\beta}\frac{h_s}{n}\frac{1+e_i}{e_i}\left(\frac{-trT}{h_s}\right)^{1-n}\left[3 + a^2 - a\sqrt{3}\left(\frac{e_{i0}-e_{d0}}{e_{c0}-e_{d0}}\right)^{\alpha}\right]^{-1} \tag{11}$$

$$f_d = \left(\frac{e-e_d}{e_c-e_d}\right)^{\alpha} \tag{12}$$

$$f_e = \left(\frac{e_c}{e}\right)^{\beta} \tag{13}$$

where:
h_s: Granular hardness.
n : Exponent relates to the sensitivity of granular skeleton to changes of pressure.
α: Exponent describes the transition between peak and critical stress.
β: Exponent represents the change of stiffness at current density.
e_i: maximum void ratio,

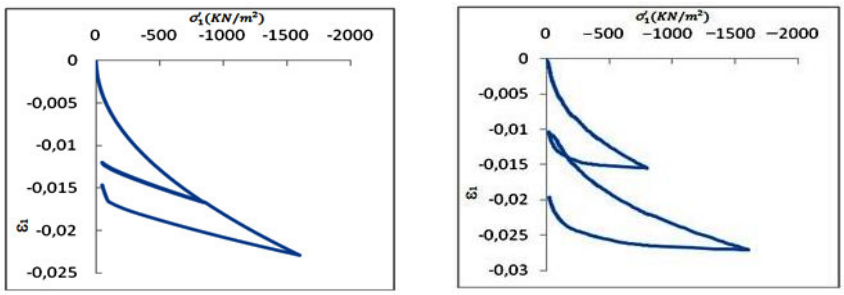
e_c: void ratio at the critical state.
e_d: void ratio at a state of maximum density.

Intergranular Strain (IGS)

The original hypoplastic model [21, 22, 31] has a shortcoming in the region of small stress cycles as an excessive accumulation of deformation occurs and therefore the displacements are overpredicted [12]. According to the experimental measurements [32, 33], soil stiffness at a given state defined by stress and void ratio depends strongly on the history of deformation and the direction of strain rate.
Niemunis and Herle [12] proposed a new state variable called the intergranular strain, *h*, to improve the performance of the hypoplastic model in the range of small load cycles. This tonsorial state variable is supposed to account for the deformation of the intergranular interface layer and particle rearrangement when small strains are applied.
It necessitates the use of five parameters that govern the behavior of the soil under small deformations:
R_{max}: The size of the elastic range (in the strain space);
βr et χ: Control the rate of degradation of the initial shear modulus G_0 ;
mR: Control the constant value of G_0 ;
mT: Control the value of *G* beyond neutral stresses.

Parameter Calibrations

The hypoplastic model was calibrated so that the curves, stress-strain of numerical oedometer tests, and numerical triaxial standard tests align the best with the curves of the HSM model. It turned out that the hypoplastic model reacts as expected, insensitive to changes in these physical constants. Therefore, we need only a small number of parameters of the dataset to be changed slightly [34]. However, the biggest impact of the hypoplastic model is to determine the initial values of two state variables' void ratio e_0 and intergranular strain *h*. In Figure 2, the stress-strain oedometric curves are represented by two models (HSM and HYPO). The HSM is unable to accurately represent unloading and reloading cycles. Hysteretic effects cannot be predicted using a model formulation with a single unloading-reloading modulus E_{ur}. Hysteretic effects can be seen in the stress-strain curve of the HYPO with IGS. The loading-unloading–reloading cycles are modeled better beside the effect of over consolidation.



(a) HSM (b) HYPO with IGS relation

Figure 2: Numerical Oedometer test

Figure 3 shows the stress-strain curves of standard shear triaxial tests under three different confining pressures for both models (HSM and HYPO).
Overall, it is estimated that curves hypoplasticity and elastoplasticity presented in Figures 2 and 3 are in good agreement.

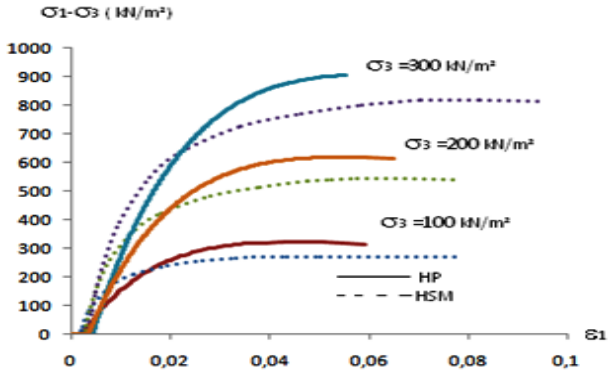


Figure 3: Numerical triaxial tests

Numerical Simulations

Numerical simulations of tunnel boring were carried out by a calculation using the Finite Element software Plaxis, adopting a plane strain model. Figure 4 shows the model geometry and geological section of the site where the Heinennord tunnel south of Rotterdam is excavated [12, 13], to a depth of 27.5m. The groundwater table is considered at a level of -1.5 m.
Tables 1 and 2 summarize the parameters characterizing such soils according to HSM and HYPO models. Heinenoord tunnel is the circular shape of diameter D = 8.3 m; the wall is modeled with linear elastic members with EA=3.75x10^6 kN, EI=1.95x10^4 kN.m², ν = 0.2 and γ=25 kN/m^3. Several methods of numerical simulation for Heinennord tunnel analysis can be found in the literature [35, 37, 38, 39]. An overview of these methods is given by Moller [5].

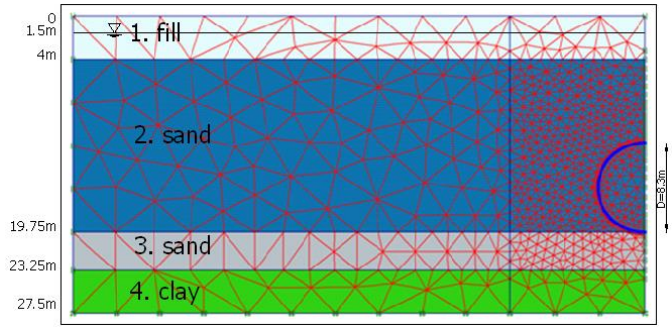


Figure 4: Geological section of the area of Heinenoord tunnel [35], Finite Element geometry and mesh

Table 1: The parameters used for the model HSM [35]

Layers	$C^{'}$(kPa)	$\varphi^{'}$ (°)	Ψ(°)	E_{oed}^{ref} (MPa)	E_{50}^{ref} (MPa)	E_{ur}^{ref} (MPa)	ν_{ur}	m	K_0^{nc0}
1 / Fill	3	27	0	14	14	42	0.2	0.5	0.58
2 / Sand	0.01	35	5	35	35	105	0.2	0.5	0.47
3 / Sand	0.01	35	5	35	35	105	0.2	0.5	0.47
4 / Clay	7	31	1	7	12	35	0.2	0.9	0.55

Table 2: The parameters used for the model HYPO

Layers	φc (°)	Hs (MPa)	N	$ed0$	$ec0$	$ei0$	α	β	$Rmax$ βr	χ	mR	mT
2/Sand	30	2.4 E^3	0.28	0.55	0.95	1.05	0.25	1.5	$1E^{-4}$	0.5	6	5	2

The implementation was realized with the hypoplastic model via the interface " User_Mod " [19].

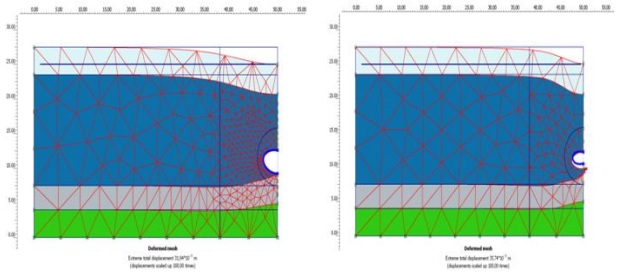
Results and Discussions

Deterministic Results

The simulation of the second Heinenoord tunnel is performed using HSM and HYPO models. The results are illustrated in Figures 5 - 8.

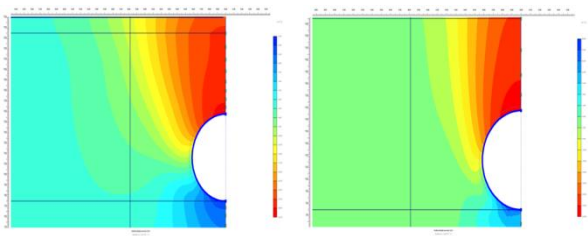
Deformed Mesh

After the construction of the tunnel, we noted that a movement of ground occurred at the level of the natural surface, and the level of the excavation (in clay).
The Finite Elements Mesh (Figure 5) clearly shows the existence of a bowl caused by the construction of the tunnel.
We also noted a certain shortening of the lining of the tunnel that is due to the various phases of construction.



(a) HSM (b) HYPO

Figure 5: Deformed Mesh



(a) HSM (b) HYPO

Figure 6: Vertical displacement U_y

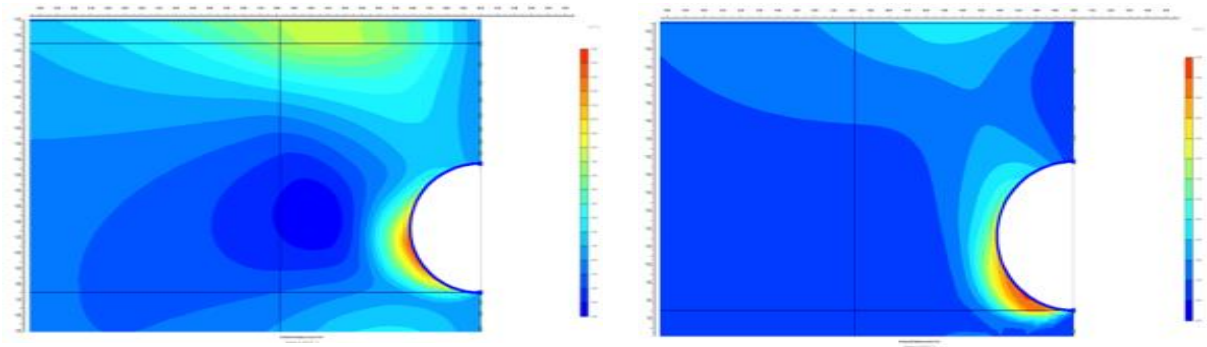
Vertical Displacement U_y

According to several authors, it appears that the displacements would probably not be significant on surfaces, but in the key of the tunnel, they become more extensive. In Figure 6,

we note a certain maximum displacement (for Hypo U_{ymax}= 35.744 mm; for HSM U_{ymax}= 31.944 mm), is just near the top of the tunnel.

Horizontal Displacement U_x

The horizontal displacements obtained after the construction of the tunnel are presented in Figure 7.
Figure 7 shows that horizontal displacements are almost null at the lower part of the tunnel and that maximum displacement is present at the level of the sides of the tunnel. This phenomenon can be explained by the effort exerted by the shield which tends to push back the ground at the level of the sides of the tunnel.

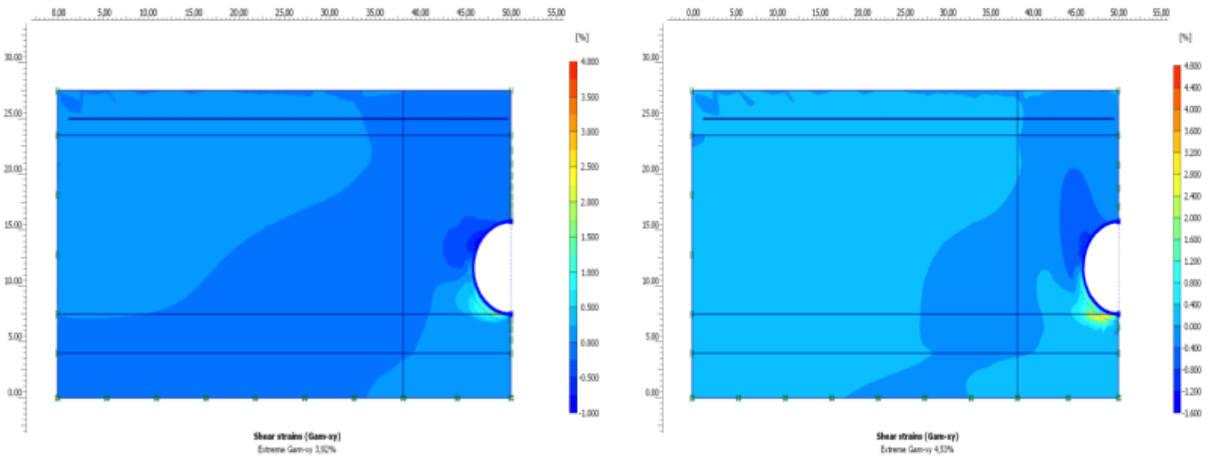


(a) HSM (b) HYPO

Figure 7: Horizontal displacement U_x

Total Deviatory Strain γ_{xy}

Figure 8 shows the total deviatory strain γ_{xy}.



(a) HSM (b) HYPO

Figure 8: Total deviatory strain γ_{xy}

Comparison of Load-Settlement Curve from in-Situ Observations and Plaxis

Figures 9 and 10 show that settlement curves and horizontal displacements nearest in situ observations are those relating to numerical simulations taken as soil behavior hypoplastic model incorporating the soil's small strain stiffness behavior in the analysis of displacement. This finding supports the conclusion that the hypoplastic model is best suited to this type of problem.

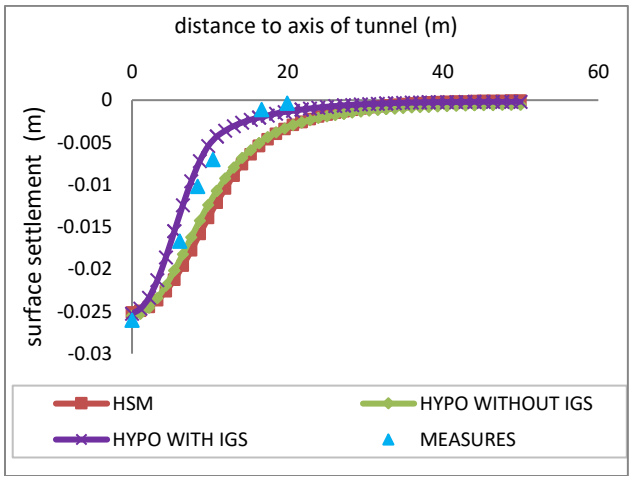
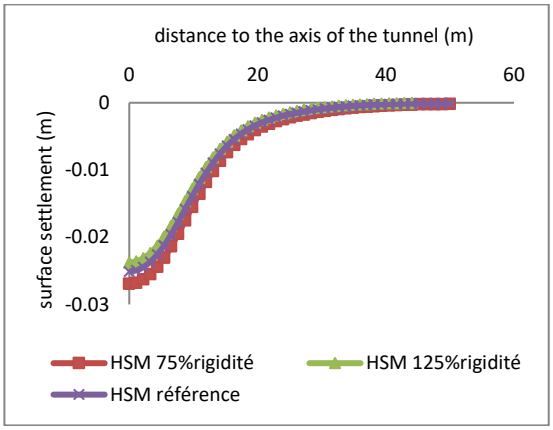


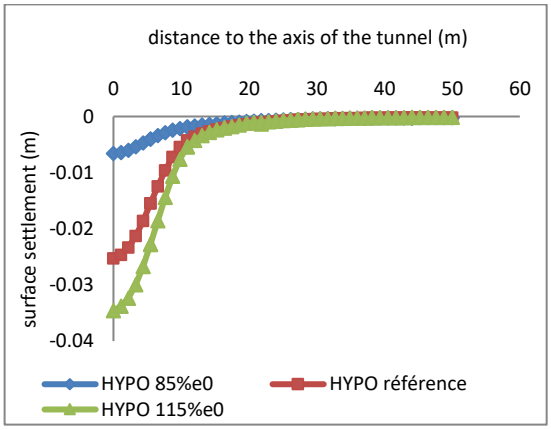
Figure 9: Surface settlements above Heinenoord tunnel, according to various constitutive models

Parametric Study

This part is devoted to a parametric study showing the effect of some parameters on settlements and horizontal displacements.
We vary the stiffness parameters of model HSM by $\pm 25\%$ and reduce the initial void ratio for the simulations with the hypoplastic model HYPO by 15% and then increase it by 15%.
Figures 11 to 14 present the results of the parametric studies.

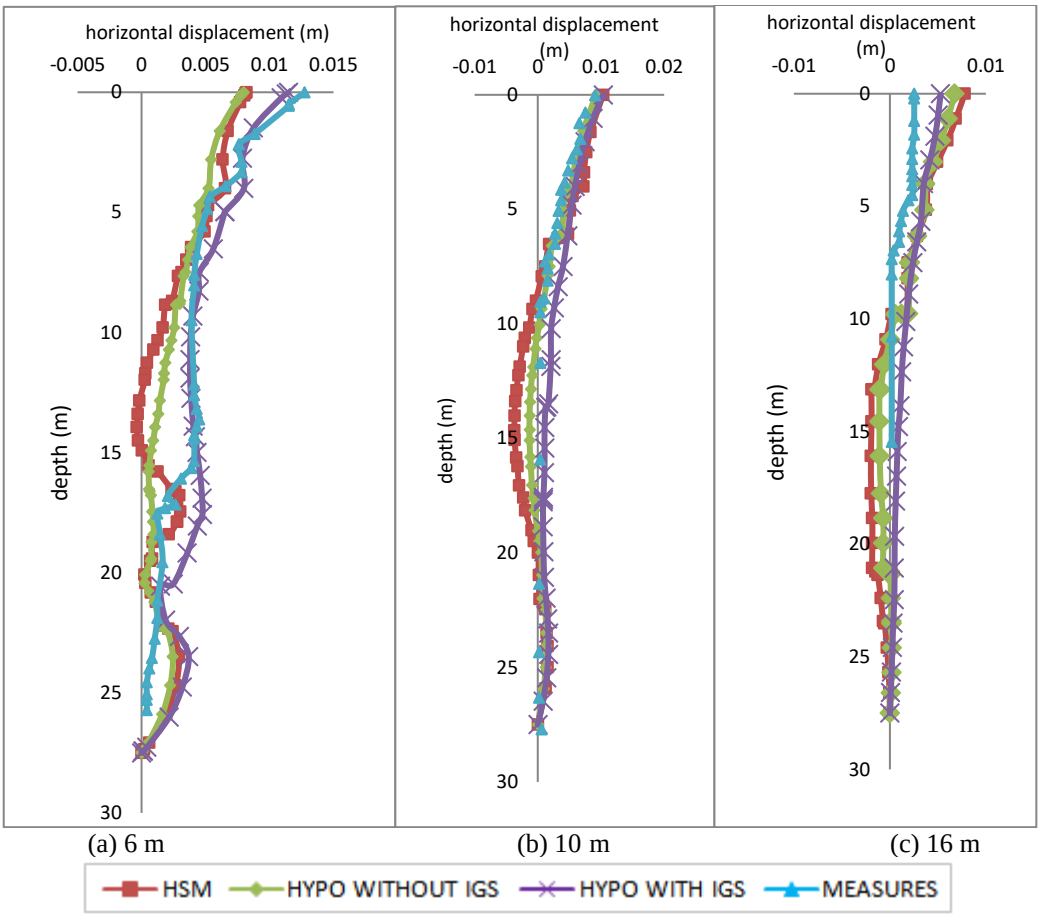


(a) HSM (with variation in stiffness



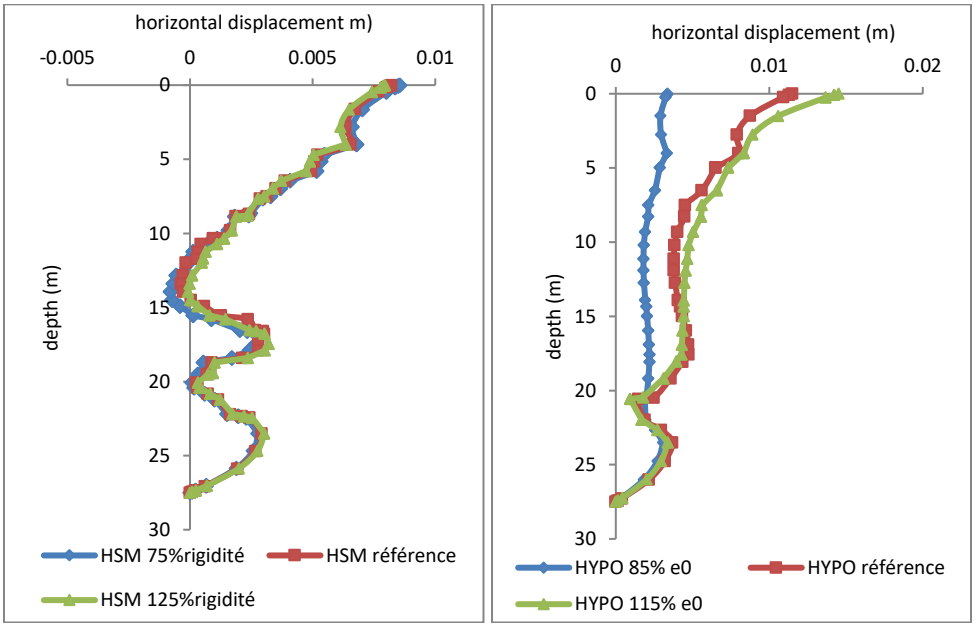
(b) HYPO (with variation in values of e_0)

Figure 10: Surface settlement of Heinenoord tunnel



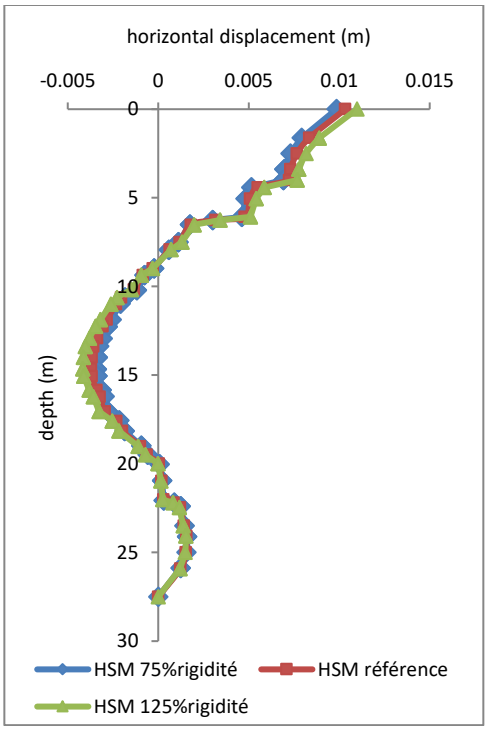
(a) 6 m (b) 10 m (c) 16 m

Figure 11: Horizontal displacements following an inclinometer away from the axis

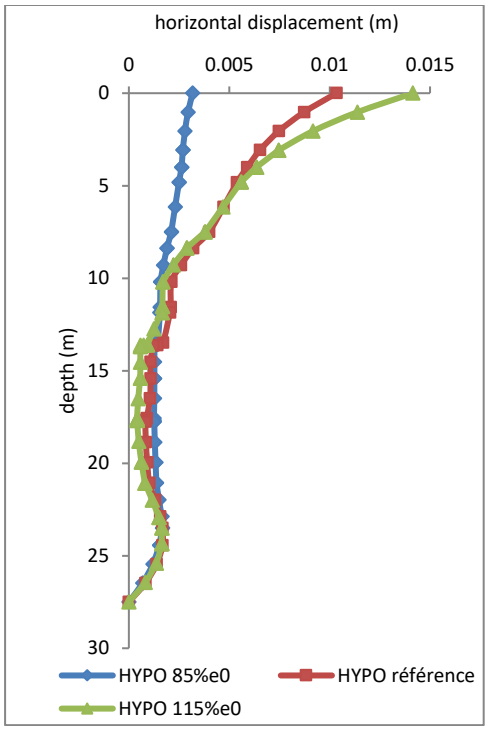


(a) HSM (with variation in stiffness) (b) HYPO (with variation in values of e_0)

Figure 12: Horizontal displacement from the axis up to 6 m

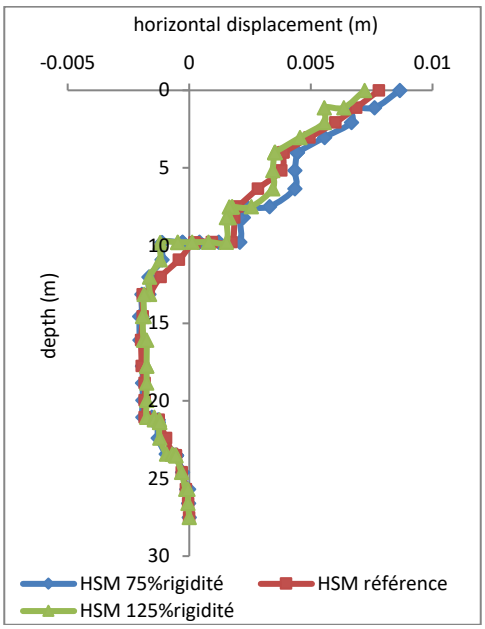


(a) HSM (with variation in stiffness)

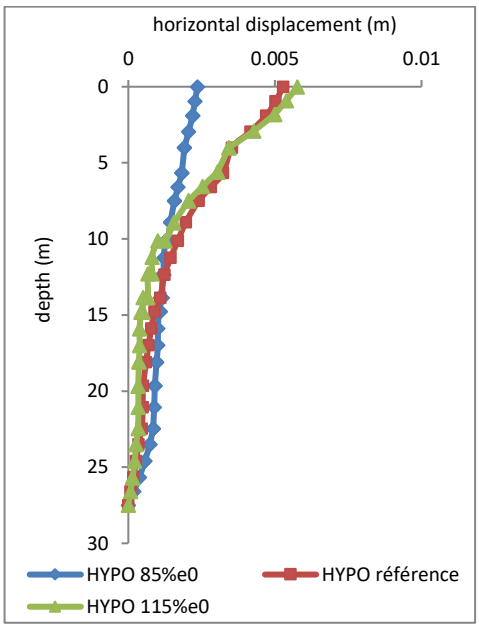


(b) HYPO (with variation in values of e_0)

Figure 13: Horizontal displacement from the axis to 10 m



(a) HSM (with variation in stiffness)



(b) HYPO (with variation in values of e_0)

Figure 14: Horizontal displacement from the axis up to 16 m

Note that the settlements and horizontal displacements determined by simulations using the hypoplastic model are more sensitive to fluctuations of a 15% void ratio than the sensitivity of results calculated using the HSM model to a fluctuation in the stiffness of 25%.

This parametric study has shown that the fluctuations of the void ratio in the calculation of hypoplasticity can have a significant impact on calculation results [36, 40].

Conclusion

This study presents a numerical calculation using FEM software Plaxis for modeling the second Heinenoord bored tunnel.
The influence of the type of the model of soil behavior on the response of the tunnel is tested by using two models of behavior, namely: the HSM model and the HYPO model with the improvement of intergranular strain (IGS).
Comparing the results of this study to measurements for settlement at the free surface and horizontal displacements shows the best adaptation of the hypoplastic model with the improvement of intergranular strain (IGS).
A parametric study was conducted to highlight the influence of various parameters on the behavior of the tunnel, and according to this study, the following conclusions should be noted:

- The void ratio, initial e_0 influences soil behavior because it is a state variable in the hypoplastic model.
- A reduction in the rate of void ratio leads to a significant increase in the rigidity and strength of the soil.
- A higher dilatancy also occurs at a reduction in the initial void ratio.

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