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Importance of small-strain stiffness on the prediction of the displacements of a flexible retaining wall on stiff clay

Importance de la rigidité à faible déformation sur la prédiction des déplacements d'un mur de soutènement flexible

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ABSTRACT: Nowadays, the subsoil plays a major role in the development of cities, particularly in the construction of underground structures. Because flexible retaining structures are usually built in highly urbanized areas, it is essential to evaluate the construction effects on neighbouring buildings. This study aims to evaluate the effects of a more comprehensive characterization of the soil response in the small strain range on the prediction of the displacement profile of the wall. The finite element code Plaxis is used with the Hardening Soil Small-strain Stiffness (HSsmall) constitutive model, as well as the standard Hardening Soil model (HS). This methodology was applied to a case study corresponding to a reinforced concrete bored pile wall for the construction of a basement in Lisbon in stiff clay. The displacement profile from the numerical simulations is compared with the values measured in the wall for different stages of excavation. This comparison shows the importance of measuring and simulating small strain stiffness in stiff soils.

RÉSUMÉ: De nos jours, le sous-sol joue un rôle majeur dans le développement des cités, en particulier dans la construction de structures souterraines. Les murs de soutènement flexibles étant généralement construits dans des zones très urbanisées, il est essentiel d'évaluer les effets de la construction sur les bâtiments voisins. Cette étude vise à évaluer les effets d'une meilleure caractérisation du sol à faibles déformations sur la prévision du profil de déplacement du mur. On utilise le code d'éléments finis Plaxis et des lois constitutifs HSsmall et HS. Cette méthodologie a été appliquée à une étude de cas correspondant à un mur de pieux forés en béton armé pour la construction d'un sous-sol à Lisbonne en argile dure. Le profil de déplacement obtenu des simulations numériques est comparé aux valeurs mesurées dans le mur pour différentes étapes d'excavation. Cette comparaison montre l’importance de la mesure et de la simulation de la rigidité sous faible contrainte dans des sols dures.

Keywords: Small-strain stiffness; embedded walls; finite elements method

1 INTRODUCTION

Flexible retaining structures are used for the support of excavations, particularly in urban environments, where both the need for underground structures and the space constraints are bigger.

The behaviour of a retaining wall is strongly dependent on soil structure interaction (Terzaghi and Peck, 1967). In stiff soils, the response of the ground is mainly dominated by the elastic part, which can be measured using seismic methods.

In this paper, it is shown an example of the relevance of identifying the small strain stiffness estimated using the surface wave method on the accuracy of the prediction of a flexible wall displacement profile.

2 CASE STUDY

2.1 General Framework

The case study is located in Lisbon (Figure 1) and refers to the construction of a new building with six underground levels. Regarding neighbouring structures, the most relevant is the Lisbon metro tunnel and an underground parking lot.

The various conditioning factors, especially those related to the existence of neighbouring structures, led to the adoption of 3 different solutions for the perimeter wall.

This paper focused on the analysis of the retaining wall near the metro tunnel. The wall consists of a reinforced concrete bored pile wall with 600 mm diameter piles, spaced at 0.80 m centres, with 2 levels of support. The horizontal thrust was supported by slab-bands which were integrated in the permanent structure.

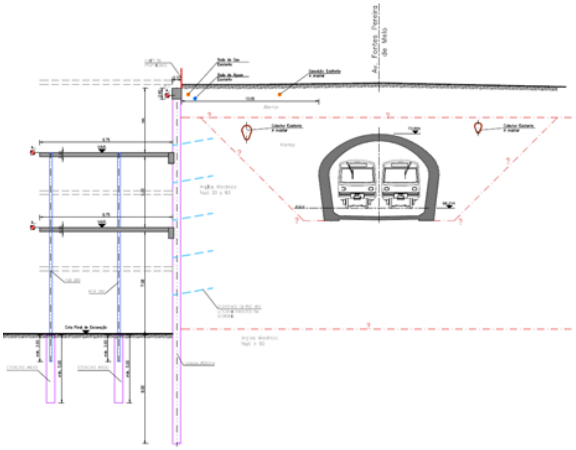

Figure 1. Cross section of case study

2.2 Geotechnical characterization

The geotechnical characterization was based on the execution of 5 boreholes and SPT tests. Soil samples were also collected to perform laboratory classification tests. The results of the tests allowed a geotechnical zoning in three distinct strata:

- ZG3 – “Fills", which is the most superficial layer (thickness ranging from 2 to 5 m) and comprising heterogeneous sandy clays and silty sands.
- ZG2 – medium to stiff clays and limestones (NSPT < 60)
- ZG1 – Very Stiff clays and limestones (NSPT > 60).

In addition to these tests, single station random vibration records and active seismic surface method (MASW) with a linear array of 24 geophones and 1,5 meters spacing records were done to determine the Vs profile (Gouveia, 2017).

Figure 2 shows the results of the SPT tests of the 5 boreholes performed, as well as the profile of shear wave velocities determined from the seismic tests.

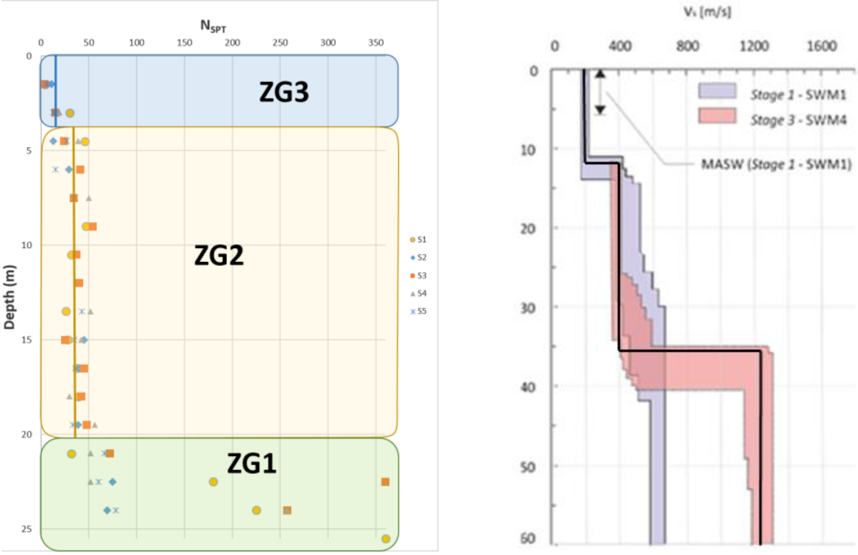

Figure 2. SPT and VS profile

3 NUMERICAL MODEL

3.1 Constitutive Models

The constitutive models have a great influence on the results obtained in geotechnical modeling. Complex models tend to represent better the behaviour of the materials, but the number of parameters that need to be defined for their implementation is often high, and the data for the correct definition of parameters is not always available. The two constitutive models used in this work were Hardening Soil Model (*HS*) and Hardening Soil Small-strain Stiffness Model (*HSsmall*).

The main advantage of *HSsmall* model is the ability of modelling with accuracy stiffness decay curve from the small strain range to large deformations, while the standard Hardening Soil (HS) underestimate the small strain stiffness, as shown in Figure 3 obtained through the numerical simulation of drained triaxial tests with both models for an isotropic confinement pressure of 100 kPa.

It can be seen in Figure 3 that both constitutive models provided similar results for larger deformations, differing fundamentally in the small strain range.

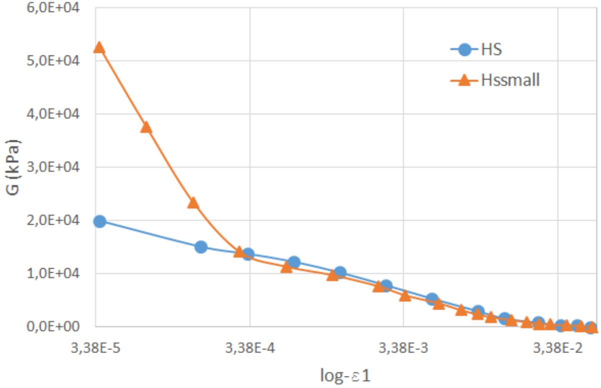

Figure 3. Results for drained triaxial test simulation

3.2 2D numerical simulation of the case study

A numerical model was prepared to simulate the different stages of the construction sequence. In the first model the soil characteristics are the same as those defined in the detailed design, and the second model the soil characteristics are complemented with the data from the seismic tests, using the HSsmall model.

The dimension of the model was 100 m x 60 m, the water table was represented as a 22.3 m deep horizontal line. In order to model the traffic in the existing road behind the wall, a load of 2 kN/m/m was considered.

3.3 Concrete materials properties

The retaining wall was simulated by a plate element, which represents a linear element in the xz plane. The concrete used in the 600 mm diameter piles is of class C30/37, and the possible cracking of the concrete after its construction was considered by reducing the E value by 50%. The values of the various input parameters of the software for the characterization of the pile wall are shown in Table 1.

Table 1. Input parameters for the concrete pile wall

EA [kN/m]	2,7x10^{-4}
EI [kNm^2/m]	5,7x10^{-4}
ω [kN/m/m]	1,7x10^{-3}

The slab band (30 cm thick) was simulated by its axial stiffness. A 2D model of the slab was developed in the Autodesk Robot Structural Analysis software to determine its axial stiffness. With this model it was possible to obtain an estimate of the displacement field caused by a unitary distributed load. In the Plaxis software slab bands are represented by fixed-end anchors, whose axial stiffness is defined by EA, which can be determined by the inverse of the calculated displacements, giving a value of 7.83 x 10^4 kN.

The tunnel lining of the Lisbon Metro was simulated with a plate element. Considering the properties of a C16/20 concrete, a tunnel thickness of 0,7 m and assuming that the cracking of the concrete causes a reduction of 50% of the deformability module the following elastic parameters were calculated: EA = 1,02 x 10^7 kN/m; EI = 4,14 x 10^5 kN/m; ω = 8,40 kN/m/m; ν = 0,15.

3.4 Geotechnical materials proprieties

3.4.1 HS Model: Design data

The first model uses the constitutive model Hardening Soil (HS). A ground profile with 3 layers was used. The characteristic values used in the simulation are defined in Table 2.

Given the clayey nature of the materials, undrained conditions were considered. Drained parameters are an input of the model, but Plaxis is able to determine the shear strength. Therefore, undrained resistance is a consequence of the model, not an input, because the analysis is done in effective stress, therefore with pore pressure generation.

Table 2. Parameters used for soil modelling (HS model)

	ZG3	**ZG2**	**ZG1**
γ kN/m^3]	17	24	24
k [m/day]	4,3x10^{-3}	4,3x10^{-3}	4,3x10^{-3}
c’ [kN/m^2]	5	40	75
$\emptyset$ [º]	28	30	35
$\boldsymbol{E_{50}^{ref}}$ [kN/m^2]	10 000	15 000	60 000
$\boldsymbol{E_{oed}^{ref}}$ [kN/m^2]	10 000	15 000	60 000
$\boldsymbol{E_{ur}^{ref}}$ [kN/m^2]	30 000	45 000	180 000
m [-]	0,8	0,8	0,8
R_{inter}	1,0	1,0	1,0

3.4.2 HSsmall Model: Seismic tests data

The application of the surface wave method (see Figure 2) allowed to identify 3 zones with different velocity of the shear waves (V_S), varying from 200 to 1 300 m/s. Considering the geometry of the HS model and the results obtained in the seismic tests, the ZG2 and ZG1 strata were divided in 2 sub geotechnical zones so that the design assumptions were not significantly altered (Figure 4).

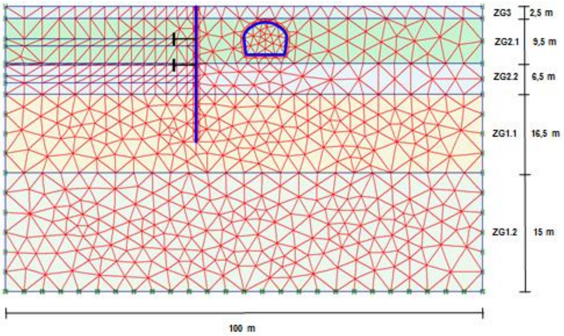

Figure 4. Layers and mesh adopted for the model with HSsmall and data from surface seismic methods.

For each layer, the additional 2 parameters required for the HSsmall model were determined. The maximum distortion modulus (G_0) was obtained from the shear propagation velocity profile (VS), and the value of $\gamma_{0.7}$ was defined using the Ishibashi and Zhang (1993) rigidity degradation equations, that are a function of the plasticity index. The calculated values are on Table 3.

Table 3. Additional input parameters for the HSsmall soil model (HSsmall model)

	G_0^{ref} [kN/m^2]	$\gamma_{0.7}$
ZG3	69 000	$2{,}7\text{x}10^{-4}$
ZG2.1	98 000	$5{,}7\text{x}10^{-4}$
ZG2.2	392 000	$8{,}0\text{x}10^{-4}$
ZG1.1	392 000	$9{,}8\text{x}10^{-4}$
ZG1.2	3 826 000	$1{,}7\text{x}10^{-3}$

3.5 Results

3.5.1 Structural forces

Figure 5 plots the structural forces in the retaining wall. The accurate modelling of the small strain stiffness leads to significant reductions in the maximum values of the transverse forces and bending moments, around 60% and 80%, respectively in comparison with standard HS model.

The results also show that the slabs act as a support of the retaining wall. Concerning the forces installed in the slab bands, in the final calculation phase, the estimated values are of -278.3 kN/m and -207.5 kN/m for the first and second level, respectively, in the case of the first simulation (HS). These values decrease to about one-third (-98.6 kN/m and -68.7 kN/m), when the simulation is done using the HSsmall model.

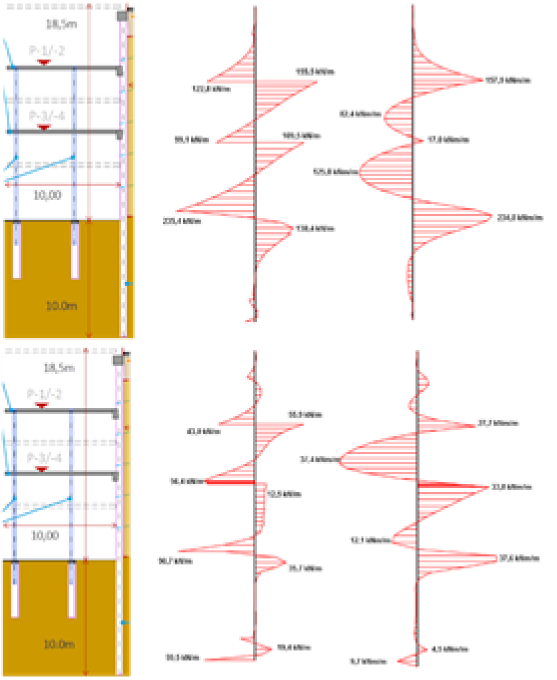

Figure 5. Shear forces and bending moment on wall (above: HS model; bellow: HSsmall)

3.5.2 Plastic points

Figure 6 plots the plastic points of both models, which show similar distribution. The main difference between the two models is that almost all of the plastification in the HS model occurs due to shear and cap and hardening, whereas in the HSsmall model there is a very significant part of points where only shear hardening occurs.

Globally, the response of both models is mainly elastic.

In the simulation with the HSsmall model, in the final excavation phase, the shear strain level is in the small deformations ($< 5\text{x}10^{-4}$). Similarly, the simulation with the HSsmall model the shear strain is in the same range of values.

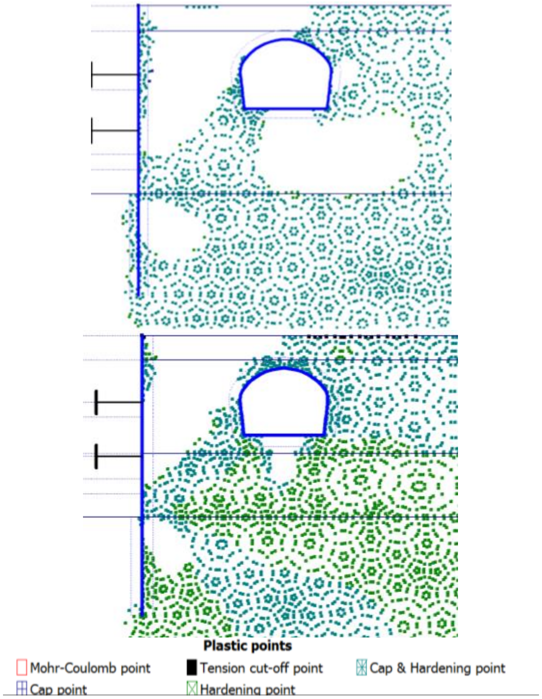

Figure 6. Plastic points plot (above: HS model; bellow: HSsmall)

3.5.3 *Displacements*

Figure 7 compares the deformed mesh on the final phase of calculation, where significant differences between the two models are visible.

It is visible that the consideration of a larger soil stiffness in the small deformations range leads not only to smaller displacements, but also to a more linear deformation of the retaining wall. The differences in the total displacements of the two models are significant, with maximum values around 41 mm for HS model and only 9 mm for HSsmall model.

Regarding the tunnel, the displacement field is relatively uniform throughout the structure of the ML, corresponding almost to a rigid body movement. Table 4 summarizes the maximum values of absolute and relative displacements obtained in the two models, where it is clear that the HSsmall model leads to much smaller values.

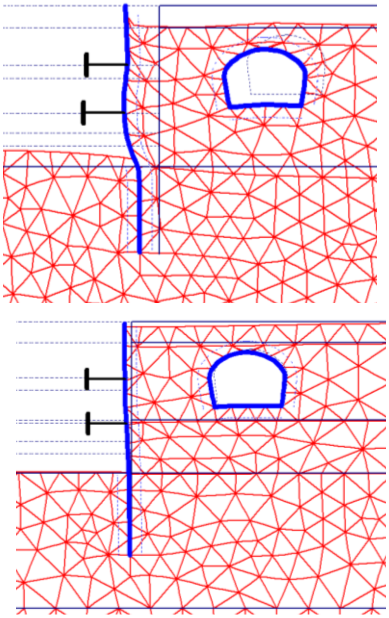

Figure 7. Deformed mesh at final excavation, scaled 100x (above: HS model; bellow: HSsmall)

Table 4. Maximum displacements in the Metro tunnel

	HS	HSsmall
Absolute values	26,63 mm	6,11 mm
Relative values	1,79 mm	0,94 mm

The displacements of the retaining wall were monitored with 2 inclinometers, during construction sequence. These measurements are compared with the displacements obtained in both numerical simulations.

It is important to highlight the higher displacements near the surface in the inclinometer I4 were influenced by a long period of time during which the construction works were stopped at a stage where the first excavation was already carried out, but the slab band had not yet been built.

Figure 8 shows a better approximation of the results of the simulation made with the HSsmall model to the measurements of the inclinometers, not only regarding the value of the displacements, but also the variation of the displacements with the depth, for all phases of excavation.

In general, the average displacement estimated by the HS model in the last calculation phase is around 33 mm, which is more than 5 times higher than the HSsmall model estimates and of the average value measured by the inclinometer I5. Analysing the differences between the estimated displacements and those measured on site, we found that the mean error of HS modelling is 262% (greater than 22 mm), while the HSsmall model manages to reduce this error to 34% (average difference smaller than 5 mm).

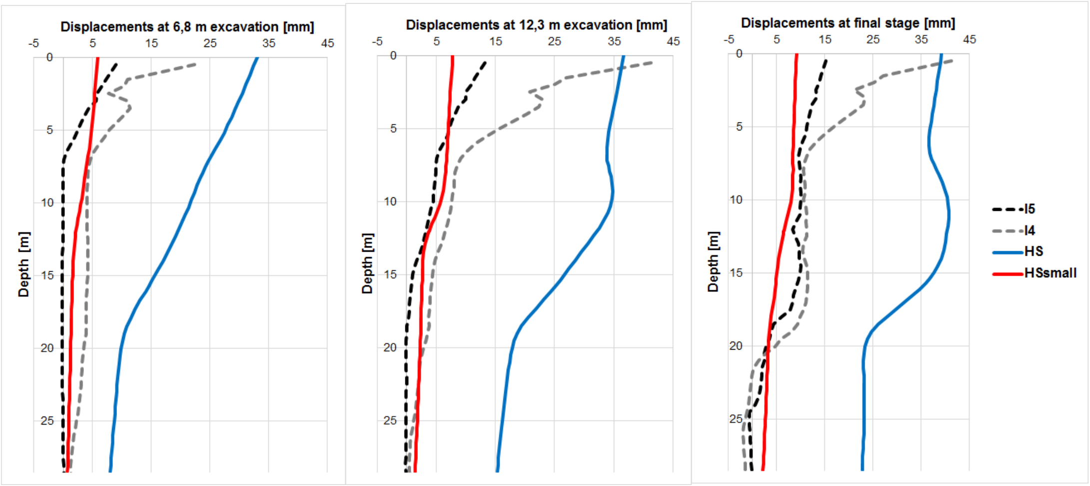

Figure 8. Displacements in the retaining wall at intermediate and final excavation phases

4 CONCLUSIONS

The influence of characterizing the deformability of the soil in the small deformations range and incorporating it into numerical modelling using the *Hssmall* model, was analysed by comparing it with traditional geotechnical characterization based on penetration and laboratory tests and the use of constitutive models that do not adequately simulate the small deformations range.

The analysis of the case study was based on the following methodology: replicate the modelling done in the design phase using mainly parameters derived from SPT test results; repeat this numerical simulation taking into account the *HSsmall* constitutive model and Vs profile from seismic surface method; and compare the displacements estimated numerically with the measured deformations during construction. It is shown the model that simulates with higher accuracy the small strain stiffness predicts better the displacements of the wall measured in the inclinometers, because the response of the stiff clay is mainly elastic range.

5 REFERENCES

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