Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-971

FE-analysis of deep excavations in lacustrine clay with different constitutive models

Comparaison de différentes lois de matériau pour l'analyse de fouilles profondes dans des argiles lacustres par la méthode des éléments finis

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ABSTRACT
In this paper finite element analyses of deep excavations in soft ground in the city of Salzburg, Austria are presented. The regional subsoil situation in Salzburg can be described as fully saturated soft clay (referred to as "Seeton") overlain by a quaternary gravel fill. The poorly graded Seeton can be classified as fine silt or fine sand respectively and shows unfavourable soil properties with respect to the deformation behaviour of deep excavations. Common calculation methods for retaining structures based on failure criterions like Mohr-Coulomb cannot take into account this complex behaviour adequately. Therefore more advanced constitutive models have been used in analysing two different deep excavations in Salzburg. Firstly the Hardening Soil model, an isotropic double hardening model as implemented in the commercial version of finite element code Plaxis and secondly a newly developed constitutive model based on the multilaminate concept. The comparison with in situ measurements showed that both models are capable of representing the behaviour of soft soils, at least for this type of problems.

RÉSUMÉ
Cette publication présente des analyses de fouilles profondes par la méthode des éléments finis dans les sols mous de la ville de Salzburg. Les sols de Salzburg sont composés d'argiles molles entièrement saturées, que l'on appelle aussi le « Seeton », ceci sont en dessous de graves quaternaires. Ce matériau à granulométrie discontinué peut être classifié comme silt fin ou sable fin avec des caractéristiques géotechniques non favorable par apport aux déformations suite à l'excavation de fouilles. Les méthodes traditionnelles de calculs basées sur le critère de défaillance par Mohr-Coulomb ne suffisent plus pour décrire ce comportement complexe d'une façon adéquate. Pour cela des lois de matériaux plus avancées ont été utilisées afin d'étudier le comportement de deux fouilles profondes à Salzburg. Premièrement, une loi Hardening-Soil, un modèle hyperbolique en élasto-plasticité, a été utilise. Cette loi est incluse dans la version commerciale du logiciel Plaxis. Deuxièmement, le concept récemment développé de la loi à multiple surface a été utilisé. La comparaison avec des données d'auscultation montre que les deux modèles sont au moins pour la situation en question capables de décrire le comportement des sols mous.

1 INTRODUCTION

Soft subsoil deposits in Austria are mainly fresh water deposits, sedimented in the post-glacial lakes after the boulder periods. These deposits are known as lacustrine clays on the foothills of the Alps. One example for a widespread lacustrine clay deposit is the basin of Salzburg, where the city of Salzburg is situated on subsoil sediments, which partly show a thickness up to 70m, called "Salzburger Seeton". The poorly graded Seeton can be classified as clayey silt and shows unfavourable soil properties with respect to the deformation behaviour of deep excavations.

To improve the design of constructions on soft soil, finite element calculations are a useful tool for the optimisation of the design and to obtain realistic predictions of the deformations to be expected. Common calculation methods for retaining structures based on simple failure criteria such as Mohr-Coulomb cannot take into account the complex material behaviour of soft soils adequately. Therefore more advanced constitutive models, namely the Hardening Soil model as implemented in the finite element code Plaxis (Brinkgreve, 2002) and a newly developed multilaminate model for soft clays (Wiltafsky, 2003) have been used to analyse two deep excavations, namely the projects "Hypobank" and "AMV". Due to space limitations a detailed description of the models and the projects will not be given here, only the most relevant results will be discussed. A schematic presentation of the geometry and the support measures for both projects is given in Figures 1 and 2.

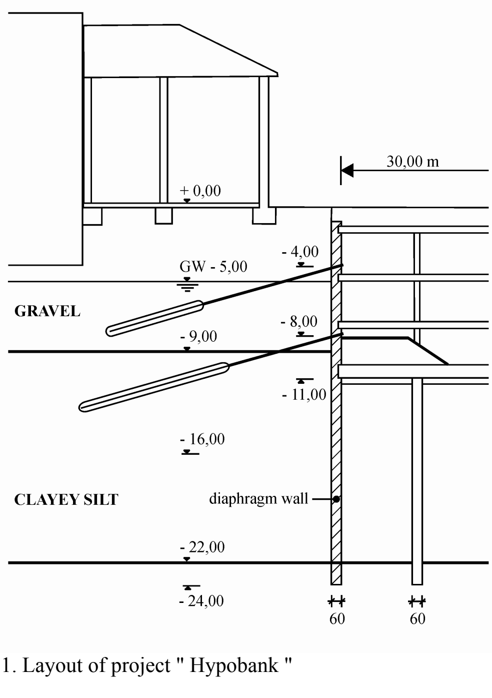

Figure 1. Layout of project " Hypobank "

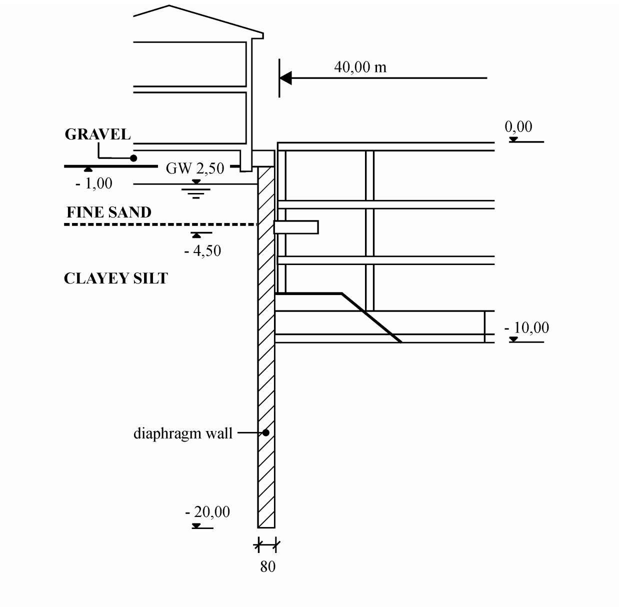

Figure 2. Layout of project "AMV"

2 PROJECT "HYPOBANK"

In this section the results of the project "Hypobank", obtained from analyses with the two different models, are compared. Figure 3 shows the model that has been derived from the geometry depicted in Figure 1 including the soil layers and the support system: a diaphragm wall with a thickness of 0.6m and a depth of 24.0m is supported by two rows of anchors and at the final excavation level, which is at -11.0m below surface, with a berm. The width of the excavation is 30.0m but only half of the system has been analysed.

The following construction sequence has been modelled in the analysis:

1. initial stresses (K_0=0.55 assumed for all layers)
2. loads representing buildings applied (displacements set to zero)
3. diaphragm wall wished-in-place
4. excavation to -3.8m
5. activation of 1st anchor row and prestressing (156 kN/m)
6. lowering of groundwater table inside excavation to -8.1m
7. excavation to -8.1m
8. activation of 2nd anchor row and prestressing (156 kN/m)
9. lowering of groundwater table inside excavation to -11.0m
10. excavation of centre part (berm left for support)
11. construction of concrete slab
12. removal of berm
13. construction of remaining part of concrete slab

The soil parameters for the Hardening Soil model used in the analysis for the silty gravel layer and the clayey silt are summarized in Tables 1 and 2. The parameter determination is based not only on site investigations and laboratory experiments but also from experience of back analyses of other deep excavations in Salzburg not discussed here. In Table 1 E_{50} denotes a reference secant stiffness for triaxial compression stress paths, E_{oed} a reference stiffness from one-dimensional compression tests and E_{ur} is the unloading/reloading stiffness, again at the given reference stress p_{ref}. m controls the stress dependency of the stiffness and ν_{ur} is the Poisson's ratio for unloading/reloading. The fine sand layer is not present in the "Hypobank" project but appears in the project "AMV". Table 2 lists the strength parameters.
For the multilaminate model these parameters had to be converted because the input for both models is not the same. However it is beyond the scope of this paper to elaborate on the parameter identification procedure for the multilaminate model (Wiltafsky et al., 2003). The main feature of this model is that it is based on the multilaminate framework, introduced for soils by Pande and Sharma (1983), and it takes into account anisotropic behaviour without introducing additional material parameters. The constitutive behaviour is formulated on so-called contact planes in terms of effective normal and shear stresses. Deviatoric and volumetric hardening is considered (Wiltafsky, 2003). The clayey silt layers have been assumed to behave as undrained material.

Table 1. Stiffness parameters for soil layers

	E_{50}	E_{oed}	E_{ur}	m	p_{ref}	ν_{ur}
	MPa	MPa	MPa	-	kPa	-
Silty gravel	52	52	208	0.0	100	0.2
Silty, fine sand	44	44	176	0.0	100	0.2
Clayey silt 1	37.6	37.6	150.4	0.30	100	0.2
Clayey silt 2	75.2	75.2	300.0	0.75	200	0.2

Table 2. Strength parameters for soil layers

	c	φ	ψ
	kPa	°	°
Silty gravel	2	35	5
Silty, fine sand	5	28	0
Clayey silt 1	30	26	0
Clayey silt 2	30	26	0

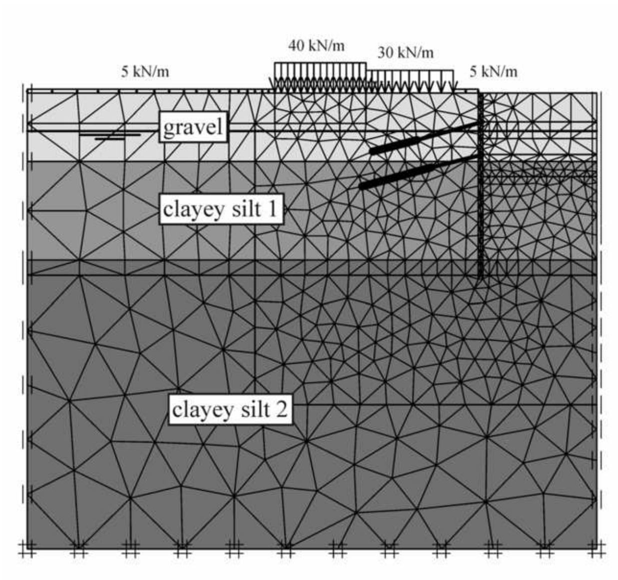

Figure 3. Plaxis model for project "Hypobank"

2.1 *Results for project "Hypobank"*

Figure 4 shows the wall deflection for the final excavation stage for both analyses. It can be seen that the horizontal displacements are higher for the multilaminate model as compared to the Hardening Soil model. However the differences in absolute values are not significant from a practical point of view. Maximum bending moments (Figure 5) calculated are similar although differences are observed at the bottom part of the wall. This can be attributed to the fact that the dependency of the stiffness on the stress state is different in both models. Corresponding to the slightly higher displacements obtained for the multilaminate model settlements behind the wall are also slightly higher than for the Hardening Soil model (Figure 6).

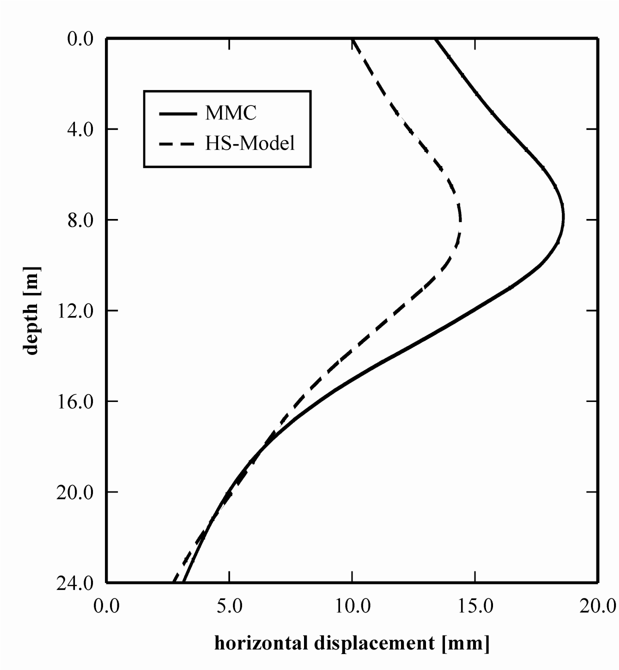

Figure 4. Wall deflection for project "Hypobank"

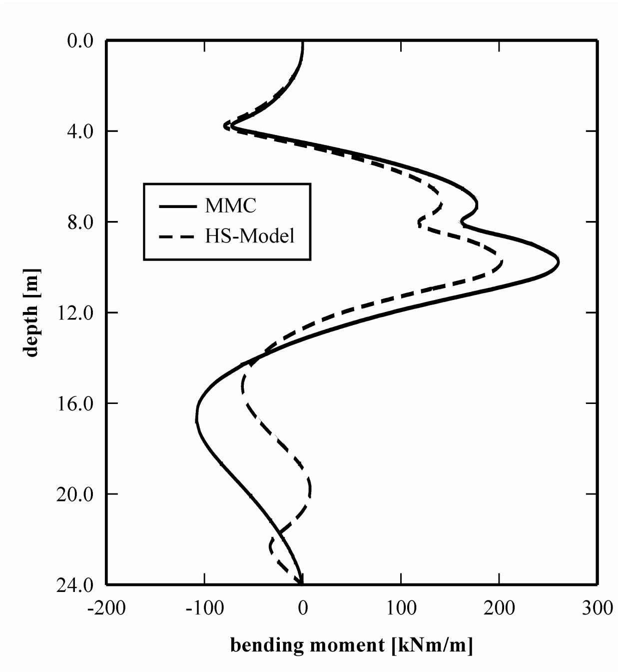

Figure 5. Bending moments for project "Hypobank"

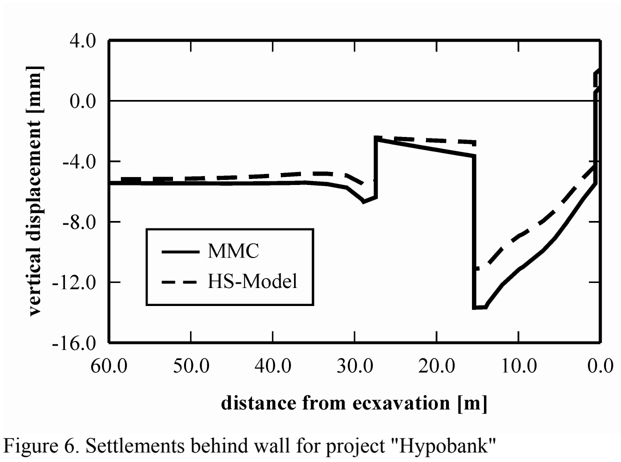

Figure 6. Settlements behind wall for project "Hypobank"

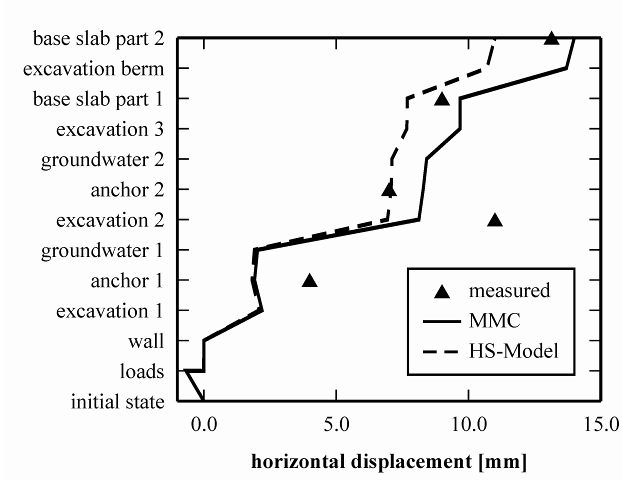

Figure 7. Horizontal displacement of wall head for project "Hypobank"

In Figure 7 the development of the horizontal displacement of the top of the wall for all construction stages is depicted together with measured values and the excellent agreement between analysis and in situ performance is obvious. Only in construction step 7 a mismatch is observed but this can be attributed to slight deviations in the construction activities as compared to the original design.

3 PROJECT "AMV"

The second example discussed here is project "AMV". In contrary to project "Hypobank" the diaphragm wall is supported by struts rather than ground anchors. Again a berm is left and the centre part is excavated first when the final excavation depth is reached. The finite element model is shown in Figure 8.

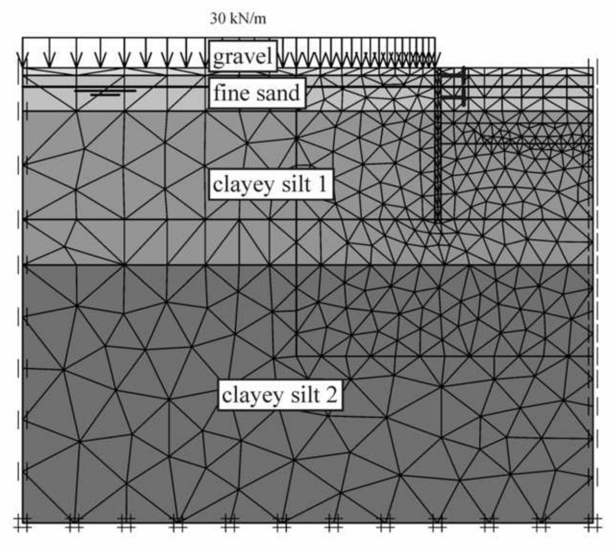

Figure 8. Plaxis model for project "AMV"

A similar construction sequence as in project "Hypobank" has been modelled:

1. initial stresses (K_0=0.55 assumed for all layers)
2. loads representing buildings applied (displacements set to zero)
3. diaphragm wall wished-in-place
4. excavation to -1.0m
5. activation of first strut
6. lowering of groundwater table inside excavation to -3.8m
7. excavation to -3.8m

8. activation of second strut
9. lowering of groundwater table inside excavation to -10.0m
10. excavation of centre part (berm left for support) and
11. construction of concrete slab
12. removal of berm
13. construction of remaining part of concrete slab

3.1 *Results for project "AMV"*

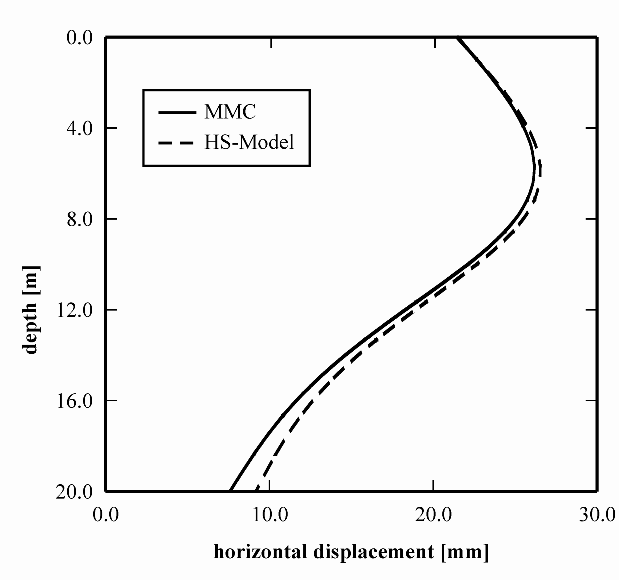

Figure 9. Wall deflection for project "AMV"

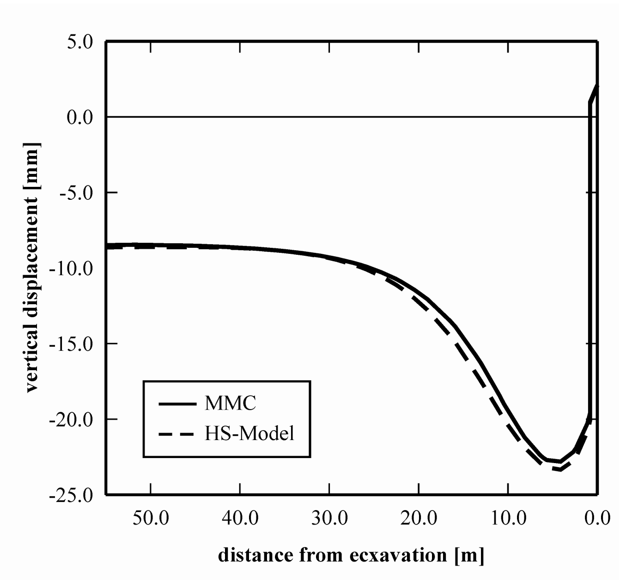

Figure 10. Settlements behind wall for project "AMV"

Figure 9 shows the wall deflection obtained from both models but the differences are negligible in this case. As a consequence bending moments calculated are almost identical as well. The relatively large horizontal movement at the top part of the wall, despite the presence of struts, can be explained by the fact that pressure cells have kept the support force at a constant value of 100 kPa. Figure 10 plots the surface settlements behind the wall and it follows that the magnitude of the maximum vertical displacements is roughly the same as for horizontal displacements. It is obvious that both models can reproduce plausible settlement troughs, which would be very difficult to achieve with a simple elastic-perfectly plastic constitutive model (e.g. Schweiger, 2002), and also the amount compares well to the measured value of 26mm. The calculated horizontal deformation of the top of the wall during construction is depicted in Figure 11. Significant wall movement only starts when excavation reaches the clayey silt layers and again the measurement at the final stage is in excellent agreement with the calculated value.

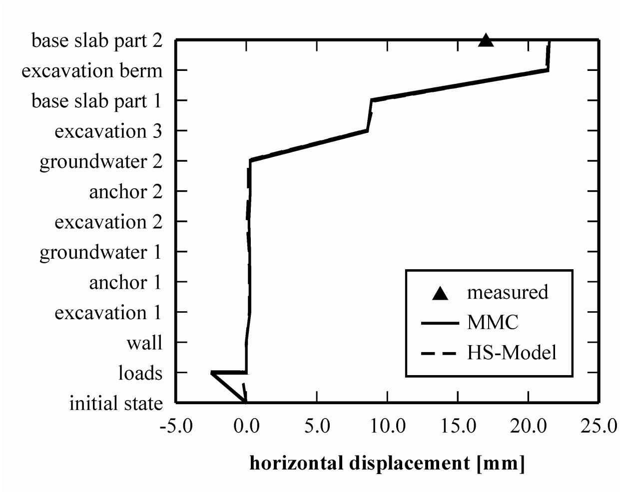

Figure 11. Horizontal displacement of wall head for project "AMV"

4 SUMMARY AND CONCLUSIONS

In this paper results from finite element analyses of deep excavations in soft soil have been presented employing two different constitutive models for soils. Calculated displacements have been compared with in situ measurements. It can be concluded that both models used, namely a standard elasto-plastic soil model and a newly developed model based on the multilaminate framework, are capable of representing the mechanical behaviour of soft soils for stress paths experienced in this type of problems. Although the multilaminate model is more complex than the Hardening Soil model the differences in results are not pronounced for the cases discussed in this paper. The reason for this is twofold: firstly it has been shown (e.g. Schweiger, 2002) that elasto-plastic models are in general suitable for analysing deep excavation problems producing results in agreement with field observation and secondly the deformation behaviour is mainly governed by the support system and thus anisotropic behaviour, as captured by the multiaminate model, does not play a significant role.

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