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FINITE ELEMENT MODELLING OF A DEEP EXCAVATION IN THE OVERCONSOLIDATED MIOCENE SOIL OF VIENNA

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ABSTRACT

This contribution deals with the numerical modelling of a 33-meter-deep excavation in the overconsolidated soil of Vienna. The retaining walls of the pit were realized by diaphragm walls which will be integrated into the newly constructed shaft of the metro station Matzleinsdorfer Platz. A comprehensive deformation monitoring system had to be installed on the site due to deformation-sensitive buildings in the vicinity of the shaft.

Numerical 2D- and 3D-models, based on the finite element method, are created and compared with each other. Elastoplastic material models with isotropic hardening (Hardening Soil Model with and without small strain stiffness) are used for the calculations. The soil stiffness parameters of the Hardening Soil Model are determined through laboratory as well as field tests. Due to the low hydraulic permeability of the soil, the study also explores the impact of various drainage conditions (drained, undrained, consolidation) on the deformation behavior of the diaphragm shaft, resulting in a set of 24 calculation models. The calculated deformations are compared with the in-situ measurements of the actual shaft to validate the used soil stiffness parameters and material models. After a thorough analysis of the results, an appropriate calculation model is chosen for soil parameter and sensitivity analyses.

In the soil parameter study, the effect of the pre-consolidation pressure of the overconsolidated miocene soil layers on the deformation of the diaphragm walls and excavation base is analyzed by varying the pre-overburden pressure (POP) in the calculation model. Furthermore, assuming that all applied soil parameters are statistically descriptable by a normal distribution, shear and stiffness parameters are varied based on standard deviations from literature. The sensitivity study further explores the influence of the diaphragm wall thickness and concrete beam prop width on the deformation behavior of the shaft.

Keywords: numerical modelling, deep excavation, hardening soil model, finite element analysis, parameter study, overconsolidation.

INTRODUCTION

The Finite Element Method (FEM) has become the dominant numerical solution method in structural engineering. While numerical methods are increasingly used for geotechnical problems in Austria, they have not yet become standard practice due to the lack of national regulations and guidelines for modelling and verification. As a result, practitioners are required to consult additional literature, such as [3].

Geotechnical problems are often highly complex, and analytical methods often reach their limitations. To obtain computational results, these methods typically rely on highly simplified assumptions and abstracted representations of soil behavior (e.g. slip surfaces in slope stability or earth pressure distribution for braced retaining walls). In contrast, numerical methods require fewer assumptions, as failure mechanisms emerge naturally from the finite element calculation rather than being predefined [6].

In geotechnical engineering, no universal material model exists that is suitable for all applications. Instead, the choice of an appropriate model depends on the specific problem and the characteristics of the soil [3].

The Hardening Soil Model (HS-Model) is an elastic-plastic material model with isotropic hardening [8]. A key aspect of this model is its formulation of stress-dependent and stress-path-dependent stiffness parameters which allow the definition of different material parameters for initial loading, unloading, and reloading, while accounting for the specific type of loading. The Hardening Soil Model with small-strain-stiffness (HSS-Model) extends the standard HS-Model by incorporating the small-strain-stiffness-effect. This effect accounts for the increased stiffness of soil at lower shear strains, enhancing the model's ability to represent more realistic soil behavior.

In this paper the effects of different material models, drainage conditions and soil stiffness

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parameters on the results of FE-calculations are investigated using the numerical modelling of a deep diaphragm wall shaft in the over consolidated soil of Vienna. To perform the modelling and the subsequent deformation analysis of the shaft, the FE-software Plaxis 2D and 3D (version 2023.1) is used, applying the Hardening Soil Model (with and without small strain stiffness). A distinction is made between two different soil parameter sets, one derived from field tests using self-drilling pressiometers, Set 1, and one derived from conventional laboratory tests, Set 2. The calculation results are then compared with the in-situ measurement results of the constructed shaft. The calculated deformations of the diaphragm walls are validated by inclinometer measurements. The calculated shaft heave is validated by means of extensometer, hose level and geodetic level measurements [6].

DESCRIPTION OF THE PROJECT "SCHACHT TRIESTER STRASSE"

The shaft was constructed using the Top-Down-Method, with the excavation pit being enclosed by a 1,20 m thick diaphragm wall. The shaft has an almost parallelogram-shaped floor plan with dimensions of around 65 m x 35 m and an excavation depth of around 33 m (Figure 1).

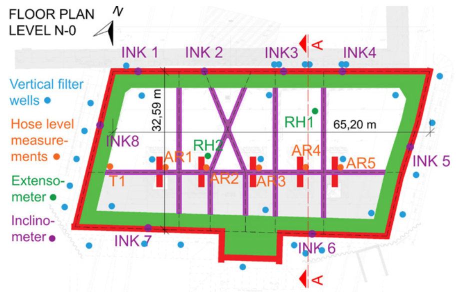

Figure 1 *Floor plan level N-0*

Four bracing horizons (levels N-0, N-2, N-3 and N-4) were constructed, whereby the bracing horizon in the lowest level N-4 was installed as temporary steel bracing and removed again after the base slab was constructed. In the middle of the shaft, free-standing diaphragm wall slats were built as temporary central pillars, which serve as supports for the bracing beams. A reinforced concrete beam in longitudinal direction of the shaft connects all the other bracing beams and rests on the temporary central pillars. To compensate the heave of the central pillars that occurs during the shaft excavation, the longitudinal concrete beam is supported on a height-adjustable hydraulic jacking system [6].

The subsurface conditions are mainly characterized by Miocene deposits of the Vienna Basin, which are overlain by Pleistocene terrace gravels (see Figure 2). The Miocene layers (also called "Wiener Tegel") are over consolidated, clayey silts. During the construction period, vertical filter wells were installed both inside and outside the shaft for groundwater lowering [6].

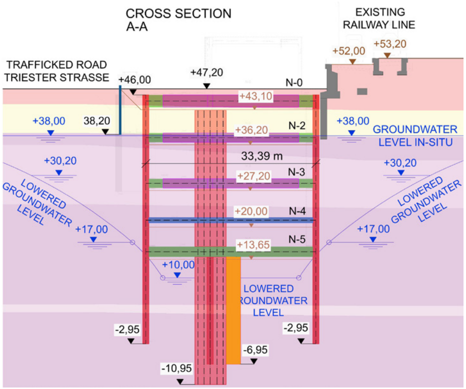

Figure 2 *Cross section A-A*

The horizontal deformation behavior of the diaphragm walls was monitored using 8 vertical inclinometers. To continuously monitor the heave of the central pillars, hose scales were installed in level N-2 and geodetic measurements were carried out (measuring points AR 1 - AR 5). Two chain-extensometers were used to monitor the heave of the excavation base (RH 1 and RH 2) [6].

NUMERICAL MODELLING OF THE SHAFT

For the HS stiffness parameters (E_{50}^{ref}, E_{oed}^{ref} and $E_{ur}^{ref)}$ of the Miocene soil layers, a lower limit was determined from conventional laboratory tests (Set 2) and an upper limit from in-situ self-drilling pressiometer tests (Set 1). The HS-parameters of the remaining soil layers and those parameters required to take the small-strain-stiffness effect into account (G_0 and $\gamma_{0.7}$) are determined using empirical equations and correlations from literature ([1], [2], [4], [5], [9]). For the exact calculation of these HS(S)- parameters, please refer to [6]. Both sets of soil parameters are summarized in Table 1.

In the 2D-model, the outer diaphragm walls and the base slab are modelled as linearly elastic, isotropic plate elements. The bracing beams and the temporary steel struts are modelled using node-to-node anchors, while square pile elements (embedded beam rows) are used for the central pillars, which are coupled to each other via rigid bars [6]. The force reduction factor $_{Rinte}$r, which defines the soil-structure-interaction, can be assumed to be 0.80 to 1.00 based on the surface and soil properties for the miocene soil layers based on the investigations by Potyondy [7].

In the 3D-model, all diaphragm walls are modelled as plate elements with anisotropic, linear elastic material behavior (cross anisotropy), allowing separate elasticity parameters to be defined in the longitudinal direction of the excavation. The reduction factor α = 0,65 proposed by Klein & Moormann [5] is adopted, to reduce the stiffness of the diaphragm wall in longitudinal direction (EI_z = 0,65 · EI_y). The connection between the outer diaphragm walls in the corners of the shaft is modelled as rigid according to [5] and [10].

Table 1 *Soil Parameter Set 1 (field tests) and Soil Parameter Set 2 (laboratory tests) of the miocene soil layers (Mz)*

Symbol	Unit	Miocene (Set 1)	Miocene (Set 2)
γ_{unsat}	kN/m³	20,0	20,0
γ_{sat}	kN/m³	20,5	20,5
γ'	kN/m³	10,5	10,5
E_{50}^{ref}	kN/m²	20 000	10 000
E_{oed}^{ref}	kN/m²	25 000	10 000
E_{ur}^{ref}	kN/m²	100 000	40 000
m	-	0,80	0,80
p^{ref}	kN/m²	100	100
ν_{ur}	-	0,20	0,20
G_0^{ref}	kN/m²	120 000	80 000
$\gamma_{0.7}$	-	4E-04	4E-04
c'	kN/m²	30	30
φ'_{HS}	°	25	25
ψ	°	0	0
R_{inter}	-	0,90	0,90
K_0	-	0,75	0,75
K_0^{NC}	-	0,58	0,58
POP	kN/m²	800	800

The concrete bracing beams are modelled as beam elements, while the temporary steel struts in level N-4 are defined as node-to-node anchors. The hydrogeological boundary conditions (groundwater lowering) are defined by the reconstruction of a drawdown funnel based on the measured groundwater levels and the well locations (Figure 1 and Figure 2) [6].

ANALYSIS AND INTERPRETATION OF THE CALCULATION RESULTS

ToTo validate the calculated diaphragm wall deformations, inclinometer measurements from measuring point INKL 3 were used. These measurements were taken after the removal of the temporary steel struts at level N-4. The best agreement with the measured diaphragm wall deformations was achieved using the consolidation calculation of the 3D-HSS-Model with Soil Parameter Set 2 (pink solid line in Figure 3).

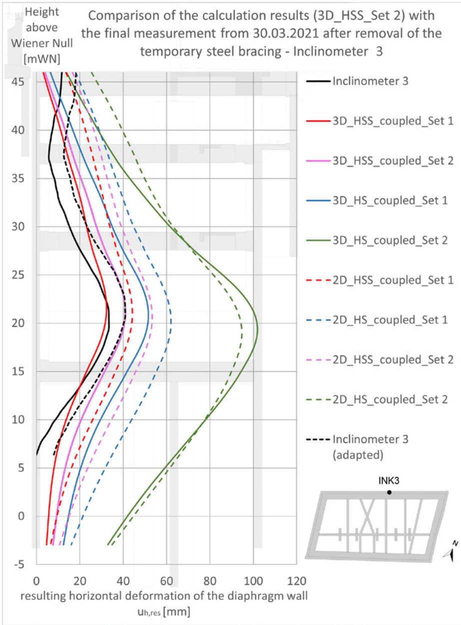

Figure 3 *Deformation of the diaphragm wall 3*

The inclinometer tubes do not extend to the end of the diaphragm wall, as would generally be desirable for deformation measurements, but instead end about 7 m above the toe. To enable comparison of the measurement results with the calculation results, the measurement curve had to be adjusted. The additional displacement of the measurement curve corresponds to the calculated base displacement from the consolidation analysis using the 3D-HSS-Model with Soil Parameter Set 2, as this configuration best represents the measured data, and serves as an estimate for the translational horizontal displacement of the wall [6].

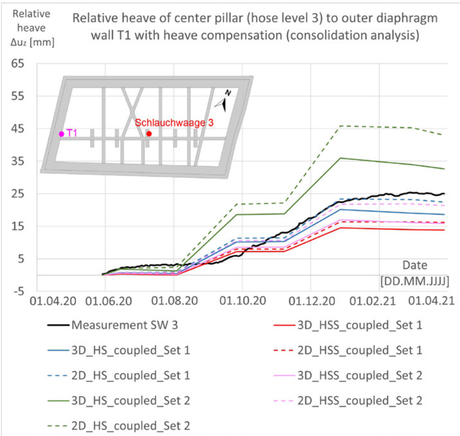

Figure 4 *Relative heave of the central pillar 3*

The results of the hose level measurements in the area of the central pillar 3 are used to compare the measured heave with the results of the FE-calculation. A distinction is made between the relative heave from the measurement data of the hose scale 3 in relation to the reference point T1 and the absolute heave from the geodetic measurement data of the measurement point AR 3 [6].

Despite deviating from the measurement results in a few areas, the consolidation calculation results of the 3D-HSS-Model with Soil Parameter Set 2 (pink solid line in Figure 4) sufficiently reproduce the measured absolute heave (geodetic measurements) and the relative heave (hose level measurements) of the central pillar. For the analysis of the excavation base heave, the force in the steel bracing, and the sensitivity and parameter study, further details can be found in [6].

CONCLUSION

The calculation results of the 3D-HSS-Models using Soil Parameter Set 1, derived from field tests, are consistently lower than the measured diaphragm wall deformations and excavation base heave. In contrast, the 3D-HS-Models with Set 1 slightly overestimate the measured shaft deformations due to the absence of the small-strain stiffness effect [6].

When using the HSS-Model, horizontal diaphragm wall deformations and excavation base heave were consistently smaller than those obtained with the HS-Model. Neglecting the small-strain-stiffness-effect resulted in calculated diaphragm wall deformations being up to 149% larger and excavation base heave up to 385% larger compared to the HSS-Models. As expected, the 2D-Models predicted greater deformations than the 3D-Models, as plane-strain analyses cannot account for spatial effects [6].

Basal heave, as determined by undrained and consolidation calculations, is significantly lower than in drained calculations. This reduction is attributed to the negative pore water pressure generated during the excavation.

The best agreement between calculated and measured results was achieved with the 3D-HSS-Model using Soil Parameter Set 2 (from laboratory test) and consolidation analysis [6].

For the broader adoption of Finite Element Analysis in geotechnical engineering, reliable material parameter determination is crucial, as the accuracy of numerical calculations heavily depends on these parameters. To accomplish this, extensive numerical comparisons and back-calculations are required to validate the derived parameters [6].

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