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Pile-Soil-Wall-Interaction during the construction process of deep excavation pits

Interaction entre les pieux et le mur de soutènement durant la construction des excavations

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ABSTRACT
In conventional design of retaining walls the influence of the foundation piles is not regarded. The results of the performed numerical examinations – based on a small scale model test series – which are presented in this paper derive an influence of the piles on the development of the passive earth pressure. This influence leads to a strengthening of the earth wedge respectively a reduction of the wall deformation and depends of several parameters like the pile grid geometry, the embedment depth of the retaining wall or the pile diameter.

RÉSUMÉ
Le dessin et la mesure des murs de soutènement ne considèrent pas l'influence des pieux de la fondation. Les résultats des simulations numériques qui sont fondées sur une série des essaies sur modèle montrent une influence forte sur le développement de poussée des terres. Ce renforcement de la sol va au pair avec une réduction de la déformation de la mur et est dépendant des paramètres comme la distance entre la ligne des pieux la plus prochain à la mur où la diamètre des pieux.

1 INTRODUCTION

In many cases deep excavations are connected to the construction of pile foundations or Combined Pile Raft Foundations (CPRFs) (Katzenbach et al., 1999). The fact that the piles are already installed before the main excavation process has started offers two benefits: On the one hand the presence of the pile leads to a reduction of the heaves connected to the unloading during the excavation process. On the other hand, the piles are loaded by the lateral movement of the retaining structure and therefore work as an earth reinforcement reducing the retaining wall displacements respectively increasing the passive earth pressure by dowelling the earth wedge. This dowel effect is evidenced by displacement measurements on retaining structures showing that the wall deformations are much less than predicted.

The impact of lateral ground movements on piles has been described by Heyman (1965) who reported about the influence of lateral earth pressure on pile foundations and Chen and Poulos (1997) who developed linear elastic solutions for simple soil movement profiles to enable approximate assessment of the pile head deflection and the maximum bending moment. Furthermore, Nalcakan and Ergun (2001) report about model tests on laterally loaded piles.

This paper deals with the development of a numerical model based on small scale model tests performed in dry quartz sand suitable for model tests (Turek et al., 2003, Heineke et al., 2001). The numerical model was calibrated by simulating the model tests and afterwards provided with the soil conditions of Frankfurt am Main for comprehending numerical parameter studies on the influence of the dowel effect on the passive earth pressure.

2 SMALL SCALE MODEL TEST SERIES

The basis for the numerical studies is a 1g small scale model test series (Moormann 2003) with the goal to gain knowledge about the quantity of the dowel effect and to achieve a data basis for the subsequent numerical simulation series. The dimensions of the small scale model test series using a model scale factor for the length of 1/50 were determined based on typical dimensions of CPRFs and excavation pits in Frankfurt am Main. The passive earth pressure has been activated by forcing the upper part of the test setup wall into the soil (figure 1).

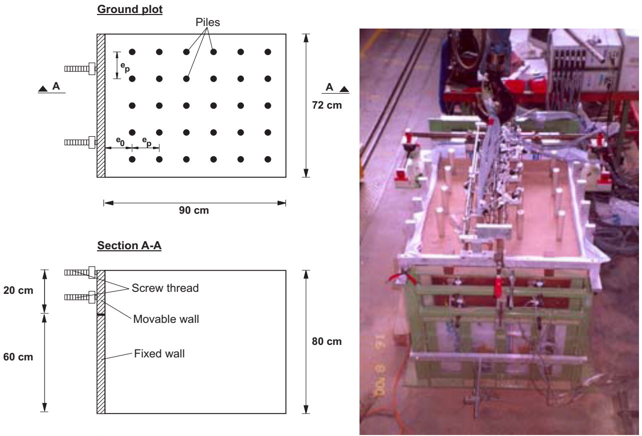

Figure 1. Exemplary layout and photo of the model test setup.

Within the model test series the following parameters were varied to quantify their influence on the increase of passive earth pressure:

- Distance between the first row of piles and the retaining wall e_0 (figure 1)
- Distance between the piles within the pile grid e_p (figure 1)
- Embedment depth of the retaining wall t
- Wall displacement type (parallel translation, rotation about wall top, rotation about wall base, rotation about a deep fixed point in a distance of 1.25 t from the wall base)

Important results of the test series are:

- The increase of earth pressure due to the dowel effect is non-linearly dependent on the wall displacement.
- The increase of earth pressure depends severely on the type of the wall displacement.
- The earth pressure increases with decreasing geometrical parameters e_0 and e_p.

3 DEVELOPMENT OF THE NUMERICAL MODEL

The numerical model used for the simulation series had to be calibrated by means of the performed small scale model test series. The results of the model tests comprise the influence of the friction at the lateral setup walls which had to be identified to be sorted out. Therefore, a method for the consideration of the lateral wall friction was developed. Furthermore, it was envisaged to model only a section of the total setup leading to the development of the "3-D-Slice Model" taking advantage of the twofold symmetry of the installed pile grids (figures 2 and 3). The results of the numerical simulations show a good agreement to the output of the small scale model test series (figure 4).

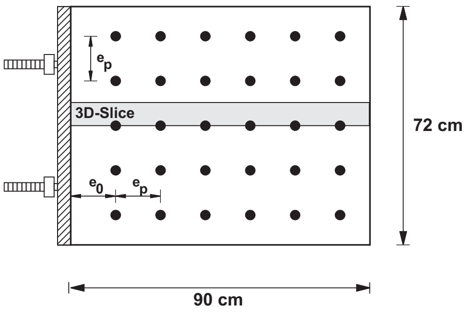

Figure 2. 3-D-Slice • Top view.

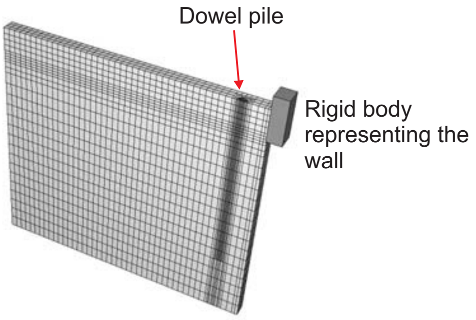

Figure 3. Exemplary numerical 3-D slice model

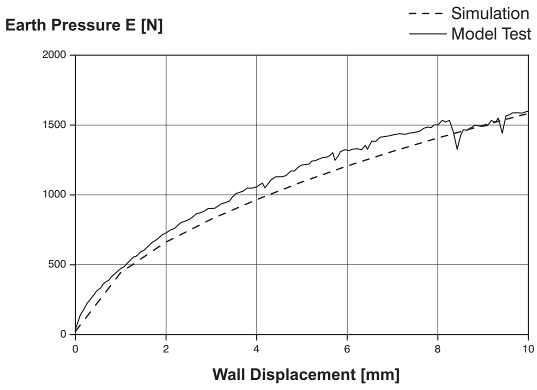

Figure 4. Example for the comparison between the results of the model tests and the numerical simulations

4 NUMERICAL PARAMETERS STUDIES

The calibrated numerical model was provided with the soil conditions of Frankfurt am Main to analyse the dowel effect of foundation piles for excavation pits in the Frankfurt clay.

The modified Drucker-Prager/cap model was used to simulate the material behaviour of the Frankfurt clay (figure 5). This constitutive law uses two yield surface segments: the pressure dependent, perfectly shear failure surface and the compression cap yield surface (Chen and Mizuno, 1990, Katzenbach et al., 1998). Changes of stress within the yield surfaces cause only elastic deformations while stress changes on the yield surface lead to plastic deformations. The shear failure surface is perfectly plastic whereas volumetric plastic strains can lead to hardening by changing the cap position. The material parameters for the Frankfurt clay are summarized in table 1.

Table 1: Material parameters of the Frankfurt clay

Material Parameter	Symbol	Dimension	Value
Angle of friction	φ'	[°]	20.0
Cohesion	c'	[kN/m²]	20.0
Young's modulus	E	[kN/m²]	50000
Poisson's ratio	υ	[-]	0.25
Buoyant unit weight	γ'	[kN/m³]	9.0

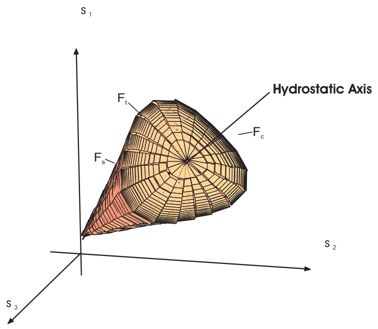

Figure 5. Yield surface of the modified Drucker-Prager/cap model

A variation of four parameters was performed to identify their influence on the dowel effect. These parameters are:

- Embedment depth of the retaining wall t
- Distance between the first row of piles and the retaining wall e_0
- Distance between the piles within the pile grid e_p
- Diameter of the foundation piles D

The analysis of the numerical studies was focused on the increase of passive earth pressure. This strengthening of the earth wedge is expressed by the displacement dependent earth pressure increase factor α_{EEF} which is defined by the ratio of the earth pressure regarding the dowel effect and the earth pressure of the simulations without piles:

$$\alpha_{EEF} = \frac{E_{with\ piles}(u)}{E_{w/o\ piles}(u)} = \alpha_{EEF}(u) \qquad (1)$$

The subsequent figures show the earth pressure increase factor α_{EEF} in dependence of the varied parameters for the configuration $e_0 = 1.5$ m, $e_p = 3$ m, $t = 3$ m and $D = 1.5$ m. During the analysis only one of the parameters was varied while the others were kept constant. The earth pressure increase factor α_{EEF} is displayed for a wall movement of u = 5 cm and u = 10 cm.

The earth pressure increase factor α_{EEF} rises with decreasing pile-wall-distance e_0. This effect is caused by the smaller buffer of soil between the first pile row and the wall (figures 6 and 7) so the magnitude of deformation required for the activation of the dowel effect is becoming smaller by decreasing pile-wall-distance e_0.

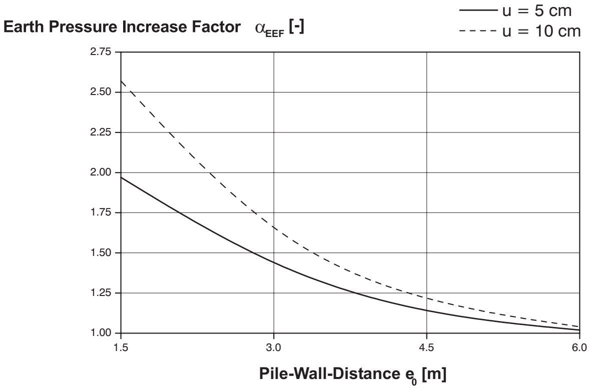

Figure 6. Earth pressure increase factor α_{EEF} in dependence of the pile-wall-distance e_0 (e_p = 3 m; t = 3 m; D = 1.5 m)

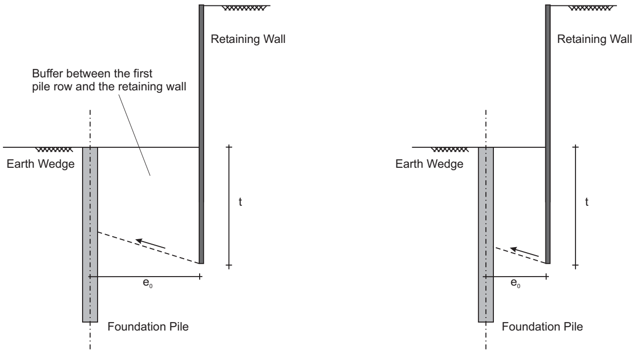

Figure 7. Section view through the earth wedge at different pile-wall-distances e_0.

A decreasing pile-pile-distance e_p and a larger pile diameter D lead to a higher compound stiffness of the whole earth wedge and therefore the earth pressure increase factor α_{EEF} rises (figures 8 and 9).

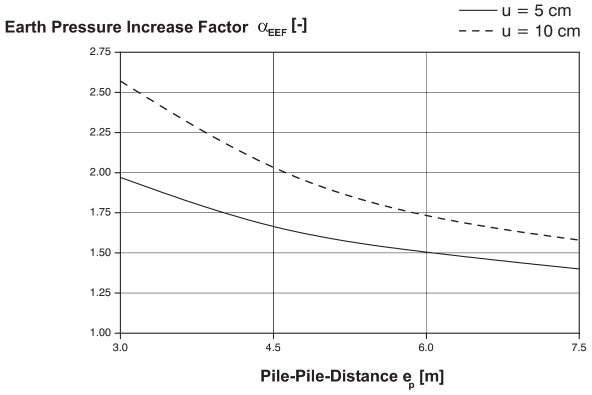

Figure 8. Earth pressure increase factor α_{EEF} in dependence of the pile-pile-distance e_p (e_0 = 1.5 m; t = 3 m; D = 1.5 m)

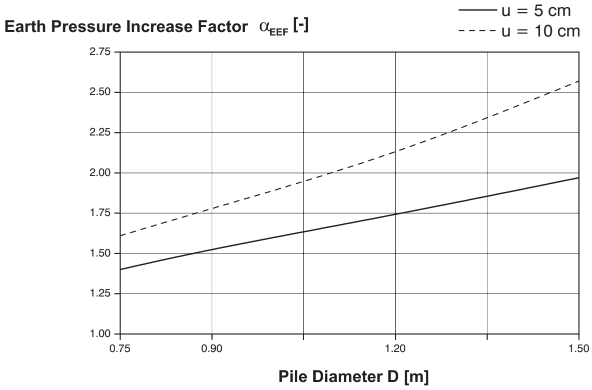

Figure 9. Earth pressure increase factor α_{EEF} in dependence of the diameter of the pile D (e_0 = 1.5 m; e_p = 3 m; t = 3 m)

An increasing embedment depth leads to smaller earth pressure increase factors α_{EEF} which has to be ascribed to the larger loading of the piles (figures 10 and 11).

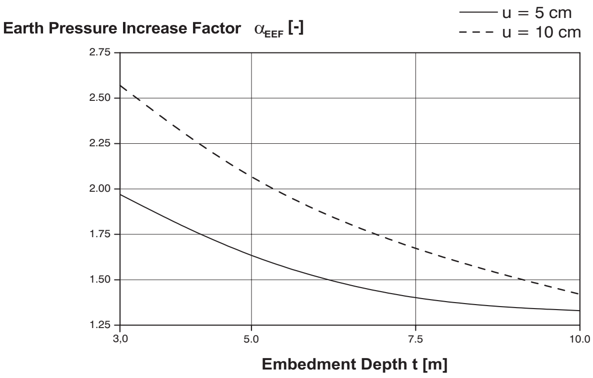

Figure 10. Earth pressure increase factor α_{EEF} in dependence of the embedment depth of the wall t (e_0 = 1.5 m; e_p = 3 m; D = 1.5 m)

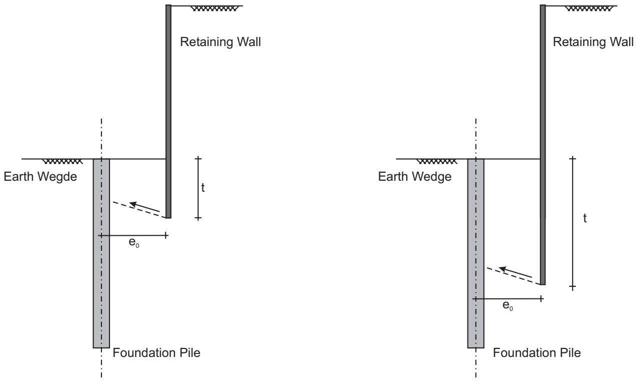

Figure 11. Section view through the earth wedge at different embedment depths t.

The comparison of the plastic strains occurring in the simulations with and without dowel piles shows a completely diverging formation of the shearing zone. The simulation without dowel piles yields a shear band as expected within the classical theories (figure 12). The inclination angle ϑ of the shear band is about 33° - 34° which comes close to the inclination angle according to Coulomb's theory of about 35°.

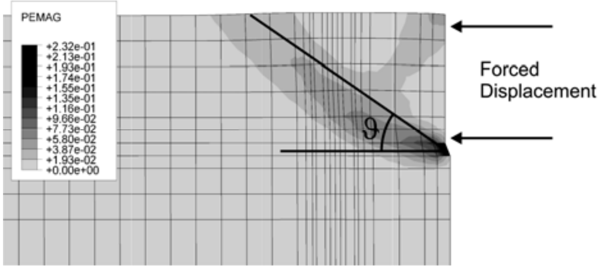

Figure 12. Magnitude of plastic strains in a simulation without dowel piles

The shearing zone in the simulations with dowel piles differs severely from the one of the simulations without piles (figure 13). Due to the stiffening and strengthening effect of the dowel pile the shearing zone is deflected steeply towards the surface and seems to be wrapped around the dowel pile. The largest plastic strains occur along the pile shaft where the soil is performing a vertical relative movement compared to the pile. Apart from these locally focused large strains, the average level of deformation is commonly lower compared to the simulation without dowel piles due to the stiffening and strengthening effect of the piles.

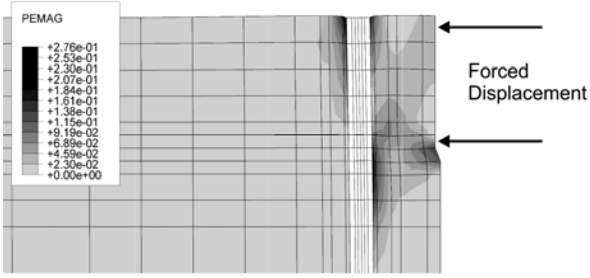

Figure 13. Magnitude of plastic strains in a simulation with one dowel pile

The formation of the plastic strains points out that in cases in which structural units like piles operate as stiffening or strengthening elements no conventional soil mechanical limit state occurs. A limit state has rather to be defined by a limit state analysis including the compound bearing capacity of piles and soil.

5 CONCLUSIONS

The increase of earth pressure due to the dowel effect of foundation piles in front of retaining walls can be simulated based on the results of the small scale model test series. The numerical model developed and validated by means of these model tests is appropriate to simulate the dowel effect increasing the passive earth pressure in dependence to the wall displacements. This model has been successfully used within a numerical parameter studies for the quantification of the earth pressure increase due to the varied parameters.

The following conclusions can be drawn:

- Increasing wall movement leads to an increasing earth pressure increase factor α_{EEF}.
- Decreasing pile-wall-distance e_0 means a super-proportionally increasing earth pressure increase factor α_{EEF}.
- Decreasing pile-pile-distance e_p causes an increasing earth pressure increase factor α_{EEF}.
- An increasing diameter of the piles means a rising earth pressure increase factor α_{EEF}.
- The earth pressure increase factor α_{EEF} rises by decreasing embedment depth of the wall.
- No conventional soil mechanical limit state can be observed soils reinforced by piles and laterally loaded by retaining walls.

Considering the dowel effect an increase of the passive earth pressure can be achieved and this permits an effective reduction of the embedment depth of the wall and thus an economical and technical optimization of the retaining structures.

The results are at present only available for soil conditions in Frankfurt am Main so the cognitions of the numerical studies have to be generalised to be adapted to arbitrary soil conditions. Moreover, it has to be investigated if the results gained within these studies are applicable on further geotechnical objectives like the stabilisation of embankments and slopes.

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