SOIL PRESSURE IN EMBANKMENT STABILIZATIONS
Analysis of the 3D shadowing effect of piles

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ABSTRACT:
Pile checks required by the codes alone are usually not sufficient when dealing with complex foundation systems or difficult sub soil conditions. A differentiated illustration of the piles as well as the adjacent components will be necessary. This leads up to the analysis of the structure together with the foundation in one total system.
The essay analyzes a modeling option of piles in the FEA analysis with non-linear volume elements. Exemplified at a container-terminal-quay, the modeling analyzes the influence of the offshore piles onto the horizontal soil pressure of the sheet pile.

1. GENERAL

Piles can be modeled in various ways using the SOFiSTiK modules. The modules PilePRO/PFAHL/ASE address non-linearly bedded pile elements for analysis of e.g. combined pile-slab foundations. In the elastic half space (GroundSlab/HASE/ASE) non-linear piles are implemented as well. However this essay only considers the pile starting point (boss) as it is also used for the example analysis. The soil will hereby be modeled with BRIC-volume elements with the non-linear material law GRAN, the piles are generated with continuous beams from normal continuous beam elements which are connected to the elements node via non-linear springs (flows). The system was generated using WinTUBE and analyzed with ASE.

Chapter 3 Exemplary analysis of embankment construction presents a concrete application of the BRIC simulation for analysis of the shading effect of the piles onto the horizontal soil pressure of a bank structure.
2. SIMULATION OF PILES IN A BRIC-STRUCTURE

2.1 Applied system

2.1.1 Geometry and modeling

A bored pile with a diameter of 1.2m and a length of 9.5m is used as a comparative system. The system is oriented at example 25 of K.Simmer, „Grundbau Teil 2, Baugruben und Gründungen“ (foundation engineering, part 2, building pits and foundations):

In order to be able to specify a boundary coat friction, the beams are not directly connected to the BRIC-nodes but through coupling fields. The effecting (acting) direction of the springs is set via a small offset (5 cm) of the beams in their longitudinal direction and determined from the boundary coat friction of the adjacent beams. The spring at the pile peak is applied linearly, so that the peak pressure can build up.

Test system with one pile

Test system with three piles
2.1.2 Materials and characteristics

The following material and spring parameters are applied for the soil:

Clay, material law GRAN:
- E-Module, loading: $E_{50}^{\text{REF}} = 40 \text{ MPa}$
- E-Module, de- and re-loading: $E_{ur} = 80 \text{ MPa}$
- Poisson’s ratio $\nu = 0.35$
- Specific gravity: $\gamma = 20 \text{ kN/m}^3$
- Specific gravity under uplift $\gamma' = 10 \text{ kN/m}^3$
- Friction angle: $\phi = 10^\circ$
- Cohesion: $c = 100 \text{ kN/m}^2$
- Tensile strength: $f_t = 0 \text{ kN/m}^2$
- Dilatancy angle: $\psi = 5^\circ$
- Exponent: $e = 0.7$
- Fraction factor: $BF = 0.9$
- Reference pressure: $P_{\text{ref}} = 100$

The boundary coat friction in the clay is applied with $\tau_{mf} = 100 \text{ kN/m}^2$.

2.1.3 Loading

The loading onto the pile’s head is applied according to the following load history. Two load case groups are analyzed:

Load case V: The load history will be applied as vertical load onto the pile’s head and each corresponding subsidence at the pile’s head will be determined from the FE analysis. The target is to determine a load settlement curve which can be compared to the trial loading. A further result shall be the course of the normal load in the pile.
Load case H: The load history will be applied as horizontal load on the pile’s head and the corresponding horizontal displacement at the pile’s head will be determined. A further result shall be the moment line.

As the loading analogue to a pile trial load not only increases during the course of the load history but it is also decreased and the material law may differ between de- and re-loading, a remaining plastic deformation should be represented in the analysis (see right side of the following diagram).

### 2.2 Determination of the load settlement curve
This curve allows determining the limit load of the pile according to DIN to about $Q_g = 1500$ kN. If trial loads of the pile to be used are already present, the FE-simulation allows calibrating the pile by selecting suited coupling fields and mesh fineness.

2.3 Analyzing the influence of the mesh fineness on the applied model

The settlement behavior of the pile model is in essence determined by three parameters:
- Applied yield point load of coupling fields (boundary coat friction)
- Actuarial assumption of the material law
- Dimension of the adjacent BRIC-elements

If the rigidity of the coupling fields has been correctly selected, they should only play a secondary role. The deformations should also arise from the adjacent BRIC-element and not from the spring’s compressive strain.

The BRIC element size in the pile’s area determines together with the soil parameters, the material law and the yield point loads of the coupling fields, whether the springs or the soil fails first. Thereby load settlement curves arise in dependence of mesh fineness.
2.3.1 Vertical load

The following graphic shows the effects of the mesh fineness. In case of the coarser mesh width the appearing load at the BRIC node is distributed on a larger element area. Thereby smaller stresses and settlements arise.

In order to represent the influence area of the pile correctly, the BRIC elements in the area of the pile should be (analogue to connection of a column at a slab) just as large as the cross section areas of the pile.
2.4 **Horizontal load**

![Graph of load vs deformation](image)

Even in case of horizontal loads, the remaining plastical deformations appear as they have been measured in field experiments.
2.5  **Analysis of the reciprocal influence of piles (shadowing effect)**

Piles standing close to one other mutually influence each other. In case of a vertical load, e.g. a common subsidence cavity develops. In case of horizontal loading a reciprocal shadowing effect appears.
2.5.1 Vertical load

The following diagram shows the settlements of three with a distance of 3*d standing single piles. Due to the symmetrical arrangement, the two outer piles settle in the same way. The middle pile receives by far larger settlements.

The normal force stress remains (in case of clack load) however almost the same:
2.5.2 **Horizontal load**

Any of the three piles receive the same horizontal load:

Displacement into Y-direction (height line) and pile moments (line removal)
3. EXEMPLARY ANALYSIS OF EMBANKMENT CONSTRUCTION

3.1 General

Larger and larger container vessels are used for maritime transport. Thereby the demands of the amount and required water depth for ships moorages rise substantially. The typical water depths at the harbor’s quays are by about 15 to 20 m below the average sea level! Due to reasons of the tidal range and the high tide water safety the upper edge of sheeting is at 5 to 8 m above NN. Therefore terrain (height) differences of 15 to 20 meters have to be mastered.
Usually the first interim storage for containers can be found in immediate proximity of the piers and thereby close to the sheet pile head. In order to protect the sheet pile from the high pile loads, usually a pile foundation grillage serving as foundation for a reinforced superstructure is applied. This superstructure also absorbs the crane tracks of the pier in case of smaller track gauges.

In case of larger piers with gauges of about 30m (and a height of often more than 100m!) the crane rail in the back is usually bedded on a separate substructure.
3.2 **Target of the analysis**

The comparative analysis was initiated by a discussion about the shadowing effect onto the horizontal soil pressure by which the sheet piling of the reinforced concrete superstructures offshore piles.

A uniformly statical concept does not exist. The government agency Electricity and Harbor Construction in Hamburg recommends applying an increased friction angle for soil pressure on the sheet piling in the style sheet 15 depending on the construction degree:
Maßgebende Werte für die Spundwandberechnung

a.) für den aktiven Erddruck:

\[ \varphi' = \varphi + \Delta \varphi \]

Ermittlung von \( \Delta \varphi \):

\[ \Delta \varphi = 400 \cdot a \times \frac{H+L}{H} \]

Anmerkung:

Die Verbesserung der Bodenwerte für die Bemessung der Spundwand und der Verankerung kann auch für die Berechnungsebene II angesetzt werden, d.h. es gelten die K3-Werte für \( \alpha \), \( \gamma' \) und \( \delta \).

b.) für den passiven Erddruck:

sandige Böden: \( \varphi' = \varphi - 32,5 \)° für \( x \leq 3,00 \) m

bindegige Böden: \( \varphi' = \varphi' - \varphi = c' \) für \( x > 3,00 \) m

Für überragend auf Wasserüberdruck beanspruchte Wände, sowie für frei ausgerändete Konstruktionen sind die Scherparameter für den Nachweis der Rammliefe wie folgt zu reduzieren:

\[ \tan \varphi' = \tan \varphi \times \frac{1}{1 + \gamma'} \]

D.h. der Abminderungsfaktor für die Bodenfläche ist nicht um \( \alpha \) erheblich erhöht.

Standsicherheit:

Für den Nachweis der Geöffnungsbrechung und des geöffneten Spundwandbereiches gelten die Grundwerte der Böden \( \varphi' \) und \( c' \).

Für die Berücksichtigung von eventuellen Erddruckumlagerungen ist die Ankerkraft aus Erddruck generell um 15% zu erhöhen.

Empfehlung für die Spundwandberechnung

Freie H. Hamburg/Musselbau GmbH

Musterblatt Nr.: 15


c) Spirale
3.3 **Statical system**

As statical system for the FEA comparative analysis a spatial (3D) BRIC-structure was selected. Due to the applied pile and plank grid the thickness of the examined section from the line structure had to be 2*2.72m.

3.3.1 **Geometry**

![Diagram](image)

3.3.2 **Materials and characteristics**

While the tender to determine the horizontal soil pressure allows for an increase of the friction angle of about 15%, the FEM model with explicit consideration of the shading effect however requires unchanged characteristics. The applied material law was GRAN – which has been implemented for volume elements as well a short while ago.
As in the present case soil exchange was conducted with a dredge up to the depth of the later harbors base before construction start, only two different layers are applied:

Clay (below the harbors base):
E-Module, Load: $E_{50}^{REF} = 40 \text{ MPa}$
E-Module, de- and re-loading: $E_{u} = 80 \text{ MPa}$
Poisson’s ratio $\nu = 0.35$
Specific gravity: $\gamma = 20 \text{ kN/m}^3$
Specific gravity under uplift: $\gamma' = 10 \text{ kN/m}^3$
Friction angle: $\varphi = 10^\circ$
Cohesion: $c = 100 \text{ kN/m}^2$
Tensile strength: $f_t = 0 \text{ kN/m}^2$
Dilatancy angle: $\psi = 5^\circ$
Exponent: $e = 0.7$
Fraction factor: $BF = 0.9$
Reference pressure: $P_{ref} = 100$

Filling (Sand):
E-Module, Load: $E_{50}^{REF} = 111 \text{ MPa}$
E-Module, de- and re-loading: $E_{u} = 222 \text{ MPa}$
Poisson’s ratio: $\nu = 0.30$
Specific gravity: $\gamma = 19 \text{ kN/m}^3$
Specific gravity under uplift: $\gamma' = 11 \text{ kN/m}^3$
Friction angle: $\varphi = 35^\circ$
Cohesion: $c = 0 \text{ kN/m}^2$
Tensile strength: $f_t = 0 \text{ kN/m}^2$
Dilatancy angle: $\psi = 30^\circ$
Exponent: $e = 0.7$
Fraction factor: $BF = 0.9$
Reference pressure: $P_{ref} = 100$

The filling planks were applied in a certain way with QUADS with a replacing thickness of 58 cm and a replacing material with the characteristics:

E-Module: $E = 11364 \text{ MPa}$
E-Module anisotropic: $E = 1136 \text{ MPa}$
Poisson’s ratio: $\nu = 0.30$
Specific gravity: $\gamma = 4.25 \text{ kN/m}^3$
Specific gravity under uplift: $\gamma' = 3.7 \text{ kN/m}^3$

So that the bending and elongation stiffness as well as the weight result analogue to the applied sheet pile ARBED AZ26.
The boundary coat friction was simulated by non-linear springs (yield point load) and in the sand it amounts to 80 kN/m² and 100 kN/m² in the clay. The wings at the piles base were considered by an according increase of the effecting pile circumference.
3.3.3 **Construction phases**

**LC1/PLF - Primary state**

**LC2/PLF1 - Installation sheet pile, tensile piles, sand filling 1**
LC3/PLF2 - Sand filling 2

LC4/PLF3 - Sand filling up to working level
LC5/PLF4 - Installation of reinforced concrete super structure incl. piles, sand filling up to final state

LC6/PLF5 - Installation of the back crane track with piles
LC7/PLF6 – Crane load

LC8/PLF6 – Crane and piling load
3.4 Results

Red line: horizontal soil pressure without consideration of the shadowing effect by the pile (cross spring rigidities of the coupling springs equal zero).
Green line: horizontal soil pressure from the 3D-FE Analysis with application of pile shadowing effect.

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<tr>
<th>LC4/PLF3 – Sand filling up to working level</th>
<th>LC5/PLF4 – Installation of the reinforced concrete super structure incl. piles and sand filling up to final state</th>
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![Diagram showing soil pressure in embankment stabilizations](image-url)
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<tr>
<th>LC7/PLF6 - Crane load</th>
<th>LC8/PLF6 – Crane and piling load</th>
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<td><img src="image1" alt="Diagram" /></td>
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- LC7/PLF6 - Crane load
  - Load values: -0.0259, -0.0287, -0.0320

- LC8/PLF6 – Crane and piling load
  - Load values: -0.0239, -0.0259, -0.0272
Green line: Determination of the soil pressure from FEA: LC8/PLF6 Crane and Piling loads
Blue line: Soil pressure for which according to EAB and with the specifications of the tender the friction angle was increased by 15%.

Even though the shielding effect in the 3D analysis is not particularly distinct, and respectively by other effects such as e.g. due to the extreme constraint effect caused by the bedding of the bearing plank at two points in the reinforced concrete super structure, the analyzed soil pressure shows an astonishing good accordance with the one determined in course of the tender - according to the style sheet 15).
4. CONCLUSION

At first one assumes that with increasing modeling complexity problem in the analysis might disappear and a higher exactness could be achieved. For problems with simplified approaches this is also the case. However the more realistic a modeling becomes, the higher will be the influences of boundary conditions which can initially be neglected. For total systems (especially when applying non-linear material laws) e.g. the construction procedure is very often of crucial relevance. In practice the analyzing engineer has a hard time to make an exact statement about the planned construction procedure, not to mention specifying them. Therefore the expected higher exactness due to the more complex modeling is thereby usually used up by the assumptions which have to be made in the area of the construction phases. A crucial effect however of the more complex model is especially the pointing out of the reachable exactness and a deeper insight into the constructions actual structural behavior.

In the ideal case (just like in the presented embankment analysis) it results that the structural behavior of the total system is different as until now assumed in simplified continuous beam analyses with separated soil pressure determination and often rigid supports. By applying the calibration factor, which arise from long year experiences (like here from the recommendations from the authority for electricity and harbor construction) a useful analysis can also be achieved with a simplified model. In this respect the research group for building pits (EAB) and embankment stabilization (EAU) play an important role by realizing the analysis models with justifiable complexity based on their long experiences. These calibrations of the simplified models are also extremely important with regards to the applicable safety coefficients. For foundation engineers they are still a problem in FE analyses with non-linear material laws.