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Effects of pile modelling in case of rigid inclusion ground improvement

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1 Introduction

Ground improvement through vertical rigid piles is an interesting method for foundations on soft, compressible soils. Recently, this process has become widespread in Europe against the traditional pile or pile raft foundations. The behavior of traditional pile foundation concepts are now well known and many researches have dealt with this area of deep foundations. These can be designed by detailed standards and prescribed methods. In contrast, there are still unclear, undeveloped areas in the design of soil improvement methods.

Rigid inclusion contains elements that are slender, often cylindrical shape, mechanically continuous and typically vertical. They are laid out according to a regular mesh pattern, which must be adapted both to the nature and geometry of applied loads and to soil conditions. The rigid inclusion concept implies that inclusion caps are not structurally connected to the supported structure. There is a well-compacted, granular load transfer platform (LTP) between the inclusions and the raft. The LTP has a very important role to ensure the transfer of loads to the ends of the piles and to uniform settlements. A minimum load transfer platform thickness is necessary to allow for appropriate load transfer between inclusions and soils, as well as to limit forces within the supported structure. This thickness, often on the order of 40 to 80 cm, proves essential in deriving an optimal design for the supported structure, particularly with the aim of reducing bending moments in the slabs.

In our research, 3D numerical modelling of rigid inclusion foundation system, the most important question is the pile modelling opportunities. In Plaxis 3D, there are two generally used options for modelling piles, but both has its disadvantages. By the combination of basic elements, so called hybrid elements can be created of which behavior are more favorable.

2 Load Transfer Mechanisms

2.1 Negative Skin Friction

Negative skin friction (NSF) is in fact a downward friction imposed on foundation pile shaft as a result of subsoil settlement. Negative skin friction is usually mobilized to ultimate stress limit in most cases except at very close proximity to the neutral plane. It needs only few millimeters of relative displacement between the settling subsoil and the pile shaft surface. The neutral plane is at the depth, where the settlement of pile and soil is the same. Above the neutral plane where the surrounding soil settles more than the pile, negative skin friction develops along the piles. This causes additional load to be transferred to the piles. Axial load-distribution inside a rigid inclusion in case of negative skin friction is shown in Figure 1.

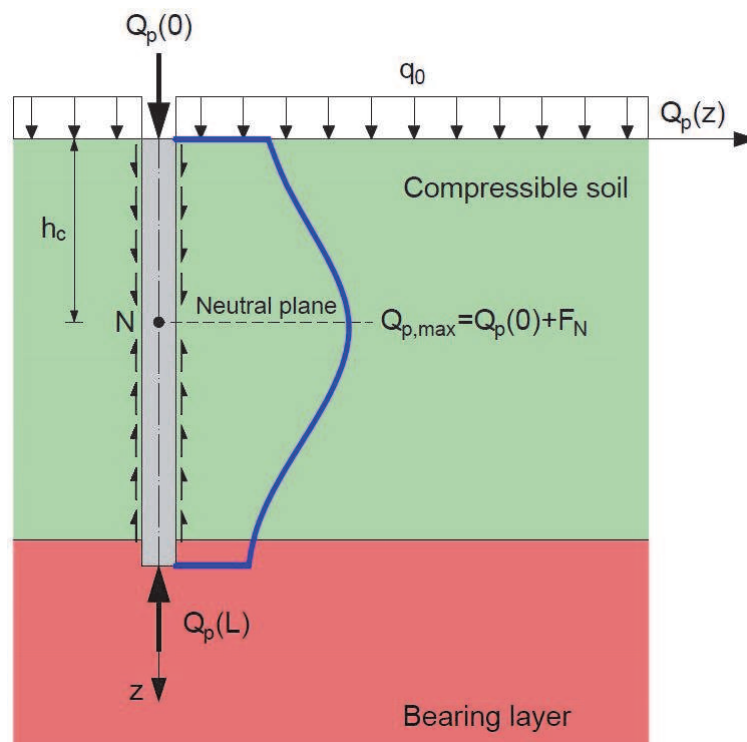


Fig. 1: Axial load-distribution inside a rigid inclusion (ASIRI 2012)

There are many conventional methods to determine the critical height (h_c), which take into account the negative skin friction. The intensity of this negative friction can be calculated based on the following relation:

$$F_N = 2\pi r_p \int_0^{h_c} K \tan \delta \sigma'_v(z, r_p) dz \quad (1)$$

where r_p =inclusion radius; K =earth pressure coefficient; $\tan \delta$ =coefficient of soil-pile friction; $\sigma'_v(z, r_p)$ =effective vertical stress at the inclusion contact in the final state, while taking into account the downdrag effect.

Combarieu (1985) went on to define a radial variation law for vertical stress at height z , by introducing the notation of downdrag effect of soft soil around the inclusion. (Fig. 2).

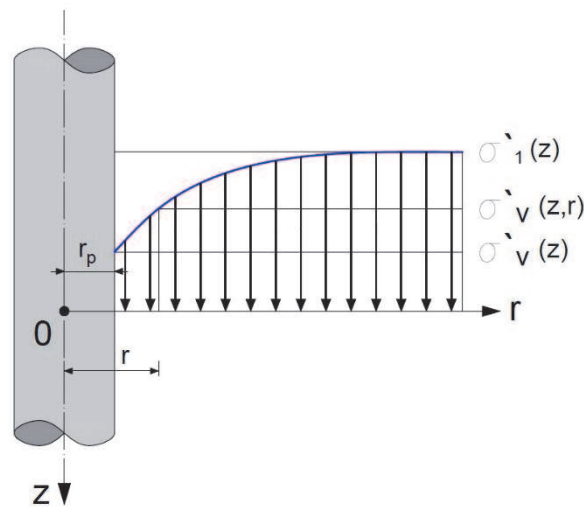


Fig. 2: Distribution of stress around the inclusion (ASIRI 2012)

In the presence of several inclusions, the group effect, which increases as the mesh becomes tighter, combines with the downdrag effect. The average vertical stress between the inclusions is expressed, over the height where negative skin friction is applied, as follows:

$$\sigma_v^*(z) = \sigma_1'(z) - [\sigma_1'(z) - \sigma_v'(z, r_p)] \frac{2K \tan \delta r_p}{(R^2 - r^2) \mu \left(\lambda, \frac{R}{r_p} \right)} \quad (2)$$

where $\sigma_1'(z)$ = effective vertical stress in free field within the ground in the final state, as calculated without taking into account the presence of the inclusions; R = radius of influence; l = downdrag coefficient; m = depends on the downdrag coefficient and the ratio of radius of influence and the inclusion radius.

The critical height is often determined by adapting the hypothesis that negative skin friction only acts if the stress in contact with inclusion is greater than the initial stress.

2.2 Load Transfer in the Platform

The columns in rigid inclusion foundation system are not structural elements, which is fundamentally different to the classic piled raft foundation concept. The column heads punch into the load transfer layer and two typical failure modes are possible (Prandtl failure diagram and shear cone type failure mode). The LTP is responsible to transmit the structural loads into the inclusion heads and into the soil between the columns. Among the various analytical methods available to

evaluate load transfer in the platform, the ASIRI National Project forwards the two following tested methods.

The first method is the fictitious inclusion method, which offers the advantage of providing a homogeneous approach consistent with the negative skin friction evaluation method.

The second method is the diffusion cone method, which entails an approach compliant with the mechanisms exposed during the various experiments and modelling exercises conducted within the scope of the ASIRI National Project.

3 Numerical Calculation

In our numerical calculations, a unit cell model was used to perform the parametric study. Unit cell models are well adapted to the design of piles in the central part of the grid and under uniform vertical surface loading. Only one homogeneous, compressible silt layer is defined in the model space. The 10 m long (L) concrete pile with a diameter (D) of 80 cm is located on the soft soil layer and the pile spacing (R) is 2.0x2.0 m. The compacted granular load transfer platform of 50 cm thickness is placed over the inclusion head and topped with a raft having a thickness of 30 cm. Vertical prescribed displacements are activated on the raft. The behavior of the different pile concepts are investigated with three different prescribed displacements which are determined as a function of the pile diameter. In this case, a force is obtained as output, which is necessary for the prescribed displacement to occur. For the evaluation of skin and base resistance mobilization, the following prescribed displacements are defined in the calculations:

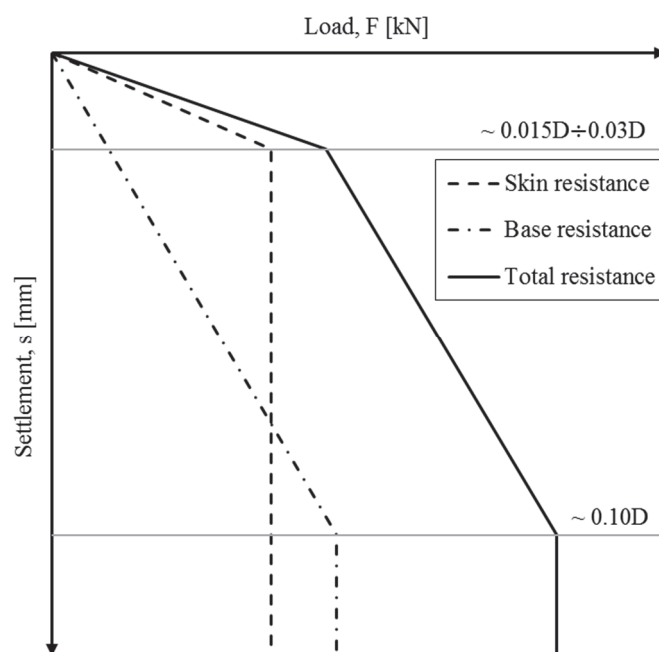
- $u_z = 0.02 \cdot D = 0.016 \text{ m}$
- $u_z = 0.10 \cdot D = 0.080 \text{ m}$
- $u_z = 0.20 \cdot D = 0.160 \text{ m}$

The soft silt layer is modelled with HSS (Hardening Soil model with small-strain stiffness) and the LTP is modelled with HS (Hardening Soil) material model. The pile and the raft are modelled with elastic (EL) material model. The properties of the investigated rigid inclusion foundation components are summarized in Table 1.

Tab. 1: Material properties

Properties	Soft silt	LTP	Pile	
			Volume pile	Embedded beam
Material model	HSS	HS	EL	EL
ρ (kN/m ³)	19	20	24	5
E (MPa)	-	-	33·10 ³	
n (-)	0.3	0.3	0.2	
E_{oed}^{ref} (MPa)	5	70	-	
E_{50}^{ref} (MPa)	5	70	-	
E_{ur}^{ref} (MPa)	18	210	-	
m (-)	0.75	0.5	-	
c'_{ref} (kPa)	16.9	1	-	
φ' (°)	26.9	40	-	
$\rho_{0.7}$ (-)	2.5·10 ⁻⁴	-	-	
G_0^{ref} (MPa)	65	-	-	
R_{int} (-)	0.9	1	-	

Based on in-situ pile load testing and the DIN 1054, the following load-settlement curve is used for the determination of prescribed displacements:

**Fig. 3:** Load-settlement curve (DIN 1054)

In this study, especially the deformations of the foundation system (soil and pile) and the stress distribution in the piles are addressed. In the numerical calculations, using Plaxis 3D, 15-noded wedge finite elements are used.

4 Results

4.1 Volume Pile Approach

During the calculations the distribution of the normal forces, the skin resistances and the soil-pile interaction (pile and surrounding soil) are investigated in case of different prescribed displacements. The inclusion is a cylindrical shape CFA (Continuous Flight Auger) pile.

In the first step, the model sensitivity was examined as a function of the mesh coarseness of the pile with $0.02D$ prescribed displacement. Multiple numerical analyses were performed with very coarse, coarse, medium, fine, very fine mesh and with local refinement mesh in the volume element and in the surrounding soil. The effect of the coarseness is shown in Figure 4.

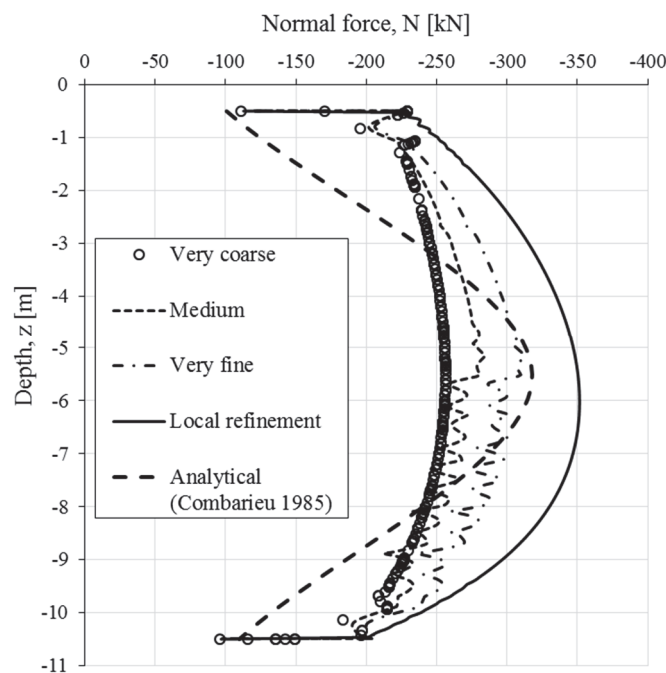


Fig. 4: Sensitivity of normal force distribution in VP in case of different mesh coarseness with $0.02D$ prescribed displacement

Shear stress in interface elements only depends on the earth pressure, coefficient of soil-pile friction, interface reduction factor and the effective normal stress so the skin resistance could be limited using the interface reduction factor; skin resistance however cannot be limited by manually defining a maximum cut-off value.

As it can be seen in Figure 4, the maximum normal force in the VP increases with mesh refinement. At the same time, the neutral plane moves deeper so the negative skin friction increases, which induces additional normal force. The neutral plane is located at 2.5 m depth if the mesh is very coarse, while with local refinement the neutral plane shifts to 4.57 m depth. In all cases, the neutral plane and the location of the maximum normal force are not at same depth. Using various mesh coarseness, there is no big difference in the forces, that are necessary for the prescribed displacements to occur.

The influence of different prescribed displacements on the stresses is shown in Figure 5. Using various (increasing) prescribed displacements the positive skin friction increase while the negative part is almost the same in all cases. Increasing the prescribed displacements the neutral plane moves upwards which is, however, not significant in the calculations.

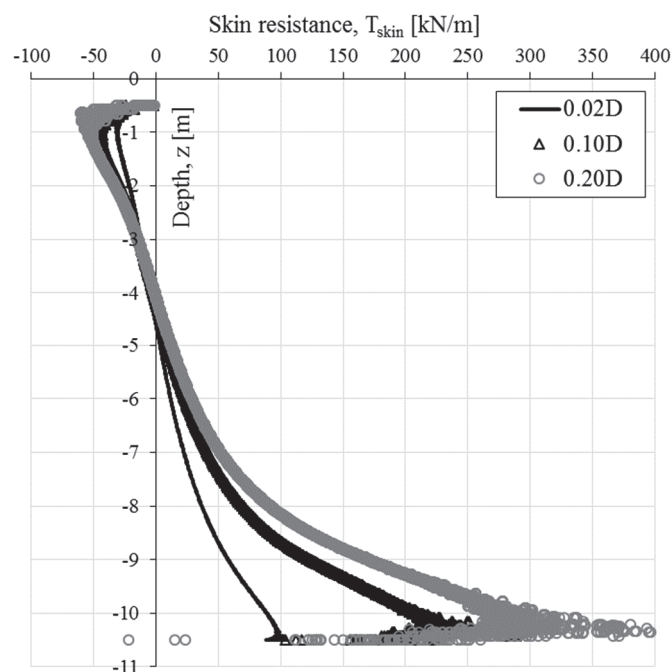


Fig. 5: Skin resistance distribution in VP in case of different prescribed displacements

It is possible to use prisms with polygonal base for modelling piles instead of cylindrical geometry to reduce the element numbers and calculation time. The circle was approximated with different polygonal such as quadrilateral, hexagon and octagon. The sensitivity of these volume pile geometries was examined with 0.02D prescribed displacement. The effect of the shape of volume pile is shown in Figure 6. As it can be seen on this figure, the maximum normal force in the VP increases with polygon numbers, but the skin friction does not change significantly. Using prism with octagon base is the most effective way to approximate the results (stresses and displacements) of cylindrical (initial) geometry.

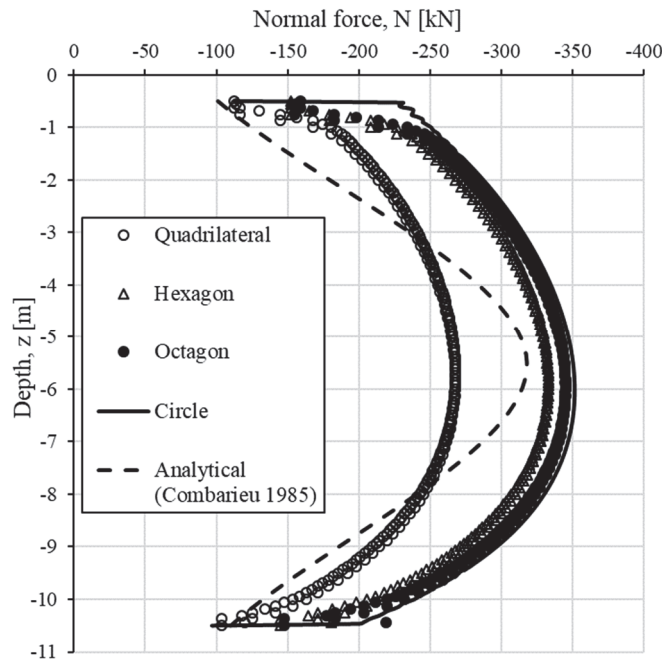


Fig. 6: Sensitivity of normal force distribution in VP in case of different pile shape

4.2 Embedded Beam Approach

Assuming embedded beam, three special options were used in the numerical calculations to define the maximum skin resistance. The first option is the layer dependent (LD) option. With this definition, the maximum shear stress of the embedded pile is related to the strength parameters of the soil and the normal stress along the interface. When using the layer dependent option, the embedded interface elements behave similar to normal interface elements as used in the volume pile approach, with the difference that the interaction is modelled along the line element. In addition, an ultimate cut-off value for the skin resistance can be defined (LD-Tmax). Based on the results of in-situ CPT (Cone Penetration Test) the ultimate cut-off value for the skin resistance could be calculated using the following recommendation of Szepesházi (2011):

$$T_{skin} = q_s D \pi = 1.2 \mu_s \sqrt{q_c} D \pi \quad (3)$$

where q_s =specific skin resistance; q_c =specific tip resistance; m_s =technological factor (1.0 for CFA pile). The second option to set the skin friction of EB is the multi-linear (ML-Tmax) distribution, with which it is possible to define values for the skin friction at certain depths.

The model sensitivity was examined as a function of the mesh coarseness of the pile with 0.02D prescribed displacement. The effect of the mesh coarseness is not significant in the forces, that are necessary for the prescribed displacements to occur. As it can be seen in Figure 7, the maximum normal force in the EB decreases

with mesh refinement, while the location of the neutral plane is almost the same. At the pile ends, the normal force is almost zero; it seems, that because the embedded beam is not connected to other structural elements at the ends, the load cannot be directly transferred to the pile.

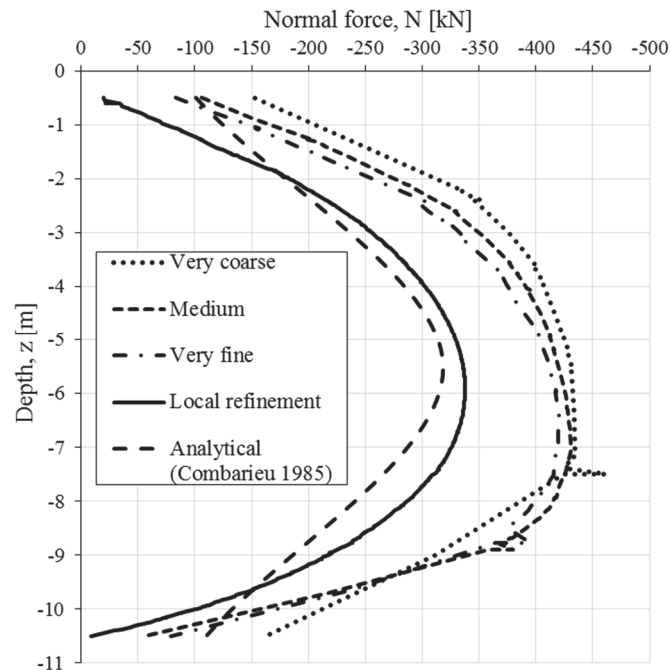


Fig. 7: Sensitivity of normal force distribution in EB in case of different mesh coarseness with $0.02D$ prescribed displacement (layer dependent option of skin resistance)

To examine the mobilization, $0.10D$ and $0.20D$ prescribed displacements were used in the calculations. The influence of different prescribed displacements on the stresses are shown in Figure 8 and Figure 9. As Figure 8 shows, as a result of increasing prescribed displacements, the normal force at the top and the bottom of the embedded beam does not increase significantly, which can be attributed to the connection problem of the EB element. Increasing the prescribed displacement, the mobilization of the shaft is getting bigger, nevertheless the position of the neutral plane is nearly the same even in that cases when diverse options are used to define the skin resistance.

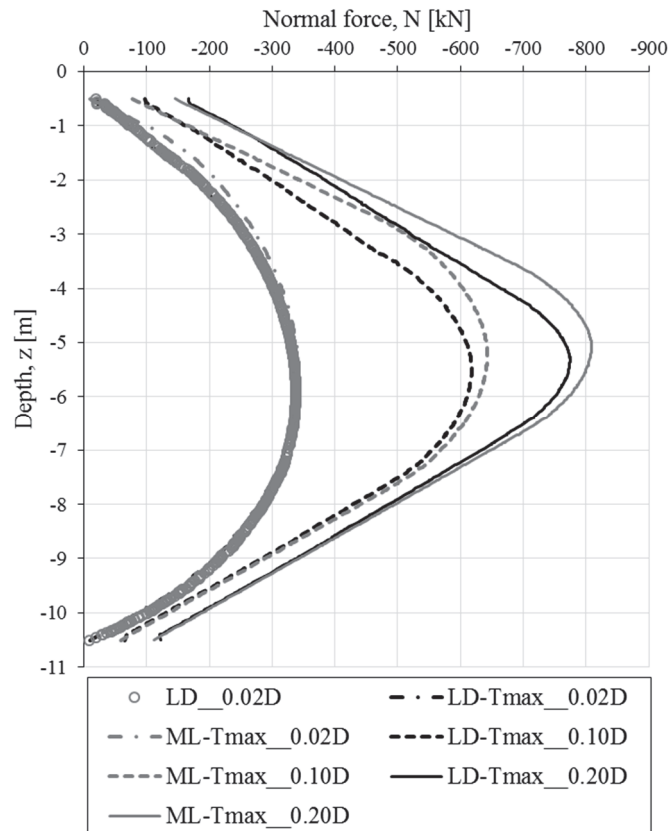


Fig. 8: Normal force distribution in EB in case of different prescribed displacements and using different skin resistance options

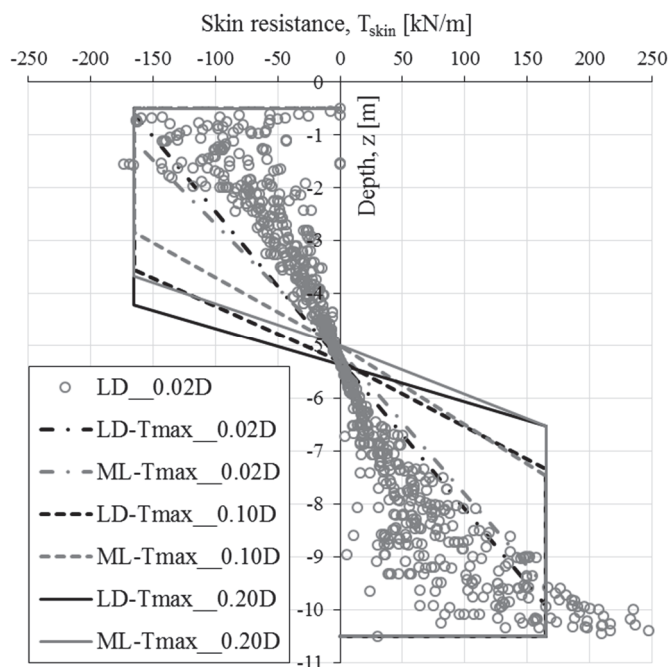


Fig. 9: Skin resistance distribution in EB in case of different prescribed displacements and using different skin resistance options

4.3 Comparison of Different Methods and the Hybrid Element

As seen in the previous results, the behavior of different pile models and the distribution of stresses are dissimilar. The maximum normal forces are almost the same in both cases, whereas the distributions are different due to the differences in the distribution of the skin resistances and the connection problem at the ends of the EB element. To solve the connection problem in the EB approach, a hybrid pile element (EB+VP) could be created. In this case, at both ends of the embedded pile, 1 cm thick VP elements are inserted, which provide appropriate stiffness and load transfer surfaces. Investigated pile models are shown on Figure 10.

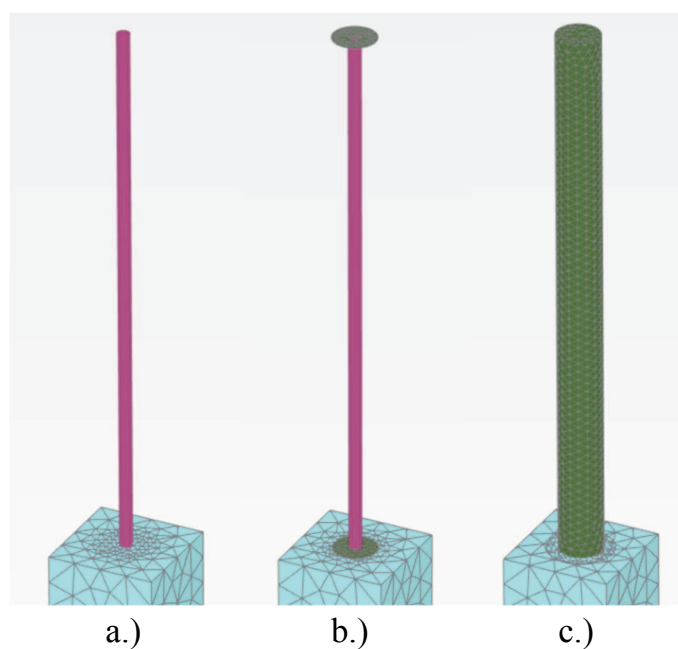


Fig. 10: Investigated pile models – Embedded beam (a.); Hybrid pile element (b.); Volume pile (c.)

As Figure 11 shows, the normal force at the ends increases if the pile is modelled with hybrid element. The distribution of the skin resistance of the hybrid element is getting closer to that in the VP, the positive part is almost the same; the negative skin resistance decreases compared to the EB concept. Using cut-off value for the skin resistance in hybrid element is a great advantage of this approach and maybe gives more realistic pile behavior.

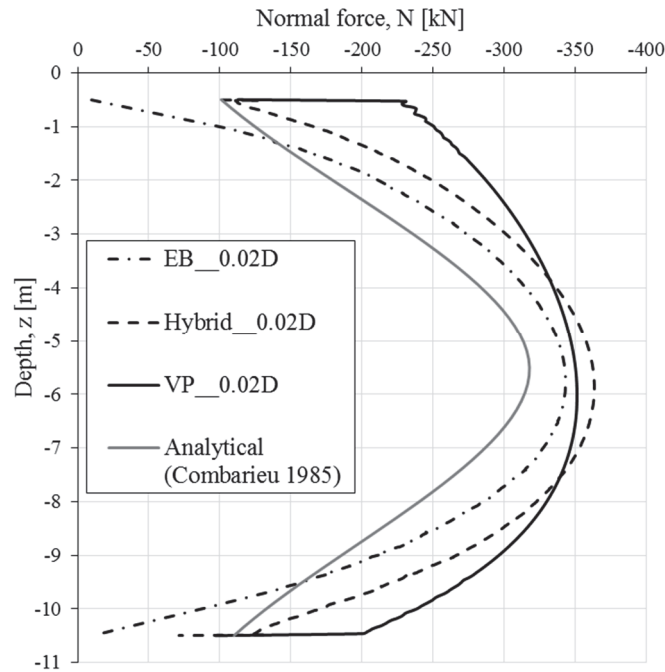


Fig. 11: Influence of different pile modelling options on the distribution of normal force

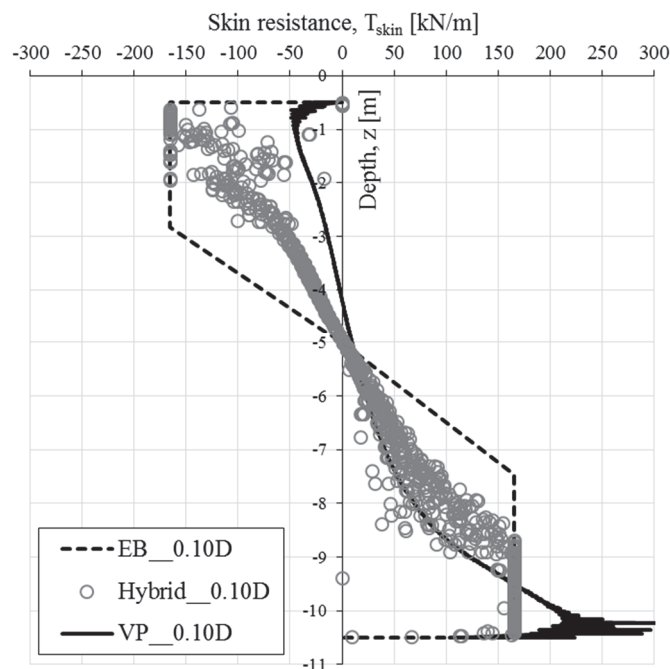


Fig. 12: Influence of different pile modelling options on the distribution of skin resistance

While the displacements are the most important results in the design calculations, the influence of the model geometry of the piles is not significant (Fig. 13). In most cases, the role of the rigid inclusion foundation is to improve the soil properties. One of the most important aspects in the design method of rigid inclusion foundation system is the improvement factor, which is the ratio of the maximum

displacement of the raft with and without inclusions. It means that if the improving factor is the question in the numerical calculation, the pile modelling option is not so important.

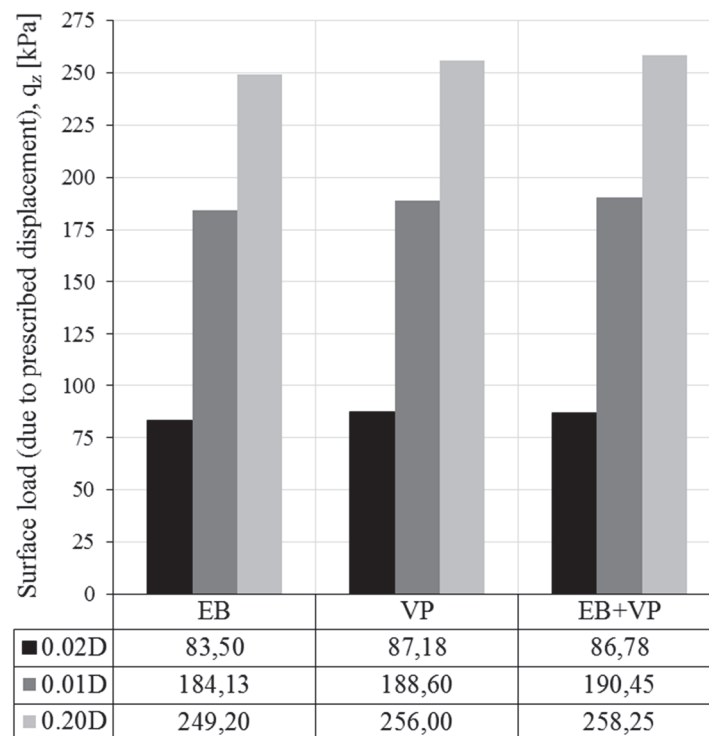


Fig. 13: Sum of the forces that are necessary for the prescribed displacements to occur

5 Conclusions

The parametric study on rigid inclusion foundation technique - especially the pile modelling opportunities - has been performed using 3D FEM via Plaxis 3D to analyze its performance in reducing the settlement and transferring the load. For the evaluation of skin and base resistance mobilization, the prescribed displacements were defined on the top of the raft. Three different types of pile model geometries were examined in the aspect of distribution of normal force, skin resistance and displacement of the complex foundation system.

The calculation results show that the influence of the mesh coarseness is not significant in the forces, that are necessary for the prescribed displacements to occur, on the other hand, creating finer mesh, the distribution of the normal force and the skin resistance are changed. Using VP, the maximum skin resistance cannot be limited, which is a disadvantage of this modelling approach, while using EB an ultimate cut-off value for the skin resistance can be defined. At the ends of the EB element, the normal force is almost zero; it seems, that because the embedded beam is not connected to other structural elements at the ends, the load cannot be directly transferred to the pile. To solve the connection problem, a hybrid

pile element could be created. Since the rigid inclusion foundation is also a soil improvement technique, the most important question is the displacement behavior of the system, which could be reached with each pile modelling options. The results could be refined by back analysis which could help in the design methods (Lődör et al. 2016).

6 Literature

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