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Estimation of Pile Group Behavior using Embedded Piles

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ABSTRACT: Embedded pile model - consisting of slender beams, skin and foot interfaces – has been successfully implemented in the Plaxis 3D Foundation Program. The interfaces represent the interaction at the contact surface between the pile and soil. Rigid/flexible connection and slippage at the pile-soil contact surface can be modelled by choosing appropriate characteristics of the interfaces. One of the advantageous is that the embedded pile can be added afterwards into the existing 3D finite element mesh, thus arbitrarily crossing the soil element interior. With this approach an efficient finite element model of pile group applications can be achieved. Previously, validation analyses of single pile behaviour have been performed and the results are compared to the field test data. The developed embedded pile model is shown capable of describing the single pile behaviour in both compression tests and pull-out tests and both the skin forces and base resistance curves are fairly in agreement with the field test data. In relation to the previous studies, the present paper aims to evaluate the performance of embedded pile in modelling the pile group behaviour. In the numerical analyses part, the pile group behaviour is considered by applying embedded piles onto idealized problems. Further, the applicability of embedded piles as reinforcements is also shortly discussed.

1 Introduction

For modelling piled foundation, the Plaxis 3D Foundation Program provides embedded pile model, in which the pile is assumed as slender beam elements which are virtually connected to the soil by means of the skin and foot interfaces. Since these elements may have arbitrary inclination and cross the soil elements at any arbitrary position, special-purposed interface elements. The interaction between the pile and the soil at the skin is modelled by means of line-to-volume interface elements and the interaction at the base by means of point-to volume interface elements (Septanika 2005a and 2005b), i.e. in addition to the embedded beam approach as developed by Sadek and Shahrour (2004). Further, the current embedded pile approach considers: (i) different types of skin traction/slippage model (constant/linear, multi-linear and layer-dependent), and (ii) foot slippage model. In the foot slippage model, the foot resistance corresponds to the maximum force that can be sustained by the foot interface during compression.

For single pile, validation studies for both compression case and tensile tests case have previously been performed – in which the numerical results according to embedded pile are compared with the field test data (Engin et al. 2007, Septanika et al. 2007). To make this paper self-contained, the background of the embedded pile model is shortly recapitulated. Next, the results of the single pile studies are also shortly discussed. As an extension to the previous studies, this paper considers pile group behaviour by applying embedded piles onto simplified cases. First, the results of embedded pile for the idealized problem as described in e.g. Poulos (2001) are compared to various methods. Then a qualitative study of the piled raft foundation is presented, considering the group effect in case the cap is detached from the soil and in case the cap touches the soil. In case the cap detaches the soil, the spacing effect is first examined, excluding the cap contribution. In case the cap touches the soil, complex interaction between the raft-pile-soil will be involved. Besides the soil-pile interaction and the pile spacing, the raft-to-soil interaction and the interaction between the cap and the pile groups will also be involved. Finally, the application of embedded piles as soil reinforcements is also presented. This is only to illustrate the range of applications into which the current embedded pile model can be applied. (Note that soil reinforcements are modelled by simply excluding the foot resistance, while in standard piled foundation applications both the skin and the foot resistances are considered).

2 Background

2.1 Embedded pile model

The embedded pile model considers the pile as slender beam elements, which is connected to the soil by embedded skin interfaces and embedded foot interfaces. The pile may cross the bulk soil elements at any arbitrary position and with an arbitrary inclination. During the post mesh-generation stage, new nodes are generated representing the pile nodes at the intersection points between the pile and the soil elements.

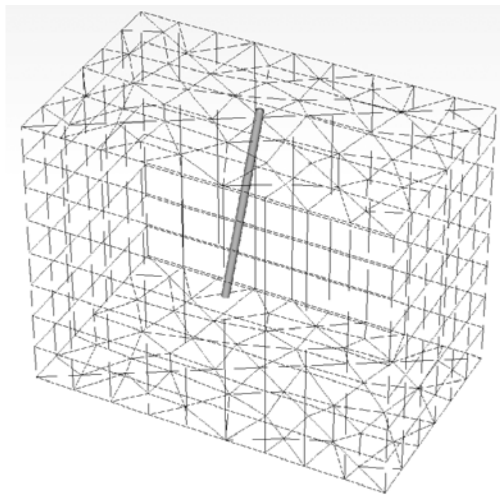


Figure 1. Schematization of single embedded pile in a soil mesh.

2.2 Pile – soil interaction model

The soil-pile interaction is represented by a so-called skin traction t (traction in kN/m = force in kN per circumference in meter). For this purpose, a special-purposed interface element has been developed for connecting the soil element and the pile element. The traction t at the skin interface is assumed to obey the following constitutive relation

$$\Delta \;{}^{skin} = \quad \Delta \quad \text{with } \Delta \;{}_{rel} = (\Delta \quad - \Delta \quad) \tag{1}$$

where $\Delta \mathbf{t}$ is the traction increments at the integration points, $\mathbf{T}^{skin}$ is the material stiffness matrix of the pseudo skin interface and $\Delta \mathbf{u}_{rel} = (\Delta \mathbf{u}_p - \Delta \mathbf{u}_s)$ represents the relative displacement vector between the soil and the pile. The element stiffness matrix $\mathbf{K}_{skin}$ representing the pile-soil interaction at the mantle has been derived based on the following internal virtual work consideration (Septanika 2005a). To include slippage at the pile-soil contact in 3D Foundation Program, one may use the skin-traction model according to: (a) constant/linear traction-depth model, (b) multi-linear model, and (c) layer-dependent model which relates the allowable traction to the strength of the adjacent soil layer.

The interaction at the foot is modeled by a special-purposed spring element to represent the foot stiffness against the relative movements at the foot. This spring connects the pile foot to the soil in the vicinity of the foot. The force acting on this spring $\mathbf{F}^{foot}$ vector is determined as

$$\Delta \mathbf{F}^{foot} = \mathbf{D}^{foot} \Delta \;{}^{foot}_{rel} \text{ with } \Delta \;{}^{foot}_{rel} = (\Delta \quad - \Delta \quad) \tag{2}$$

where $\Delta \mathbf{F}^{foot}$ is the force increment, $\mathbf{D}^{foot}$ represents the material stiffness matrix of the pseudo spring element at the foot, $\Delta \;{}^{foot}_{rel}$ represents the relative displacement vector between the soil and the pile at the foot. For the maximum foot resistance representing the base failure (due to penetration or pulled-out) at the pile foot, the following simplified criterion has been utilized

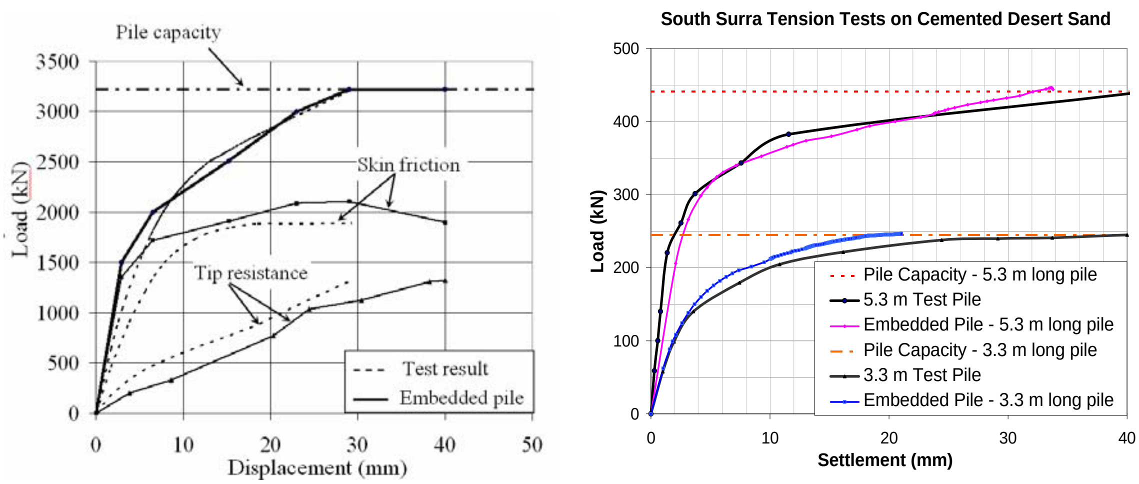
$$F_{axial}^{foot} \leq F_{max}^{foot} \text{ (compression) and } F_{axial}^{foot} = 0 \text{ (tension)} \quad (3)$$

where F_{axial}^{foot} is the axial component of the force at the pile foot. In case of reinforcement the base resistance is set to zero. Further, the mesh-dependent behaviour has been improved by the application of an elastic zone approach for the soil region within the pile. This approach appears sufficient for reducing the undesirable mesh-dependent effects (Engin et al., 2007).

3 Single Pile Behaviour

3.1 Compression pile test

For simulating the real case, the Alzey Bridge pile load test (El - Mossallamy et al. 1997 and 1999) has been reanalyzed using embedded pile. During the load test load cells were installed at the pile base to measure the loads carried directly by pile base. The upper subsoil consist of silt (loam) followed by tertiary sediments down to great depths. These tertiary sediments are stiff plastic clay similar to the so-cal1ed Frankfurt clay, with a varying degree of over-consolidation. It is located completely in the over-consolidated clay. Skin friction curves are obtained by subtracting the base resistance from total load–displacement curve. The results of embedded pile (Figure 2a) are quite in good agreement with the pile load test results (Engin et al., 2007).



(a) (b)

Figure 2. (a) Load-displacement curve of the Alzey bridge pile load test together with embedded pile results and (After Engin et al., 2007) (b) Load-displacement curve of the South Surra pile load test together with embedded pile results. (Engin, 2007)

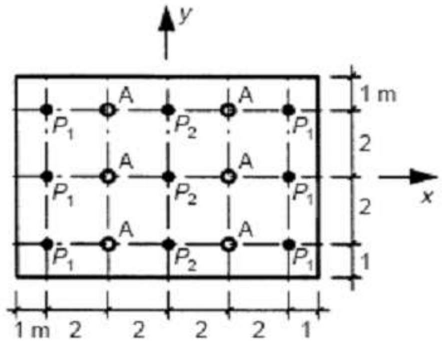
3.2 Tension pile test

The tension tests on bored piles in cemented desert sands (which were carried out in Kuwait) have also been analyzed using the Plaxis 3D Foundation Program (Septanika et al., 2007). The details of the geometry and soil parameters are given in Ismael et al. (1994). The load transfer of bored piles in medium dense cemented sands was investigated by field tests at two sites. The first site (South Surra) has a profile of medium-dense and very-dense weekly cemented calcareous sand. Two short bored piles were tested in axial tension to failure. It was also shown that the total pile capacity according to embedded pile is in reasonably agreement with the results of the tension tests (Figure 2b).

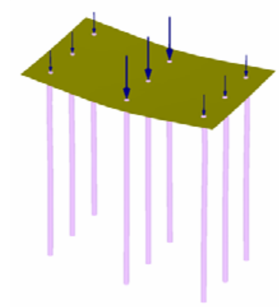
4 Pile Group

4.1 Idealized problem

In the present study, the idealized hypothetical problem (Poulos et al.,1997 and Poulos 2001) has been considered as schematized in Figure 3a. The raft foundation is supported by nine piles. Bearing capacity of raft is 0.3 MPa, load capacity of each pile is 0.873 MN (compression) and 0.786 MN (tension). The pile diameter is 0.5 m and the length is 10 m. The pile and raft properties are $E_p = E_r = 30$ GPa and $\nu_p = \nu_r = 0.2$.



(a)



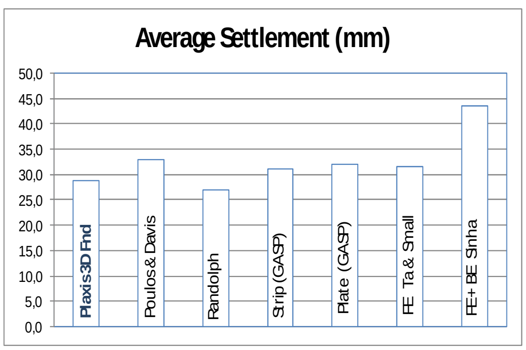
(b)

Figure 3. (a) Idealized problem and (b) FE-model in PLAXIS 3D Foundation Program.

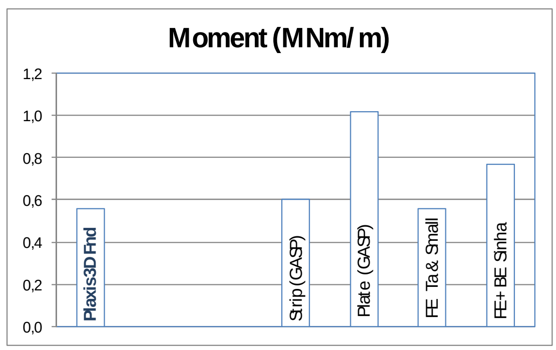
The results of analyses in 3D Foundation Program (Figure 3b) have been compared to the results from six different methods as reported in Poulos (2001), according to:

- Poulos and Davis (1980)
- Randolph (1994)
- Strip on spring analysis using GASP (Poulos, 1991)
- Plate on spring approach using GARP (Poulos, 1994)
- Finite element and boundary element method of Ta and Small (1996)
- Finite element and boundary element method of Sinha (1996)

Figure 4 show the comparison results of the computed characteristics of behaviour of a raft supported by nine piles. The applied load of 12 MN exceeds the ultimate capacity of the piles alone, and hence the global behaviour will be highly non-linear. Despite some differences between various methods, the computed characteristic results are somewhat similar



(a)



(b)

Figure 4. (a) Average settlements and (b) Bending moments according to various methods.

4.2 Piled Raft - Cap not touching the soil

Next, the group behaviour of embedded piles with different spacing in over-consolidated clay is considered. To exclude the interaction between the cap and the pile-soil system, the raft has been detached from the soil. This simplified model is mainly purposed for numerical validations, i.e. to investigate the group effect considering the neighbouring piles and the spacing between them without the interference of the cap. The raft foundation and the properties are shown in Figure 5. The pile spacings and corresponding patterns are given in Figure 6. The plots of the force-displacement curve for different spacing are shown in Figure 7. As expected (since the cap is detached from the soil), the total capacity for all spacing is according to the capacity of a single pile times the number of piles. It is to be noted that for s/d=2 a very large settlement at failure is found. This is probably due to overlapping of the pile influence regions (causing stress bulbs). The soil between the piles may be “locked”, and hence, the skin capacity is mainly be contributed by the corner piles. However, the traction profiles at failure for different spacing appear uniform as shown in Figure 8. This indicates that for the present case the skin traction is fully mobilized at each pile when the raft foundation fails.

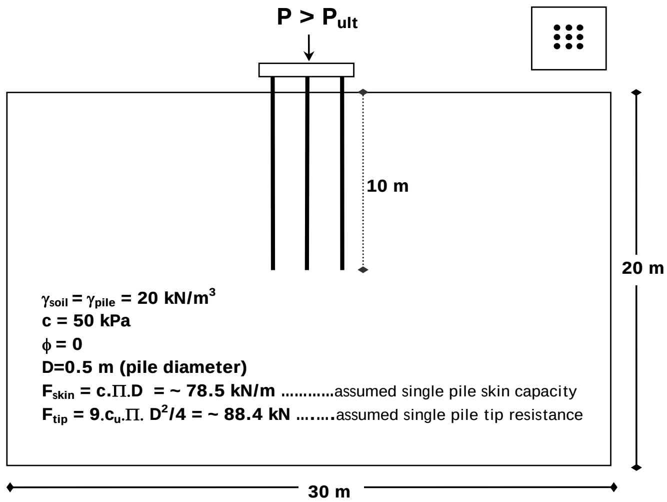


Figure 5. Pile group model of 3x3 piles.

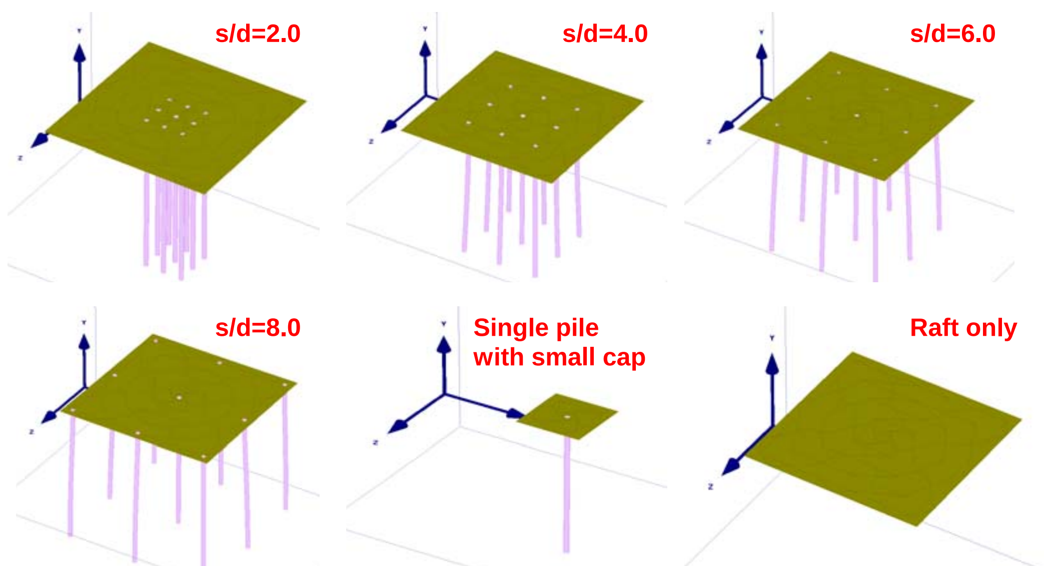


Figure 6. Patterns used in the analyses for the investigation of pile spacing effect.

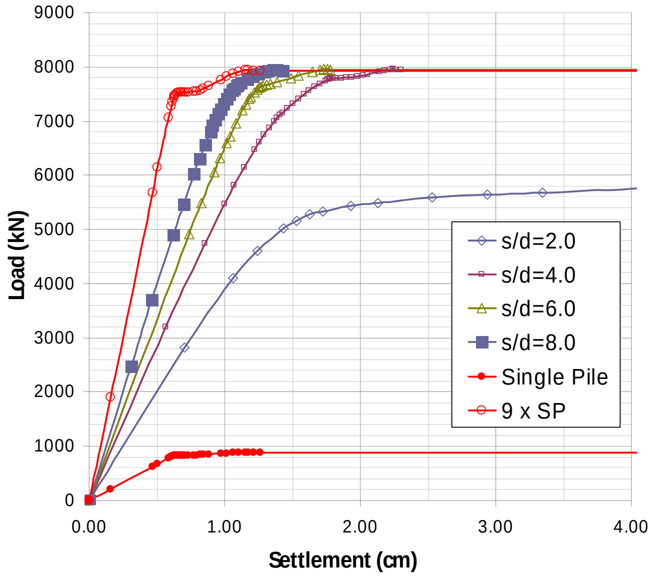


Figure 7. Load-displacement curves for various spacing.

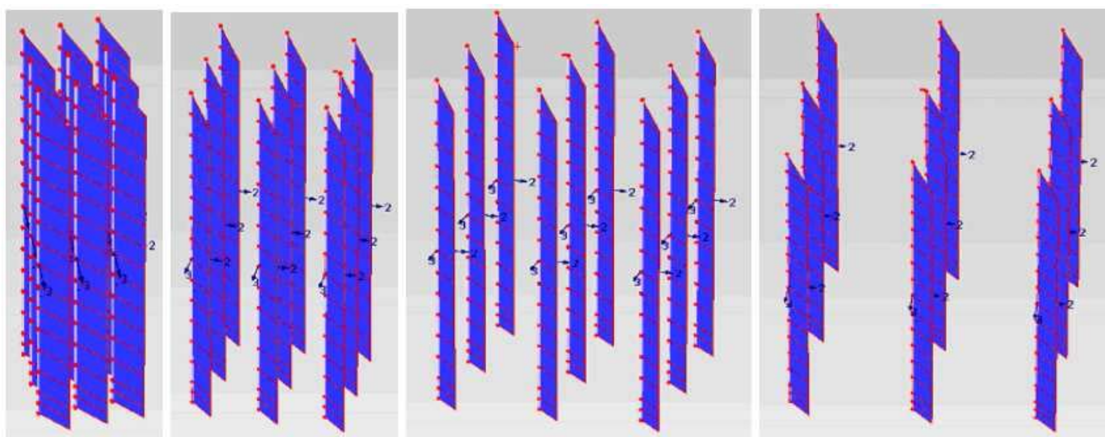
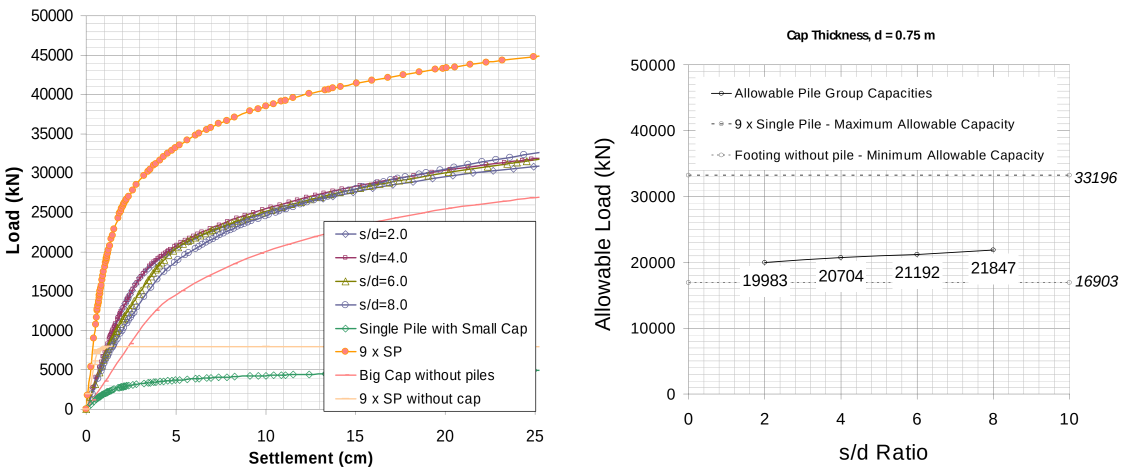


Figure 8. Skin traction (shear force per unit length) profiles at embedded piles for various spacing.

4.3 Piled Raft - Cap touching the soil

The present case considers similar idealized raft foundation as before, except now the cap is touching the soil. This case is much complicated than the previous one, since the global response will also depend on interaction between the cap and the soil-pile system and the group effect. The plots of force-displacement curves for different spacing are shown in Figure 9a. It can be seen that the group capacity depends on the spacing. For s/d=2 the full mobilization of skin friction is achieved at a very large settlement - i.e. the (premature) failure will be soil-driven rather than at the pile-soil interfaces. For an allowable settlement of 5 cm the corresponding allowable loads are shown in Figure 9b. The lower bound corresponds to the foundation by cap only (without pile) and the upper limit corresponds to the idealized case of 9 times the capacity of single pile. It can be deduced that for this case the increase of the spacing increases the allowable capacity. Above s/d=8 (not shown in the figure) it appears that only a very little increase of the allowable load is observed. Hence, further enlargement of the spacing above s=8d seems to be un-effective (at least for the particular case). In the real situation there will be also a certain upper limit of spacing above which no significant benefit will be gained.

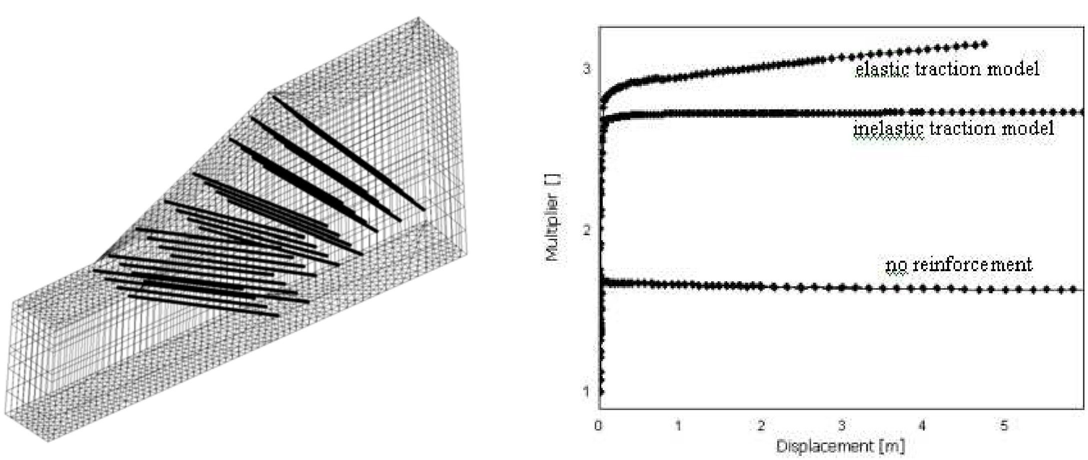


(a) (b)

Figure 9. (a) Force-displacement curves for different spacing and (b) Allowable loads in case of allowable settlement is 5 cm.

4.4 Soil Reinforcement

Finally, to illustrate the range of applicability of the current embedded pile model, an idealized reinforced slope problem (Septanika et al. 2007) is shortly discussed. The reinforcements are modelled by means of inclined embedded piles (Figure 10a). The slippage between the reinforcements and the soil is described using the skin traction model available in the Plaxis 3D Foundation Program. For the present soil reinforcement application, the foot resistance has been set to zero. The purpose of this simplified analysis is to show the capability of the embedded piles in capturing the desired reinforcement effects, i.e. for increasing the slope capacity. The safety analysis of the slope with and without reinforcement has been performed, by employing the phi-c method in Plaxis 3D Foundation. As expected, the existence of reinforcements increases the slope capacity and hence the safety factor as shown in Figure 10b.



(a) (b)

Figure 10. (a) FE-model of reinforced slope and (b) Computed safety factor based on the phi-c method.

5 Concluding Remarks

This paper shortly describes the performance of the current embedded pile model available in 3D Foundation Program. The accuracy of single pile model has been validated, by considering the pile compression tests in Frankfurt and the pile tension tests in Kuwait. For both cases, the results are reasonably in agreement with the field test results. The numerical performance of the current embedded pile implementation has been verified by considering the idealized problem and comparing the results to the various methods. Further, to verify the accuracy of the skin and foot interaction models in case of pile groups, the piled raft has been considered in which the cap is detached from the soil. Full mobilization of the skin tractions and foot resistance illustrates the accuracy of the present interaction models. In the piled raft case with the cap touching the soil, the embedded pile group appears capable of catching the spacing effects on the resulting allowable capacity. For all cases the piled raft capacities are higher that the raft capacity alone. For this particular case, the allowable capacity seems to increase with spacing and reaching the upper limit at spacing nearly eight times pile diameter. Finally, to illustrate the range of applicability of the current embedded pile model, an idealized reinforced slope problem is also presented.

6 Acknowledgements

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