CONCEPT ON SOIL PLUGGING IN CLAY DEVELOPED FROM NUMERICAL CEL-SIMULATIONS CONSIDERING TOTAL STRESSES

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KEYWORDS

Numerical Modelling, Pile Installation, Soil Plugging, CEL

ABSTRACT

While the topic of soil plugging in open ended piles in sands has been met with great interest by many researchers, in the past very little attention has been paid on the complex interactions during soil plug formation in clayey soils. In recent time breakthroughs in numerical modelling considering large deformations using the coupled Eulerian-Lagrangian (CEL) method have led to new possibilities for investigations on pile installation processes. This paper is dedicated to the numerical modelling of the jacking process of open-ended piles in clay using a total stress approach for deviatoric continuum stresses and for Coulomb contact friction. An analytical approach for determination of plug capacity and plug height is presented and evaluated on the numerical results. It is shown, that from the numerical simulations occurring mechanisms leading to plug formation can be described analytically with good agreement. The derived analytical approach is then applied to a field case from literature, which yields satisfying results. Further development of the approach as well as experimental tests regarding soil plugging in clays are planned in the future.

1. INTRODUCTION

For the vertical and to some extent the horizontal load transfer of quay walls, offshore-wind turbines or dolphins steel pipe piles are often employed. For piles in general the axial bearing capacity is determined by the outer skin friction as well as the tip bearing resistance, whereas for open-ended pipe piles the tip resistance is controlled by the inner skin friction of soil moving inside the pile. If the bearing capacity of that inner soil column exceeds the bearing

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capacity of the soil below, soil plugging occurs [1]. The pile base resistance may drastically increase due to a soil plug, as the pile base area increases from just the annulus to the full circumferential area of the pile tip including the internal soil plug. Furthermore, as the pile behaves as a closed-ended pile during installation, more soil is displaced around the pile, leading to higher lateral stresses and therefore higher skin friction [2].

In the past, investigations on the development of soil plugs were almost exclusively performed on non-cohesive soils, see for example [3], [1], [4] or [5]. Investigations in a geotechnical centrifuge also focus on sands, see [6] or [7]. Soil plugging in clays, in which deep foundations are primarily being employed due to the soil's low bearing capacity, is currently to most extend unexplored and requires further investigations [8].

Plug development in clays is heavily dependent on the applied installation method. While vibrated piles show no tendency [5,9] and driven piles low tendency of plug development [10,11], plugging during jacking is much more likely to occur [2,8]. The type of soil is also pivotal to plugging as higher ratios of over-consolidation go along with a higher tendency to plugging [2].

In this paper, a concept on plug development employing an analytical approach is presented. Verification is done by numerical simulations using the Coupled-Eulerian-Lagrangian (CEL) method, considering undrained soil behavior and total stresses. The concept is validated by comparison with field test data from literature.

2. CONCEPT ON PLUG DEVELOPMENT

A new concept on plug development was recently developed in [12] and is briefly presented here. The concept builds on the different stages after [1], which are fully coring, partial plugging and fully plugged behavior, and is extended by also incorporating the stress state of the soil. Four different stages are considered, see Figure 1:

Stage 1: Near the ground surface at shallow depths the pile tip resistance only consists of the soil's weight inside the pile. Note that, as long as the soil body can stand on its own and therefore does not lead to any normal stress on the inner pile wall, no inner skin friction is mobilized. The displaced soil is completely moved into the inside of the pile.

Stage 2: As soon as the stresses inside the soil body exceed the undrained shear strength, effective normal stresses act on the inner pile which determine skin friction [13]. The vertical stress increases exponentially from the soil's weight and the transferred inner skin friction, considering the equation from [14] for drained response. This assumption may only be valid for over-consolidated clays as it implies that from skin friction the resulting increase in vertical stresses generates little to no positive excess pore pressures.

Stage 3: The skin friction is limited to the soil's undrained shear strength. It is assumed that shear failure develops in a shear zone close to the pile wall but not at the interface, which is likely to be the case for soft clays [15]. When this critical depth is reached the grade of vertical stress increase slows down.

Stage 4: The plug resistance is limited to the pile tip resistance of a closed-ended pile [1]. If this state is reached, no more soil can move into the pile.

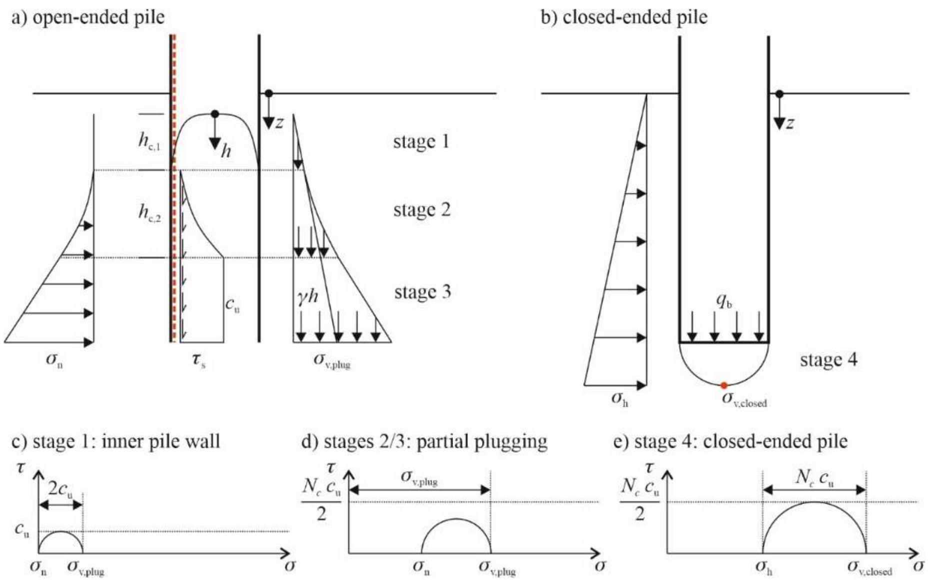

Figure 1 Concept on soil plug development.

The plug resistance can be calculated from equations (1) to (3), depending on the stage, which is determined by the plug height h.

For $h \leq h_{c,1}$:

$$\sigma_{v,plug,1} = (\gamma' + \gamma_w)h \quad (1)$$

for $h_{c,1} < h \leq h_{c,1} + h_{c,2}$:

$$\sigma_{v,plug,2} = \gamma' h_{c,1} + \gamma_w h + \gamma' \frac{A}{U K_0 \mu}\left(e^{\frac{(h-h_{c,1})A}{U K_0 \mu}} - 1\right) \quad (2)$$

for $h > h_{c,1} + h_{c,2}$:

$$\sigma_{v,plug,3} = \gamma' h_{c,1} + \gamma_w h + \frac{c_u}{\mu} + \left(h - h_{c,1} - h_{c,2}\right)\left(\gamma' + c_u \frac{U}{A}\right) \quad (3)$$

where

$$h_{c,1} = \frac{2c_u}{\gamma' + \gamma_w} \tag{4}$$

$$h_{c,2} = \ln\left(1 + \frac{c_u}{\gamma'} \cdot \frac{U}{A}\right) \cdot \frac{A}{UK_0\mu} \tag{5}$$

Herein c_u is the soil's undrained shear strength, γ' the effective unit weight of the soil, γ_w the unit weight of water, A the inner cross-sectional area of the pile, U the pile's inner circumference, K_0 the lateral earth pressure coefficient and μ the friction coefficient between pile and soil.

For the base resistance of a closed-ended pile a dependency over depth z is considered. To achieve equilibrium, a connection between plug height h and penetration depth z needs to be established. This is done by assuming a bilinear course of the incremental filling ratio $IFR = \frac{dh}{dz}$, from which the plug height h can be integrated, see Figure 2. The depth at which the turning point from constant to linear behavior of IFR is situated is $z_{c,1}$ which corresponds to the critical plug height $h_{c,1}$. At the depth z_{plug} the bearing pressure of the plug is equal to that of a closed-ended pile. For further details on the concept see [12].

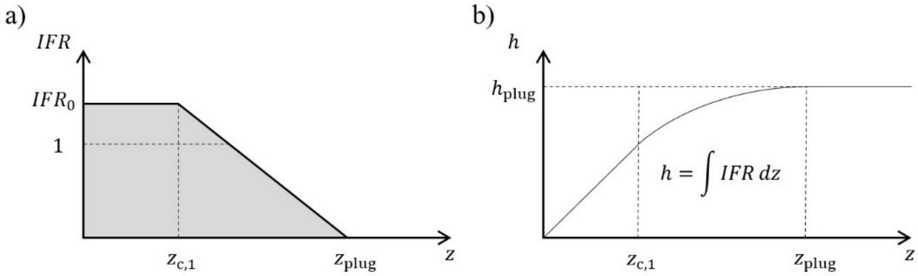

Figure 2 Development of incremental filling ratio IFR and plug height h over penetration depth z.

3. NUMERICAL ANALYSIS

To investigate the plugging behavior numerical simulations employing the Coupled-Eulerian-Lagrangian (CEL) method were performed using the commercial software Abaqus. The CEL method has recently been used by other researchers for modelling pile installation processes with great success, e.g. [16,17]. The model used in this study is displayed in Figure 3. For the pile an outer diameter of 0.5 m and a wall thickness of 0.04 m are chosen. The soil is modelled with $c_u = 25$ kPa, $E = 5000$ kPa, $\gamma' = 20$ kN/m³ and $\gamma_w = 0$, as no pore pressure is considered in the total stress analysis. A friction coefficient $\mu = 0.1$ is selected for the exemplary simulations. Besides the open-ended pile calculations further simulations are performed considering a closed-ended pile. The results in form of base pressure and incremental filling ratio over penetration depth are given in Figure 4.

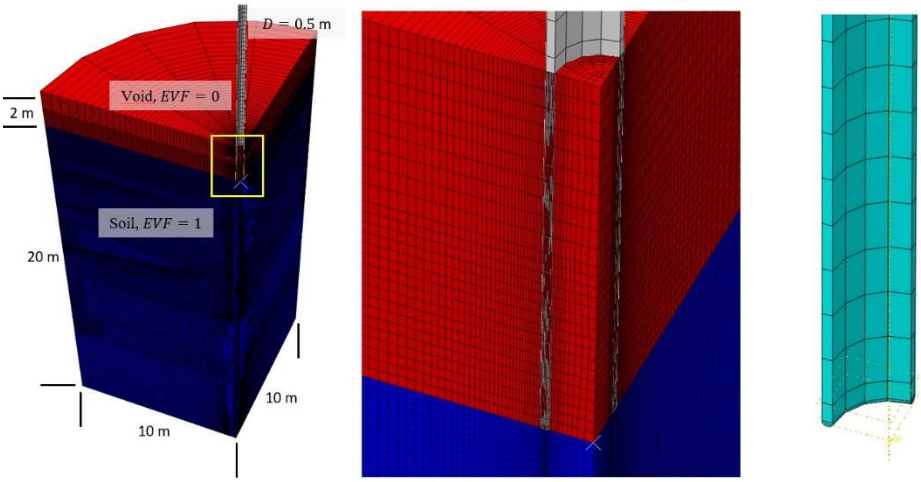

Figure 3 CEL model for pile installation process.

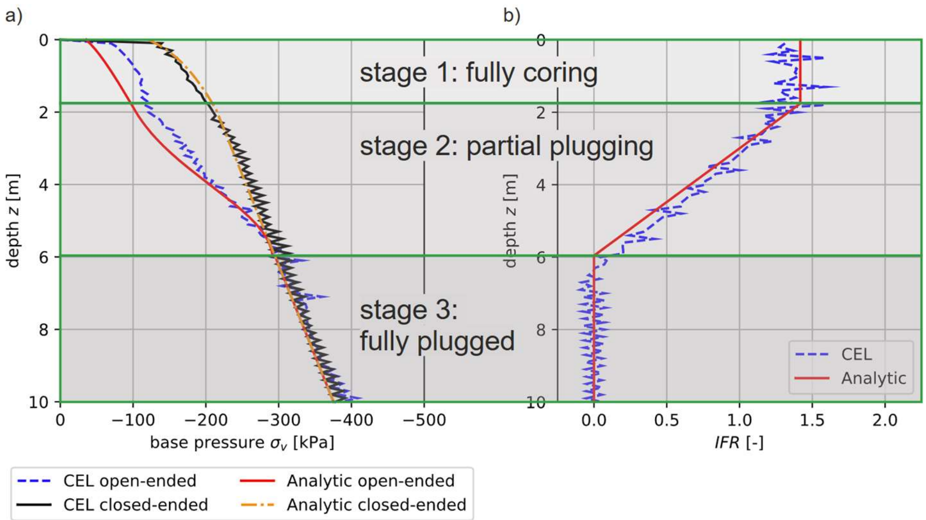

Figure 4 Results of CEL simulations compared to analytical approach.

From the numerical simulations presented in Figure 4, it can be identified that the open-ended pile passes through the stages fully coring, plug development and fully plugged with increasing penetration depth. After reaching the fully plugged state, in which $IFR = 0$, base resistance is identical to that of the closed-ended pile. For the analytical approach first the base resistance of the closed-ended pile is taken from the simulation to receive a suitable value for

N_c. Afterwards the analytical calculation is performed. The base resistance and incremental filling ratio behave similarly to the numerical simulation. In total 12 simulations with varying strength and stiffness parameters were performed, which are displayed in [12], showing good agreement for the analytical approach.

4. COMPARISON WITH FIELD TEST DATA

For validation of the presented concept, calculations were performed and compared to field test data given by [8]. As with the numerical simulations the base resistance of the closed-ended pile was taken as reference for computing a value for N_c. Divergences occurred when calculating the critical plug height $h_{c,1}$ and accordingly the depth at which the incremental filling ratio drops from its initial value and decreases further with depth. By manually choosing a value of $h_{c,1} = 0.7$ m and $IFR_0 = 1$ very good agreement with the field test data is achieved, see Figure 5. This shows that the analytical approach, despite its limitations of only considering total stresses, is in good accordance with reality.

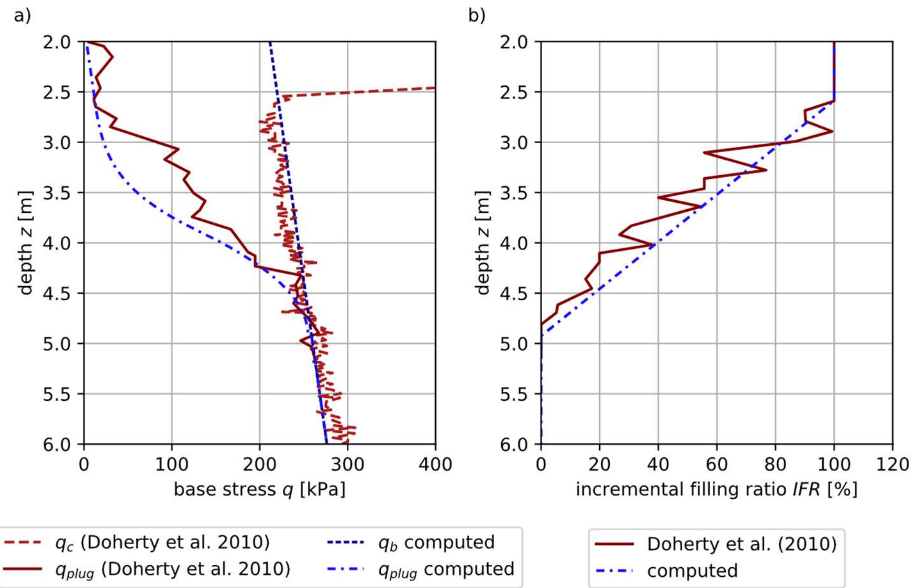

Figure 5 Comparison of field test data from [8] with the analytical approach.

5. CONCLUSION

In this paper, soil plugging in clays was investigated and a first concept on evaluating plug development in clayey soils is presented. Performed calculations showed that the new concept for plug development gives results for base resistance and plug height inside the pile during jacking which closely match those from numerical simulations. During jacking of open-ended piles, the different stages of fully coring, plug development (partial plugging) and fully plugged behavior are considered. When the pile is fully plugged, its base resistance reaches values comparable to those of a closed-ended pile.

The plugging behavior is dependent on employed values like turning point from fully coring to plug development $h_{c,1}$ and the initial incremental filling ratio IFR_0. This turned out to be critical for predicting plugging evaluated out of field tests. When employing field test data, the calculations showed good agreement with vertical stresses and plug height. Considering the approach's simplicity and limitations of only employing total stresses, the conformity to observations from field test is very good and further development is planned.

So far, the analytical formulas do not consider excess pore pressures, which will influence the effective stresses and therefore will affect the plugging behavior. For future investigations pore pressure development will be analyzed by means of numerical simulations. For validation purpose of the concept centrifuge tests at the University of Western Australia in Perth are planned.

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