Numerical study of pile soil interface using press-replace method in undrained soil

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ABSTRACT

Press-Replace Method is a numerical method based on small-strain deformation theory that simulates deep penetration problem. It involves a progressive application of prescribed displacement on top of a pile followed by geometry update resembling staged construction. The method is relatively new and there is yet comprehensive understanding of its ability and limitations in predicting the soil behaviour when subjected to pile installation. This paper presents the numerical modelling of pile soil interface using Press-Replace method to simulate deep penetration of displacement piles in undrained soil. Undrained condition is selected as typically, piles are installed relatively fast and dissipation of excess pore-water pressure takes considerable time. The pile installation is analyzed using the Modified Cam-Clay (MCC) model. This research intends to shed light on the influence of pile-soil interface on pile capacity which is inherent in modelling soil-structure interaction. At pile-soil interface, the shear strength is substantially weaker thus its effect on radial and shear stresses is investigated via sensitivity study.
Keywords: pile-soil interaction; Press-Replace, set-up effects; interface; jacked-in piles; numerical modelling

1 INTRODUCTION

The main function of a pile is to carry structural loads into deep competent ground. The geotechnical resistance can be derived from the sides of the pile through shaft friction and pile toe via end bearing. However in most cases of numerical analysis, the piles whenever present are assumed to be wish-in-place in the ground and then subjected under various actions as equilibrium takes place. In fact, ground deformation and stress changes around the pile have taken place the moment they were installed into the ground. This was proven by Sivasithamparam et al. (2015) in carrying out numerical analysis of pile load test between wish-in place piles and Press-Replace piles accounting for installation effects. The effect has also been thoroughly researched via field tests (Konrad and Roy 1987; Skov and Denver 1988; Haque et al. 2017). They have also been investigated numerically using more popular large deformation techniques such as Arbitrary Lagrangian-Eulerian (ALE) Techniques (Konkol and Balachowski 2016) and Material Point Method (MPM) (Phuong et al. 2014; Tehrani et al. 2016). These methods are computationally more demanding and not commonly incorporated or applied in standard commercial finite element programs.

Recognizing the nature of the pile installation which causes large displacement of soils around it, typically the conventional finite element method (FEM) is less preferred as they are more suited in working environment associated with small deformation problems. Recently, there was much success reported on the ability of modelling pile installation using the Press-Replace Method (PRM) initiated by Andersen et al. (2004) in modelling set-up of suction anchors. PRM is a simple numerical method following framework of small strain theory to capture the effect of penetrating object into ground. It is simple because the initial finite element mesh is preserved while the stages (depicting a form of staged construction) involves a step-wise updated geometry of straining and geometry update. The technique was further validated by Engin (2013) for undrained cone penetration test and refined for installation of piles in sand. This method further gained popularity as they are also published in the works by Lim et al. (2018) and Wang and Goh (2018). Hence, the method needs to be further investigated to prove its validity in predicting the behaviour of soil subjected to undrained pile installation. This leads to the objective of this research that is to investigate the influence of pile-soil interface roughness as part of pile installation effects. There is a need to investigate this because the region of shearing between the pile and the soil determines the amount of load able to be transferred from pile to soil. It is envisaged that this method would further gain recognition due to its simplicity, versatility and a reliable approximate technique.

2 FINITE ELEMENT MODEL

2.1 Selection of soil model

The Modified Cam-Clay Model (Roscoe and Burland 1968) is an elastic-plastic strain hardening model based on the Critical State Theory. It is an improvement over the original Cam Clay Model with an ellipse yield surface, suitable to be used for normally consolidated soil and accounts for non-linearity which better represents realistic soil behaviour. It can also be used to model both drained and undrained condition of soils. However, one of its drawbacks is that it does not account for anisotropy. The consideration of anisotropy would require a different constitutive soil model which has been reported by Sivasithamparam et al. (2015). **Table 1** presents the soil parameters of clay adopted.

Table 1. Modified Cam-Clay input parameters

Parameter	e_o [-]	λ [-]	κ [-]	v [-]	M [-]
Value	2	0.3	0.06	0.20	1.2

e_o = Initial void ratio

λ = Virgin compression index

κ = Recompression index

v = Poisson's ratio

M = Gradient of critical state line in q-p' plane

2.2 Numerical setup

In this study, a pile of an arbitrary diameter, D of 1.0m and length 10m is adopted. The pile shall be installed from ground level. The analysis is a 2D axisymmetric condition which is representative of the pile problem and computational time can be reduced compared to a 3D model.

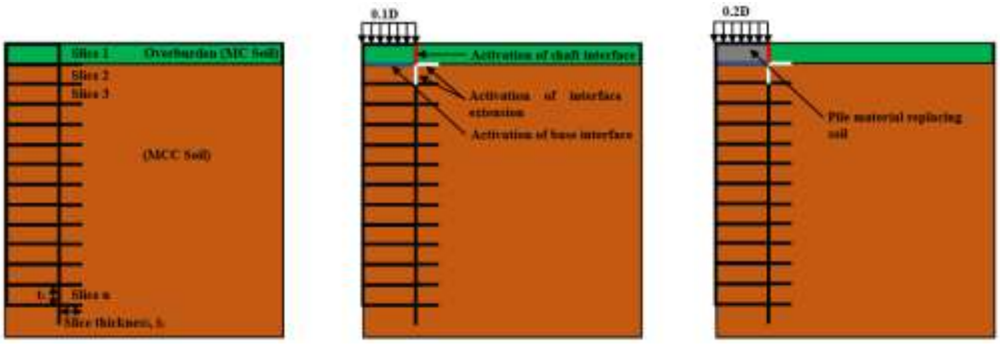
The ground consists of homogeneous clay adopting Modified Cam-Clay constitutive model underlying a thin but heavy Mohr-Coulomb (MC) overburden. It is introduced for two reasons. First, to prevent numerical problems at the stress-free surface as the piles are installed from the ground surface rather than at a certain penetration depth below ground. Second, the overburden and weightless clay creates a uniform vertical stress on the clay allowing the ease to study stress changes around the pile as it is further advanced into the soil. The effective vertical stress is 100kPa. Initial phase is generated using the "K_o procedure" where K_o is determined following Mayne and Kulhawy (1982) relationship of $K_o = (1\text{-}\sin\varphi)OCR^{\sin\varphi} = 0.61$ assuming $\varphi = 30^o$ and OCR = 1.5.

The first few stages of PRM are illustrated in **Fig. 1**. The technique adopting Engin (2013) involves a series of press by prescribing Dirichlet boundary condition (vertical displacement) on the pile head followed by geometry update where the soil material within the slice is substituted with the pile material. In this case, the initial mesh is preserved, and the analysis does not suffer from mesh distortion effects. This process is repeated until the desired penetration is reached. The slice thickness (t_s), prescribed displacement (u_y) and interface extension (t_s) are kept at 0.1D (D = pile diameter). The function of interface extension is to avoid stress oscillations at the corner of the pile. Further details can be referred to van Langen and Vermeer (1991).

2.3 Geometry & Mesh

For the current study, the commercial software Plaxis 2D 2017 is used. The finite element mesh (**Fig. 2**) consists of 4,860 15-noded triangular elements and 41,573 nodes. The horizontal and vertical extent of the model is 20D with open drainage boundary. Groundwater table is set at the lower boundary. The pile body behaving as linear elastic with non-porous drainage has Young's Modulus and Poisson's Ratio of 200MPa and 0.1 respectively.

According to Engin et al. (2014) there were challenges associated with the selection of appropriate interface strength for converging solution. Therefore, a separate material with varying fraction of soil actual undrained shear strength, s_u is assigned between the soil and pile to investigate the stability of the solution and its effect on surrounding soil. The strength of the interface extension remained the same as the soil to avoid unrealistic weak zones. Based on equation provided by Chang et al. (1999), the K_o consolidated soil has an undrained shear strength of 42kPa. Sensitivity study is carried out to progressively reduce



Initial Stage - K_o Procedure **Stage 1 – Press** **Stage 2 – Press & Replace**

Fig. 1. Press-Replace procedure

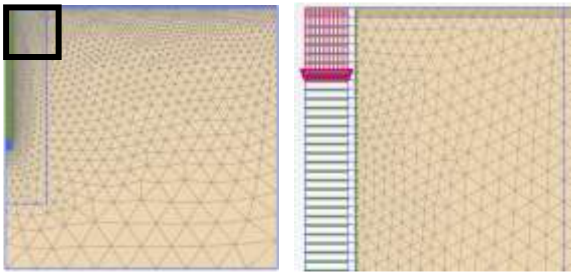
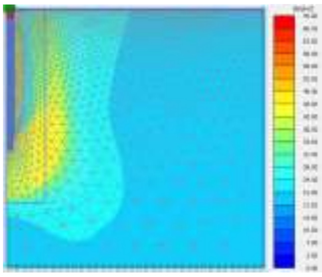


Fig. 2. Finite element mesh (overall) (left) and enlarged view (right)

the interface roughness or strength for both shaft and base simultaneously from soil full strength (1.0 s_u) to 70% (0.7 s_u) of the soil undrained shear strength. This approach is considered realistic to simulate the reduced strength of pile soil interface in a simplistic manner because remoulding of the soil around the pile occurs during installation within a brief period when the soil is assumed relatively undrained.

3 RESULTS & DISCUSSION

The typical shear strength and total radial stress contours are illustrated in **Fig. 3** and **Fig. 4** respectively at the end of pile installation. It is observed that the shear strength along the pile-soil interface is fully mobilized due to the relative movement between soil and pile. Meanwhile, it is expected that large radial stresses occur at the pile toe as the soil is laterally push sideways along with pile penetration. **Fig. 5** shows the normalized total radial stresses along the pile length at pile-soil interface for various interface strength. The radial stresses depict an exponential curve from 8D downwards which demonstrate the large total stresses mainly from the generation of excess pore-water pressure. It can be as high as 10 times the soil undrained shear strength at the pile toe. From observation, higher strength of interface meaning higher roughness result in lower radial stresses because the soil mass adjacent to shaft has tendency to be pushed downward more than laterally. This phenomenon is consistent with the behaviour from large deformation analysis as reported by Konkol (2017) adopting total stress analysis of Tresca plasticity with varying frictional coefficient of friction, $\mu = \tan \delta$. **Fig. 6** depicts the soil horizontal and vertical displacement along pile shaft under various friction strength at the end of pile installation. The vertical displacement shown in negative magnitude has a more distinct difference compared to horizontal displacement which implies it has more influence by interface strength. Higher interface strength indicated more vertical displacement of soil along the pile shaft. **Fig. 7** shows the normalized shear stress distribution at elevation 6D, 8D and 10D under different interface strength. One of the observations is that the mobilized shear strength is slightly higher than the soil undrained



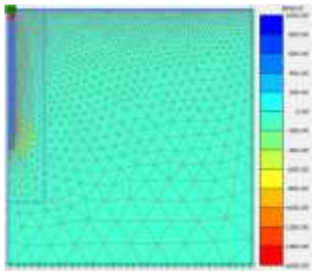


Fig. 3. Mobilized shear strength contour (left)
Fig. 4. Total radial stress contour (right)

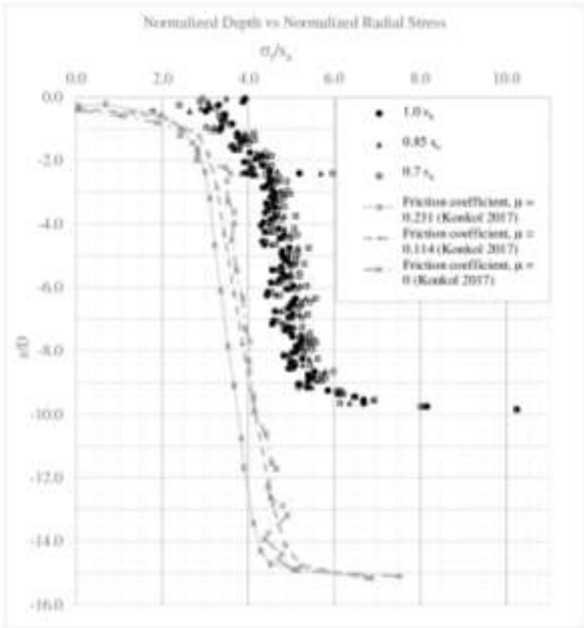


Fig. 5. Normalized Radial Stress along pile shaft

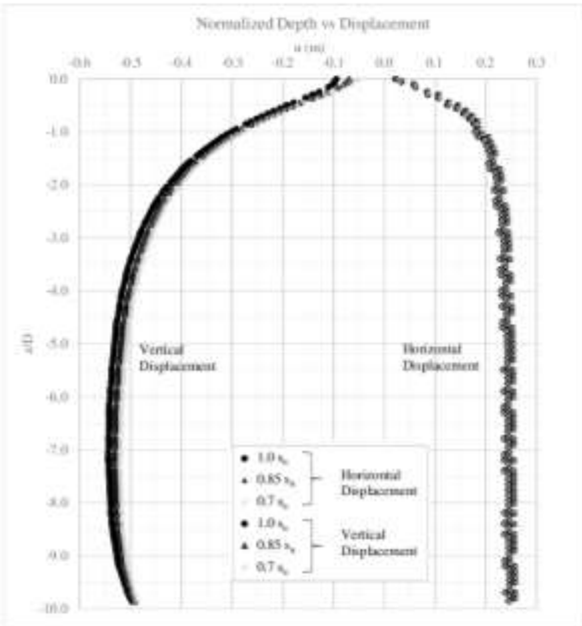


Fig. 6. Vertical (left) and horizontal (right) displacement of soil along pile shaft

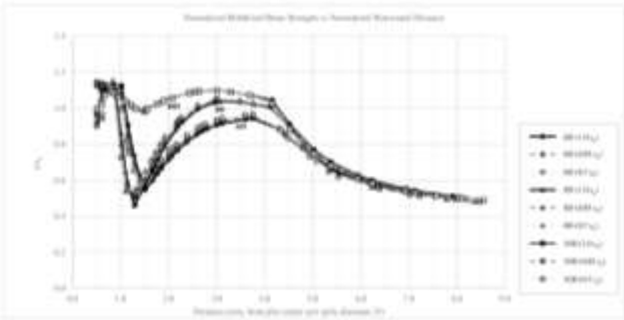


Fig. 7. Normalized mobilized shear strength at section 6D, 8D and 10D

shear strength. This could be due to some dissipation of excess porewater pressure during pile installation thus explaining the results. The second observation is the zone of fully mobilized shear strength near the pile toe is within 4D away from the pile axis as compared to shallower depth (6D & 8D) which is less influenced by toe effect. The effect of interface strength has only slight impact on the mobilized shear strength with their effect diminish at 4.5D away from pile axis. At end of respective installation (6D, 8D & 10D), the depth at which shear strength were mobilized at a certain magnitude becomes independent when it is 7D away from pile axis.

4 CONCLUSION

In this study, the Press-Replace Method (PRM) is applied to investigate the effect of interface strength on the soil behaviour around the pile in an undrained condition. The soil is modelled as a Modified Cam-Clay material. The results indicated almost twofold increase in mobilized shear strength at 1.5D away from pile due to the influence of toe effect. The interface strength/roughness does have influence on the mobilized shear strength and radial stresses though insignificant as it affects the movement of the soil around the pile shaft. Vertical displacement of the soil adjacent to the pile shaft has a more distinct effect than horizontal displacement under the influence of interface strength. It would be worthwhile to investigate this behaviour with the consideration of other factors such as anisotropy and cementation by adopting other more advanced soil model for future studies.

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