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Simulation of pile installation in chalk: Discrete and continuum approaches

Simulation de pose de pieux dans la craie: Approches discrètes et continues

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ABSTRACT: Chalk is a type of porous rock formed from cemented calcite grains. It is widely found in areas across the UK, and is present beneath the North Sea where offshore wind turbines are being installed. Large piles are often driven into chalk to support these turbines. However, the installation process can cause the intact rock below the pile to crush, creating a putty-like material with different mechanical properties from the original rock. This unpredictability has made it difficult to design piles that are appropriate for use in chalk. This paper presents two approaches to modelling open-ended pile installation in chalk. The first approach is based on the Discrete Element Method (DEM), which represents the rock as separate particles bonded together. A new contact model is proposed for highly porous rocks. The second approach uses the Geotechnical Particle Finite Element Method (GPFEM), which has been adapted to account for the large displacements and nonlinearities of the problem. With GPFEM the coupled hydromechanical effects developing during pile installation are investigated using a robust and mesh-independent implementation of an elasto-plastic constitutive model at large strains. With DEM the micromechanical features of pile plugging are explored and the mechanisms behind radial stress distributions inside and outside the plug are unveiled. Although both approaches have their challenges, they have been successful in modelling pile installation experiments at model scale. This offers the potential for a closer examination and improved understanding of the mechanisms underlying open-ended pile installation in chalk.

RÉSUMÉ: La craie est un type de roche poreuse formée de grains de calcite cimentés. Elle est largement répandue au Royaume-Uni et se trouve sous la mer du Nord, où des éoliennes offshore sont installées. De grands pieux sont souvent enfoncés dans la craie pour soutenir ces éoliennes. Cependant, le processus d'installation peut entraîner l'écrasement de la roche intacte située sous le pieu, créant ainsi un matériau semblable à du mastic dont les propriétés mécaniques sont différentes de celles de la roche d'origine. Cette imprévisibilité a rendu difficile la conception de pieux adaptés à une utilisation dans la craie. Cet article présente deux approches pour modéliser l'installation de pieux ouverts dans la craie. La première approche est basée sur la méthode des éléments discrets (DEM), qui représente la roche comme des particules séparées liées entre elles. Un nouveau modèle de contact est proposé pour les roches très poreuses. La seconde approche utilise la méthode des éléments finis à particules géotechniques (GPFEM), qui a été adaptée pour tenir compte des grands déplacements et des non-linéarités du problème. Avec la GPFEM, les effets hydromécaniques couplés qui se développent pendant l'installation des pieux sont étudiés en utilisant une implémentation robuste et indépendante du maillage d'un modèle constitutif élasto-plastique à grandes déformations. Avec le DEM, les caractéristiques micromécaniques du colmatage des pieux sont explorées et les mécanismes qui sous-tendent les distributions radiales des contraintes à l'intérieur et à l'extérieur du colmatage sont dévoilés. Bien que les deux approches présentent des difficultés, elles ont permis de modéliser avec succès des expériences d'installation de pieux à l'échelle du modèle.

Keywords: Displacement piles; DEM; GPFEM; Chalk.

1 INTRODUCTION

Designing foundations in soft, cemented porous rocks presents a significant challenge due to the material's complex mechanical behaviour. Upon loading soft rocks may crush and collapse and, if saturated, consequent pore water pressure build up would further reduce the effective stress. Material behaviour would then change from stiff elastic to a non-linear irreversible soil-like one, characterised by completely different hydraulic properties. Whilst for low levels of loading, an elastic response may facilitate design, the insertion of a rigid body like a steel pile will definitively remould the rock (Buckley et al., 2017) and therefore suffer from the above-mentioned consequences. Small scale physical modelling in soft rocks has revealed that the damage process is completely different when comparing a closed-ended cone shaped pile with an open-ended tubular one (Alvarez-Borges et al., 2018). For this reason, the post-installation stress field will change depending on the geometry of the penetrating object. To incorporate installation effects, current practice for pile design in soft rocks is moving towards cone penetration test (CPT) methods (Jardine et al., 2023) where radial stress profiles around open-ended piles pushed into soft rocks are inferred from the CPT response.

In recent years, several numerical methods able to overcome difficulties related to large deformations and various types of non-linearities (e.g. material, contact) have been developed. On one side, the Discrete Element Method (DEM), often used to investigate elemental soil behaviour, has been shown to be an appropriate tool that with reasonable computational power can be used to simulate boundary value problems (BVPs). Several boundary value problems including pile penetration (Cerfontaine et al., 2023; Ciantia et al., 2019) and screw piles (Sharif et al., 2021) have been investigated using the DEM.

On the other hand, amongst various continuum approaches (CEL, MPM, SPH), the Geo-Particle Finite Element Method (GPFEM) has been shown to be able to manage large deformations and address the complexities of nonlinear soil behaviour (Carbonell et al., 2022). GPFEM has been shown to be suitable to investigate CPT installation and interpretation in structured ground (Oliynyk et al., 2021). Thanks to its robust large deformation hydro-mechanically-coupled formulation it was used to study installation problems in chalk in partially drained conditions (Previtali et al., 2023).

Both DEM and GPFEM have advantages and disadvantages. For example, whilst DEM only requires calibration of simple physical parameters to capture soil behaviour quite realistically at the macroscale, it is computationally demanding, particularly if hydro-mechanical problems need to be modelled. In contrast, continuum approaches were developed from the outset to solve BVPs, but strongly depend on the ability of the constitutive relationship used to accurately simulate soil behaviour. In this work DEM and GPFEM are used to investigate the installation process of an open-ended pile in a soft rock. Reference experimental data by Alvarez-Borges et al. (2018) that used X-ray tomography will be used as a validation dataset.

2 NUMERICAL FRAMEWORKS

2.1 DEM for highly porous rocks

The behaviour of rocks has been historically modelled in DEM by introducing cohesive bonds through the Bonded Particle Method (BPM) (Potyondy & Cundall, 2004). Zheng et al. (2023) recently developed a bond-softening damage model able to capture the complex pressure dependent behaviour of weakly cemented porous rocks. Such a contact model, which is used in this study, is defined within the macro-element framework characterized by a generalized force-displacement failure envelop:

$$f = \left|\frac{\breve{M}}{\tilde{M}}\right|^{1.001} + \left(\frac{N}{\bar{N}}\right)^2 + \left(\frac{V}{\bar{V}}\right)^4 \left[1 - \left(\frac{N}{\bar{N}}\right)^2\right]^{-1} - 1 \quad (1)$$

The behaviour in the (i) normal (*N*), (ii) tangential (*V*) and (iii) bending direction ($\breve{M}$) is linear elastic within the yield surface, according to Euler beam theory. The overbar symbols $\tilde{M}, \bar{N}$ and $\bar{V}$ represent the size of the yield surface on a given axis and are function of the bond tensile (σ_{t0}), compressive (σ_{c0}) and shear (τ_0) strength. Unlike in the BPM, the bond does not instantaneously fail once the combined load reaches the yield surface but starts accumulating damage. This damage variable (D_d) then affects the size of the yield surface modifying σ_0 and τ_0 through plastic softening. D_d depends on the irreversible displacements in the normal u_n^p and tangential u_s^p direction and the irreversible rotation θ_b^p:

$$D_d = 1 - e^{-\left(\frac{|u_n^p|}{u_n^c} + \frac{u_s^p}{u_s^c} + \frac{\theta_b^p}{\theta_b^c}\right)} \quad (2)$$

Table 1. Chalk DEM parameters (see. Zheng et al. (2023)).

Parameter	**Value**	**Parameter**	**Value**
$\bar{E}^*[GPa]$	1.7	θ_b^c[rad]	6e^{-3}
$\bar{\kappa}^*[-]$	5	$\sigma_{c0}[MPa]$	50
$u_n^c[m]$	2e^{-5}	$\sigma_{t0}[MPa]$	1
$u_s^c[m]$	2e^{-5}	$\tau_0[MPa]$	2

2.2 GPFEM of structured soils

The GPFEM is based on a standard FEM framework that, through continuous remeshing, mitigates mesh distortion issues. The efficiency of the numerical approach lies in the use of low-order triangular elements which simplify the remeshing process. To avoid interlocking issue, a mixed formulation is used. The constitutive model used in this work is an extension of Modified Cam Clay to incorporate bonding (Monforte et al., 2019). In addition to the standard preconsolidation pressure of the unbonded material p_s, an extra internal variable related to the tensile strength of the rock (p_t) is used to account for bonding. The shape of yield surface is controlled by M_f while $M_g$controlles the plastic flow. The hardening internal variables evolve with deviatoric and volumetric plastic strains. $\rho_{s,t}$ and $\xi_{s,t}$ are constitutive model parameters controlling the rate of hardening and softening. The material parameters listed in Table 1 and 2 were calibrated against a combination of literature data and element tests on Saint Nicholas at Wade (SNW) chalk (Riccio et al., 2023). Refer to Previtali et al, (2023) for further details.

Table 2. Constitutive model parameters for chalk.

Parameter	Value	Parameter	Value
$\boldsymbol{e_0}\ [-]$	0.83	$p_{s_0}\ [kPa]$	3000
$\boldsymbol{\rho'}\ [\boldsymbol{Mgm^{-3}}]$	1.4	$p_{t_0}\ [kPa]$	200
$\boldsymbol{\nu}\ [-]$	0.12	$E\ [GPa]$	1
$\boldsymbol{\rho_s}\ [-]$	19	$\rho_t\ [-]$	15
$\boldsymbol{\xi_s}\ [-]$	0.5	$\xi_t\ [-]$	0.5
$\boldsymbol{M_f}\ [-]$	1.0	$M_g\ [-]$	1.2

3 MODEL PILE SIMULATIONS

Figure 1 shows the numerical model reproducing the experimental set up for the model pile installation tests in SNW chalk by Alvarez-Borges et al. (2018). In the experiment a tubular pile with external diameter of 8 mm and wall thickness of 1 mm was jacked to a depth of 2 cm in a cylinder of diameter 100 mm and length of 120 mm. The axisymmetric simplification of the geometry along with some geometrical quantities are represented in Figure 1. The figure also shows the DEM and GPFEM numerical model initial conditions.

Axisymmetric conditions for DEM models are extremely challenging due to the particles on the symmetry axis and therefore a 3D model is used. The rock domain is generated using the periodic cell replication method PCRM (Ciantia et al., 2018) . It consists of a combination of different techniques aimed at speeding up large DEM models generation. To reduce the computational burden, the PSD of destructured chalk was upscaled by a factor of 2.1 near the pile (<0.6D) increasing to a factor of 4.8 at 2.5D. Considering that the damage model is framed to be scale independent the scaling used does not affect the calibrated parameters (Zheng et al. 2023). The maximum and minimum particle size was 0.18 mm and 0.066 mm, respectively, with a d50 of 0.116 mm. To limit scale effects on potential plugging behavior (Cerfontaine et al., 2023), this scaling value was chosen to provide a sufficient number of particles in contact with the pile whilst keeping the computational burden manageable. Pile wall thickness (t_w) to d50 ratio is 4.0.

To mitigate computational load and prevent boundary effects, the edges of the DEM domain are coupled with a Finite Difference Model (FDM). Additional details on DEM-FDM model coupling are available in Zheng et al. (2023). Given the significant stiffness contrast between the pile and the rock, the pile representation is simplified by using a rigid, non-deformable wall and the installation force is obtained as the sum of the vertical contact forces.

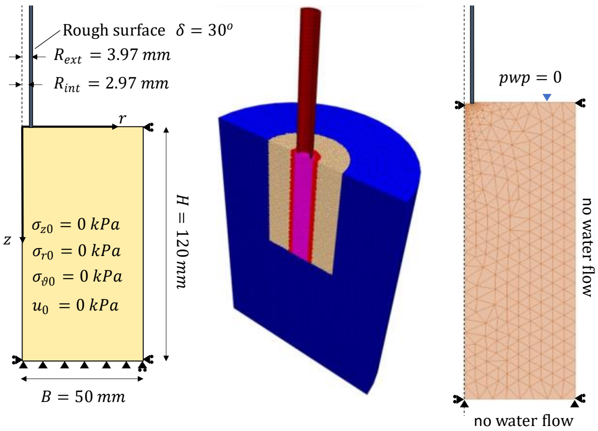

Figure 1. (left) Model pile tests experimental setup by Alvarez-Borges et al. (2018) along with geometrical quantities and snapshots of the discrete (middle) and continuum (right) numerical model initial states.

The GPFEM model generation is much simpler as initial conditions can be directly assigned as for classic FE models. Moreover, axisymmetric conditions are easily modelled with continuum methods and are hence here used. Although the experiments were performed pushing the pile slow enough to attain drained conditions, the simulations were carried out using a coupled hydro-mechanically formulation. As with the DEM model, the pile is simplified as a perfectly rigid wall and the installation force is measured as the sum of the contact forces. Boundary conditions are represented in Figure 1.

4 RESULTS AND DISCUSSION

Figure 2a compares the experimental results against the load displacement curve predicted by the two numerical models. The general trend is very similar although the GPFEM simulation seems to underpredict the penetration force. There are several reasons for such discrepancy. These include for example, the constitutive model softening parameters or the approximation of the flat tip with a curved geometry to avoid the sharp corners. Figure 2b shows contours of the radial stresses close to the pile tip. Whilst the continuum and discrete model results appear very similar a more quantitative comparison would be required for a proper comparison.

5 CONCLUSIONS

Two different numerical approaches, namely the DEM and GPFEM have been used to simulate open- ended pile installation in a soft chalk. Both procedures were able to overcome the difficulties associated with large displacements, large strains as well as geometrical, material and contact nonlinearities. The good agreement between the two methods and the experimental data indicates that both approaches are adequate for the investigation of open-ended pile installation in chalk.

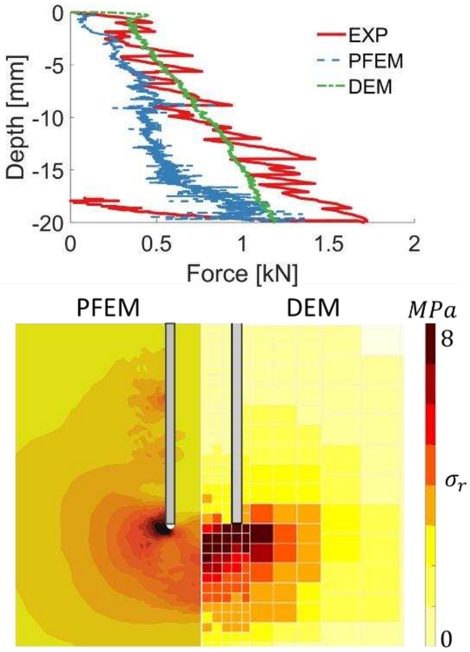

Figure 2. (top) Force displacement curves and (bottom) radial stress contours at the end of installation.

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