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COMPARISON OF CONTINUUM (PFEM) AND DISCRETE (DEM) APPROACHES FOR LARGE INSERTION BVPS IN SOFT ROCKS

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Abstract. In recent years, significant advancements in computational efficiency have enabled the application of advanced numerical models to solve boundary value problems (BVPs) in geotechnics, including those related to large-displacement problems. However, challenging problems, such as those involving open-ended piles (OEs) in soft rocks, require specialized approaches due to material and geometrical non linearities combined to the large deformation soil-structure interaction. This paper presents a comparison of two approaches for modeling OE pile installation in soft rocks. The first approach employs the Discrete Element Method (DEM), which represents the rock as separate particles bonded together, and introduces a new contact model for highly porous rocks. The second approach uses the Geotechnical Particle Finite Element Method (GPFEM) and investigates the coupled hydromechanical effects during pile installation using a robust and mesh-independent implementation of an elastic-plastic constitutive model at large strains. The DEM approach explores the micromechanical features of pile plugging and unveils the mechanisms behind radial stress distributions inside and outside the plug. The study highlights the strengths and limitations of each modeling approach, providing insights into the behavior of OE piles in soft rocks.

Keywords: Displacement piles, DEM, GPFEM, Framework comparison.

1 INTRODUCTION

Designing foundations in soft, cemented porous rocks presents a significant challenge due to the material's mechanical behaviour, which may crush and collapse under load. Material behaviour would then change from stiff elastic to a non-linear irreversible soil-like one characterised by completely different hydraulic behaviour. Whilst for low levels of loading an elastic response may facilitate design, the insertion of a rigid body like a steel pile will definitively destructure the rock [1] and therefore suffer from the above-mentioned consequences. Cone penetration test (CPT) interpretation and the design of displacement piles in soft rocks are exemplar geotechnical engineering situations where damage effects induced by installation play a key role [2]. Small scale modelling in soft rocks has revealed that the destructuration process is completely different when comparing a closed ended cone shaped pile with an open-ended tubular one [3]. For this reason, the post installation stress field will change depending on the geometry of the penetrating object. Nonetheless current practice for pile design in soft rocks is moving towards CPT methods [4] where radial stress profiles around open-ended piles pushed into soft rocks are inferred by the CPT response.

In recent years, several numerical methods able to overcome difficulties related to large deformations and various types on non-linearities (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 sued to simulate boundary value problems [5]. for the first time show that the DEM is suitable to model CPT in calibration chambers. From this seminal work several boundary value problems including, pile penetration [6], [7], SPT [8] and screw piles [9] have been investigated using the DEM.

On the other hand, amongst various continuum approaches, the Geotechnical Particle Finite Element Method (GPFEM) has recently been shown to be able to manage large deformations and address the complexities of nonlinear soil behaviour [10], [11]. GPFEM has shown to be suitable to investigate CPT installation and interpretation in various soil types [11]–[13]. Thanks to its robust large deformation HM coupled formulation it was used to study installation problems in chalk also in partially drained conditions [14].

Both DEM and GPFEM have advantages and disadvantages. For example, whilst the DEM just 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. The time required to initialise a large DEM model, for example, can be the main obstacle to its use for BVP. On the other hand, continuum approaches are born to solve BVP but strongly depend on the constitutive relationship ability to predict soil behaviour. To this end open source GPFEM platform (https://gitlab.com/pfem-research/kratos) has a wide range of constitutive models of various complexities. In this work the DEM and GPFEM are used to investigate the installation process of an open-ended pile in a soft rock. Reference experimental data by [15] that used X-ray tomography to investigate how the process affected the material around the pile will be used. In the scope of this paper, the authors aim to replicate the small-scale pile installation tests to compare the features observed in both numerical methods.

2 NUMERICAL FRAMEWORKS

As mentioned above the goal of this study is to compare two completely different numerical frameworks to investigate open ended installation in a soft rock: (i) the Discrete Element Model (DEM) [16] and (ii) the Geotechnical Particle Finite Element Method (GPFEM) [17]. The former simulates the behaviour of granular material as discrete objects with a given mass and shape, interacting with each other through contact mechanics (i.e. partial particle overlap with force-displacement relationships). On the other hand, G-PFEM leverages classic finite element techniques but addresses the mesh distortion challenges associated with large displacements through remeshing.

2.1 Discrete Element Model for Soft highly porous rocks

The behavior of rocks has been historically modelled in DEM by introducing tensile bonds between contacting particles through the so-called Bonded Particle Method (BPM) [18]. Since then various authors improved on this method by introducing beam theory in the contact interaction and providing a physical rationale to the bond strength and stiffness [19], [20]. Following [21], [22] and who introduced the macro element framework to frame DEM contact models, [23] recently developed a bond-softening damage model able to capture the complex pressure dependent behavior of soft highly porous rocks. Such contact model, which will be used int this study, is defined within the macro-element framework characterized by a generalized force-displacement failure envelop defined as

$$f_{yield} = \left|\frac{\tilde{M}}{\tilde{\bar{M}}}\right|^{1.001} + \left(\frac{N}{\bar{N}}\right)^2 + \left[\left(\frac{V}{\bar{V}}\right)^4 \Big/ 1 - \left(\frac{N}{\bar{N}}\right)^2\right] - 1 \tag{1}$$

The behavior in the (i) normal (N), (ii) tangential (V) and (iii) bending direction (M) is linear elastic, according to Euler beam theory. The underbar symbols ($\tilde{\bar{M}}, \bar{N}, \bar{V}$) represent the size of the yield surface on a given axis. Unlike in the standard parallel-bond model, the bond does not disappear once the combined effect of force and rotation reaches the yield surface but starts accumulating damage. This damage variable then affects the size of the yield surface through plastic softening:

$$\begin{bmatrix} \bar{N} \\ \bar{V} \\ \tilde{\bar{M}} \end{bmatrix} = \begin{bmatrix} \bar{N} \\ \bar{V} \\ \bar{M}/\bar{R} \end{bmatrix} = \begin{bmatrix} N_0 \\ V_0 \\ M_0/\bar{R} \end{bmatrix}(1-D) = \begin{bmatrix} \sigma_0 \bar{A} \\ \tau_0 \bar{A} \\ \sigma_0 \bar{I}/\bar{R}^2 \end{bmatrix}(1-D) \tag{2}$$

$\bar{R}$ is the bond radius, σ_0 and τ_0 are the normal and shear strength of the bond; σ_0 includes two components, $\sigma_0 = \sigma_c$ under compression and $\sigma_0 = \sigma_t$ under tension, respectively, and $\bar{A}$ and $\bar{I}$ are the area and moment of inertia. Finally, the damage variable is updated according to the irreversible displacements in the normal u_n^p and tangential u_s^p direction and the irreversible rotation θ_b^p:

$$D_d = 1 - e^{-\left(\frac{|u_n^p|}{u_n^c} + \frac{u_s^p}{u_s^c} + \frac{\theta_b^p}{\theta_b^c}\right)} \tag{3}$$

u_n^c, u_s^c and θ_b^c in eq. (3) are model parameters to control the softening rate of the bond. The effectiveness of the model to capture the ductile failure of soft rocks is shown in [23]. The DEM contact model elastic (the effective modulus $\bar{E}^*$, the normal-to-shear stiffness ratio $\bar{\kappa}^*$) and strength (σ_0 and τ_0) parameters are calibrated by matching experimental Young's Modulus (E) and Unconfined Compression Strength (UCS). All material parameters are reported in Table 1.

Table 1. DEM Bond damage model parameters to model chalk.

Parameter	$\bar{E}^*$	$\bar{\kappa}^*$	u_n^c	u_s^c	θ_b^c	σ_0	τ_0
Units	*GPa*	/	*m*	*m*	/	*MPa*	*MPa*
Value	1	5.0	2e-5	2e-5	6e-3	50	2

2.2 G-PFEM

The Particle Finite Element Method was originally developed for fluid mechanics applications [17] and through continuous remeshing mitigates mesh distortion issues. The numerical method is still based on a standard FEM framework, while boundary identification induced by the large deformation/displacements is carried out through an alpha-shape approach. PFEM has recently been extended to solve large deformation geotechnical problems by [11]. The efficiency of the numerical approach mainly lies in the use of low order triangular elements which simplify the remeshing process. Nonetheless, mixed formulation are required to avoid interlocking issues [11] to cope with H-M coupled problems and soil mechanics constitutive models.

The constitutive model used here is an extension of a Modified Cam Clay to incorporate bonding [24]. In addition to the standard pre-consolidation pressure of the unbonded material $\boldsymbol{p_s}$, an extra internal variable related to the tensile strength of the rock (p_t) is used to account for bonding. The size of the yield surface is hence given by $p_c = p_s + k \cdot p_t$ where k is a model parameter that correlates tensile strength to the isotropic compressive strength increase due to bonding. The hardening internal variables evolve with deviatoric $\widehat{\boldsymbol{D}}$ and volumetric $\widehat{\boldsymbol{V}}$ plastic strains incerments according to the following hardening law

$$\begin{aligned} \dot{p_s} &= \dot{\gamma}\, \rho_s p_s\left(-\hat{V} + \xi_s \widehat{D}\right) \\ \dot{p_t} &= -\dot{\gamma}\, \rho_t p_t\left(\left|\hat{V}\right| + \xi_t \widehat{D}\right) \end{aligned} \tag{4}$$

where $\rho_{s,t}$ and $\xi_{s,t}$ are constitutive model parameters controlling the rate of hardening and softening. The material parameters listed in Table 2 were calibrated on a combination of literature data and element tests on SNW chalk as described in [25]. Further details can be found in [26].

Table 2. Constitutive model parameters for chalk.

Parameter	e_0	ρ'	ν	ρ_s	ξ_s	p_{s_0}	p_{t_0}	E	ρ_t	ξ_t
Units	/	Mgm^{-3}		/	/	kPa	kPa	kPa	/	/
Value	0.83	1.4	0.12	19	0.5	3000	200	1	15	0.5

3 MODEL PILE SIMULATIONS

Figure 1a shows the experimental set up for the model pile installation tests in Saint Nicholas at Wade chalk by [15]. The test setup consists in a pile with diameter of 8 mm and wall thickness of 1 mm is installed (jacked) to a depth of 2 cm in a cylinder of diameter 100 mm and length of 120 mm. The plain strain axisymmetric simplification of the geometry along with some geometrical quantities are represented in Figure 2b. Finally Figure 2c and d show the DEM and GPFEM numerical model initial conditions.

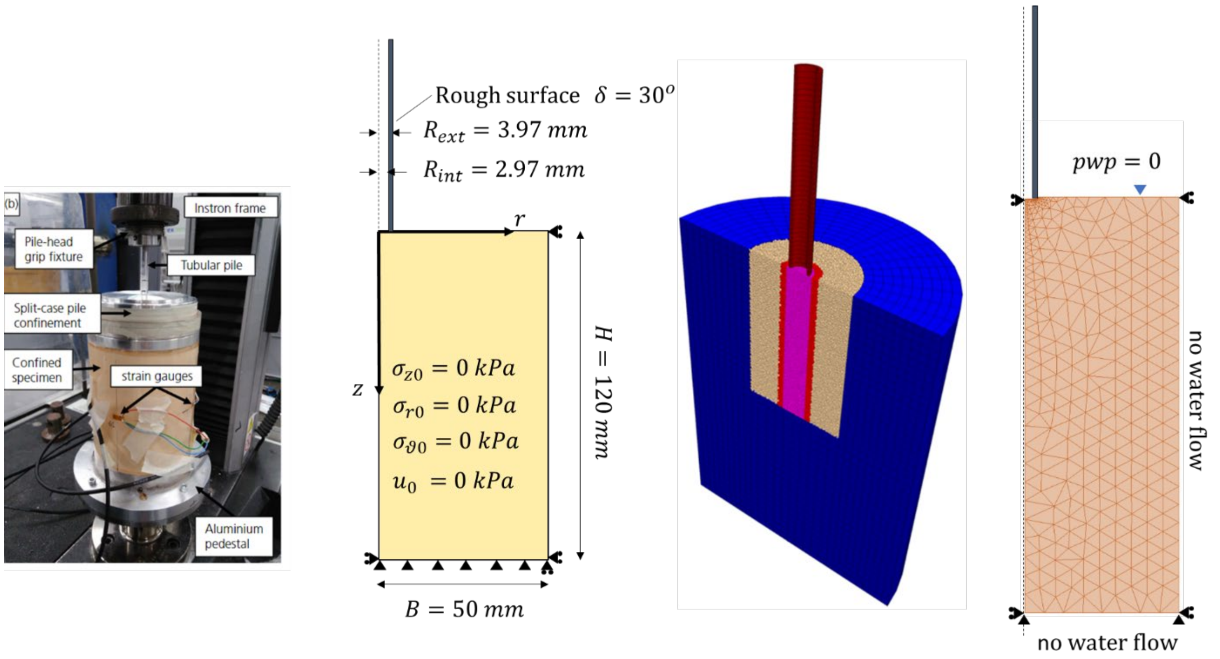


Figure 1: Model pile tests experimental setup by [3] *along with geometrical quantities and snapshots of the discrete and continuum numerical model initial states.*

Axisymmetric conditions for DEM models are extremely challenging due to the particles on the symmetry axis and therefore a 3d model is required. The 3D rock domain is generated using the periodic call replication method PCRM detailed in [27]. It consists in a combination of different techniques aimed at speeding up large DEM models generation: first, a semicircular brick with a diameter (D) of 40mm and a height of 6 mm is generated in periodic space using the radii expansion method. As shown in [28], the macroscopic modelled rock behavior depends on Particle Size Distribution (PSD) and coordination number. To reduce the computational burden, following [29] the PSD of destructured chalk has been upscaled by a factor of 2.1 near the pile (<0.6D) up to a factor of 4.8 at 5D. Considering that the damage model is framed to be scale independent the scaling used does not affect the calibrated parameters. The maximum and minimum particle size is 0.181 mm and 0.0655 mm, respectively, with a d50 of 0.116 mm. To limit scale effects [30], 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 mean particle size ratio is 4.0.

The periodic space brick is stabilized at a target stress state of 10 kPa vertical stress and 2.5 kPa radial stress and replicated up to fill a domain of size 40x60 mm (5D in the horizontal direction). The contact force and particle-to-particle reference gap are then rescaled to obtain a linear stress distribution with depth [31]. To mitigate computational load and prevent boundary effects, the edges of the DEM domain are coupled with a Finite Difference (FDM) domain (Figure 1c). The effectiveness of the coupling can be evinced by the displacement contours shown in Figure 2, that represents a 2D section of the 3D model. Additional details on model the coupling are available in [23], [28]. 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 components of the contact forces between the wall and the DEM particles.

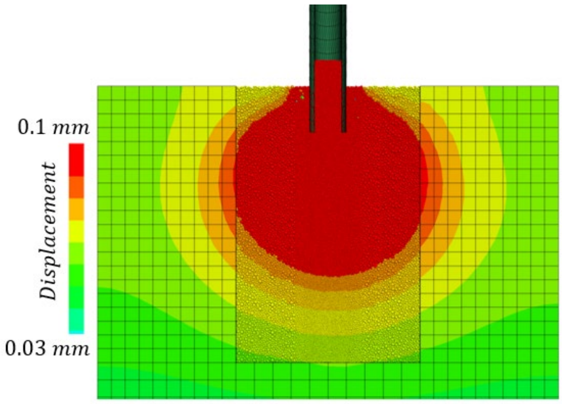
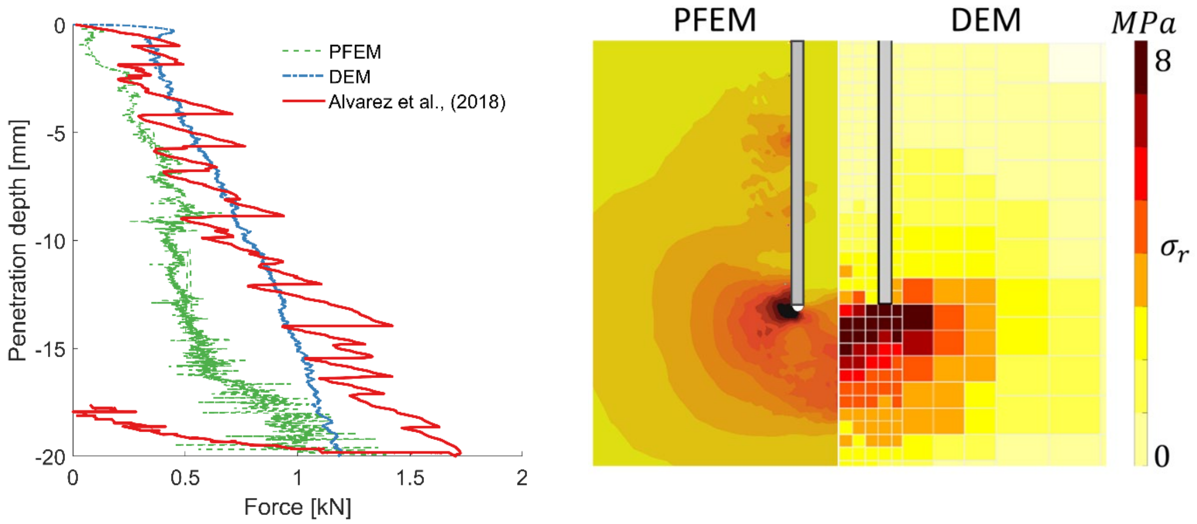


Figure 2: Continuity of the displacement field between the DEM and FDM domains during pile installation

The G-PFEM 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 where performed to push the pile slow enough to attain drained conditions, the simulations where carried out using a coupled H-M 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 for both DEM and GPFEM model are represented in Figure 1.

4 RESULTS AND DISCUSSION

Figure 2a compares the experimental data [15] 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. Stress contours for the DEM model were determined using the averaging techniques and criteria detailed in [28]. Whilst the continuum and discrete model results appear very similar a more quantitative comparison would be required for a proper comparison.



a) b)

Figure 3: (a) Force displacement curves and (b) radial stress distribution at the end of installation

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 considerable difficulties associated with large displacements, large strains and rotations, severe domain distortion as well as geometrical, material and contact nonlinearities.

The good agreement between the two different methods with the experimental data indicates that both approaches are adequate for the investigation of open-ended pile installation in chalk. Both methods could hence be used to better understand the mechanisms responsible for the response recorded at the global scale.

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