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Physical Modelling in Geotechnics

Coupled DEM-FDM investigation of centrifuge acceleration on the response of shallow foundations in soft rocks

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ABSTRACT: The investigation of the response of cemented materials to the installation of rigid foundations is a complex problem due to the presence of material and geometric non-linearities, large deformations and sometimes dynamic conditions. Centrifuge testing is typically employed to carry out laboratory-scale physical models with field-like stress levels. Numerical models such as the discrete element method (DEM) can be used to improve our interpretation of physical models by replicating the laboratory tests virtually, i.e. creating a "digital twin", and subsequently accessing information which can be difficult or impossible to measure in the laboratory. DEM models of boundary value problems are however challenging and require numerical procedures to reduce the computational burden. In this work, particle upscaling and DEM-FDM (Finite Difference Method) coupling is used to simulate the penetration of a shallow foundation into weakly cemented granular materials under different gravity levels. A fast-generation technique for the preparation of the digital twin, considering the distribution of particle weight is also proposed. The numerical results show that load-displacement curves are very similar to each other, indicating that the failure mechanism at shallow depths is governed by a punch-like mechanism. It is also shown that the punching response is largely influenced by the post peak response of the bonded material.

Keywords: coupled DEM-FDM, soft rocks, particle upscaling, centrifuge model simulation.

1 INTRODUCTION

In recent years, offshore wind has become a major part of the global effort to achieve carbon neutrality in the next 30-40 years. However, deep sea foundation design presents significant challenges due to the widespread presence of soft carbonate rocks, characterized by high porosity and low strength (Ciantia, 2021). The brittle and collapsible structure of such seabed can be the cause of detrimental phenomena such as spudcan punch-through failure, usually mitigated by conservative design and oversizing the foundations. Performing field-scale tests is typically not economically viable, hence centrifuge modelling has become standard practice in geotechnics to investigate the material response under realistic stress states (Zhang et al., 2021). The interpretation of centrifuge tests can be quite challenging, due to the inherent complexity of instrumenting the domain, especially for 3D problems, and they are typically limited to the installation force and torque on the foundation and water pressure at discrete points. In this context, numerical methods can be used to reproduce the laboratory-scale experiment, a procedure typically referred to as digital twin, in order to gain valuable insight on the underlying mechanisms of certain processes.

The Discrete element method has proven to be a numerical tool able to realistically reproduce soil behavior with limited assumptions, even in centrifuge environments (Ciantia et al., 2018; Sharif et al., 2021) by representing each individual particle as a discrete body. Two techniques have been historically used to reduce the computational burden of this method, decreasing the number of DEM elements: (i) particle upscaling and (ii) coupled methods to reduce the domain size (Ciantia et al., 2016; Tu et al., 2017; Coetzee, 2019; Sharif et al., 2019; Gholaminejad et al., 2021). In addition, imposing the correct initial conditions, considering the stress distribution of self-weight using DEM through traditional methods such as pluviation can be very time-consuming. Ciantia et al. (2018) proposed a fast generation technique based on first producing a small sample in periodic space at a target stress level, then replicating it and scaling contact forces with depth to obtain the desired gradient. Herein, the same technique was adapted to cemented materials and coupled with continuum techniques, i.e. Finite Differences, to further enhance the model performance.

When designing a centrifuge experiment, load cells, motor capacity and scale effects should be considered carefully. To this end numerical modelling can aid the design of a centrifuge testing campaign. Simulating the experiment in advance can provide useful information which can feed the decision-making process when designing experiments.

In the following, the scale effect of particle size on the macroscopic properties of a numerical model of soft rock is investigated. Two DEM contact models, namely the soft bond contact model (SBM) (Ma & Huang, 2018) and the parallel bond model (PBM) are used. Finally, several penetration simulations of shallow foundation were carried out at different gravity levels to study the failure mechanism of shallow foundations in soft rocks.

2 SCALE EFFECT OF SBM

The effect of upscaling the particle size on the macroscopic properties of a DEM numerical rock sample (i.e. Young's modulus and unconfined compression strength, UCS), is investigated by simulating uniaxial compression tests. All samples have the same size: 4 x 4 x 2 mm. The maximum and minimum particle size is 0.181 mm and 0.0655 mm, respectively. The medium particle size (*d*50) is 0.116 mm. The micromechanical characteristics of these samples are reported in Table.1, to make sure the initial conditions at all scales are the same. N_p is the number of particles in the sample, n is the porosity and Z is the average number of contacts per particle, i.e. coordination number. In addition, the parameters of SBM are listed in Table 2.

Table 1. Initial states of three samples.

	Scale=1	Scale=1.3	Scale=1.5
n	0.5195	0.5188	5.2042
Z	6.82	6.83	6.75
N_p	25835	11781	7664

Table 2. Contact parameters of SBM and PBM (Italics for PBM).

Parameters	Value
Effective modulus E^*	2.8 GPa
Normal-to-shear stiffness ratio κ^*	2.4
Bond effective modulus $\overline{E^*}$	2.8 GPa
Bond normal-to-shear stiffness ratio $\overline{\kappa^*}$	2.4
Cohension c	0.45 MPa
Tensile strength σ_c	0.45 MPa
Friction angle φ	32°
Bond softening factor ζ	100
Bond softening tensile strength factor γ	0.05

The axial stress-strain ($\sigma_z - \varepsilon_z$) responses of the bonded assemblies are shown in Fig.1. Since the macro-scale properties, such as UCS, appear unchanged after particle upscaling, the DEM contact model employed can be considered scale-invariant.

3 A FAST GENERATION TECHNIQUE OF COUPLED DEM-FDM MODEL

The brick replacement method from Ciantia et al. (2018) has been adapted to generate bonded assemblies. The procedure is listed in the following:

Step 1: generating a $L_c \times W_c \times H_c$ Representative Element Volume (REV) using periodic boundaries and compressing this REV to a prescribed vertical stress σ_v and lateral stress σ_h.

Step 2: Replicating the REV α times in the x direction, β times in the y direction and γ times in the z direction. Note: i.e. the sample has been replicated 5 times in the z direction, see Fig.2.

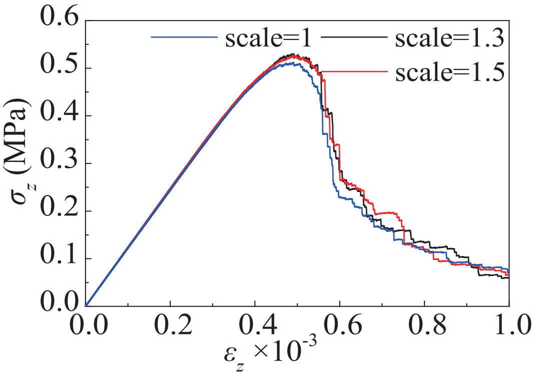

Fig. 1. Comparison of uniaxial compression response of numerical rock samples generated with different PSD scaling factors (1 1.3 and 1.5)

Step 3: The FDM elements are generated at the extremities of the DEM model and successively coupled with DEM (Breugnot et al., 2016). The final size of DEM part and this coupled model is $L_\mathrm{D} \times W_\mathrm{D} \times H_\mathrm{D}$ and $L \times W \times H$, respectively. in the sample here, $L_\mathrm{D} = L_c$, $W_\mathrm{D} = W_c$. Herein, the ball-facet contacts are parallel bonded contacts, meaning the bond is modelled as an elastic spring for both normal and shear, which has been shown to reproduce beam behavior (Potyondy & Cundall, 2004).The compressive forces that would arise from FDM-DEM overlaps are removed by assigning zero stiffness contact resistance within the linear part.

Step 4: for each contact, the force is scaled by a ratio $z/\ H_\mathrm{D}$ where z is the distance in z direction from the bottom of DEM part to the contact location. All contact forces between coupling-wall and balls are the mean value of contact forces in ball-ball contacts. This scaling is achieved by re-assigning bond forces.

Gravity is then introduced and the DEM model is cycled until equilibrium. Finally, the target initial stress distribution is assigned to the continuum FDM elements.

The final stress distribution of this coupled model is shown in Fig.3, showing that the initialization approach is successful.

4 PENETRATION OF SHALLOW FOUNDATION

4.1 Domain size of the coupled model

The geometry size of REV, DEM part and whole coupled model are shown in table 3.

Table 3. Geometry size of the model.

	Length (m)	Width (m)	Height (m)
REV	0.004	0.004	0.002
DEM	0.004	0.004	0.01
Coupled model	0.016	0.016	0.016

The diameter D_f and height H_f of the cylinder-shaped shallow foundation are 1.2mm and 0. 6mm, respectively.

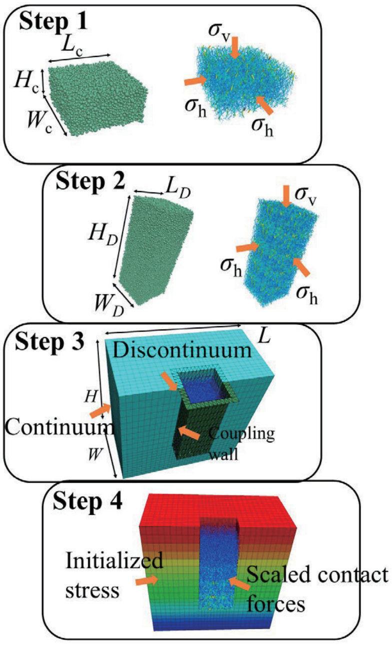

Fig. 2. Flow chart of the fast-generation technique of coupled DEM-FDM model.

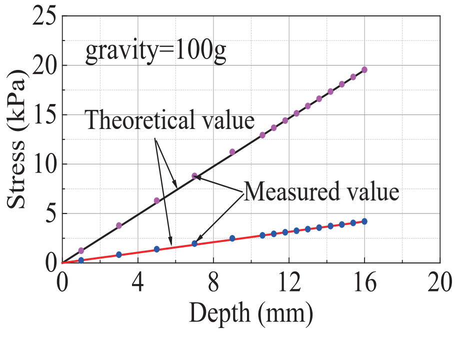

Fig. 3. Stress distribution at the case of 100g.

4.2 Description of penetration test

Several penetration tests were performed at different gravity levels. Following Ciantia et al. (2019), the penetration rates were determined such that

$$v_{pile} = \dot{\gamma} L_p \tag{1}$$

$$\dot{\gamma} = \frac{I}{d_{50}\sqrt{\rho/P}} \tag{2}$$

Where v_{pile} is the penetration velocity, L_p is the width of the plastic zone, assumed to be 3 times the diameter of the foundation D_f. $\dot{\gamma}$ is the shear strain rate. I is the inertial number, set to less than 10^{-2} to guarantee the quasi-static conditions during penetration (Janda and Ooi, 2016). d_{50} is defined as above and ρ is density and P is the mean stress at the pile tip. All tests considered a penetration depth h_1 equal to 20% of the foundation diameter.

5 RESULTS

Fig.4 compares the load-displacements curve at 100g between SBM and PBM, the two contact bond models typically used to reproduce cemented materials. They have similar elastic responses, although the result of SBM exhibits more plastic hardening. SBM is used to simulate the penetration in the below because bond softening is more realistic compared to break directly. From Fig.5 and Fig.6, the bearing capacity of the foundation is affected by the gravity while the initial elastic response is non-dependent to the gravity level.

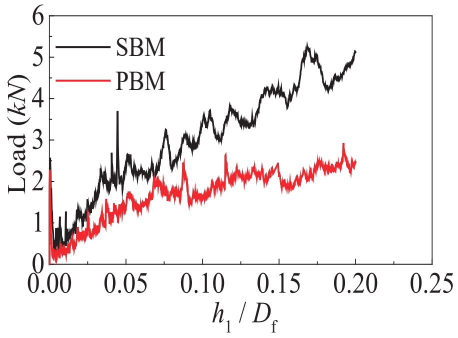

Fig.4 Comparison between SBM and PBM.

6 CONCLUSIONS

In this work it is shown how numerical modelling can aid the design of experimental centrifuge testing. To this end an efficient FDM-DEM coupled model generation technique is presented Particle upscaling is a viable approach to improve the computational efficiency of DEM with little to no influence on the macro-scale results. Coupled with fast generation procedures and domain reduction through FDM, it significantly reduces the computational burden inherent to DEM models, making it a practical tool for investigating large deformation problems in centrifugal conditions.

To show how this approach can be used the response of shallow foundations in soft rocks is modelled. the results show that failure mechanism of shallow foundations in soft rocks is mainly controlled by the bond post-breakage behaviour rather than gravity levels. This information can be used to plan eventual laboratory experiments in the centrifuge.

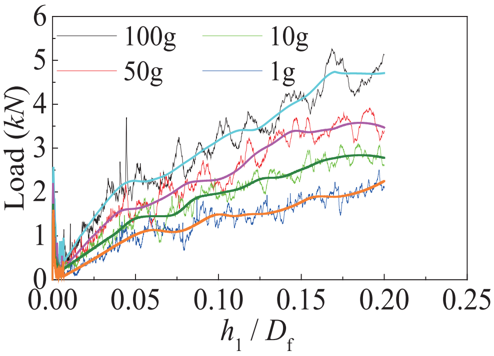

Fig. 5. Load – displacement curves under different gravity levels.

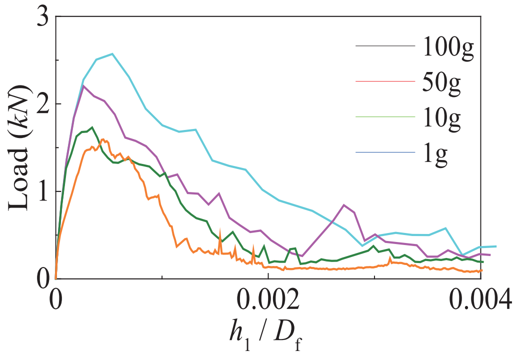

Fig.6 Initial stage of penetration under different gravity levels.

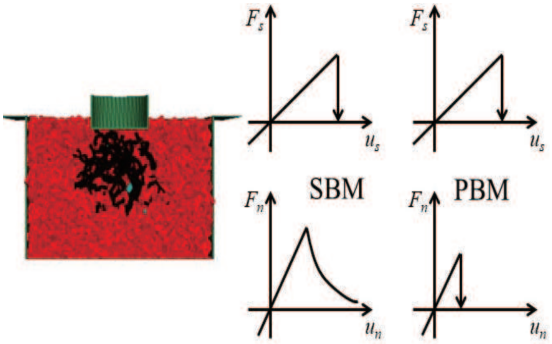

Fig. 7. Bond state (black bonds mean they are broken by shear).

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