Effect of the shape of slurry particles on their infiltration behaviour

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1. Introduction

Slurry shield tunnelling is often used for the construction of undersea tunnels (Min et al., 2019; Funasaki et al., 1997; Morris et al., 2016). This construction method relies on the development of a low-permeability filter cake: a scenario which is amenable to numerical investigation using coupled computational fluid dynamics (CFD)–discrete element method (DEM) simulations. Whenever CFD–DEM has previously been adopted to simulate the infiltration of slurry particles into a sand column, e.g., Lin et al. (2022), Yin et al. (2021) or Zhang et al. (2019), spherical particles have been assumed for the bentonite mineral (the primary solid constituent of the slurry). In reality, bentonite has a lamellar structure formed from clay platelets (Jönsson et al., 2009) so the assumption of spheres may not be appropriate, particularly since particle shape strongly influences properties such as packing density (Zou and Yu, 1996). Hence the objective of this research – part of a PhD project on slurry infiltration in granular soils – is to understand how the shape of slurry particles affects their infiltration behaviour using CFD–DEM.

2. Methodology and simulation setup

For convenience and computational tractability, the bentonite slurry particles are represented as oblate spheroids using superquadrics. This class of shapes is available within Aspherix, which was used for this study along with OpenFOAM to model the water component of the slurry. The non-spherical form of the CFDEM module was used to couple OpenFOAM and Aspherix. The particles were subjected to drag force (Hölzer and Sommerfeld, 2008), lift force (Zastawny et al., 2012), viscous force and pressure gradient force. A pitching torque model proposed by Zastawny et al. (2012) was added to CFDEM (Erken, 2023); this addition is necessary for non-spherical particles so that a single ellipsoidal particle settling in a Newtonian fluid reorients with its major axis orthogonal to its direction of motion (Pan et al., 2002).

The adaptive cohesion model in Aspherix was applied between the slurry particles. The Hertz contact model with mean curvature radius was used. In this white paper, we present the results corresponding to slurry particle aspect ratios of 1 (i.e., perfect spheres), 3 and 5. The sand column into which the slurry particles infiltrate was composed of monodisperse spheres with particle diameters six times larger than the volume-equivalent diameter of the ellipsoidal slurry particles. Sand and slurry particles were assigned interparticle friction coefficients of 0.3 and 0.05, respectively. Other modelling parameters were adopted from the study of Yin et al. (2021).

3. Results and discussion

The filter cake morphology is illustrated in Fig. 1. In each row, the left column shows a single slurry particle, the middle column depicts the slurry particles and sand particles together post-infiltration, and the right column shows only the slurry particles. As the aspect ratio increases, particles are less able to penetrate deeply into the sand column, leading to the formation of external filter cakes on the surface of the sand column.

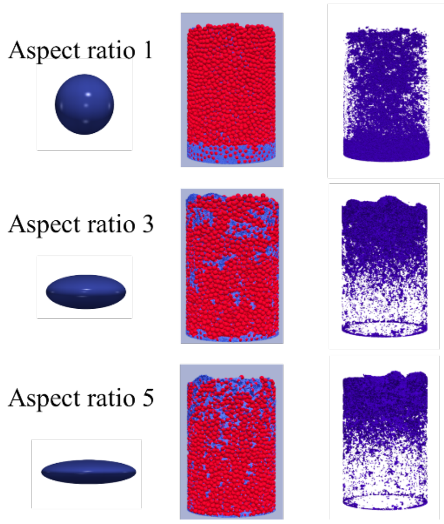

Fig. 1: Illustrations of filter cake morphologies with slurry particle aspect ratios of 1, 3 and 5.

Fig. 2(a) shows the void fraction curves of the filter cake formed with these three different aspect ratios. Slurry particles can deeply penetrate into the sand column. However, for aspect ratios of 3 and 5, the particles tend to clog at the upper part of the sand column, leading to the formation of external and internal filter cakes. At a distance of 0.08 m to 0.085 m from the bottom, these high-aspect-ratio cases have a significantly lower void fraction than when spherical slurry particles are used. Fig. 2(b) shows the pressure drop curves of the filter cake. Due to the low local porosity caused by deep penetration of spherical particles, there is a noticeable pressure drop at the bottom of the sand column for this case. The increase in aspect ratio results in the accumulation of slurry particles near the sand surface, which in turn leads to a rising trend in pressure drop.

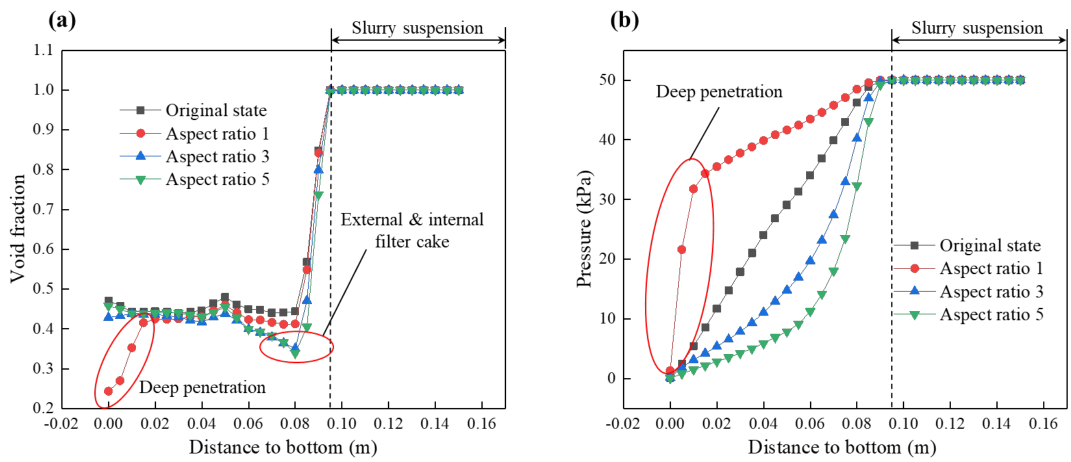

Fig. 2: (a) Void fractions and (b) pore pressure distributions of the filter cakes composed of slurry particles with aspect ratios of 1, 3 and 5. 'Original state' refers to the sand column before infiltration occurs.

4. Preliminary conclusions and future work

The infiltration distances of slurry particles into a sand column, and pressure distributions and void fractions within the column, are highly dependent on the aspect ratio of the slurry particles. Using spherical particles to represent what in reality are non-spherical particles leads to an over-prediction of infiltration distances in the simulations. This preliminary study will be extended to consider a wider range of aspect ratios, to vary the size ratio between the sand and slurry particles (fixed at 6:1 in this white paper), and analyse the orientations of the ellipsoidal slurry particles within the filter cakes formed.

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