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Research Paper

On the micro mechanics of yielding and hardening of crushable granular soils

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ABSTRACT

Stress path tests are used to investigate the yield surface of a crushable numerical soil. Triaxial samples with isotropic and anisotropic stress histories are examined to determine the nature of the yield surface and to establish what governs yield. Two separate yield surfaces are exposed: a shear yield surface at low p' and high η which is governed by minor breakage of fine particles, and a compressive yield surface at high p' and low η, governed by bulk breakage across all particle sizes. The shear yield surface is dependent on stress history, whilst the compressive yield surface is isotropic.

1. Introduction

It has recently been shown that it is possible to reproduce a wide range of aspects of soil behaviour using the discrete element method (DEM). With a simple crushing model and real particle strengths, the authors have produced realistic normal compression lines, whilst also resulting in the correct fractal particle size distribution when compared to experimental data [1,2].

Following this, the same crushing model was used to explore triaxial shearing and critical states, and a realistic critical state line was obtained, parallel to the NCL in log e–log p' space at high stresses [3]. A range of constant-σ_3, constant-p', and constant-volume triaxial tests were performed, resulting in realistic stress-dilatancy plots, and by normalising the stress states by the apparent pre-consolidation pressure, a state boundary surface was established.

It is the intention here to take a closer look at yielding and to establish the yield surface of this numerical soil as a function of stress history. This will begin first by briefly mapping out the yield surface(s) using a suitable definition of yield from the macroscopic stress-strain responses. Then focus will be given to the micro scale behaviour and underlying mechanisms that result in yield at various combinations of stresses, as well as analysing the effects of anisotropy and stress-history on the yield surface.

2. Model background

The results presented here are all obtained from simulations using the DEM software PFC [4], using spheres to model sand. The crushing model used is identical to that used previously [1,5], and uses the average octahedral shear stress in the particles to determine whether or not a particle breaks:

$$q = \frac{1}{3}[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_1-\sigma_3)^2]^{1/2} \tag{1}$$

where $\sigma_{1,2,3}$ are the average principal stresses in the particle, caused by and calculated from contacts with neighbouring bodies. When a particle is in a state of incipient breakage, it is replaced by two smaller spherical fragments positioned within the former boundary of the 'parent' particle. Conservation of mass is obeyed, which means that the fragments overlap (this overlap requires a number of timesteps to be completed immediately following breakage to allow energy dissipation). For full details of the crushing mechanism, readers are referred to the original publication [1], which includes an investigation of the number of fragments, and to slightly more recent work [5] which compares a range of breakage criteria. The particles strengths are attributed according to a hardening law of the form:

$$q_0 \propto d^{-b} \tag{2}$$

where q_0 is a representative strength and the parameter b represents the size-effect on particle strength. The strengths used were obtained experimentally from a silica sand [6]. The strength q_0 is a value such that 37% of particles of that size are stronger, and, together with a Weibull modulus m, is used to describe a Weibull distribution of strengths. For the silica sand, the q_0 value for 2 mm particles is 37.5 MPa, and the Weibull modulus for the silica sand is 3.3. The q_0 values for other sizes of particle is calculated according to Eq. (2), where $b = (3/3.3) \approx 1$. Individual particle strengths for any given size are distributed according to a Weibull distribution using the q_0 value and $m = 3.3$.

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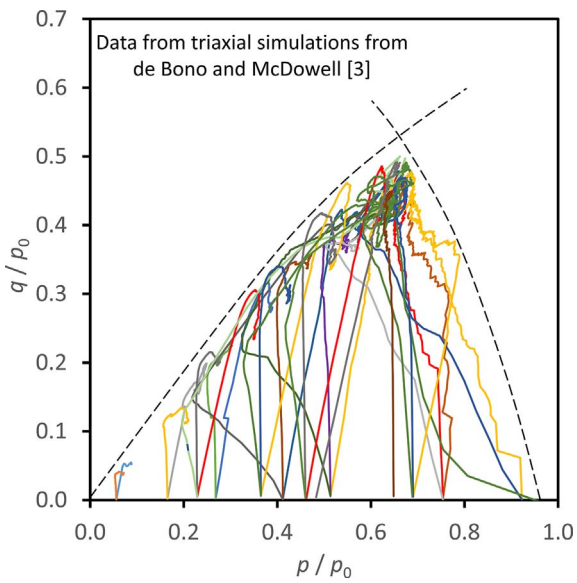

Fig. 1. State boundary surface obtained from triaxial tests.

Using these strengths and hardening law, the authors recently performed a series of constant-σ_3, constant-p' and constant-volume triaxial test simulations on samples with a range of stress histories [3]. These resulted in a realistic critical state line which was parallel to the NCL at high stresses and non-unique at low stresses for compacted or over-consolidated samples, in agreement with experimental data for sand [7]. By normalising the stress states during the triaxial tests by the apparent pre-consolidation pressure a unique state boundary surface was obtained, which is shown in Fig. 1. The shape of this state boundary surface agreed well with experimental data for sand [8], and suggests two distinct mechanisms of yielding (as opposed to a single elliptical yield surface), as suggested by authors such as Chandler [9] and Wood [10].

To examine the yielding and establish yield surfaces for this sand, a comprehensive series of stress-path tests are now simulated, covering all directions in q–p' space on triaxial samples with a range of stress-histories. The stress-paths performed on each sample are shown schematically in Fig. 2(a). Similar 'rosettes' of stress-paths tests were performed experimentally by Yasufuku et al. [11] and Smith et al. [12], and numerically using DEM by Cheng et al. [13], albeit with agglomerates.

The triaxial samples are enclosed vertically by 2 rigid platens and laterally by a flexible, faceted cylindrical membrane, an example image of which is given in Fig. 2(b), and described in more detail in [3]. The samples on which the stress-path tests are performed are all derived from an initially mono-disperse sample, 30 mm in height and 15 mm in diameter, consisting of 723 particles of 2 mm diameter. This sample is subjected to compression to various stresses and crushing before any stress-path tests to create more realistic graded samples with a much larger number of particles.

The simulations are stress-controlled, using stress-path increments of 25 kPa ($=\sqrt{(\delta q^2 + \delta p^2)}$). Stresses are applied to the samples via both the platens and membrane using servo-controls, and each simulation is terminated when $|\delta\varepsilon_1| \geq 0.5\%$.

3. Experimental yielding of granular soil

Yielding is understood to be the transition from elastic to plastic behaviour. For soils, this is usually interpreted as a clear change in the stress-strain response, whereby the behaviour changes from a stiff to a less-stiff regime. Soils do not in general show a discontinuous stress-strain response, like an ideal elastic-plastic material. Any truly-linear elastic behaviour typically only spans very small strains, e.g. < 0.001% [14], and significant changes in stiffness may occur relatively gradually, making identification of a yield point less obvious. As such, there are a variety of methods typically used for identifying the yield point—e.g. the end of linear behaviour, the point of intersection between two fitted lines, the point of maximum curvature, or simply taking an intuitive judgement 'by eye', which is, of course, rather unscientific.

Experimentally, one of the prominent earlier studies on the yielding of sand is that by Poorooshasb et al. [15], who performed multiple stress-path tests using the triaxial apparatus to establish enough yield points to construct a yield surface. A feature of their tests was that each yield point was reached through increasing the stress ratio η (at relatively moderate stress levels for a silica sand), and so their established yield surface was 'open' along the p-axis in q-p' space, and did not

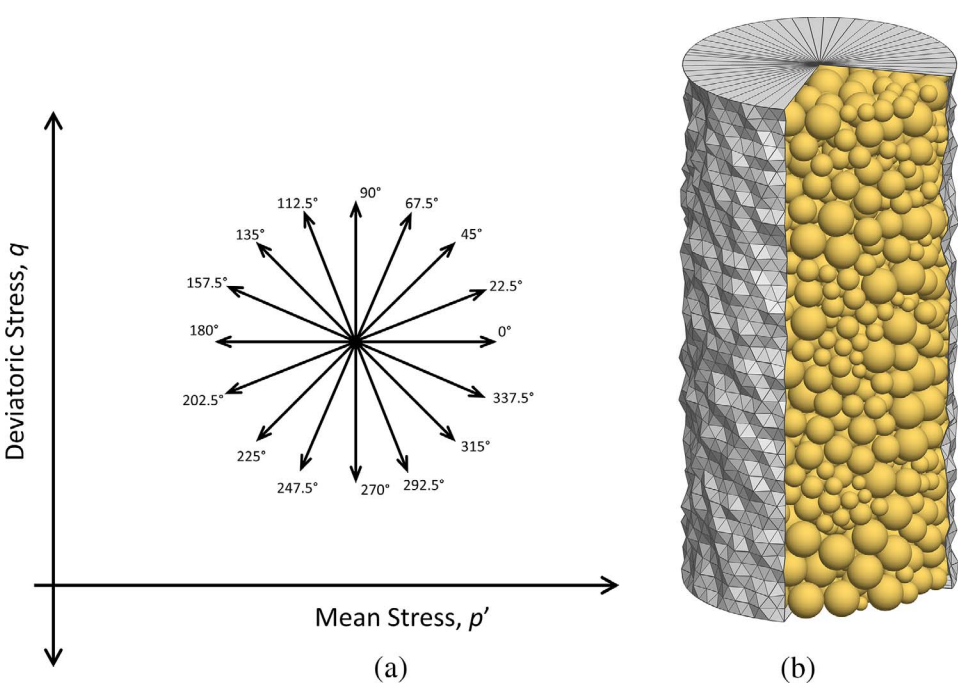

Fig. 2. Stress-paths (a) and image of typical triaxial boundaries and sample (b).

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