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DISCUSSION

DEM analysis of soil fabric effects on behaviour of sand

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Using DEM simulations, the authors have made an interesting contribution to advance understanding of the effect of fabric on sand behaviour. To create specimens with different initial fabrics, they applied loading paths involving pre-shearing to failure, either in compression or in extension; subsequently they reconsolidated the samples to the initial isotropic stress state. The fabric anisotropy formed in this way can be termed a stress-induced anisotropy. Using this approach, considerable computational time may be required to create samples with different anisotropic fabrics and to bring them to an identical target stress state and void ratio, prior to subsequent shearing. An additional point to consider is that the specimen geometry may affect the simulation results; using this approach the different specimens may have different sizes and shapes (see Fig. 17). In this written discussion, an alternative approach that uses DEM to study the effect of soil fabric on mechanical response is presented. This approach is more closely related to the sample preparation methods used in laboratory testing (i.e. an inherent anisotropy is created). Selected results using this approach are presented here to communicate the contributors' ideas on this topic.

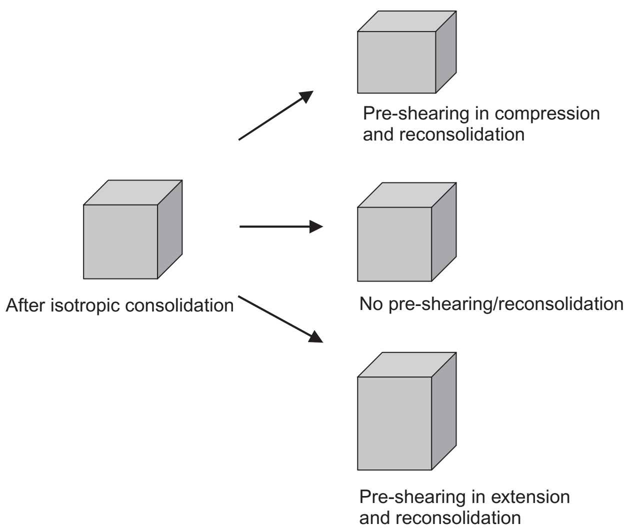

Fig. 17. Schematic illustration of the effect of preloading on specimen geometry

Analysis was performed using the commercial code PFC^{2D}. A simple contact model was used, which assumes a linear relation between the contact forces and the contact overlaps. A Coulomb friction criterion was adopted, and the coefficient of interparticle friction selected was 0·5. The particles used were fused discs with equivalent diameters varying between 0·26 and 0·66 mm so that the effects of particle shape and size could be accounted for. To simulate the fabric anisotropy formed in the deposition process, a set of specimens was generated using a gravitational deposition method and varying the bedding plane. As shown in Fig. 18, when $\alpha = 0°$ the particles were deposited to lie on a plane that is parallel with the x_2 axis, whereas in the case where $\alpha = 90°$ the particles were deposited onto the plane that is normal to the x_2 axis. After deposition, each specimen was isotropically compressed to 1000 kPa, to attain a void ratio of 0·217, with the same dimensions of 25 mm × 25 mm, and was then subjected to biaxial shear in compression at a constant volume. This constant-volume condition was used to mimic the undrained condition that is of particular interest here. More details about the particle characteristics and the boundary conditions can be found in Yang & Dai (2010).

The macroscale response of each specimen is shown in Fig. 19 in terms of the stress path and stress–strain relationship. Here the deviatoric stress is defined to be the difference between the principal stresses σ_1 and σ_2 (acting in the x_1 and x_2 directions respectively), and the mean normal stress is taken to be the average of σ_1 and σ_2. Qualitatively, these responses resemble the typical responses observed in the laboratory for loose to dense sand sheared under undrained conditions (e.g. Ishihara, 1993). The importance of fabric effects is very clear: under otherwise identical conditions, the specimen with a bedding plane of 90° shows a much more *contractive* response, whereas the specimen with the bedding plane of 0° exhibits a response that is *dilative*. A transition from a strain-softening response to a strain-hardening response is observed for the specimen with the bedding plane of 90°. This state, macroscopically known as the quasi-steady state, has been considered in more detail by Yang & Dai (2010) from the microscale point of view. The specimens with bedding planes of 30° and 45° show responses that are intermediate between these two limiting cases.

The observed differences in the macroscale responses are closely associated with the microscale characteristics of the assemblies. Fig. 20 compares the distributions of contact normals at the initial state and at 25% axial strain for three

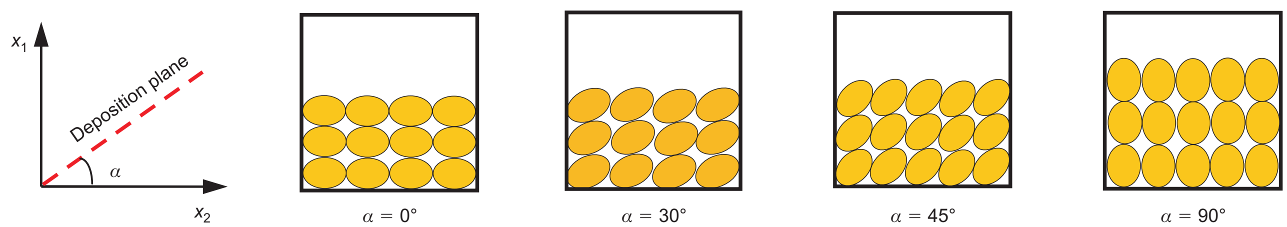

Fig. 18. Schematic diagrams of sample preparation using a gravitational deposition method (after Yang & Dai, 2010)

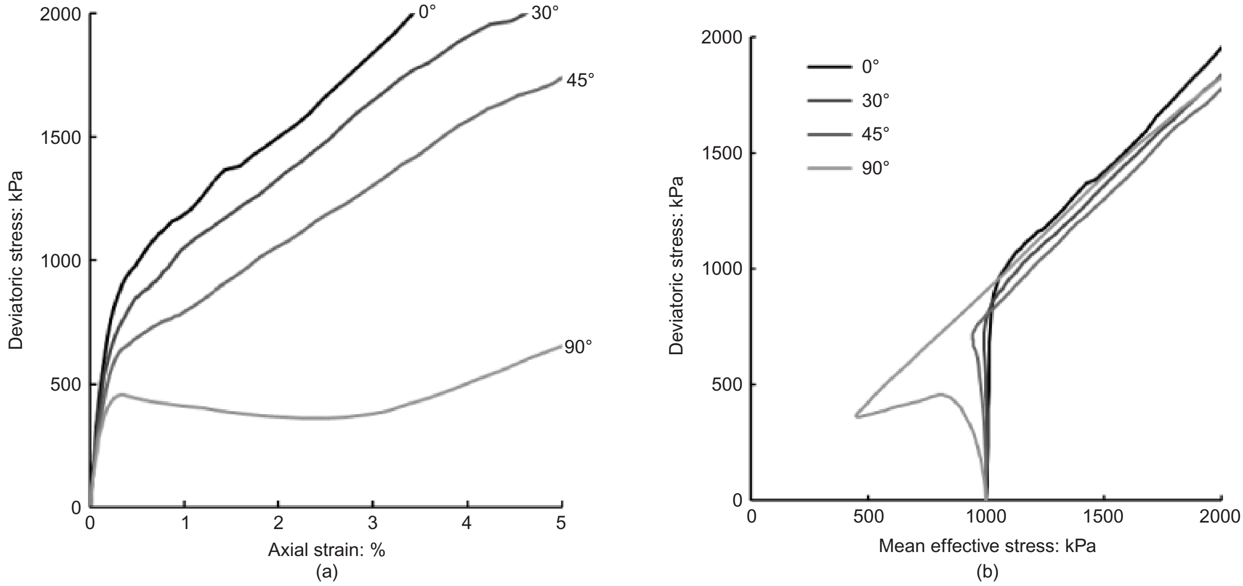

Fig. 19. Macroscale responses of four specimens with distinct bedding planes

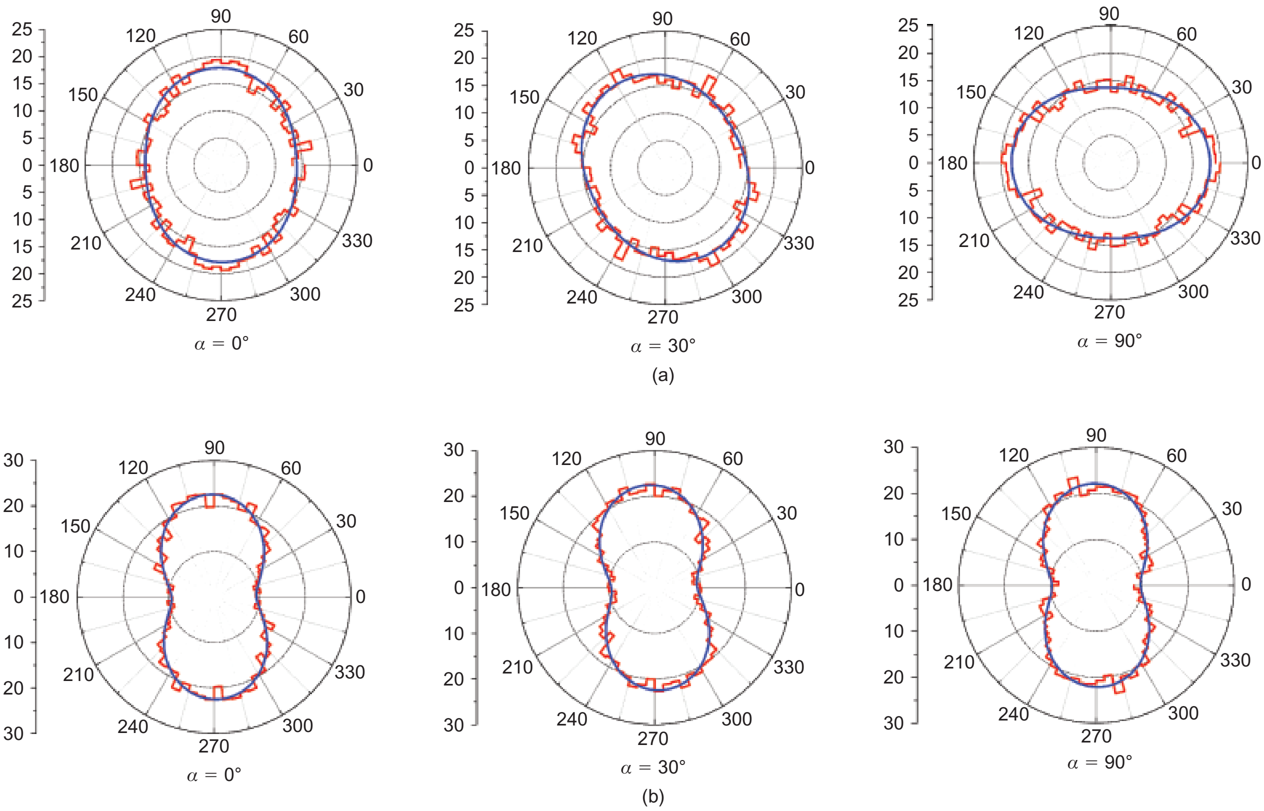

Fig. 20. Distributions of contact normals in specimens: (a) initial state; (b) 25% axial strain

of the specimens, and it is clear that the distinct difference in the initial fabric in terms of contact orientation is erased at large strains. The same trend was observed for the evolution of particle orientations. Fig. 21 presents a series of rose diagrams that show the magnitude of the average contact normal force in each polar segment. Referring to Fig. 21(a), the distributions of contact normal forces for the three specimens are similar in the initial state, showing an approximately isotropic state or weak anisotropy, but, at large strains, strong anisotropy is established in all three specimens (Fig. 21(b)).

Of particular interest is the evolution of coordination number (i.e. the average number of contacts per particle) during shearing, as presented in Fig. 22. For all four specimens the coordination number tends to reduce rapidly during the early stages of shearing, and then to increase gradually towards an approximately constant value at large deformations. It appears that the loss of contacts is most pronounced for the most contractive specimen in the quasi-steady state where both the deviatoric stress and the mean effective stress attain the smallest values. For the other three specimens the coordination number also appears to attain its minimum

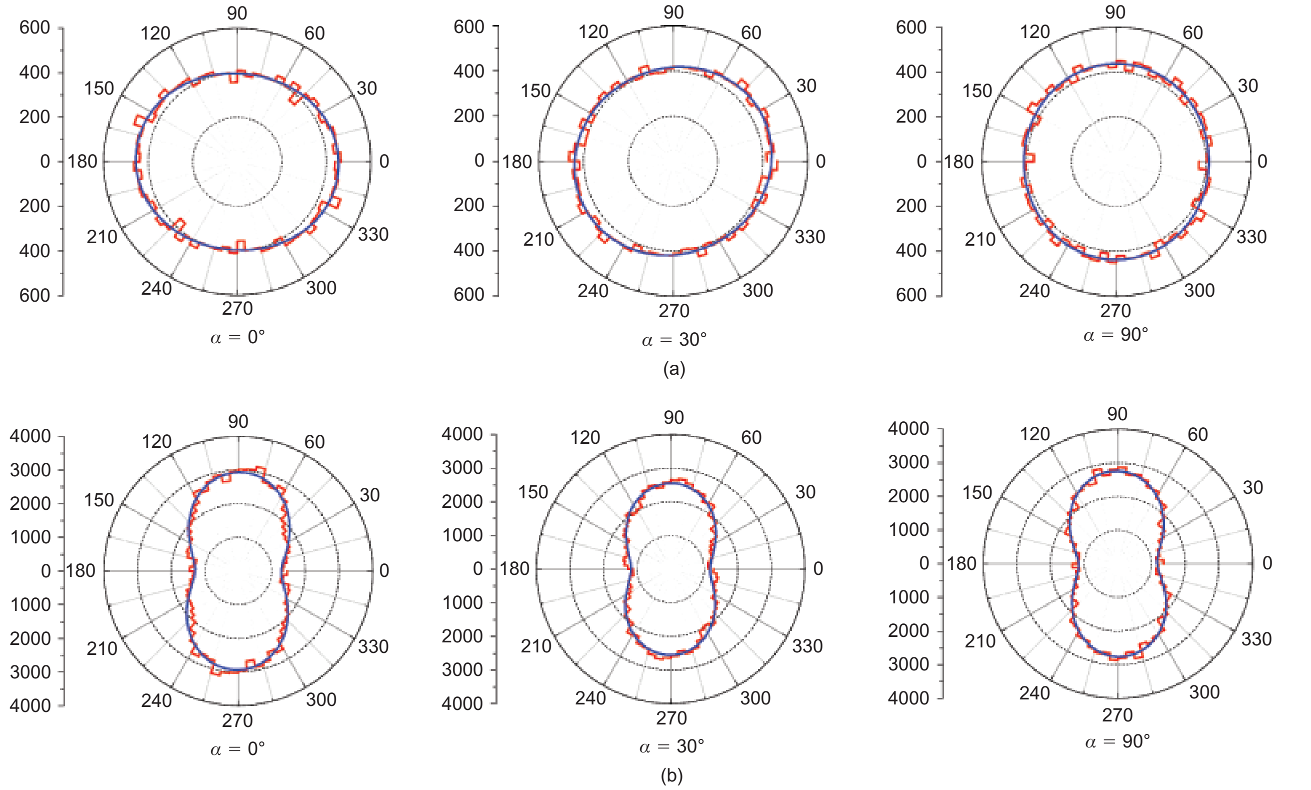

Fig. 21. Distributions of contact normal forces in specimens (units: N): (a) initial state; (b) 25% axial strain

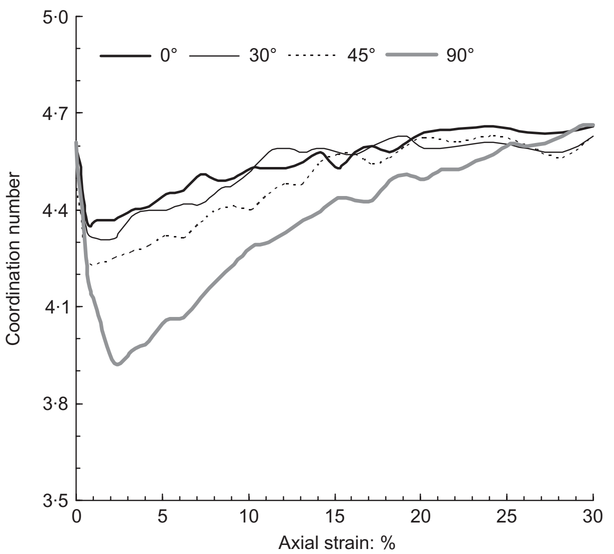

Fig. 22. Evolution of coordination number during shear deformation

value approximately at the point where the stress path is about to turn its direction. Macroscopically, this point has been termed the 'phase transformation' point (Ishihara, 1993); it is a temporary state of transition from contraction to dilation, leading to a minimum mean effective stress. In this connection, the quasi-steady state may be regarded as a special case of the phase transformation state.

Finally, it is worth pointing out that the specimen with $\alpha = 90°$ subjected to biaxial compression will exhibit the same response as a specimen with $\alpha = 0°$ subjected to biaxial shear in extension. This implies that the effect of shearing mode observed in the laboratory (e.g. triaxial compression against triaxial extension) on the mechanical response originates mainly from the soil fabric at the particle level.

Authors' reply

The authors appreciate the comments and welcome the contribution from the discussers. In this reply, the authors would like to address several points made by the discussers.

The objective of the paper was to study the inherent anisotropy of sand. In the authors' opinion, it is actually difficult to distinguish inherent and stress-induced anisotropies. Since the change in stress state can in turn alter the soil fabric and hence modify its inherent anisotropy, these two types of anisotropy can sometimes be difficult to separate. Some researchers refer to the anisotropic state after consolidation and before shearing as the 'initial anisotropy' (e.g. Zdravkovic & Jardine, 2000).

The discussers correctly argue that the sample preparation technique presented in the original paper requires considerable time and care to create different initial anisotropic fabrics (as defined by the spatial distribution of contact normal direction) at given initial void ratio and confining pressure. The discussers propose a 'gravitational deposition' sample preparation technique, which also creates an initial anisotropic fabric. However, in the authors' opinion, the discussers' technique also itself requires computational effort in order to create different initial anisotropic fabrics for a given initial void ratio and confining pressure. In fact, the authors believe any approach used to prepare this type of sample in DEM will have a considerable computational cost. The discussers also argue that the preparation technique presented in the original paper creates specimens with differing sizes. Since the particle sizes used for the study are much smaller than the specimen size, and the authors' interest is in studying scale-independent macroscopic mechanical properties, the slight differences in sample size and shape will not affect the results, nor the conclusions drawn from these results.

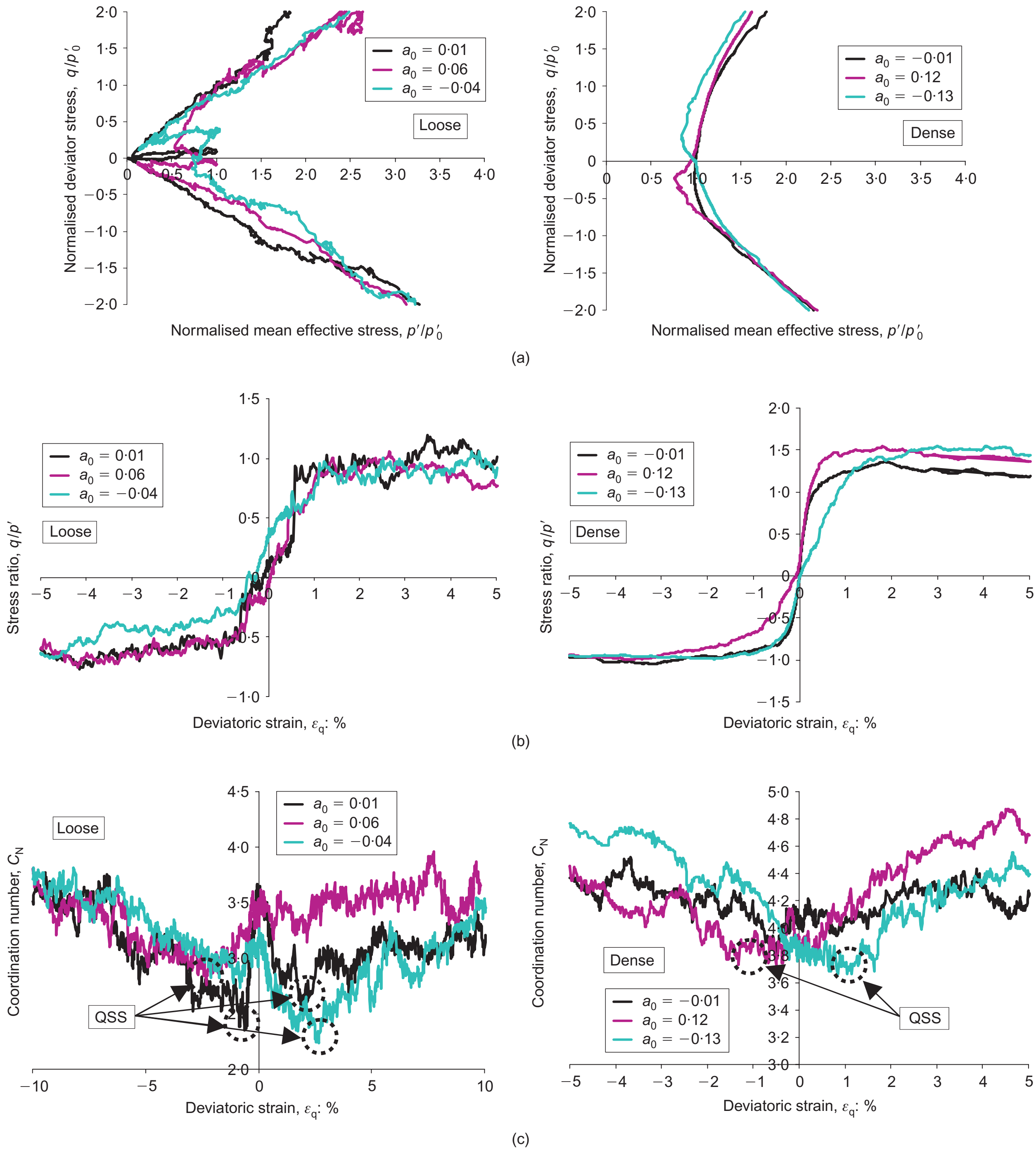

Fig. 23. Undrained behaviour of loose and dense specimens: (a) stress path; (b) stress–strain curve; (c) coordination number

The discussers pay particular attention to the evolution of coordination number (C_N) during CIUC tests. Their results show that the loss of contact is most pronounced for the most contractive specimen, and the minimum C_N coincides with the quasi-steady state. The authors found a similar trend in their undrained simulations, as shown in Fig. 23. All of the loose specimens, as well as the dense specimens that were loaded in a direction that was opposite to the direction of initial degree of fabric anisotropy, showed an initial contractive behaviour prior to dilating. The point where the response changed from being contractive to being dilative, which may be called the 'phase transformation point' (PT) or the 'quasi-steady state (QSS)', coincides with the minimum coordination number. Fig. 24 presents the evolution of degree of fabric anisotropy and coordination number during undrained shearing. At the point of change from contractive to dilative (maximum excess pore pressure), the results show: (a) that the coordination number is at its minimum value; and (b) that the soil fabric anisotropy changes dramatically. The reduction in coordination number seems to facilitate the change in fabric anisotropy. The fact that the reduction in C_N is not pronounced for the dense specimens may be because the particles in the dense samples have less freedom to move. This hypothesis is also supported by the work by the discussers (Yang & Dai, 2011).

The differences between the two sets of DEM analyses should be noted. The discussers performed their two-dimensional DEM analyses using fused discs to create non-circular particles, whereas the authors performed three-dimensional DEM analysis using spherical particles. The discussers used a linear contact model, whereas the authors used the non-linear Hertz–Mindlin contact model. The use of spherical

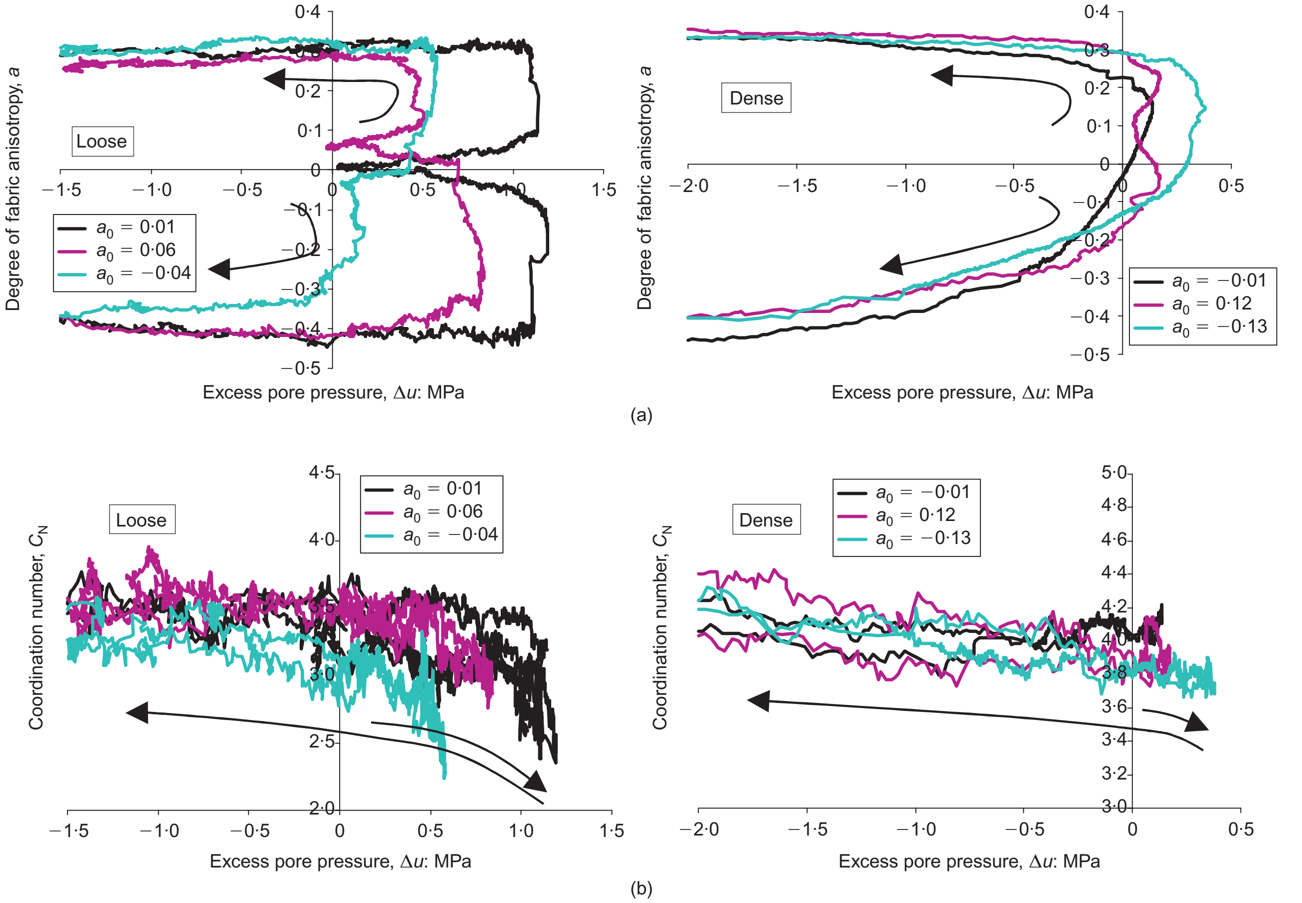

Fig. 24. Evolution of degree of fabric anisotropy and coordination number during undrained shearing: (a) degree of fabric anisotropy; (b) coordination number

particles allows the influence of the non-uniform distribution in the contact normal directions on the mechanical behaviour to be isolated. The use of non-circular particles by the discussers means that the effects of particle shape and contact normal anisotropy are combined. The two sets of results show similar behavioural trends, implying that contact normal anisotropy alone can produce the anisotropic behaviour that is observed in the laboratory. Nevertheless, further work is needed to investigate the relative contributions of the anisotropy caused by the orientations of non-circular/non-spherical particles and the contact normal anisotropy to the overall anisotropic material behaviour.

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