UNIFIED PEAK SHEAR STRENGTH BEHAVIOR OF INTERFACE SHEAR TEST AND DIRECT SHEAR TEST — NEW INSIGHTS FROM DEM SIMULATIONS

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Summary This paper provides a new perspective which unifies the soil mechanics observed in an interface shear test and a direct shear test under the concept of "boundary-induced" soil behavior. Based on the detailed analysis of micromechanical data from DEM simulations, a complete understanding of the mechanisms by which the different types of testing device boundaries control the shear strength and stress ratio – displacement behavior of granular soils is achieved.

INTRODUCTION

The interface shear test (IST) and the direct shear test (DST) are two important standard laboratory tests widely used in the geotechnical community for totally different purposes. No linkage has been made between the two tests in the literature except that the shear strength parameters of granular soils determined in the direct shear test are often taken to be the basis to which the interface shear strength parameters are normalized. This paper intends to unify the soil mechanics in an interface shear test and a direct shear test under the concept of "boundary-induced" soil behavior. This is achieved through a comprehensive analysis of the micromechanical data from a 2D DEM parametric study on the two types of tests.

Numerical simulation program

The parametric numerical study on the IST and the DST was conducted using the two-dimensional discrete element program PFC2D, Version 3.0 (Itasca Consultants, Inc.). DEM models of the IST and the DST were developed and validated against the laboratory data [1-3]. The model setup is briefly described as follows. The IST device is a 128 mm-long, 28 mm-high shear box formed by two fixed, rigid lateral boundaries, a bottom rough boundary and a top boundary that applies a constant normal stress using a servo mechanism. Quasistatic horizontal shear displacement is applied to the entire bottom boundary at a constant velocity of 1 mm/min. The granular material is poly-dispersed (well-graded) with an almost linear size distribution between the maximum and minimum particle diameters (D_{max}, D_{min}) of 1.05 mm and 0.35 mm, respectively, and a median particle diameter (D_{50}) of 0.7 mm. The interparticle and particle to lower boundary friction coefficients are 0.5 and 0.05, respectively. Five groups of DEM simulations of the IST on three types of representative surfaces, namely, idealized regular sawtooth surfaces, random irregular asperity surfaces and real manufactured material surfaces, were conducted under a normal stress of 100 kPa.
The previous DEM study on the DST focused on the effects of specimen size/scale by varying the box length scale L/D_{50}, the box height scale H/D_{50} and the box aspect ratio (L/H) [5]. A uniform particle to boundary friction coefficient of 0.9 is used to ensure a rough boundary condition in all the simulations. In the current study, in order to facilitate a strict comparison between the IST and the DST under the perspective of "boundary-induced soil behavior", all the DST simulations are rerun by employing a value of 0.05 for the particle to lower moving boundary friction coefficient, which is the same as the value used in the IST simulations. Furthermore, the stress ratio measured at the boundaries is calculated based on the total lateral and vertical forces measured on the lower moving boundaries. This is made also to be consistent with the stress ratio calculation in the IST simulations.

SIMULATION RESULTS

Control of the contact total force anisotropy on the shear strength behavior

It has been shown previously that the principal direction (θ_r) of the contact total force anisotropy developed at the particle-surface boundary in an IST has a dominant control over the peak interphase strength behavior [1,2]. It is now interesting to see whether the methodology can be extended to the DST. Fig. 1 shows the peak stress ratios $(\tau/\sigma)_{boundary}$ measured at the lower moving boundaries in all the IST and DST simulations. It is clear in Fig. 1 that all the DST data fall within the horizontal portion of the correlation, which approximately starts when θ_r is greater than 30°. In this region, the amplitude of variation of $(\tau/\sigma)_{boundary}$ from the DST simulations agrees well with that from the IST simulations, except one higher value from the DST with L = 35 mm and H = 14 mm. Its higher $(\tau/\sigma)_{boundary}$ value is attributed to the

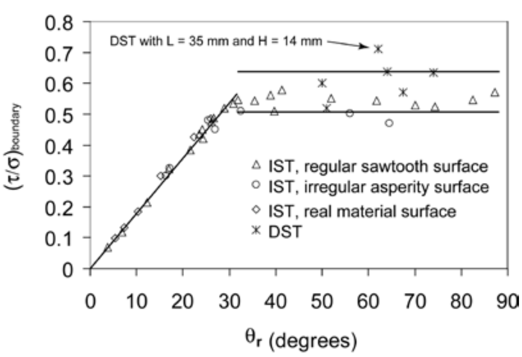

Fig. 1. Control of the principal direction of the contact total force anisotropy on the peak strength ratio measured in ISTs and DSTs

insufficient number of particles contained in that simulation.

The consistent correlation pattern obtained in Fig. 1 suggests that the $(\tau/\sigma)_{boundary}$ values in ISTs and DSTs can be quantified in a unified way by means of θ_r measured along the same boundary, despite the large difference between the two types of the testing device boundaries. None of the DST data points lies in the inclined portion of the correlation with $\theta_r < 30°$, which reflects a remarkable control of θ_r on $(\tau/\sigma)_{boundary}$ for those surfaces with inadequate roughness to fully mobilize the shear strength of the material. When the boundary roughness is high enough, the mobilized shear strength is nearly a constant and equal or close to the maximum shear strength of the material. The data scatter in the region of $\theta_r > 30°$ indicates the insufficiency of θ_r alone to accurately quantify the mobilized shear strength.

Shear strain localizations in ISTs and DSTs

Fig. 2 show the typical configurations of shear strain localizations from an IST simulation and a DST simulation at their peak stress states, respectively. Specifically, the lower boundary of the IST has a regular sawtooth pattern with 45° asperities, and the DST has a length (L) of 88 mm and a height (H) of 56 mm. The dimensions of the DST and IST boxes are drawn in scale so that the strain localizations can be compared directly. The shear strain distributions are calculated using the mesh-free strain calculation method previously developed by the author [4]. It can be seen that for a highly rough surface, the zone of strain localization (marked by the blue curve) (Fig. 1b) could be comparable to that in a direct shear test (Fig. 1a). On the other hand, the degree of shear strength mobilization in a DST depends on the box aspect ratio. Due to its smaller aspect ratio, a higher peak stress ratio is obtained at a larger displacement in DST which allows the contact force chains stemming from the lateral boundaries to extend farther into the inner part of the specimen. As a result, a global failure featured with a primary zone of localization around the mid-height of the box dominates the peak stress state (Fig. 1a). The shear band, however, appears less uniform and concentrated than that shown in [5], because the particle to lower boundary friction is much lower than the one (i.e., 0.9) used in that study. This reconfirms the importance of adopting rough boundaries in a DST. When the box aspect ratio becomes larger, a lower stress ratio is obtained at a smaller displacement at the peak state. This is caused by the inability of the DSA to engage the main portion of the material at the middle of the box into shearing at the peak state due to the severe interference of the upper and lower boundaries upon the formation of long-range force chains. Consequently, the primary zone of localization is forced to develop along the bottom of the box, deviating from the mid-height [5]. Based on the above information, it is justified to conclude that a DST does not necessarily provide the "standard" shear strength parameter while an IST may yield the fully mobilized shear strength as well.

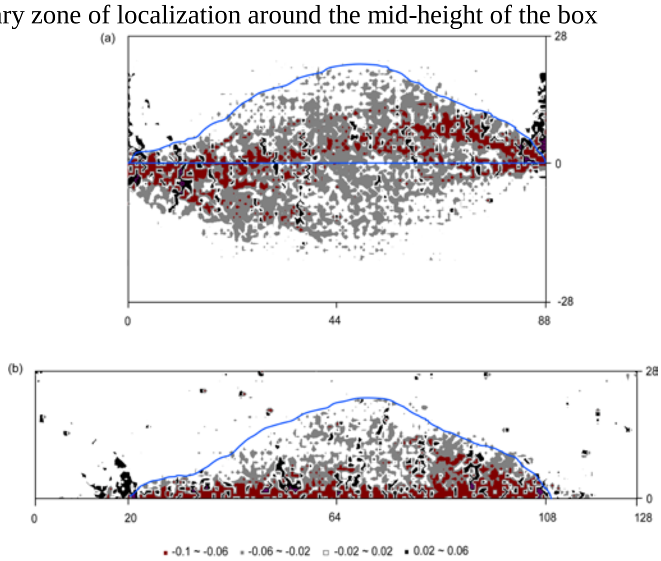

Fig. 2. Shear bands in a DST and an IST at their peak states

CONCLUSIONS

Based on the detailed analysis of micromechanical data from DEM simulations, a complete understanding of the mechanisms by which the different types of testing device boundaries control the shear strength behavior of granular soils is achieved. It is shown that the mobilized shear strength measured at the testing device boundaries depends on the degree and extent of the strain localization and shear banding developed inside the specimen. The peak stress ratios measured in ISTs and DSTs can be well quantified using the principal direction of the contact total force anisotropy.

References

[1] Wang J., Dove J.E. & Gutierrez M.S.: Determining Particulate-Solid Interphase Strength using Shear-induced Anisotropy. *Granular Matter*, Volume 9, Numbers 3-4: 231-240, 2007.

[2] Wang J., Dove J.E. & Gutierrez M.S.: Anisotropy-based Failure Criterion for an Interphase System. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 133, No. 5: 599-608, 2007.

[3] Wang J., Dove J. E. & Gutierrez M. S.: Discrete-continuum analysis of shear banding in the direct shear test. *Géotechnique* **57**, No. 6: 513–526, 2007.

[4] Wang J., Gutierrez M. S. & Dove J. E.: Numerical studies of shear banding in interface shear tests using a new strain calculation method. *Int. J. Numer. Anal. Meth. Geomech.* **31**, No. 12: 1349–1366, 2007.

[5] Wang J. & Gutierrez M. S.: Discrete element simulations of direct shear specimen scale effects. *Géotechnique*, Vol. 60, No. 5: 395-409, 2010.