Unified soil behavior of interface shear test and direct shear test under the influence of lower moving boundaries

Jianfeng Wang · Mingjing Jiang

Received: 11 February 2011 © Springer-Verlag 2011

Abstract Based on a detailed analysis of DEM simulation data, this paper provides new insights into the effects of boundary surface topography on the mobilized stress ratio and stress-displacement behavior in the interface shear test and the direct shear test. The soil mechanics observed in the two types of tests are unified under a novel perspective of boundary-induced soil behavior. It is shown that the principal direction of the contact force anisotropy developed at the soil-surface boundary has an exclusive control over the peak stress ratio measured both at the boundary and inside the sampling window. However, a subtle change in the roles of the principal direction and the magnitude of contact force anisotropy is found as the contact force chains extend from the surface into the interphase soil.

Keywords Discrete element method · Boundary-induced soil behavior · Direct shear test · Interface shear test · Contact force anisotropy

1 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. The IST is intended for the determination of the shear resistance developed at the interface between a soil and a rough, continuous manufactured or natural material surface when shear displacement occurs between the two entities [1]. In an IST, the interphase refers to a region which consists of the surface with its asperities, and a variety thickness of granular soil directly adjacent to the surface. The interphase governs the overall behavior of a geotechnical composite system. The DST is the conventional shear box test intended for the determination of the drained shear strength of a soil material under the direct shear condition [2]. 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 to obtain the efficiency parameter an index indicating how much percentage of the full shear strength of the granular soil is mobilized by the construction material surface.

A rich body of research has been dedicated to the determination and quantification of effects of surface topography on the interphase strength behavior (e.g., [5, 4, 9, 14, 15, 17, 18]). The primary mechanism by which the rough surface controls the peak interphase strength behavior was previously shown by the first author to be rooted in the anisotropies of fabric and contact forces developed at the soil-surface boundary [17]. Based on this mechanism, a semi-empirical failure criterion which relates the peak interphase strength to the principal direction of surface normal distribution was proposed [18].

The direct shear test, on the other hand, has also received extensive experimental and numerical studies due to its simplicity and relatively low testing cost. Significant advances have been achieved in understanding the development of internal stress and strain localization conditions during the shearing process, and their relationship with the external stress measurements at the lateral boundaries (e.g., [7, 10, 12, 19]), as well as the variation of these behavior under the influence of varying shear box size/scale (e.g., [6, 22]).
However, no effort is known to the authors that has been made to link the soil mechanics occurring in the two types of tests. The goal of this paper is to provide a new perspective which unifies the soil behavior observed in the interface shear test and the direct shear test, and to promote a coherent understanding of the soil mechanics under the influence of geometric boundaries.

2 Background

The first author has made comprehensive investigations into both types of tests using the DEM approach [16–22]. The content of the current paper is built upon these previous studies but the idea and results presented are novel and significant enough to make themselves stand alone.

In an interface shear test, while the shear stress ratio measured along the surface is directly determined by the interaction between the surface and the first layer of particles that touch the surface, the source of this shear resistance lies in the internal shear strength of the interphase soil adjacent to the surface that is mobilized. The degree of mobilization of internal shear strength depends on the maximum anisotropies of fabric and contact force that can be supported by the rough surface. It was shown that the average shear stress ratio based on the homogenization of granular contact quantities within a small sampling window above the surface represents a downscaled boundary measurement [17,18].

In a direct shear test, the boundary measurement is usually taken to be the full shear strength of the granular soil. This is based on the assumption that the stress and shear strain distributions are uniform inside the direct shear apparatus (DSA). However, the detailed DEM studies by the first author [19] show that the boundary-induced strain localization propagates gradually from the two lateral boundaries towards the middle of the DSA, and the final configuration of the shear band depends on the initial density, normal stress, and specimen size/scale, etc. More importantly, it was shown that the specimen size and aspect ratio (i.e., box length/box height) have considerable effects on the boundary measurement. The underlying mechanism of this geometric effect is the different failure modes of the specimen: when the specimen aspect ratio is small, the global failure will control the macroscopic strength behavior; and when the specimen aspect ratio is large, progressive failure becomes a more likely option. The global vs. progressive failure modes refer to the different degrees and extents of the fabric change, strain localization and shearing banding in the DSA as the peak stress ratio is reached. Specifically, the global failure implies the formation of a uniform and coherent shear band at the mid-height plane of the DSA at the peak stress state and the full mobilization of the shear strength of the granular specimen inside the shear band; whereas the progressive failure implies the propagation of the boundary-induced shear localization from the lateral boundaries towards the middle of the box and the partial mobilization of the shear strength of the granular specimen at the peak stress state [22].

3 Unified soil behavior of interface shear test and direct shear test

With the previous knowledge, it is now possible to unify the soil mechanics in an interface shear test and a direct shear test under the concept of “boundary-induced” soil behavior. In a generic sense, the study of soil behavior in any field or laboratory testing condition is the study of the effects of certain kinds of external boundary condition on the soil. Following this idea, an analogy between the two types of tests can be made by treating the moving boundaries of the DSA as a special type of “U-shaped asperity” which engages and displaces a much greater amount of matrix soil than the surface asperities in an interface shear test. Under such a perspective, the soil mechanics occurring in an IST and a DST can be treated, in a unified way, as a consequence of the movement of lower boundaries. Despite the drastically different amount of the matrix soil displaced in the two types of the tests, the mobilized shear strength measured either at the testing device boundaries or inside the sampling window depends totally on the degree and extent of the strain localization and shear banding inside the specimen, as will be demonstrated below. With such a common basis, it is easier to achieve a coherent understanding of the shear behavior in the two types of the tests.

3.1 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 [16] and validated against the laboratory data [4,8]. 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. The bottom boundary consists of a 88 mm-long rough material surface to be tested and two 20 mm-long, frictionless and flat zones located adjacent to each lateral boundary. 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 ($D_{\text{max}}$, $D_{\text{min}}$) of 1.05 mm and
0.35 mm, respectively, and a median particle diameter ($D_{50}$) of 0.7 mm. The interparticle and particle-boundary friction coefficients are 0.5 and 0.9, 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 main difference between the three types of surfaces is that the first two types are numerically generated, artificial surfaces whereas the third type is real material surfaces which are obtained by scanning the surfaces using a stylus profilometer at a 1 μm data point spacing. Four examples of the three types of surfaces are given in Figs. 1a-d. Three values of the particle to surface friction coefficient ($\tan \varphi_{\mu}$), i.e., 0.05, 0.2 and 0.5 were employed in the previous studies [17,18]. Full details of the IST model setup and simulation program can be found in these papers.

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 ($L/H$) [22]. Two typical examples of the direct shear box with different aspect ratios are shown in Figs. 1e and f. 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 using the poly-dispersed materials under a constant normal stress of 100 kPa are rerun by employing three different values of the particle to lower moving boundary friction coefficient ($\tan \varphi_{\mu}$), i.e., 0.05, 0.2 and 0.5, which are the same as the $\tan \varphi_{\mu}$ values used in the IST simulations. The particle to upper fixed boundary friction coefficient remains 0.9 in the DST 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.
two DSTs and four ISTs, and inside the sampling window against shear displacement for Fig. 2.

Evolutions of stress ratios measured at the testing device boundary from two DST simulations and four IST simulations, whose configurations of the shear box or surface profile are shown in Fig. 1. The stress ratios measured on the lower moving boundaries and in the sampling windows are compared respectively. For the average stress ratio calculated in the sampling window, a 7 mm high sampling window sitting over the rough surface is used in the ISTs, and a 14 mm high sampling window symmetric about the middle plane of the box (i.e., 7 mm above and 7 mm below the middle plane) is used in the DSTs.

In Fig. 2a, it is seen that the boundary-measured peak stress ratio is obtained at a smaller displacement at the peak state (Fig. 3b) could be comparable to that in a direct shear test (e.g., DST1) (Fig. 3b and c). On the other hand, the degree of shear strength mobilization in a DST depends on the box aspect ratio. It is seen in Fig. 2a that a higher peak stress ratio is obtained at a larger displacement in DST1 due to its smaller aspect ratio, 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. 3b). The shear band, however, appears less uniform and concentrated than that shown in [22], because the tan $\phi_{\mu}$ value 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.

The steady-state portions of the curves of DST1, DST2 and DST3 IST1, the zone of strain localization (marked by the blue curve) could be comparable to that in a direct shear test (e.g., DST1) (Fig. 3b and c). On the other hand, the degree of shear strength mobilization in a DST depends on the box aspect ratio. It is seen in Fig. 2a that a higher peak stress ratio is obtained at a larger displacement in DST1 due to its smaller aspect ratio, 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. 3b). The shear band, however, appears less uniform and concentrated than that shown in [22], because the tan $\phi_{\mu}$ value 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.

A better way to study the boundary-induced macroscopic strength behavior is to look into the homogenized, average stress ratio calculated within the sampling window which encompasses the primary zone of strain localization in both types of tests. It is clear that the average stress ratio curves in Fig. 2b resemble their corresponding boundary-measured curves in Fig. 2a for each simulation but have overall lower magnitudes and higher smoothness. The average stress ratio has been shown to be closely related to the height of the sampling window, and will be equal to the boundary measurement when the sampling window is narrow enough [19]. The steady-state portions of the curves of DST1, DST2 and IST1 are very similar, although some differences are found in their peak stress ratios. This observation indicates that similar micromechanical conditions are established at the large-deformation stage within the primary zone of strain localization.

Figure 3 show the shear strain localizations in these simulations at their peak stress states. 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 first author [20]. It can be seen that the primary zone of strain localization reduces significantly with the reduction of the surface roughness (Fig. 3c-f). However, for a highly rough surface (e.g., IST1), the zone of strain localization (marked by the blue curve) could be comparable to that in a direct shear test (e.g., DST1) (Fig. 3b and c). On the other hand, the degree of shear strength mobilization in a DST depends on the box aspect ratio. It is seen in Fig. 2a that a higher peak stress ratio is obtained at a larger displacement in DST1 due to its smaller aspect ratio, 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. 3b). The shear band, however, appears less uniform and concentrated than that shown in [22], because the tan $\phi_{\mu}$ value 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.

A better way to study the boundary-induced macroscopic strength behavior is to look into the homogenized, average stress ratio calculated within the sampling window which encompasses the primary zone of strain localization in both types of tests. It is clear that the average stress ratio curves in Fig. 2b resemble their corresponding boundary-measured curves in Fig. 2a for each simulation but have overall lower magnitudes and higher smoothness. The average stress ratio has been shown to be closely related to the height of the sampling window, and will be equal to the boundary measurement when the sampling window is narrow enough [19]. The steady-state portions of the curves of DST1, DST2 and IST1 are very similar, although some differences are found in their peak stress ratios. This observation indicates that similar micromechanical conditions are established at the large-deformation stage within the primary zone of strain localization.

Figure 2. Evolutions of stress ratios measured at the testing device boundary and inside the sampling window against shear displacement for two DSTs and four ISTs, a boundary-measured stress ratio; b window-measured stress ratio.

3.2 Stress-displacement behavior and shear strain localization

Figure 2 compares the stress ratio-displacement relations from two DST simulations and four IST simulations, whose configurations of the shear box or surface profile are shown in Fig. 1. The tan $\phi_{\mu}$ value is 0.05 in these simulations. The stress ratios measured on the lower moving boundaries and in the sampling windows are compared respectively. For the average stress ratio calculated in the sampling window, a 7 mm high sampling window sitting over the rough surface is used in the ISTs, and a 14 mm high sampling window symmetric about the middle plane of the box (i.e., 7 mm above and 7 mm below the middle plane) is used in the DSTs.

In Fig. 2a, it is seen that the boundary-measured peak stress ratios and steady state stress ratios in the ISTs are very close to those measured in the DSTs if the surface is rough enough, but they drop remarkably as the surface roughness decreases, particularly for the coextruded geomembrane surface and the concrete surface. In a unified sense, 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. 3 Shear strain distributions of the two DSTs and four ISTs at their peak states ($\tan \varphi_{\mu} = 0.05$ for all the simulations): a DST2; b DST1; c IST1; d IST2; e IST3; f IST4
two-dimensional, second-order density distribution tensors

force and average contact total force are described by the

peak interphase strength behavior [17]. The anisotropies
of the average contact normal force, average contact shear
force and average contact total force calculated by:

$(\tau/\sigma)_{\text{boundary}} = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{f_k}{f_0} n_k^i n_k^j,$

$(\tau/\sigma)_{\text{boundary}} = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{f_k}{f_0} t_k^i t_k^j,$

and

$R_{ij} = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{f_k}{f_0} r_k^i r_k^j,$

where, $f_n(\theta), \tilde{f}_n(\theta)$ and $\tilde{f}_r(\theta)$ are the corresponding density distribution functions; $f_n, f_r$ and $f_t$ are the contact normal force, contact shear force and contact total force, respectively; $N_c$ is the total number of contacts within the granular volume; $n = (\cos \theta, \sin \theta)$ is the unit contact normal vector, $t = (-\sin \theta, \cos \theta)$ is the vector perpendicular to $n$; $m = (\cos \alpha, \sin \alpha)$ is the unit vector in the direction of the granular total force; and $f_0$ and $f_r$ are the average contact normal force and total force calculated by:

$\tilde{f}_0 = \frac{1}{2\pi} \int_{0}^{2\pi} f_n(\theta) d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} f_k,$

and

$\tilde{f}_r = \frac{1}{2\pi} \int_{0}^{2\pi} f_r(\theta) d\theta = \frac{1}{N_c} \sum_{k=1}^{N_c} f_k r_k.$

The Fourier series approximations for $\tilde{f}_n(\theta), \tilde{f}_s(\theta)$ and $\tilde{f}_r(\theta)$ are written as:

$\tilde{f}_n(\theta) = \hat{f}_0 [1 + a_n \cos 2(\theta - \theta_n)],$

$\tilde{f}_s(\theta) = \hat{f}_0 [-a_s \sin 2(\theta - \theta_s)],$

and

$\tilde{f}_r(\theta) = \hat{f}_r [1 + a_r \cos 2(\theta - \theta_r)],$

where $a_n, a_s$ and $a_r$ are the magnitudes of the corresponding anisotropies; and $\theta_n, \theta_s$ and $\theta_r$ are the principal directions (all measured from the vertical) of the corresponding anisotropies.

Based on the previous result, it is now interesting to see whether the methodology can be extended to the DST. Figure 4 shows the peak stress ratios $(\tau/\sigma)_{\text{boundary}}$ measured at the lower moving boundaries in all the IST and DST simulations. The data from the IST simulations are identical to those shown in [17, 18] but the data from the DST simulations are newly included to see whether a consistent correlation pattern could be obtained by treating the DST as a special type of the IST. It is clear in Fig. 4 that for any $\tan \varphi_{\mu}$ value,

localization when the boundaries are rough enough to sufficiently mobilize the shear strength of the material, regardless of the type of the testing device boundary.

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

It has been shown previously that the principal direction 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 [17]. The anisotropies of the average contact normal force, average contact shear force and average contact total force are described by the two-dimensional, second-order density distribution tensors.
Table 1  Peak stress ratios measured at the lower moving boundaries using two methods from all DST simulations

<table>
<thead>
<tr>
<th>$\tan \phi_\mu$</th>
<th>$L$ (mm)</th>
<th>$H$ (mm)</th>
<th>$L/H$</th>
<th>$N$</th>
<th>$(\tau/\sigma)_{\text{boundary}} - \text{asp}$</th>
<th>$(\tau/\sigma)_{\text{boundary}} - \text{con}$</th>
<th>$(\tau/\sigma)_{\text{boundary}} - \text{asp}$</th>
<th>$(\tau/\sigma)_{\text{boundary}} - \text{con}$</th>
<th>$(\tau/\sigma)_{\text{boundary}} - \text{asp}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>88</td>
<td>56</td>
<td>1.57</td>
<td>11239</td>
<td>0.634</td>
<td>0.708</td>
<td>11.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>28</td>
<td>3.14</td>
<td>5669</td>
<td>0.57</td>
<td>0.639</td>
<td>12.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>14</td>
<td>6.28</td>
<td>2884</td>
<td>0.52</td>
<td>0.575</td>
<td>10.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>28</td>
<td>2.25</td>
<td>4087</td>
<td>0.637</td>
<td>0.731</td>
<td>14.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>14</td>
<td>4.5</td>
<td>2093</td>
<td>0.6</td>
<td>0.689</td>
<td>14.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>14</td>
<td>2.5</td>
<td>1186</td>
<td>0.711</td>
<td>0.845</td>
<td>18.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>88</td>
<td>56</td>
<td>1.57</td>
<td>11239</td>
<td>0.65</td>
<td>0.791</td>
<td>21.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>28</td>
<td>3.14</td>
<td>5669</td>
<td>0.582</td>
<td>0.654</td>
<td>12.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>14</td>
<td>6.28</td>
<td>2884</td>
<td>0.531</td>
<td>0.588</td>
<td>10.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>28</td>
<td>2.25</td>
<td>4087</td>
<td>0.63</td>
<td>0.741</td>
<td>17.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>14</td>
<td>4.5</td>
<td>2093</td>
<td>0.603</td>
<td>0.693</td>
<td>14.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>14</td>
<td>2.5</td>
<td>1186</td>
<td>0.724</td>
<td>0.88</td>
<td>21.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>88</td>
<td>56</td>
<td>1.57</td>
<td>11239</td>
<td>0.665</td>
<td>0.807</td>
<td>21.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>28</td>
<td>3.14</td>
<td>5669</td>
<td>0.572</td>
<td>0.636</td>
<td>11.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>14</td>
<td>6.28</td>
<td>2884</td>
<td>0.52</td>
<td>0.57</td>
<td>9.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>28</td>
<td>2.25</td>
<td>4087</td>
<td>0.63</td>
<td>0.738</td>
<td>17.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>14</td>
<td>4.5</td>
<td>2093</td>
<td>0.606</td>
<td>0.697</td>
<td>15.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>14</td>
<td>2.5</td>
<td>1186</td>
<td>0.724</td>
<td>0.89</td>
<td>22.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$N$ the total number of particles in the simulation.

the DST data fall within the horizontal portion of the correlation, which approximately starts when $\theta_r$ is greater than 30°. In this region, the amplitude of variation of $(\tau/\sigma)_{\text{boundary}}$ 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 $(\tau/\sigma)_{\text{boundary}}$ value is attributed to the insufficient number of particles contained in that simulation. The consistent correlation pattern obtained in Fig. 4 suggests that the $(\tau/\sigma)_{\text{boundary}}$ values in ISTs and DSTs can be quantified in a unified way by means of $\theta_r$ 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 $\theta_r$ on $(\tau/\sigma)_{\text{boundary}}$ 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 $\theta_r$ alone to accurately quantify the mobilized shear strength.

It is worth pointing out that the $(\tau/\sigma)_{\text{boundary}}$ values from the DST simulations deviate considerably from the values calculated in the conventional way. In the conventional way, $(\tau/\sigma)_{\text{boundary}}$ is calculated by dividing the horizontal stress which presumably acts on the mid-height shearing plane by the constant normal stress (i.e., 100 kPa in this study), and the horizontal stress is obtained by dividing the total horizontal force measured on the lower moving boundaries by the effective area of the shearing plane. Table 1 lists the values from all DST simulations calculated in both ways, with $(\tau/\sigma)_{\text{boundary}} - \text{asp}$ denoting the values calculated in the current way and $(\tau/\sigma)_{\text{boundary}} - \text{con}$ denoting those calculated in the conventional way. It is seen that the $(\tau/\sigma)_{\text{boundary}} - \text{asp}$ values are about 10-20% lower than the $(\tau/\sigma)_{\text{boundary}} - \text{con}$ values, indicating an overestimation of the actual peak stress ratio in the laboratory. Apparently, the consistent bilinear correlation would not be obtained if the $(\tau/\sigma)_{\text{boundary}} - \text{asp}$ values are plotted in Fig. 4. In Fig. 5, the difference between the two values is plotted as a function of the box aspect ratio, and the trends of variation against the box length scale and the box height scale are marked by two groups of arrows. Obviously, in all the $\tan \phi_\mu$ cases, the difference between the two values increases with the decreasing aspect ratio in both directions but the rate of change is much higher in the direction of constant box height scale and decreasing box length scale. This observation indicates that an overestimation of the actual peak stress ratio can be minimized when a larger box length is used.

Figure 6 shows the correlations between the average peak stress ratios $(\tau/\sigma)_{\text{ave}}$ measured inside the sampling windows and $\theta_r$ measured at the lower moving boundaries. The $(\tau/\sigma)_{\text{ave}}$ values from the IST simulations are different from those shown in [17,18] due to a larger sampling window used in the current study. An equally well-defined bilinear profile with an even less amount of data scatter in the
horizontal portion is found in each $\tan \phi_\mu$ case. Interestingly, the abnormally high value of $(\tau/\sigma)_{\text{boundary}}$ in the DST with $L = 35$ mm and $H = 14$ mm is found to be replaced with a lower $(\tau/\sigma)_{\text{ave}}$ value that conforms well to the horizontal portion of the profile. This observation reconfirms the unified shear strength behavior of the DST and IST inside the matrix soil under the influence of lower moving boundaries.

3.4 Control of the contact force anisotropy on the stress-displacement behavior

Besides the control of $\theta_r$ on the peak strength behavior, it is interesting to further examine the relationships between the contact force anisotropies and the entire stress-displacement behavior both at the boundaries and inside the sampling windows. Figure 7 shows the typical simulation results from IST1, IST2 and IST4 with $\tan \phi_\mu$ equal to 0.05. To clearly demonstrate the influences of the contact total force anisotropy measured at the lower boundaries on the stress ratio-displacement behavior, the scales of $a_r$, $\theta_r$ and $(\tau/\sigma)_{\text{boundary}}$ are adjusted appropriately in the same plot to facilitate a better examination on their relationships.

It is seen in Fig. 7 that $a_r$ and $\theta_r$ play different roles in the evolution of stress ratio-displacement behavior for different types of surfaces. Clearly, for a random, irregular surface, the stress ratio evolution is mainly controlled by $\theta_r$ (Figs. 7b and c); while for a regular sawtooth surface, the role of
Unified soil behavior of interface shear test and direct shear test

(a) IST1

(b) IST2

(c) IST4

Fig. 7 Evolutions of the stress ratio, magnitude and principal direction of contact total force anisotropy developed at the particle-surface boundary against shear displacement in ISTs (tan $\phi_\mu = 0.05$): a IST1; b IST2; c IST4

$\alpha_t$ becomes more dominant (Fig. 7a). The former result is consistent with the critical role of $\theta_t$ on the peak stress ratio and indicates further that $\theta_t$ is a great predictor for the entire stress-displacement behavior. The latter result is interesting and a bit surprising too at a first glance because the dominant role of $\alpha_t$ seems to be contradictory with the previous results. However, an understanding of this behavior is achieved quickly by noting that the variation of $\theta_t$ is much smaller during the shear process as compared to the case of

irregular surfaces. The fact is that a large rotation of the principal stress or major contact force chains takes place in an irregular asperity surface, due to the initial wider distribution of the particle-surface contact normals; whereas only a limited rotation of the principal stress, especially after the peak state, occurs in a regular sawtooth surface due to the constant asperity slope during shear. When the direction of the major contact force chains is relatively stable, the accumulation or loss of contact normal and contact force magnitude in that direction, i.e., the magnitude of anisotropy, $\alpha_t$, becomes a decisive factor. Based on the above analysis, it is not hard to conclude that the effect of $\theta_t$ is a first-order, decisive one in controlling the stress-displacement behavior of the interphase system, and the effect of $\alpha_t$ is a second-order one which will only rise to play a major role when $\theta_t$ is relatively fixed.

A similar examination into the results from two DST simulations shown in Fig. 8 indicates that the amplitudes of variations of $\alpha_t$ and $\theta_t$ allowed in a DST are significantly affected by the box aspect ratio. A much larger variation of $\alpha_t$ and a smaller variation of $\theta_t$ is found when the box aspect ratio is larger. However, the variations of the two quantities are overall more consistent than those in the ISTs, indicating the measured $(\tau/\sigma)_{\text{boundary}}$ reflects more a combined effect of $\theta_t$ and $\alpha_t$. However, a more prevailing role of $\theta_t$ in the evolution
of the stress ratio-displacement behavior can be discerned in both DSTs.

Further insights of the micromechanics inside the sampling window are given by the evolutions of anisotropies of contact normal force and contact shear force with shear displacement shown in Fig. 9. It is interesting to examine the roles of $\theta_n$, $\theta_s$, $a_n$ and $a_s$ on the average stress ratio inside the sampling window, and compare them with the roles of $\theta_r$ and $a_r$ on the boundary-measured stress ratio discussed before. Apparently, the value of $\theta_n$ becomes relatively stable and lies between about $30^\circ \sim 60^\circ$ after a significant rotation at the early stage for almost all the simulations. The only exception is IST4 (i.e., the concrete surface) whose $\theta_n$ value keeps fluctuating and stays below $20^\circ$ throughout the whole shearing process, as shown in Fig. 9a. A complete opposite scenario is found in the $a_n$ evolutions in Fig. 9b. It is seen that all the simulations have overall $a_n$ profiles resembling their corresponding average stress ratio curves except IST4, whose $a_n$ value is fairly stable and much lower than the other simulations. Obviously, inside the sampling window, the effect of $a_n$ is a first-order, decisive one in controlling the average stress ratio-displacement behavior of the interphase soil for all the rough boundaries that are capable of supporting stable contact force chains oriented within $30^\circ \sim 60^\circ$. However, the effect of $\theta_n$ becomes dominant for those smooth boundaries, like the concrete surface which has limited capability of altering the contact force network away from the surface. For the latter case, the variation of $\theta_n$ is caused by the limited change of contact force direction at the particle-surface boundary, and the value of $a_n$ can gain very little change. As a result, the mobilized shear strength must be low.

As compared to the contact normal force anisotropy, the effects of contact shear force anisotropy are secondary. This is evidenced by the overall much lower values of $a_s$ for all the simulations (Fig. 9d). However, the responses seem to be more consistent for all the testing device boundaries, with $a_s$ showing more influences than $\theta_s$. Furthermore, $\theta_s$ also exhibits less disparities for different testing device boundaries than $\theta_n$ (Fig. 9c).

4 Conclusions

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. It is shown that the mobilized shear strength measured either at the testing device boundaries or inside the sampling window 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. However, a subtle distinction is found in the roles

---

Fig. 9 Evolutions of anisotropies of contact normal force and contact shear force within the sampling window against shear displacement for two DSTs and four ISTs: a $\theta_n$ vs. horizontal displacement; b $a_n$ vs. horizontal displacement; c $\theta_s$ vs. horizontal displacement; d $a_s$ vs. horizontal displacement.
of the principal direction and the magnitude of contact force anisotropy in controlling the stress ratio-displacement behavior as the contact force chains extend from the boundary into the interphase soil. The origin of this distinction is the pure geometric factor, i.e., the rigid boundary surface geometry vs. the adjustable interphase soil fabric.

Acknowledgments The study presented in this article was jointly supported by the Strategic Research Grant from City University of Hong Kong under Grant No. 7008083 and the China National Funds for Distinguished Young Scientists with Grant No. 51025932. These supports are gratefully acknowledged.

References
1. ASTM D5321-02: Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method. ASTM, West Conshohocken, PA, USA
2. ASTM D3080-04: Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. ASTM, West Conshohocken, PA, USA