Effect of Box Size on Dilative Behaviour of Sand in Direct Shear Test

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Abstract: In this paper an attempt is made to analyze the dilative behaviour of dense sand at two different sizes of the direct shear box, i.e. small (60 mm×60 mm×30 mm) and large (305 mm×305 mm×140 mm). A three-dimensional numerical model is developed using the FLAC^{3D} software to analyze the size effect on dilative behaviour of dense sand along the top and the shear plane of the box at 15 kPa normal pressure. It is observed that the vertical deformation of soil on top plane increases linearly with horizontal displacement, whereas on shear plane the vertical deformation remains constant after yielding of sand. It is also found that there is greater movement of sand particles at the front and the back of the box for the large shear box compared with that for the small shear box.

Keywords: *direct shear, numerical modelling, FLAC, dilation, Mohr-Coulomb*

1. Introduction

Granular soils are primarily used as a backfill material for mechanically stabilized earth wall and reinforced soil slopes. A direct shear box (DSB) is commonly used in most of the geotechnical laboratories to measure the shear strength parameters (cohesion interpcept *c* and friction angle ϕ) of granular soils (Jewell and Wroth 1987, Jewell 1989, Thronton and Zhang 2003, Cui and O'Sullivan 2006, Zhang and Thronton 2007, Indraratna 2014). It consists of an upper box and a lower box. Usually the upper box is restrained and the lower box moves relative to upper box. The shear force is measured using a proving ring or load cell (Mohapatra *et al.* 2014, 2016). DSBs of various shapes (square and circular) and sizes (small, medium and large) are used according to the maximum particle size of the soil (Shibuya *et al*. 1997, Lings and Dietz 2004, Bareither *et al.* 2007). According to AASHTO T236-08-UL (AASHTO 2008) or ASTM D3080 (ASTM 2011), the width of the DSB must be 10 times the maximum particle size and the initial specimen thickness must be 6 times the maximum particle size of the soil. To satisfy the above criteria mostly three different sizes of DSB, i.e. small (60 mm×60 mm), medium (150 mm×150 mm) and large (305 mm×305 mm) are normally used in a typical geotechnical laboratory.

Various studies are reported in the literature to compare the shear strength parameters of the granular soil (mostly sand) measured using DSBs of different sizes. Bareither *et al.* (2008) carried out laboratory experiments to understand the size effect of DSB on measured shear strength of sand backfill. They concluded that friction angles measured using small and large DSBs are essentially same. Wu *et al.* (2007) carried out laboratory study using four different DSBs having specimen length ranging from 40 mm to 800 mm. Fine poorly-graded sand was used for the study. They attributed the size effect of the specimen to the shear zone thickness and number of shear bands developed in the shear zone.

In a DSB, the vertical movement of the top cap is measured using a dial gauge or a LVDT for the estimation of angle of dilation. The vertical displacement vs the horizontal displacement plot does not give the entire picture of dilative behaviour of the soil, which may vary from the top cap to the shear plane. Various studies are reported in the literature to understand the dilation behaviour of granular soil (Newland and Allely 1957, Bolton 1986, Houlsby 1991, Chakraborty and Salgado 2010, Cinicioglu *et al*. 2015). To the authors' knowledge very limited studies have been conducted to understand the effect of box size on dilative behaviour of sand in a direct shear test.

In the present study an attempt is made to analyze the dilative behaviour of dense sand using two different sizes of DSB, i.e. small and large. A three dimensional (3D) numerical model is developed using the finite difference software FLAC^{3D} (Itasca 2005) to analyze the size effect on dilative behaviour of dense sand under low normal pressure (σ_n =15 kPa). The behaviour is analyzed along the top boundary and the shear plane. Additionally, the movement of soil particles along the front and back boundaries of the DSB are also analyzed and compared for the small and the large DSB.

2. Numerical Modelling Procedure

Three-dimensional finite difference grid models were created in FLAC^{3D} for the small and the large DSBs. Rigid walls of the DSB were not modelled explicitly. Instead boundary conditions as described below were used to simulate the conditions during direct shear tests. Roller boundary conditions were given to four vertical sides of top and bottom part of the sample, similar to the test condition. All the grid points on four vertical faces of bottom box and the bottom surface of the box were given equal horizontal displacement to simulate shearing of soil during the direct shear test. Potts *et al*. (1987) used similar approach for two dimensional finite element modeling of the direct shear test. Size of the model was similar to the sample size inside the DSB, i.e. 60 mm × 60 mm × 30 mm for the small and 305 mm × 305 mm × 140 mm for the large DSB. To improve the solution accuracy, very fine grid meshes are used along the shear plane (Figure 1). In the current model an equal horizontal velocity was applied to all the nodes on the bottom box and the model is allowed to run for certain time steps to achieve the required horizontal displacement. The unbalanced forces generated due to the displacement of the bottom box were summed up and divided by the plan area of the shear box to determine the shear stress corresponding to different horizontal displacements.

Elastic perfectly plastic Mohr-Coulomb (MC) model was used to model the dense sand. Properties of sand used for the modeling is given in Table 1. Grain size distribution of sand is given in Figure 2. The input parameter ϕ and ψ for sand are obtained from laboratory experiments (Mohapatra *et al*. 2016). From the shear stress vs. horizontal displacement plot (Figure 3) friction angle at peak (ϕ) and 40 mm horizontal displacement (ϕ_{cv}) are obtained using eq. (1) and eq. (2).

$$\phi = \tan^{-1}\frac{\tau}{\sigma_n} \text{ ------------------- } (1)$$

$$\phi_{cv} = \tan^{-1}\frac{\tau_{cv}}{\sigma_n} \text{ ----------------- } (2)$$

where τ and τ_{cv} are the shear stresses mobilized at peak and at 40 mm horizontal displacement, respectively and σ_n is the applied normal pressure. The dilation angle (ψ) of soil was obtained from the eq. (3) proposed by Bolton (1986)

$$\phi = \phi_{cv} + 0.8\psi \text{ ----------------- } (3)$$

Table 1 Properties of sand used in the modeling

Shear box type	Peak friction angle; ϕ (°)	Dilation angle; ψ (°)
Large	53	16
Small	48	5

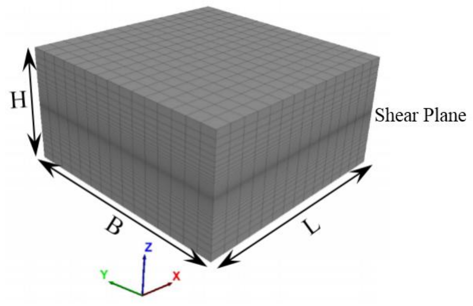

Figure 1. Isometric view of the direct shear model

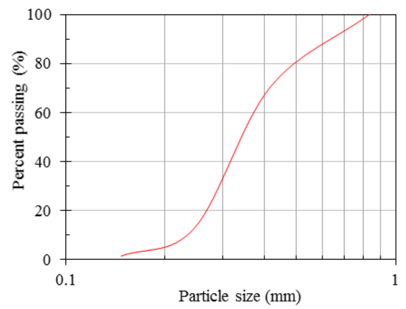

Figure 2. Grain size distribution of sand

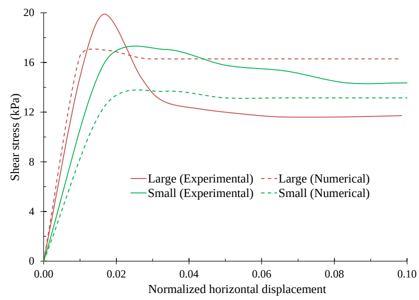

Figure 3. Shear stress vs. Normalized horizontal displacement

3. Results and Discussion

The results from the numerical simulation are validated with the laboratory tests and some other relevant data are also extracted from the numerical modelling thereafter. Figure 3 shows the validation using MC model with the shear stress vs. normalized horizontal displacement plot obtained from the experiments. The horizontal displacement is normalized with the length of the box. As MC model is an elastic-perfectly plastic model, the post-failure strain softening of granular material cannot be modelled. However, the model can be seen to assume the failure stress states appropriately.

As there was no provision to measure the vertical displacement during the experiments, the relevant data is extracted from the numerical simulation and is shown in Figures 4 and 5. The values are normalized with the respective dimensions of the box. Generally in the laboratory only the top box movements are measured but the same extent of dilation may not be occurring at the shear plane which is actually the plane of interest. The shear behavior is studied at the shear plane whereas the dilation behavior is observed at the top boundary. The 3D model helps in determining the spatial variation throughout the box rather than just on a particular plane as in the case of a 2D model.

Figure 4 and 5 shows the variation of vertical displacement at two planes, (a) top plane and (b) shear plane of the DSB. From the Figures it can be observed that the vertical displacement of the top box increases at a constant rate throughout the test, whereas in shear plane, it remains constant after the yielding. This behaviour is observed for both sizes of the DSBs.

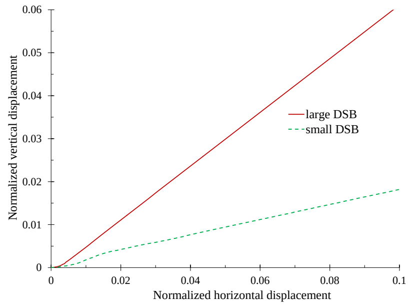

Figure 4. Comparison of vertical displacement at top plane

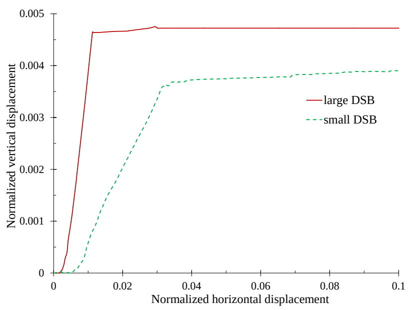

Figure 5. Comparison of vertical displacement at shear plane

Figure 6 shows the contours of vertical displacement in case of large and small DSB. From the figure it can be observed that soil grains at the back side of the bottom box undergo downward movement in case of large DSB whereas in case of small DSB the particle movement is restricted to the top box. The relative magnitude of vertical displacement is higher in case of large DSB. This particle movement in large DSB results in the particle-to-particle force concentrations that are transferred to the particle–box interface, resulting in increased measured shear resistance (Figure 7).

In the small DSB, particle-box interaction was insignificant compared to that in the large DSB due to greater number of particles moving within the shear band (Christopher *et al.* 2008). Liu (2006) reported similar observation from the results obtained from discrete element modeling of direct shear test of dense sand. As per Wu *et al.* (2008), as L/D_{50} (L= length of shear box) increases, multiple shear bands develop in the shear zone.

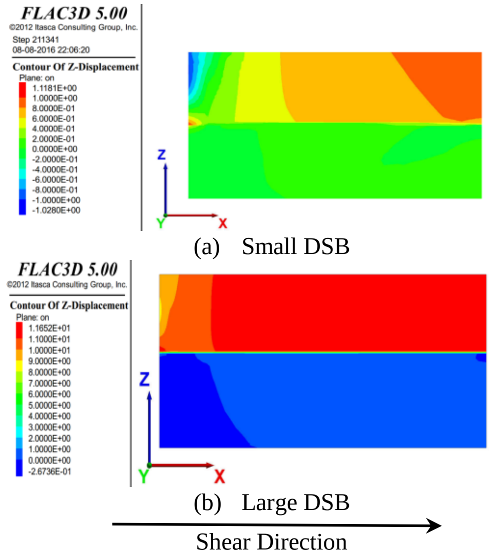

Figure 6. Contours of vertical displacement after shearing

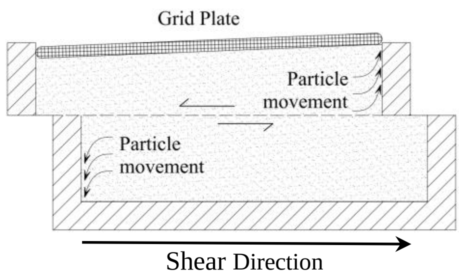

Figure 7. Particle movement during shearing in large DSB

4. Conclusion

From the above study following conclusions can be derived

- Dilation angle of sand measured from small and large DSB are not same and significant variation in dilation angle is observed due to the difference in particle movement in small and large shear box.
- Vertical displacement measured at top of the box during laboratory experiment does not

give entire picture of dilative behaviour of sand inside the shear box.

- Higher shear forces are measured in large DSB due to larger number of particle movement.

Abbreviations and Notations

B	Width of the shear Box
DSB	Direct shear box
H	Height of the shear box
L	Length of the shear box
MC	Mohr-Coulomb
2D	Two dimensional
3D	Three dimensional
D_{50}	Diameter corresponding to percentage finer than 50%
ψ	Dilation angle
ϕ	Peak Friction angle
ϕ_{cv}	Friction angle at 40 mm horizontal displacement
σ_n	Normal pressure
τ	Peak shear stress
τ_{40}	Shear stress at 40 mm horizontal displacement

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