

Modification of direct shear apparatus for soil-soil and soil-solid interface testing

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Abstract. The conventional direct shear apparatus has been widely used to analyze the shear behavior of the soil-soil and soil-solid interfaces. However, it has certain limitations, such as tilting of loading plate and rotation of upper shear box, which eventually lead to unfavorable shear responses and hinder the evaluation of accurate shear strength parameters. Therefore, in this study the direct shear apparatus is modified as follows: (1) application of constant vertical stress through a loading rod fixed to a circular loading plate for soil-soil tests and rectangular loading plate for interface testing; and (2) a provision of linear motion (LM) guide for smooth horizontal movement of shear box during shearing process and construction of upper and lower shear boxes for soil-solid interface testing. The modified direct shear apparatus is tested with soil-soil at different initial relative densities and interface testing using solid plate under three vertical stresses. The experimental results confirm that the vertical stress, which is imposed through the new loading system, remains constant during the shearing phase. Further analysis is conducted to establish the empirical relation of friction angle as a function of initial relative density.

Keywords: constant vertical stress; friction angle; initial relative density; modified direct shear apparatus; rotation of upper shear box; tilting of loading plate

1. Introduction

For construction materials including soil-soil and soil-other material interface, direct shear (DS) testing can characterize the shear response and quantify the shear strength parameters (Ilori *et al.* 2017, Kodicherla 2023, Lee *et al.* 2023, Park *et al.* 2022, Yang *et al.* 2018). Compared to other shearing tests, it has some advantages, such as a relatively short drainage distance and lower time requirement for sample preparation. However, improper constrained condition among the loading system consisting of upper shearing box, loading plate, and loading rod changes the vertical loading imposed during the shearing process. The variation of vertical load during the shearing process results in tilting of the loading plate and rotation of the upper shear box. These limitations unfavorably form non-uniform stress and strain distributions along the pre-defined shear plane, which eventually produce inaccurate shear responses.

Previous studies have proposed some modifications to the DS apparatus for vertical load application. Fig. 1 shows three types of constrained conditions among the upper shear box, loading plate, and loading rod. In Type 1, the loading plate and upper shear box are not connected to each other and the ball bearing is installed on the loading plate (Skempton and Bishop 1950). The hinged connection

through a ball bearing between the loading plate and loading rod can apply unfavorable moment, induced by the rotation of loading plate during shearing.

In contrast, the upper shear box and loading plate in Type 2 are fixed, while the loading rod and loading plate can be fixed or unfixed (Jewell 1989, Jewell and Wroth 1987). The shear box and the loading plate move as one unit with fixed connection between the loading plate and loading rod. This loading configuration hinders either the upward or downward movement of particles below the loading plate, and inaccurately produces volumetric response during shearing.

In Type 3, the loading plate and upper shear box are not connected, but the loading plate and loading rod are fixed (Mikasa 1960). While the loading plate can move up and down during shearing, its tilting and rotation can be controlled using the new loading system.

Nevertheless, the existing versions of DS apparatus fail to maintain constant vertical stress during shearing in preventing the upper shear box and loading plate from rotating. Therefore, for soil-soil and soil-solid interface tests, it is necessary to modify the DS apparatus to maintain constant vertical stress application during the shearing.

This study invents the DS apparatus to analyze the shear response and interface behavior of soil-soil and soil-solid surfaces, respectively, which is the novelty of this study. The main modifications include the constrained connection among the loading system and smooth horizontal movement of the shear box during the shearing process. The modified direct shear apparatus is tested with soil-soil at different initial relative densities and interface testing using the solid plate under three vertical stresses.

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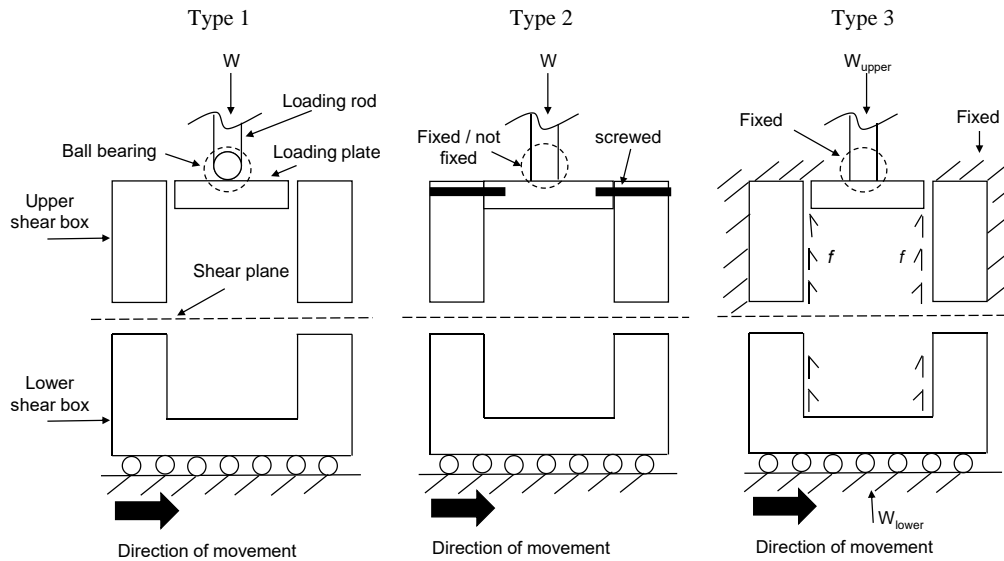


Fig. 1 Three types of widely used conventional shear boxes: Type 1 – loading plate and upper shear box are not connected and the ball bearing is installed on the loading plate (Skempton and Bishop 1950); Type 2 – loading plate and upper shear box are fixed, but the loading rod and loading plate is fixed or not fixed (Jewell and Wroth 1987); Type 3 – loading plate and upper shear box are not connected, but the loading rod and loading plate are fixed (Mikasa 1960)

2. Modified direct shear apparatus

Fig. 2 shows each component of the direct shear apparatus modified from Type 3 apparatus. The linear motion (LM) guide actuator (1 in Fig. 2) is used to facilitate the vertical loading system (6, 12, 15, and 17, respectively, in Fig. 2), thus imposing the vertical stress by the steering handle (10 in Fig. 2). For the soil-soil test, circular loading plate of the conventional DS apparatus installed on the ball bearing is replaced with a circular loading plate by fixing it to the vertical loading rod. For constant application of the vertical stress during the shearing process, linear motion (LM) guide (2 in Fig. 2) is additionally used for frictionless movement between the outer and lower shear box. Note that, for interface testing, the circular shear box (9 in Fig. 2) and circular loading plate (63 mm diameter) are replaced with rectangular shear box assembly. To avoid unfavorable moment, the horizontal loading rod (18 in Fig. 2) is connected to the middle and side of upper shear box. This loading system moves as a unit which eventually satisfies the moment force equilibrium by balancing the rotation induced by horizontal and vertical forces.

The vertical force is applied through the air cylinder attached to the air compressor (15 in Fig. 2). The vertical stress is calibrated based on the working principle of air cylinder. The double acting pneumatic cylinder applies pressure using compressed air, and the pressure gauge (16 in Fig. 2) is used to monitor the imposed stress. The applied force is calculated by multiplying the air pressure with the cross-sectional area of cylinder.

$$F_{\text{air}} = P_{\text{air}} \times A_{\text{air}} \quad (1)$$

where P_{air} is the compressed air pressure [kPa], A_{air} is the cross-sectional area of air cylinder [m²], F_{air} is the force applied by air [kN]. Furthermore, the vertical stress on the soil specimen is obtained by dividing the applied force by

the cross-sectional area of the loading plate. The shear stress is calculated by dividing the measured horizontal stress by the cross-sectional area of specimen.

The load cells (5 and 6 respectively in Fig. 2) measure the horizontal and vertical loads. Moreover, the linear variable differential transducers (LVDTs 3 and 4 respectively in Fig. 2) evaluate the horizontal and vertical displacements. The shear motor (11 in Fig. 2) is capable of applying the shear force in both the forward and reverse directions under controlled strain rates for analyzing the anisotropic behavior. The LabView program monitors and records the measured results in real-time while saving data using the sensors attached to the data logger.

For the interface testing, previous studies have proposed various modifications to the DS apparatus. To investigate the peak shear strength response of sand-steel interfaces, a modified winged DS apparatus was proposed. The load is applied in the middle of the sample to ensure symmetry (Lings and Dietz 2005). Additionally, the DS apparatus was modified by swapping out the lower shear box with a five-legged steel plate to examine the bio-cemented soil-steel interface behavior (Bak *et al.* 2021). To analyze the expandable foam grout-sand interface characteristics, a stepper motor was installed in the DS apparatus to apply vertical stress on the specimen following the pseudo-strain principle (Lee *et al.* 2020). Herein, a rectangular loading plate with a length, width, and thickness of 100, 63, and 20 mm, respectively, and newly constructed rectangular shear boxes are used for interface testing. Fig. 3(a) represents the top view of the upper shear box with inner dimensions representing soil specimen area having a length and width of 101.6 and 63.5 mm, respectively, which provides enough room for the specimen to undergo shearing without excessive disruptions induced by sidewalls. The length, width, and thickness of the lower shear box are 162, 120, and 25 mm, respectively.

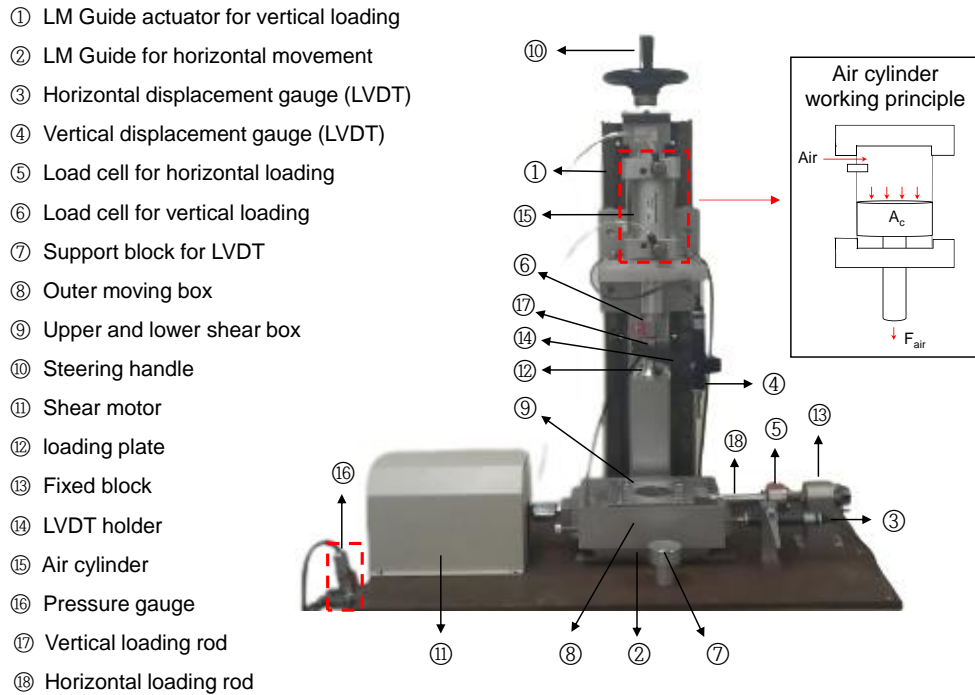


Fig. 2 Modified direct shear apparatus including each component (modified from (Lee and Chong 2022)). The top loading plate is fixed with the vertical loading rod attached to the load cell. The horizontal loading rod is connected to the middle and side of the upper shear box to avoid unfavorable moment. Pressure gauge is used to monitor the vertical stress applied by pushing-type air cylinder. The force applied by air (F_{air}) is calculated by the compressed air pressure (P_{air}) and the area of air cylinder (A_{air}). For interface testing, the circular loading plate and shear box are replaced with rectangular loading plate and shear box

Table 1 Basic properties of Jumunjin standard sand used in this study. The maximum and minimum void ratios are measured according to ASTM D4254 (ASTM 2006) and ASTM D4253 (ASTM 2006), respectively

| Properties | Value |
|-------------------------------------|-------|
| Coefficient of curvature C_c [] | 0.92 |
| Uniformity coefficient C_u [] | 1.48 |
| Average particle size D_{50} [mm] | 0.57 |
| Maximum void ratio e_{max} [] | 0.92 |
| Minimum void ratio e_{min} [] | 0.63 |
| Specific Gravity G_s [] | 2.62 |

The opening size between the shear boxes play a critical role in evaluation of the interface shear response (Kim 2021). Previous study recommends an opening size of $5D_{50}$ (D_{50} is the average soil particle size) between the shear boxes (Lings and Dietz 2004). Additionally, the threshold point (TP) method established from a series of DS tests proposes the optimal opening size between the upper and lower shear box (Kim *et al.* 2012). This study adopts an opening size of 1 mm, which is kept constant during the shearing process.

The upper shear box is bolted to the LM guide block, and it moves over the LM guide rail fixed to the lower shear box. As shown in Fig. 3(b), the LM guide is comprised of three primary elements: (1) lower shear box, (2) a rail that supports the carriage's movements, and (3) LM guide block.

The addition of a recirculating mechanism of the ball bearings inside the LM guide block allows for a smooth

linear motion. For interface testing, the solid plate made of a polycarbonate material is used as shown in Fig. 3(c). The solid plate is bolted to the lower shear box before the test.

3. Testing procedure

Jumunjin standard sand is used; and its basic properties are listed in Table 1. The soil-soil tests are performed with five different initial relative densities under three vertical stresses (50, 100, and 200kPa). To achieve the targeting initial relative density, the sand is poured into circular shear box using air-pluviated method. The specimen is sheared at the strain rate of 1 mm/min up to a displacement of 6 mm (10% strain criteria). For the soil-solid interface tests, the Jumunjin standard sand is poured over the solid plate using air-pluviation method. The specimen is sheared until a displacement of 10 mm. Note that the surface of the sand is flattened for uniform contact of loading plate to avoid the stress concentration induced by the uneven surface (Chong 2014).

4. Results and analysis

4.1 Soil-solid interface shear behavior

Fig. 4 shows the results of interface testing conducted by shearing sand against a smooth solid plate at 40% initial relative density. The vertical stress imposed on the loading

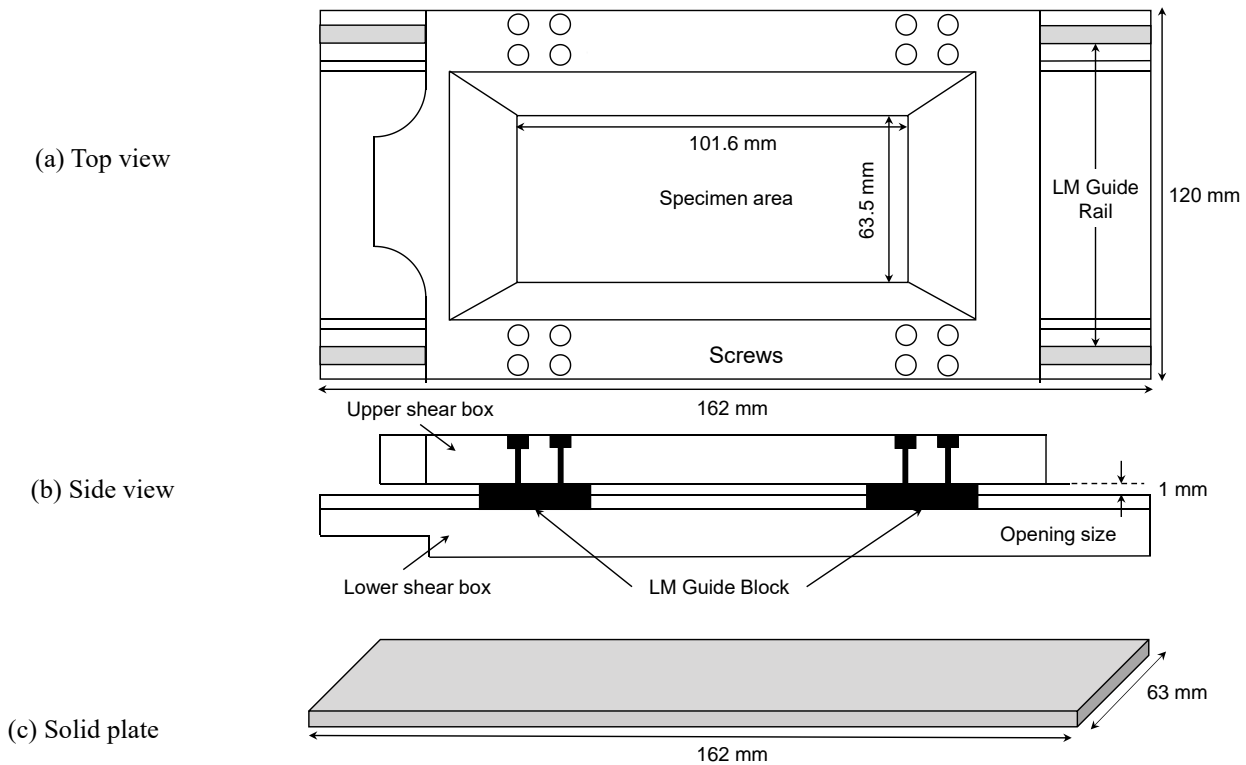


Fig. 3 Schematic of rectangular shear box equipped with linear motion (LM) guide and solid plate: (a) Top view of the modified upper and lower shear boxes, (b) Side view of the LM guide framework to facilitate frictionless movement of lower shear box during the shearing phase and (c) Solid plate for interface testing. Solid plate is installed on outer moving box using four screws for soil-solid interface testing

plate remains constant during the shearing phase as shown in Fig. 4(a). In fact, the volumetric change induces a small fluctuation in the vertical stress; dilative response increases the vertical stress owing to the upward movement of particles below the loading plate. The constant application of vertical stress confirms the following factors: (1) the specimen is not

affected by the friction from sidewalls of shear box; (2) LM guide minimizes the frictionless movement of lower shear box; (3) the invented loading system prevents tilting of the loading plate and rotation of upper shear box by imposing the constant vertical stress at a central plane of shear.

Fig. 4(b) shows the horizontal displacement against shear stress under three vertical stresses. In all the cases, the strain softening response is observed and the peak shear stress occurs at a relatively lower strain value. As expected, higher vertical stress produces larger mobilized shear resistance. As shown in Fig. 4(c), the contractive responses are observed, and lower vertical stress produces more vertical displacement. The soil-solid interface failure envelop shows a relatively smaller interface friction angle between sand and plate ($\phi = 14^\circ$ at $D_r = 40\%$ in Fig. 4(d)).

This is because the solid plate used in this study has a smooth surface. The rectangular shear box modified in this study is not limited to a single type of solid surface and can be adopted for analyzing the interface behavior of other structural elements, such as geosynthetics, concrete, and bio-inspired surfaces.

4.2 Effect of Initial relative density on the shear response

Figs. 5(a)-5(c) show the shear response of soil-soil tests under three vertical stresses (50, 100, and 200 kPa) at 35% initial relative density. As shown in Fig. 5(a), the modified direct shear apparatus maintains a nearly constant application of vertical stress during the shearing process. Small fluctuation of the vertical stress is attributed to the volumetric change propagated from the pre-defined shear plane, which guarantees the accuracy of the modified DS apparatus. The strain softening behavior is clearly observed at the higher vertical stress. Conversely, the strain hardening response is observed at lower vertical stresses [Fig. 5(b)]. The vertical displacement response at different vertical stresses is represented by Fig. 5(c). The results show the initial volumetric contraction and subsequent dilation for each case. As expected, the dilative response prevails for higher vertical stress.

Figs. 5(d)-5(f) present the shear behavior of the soil at varying initial relative densities under constant vertical stress. Vertical stress remains nearly constant during shearing for each initial relative density case. At the given vertical stress, higher initial relative density produces higher shear resistance at a relatively lower strain value. The stress-displacement response shows the increase in the initial stiffness (not shown here but can be indirectly

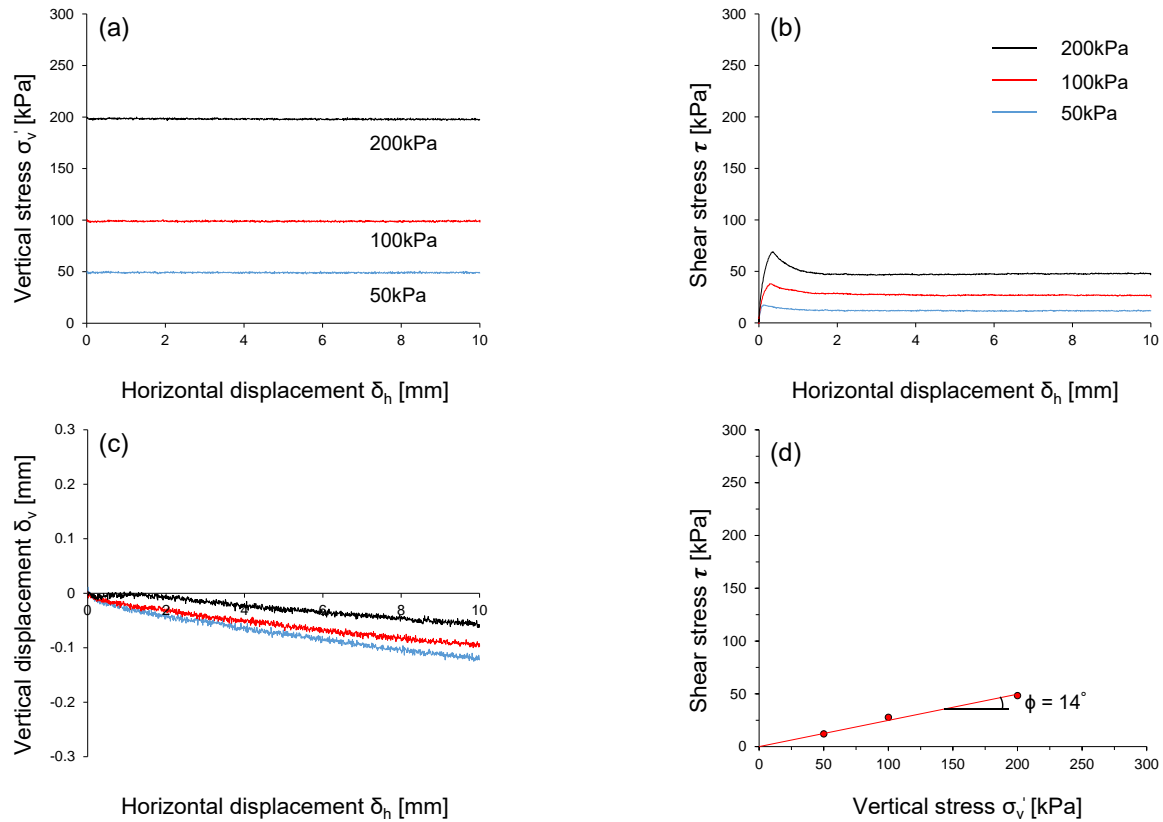


Fig. 4 Interface shear response obtained using a modified rectangular direct shear apparatus at three different vertical stresses and 40% relative density: Horizontal displacements against (a) Vertical stress, (b) Shear stress, (c) Vertical displacement and (d) Failure envelop for the soil-solid interface test. The solid plate with smooth surface is bolted over the lower shear box connected with outer moving box

Table 2 Summary of friction angle of soil-soil tests using modified direct shear apparatus at different initial relative densities and soil-solid test at 40% initial relative density

| D_r [%] | σ'_v [kPa] | τ_{peak} [kPa] | ϕ_{peak} [°] |
|-----------------|----------------------|------------------------|----------------------|
| 35 | 50 | 42.7 | 37.4 |
| | 100 | 69.5 | |
| | 200 | 155.1 | |
| 40 | 50 | 43.8 | 38.0 |
| | 100 | 78.3 | |
| | 200 | 153.9 | |
| 50 | 50 | 50.8 | 40.5 |
| | 100 | 79.5 | |
| | 200 | 172.3 | |
| 55 | 50 | 52.9 | 42.2 |
| | 100 | 93.9 | |
| | 200 | 177.9 | |
| 65 | 50 | 56.1 | 46.6 |
| | 100 | 103.6 | |
| | 200 | 212.7 | |
| Soil-solid test | | | |
| 40 | 50 | 12.1 | 14.0 |
| | 100 | 27.8 | |
| | 200 | 48.3 | |

Fig. 6 presents the evolution of friction angle through failure envelopes of soil-soil tests at different initial relative densities. The accuracy of measured friction angle values is higher ($R^2 > 0.98$) in all the cases. It is observed that friction angle increases with the increase in initial relative density. By varying the initial relative density between 35% and 65%, the difference in friction angle becomes approximately 9.2° . Further analysis is conducted to estimate friction angle as a function of initial relative density (Fig. 7). Note that the empirical equation proposed in the previous study is superimposed for comparison. It is observed that the significant difference exists in the predicted responses of friction angle (from $\phi = 4^\circ$ at $D_r = 35\%$ to 10° at $D_r = 65\%$).

This difference can be explained as the previous study employed conventional DS apparatus which leads to erroneous measurements caused by its limitations. In addition, the previous study does not mention the sampling procedure and initial state of sand specimen. Thus, the empirical relation established from this study should replace the previous one.

5. Conclusions

This study modifies the conventional direct shear apparatus for soil-soil and soil-solid interface tests. The

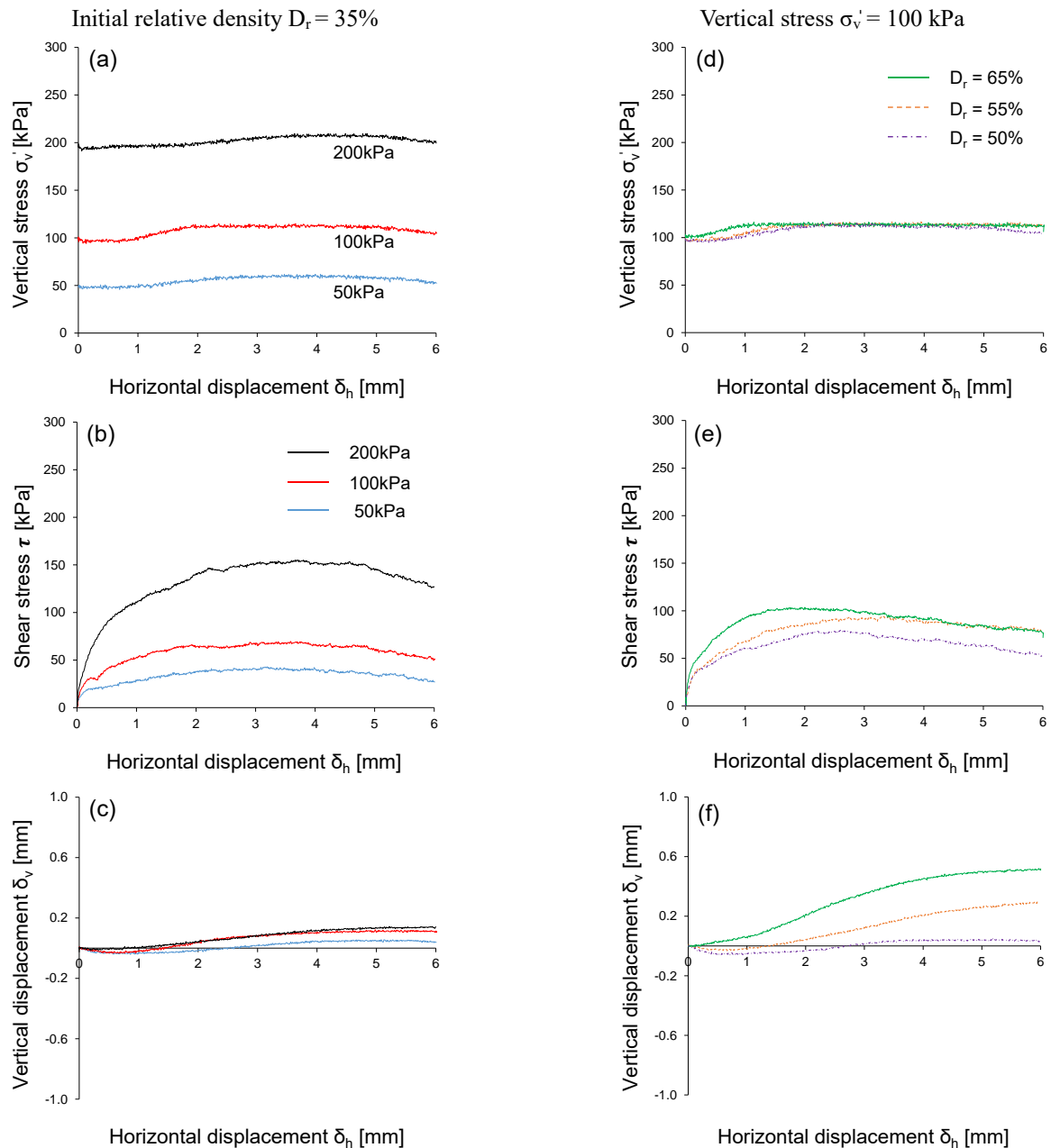


Fig. 5 Response of shear testing using a modified circular direct shear apparatus: Horizontal displacement against (a and d) Vertical stress; (b and e) Shear Stress; (c and f) Vertical displacement

modified direct shear apparatus is tested with soil-soil at different initial relative densities and interface testing using a solid plate. The salient conclusions are drawn as follows:

- The main improvements of the direct shear apparatus include constant application of vertical stress through a loading plate fixed to the loading rod. For interface testing, the circular loading plate is replaced with a rectangular loading plate and new rectangular shear boxes are constructed to accommodate solid surfaces. The linear motion (LM) guide is provided for frictionless movement of the shear box during the shearing phase and to prevent the variation in opening size between the shear boxes.
- The soil-solid interface tests using rectangular shear

box result in constant vertical stress due to symmetric and uniform distribution of stresses during the shearing phase. This develops equilibrium of moments induced by vertical and shear forces during the shearing phase and hinders the tilting of loading plate and rotation of shear box.

- The soil-soil tests are conducted at different initial relative densities under three vertical stresses and the results show that circular loading framework invented in this study, applies a nearly constant vertical stress. The higher vertical stress produces strain softening behavior while lower vertical stress produces strain hardening behavior. These results are in general agreement with the previous studies.

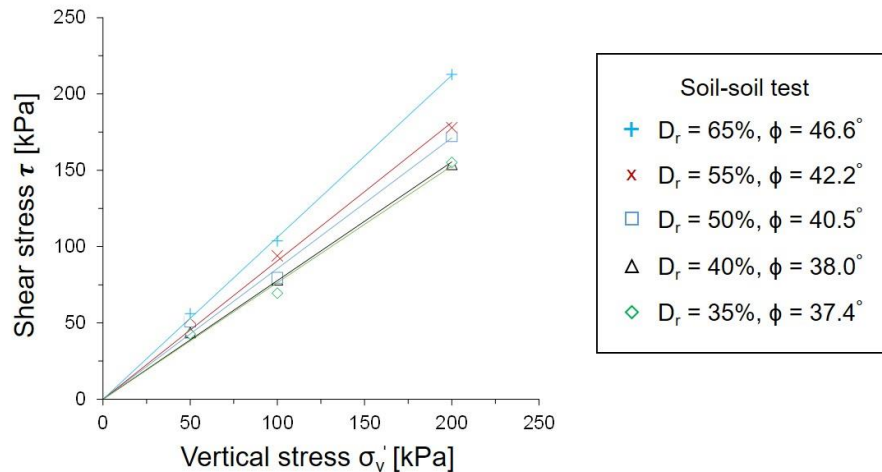


Fig. 6 Failure envelopes for the soil-soil tests at different initial relative densities according to the Mohr-Coulomb theory

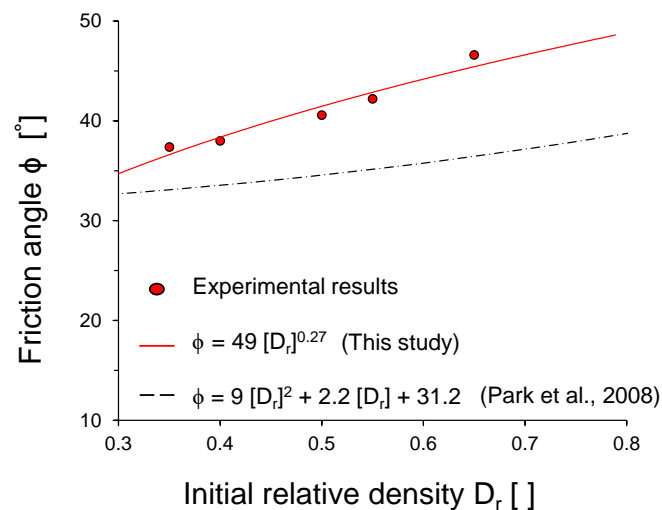


Fig. 7 Friction angle as a function of initial relative density. The continuous line indicates the empirical equation established in this study. Dashed line is proposed by the previous study (Park *et al.* 2008)

- The responses of soil-soil and soil-solid interface tests are consistent indicating that the LM guide ensures frictionless movement of lower shear box during the shearing. Indeed, the proposed modifications in direct shear apparatus lead to accurate measurement of the shear responses and can be deployed for analyzing the soil-soil and soil-solid interfaces.

Acknowledgments

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