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A tilt table device for testing geosynthetic interfaces in centrifuge

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Abstract

The shear strength of geosynthetic interface can be determined by either tilt table tests under low pressure or direct shear tests under high pressure. In the present paper, a tilt table device for testing the interface shear strength in geotechnical centrifuge is presented for the first time. By combining the advantages of tilt table and centrifuge, our tests cover a wide range of pressure from 10 to 100 kPa. After a detailed description of the tilt table device, the test process and evaluation procedure are presented. The softening behaviour in the post peak regime is investigated by controlling the displacement with a relaxation mechanism. The test results in centrifuge are discussed and compared with tilt table tests and large direct shear tests in 1-g environment.

Keywords: Geosynthetic interface; Tilt table test; Geotechnical centrifuge

1. Introduction

Correct estimates of the shear strength of soil–geosynthetic interface are crucial for safe and economic design of soil–geosynthetic structures. The shear strength of soil–geosynthetic interfaces is currently the subject of considerable research interest (Akpinar and Benson, 2005; Fleming et al., 2006; Sia and Dixon, 2007). Inadequate knowledge and false use of the interface shear strength are thought to have caused some incidents reported in the literature (Mitchell et al., 1990; Seed et al., 1990; Giroud et al., 1990). The interface shear strength can be determined either by tilt table test or direct shear test, e.g. ASTM 5321 (1997). Usually, tilt table tests are carried out at extremely low stress level of less than 10 kPa. Such tests are particularly relevant for the design of surface liners. In principle, the pressure in tilt table tests can be increased by stacking dead weight. However, towering dead weight often leads to overturning and non-uniform stress distribution. As a consequence, the interface strength under high pressure (from 50 to 500 kPa) is the domain of direct shear tests. Due to mechanical difficulties, however, direct shear tests at extremely low stress level do not provide reliable results. Comparisons between both tests indicate that the shear strength determined in direct shear tests is somewhat higher than in tilt table tests (Girard et al., 1990; Koutsourais et al., 1991; Izgin and Wasti, 1998; Lalarakotoson et al., 1999). A plausible explanation of this discrepancy is not available. Therefore, it is desirable to have one kind of test covering the entire range of stress level.

Moreover, tilt table tests and direct shear tests differ in boundary conditions. Tilt table tests are force-controlled, while direct shear tests are controlled by displacement. Once the shear strength is fully mobilised in a tilt table test, the soil specimen loses its stability and starts an accelerated motion downwards. The tilt table test provides the peak strength but not the residual strength. In a direct shear test, the soil specimen is restrained and remains stable when the peak strength is reached and beyond. The complete stress–displacement curve can be obtained providing both peak strength and residual strength. In spite of this, some recent publications in the literature suggest that the tilt table test is more appropriate for characterising soil–geosynthetic interfaces (Lopes et al., 2001; Ling et al., 2002; Narejo, 2003; Briançon et al., 2002; Pedersen et al., 2003). It is interesting to inquire whether the tilt table test can be improved to explore the behaviour beyond the peak strength.

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In view of the above exposition, the main objective of the present paper is twofold. First, the tilt table device is improved to allow for the investigation of the softening behaviour beyond the peak strength. This is made possible by a relaxation mechanism, which first holds back the soil specimen from sliding down and then mobilises the shear strength by translating the soil specimen with prescribed displacement. Second, the tilt table device is integrated into a geotechnical centrifuge to increase the pressure in the tilt table test.

2. Tilt table device

As shown in Fig. 1, the tilt table device consists of a base platen (1), a trough (2) and a shear box (12). The shear box is about 193 mm long and 174 mm wide. The shear box is guided by a linear slide on each side and slides along the trough base. The base platen and the trough are hinged at the pivot (3) on the one side. On the other side, the trough is connected to a lead screw of a spindle lift. The spindle lift (4) is hinged to the base platen on the pivot (5). The trough can be raised by the spindle lift, which is driven by a stepper motor M2 and worm gear box, which allows for a precise transformation of the rotary motion into linear motion via a lead screw. Since the tilt table in the centrifuge is not accessible during testing, the stepper motor is connected to the I/O control panel of the centrifuge. From the control panel the tray can be raised or lowered at a given rate, e.g. 1°/min.

The tilt table device is designed to accommodate soil specimen in a mould in the trough base. The friction behaviour of geomembrane can be studied on both sides, e.g. a sand specimen in the shear box and a clay specimen in the mould. The geomembrane is sandwiched between the shear box and the mould. By measuring the forces of the shear box and in the geomembrane during the tilt table test, the shear force between the geomembrane and the clay in the underlying mould can be calculated. In this way, the strength of the two interfaces can be determined. In the present paper, however, we confine ourselves to the interface between sand specimen in the shear box and geomembrane and an aluminium plate is put into the mould.

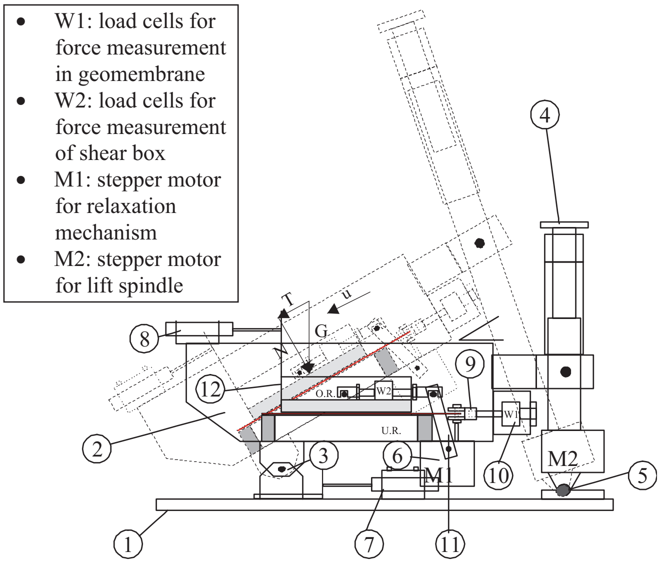

Fig. 1. Components of the tilt table device.

During testing the base platen is mounted to the base of the centrifuge loader by four screws. The shear box is placed on the trough base. The displacement of the shear box is measured by a displacement transducer (8), which is mounted on the trough. The transducer allows for a maximum displacement of 40 mm. The traction force exerted by the shear box is measured by two parallel load cells (W2 in Fig. 1). The tilt table device weighs about 37 kg.

An important component of the tilt table device is a relaxation mechanism (11), which is introduced to measure the properties in the post peak regime. The relaxation mechanism consists of the following components: a stepper motor M1, a worm gear box and linear guides with a holder for load cells W2. The stepper motor provides the drive for the gear box, which converts the rotation to translation. The holder for the displacement transducer provides also the guide for a parallel translation of the shear box and the load cells and guarantees that the shear box and the load cells W2 are translated as an entity. The relaxation mechanism is mounted onto the rear bottom of the trough and connected to the load cells trough two openings in the trough bottom. When the critical inclination of the trough is reached, the shear box tends to slide down the trough. The relaxation mechanism will hold back the shear box. Meanwhile, the traction force is measured by the load cells W2. After the spindle lift is stopped, the shear box is “relaxed” by prescribing a displacement increment down slope. This is done by switching on the stepper motor M1.

To facilitate automatic measurement of the inclination, the rotation around the hinge (3) is converted into a linear displacement via rack and pinion. The pinion is a cogwheel, which is welded onto the rear bottom of the trough and mounted on the hinge. The cogwheel meshes with a toothed rod, which slides long a guide. As the trough is raised via the spindle lift, the pinion rotates on the pivot and transforms the rotation into a linear displacement. By measuring the displacement with a LVDT ((7) in Fig. 1) the tilting angle can be easily calculated.

The geomembrane is held in place by two steel clamps. Each clamp is fixed by five screws to ensure uniform stress within the geomembrane. Two parallel load cells are integrated into the steel clamp to measure the tensile force in the geomembrane (W1 in Fig. 1). As will be shown later, the tensile force in the geomembrane provides an excellent indication for the post peak behaviour.

To sum up, the following measurements are made during a tilt table test in centrifuge: the inclination of the trough, the traction force exerted by the shear box, the displacement of the shear box and the traction force in the geomembrane. A photo of the tilt table device is shown in Fig. 2.

3. Geotechnical centrifuge

Geotechnical centrifuge model testing is widely recognised as an important tool for investigation complex geotechnical problems via small sized models (Schofield, 1980). In order to achieve mechanical similitude in small sized models, however, it is necessary to replicate the in situ stress state. As an example, reducing the size of structure at 1/10 scale requires an acceleration 10 times earth's gravity (Scott and Morgan, 1977).

A wealth of literature on model testing in geotechnical centrifuge is available. Beside model tests, e.g. geosynthetic-clay liner in landfill by Viswanadham and Jessberger (2005), small scale in situ tests are also reported, e.g. cone penetration by Bolton et al. (1999). To our knowledge, however, tilt table tests in a centrifuge are reported for the first time. In small sized models, the geotechnical centrifuge is used to increase the stress level to reach mechanical similitude. In the tilt table test, the specimen size is not reduced and the centrifuge is used only to increase the stress level.

Fig. 2. Photo of tilt table device.

The geotechnical centrifuge at Universität für Boden-Kultur (BOKU) in Vienna was manufactured by Trio-Tech, USA and was put into operation in 1990 with partial financial support form the Austrian Science Foundation. The centrifuge has mainly the following components: swinging basket, balancing counterweight, DC motor and aerodynamic enclosure (Fig. 3). The centrifuge is equipped with 56 electrical slip rings for process control and data acquisition. By using the dual platforms, two models can be tested at the same time. However, it is usual to have only one swinging basket carrying model, while the other platform carries balance weight. The technical specifications of the centrifuge are provided in Table 1.

4. Testing procedure and materials

The geomembrane is placed on the trough base and fixed by the two clamps. The geomembrane should be slightly stretched by adjusting the screws of the clamp in order to measure the stress from the beginning of test. After putting the shear box in place, the displacement transducer, the load cell and the relaxation mechanism are connected to

Table 1
Technical specification of geotechnical centrifuge

Diameter of centrifuge (m)	3.0
Radius of swinging basket (m)	1.3
Maximum angular velocity (1/min)	400
Maximum radial acceleration (g)	200
Maximum model weight (kg)	90
Maximum model height (cm)	56

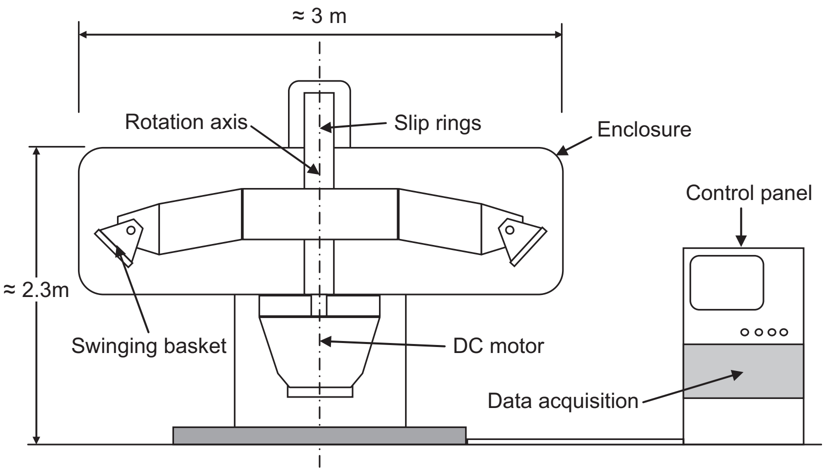

Fig. 3. Geotechnical centrifuge at BOKU.

the shear box. The shear box should be moved back and forth several times while the readings of displacement transducer and load cell are taken in order to avoid free play. Afterwards, the shear box is filled with a batch of sand of about 445 g. The maximum fill height is about 80 mm. Loose sand can be obtained by pouring and dense sand by tamping. A steel plate of 7648 g is placed on the top of the sand surface. The total weight on the geomembrane is about 8093 g. By varying the acceleration in the centrifuge, the shear strength of interface can be investigated in a wide range of stress level from 10 to about 300 kPa.

After finishing the specimen preparation, the tilt table is placed into the platform of the centrifuge. The base platen is mounted onto the platform by screws. The centrifuge is put into operation and an input of rotation speed is made at the control panel. The revolution per minute can be read off the digital display. After the specified rotation speed is reached, the first readings are made, which serve as the reference. By switching on the stepper motor M2 the trough is raised at the speed of about 1°/min. With increasing inclination, the shear strength at the interface is gradually mobilised, which is characterised by an increase in displacement, in force exerted by the shear box and in force in the geomembrane. After the shear stress (the friction angle) reaches a certain level, e.g. 20°, the stepper motor of the spindle lift is stopped and the shear box and the load cell are translated down slope by a displacement increment of 1–2 mm. In general, a displacement increment down the slope will reduce the shear force in W2 to some extent. After the relaxation, the shear box is again held back. The trough is raised by switching on the stepper motor of the spindle lift. The increase in inclination gives rise to further mobilisation of the shear force in the regime before peak. In the post peak regime, however, further tilting does not lead to further increase in shear force. A tilt table test in centrifuge consists of a number of sequences of mobilisation and relaxation. In this way, the post peak behaviour can be investigated incrementally.

A HDPE geomembrane with a thickness of 2.5 mm is used in our investigation. The surface of the geomembrane is structured with an asperity of about 0.4 mm (Fig. 4). The short and long axes of the ellipses are 5 and 14 mm, respectively. The tensile strength of the geomembrane is about 18 MPa and the corresponding strain about 16%.

The tested soil is coarse sand with the properties given in Table 1. Sand with similar properties is often used as drainage material in practice. The sand consists mainly of quartz and has subrounded grains. As can be seen from Table 2, the extremely low uniformity coefficient indicates that the sand grains are uniform with small size variations.

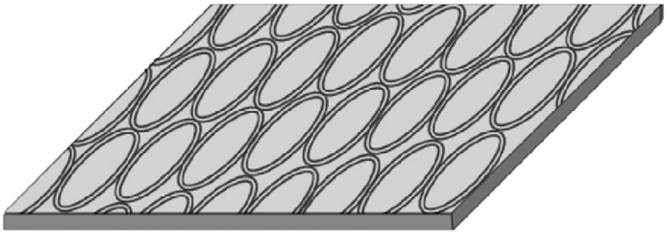

Fig. 4. HDPE geomembrane with elliptical surface structure.

Table 2
Physical properties of sand

Specific gravity γ_s (g/cm^3)	2.64
Minimum void ratio $e_{\min}$	0.54
Maximum void ratio $e_{\max}$	0.78
Mean grain diameter d_{50} (mm)	0.95
Maximum grain diameter $d_{\max}$ (mm)	2.00
Uniformity coefficient: d_{60}/d_{10}	1.4
Curvature coefficient: $d_{30}/d_{60}/d_{10}$	1.0

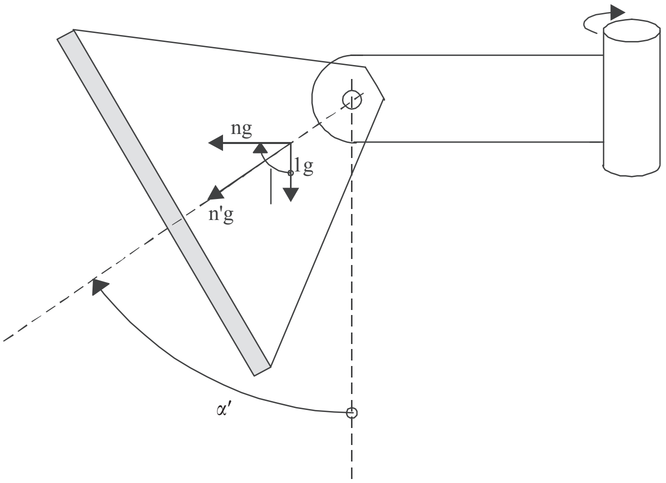

Fig. 5. Resultant acceleration from Earth gravity and radial acceleration.

5. Test evaluation

The tilt table device and the testing materials in the basket of the centrifuge rotating at the angular velocity of ω are subjected to an acceleration of

$$ng = \omega^2 r, \tag{1}$$

where n is the scale factor for the radial acceleration in centrifuge; g is the Earth acceleration; r is the radius from the model to the axis of rotation; ω is the angular velocity of centrifuge.

Note that the Earth acceleration is always present. Therefore, the radial acceleration ng must be combined with the downward Earth acceleration g to give the resultant acceleration (Fig. 5)

$$n'g = \sqrt{1+n^2}g, \tag{2}$$

where n' is the scale factor of the resultant acceleration. The resultant acceleration is assumed to be perpendicular to the platform, i.e. to the base platen of the tilt table device. The angle between the resultant acceleration and

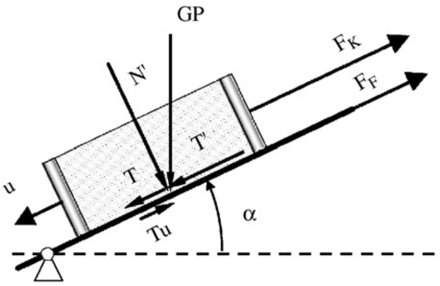

Fig. 6. Measured forces and forces acting on geomembrane.

the vertical can be easily shown to be

$$\tan \alpha' = n. \tag{3}$$

In the environment of the resultant acceleration $n'g$, the soil weight in the shear box is known to increase by the scale factor n, i.e.

$$G = n' G_{\mathrm{p}}, \tag{4}$$

where G_{p} is the soil weight in the 1-g environment; G is the weight of soil in a $n'g$ environment. Suppose that the trough is raised to an inclination of α, the normal and shear forces resulting from the soil can be written out as follows (Fig. 6):

$$N' = G \cos \alpha, \tag{5}$$

$$T' = G \sin \alpha. \tag{6}$$

Now we turn to the forces measured in the tilt table test and denote the traction exerted by the shear box by F_{K} and the traction in the geomembrane by F_{F}. Since the shear box is restrained by the relaxation mechanism, the traction force must be subtracted from the shear forces T' to give the shear force in the soil–geomembrane interface.

Note that the shear box itself is also subjected to the resultant acceleration $n'g$, which gives rise to increased self-weight and the corresponding shear force. This shear force due to the self-weight of the shear box must be subtracted from the measurement. In order to take this effect into consideration, a null test needs to be conducted by placing the shear box on the geomembrane without soil. The traction forces measured in such a null test are denoted by F_{KE}: traction force exerted by the shear box and F_{FE}: traction force in the geomembrane, respectively. The same acceleration shall be used for the test with soil and without soil (the null test). The measured forces are corrected by subtracting the forces in the null test to obtain

$$F'_{\mathrm{K}} = F_{\mathrm{K}} - F_{\mathrm{KE}}, \tag{7}$$

$$F'_{\mathrm{F}} = F_{\mathrm{F}} - F_{\mathrm{FE}}. \tag{8}$$

The normal stress in the interface is defined by

$$\sigma = N'/A_{\mathrm{K}}, \tag{9}$$

where A_{K} is the area of the shear box. Inserting (5) into the above expression, the relationship between the normal stress and the inclination can be obtained

$$\sigma = \frac{G}{A_{\mathrm{K}}} \cos \alpha. \tag{10}$$

The above equation shows that the normal stress decreases with the inclination. Note that the normal stress in direct shear tests remains unchanged. Therefore, comparison between tilt table tests and direct shear tests should be compared at the same stress level. The shear stress in the interface can be obtained by

$$\tau = T/A_{\mathrm{K}} \tag{11}$$

with

$$T = T' - F'_{\mathrm{K}}. \tag{12}$$

The mobilised friction angle is defined by

$$\tan \varphi' = T/N'. \tag{13}$$

With the help of the measured traction in the geomembrane, the tensile stress in the geomembrane can be defined as

$$z = F_{\mathrm{F}}/A_{\mathrm{K}}. \tag{14}$$

Furthermore, the shear stress between the geomembrane and the trough base can be obtained

$$\tau_{\mathrm{u}} = T_{\mathrm{u}}/A_{\mathrm{K}}, \tag{15}$$

where

$$T_{\mathrm{u}} = T - F'_{\mathrm{F}}. \tag{16}$$

The mobilised friction angle between the geomembrane and the trough base can be defined accordingly

$$\tan \varphi'_{\mathrm{u}} = T_{\mathrm{u}}/N'. \tag{17}$$

Note that an increase in trough inclination results in a reduction of the distance between the shear box and the rotation axis of the centrifuge. According to Eq. (1), this gives rise to smaller radial acceleration. This effect is taken into consideration in the evaluation.

A further issue is concerned with the Corioli effect in geotechnical centrifuge. The Corioli acceleration a_{c} is defined by $a_{\mathrm{c}} = 2\omega v$, where ω is the angular velocity and v is the velocity of the specimen relative to the rotation axis. The inertial acceleration a can be obtained from (1) $a = \omega^2 r$. Comparison between a and a_{c} shows that the Corioli effect can be neglected except for dynamic tests with high deformation velocities.

6. Experimental results

A series of six tests are carried out with the tilt table device in the centrifuge. The radial accelerations in these tests are 6g, 12g, 18g, 24g, 30g and 36g. The initial void ratio of sand in these tests is about 0.68.

A typical test under a radial acceleration of 24g is shown in Fig. 7. A short description of the test procedure, which is shown in Fig. 7c, is given below. Starting from $\alpha = 0°$, the trough is raised continuously until an inclination of about

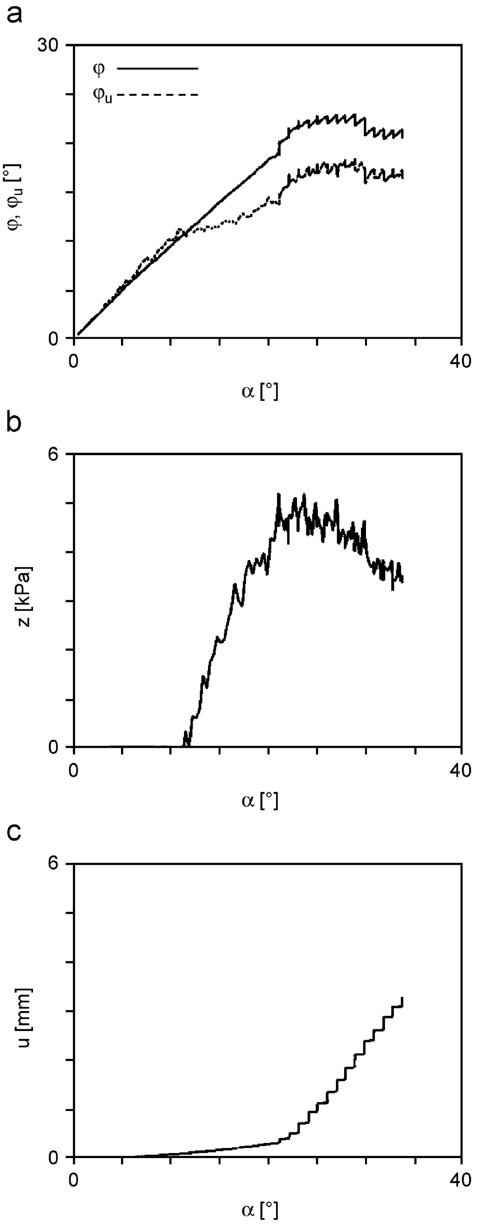

Fig. 7. Tilt table test on sand–geomembrane interface under 24*g*: (a) friction angle vs. inclination; (b) tensile stress in geomembrane vs. inclination; (c) displacement of shear box vs. inclination.

22°, where the trough is stopped and the first relaxation is started. Afterwards, the relaxation mechanism is locked and the trough is raised by $\Delta\alpha \approx 1°$. The test is continued by alternating between relaxation and mobilisation and terminated at $\alpha \approx 34°$. The displacement is about 0.3 mm at the first relaxation ($\alpha \approx 22°$) and about 3.2 mm at test end ($\alpha \approx 34°$).

For the geomembrane–sand interface, the following observations can be made from Fig. 7a (solid line). Starting from $\alpha = 0°$, the mobilised friction angle increases approximately linearly with the inclination until the first relaxation at $\alpha \approx 22°$. The first five relaxations till $\alpha \approx 25°$ lead to hardening response, which is characterised by increasing mobilised friction angle with the inclination. From $\alpha \approx 25°$ to $\alpha \approx 30°$, the mobilised friction angle remains nearly unchanged with a peak friction angle of about 22.5°. Beyond $\alpha \approx 30°$ the interface shows softening response, which is characterised by decreasing mobilised friction angle. The interface shows moderate softening behaviour with a residual friction angle of about 21.9°. Similar observations can also be made for the friction behaviour between the geomembrane and the underlying trough base (dotted line in Fig. 7a). As can be expected, the friction between the geomembrane and the underlying trough base is lower than in the geomembrane–sand interface.

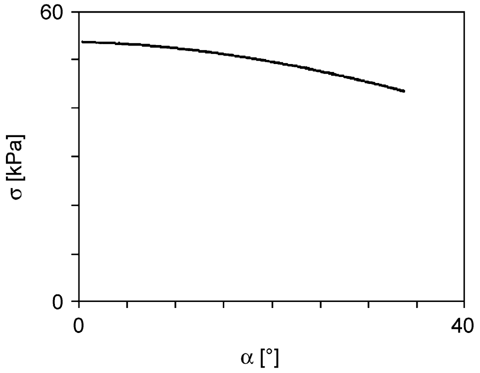

Fig. 8. Variation of normal stress with inclination in tilt table test under the acceleration of 24*g*.

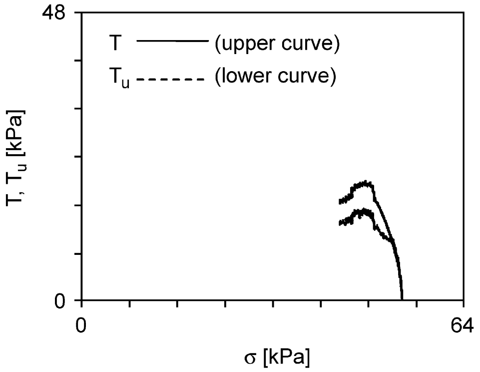

Fig. 9. Stress path in tilt table test under the acceleration of 24*g*.

The traction in geomembrane (Fig. 7b) corresponds well with the above observation. The hardening and softening regime in Fig. 7a is characterised by increasing and decreasing traction force in Fig. 7b respectively. A perusal of Fig. 7b reveals that the force in geomembrane is registered by the load cells for the first time at $\alpha \approx 12°$. Sandwiched between the trough base and the shear box, the geomembrane must first overcome the friction before the force can be transferred to the load cells W1 in Fig. 1.

As can be expected from (10), the normal stress decreases with the inclination. For the test in Fig. 7, the variation of normal stress is shown in Fig. 8. The normal stress decreases by about 10 kPa from about 54 kPa at test begin to about 44 kPa at test end. The stress path is shown in Fig. 9. It is interesting to observe that the stress path is

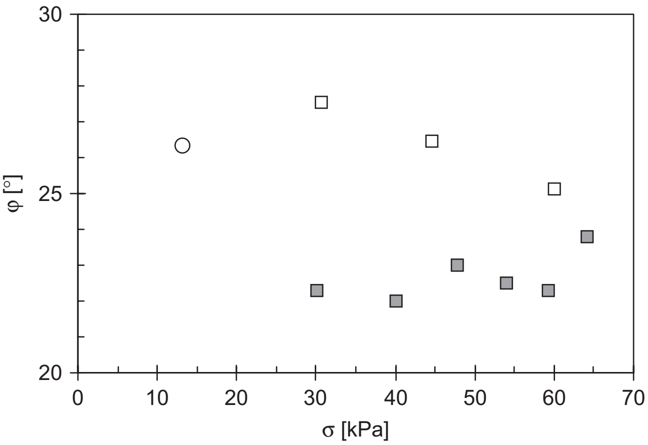

Fig. 10. Comparison between tilt table tests in centrifuge, tilt table tests and large direct shear tests in 1-*g* environment (peak friction angle): ■: friction angle from tilt table tests in centrifuge; □: friction angle from large direct shear tests; ○: tilt table test in 1-*g* environment.

similar to the effective stress path in an undrained triaxial test. The normal stress decreases monotonically, while the shear stress first increases to reach its maximum and then declines to approach the residual shear strength.

In order to compare the results from the centrifuge with other tests, the same materials are tested in 1-*g* environment in our laboratory. These tests include tilt table tests in a large tilt table with an area of 50 cm by 50 cm and direct shear tests in a large shear apparatus with an area of 50 cm × 50 cm. As mentioned before, the normal stress in tilt table tests need be corrected, when comparison with direct shear tests is made. The peak friction angle from tilt table tests (1-*g* and *n*-*g*) and direct shear tests are summarised in Fig. 10.

The following observations can be made from Fig. 10. The frictional angle from the tilt table tests in centrifuge does not show clear dependence on the stress level. The friction angle from the direct shear tests is found to increase with decreasing stress level. In general, the friction angle from direct shear tests is higher than from the tilt table tests in centrifuge. This experimental finding is well corroborated by some published 1-*g* data in the literature (Girard et al., 1990; Koutsourais et al., 1991; Izgin and Wasti, 1998). For our own tests, the difference of friction angle between these two tests is more pronounced for low stress level. The friction angle at $\sigma \approx 12$ kPa is about 27.5° for the direct shear test and about 22° for the tilt table test in the centrifuge. The friction angle from the 1-*g* tilt table test at an extremely low stress level of $\sigma \approx 12$ kPa is about 26.1°.

Note that the normal stress in direct shear tests remains unchanged; while the normal stress in tilt table tests decreases with the inclination (see Fig. 9). The normal stresses of the tilt table tests in Fig. 10 are calculated according to (10), i.e. the normal stresses at peak. Another difference between the two tests lies in the boundary conditions. Direct shear tests are displacement controlled, while tilt table tests are load controlled. These differences might be responsible for the higher friction angle from direct shear tests.

7. Conclusion

The behaviour of geosynthetic interface is investigated in a tilt table device in a geotechnical centrifuge for the first time. The tilt table device in centrifuge provides an alternative to the direct shear test for a wide rage of normal stress. By using radial acceleration up to about 40*g*, we are able to cover the range of normal stress from 10 to 100 kPa. The softening behaviour in the post peak regime is investigated by controlling the displacement of the shear box with a relaxation mechanism. The tilt table tests in the centrifuge are compared with the tilt table tests and the large direct shear tests in 1-*g* environment.

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