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Chadi S. El Mohtar[1] *and Milind V. Khire*[2]

Vertical Pullout Test for Measurement of Soil-Geomembrane Interface Friction Parameters

ABSTRACT: This paper presents a vertical pullout test (VPT) developed to measure the peak interface friction angle (δ) and adhesion (a) between soil and planar geosynthetic products. The key advantages of this test are (1) relatively low capital cost for the equipment, (2) relatively simple compared to the conventional methods, (3) the setup can be relatively easily adapted by small conventional soil testing laboratories, and (4) the setup can be transported to the field for field measurement for relatively quick preliminary evaluation of soils. The testing method was evaluated by comparing the δ and *a* obtained from the VPT to (1) those parameters measured using a conventional soil direct shear apparatus modified to also measure interface friction between planar geomembranes and soil according to ASTM D5321-02, and (2) values published in the literature. Three coarse-grained soils and three types of geomembranes having three sample sizes were evaluated using the pullout test. The peak interface parameters obtained from the VPT were within 12 % of the values obtained from the direct shear test.

KEYWORDS: geomembrane, interface friction, vertical pullout test, direct shear test

Nomenclature

a = Adhesion
c = Cohesion
δ = Angle of interface friction between soil and geosynthetic
ϕ = Angle of internal friction
τ = Shear stress
D_{10} = Soil particle diameter at 10 % passing
D_{30} = Soil particle diameter at 30 % passing
D_{50} = Soil particle diameter at 50 % passing
D_{60} = Soil particle diameter at 60 % passing
F_{VPP} = Peak vertical pullout force
K_o = Lateral earth pressure coefficient at rest
DST = Direct shear test
GCL = Geosynthetic clay liner
HDPES = High density polyethylene having smooth surface
HDPET = High density polyethylene having textured surface
LDPES = Low density polyethylene having smooth surface
SPT = Standard penetration test
USCS = Unified Soil Classification System
VPT = Vertical pullout test

Introduction

Due to wide applications of geosynthetics in everyday construction, measurement of the interface friction angle between geosynthetics and soils is quite common. Over the last two decades, many researchers have developed various techniques to measure the interface properties of planar geosynthetics. In this paper, a relatively simple new testing procedure, the vertical pullout test (VPT), was evaluated to provide preliminary estimates of the peak interface friction angle between planar geomembranes and granular soils. The test consists of pulling out a vertically embedded geomembrane from a soil. Because the results of VPT provide preliminary values, these values are useful in concept level design and need to be confirmed using controlled conventional tests for the final design. An analogy of Standard Penetration Test (SPT) may be appropriate. A SPT is a relatively basic test that provides preliminary values of relevant soil properties. A SPT test does not always provide very accurate values but the results are accurate enough to screen samples for further testing. In addition, data obtained from a SPT can be used as an input for preliminary design. The VPT test could be used for preliminary design or screening level analysis when two or more interfaces need to be tested and compared to make a selection of the most appropriate geosynthetic product.

Three types of geomembranes and three coarse-grained soils were tested using the VPT. The internal friction angle ϕ of the soils was determined using the conventional direct shear test (DST) and the interface friction angle δ was also measured using a conventional direct shear apparatus. The results from the conventional and the new tests were compared. In addition, interface friction values reported in the literature for the geomembranes tested were also compared to evaluate the relative accuracy of the VPT.

Background

The DST has been the method of choice (Martin et al. 1984; Koerner et al. 1986; Mitchell et al. 1990; Sharma and Hullings 1993) for measuring the interface friction parameters. Researches have used various setups for the DSTs. These setups vary from dimensions and boundary conditions to the load application. ASTM D5321-02 and ASTM D6243-06 provide guidelines for the stan-

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[1]Ph.D., Assistant Professor, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, Austin, TX 78712.
[2]Ph.D., Professional Engineer, Associate Professor, Dept. of Civil and Environmental Engineering, Michigan State Univ., E. Lansing, MI 48824 (corresponding author), e-mail: khire@egr.msu.edu

dard testing methods for measuring the coefficient of soil to geosynthetic or geosynthetic to geosynthetic internal and shear resistance using the DST. However, other tests have been developed and used to measure the interface friction angle. Selective tests are discussed as follows.

The rotational shear device has been used by Negussey et al. (1989), Fennick and Evans (1994), Stark and Poeppel (1994), and Evans and Fennick (1995). The key advantage of this test is that significant relative displacements can be developed without the reversal of shearing direction. Negussey et al. (1989) introduced a dual interface shear apparatus to evaluate the distribution and magnitude of friction between solid inextensible surfaces and granular materials. A model was introduced to evaluate the interface friction mechanism based on a micromechanical approach. Fennick and Evans' (1994) rotation shear device was modified so that a geosynthetic specimen can be attached to the upper platen. Interface friction angles and interface efficiencies for three geosynthetic products with two ash samples and Boston Blue Clay were reported and compared. Shear displacements of up to 300 mm were reported, showing that large displacements may accumulate in the rotational shear device without the need for directional reversal. A torsional-ring-shear apparatus and test procedure were introduced by Stark and Poeppel (1994) for measuring soil/geosynthetic and geosynthetic/geosynthetic interface angles. Double-composite liner system interface strengths were presented and the relevancy of ring-shear strengths was illustrated using the slope failure at the Kettleman Hills Waste Repository located in Kettleman City, California.

A circular arc test for soil geosynthetic interface strength has been developed by Ghiassian et al. (1997). The test is based on the variation of the tension in a circular arc mounted over a soil with static "dead" loading on both ends. This test is used to determine the residual strength of a fabric. The test method is simple and boundary conditions are well defined. The interface friction angle between dry Muskegon sand and three geosynthetic materials, a cotton fabric, a fiberglass mesh, and a nonwoven Geolon N35 filter, were presented.

The pullout shear machine used by Fox et al. (1997) is a large (406 mm by 1,067 mm) direct shear box. The geosynthetic clay liner (GCL) is mounted on a rigid plate to ensure uniform shear strain at failure. The maximum horizontal displacement was large enough (~200 mm) for measuring both peak and residual shear strengths. The performance of this direct shear machine was illustrated by testing unreinforced and reinforced geotextile-supported GCLs.

Dual interface friction apparatus for testing unrestricted friction of soil along solid surfaces was developed by Paikowsky et al. (1995). This test allows measurement of friction distribution along the interface and volume changes within the specimen. Standard and natural granular materials were sheared along controlled and random solid surface geometries. The test results indicated that the grain shape and the surface roughness, quantified with respect to the grain size, are the primary parameters controlling the interfacial shear strength at a given normal stress level.

ASTM D6706-01 describes the standard method for measuring geosynthetic pullout resistance in soil. The geosynthetic membrane is embedded horizontally between two layers of soil. A vertical normal load is applied on the top soil layer and the horizontal force required to pull the geosynthetic out of the soil is recorded. The box should be rectangular or square with minimum dimensions of 610 mm long, 460 mm wide, and 305 mm deep with minimized side-wall friction. The geosynthetic is pulled out at a constant displacement rate of 1 mm/min (or the maximum rate described in ASTM D3080-04 to allow for pore pressure dissipation).

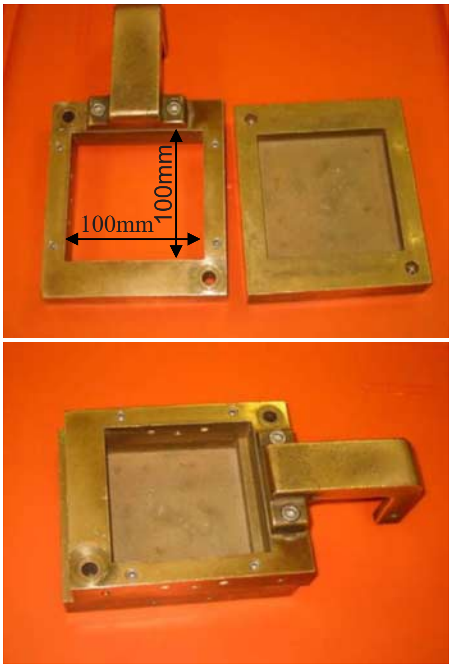

FIG. 1—*Conventional direct shear box setup for testing sand internal friction angle.*

Experimental Setup

This paper presents a test developed to measure the peak interface shear strength parameters for soil and planar geomembranes. To measure the peak interface friction angle, the internal friction angle of the soil is required. In this study, the accuracy of the new test was evaluated by independently measuring the interface friction parameters using conventional direct shear equipment.

Direct Shear Test

The original design of the direct shear equipment used consisted of two square split boxes made up of brass that allowed soil specimen having these dimensions: 100 mm long by 100 mm wide by 25 mm tall (Fig. 1). The normal stress is applied to the top of the specimen, the locking screws are then removed, and the specimen is sheared along a horizontal plane by moving the lower box.

To test the interface friction angle between geomembrane and soil, the bottom part of the direct shear box was replaced by a plate that can provide a rigid bed to support the geomembrane (Fig. 2). Two guiding pieces were used to assure correct alignment of the upper part with the horizontal shearing axis. Additionally, the guiding pieces were used to anchor the geomembrane to the bottom half. The dimensions of the geomembrane that could be tested in this setup are 100 mm by 100 mm. After the geomembrane was placed in position and anchored, the upper portion of the box was placed on top and locked in position using two screws. The soil is placed in the box and compacted to a desired density. The normal load is applied and the locking screws were removed before shearing began. Tests were carried out at four normal stresses to deter-

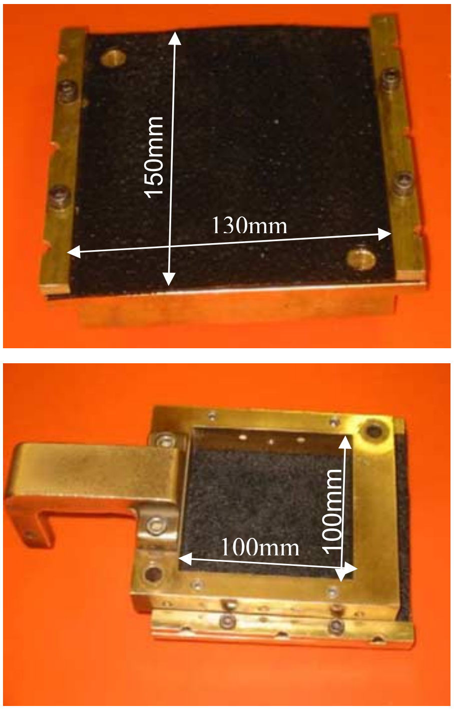

FIG. 2—*Direct shear box setup for testing sand-geomembrane interface friction angle.*

mine the interface friction angle. Figure 3 shows two geomembrane samples after they were tested using the direct shear box.

The dimensions of the shearing box used for this experiment were smaller than the minimum dimensions specified by the ASTM D6243-06 standard (300 mm). However, the dimensions of the soil sample were larger than the specified minimum dimensions based on particle size. ASTM specifies a minimum width of 15 times d_{35} of the coarser soil and a depth of 6 times the maximum particle size. Interface friction angles published in the literature were also used to verify the accuracy of the interface friction parameters.

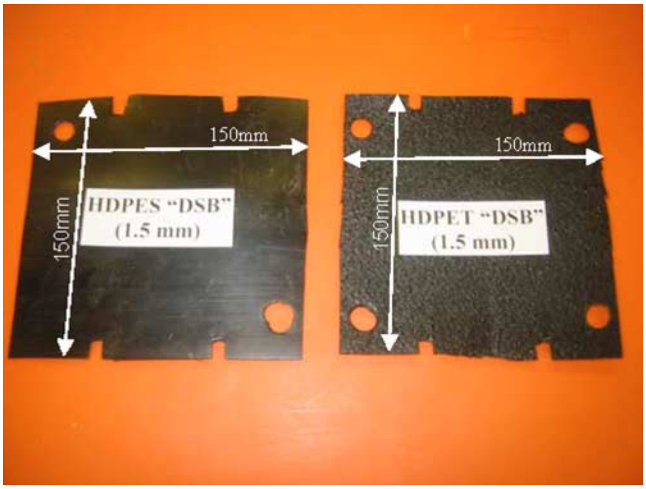

FIG. 3—*Geomembranes tested in the conventional direct shear box.*

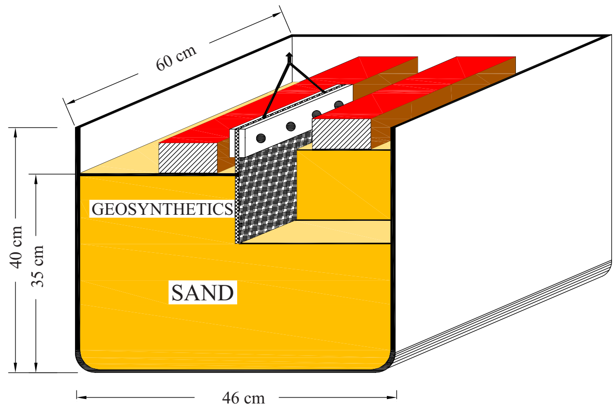

FIG. 4—*VPT setup.*

Vertical Pullout Test

The VPT consists of pulling out a vertically embedded geomembrane from the soil and measuring the maximum force or load required to mobilize the membrane-soil interface. Figure 4 shows a schematic of the setup used for the VPT.

Concept—In VPT, the lateral earth pressure applied by the soil on the two faces of a piece of geomembrane inserted vertically is utilized as the normal stress. To achieve greater normal stresses, surcharge load is symmetrically placed on both or all sides of the geomembrane (Fig. 4). The shearing force is applied by vertically pulling out the geomembrane to mobilize it. The peak value of the vertical pullout shearing force is recorded. Figure 5 shows the stresses used to analyze the test data.

The lateral earth pressures are determined by assuming at rest (K_o) conditions using the measured or estimated internal friction angle of the soil. For the tests performed in this study, the soils were dry. However, if water is present, the lateral earth pressures can be calculated using the effective stress. The lateral pressure/load acting on the geomembrane (the normal stress) is determined using Boussinesq's method. The shear strength parameters, the peak interface friction angle (δ) and adhesion (a) between the soil and the planar geosynthetic product, were determined by repeating the test for various surcharge loads and measuring the corresponding shear stresses by pulling out the geomembrane.

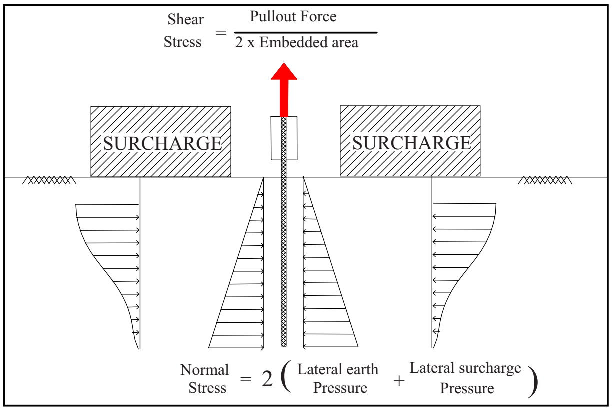

FIG. 5—*Lateral earth and surcharge stresses in a VPT.*

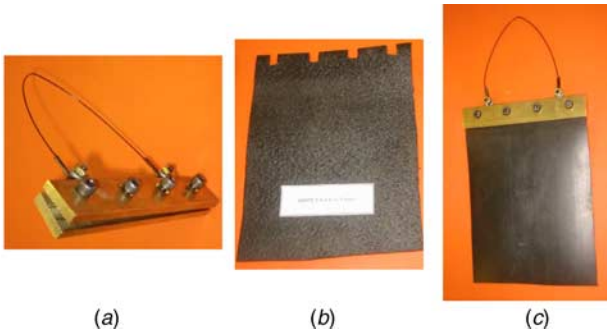

FIG. 6—*(a) Geomembrane clamp used in VPT, (b) textured, and (c) smooth geomembrane specimens tested in VPT.*

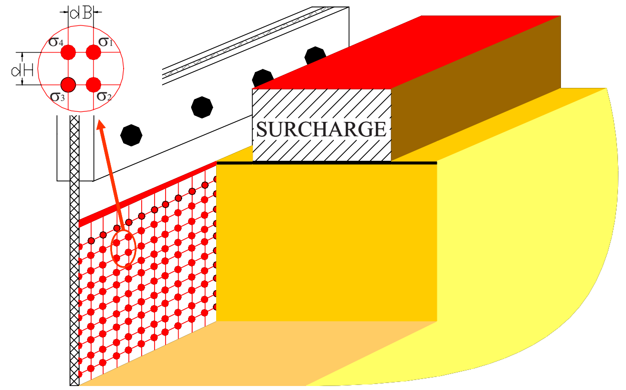

FIG. 8—*Calculation of normal stresses for VPT.*

Testing Procedure—A sample of the geomembrane is cut to the desired dimensions. Three sample sizes were tested: 75 mm by 150 mm, 150 mm by 150 mm, and 300 mm by 300 mm. The sample needs to have at least additional 5-cm height in the loading direction to allow mounting using the clamps (Fig. 6) and to allow clearance above the soil (Figs. 4). Figure 7 shows photographs of the VPT setup. The sample is placed in the clamp and held vertically inside the container. Soil is placed around the sides while maintaining a vertical alignment of the membrane. The sand is added until the desired embedded length is achieved. The soil can be compacted to achieve a target unit weight. The length of the geomembrane above the soil surface is measured to determine the exact embedded length. Surcharge load was added using bricks to achieve the desired normal stress. The clamp holding the geomembrane is hung using a digital load scale. The accuracy of the digital scale used in this study was 0.01 kg. The scale was also capable to "hold" the peak reading automatically. The scale was lifted vertically to pull out the geomembrane using a predetermined pace, such that the membrane was completely pulled out in about 120 s.

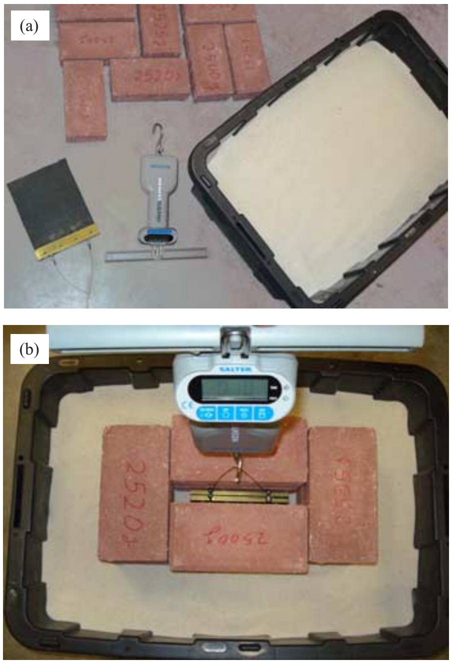

FIG. 7—*(a) Photographs of various components used for VPT setup and (b) the assembled VPT setup.*

The load reading on the scale (pullout force) increases until the interface friction is fully mobilized. The pullout force drops rapidly when the interface friction peaks and the membrane gets pulled out. The maximum load or force recorded by the digital scale is the peak pullout force. For greater normal stresses, additional surface surcharge was symmetrically applied (Fig. 7). The surcharge was placed about 1 cm from the geomembrane to prevent physical obstruction of the clamp.

Analysis—The normal stresses acting on the geomembrane during the VPT are determined by summing up the lateral earth pressure and the lateral surcharge pressure. The normal stresses on the geomembrane (horizontal) due to the soil and surface surcharge load are determined at a given point and the average normal stress over a finite area is calculated (Figs. 5 and 8).

$$\text{Average normal stress}(\sigma_i)_{\text{avg}} = \frac{\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4}{4} \tag{1}$$

where:

σ_1, σ_2, σ_3, and σ_4=normal stresses at location i on the embedded portion of the geomembrane (Fig. 8), and

$(\sigma_i)_{avg}$=average of the stresses at the location.

The normal force over the incremental area is determined and the values are integrated over the embedded area of one side of the geomembrane to determine the total normal force.

$$\text{Total normal force: } N = \sum (\sigma_i)_{\text{avg}} x(dHxdB) \tag{2}$$

where:

dH and dB=length and width of the grid block (Fig. 8) used to estimate the stresses on the geomembrane.

The normal stress is determined using Eq 3. The shear stress is calculated, as shown in Eq 4, by dividing the peak vertical pullout force by the embedded area of the geomembrane. These calculations are performed in a spreadsheet program.

$$\text{Normal stress: } \sigma = \frac{N}{B \times H_e} \tag{3}$$

$$\text{Shear stress: } \tau = \frac{F_{\text{VPP}}}{2 \times B \times H_e} \tag{4}$$

where:

F_{VPP}=peak vertical pullout force,

B=width of the geomembrane, and

TABLE 1—*Properties of soils tested*

Soil →	Coarse angular sand	Concrete sand	Ottawa sand
% passing sieve #4	100	98.691	100
% passing sieve #200	0	0.556	0.32
D_{10}	0.8	0.3	0.31
D_{30}	1.2	0.48	0.36
D_{50}	1.5	0.78	0.43
D_{60}	1.7	1.05	0.46
Coefficient of uniformity	2.13	3.50	1.48
Coefficient of curvature	1.06	0.73	0.91
USCS Classification	SP	SP	SP

TABLE 2—*DST results*

Geosynthetic type →	Sand	HDPET	HDPES	LDPES
	Coarse angular sand			
ϕ or δ(°)	33.8[a]	31.5	21.4	⋯
c or a (kPa)=	10.5	6.9	1.3	⋯
R^2=	0.986	0.996	1.000	⋯
	Concrete sand			
ϕ or δ(°)	38.3[a]	31.3	21.3	⋯
c or a (kPa)=	9.5	9.2	5.1	⋯
R^2=	1.00	0.99	0.99	⋯
	Ottawa sand			
ϕ or δ(°)	29.8[a]	30.2	18.7	20.4
c or a (kPa)=	8.7	7.0	1.4	4.7
R^2=	0.98	0.99	0.99	0.99

[a]Internal friction angle of the sand.

H_e=embedded height (or length) of the geomembrane.

The shear stresses for various values of normal stresses calculated from Eqs 3 and 4 are plotted to estimate the interface friction angle and the adhesion of the interface.

Materials

Soils

Three coarse-grained soils were used in this study: coarse angular sand (driller's sand), concrete sand, and Ottawa sand. Table 1 summarizes the gradation properties and classification using the United Soil Classification System. For this study, all tests were performed at relative densities between 50 % and 65 %.

Geomembranes

Three types of geomembranes were tested with the three sands. The geomembranes included high density polyethylene having smooth surface (HDPES), high density polyethylene with textured surface (HDPET), and low density polyethylene having smooth surface (LDPES). All geomembrane specimens used in the study were 1.5 mm thick. Three sizes of the geomembranes were tested: 75 mm by 150 mm, 150 mm by 150 mm, and 300 mm by 300 mm. These dimensions refer to the embedded area.

Results

Direct Shear Test

The DST was used to determine the internal friction angle of the soils used in this study and also to determine the interface shear strength properties of the geomembranes. Figure 9 shows the results obtained from the DST for Ottawa sand. The shear strength parameters were determined by performing the test at four normal stresses. Triplicate tests were carried out to determine the shear strength parameters for Ottawa sand as well as for the sand-HDPES and sand-HDPET interfaces. Single tests were performed for the sand-LDPES strength parameters. The internal friction angle of the sand-HDPET interface was closer to the internal friction angle of the sand, whereas the sand-HDPES and sand-LDPES had lower interface friction angles. The interface friction parameters and the friction angles of the three sands measured using the direct shear setup are summarized in Table 2.

Concrete sand had the highest internal friction angle (38.3°), whereas Ottawa sand had the lowest friction angle (29.8°). The interface friction angles for Ottawa and coarse angular sand with HDPET were close to the internal friction angles of the corresponding sand while with HDPES, the interface friction angle dropped to approximately 63 % of the internal friction angle of the corresponding sand. For the concrete sand, the difference between the internal friction angle and the interface friction angle was more for both HDPES and HDPET. The LDPES specimen was tested with Ottawa sand only and had an interface angle slightly higher than that of the HDPES. This can be attributed to more sand-polyethylene interlocking due to the softer texture of the geomembrane.

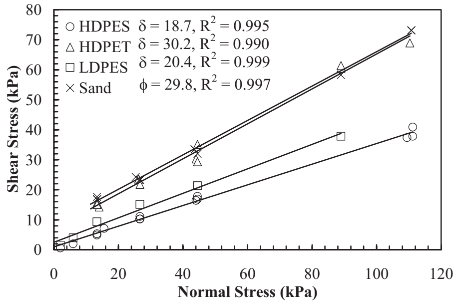

FIG. 9—*DST results for Ottawa sand.*

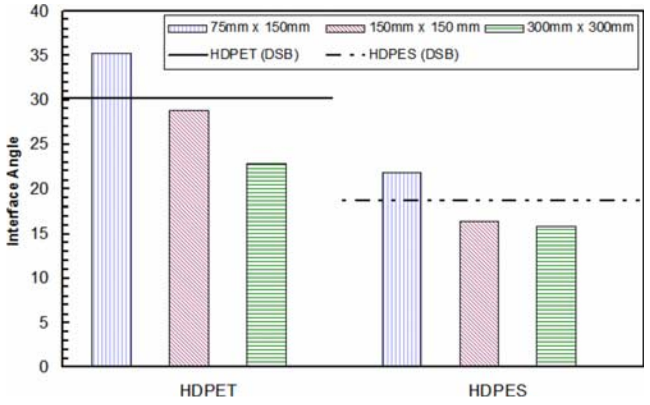

FIG. 10—*Effect of geomembrane size on measured interface friction angle.*

TABLE 3—*Comparison of interface friction angles measured by VPT, DST, and reported in literature*

Sand →	Coarse angular sand		Concrete sand		Ottawa sand		
Geosynthetic type	HDPES	HDPET	HDPES	HDPET	HDPES	HDPET	LDPES
VPT[a]	19°	31.6°	21.3°	30.2°	16.5°	28.8°	19.3°
DST[b]	21.4°	31.5°	21.3°	31.3°	18.7°	30.2°	20.4°
% difference	11.2 %	0.2 %	0.14 %	3.7 %	12 %	4.8 %	5.8 %
Koerner (2005)	⋯	⋯	18°	30°	18°	26°	⋯
% difference	⋯	⋯	18.2 %	0.5 %	8.5 %	10.6 %	⋯

[a]VPT friction angles are plotted in Figs. 11–14.

[b]DST friction angles are plotted in Figs. 9 and 14.

Vertical Pullout Test

The first step in the evaluation of the VPT was to determine the geomembrane size that would give representative and consistent interface strength parameters. Hence, three sizes (75 mm by 150 mm, 150 mm by 150 mm, and 300 mm by 300 mm) of HDPET and HDPES geomembranes were tested with Ottawa sand and the results are presented in Fig. 10. The measured interface friction angle decreased as the size of the geomembrane embedded in the soil decreased. The interface strength parameters measured using the 150 mm by 150 mm specimen agreed most closely with the DST results. The effect of sample size on the estimated interface properties is a function of the geometry of the setup and the size of the container used for containing the sand and the surcharge load. For the dimensions of the setup used in this study, 150 mm by 150 mm geomembrane sample size was most representative.

Hence, 150 mm by 150 mm specimens were used in all tests carried out in the experimental program. Table 3 summarizes all VPTs performed in this study. Figures 11–13 summarize the results obtained from the pullout tests performed on the coarse angular sand, concrete sand, and Ottawa sand, respectively. For each geomembrane-soil combination, three tests were performed for each normal stress value and six normal stress values were tested to ensure reproducibility. The lowest stress level did not include any surcharge; lateral earth pressure was the only normal stress applied on the geomembrane.

Figure 12 shows the results obtained for the concrete sand. The measured interface friction angle for the HDPES specimen (21.3°) is 71 % of that for the HDPET. The DST resulted in HDPES interface angle equal to 68 % of the HDPET angle. LDPES, HDPES, and HDPET specimens were tested with Ottawa sand using the VPT (Fig. 13). The interface friction angles using VPT were similar for LDPES and HDPES geomembranes had, whereas the LDPES had greater friction angle when DST was used. It is because of relatively low normal stress levels applied in the VPT, thus reducing the effect of the softness of the geomembrane on the strength properties. Because the normal stresses in a DST are relatively high, the sand particles tightly grip the surface of the softer geomembrane (LDPES), thus resulting in a greater friction angle. All measured adhesion values (a) from the VPT tests were negligible (<0.5 kPa) (Figs. 11–13). It is because all soils used in this study were cohesionless sands.

Table 3 summarizes the results from the DSTs and the VPTs. Table 3 also shows a comparison of the measured interface angles and typical values reported by Koerner (2005). Figure 14 presents the interface friction data plotted on a log scale for Ottawa sand

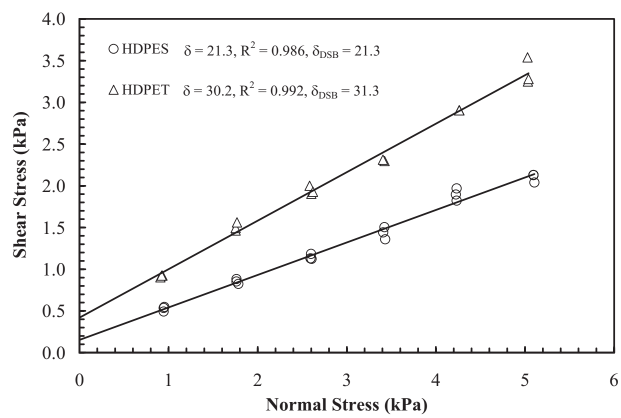

FIG. 12—*VPT results for concrete sand.*

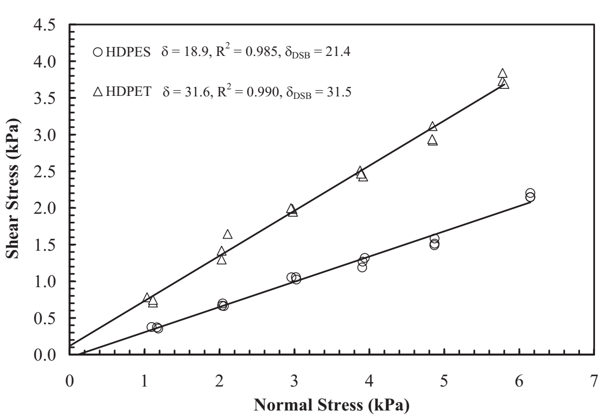

FIG. 11—*VPT results for coarse angular sand.*

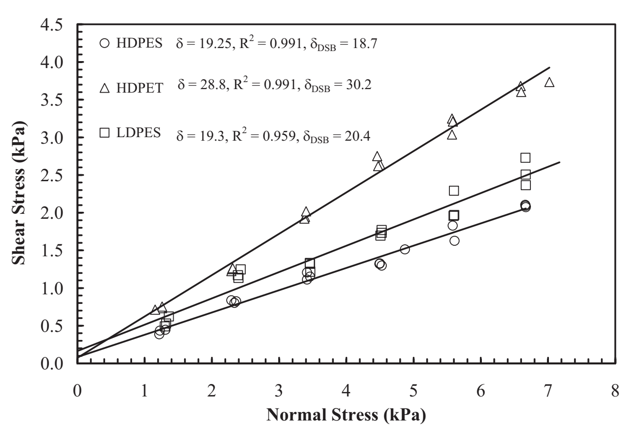

FIG. 13—*VPT results for Ottawa sand.*

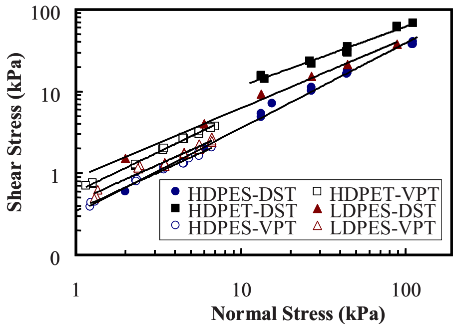

FIG. 14—*Results from VPT and DST for Ottawa sand.*

using VPT and DST. The graph shows that the normal stresses applied to the geomembrane during the VPTs were an order of magnitude lower than the stresses applied during the DSTs. Hence, the interface properties measured are more appropriate where the vertical stress levels are relatively small or where preliminary values are adequate.

The VPT results were relatively close to those obtained from the conventional DSTs and the maximum difference in the friction angles ranged from 0.2 % to 12 %. The results for VPT were closer to the DST values for textured surface than for smooth surface. With textured surface, the interface friction is higher mainly due to interlocking of soil particles with the textured surface whereas with smooth surface, the interface strength is achieved due to the friction between the soil particles and the surface of the membrane. The VPT test tends to underestimate the interface angle between soils and smooth surfaces because of the relatively low normal stresses applied during the test, which might not be high enough to allow for full friction mobilization. Results for HDPES and HDPET reported by Koerner (2005) for similar sandy soils are presented in Table 3 as a reference. The VPT results were within 20 % of the values reported by Koerner (2005). The difference is because the interface friction angle is specific to the geomembrane and the soils used. The concrete sand reported by Koerner (2005) had a lower internal friction angle, 33° as compared to 38° for the concrete sand used in this study. This could result in greater difference in the results for concrete sand as compared to the standard Ottawa sand.

Summary and Conclusions

A vertical pullout test (VPT) was developed to estimate the interface friction parameters for the interface between planar geomembranes and coarse-grained soils at relatively low normal stresses. The test apparatus uses relatively inexpensive components. The results obtained from the VPT were within 12 % of the DST results for smooth HDPE geomembrane and within 5 % for textured HDPE geomembrane. For smooth LDPE geomembrane, the results from the VPTs were within 6 % of the DST results. The measured parameters were within 20 % of the values reported by Koerner (2005) for similar geomembranes and soils. Based on these results, VPT can be used for measurement of interface friction parameters. These values need to be verified using appropriate conventional methods before the design is implemented in the field.

Acknowledgments

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