ASSESSMENT OF SANDBAG DIKE INTERFACE SHEAR USING TWO DIRECT SHEAR DEVICES

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ABSTRACT
This paper describes large-scale and small-scale direct shear tests on soil-geosynthetic, grass-geosynthetic, and geosynthetic-geosynthetic interfaces representing material interfaces that exist in sandbag dikes. Both woven geotextiles (woven slit film polypropylene) and polyethylene sheet were tested in combination with a cohesionless soil and typical grass sod. The large-scale shear apparatus used has a 1.0m^2 interface area, which minimizes edge effects on the interaction between the surfaces being tested. Small-scale direct shear tests using a typical direct shear apparatus (62mm x 62mm box) have also been conducted to compare with the large-scale results. The results are summarized using interpreted Mohr-Coulomb failure parameters to quantify the cohesive and frictional characteristics for each interface. The importance of the results with respect to understanding the behaviour of sandbag dikes under typical hydraulic operating conditions is also presented.

RÉSUMÉ
Ce rapport décrit des tests directs à grande échelle et à (small-scale) fait sur des interfaces du sol-géosynthétique, du gazon-géosynthétique et du géosynthétique-géosynthétique qui représentent des interfaces essentielles qui existent dans des digues renforcer avec des sacs de sable. Tous les deux, les géosynthétiques tissés (une couche de fente de polypropylene) et une feuille de polyéthylène ont été testés, ainsi que des sols sans cohésion et des mottes de gazon typiques. L'appareil de tonte utiliser consiste d'une aire de 1,0m2, ce qui minimize les effets du bord des interactions entre les surfaces testées. Les tests directs à (small-scale) qui utilisent un appareil pour arracher typique (une boîte de 62 mm par 62 mm) ont été comparé avec les résultats à grande échelle. Pour quantifier les caractéristiques cohésives et de friction pour chaque interface, les résultats sont résumées en utilisant les paramètres d'échec interprêter par Mohr-Coulomb. Il y a aussi la présentation qui démontre l'importance des résultats en ce qui concerne la compréhension du comportement des digues de sacs de sable sous des conditions typiques de l'opération hydraulique.

1. INTRODUCTION

As the rising Red River became a flooding threat in the spring of 1997, the City of Winnipeg initiated emergency response measures to ensure adequate safety against flooding for the citizens of Winnipeg and their property. As part of the flood protection effort, thousands of volunteers assisted with the construction of sandbag dikes. It is estimated that 150,000 volunteer days of work contributed to the flood fighting efforts in the form of construction of sandbag dike protection.

The City of Winnipeg Water and Waste Department and Public Works Department ensured adequate materials and resources were available for construction of the secondary sandbag dikes. City crews and volunteers filled over eight million sandbags in total. The rapidly-built dikes performed with varying levels of success. A plan for around the clock inspection of all permanent and temporary dikes was implemented to identify any problem areas prior to failure. Before the river crested, 33 two-person teams patrolled and monitored dikes on a 24-hour basis. The monitoring teams were supported by on call survey crews, geotechnical engineers, and military personnel to respond to any dike concerns.

The secondary dikes provided an integral component of the flood fighting infrastructure during the 1997 flood and in many past floods. Experience gained during the 1997 flood demonstrated that there are considerable uncertainties surrounding their construction and behaviour when the structures are built to heights exceeding two meters. In many cases dikes as high as three and one half to four meters were required to provide adequate freeboard at selected locations. The flood of 1997 led to higher predicted flood protection levels for the City of Winnipeg. It also increased awareness that higher primary and secondary dikes will be required in the future should a comparable or larger flood occur. It is recognized that sandbag dikes are not a permanent protection measure. While permanent facilities are being funded and constructed at various locations throughout the City under the Canada-Manitoba-City of Winnipeg Secondary Diking Enhancements Agreement, sandbag dikes will continue to be an integral part of flood protection for all sites outside the Primary Diking System in the City of Winnipeg.

Any improvements in understanding the behaviour of these structures to better define construction procedures and height restrictions will benefit the City and its citizens in future flood fighting efforts.

The University of Manitoba is now undertaking a study to examine the behaviour of sandbag dikes to help provide further physical information regarding their behaviour and performance to benefit the citizens of Manitoba. The study involves a laboratory testing component where the material interfaces in sandbag dikes are characterized using in-isolation testing, a field component where six instrumented full-scale dikes will be constructed and loaded to failure, and finally a modeling component where the physics of the measured behaviour will be formulated using an analytical approach that will allow designers to evaluate new construction and design methodologies. One final objective is to define height restrictions on the use of the existing City of Winnipeg template for constructing sandbag dikes (Figure 1) where none currently exists. This paper focuses on the results of the laboratory testing of the material interfaces using two direct shear devices.

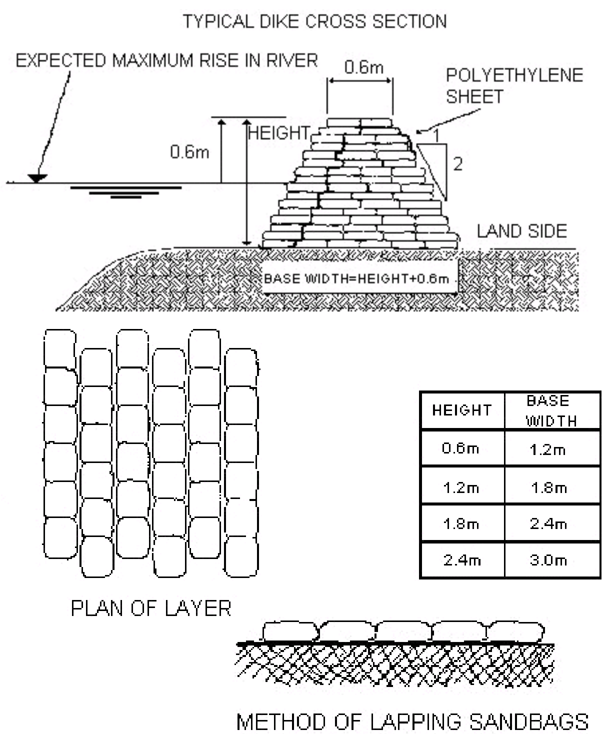

Figure 1. Construction guideline for sandbag dikes (after City of Winnipeg http://www.winnipeg.ca/interhom/aboutwinnipeg/historyofwinnipeg/flood/flood_dike_construction.stm)

2. LABORATORY TESTING PROGRAM

The laboratory testing included large-scale and small-scale direct shear testing on eight interfaces representing the interfaces found in sandbag dikes. The interfaces included polyethylene sheet / polyethylene sheet, polyethylene sheet / woven slit film polypropylene (sandbag material), polyethylene sheet / grass sod, woven slit film polypropylene / woven slit film polypropylene, woven slit film polypropylene / grass sod, sand (without the bag) / woven slit film polypropylene, sandbags (actual size filled with sand) / turf grass sod, and sandbags / sandbags. The tests with the grass sod and the actual sandbags were not conducted with the small-scale direct shear apparatus due to the obvious size limitations. In all cases with the raw geosynthetic products or with the plastic sheet material, a square template was used to ensure 100% surface contact between the materials in each direct shear apparatus. The surface contact was achieved by attaching the materials to the surface of a wooden plate (template) matching the size of the direct shear box in both cases.

2.1 Large-Scale Tests

Large-scale direct shear tests were conducted at the laboratories of Bathurst Clarabut Geotechnical Testing (BCGT) in cooperation with the GeoEngineering Centre at Queen's-RMC and the University of Manitoba.

2.2 Equipment Calibration and Interface Location

The large-scale direct shear test apparatus used for the testing is a custom built apparatus that is equipped with a 1 m^3 shear box that can be separated into four equal sections of 250 cm in height, each with a plan view cross-sectional area of 1 m^2. The principal shear plane was located at the 500 cm mark, as shown in Figure 2.

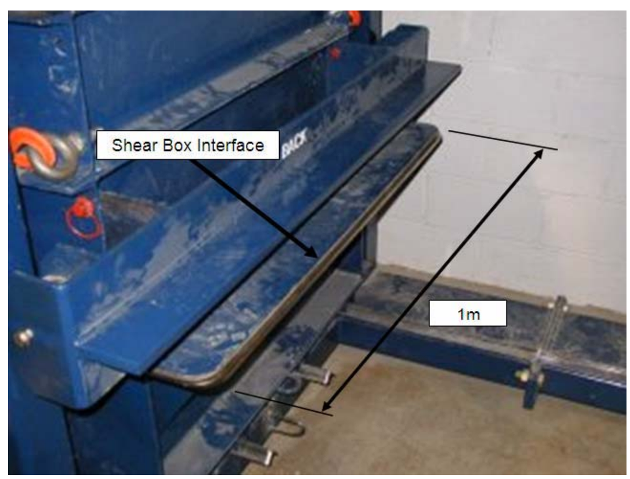

Figure 2. Photograph showing interface of large-scale direct shear device (1m^2 plan area)

The apparatus is mobile so that it can be transported and used on-site. The apparatus is linked to a custom data acquisition system to control and monitor the normal stress, horizontal loading, vertical displacement, and horizontal displacement. The horizontal load and stroke is provided by a 222 kN hydraulic actuator. Figure 3 is a photograph of the test apparatus at the BCGT laboratories.

Figure 3. Photograph of large-scale direct shear apparatus (1m^2 plan area)

One important component of the testing was to ensure that the interface plane being investigated by the apparatus was as close as possible to the enforced horizontal shear plane between the two box halves. As expected, the amount of vertical displacement for each interface varied as a function of normal stress applied. Sheet metal shims of a known thickness were used to adjust the height of the interface surface so that it matched the shear plane of the apparatus as closely as possible for each test.

Figure 4. Photograph of normal load platen for large-scale apparatus

Vertical displacement was recorded during the initial normal loading as well as throughout the duration of the shearing phase of the tests. Figure 4 is a photograph of the normal loading platen in the large scale direct shear apparatus immediately following placement in the direct shear box.

2.3 Interface Tests Between Geosynthetic Materials

In order to measure the interface frictional resistance of the geosynthetic materials in-isolation, templates were constructed using flat wooden plates cut to the size of the direct shear box to attach the geosynthetic products as previously discussed. Once the products were attached and installed into the direct shear box, the surfaces were assumed to be in direct contact. This method was used for tests on the materials to minimize irregularities with the interface contact area. The influence of contact area is discussed in a subsequent section where results of testing on sandbags are presented.

The tests performed on polyethylene sheet against polyethylene sheet, woven slit film polypropylene against woven slit film polypropylene and polyethylene sheet against woven slit film polypropylene gave interface frictional values within the expected range for these materials (Martin *et al*. 1984).

A typical set of stress-strain curves is shown in Figure 5 for the woven slit film polypropylene material. The three curves represent the stress-strain response of the selected material under three different normal loads. The stress-strain curves show an initial stiff response (arguably linear) until a peak shear resistance is reached. Once the peak is achieved, a sharp drop in the shear stress occurs followed by continued shearing at a constant to slightly increasing shear resistance with shear strain (depending on the normal stress level).

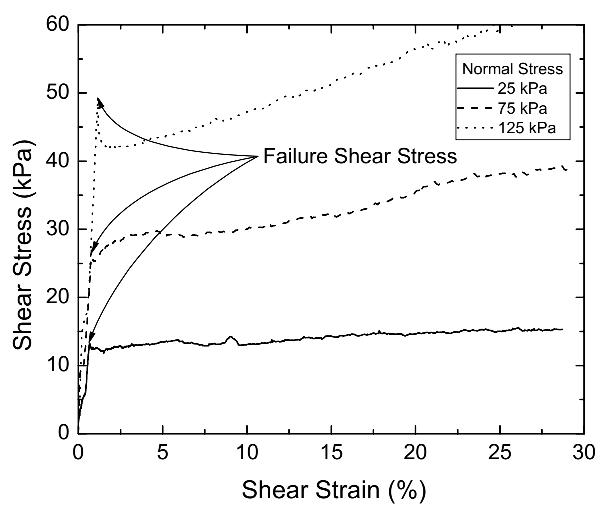

Figure 5. Shear-stress versus strain for slit film polypropylene / slit film polypropylene interface tests

The peak shear resistance is then interpreted from the curves and plotted as a function of normal stress to determine the Mohr-Coulomb frictional parameters. Figure 6 shows a typical linear regression through three peak points for the woven slit film polypropylene on woven slit film polypropylene.

2.4 Interface Tests Between Woven Slit Film Polypropylene and Cohesionless Soil

Tests were conducted to measure the Mohr-Coulomb parameters for the interface between sand and the woven slit film polypropylene. This test series was conducted to measure the shearing resistance of the sand in the sandbags with the sandbag material. This frictional resistance of the bags influenced the distortion under shear load due to internal slippage between the sand and the bag. Again a template was used to ensure full surface area contact in the apparatus. To minimize slippage of the sand with the loading cap, sand was glued to the wooden template to produce a rough frictional finish on the top surface (equal to that of the sand).

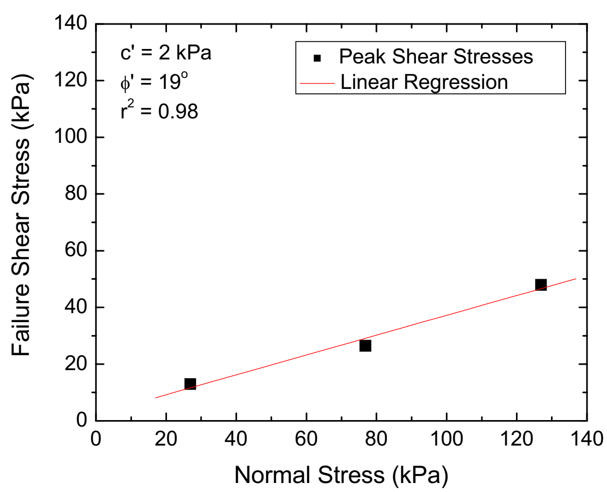

Figure 6. Selected failure shear-stress versus normal stress for slit film polypropylene / slit film polypropylene

2.5 Interface Tests Between Geosynthetics, Sod and Sand

One benefit of the large direct shear apparatus is the ability to test materials with large particle sizes. The final series of interface tests measured the interface friction angle of materials in their as-constructed condition. One aspect of the sandbag dike application is the manner in which the sandbags deform and interlock as loading is applied following placement. Another interface of considerable interest is the base sliding interface where the sandbags are placed on native grass. Although in many cases during the season when flooding occurs the ground can often be snow-covered and frozen, these conditions were not examined in this study.

The sandbags were filled to 60% of their volumetric capacity, which is approximately 23kg of sand. A pail was used with a hanging scale equipped with an electronic voltage resistance meter to ensure that each bag was filled with a roughly uniform amount of sand. Filling to 60% of volumetric capacity allows bag overlap of approximately 25% of bag length, or about 18cm on a 72cm long bag. The sandbag on sandbag interface shear strength was measured by placing full sandbags directly on top of one another using the design overlap pattern outlined in the City of Winnipeg construction guidelines (Figure 1). The contact angle and deformation of the bags influenced the interface friction angle as compared to the perfect condition using the wooden templates where the surface contact area was constant and also total normal stress was distributed more or less evenly. Figure 7 shows typical stress-strain curves for the sandbag to sandbag tests. Unlike the woven slit film polypropylene on woven slit film polypropylene in-isolation case, the stress-strain curves show a markedly non-linear shape with the highest normal stress case showing a distinct step at approximately 1% strain. The non-linearity and the strain-hardening behaviour noted are attributed to the interlocking of the bags, the dilation of the materials and the change in surface contact area as shearing progresses. Selection of a well-defined 'failure' shear stress was problematic and hence a strain criterion of 3% was used. It was felt that strains beyond 3% could potentially lead to large movements although other values could be justified.

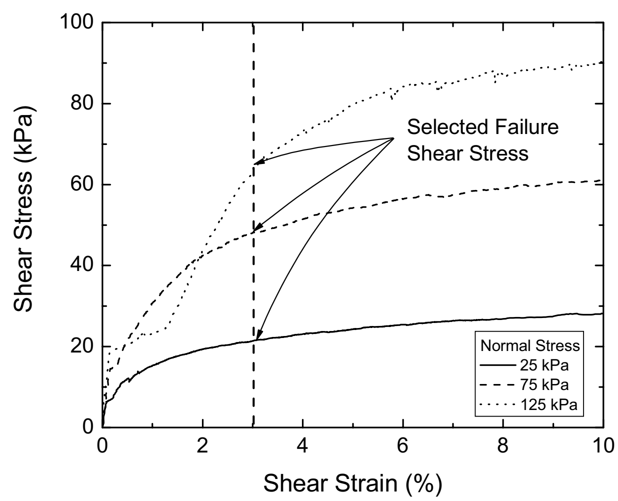

Figure 7. Shear-stress versus strain for sandbag / sandbag interface tests

Figure 8 shows the three selected shear stress values and the best-fit regression through the points to determine the Mohr-Coulomb failure parameters.

Figure 9 shows one square metre of sod placed in the shear box at the appropriate height to test with overlying sandbags at three different normal stresses (representing different dike heights). The direct shear testing conducted using the actual sandbags allowed the influence of varying contact area to be examined.

Figure 10 shows a partially disassembled test after shearing took place between the filled sandbags and the sod.

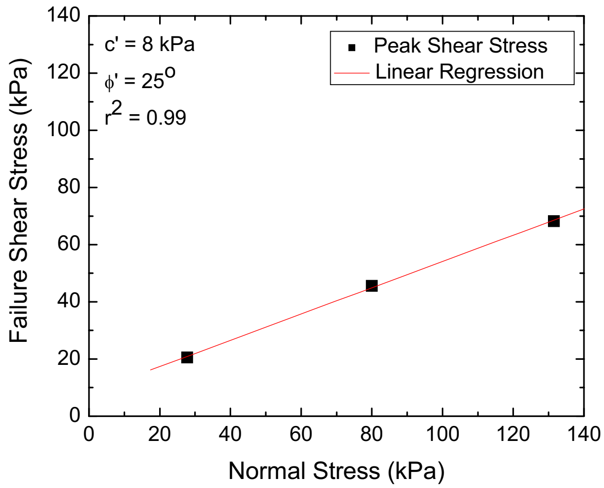

Figure 8. Selected failure shear-stress versus normal stress for sandbag / sandbag

Figure 9. Photograph of sod placed in large-scale ($1m^2$ plan view) direct shear box prior to testing

2.6 Small-Scale Direct Shear Tests on Geosynthetics and Cohesionless Soils

The small-scale direct shear apparatus used in this investigation is a conventional strain-controlled Wykeham-Farrance 2.2 kN system. A 62mm by 62mm square box was used for the tests which limited the testing to examine the in-isolation frictional properties of the geosynthetics and the sand material. The small-scale means that the actual sandbags and sod materials could not be measured and compared with the large-scale test results. The testing protocol and setup for the small-scale tests were designed to follow the protocol used in the large-scale direct shear tests. This was done to allow for ease of comparison between the large-scale and small-scale test results.

Figure 10. Photograph of sandbags / sod following testing in large-scale ($1m^2$ plan view) direct shear box

3. TEST RESULTS

As discussed previously, a minimum of three stress-strain curves for each interface at three different normal stress levels were measured directly. The Mohr-Coulomb frictional parameters were then interpreted by selecting peak values of shearing resistance or the value at selected strain levels where the peak shear resistance was at large strain levels (see Figure 7). Figure 11 shows the selected failure values for all the interfaces tested in the large-scale test apparatus. Figure 12 shows the corresponding results for the interfaces tested in the small-scale apparatus. In both cases the interpreted linear regression curves for each of the interfaces generally showed acceptable regression coefficients.

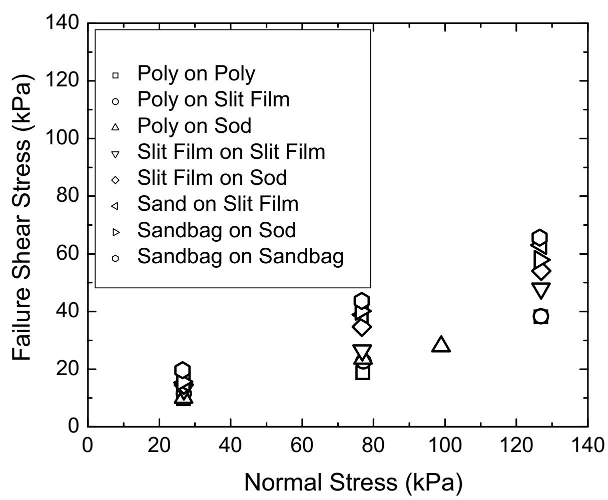

Figure 11. Selected failure shear-stress versus normal stress for all interfaces tested with the large-scale apparatus

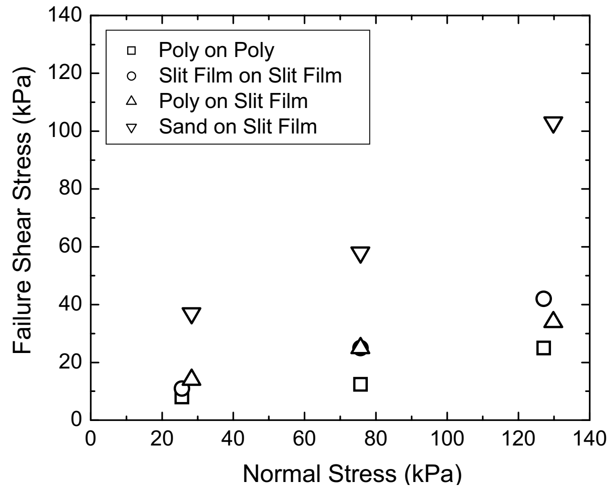

Figure 12. Selected failure shear stress versus normal stress for all interfaces tested with the small-scale apparatus

Table 1 is a summary of the Mohr-Coulomb frictional values interpreted from the large-scale and small-scale direct shear test results. N/A in the left column under the small scale tests represent cases where the materials could not be tested in the small-scale apparatus due to the size limitation of the equipment.

3.1 Discussion of Results

The results of the direct shear tests have provided valuable insights into the behaviour of the interfaces present in sandbag dikes used for flood protection. The tests provide frictional parameters for the interfaces in sandbag dikes that can be used for engineering analysis of these structures. In addition the tests using the large-scale and small-scale devices provides a useful comparison of the influence of size effects associated with testing synthetic products in direct shear.

Table 1. Summary of interpreted frictional parameters for interfaces tested with both direct shear devices.

Test Results				
Material Interface	Large-Scale		Small-Scale	
	c (kPa)	ϕ	c (kPa)	ϕ
PES[1] on PES	0	16^{o}	2	10^{o}
PES on WSFPP[2]	4	15^{o}	8	11^{o}
PES on Sod	4	14^{o}	N/A	N/A
WSFPP on WSFPP	2	19^{o}	6	20^{o}
WSFPP on Sod	4	22^{o}	N/A	N/A
Sand on WSFPP	2	26^{o}	15	33^{o}
Sandbag on Sod	6	23^{o}	N/A	N/A
Sandbag on Sandbag	8	25^{o}	N/A	N/A

[1] Polyethylene Sheet
[2] Woven Slit Film Polypropylene

The results for the polyethylene and woven slit film polypropylene materials using the wooden template gave the smallest values of friction angle and apparent cohesion. The use of the same materials in placed condition with sandbags on sod and sandbags on sandbags gave the highest friction angles which is likely due to interlocking effects and the higher normal stresses along the failure interface due to the reduced surface contact area. This is an important consideration for back analyzing failed sandbag dikes where peak frictional parameter values likely govern dike stability.

4. CONCLUSIONS

A series of direct shear test results have been reported for materials generally found in sandbag dike structures. The large-scale direct shear tests provided data for comparison of the influence of contact area and shape effects for sandbags as compared to the sandbag material in-isolation. The results showed that the distortion and contact area that occurs between sandbags in the dike application affects the frictional resistance notably.

The comparison of measurement between small-scale and large-scale test results showed similar results with some systematic differences. The most significant benefit of the large-scale direct shear device was the ability to test the sandbags themselves against one another and against the grass sod. The fact that the results of the sandbags / sandbags varied from the sandbag material (woven slit film polypropylene) / sandbag material (woven slit film polypropylene) indicates the importance of testing the materials in the as-constructed condition as anticipated. The value gained from being able to test the materials in the as-constructed condition is considered to be of considerable value since the results will be used to back analyze full-scale instrumented structures that will be built and loaded to failure in the summer of 2004 using conventional limit equilibrium methods.

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