Effects of temperature and moisture on large-scale interface shear testing of sandbag dikes

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ABSTRACT
This paper presents the results of large-scale interface direct shear testing between sandbags and the foundations which sandbag dikes are typically built upon in Manitoba under various temperature and moisture conditions. Tests were carried out at room temperature and at -5°C in the environmental chamber at the University of Manitoba. The foundation material used was sod (of a native Manitoba grass species) saturated in water, frozen or covered in snow. The interface test results are summarised using Mohr-Coulomb shear strength parameters. These results provide design parameters necessary for engineers to specify acceptable ground conditions upon which to construct sandbag dikes during floods. This insight into the strength characteristics of sandbag dikes will be used to better protect against future flood events.

RÉSUMÉ
Cette redaction present les resultats des tests de l'interface a grande echelle de cisaillement direct entre des sacs de sable et l'infrastructure typique qui support les digue construit des sacs de sable en Manitoba. Les tests ici considerent les conditions de temperature et mouillure typiques en Manitoba. Les tests on etes conduit a temperature ambiante et a -5°C dans un cadre environmental a l'University de Manitoba. Le gazon a ete utilize comme matiere de l'infrastructure (de specis trouvee en Manitoba) et a ete imbime en eau, congelee ou covert de neige. Les resultats de ces tests de l'interface sont en resume utilisant les parametres de cisaillement de Mohr-Coulomb. Les resultats donnent aussi les parametres d'ebauche que necessitent les ingenieurs pour determiner les conditions de terre pour la construction des diques de sacs de sable. Les apercus de cette recherche determine les caracteristiques de solidite et seront de valeur a mieux proteger contre les inondations a l'avenir.

1 INTRODUCTION

Sandbag dikes have served and will continue to serve an essential role in temporary flood protection in the City of Winnipeg. Winnipeg, located within the flood plain of the Red River in Manitoba, experiences some level of annual flooding. In 1997, the City experienced a 90-year flood, requiring the use of 8 million sandbags to protect private and public infrastructure. While the dikes constructed from these sandbags performed successfully for the most part, little was known about the technical behaviour of these structures. This flood event led to a research program at the University of Manitoba established to assess the baseline strength parameters and test the performance of sandbag structures. The results of this research by Krahn (2005) and the subsequent paper by Krahn (2007) examined the shear strength parameters of sandbags on sod (foundation material) using a large-scale direct shear apparatus. The results provided shear strength parameters which could be used to quantify shear behaviour along the interface with the dike foundation. One of the recommendations of this research program was the need for further research into the effects of spring flooding and frozen ground conditions on the sandbag/foundation interface. The focus of this paper is to present results of large-scale interface behaviour of sandbags on foundations with varying temperature and moisture conditions.

This paper assesses the interface strength properties of sandbag dikes under typical environmental conditions encountered during the period leading up to flood conditions in Winnipeg, Manitoba. The exact date of arrival of flood water varies in Winnipeg, however, they are commonly observed at the end of March to the beginning of April. In years where forecasted flood levels rise above the City's permanent dikes, as in 1997, construction of sandbag dikes begins before the arrival of the flood water. These dikes are often constructed on frozen ground or on frozen ground covered in snow. These are not preferred foundation conditions and all attempts are made to find the best conditions available but given high demand for construction equipment to build clay dikes, often sandbag dike foundation conditions are what is dictated by the existing ground cover. As the flood water rises, seepage under a dike can saturate the foundation material (commonly grass covered earthen slopes). As further rising of the flood water occurs, the moisture content of the bottom layer of sandbags will increase and the interface between the bags and the foundation material may become saturated. As time passes, and temperature increases, both the bags and the foundation material while still potentially saturated, will thaw providing the final state in which shear strengths may vary. These changing moisture and environmental conditions were modified during the testing to examine what effect they had on the shear strength parameters. The testing matrix shown in Table 1 outlines the various conditions tested.

Table 1 : Testing Matrix

Test Materials	Dry Sandbag	Wet Sandbag
Unfrozen - Dry Sod	X	
Frozen – Dry Sod with Snow	X	
Frozen - Dry Sod	X	
Frozen- Wet Sod	X	X
Unfrozen – Wet Sod		X

2 TESTING MATERIALS

2.1 Sandbags

The sandbags used were woven slit film polypropylene (WSFPP) bags similar to those used in Krahn (2005). All bags tested came from the same stock and were supplied directly by the City of Winnipeg. The sand used to fill the bags was taken from the same sand stockpile that the City of Winnipeg uses to fill their sandbags. The sand was classified as SP according to the Unified Soil Classification System and has D_{50} = 0.62, UC = 3.41 and CC = 1.02.

The in-situ moisture content of the sand in the sandbags varies depending on weather conditions at the time the bags are filled. During testing, the moisture content of the sand was estimated at the time of filling. Following each test, the moisture contents were confirmed by taking a bulk sample from the four bags. For 12 of the tests, where "dry sandbags" were used, the average moisture content was determined to be 2.8% with a standard deviation of 0.6%.

2.2 Sod Samples

The slopes along Winnipeg's riverbanks where the temporary dike construction corridors are located are covered in a variety of plants and grasses. Krahn (2005) selected Kentucky blue grass as the sod to be used in his testing because of its common presence in Manitoba. To provide consistency between the current study tests and those carried out by Krahn (2005), Kentucky blue grass was chosen as the sod variety. This consistency was important, as initial tests were selected to reproduce the results of previous work for use as baseline data.

3 TESTING PROCEDURES

3.1 General

Shear strength parameters were determined using a large-scale direct shear apparatus, similar to the apparatus used by Krahn (2005). Testing was carried out with filled sandbags on sod under varying moisture and temperature conditions in general accordance with ASTM D 5321. To control the temperature, tests were carried out within an environmental chamber.

3.2 Specimen Preparation

In order to test the variable moisture conditions, several different sod and sandbag specimens were prepared. The following three terms are used to describe the different sod and/or sandbag specimens: dry; dry with snow and saturated. 'Dry' conditions are defined as having a moisture content of the sod specimen that was typical of the sample lot upon delivery; the moisture content of the sandbags was that of the sand upon filling. Specimens referred to as 'saturated' were submerged under water for 24 hours prior to testing. Selection of 24 hours is consistent with ASTM 5321 for direct shear testing of geosynthetics in wet conditions. The last term, 'dry with snow" refers exclusively to the sod specimen preparation. This was meant to mimic the situation of sandbag dikes being constructed on snow. In this case snow was passed through a #4 sieve to produce an even layer of two inches above the entire sod specimen.

Each test was performed in either 'frozen' or 'unfrozen' conditions. The unfrozen tests were carried out at room temperature while the frozen tests were carried out at -5^{o}C in the environmental chamber at the University of Manitoba. The temperature of -5^{o}C was selected to represent the average ambient temperature experienced when flood waters typically arrive in Winnipeg. Average temperature for the months of March and April are -6.1^{o}C and 4.0^{o}C respectively (Environment Canada, 2007). All frozen specimens were placed in the environmental chamber for 24 hours prior to testing to ensure that the sod or sandbags had acclimatized to the selected test conditions.

3.2.1 Sod Specimen Preparation

The sod specimens were trimmed to fill the entire area of the lower box of the direct shear apparatus. The trimmed specimens ware attached to a sheet of 0.5 inch plywood using deck screws placed at a 100mm square grid pattern in accordance to Krahn (2005). The screws protruded 6mm providing resistance of the sod to horizontal movement during shearing.

3.2.2 Sandbag Specimen Preparation

The apparatus allows for four filled bags to be used during each test. The sandbags filled by the City's sandbag machine are variable in size and would not provide a consistent shear surface during testing. To provide an equal filled sandbag surface area to be in contact with the sod, the bags were hand filled. Each sandbag was filled to approximately 14.1kg. This weight was determined by filling four bags simultaneously and averaging the weight of the bags that provided the tightest fit within the template in the upper box.

3.3 Direct Shear Apparatus

The large-scale direct shear box used is one of two, 1.2mx0.6mx0.5m direct shear machines located at the University of Manitoba geotechnical laboratory in Winnipeg, Manitoba. The direct shear apparatus is comprised of a lower stationary box and an upper box which is free to slide along a set of linear guide bearings that connect the two halves. The upper box is loaded horizontally using a screw jack loading device with a capacity of 100kN. Normal loads are applied via a pressurized bladder with a capacity of 200 kPa. A built in pressure gauge, load cell and displacement transducer are used to measure applied normal loads, horizontal loads and horizontal displacements respectively. Pull wire extensometers and LVDT's are used to measure horizontal and vertical displacements within the sample. A built in jack aligns the test specimens within the lower box with the linear guide bearing (shear plane). To assist with assembly and disassembly, the machine is equipped with an overhead crane. A side view of the apparatus can be seen in Figure 1.

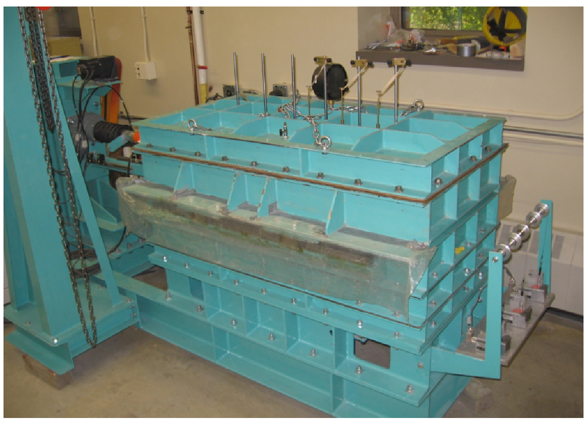

Figure 1: Large Scale Direct Shear Apparatus

Figure 2: Test Apparatus in Environmental Chamber

3.4 Environmental Chamber

The frozen tests were carried out in one of the environmental chambers at the University of Manitoba structures laboratory. The chambers are Conviron environmental rooms capable of providing temperatures of -40 to +40 degrees Celsius. For the purpose of this test the temperature was maintained at -5^{o}C.Figure 2 shows the directs shear machine within the environmental chamber.

3.5 Test Preparation

A standard test method was established to ensure consistency between tests. The method required that the direct shear machine be filled from the bottom up in the manner described herein and as shown in Figure 3. Firstly, a crib was constructed of 4 inch by 4 inch timbers and placed in the lower box of the direct shear machine. The crib was necessary because the sod samples, which were placed in the lower box, did not have sufficient depth to fit the lower box half and have the failure surface at the intended location. Above the timbers 0.5 inch sheets of plywood were placed. These sheets were used to ensure that the top of the sod sample would sit at the shear plane when placed in the box. While the machine is equipped with a jack for adjusting the contents of the lower box to be in line with the shear plane, this jack was not used during the tests. Since there was a potential for water leaking from the machine during our saturated tests and freezing on the floor of the cold chamber, a polypropylene liner was added to the lower box. The use of the jack to lift the samples into place had the potential to tear the liner. As such, this alternate technique to avoid tearing of the liner was established. The sod specimen was placed above the plywood. These specimens varied from test to test as described in section 3.2.1. To best mimic the effect of a dike sliding on its foundation, a 0.6m x 0.6 m template was inserted in the upper box of the apparatus. This template allowed the four filled sandbags to remain in full contact with the prepared sod below for the duration of the test. Sandbag specimens were placed inside the template and above the sod specimen. Again, these bags were filled as described in section 3.2.2 to make certain that a consistent surface area was in contact with the sod during each test. A flexible geotextile was used to separate the sand above from the sandbags below. The weight of the sandbags and sand was recorded and included in the normal load calculations for each test. Finally the bladder, used to apply the required normal load, was placed above the sand and the machine was sealed for testing.

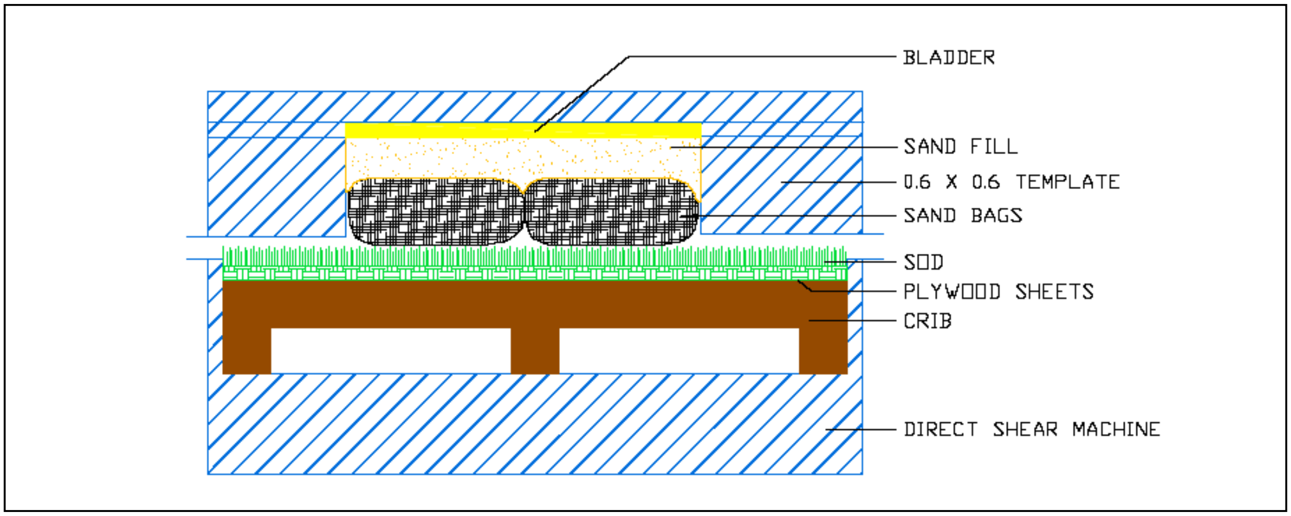

Figure 3: Cross Section of Direct Shear Apparatus

3.6 Normal Loads, Shear Displacement and Rate

The normal loads selected for this project are consistent with both those used in Krahn (2005) and the range of sandbag dike heights used in the 1997 flood. These heights range from 1.20m to 4.25m. Krahn (2005) used a saturated unit weight for sandbags of 20kN/m^3 providing a range from 24 to 85 kPa equivalent to the 1997 heights. The normal loads used in Krahn (2005) tests were 25, 75 and 125 kPa. Due to the nature of our testing method and our apparatus, the exact value of the normal load varied from test to test. The normal load resulting from the sandbags used in each test were higher for tests using wet sandbags and lower for tests using dry sandbags. In each case, the bags were weighed directly after the test and the measured weight was used in calculating the normal load. Further, by filling the upper box of the apparatus above the sandbags with sand fill, an additional normal load was applied to the sample. Again, following each test, this sand was removed from the upper box and weighed to be included in the normal load calculations. The resulting range of normal loads used during these tests was approximately 27.5, 77.5 and 127.5kPa.

A shear rate of 5mm/min was used to ensure that the excess porewater pressures were dissipated during our saturated tests. This shear rate was selected in general accordance with ASTM D 3080.

Horizontal displacement is measured via displacement transducer with a capacity of 50mm. Tests carried out by Krahn (2005) were measured to a displacement of 300mm. However, in his analysis, Krahn (2007) used operational peak strengths which were specified as those observed at 30mm of displacement. Movements beyond 30mm would likely result in a breach of the dike due to excessive leakage and structural distortions. Thus, test measurements of 50mm exceed the operational requirements set forth by Krahn (2007) and were sufficient in capturing specific failure conditions.

4 RESULTS

4.1 Correlation to Existing data

The first test was conducted to reproduce the results of Krahn (2005) for use as baseline data. For this test, dry sod and dry sandbags were tested and analysed according to Mohr-Coulomb strength behaviour. The tests are compared at operational peak values equalling 30mm of displacement. The values of cohesion (c') and friction angle (ϕ') from Krahn (2005) were 8 kPa and 22°,

Table 2: Shear Strength Properties

			Peak		Operational peak (@ 30mm)		End-of-Test (@50 mm)	
Test	Temperature	Test #'s	c'	ϕ'	c'	ϕ'	c'	ϕ'
Dry Sod & Dry Bags	Unfrozen	T1-T3	10	26	11	25	10	27
Wet Sod & Wet Bags	Unfrozen	T4-T6	0	28	0	28	1	27
Dry Sod & Dry Bags	Frozen	T7-T9	0	31	0	31	0	31
Dry Sod & Dry Bags	Frozen	T10-T12	1	32	1	31	3	31
Dry Bags & Sod with Snow	Frozen	T13-T15	3	20	3	20	3	19
Wet sod & Dry Bags	Frozen	T16-T18	0	32	2	30	2	31
Wet Sod & Wet Bags	Frozen	T19-T21	0	32	0	31	0	32

compared to values from the present study of 11 kPa and 25°. Overall, there is a strong correlation between the two sets of data.

4.2 Mohr-Colulomb Parameters

Mohr-Coulomb shear strength parameters were determined for each test. Shear strength was calculated at observed peak values, operational peak values occurring at 30 mm of lateral displacement, and end-of-test values occurring at 50 mm of lateral displacement. Table 2 shows the c and ϕ values for each test.

The trends observed within the varying interpretations of peak strength and end of test values are similar. For the purpose of this paper, comparison of the observed peak values only will be considered.

As discussed, four main testing conditions were carried out: dry; wet; frozen and unfrozen. These conditions were compared to examine their effects on the shear strength of the sod/sandbag interface. Figures 4-7 show the Mohr-Coulomb envelopes for data sets that experienced the same testing conditions.

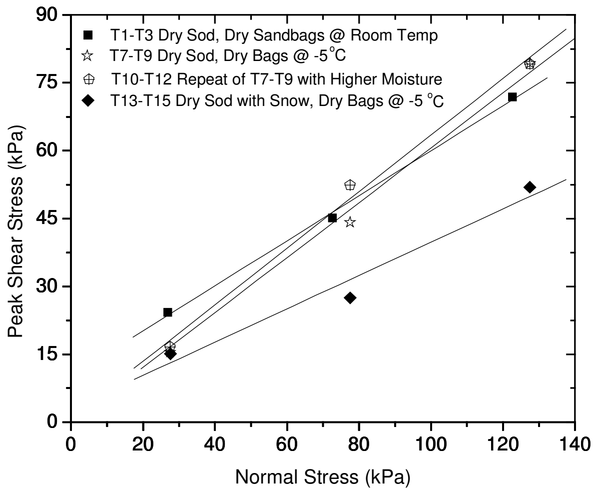

Figure 4: Dry Condition Failure Envelopes

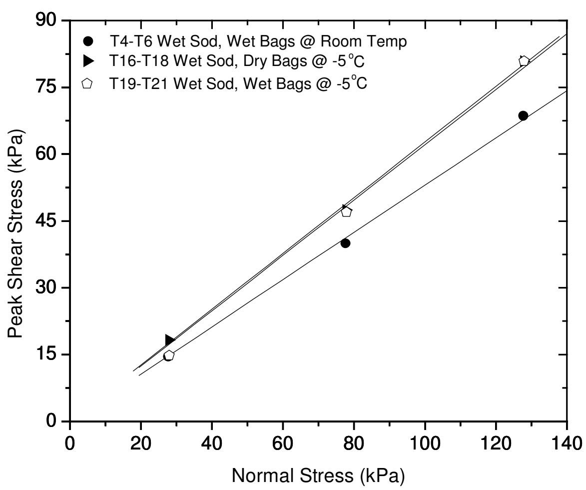

Figure 5: Wet Condition Failure Envelopes

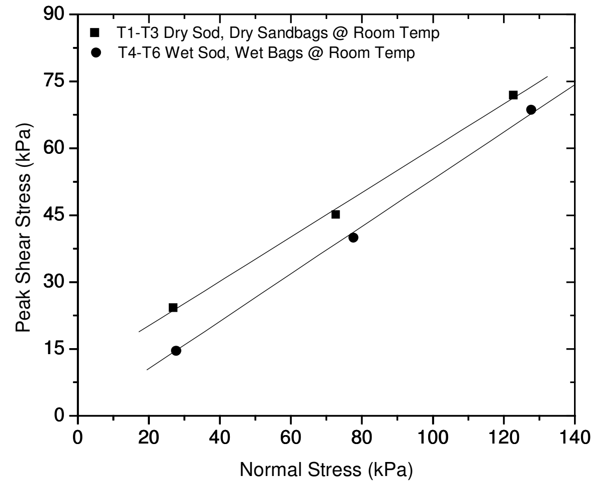

Figure 6: Unfrozen Condition Failure Envelopes

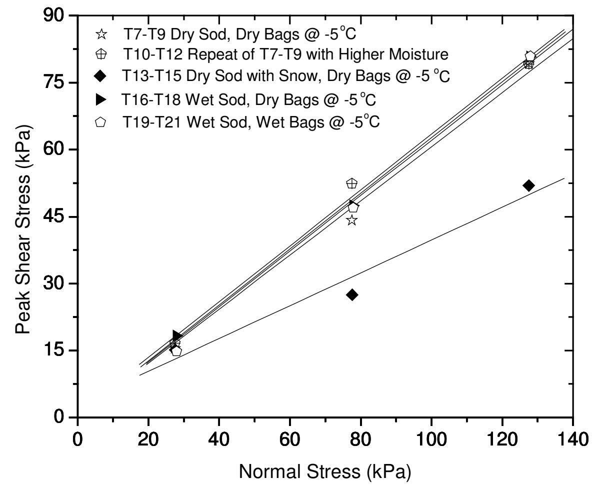

Figure 7: Frozen Condition Failure Envelopes

4.3 Shear Strength of the Dry Interface

The first comparison is that of the dry interface as shown in Figure 4. Here we compare dry sandbags and dry sod at room temperature (T1-T3) at –5°C (T7-T9 & T10-T12) and at -5°C with snow. It should be noted that the dry interface test at -5°C was carried out twice at slightly different moisture contents. This was done because the three sod specimen prepared for use in Tests 7-9 appeared to have become excessively dry before the cold chamber was ready for testing. The average final moisture contents for T1-T3, T7-T9 and T10-T12 were 137%, 80% and 143% demonstrating the loss of moisture in Tests 7-9. The results of the repetition of the dry bags tested at -5°C shows that the change in moisture content experienced had little if any affect on the shear strength. In fact the data sets of these tests are nearly identical demonstrating good repeatability of the test procedure.

The analysis of the dry interface illustrates that the friction angle of the frozen conditions is greater than that of the unfrozen conditions. This effect is likely due to the sandbags becoming keyed into the stiffened sod. In the frozen conditions, the sod becomes extremely firm. As normal loads increase, the sandbags are pressed or keyed further into the stiffened sod. When horizontal displacement is initiated, the sandbags must overcome the extra resistance of the stiffened sod resulting in increased shear strength.

Concurrently the adhesion of the frozen WSFPP bags to the frozen sod is much less compared to the unfrozen conditions. This may be attributed to the fact that at -5°C the water molecules are frozen and the suction effects that would cause adhesion of the geotextile are no longer present.

The effect of the snow eliminates the keying function of the frozen ground and in fact produces a layer of frozen ice over which the sandbags can slide more easily. The sliding of the bags on the ice reduces the shear strength relative to that of the tests without snow covered sod.

4.4 Shear Strength of the Wet Interface

Figure 5 examines those tests having a wet interface. Here we compare wet sandbags and wet sod at room temperature (T4-T6) , dry sandbags and wet sod at –5°C (T16-T18) and wet sandbags and wet sod at –5°C (T19-T21). Similar to the dry interface conditions, the sod in the frozen tests has a stiffness to it that inhibits lateral movement. Again, the sandbags become keyed into the stiffened sod further inhibiting their lateral movement and increasing their shear strength.

4.5 Shear Strength of the Unfrozen Interface

Only two tests were carried out at room temperature (unfrozen conditions): Dry bags on dry sod (T1-T3) and wet bags on wet sod (T4-T6). The Φ' values for these conditions are comparable; however, the c' values differ greatly. This effect is likely the cause of the saturated interface eliminating the adhesion effects. Figure 6 shows this relationship between the two tests carried out under unfrozen conditions.

4.6 Shear Strength of the Frozen Interface

Four different tests were carried out under frozen conditions: dry bags and dry sod (T7-T9 & T10-T12), dry bags and dry sod with snow (T13-T15), wet sod and dry bags (T16-T18) and wet sod and wet bags (T19-T21). The failure envelopes for these tests are shown in Figure 7. Of these tests, all except the one involving snow in the interface (T13-T15) showed similar strength characteristics with friction angles values ranging from 31°-32°. The keyed effect of the sandbags and stiffened ground is the dominant influence here. The moisture content of the sod/sandbag interface does not have significant impact on the shear strength resulting from the keyed effect. Finally, in the tests with snow within the interface (T16-T18) the snow produced a layer of frozen ice over which the sandbags slid reducing the shear strength relative to the other frozen conditions.

5 CONCLUSIONS

Large scale direct shear tests were carried out to evaluate the change in shear strength of sandbag dikes constructed on sod as a result of the rising flood waters and temperature and precipitation conditions. The tests demonstrated changes in Mohr Coulomb parameters resulting from temperature, moisture and the presence of snow in the interface.

Temperature provided the most consistent effect on the shear strength of the dike. At -5°C under varying moisture levels, the shear strength of the dike/foundation interface increased relative to the unfrozen conditions. This effect was caused by the sandbags becoming keyed into the stiffened sod resisting lateral displacement. This result would be eliminated if snow is present at the time of construction. The presence of snow produced a slick interface which significantly lowered the shear strength. While frozen conditions provide increased shear strength they also provide an environment for snow to be present. For safety when designing sandbag dikes under frozen conditions, a conservative approach would be to use the Mohr Coulomb parameters determined with snow in the interface.

Under unfrozen conditions, the saturated interface should be considered when designing sandbag dikes. Seepage under the dike will likely saturate the interface of the sandbags and the vegetative covered slopes below. In unfrozen conditions, this saturated interface will eliminate the adhesion effects exhibited from the dry interface. Thus, when using Mohr-Coulomb shear strength parameters for sandbag dike design, the cohesion parameter should be excluded.

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