Field testing large sand-filled geotextile containers used as a temporary flood protection system

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Harms, S.M., Blatz, J.B. & Clark, S.P.
Department of Civil Engineering – University of Manitoba, Winnipeg, MB, Canada

ABSTRACT

The effectiveness of temporary flood protection is highly variable depending on the location, application, and the nature of flood events. This paper evaluates sand-filled interconnected geotextile containers used as flood protection products within a framework of standardized tests. Two single-layer configurations and two stacked configurations were tested under a variety of flood conditions while seepage rates and product displacements were measured during each test. Researchers implemented a modified version of the US Army Corps of Engineers Standardized Testing Protocol for the Evaluation of Expedient Floodfight structures at an outdoor test facility constructed at the University of Manitoba. Each product configuration was evaluated under hydrostatic loading, wave-induced hydrodynamic loading, overtopping and debris impact conditions. This allowed for informed decisions to be made regarding appropriate applications for each temporary flood protection product configuration, and identifies areas for product improvement and development.

RÉSUMÉ

L'efficacité des protections temporaires contre les inondations est très variable selon le lieu, l'application, et la nature de l'inondation. Cet article évalue l'efficacité de sacs interconnectés en géotextile remplis de sable en suivant un protocole d'essai normalisé. Deux configurations en couche simple et deux configurations en empilement sont testées sous diverses conditions d'inondation. Durant chaque essai, les vitesses d'écoulement, ainsi que les déplacements des sacs sont mesurés. Une équipe de recherche a élaboré une version modifiée du protocole établi par le Corps des ingénieurs de l'armée américaine, le « Standardized Testing Protocol for the Evaluation of Expedient Floodfight Structures ». Ce protocole modifié a fait l'objet d'une analyse sur le site expérimental extérieur de l'université du Manitoba. Chaque configuration a été testée sous les conditions suivantes : chargement hydrostatique, chargement hydrodynamique induit par des vagues, basculement et impact de débris. Cette étude a permis, d'une part, de formuler des recommandations concernant les applications appropriées à chaque configuration, et d'autre part, d'identifier les améliorations qui pourraient être apportées à ce produit.

1 INTRODUCTION

Permanent flood protection infrastructure has significantly reduced the detrimental impact of flooding in Manitoba. Temporary flood protection, however, still plays a vital role in quickly adapting to flood events for which permanent flood protection structures are not available, or are under-designed. Temporary flood protection is often the only option available to protect homes and property from floodwaters where permanent flood protection infrastructure has not been developed or is not feasible.

This research evaluates the performance of sand-filled woven geotextiles used as temporary flood protection products (TFPP). Standardized tests were performed on the Syn-Tex Wave Breaker and Syn-Tex Super Sandbag under various flood conditions, in a controlled environment. Obtaining quantitative data allows the performance of these products to be objectively compared with other temporary flood protection products available on the market. This also allows designers to anticipate the performance of the products tested in future installations, and highlight aspects of product design that can be improved upon. Although the focus of this research project has been on the specific Syn-Tex products identified, the results are applicable to the wider engineering community by providing a better understanding of the performance of large sand-filled geotextile containers as a flood protection system.

2 PRODUCT SPECIFICATIONS

The Wave Breaker (WB) is a series of inter-connected rectangular chambers made of a woven polypropylene (WPP) geotextile with an apparent opening size (AOS) of 0.425 mm. The geotextile has a mass of 1.9 kg/m^2, and is referred to in industry as a black 4x6 WPP fabric. The product comes in standard 30.5 m lengths and a variety of heights; the 1.52 m and 0.91 m tall models were used in this testing, which have widths of 1.52 m and 1.22 m, respectively. The product is designed to be filled with sand, which is typically done using a machine with a bucket (*i.e.* a bobcat or front-end loader). Loops at each of the four corners of the chambers allow the product to be held open as it is filled.

The Super Sandbag is also a sand-filled geotextile, but differs from the Wave Breaker in several ways. The chambers not connected, so they are normally filled using a machine with a bucket and then lifted and placed using a machine with forks. The geotextile used is also lighter at 0.6 kg/m^2, and is commonly referred to as a flexible intermediate bulk container (FIBC) fabric. This FIBC fabric is a woven fabric, and although it is uncoated it is deemed water-resistant. Each Super Sandbag has a footprint of 1.22 m by 1.22 m, and has an empty height of 1.32 m.

3 TESTING OVERVIEW

The US Army Corps of Engineers (USACE) developed the Standardized Testing Protocol for the Evaluation of Expedient Floodfight Structures (STP) to objectively compare the performance of the wide range of temporary flood protection products available on the market. The STP evaluates the constructability of a product along with its performance when subjected to different controlled flood conditions (hydrostatic loading, wave-induced hydrodynamic loading, overtopping, and debris impact) at prescribed magnitudes and durations. Wibowo *et al.* (2010) provides a comprehensive overview of the (USACE) STP. This research was inspired by the STP in terms of the product position and the type of tests carried out, but the loading conditions and test durations were modified at times to gain additional data or due to logistical considerations. Table 1 summarizes the tests performed on each configuration.

An outdoor test facility was constructed to administer the tests as shown in Figure 1. It features a 9.14 m long inset permanent wall with two 2.43 m wing-walls at either end. The three product walls were constructed as stipulated in the STP: wall 1 extends outward from the wing-wall with an interior length of 6.10 m, wall 2 forms a 90 degree angle with wall 1 also with an interior length of 6.10 m, and wall 3 angles back from wall 2 to join up with the other wing-wall. The most notable difference between this facility and the USACE facility is where the water is impounded. This facility creates a pool within the three product walls and the permanent wall, whereas in the Coastal Hydraulics Laboratory where the Army Corps carries out their testing, the water is on the opposite side of the product (Wibowo *et al.* 2010). Interior pool loading creates a more severe loading condition on the product, as it tends to be pushed away from the permanent wall, as opposed to external loading which pushes the product into the permanent wall which provides additional resistance.

Waves in the pool were generated using a 6.1 m long wedge with a triangular cross-section that was plunged in and out of the water. The wedge was situated just in front of the permanent wall and inset between two wing-walls where the product walls terminated. A trench was dug around the facility to collect seepage and transport it to a sump pit, where it could then be recycled back into the pool to maintain a constant water level.

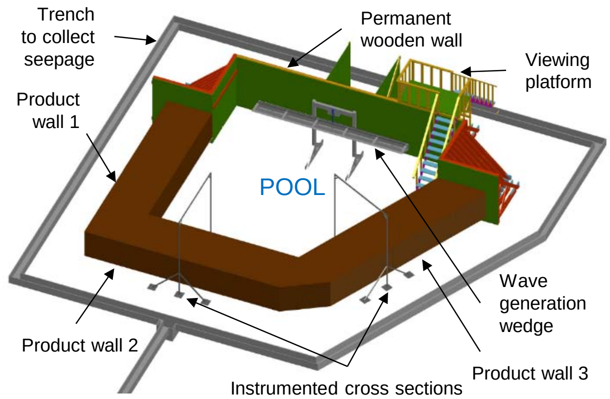

Figure 1. Test facility overview

Four product configurations were tested: two single layer and two stacked. The configurations are summarized below and reported referred to herein as follows:

C1: 1.52 m WB
C2: 0.91 m WB on 1.5 m WB
C3: 0.91 m WB
C4: Super Sandbags on 0.91 m WB

The product sizes were selected on the basis of local availability and the stacked configurations were chosen because they were untested and potentially effective ways to quickly add freeboard to an existing installation. Figures 2 and 3 show configurations C2 and C4, respectively. Note that the base layer of C2 is C1 (the 1.52 m WB) and the base layer of C4 is C3 (the 0.91 m WB).

Figure 2. C2: 0.91 m (3 ft) WB on 1.52 m (5 ft) WB

Figure 3. C4: Super Sandbags on 0.91 m (3 ft) WB

Table 1. Testing Overview

Test Number	Water Depth (m)	Wave Height (cm)	Log Diameter (cm)	Duration C1	Duration C2	Duration C3	Duration C4
Hydrostatic							
1	0.30			5 h		3.5 h	
2	0.61			5 h		6 h	
3	0.72					3.75 h	
4	1.09			2 h			
5	1.52				4 h		0
6	1.83				3.5 h		
Hydrodynamic							
7	0.51	8 – 13				1.5 h	
8	0.61	13 – 25				1.5 h	
9	0.76	5 – 15		7 h			
		25 – 36		1 h			
10	0.91	25 – 30		1.7 h			
11	1.68	20			1.75 h		
12	1.83	10 – 20			1.5 h		
Overtopping							
13	1.22			1 h			
	0.84					1 h	
Impact							
14	Varied		30	6 impacts	3 impacts	3 impacts	
	Varied		43	8 impacts	4 impacts	3 impacts	

The hydraulic conditions in the pool and the physical response of the product were monitored throughout each test. Two cross sections were instrumented; one on wall 2 and one on wall 3 as indicated in Figure 1. Wave height gauges were used to measure the water level and wave heights impacting the product, draw-wire sensors measured both horizontal and vertical displacement, and piezometers measured the phreatic surface through the product. Figure 4 shows a typical instrumented cross section.

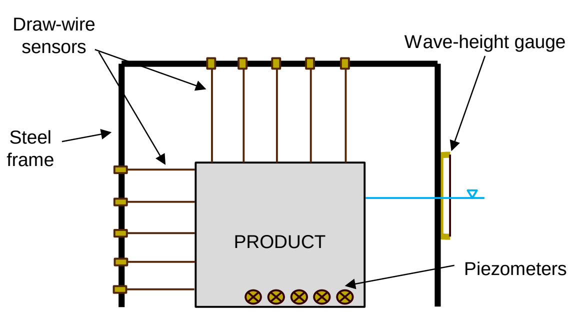

Figure 4. Typical instrumented cross section

For this field testing, the piezometer data was inconclusive and had to be verified with a laboratory testing program. Therefore, that aspect of the research has not been included in this paper, but is described in Harms (2014) for the interested reader.

4 CONSTRUCTABILITY

Constructability was the first aspect of each configuration that was investigated. Each installation was documented and timed to determine the equipment and man-hours required for installation. This information is summarized in Table 2.

Table 2. Construction duration

Configuration	Duration (hours)	Man-Hours
C1	9.25	32.50
C2*	8.00	25.50
C3	6.25	24.25
C4*	6.25	26.50

**Duration reported for second layer only.*

Each configuration had a different installation procedure, which in some cases was modified from previous configurations based on potential improvements that were identified. One such improvement was the frame used to hold open the Wave Breaker chambers in for C1, C2 and C3 installations. For the C1 installation both a free-standing PVC frame and steel x-frame hung from a backhoe were used to support individual chambers during filling (Figure 5a), whereas for C2 and C3 a multi-chamber steel frame was used with greater success (Figure 5b). A certain amount of bulging and an associated decrease in product height was observed to occur as the chambers were filled with sand. This was minimized by applying adequate tension to the product walls during installation, which was achieved more effectively using a rigid frame (in the case of this testing, steel) attached to a machine that could pull upward. In certain cases there were chambers that lost 20% of their empty height when installed with the PVC frame, whereas there was only an 11% reduction in height when using the multi-chamber steel frame. The super sandbags were filled outside of the test facility and held open and put into place using a front-end loader with forks.

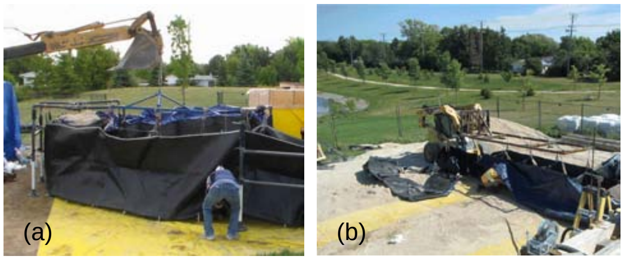

Figure 5. Filling frames used for installation of (a) C1 and (b) C3

Large construction equipment (*i.e.* a bobcat or front-end loader) was required to install both the Wave Breaker and the Super Sandbag. It is the compatibility of these products and others like them with heavy machinery that provides their greatest advantage over the traditional sandbag: a reduced number of man-hours required for installation. All four configurations were installed much more efficiently than traditional sandbags, which served as a convenient baseline for comparison due to their ubiquitous use. Pinkard *et al.* (2007) summarize a series of USACE tests that were conducted to compare different classes of temporary flood protection products, including a 0.91 m tall traditional sandbag dike. Pinkard *et al.* (2007) report it took 205.1 man-hours to construct the sandbag dike. Configuration C3 provided a direct comparison to this, as it was also 0.91 m tall and was in the same orientation as prescribed in the STP. As shown in Table 2 previously, C3 took 24.25 man-hours to construct, which was only 12% of the labour required to construct a traditional sandbag dike.

The installation of all configurations was achieved with a maximum of 7 people working on the installation at a time. At a minimum, two equipment operators and one person on the ground was required to install configurations C1, C3 and C4. One additional operator was required to install C2 because the filling frame had to be hung from two backhoes instead of one.

5 STABILITY

Stability is a primary concern when selecting a temporary flood protection product. The position of each product configuration was measured throughout each test to determine the physical response to various loading conditions. The following sections briefly describe the behaviour of the products associated with each loading condition. Figure 10 then provides a comprehensive graphical summary of the deflections measured during each test.

5.1 Hydrostatic Loading

Hydrostatic loading was the first test performed on each configuration. In general, a bulging outward of the exterior face and a downward settlement of the products was observed. It was concluded that the deflections were associated with the densification of the sand fill as it saturated. Three key observations led to this conclusion:

1. Deflections were coincident with the increasing pool water level. Figure 6 shows an example of the typical behaviour of these sand-filled geotextiles to hydrostatic loading. The data has been reduced to show the average deflections from the three horizontal and three vertical draw-wire sensors on wall 2.
2. In spite of the polyethylene sheet used to line the interior face of each product, water could be seen seeping through the exterior face of the products in all configurations. This observation is supported by laboratory test data that shows the material of both products allows water to pass through.
3. Draining the pool and repeating the same hydrostatic loading condition did not result in further displacement. This indicated that no sliding or rotational behaviour occurred.

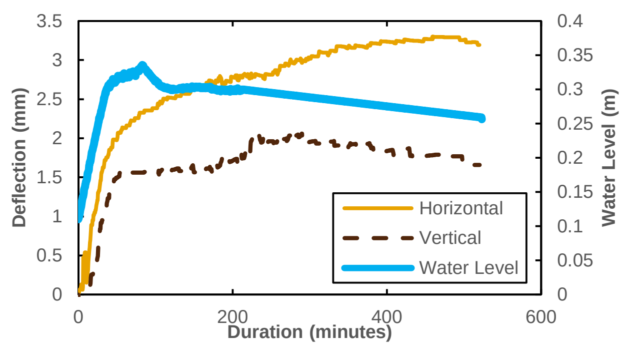

Figure 6. Average deflections measured during test 1 on C3

Configurations C1, C2 and C3 all proved stable under hydrostatic conditions, if not becoming increasingly stable due to the lowering of the center of gravity as the sand fill densified. Both horizontal and vertical deflections were measured to be as large as 10.3 mm horizontally outward and 1.5 mm vertically downward (Figure 10).

Configuration C4, however, was shown to be unstable. Just as the water reached the first test depth of 1.52 m, three super sandbags toppled over on wall 1 as shown in Figure 7a. This configuration appears stable under simple rigid body static analysis, but this is not an accurate representation of the true behaviour of the configuration. Figure 7b shows the base layer Wave Breakers of C4 after the toppled Super Sandbags were removed. The wrinkled and folded outside face of the base layer along wall 1 indicates it was in compression at the time of failure. As the pool was filled and the sand fill of the upper layer began to saturate and densify, it bulged outward and compressed the outer face of the foundation layer. The geotextile, which has no strength in compression, yielded to the load causing the rotation and toppling of the upper

Super Sandbag layer. This failure was not due to any design flaw of either product individually, but rather the selection of the combination of the two. It is imperative that when stacking sand-filled geotextile containers, the outer faces of the foundation layer remain in tension to maintain the product's ability to support the overlying layers.

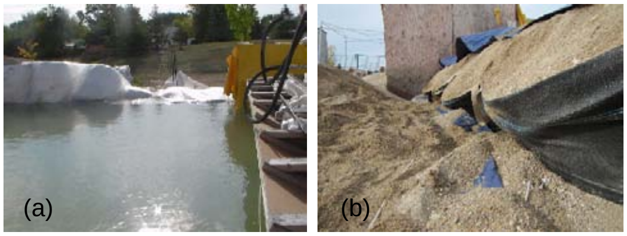

Figure 7. C4 failure (a) immediately after and (b) after upper layer was removed

Adding a second layer of product directly on top of an existing installation may be tempting to raise the flood protection level in an emergency situation. To do this safely, the upper layer should always be narrower than the foundation layer, or an additional foundation layer should be added to create a pyramid configuration (although this configuration was not tested in this study).

5.2 Hydrodynamic Loading

The hydrodynamic (wave) loading tests elicited a similar product response as the hydrostatic loading. Before each test was begun the water was brought up to the required static depth, and no deflection was recorded. Once the waves began to impact the product, however, additional displacements were measured. Figure 8 shows the influence on wave action on the densification of the sand fill using one horizontal and one vertical draw-wire sensor from test 12 on C2 as an example. The shaded vertical bars indicate the time intervals that waves were being generated. The additional unrecovered deflections that took place during wave loading became smaller with each successive increment. No deflection was observed in the final wave loading increment, indicating that the product had densified as much possible under the current loading condition.

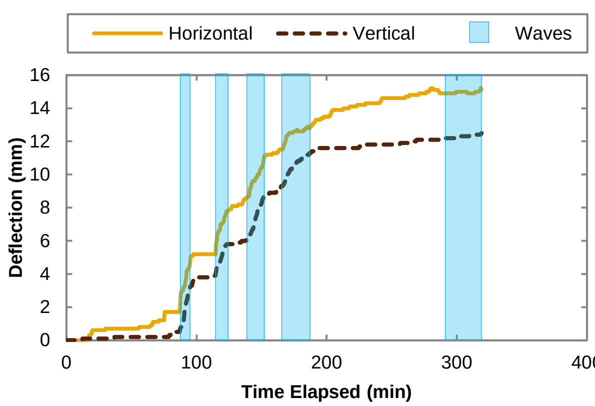

Figure 8. Deflections from select sensors during test 12 on C2

5.3 Overtopping

Both single layer configurations (C1 and C3) remained stable during overtopping conditions, which were sustained for one hour. Water did not overtop the entire structure as planned due to flow restrictions at the test facility. Therefore, for both configurations the water flowed over the structure at the low point, which in both cases was at the instrumented cross-section on wall 2. Stacked configuration C2 was not subjected to overtopping testing due to facility limitations.

The overtopping condition marked the largest measured deflections for configuration C1, which until this point had been largely unresponsive to hydrostatic and hydrodynamic loading conditions. One additional piece of information is required to explain this phenomenon: a facility demonstration had been carried out previously for local stakeholders, during which water was put in the pool and waves were generated with no operational instrumentation. During this demonstration, the product presumably settled vertically downward and bulged outward as the sand fill became saturated. Therefore, when the instrumentation was installed, there was no more deflection left to measure associated with the loading conditions the structure had already experienced. The overtopping test was the first new loading condition C1 experienced after being instrumented, and therefore was the first loading condition to register any deflection (Figure 10).

A second overtopping test was performed on C1 which confirmed that no additional deflections took place when repeating the same overtopping loading conditions. The localized overtopping conditions created in this testing resulted in a similar product response to hydrostatic loading. The product stability under more severe and widespread overtopping conditions was not tested.

5.4 Impact Tests

Each product configuration was impacted multiple times at the instrumented cross section on wall 2 using 0.30 m and a 0.43 m diameter logs, both with a length of 3.7 m. Each impact was made at approximately 8 km/h and at an angle of 20 degrees as outlined in the STP (Wibowo *et al.* 2010). Figure 9 shows an impact test on configuration C1.


Figure 9. 0.43 m diameter log impact on C1 during test 14

All configurations that were subjected to impact tests (C1, C2 and C3) recorded additional horizontal deflection away from the pool. The 1.52 m wide product (C1) only registered 3 mm of deflection, while the 1.22 m wide product impacted in C2 and C3 deflected outward by approximately 20 mm (Figure 10). Vertical deflection measurements could not be taken during the impact tests for fear of damaging the vertical draw-wire sensors. All these deflections were permanent, which indicates a rearrangement of the sand fill occurs upon impact as the energy is absorbed into the product. All three configurations remained stable during impact.

6 SEEPAGE

The ability of a flood protection product to hold back water is fundamental to its effectiveness. Seepage rates can vary from product to product, and from installation to installation. Therefore, it is important to have an understanding of the range of seepage rates that may be anticipated for a particular temporary flood protection product to plan for seepage control measures.

This test facility was not designed with the capability to collect and measure the volume of water lost due to seepage (the drainage trench collected most but not all of the seepage). Therefore, the hydrostatic load tests allowed for the only opportunity to measure seepage rates. Two methods were used to calculate the seepage rate: the first was to monitor the change in water level in the pool over time, and the second was to measure the flow in to the pool required to maintain a constant water level.

For each configuration, the products were sealed to the wing-walls and lined using a polyethylene sheet (PES). The PES was weighed down at the toe using one continuous layer of traditional sandbags (0.36 m wide by 0.66 m long when empty), and the PVC fabric pool liner was extended out from the wing-wall and sealed to the PES with a polyurethane sealant. These seepage reduction techniques could be applied in the field, and are permitted under the STP. The seepage results measured during these tests have been normalized with product length in Figure 11 to facilitate comparisons with other temporary flood protection product installations. Two sets of seepage rates for C3 labeled 'saturated' and 'unsaturated' are included, and discussed further below.

Throughout testing on all configurations, water could be seen seeping out between the wing-wall and the product in spite of the efforts made to seal off this interface. As the configurations were subjected to successive tests, the seepage at the product/wall interface visually reduced. A second set of seepage tests was conducted on configuration C3 to measure the difference between the initial (termed 'unsaturated' in Figure 11) and the reduced (termed 'saturated' in Figure 11) seepage rates. It was found that seepage rates had dropped to approximately half of the original value in the second round of tests. This reduction is attributed to the product conforming more closely to the rigid wing-wall as the fill saturates and densifies, thus forming a better seal and reducing seepage. The product/wall interface, therefore, appears to contribute to a relatively large portion of the seepage.

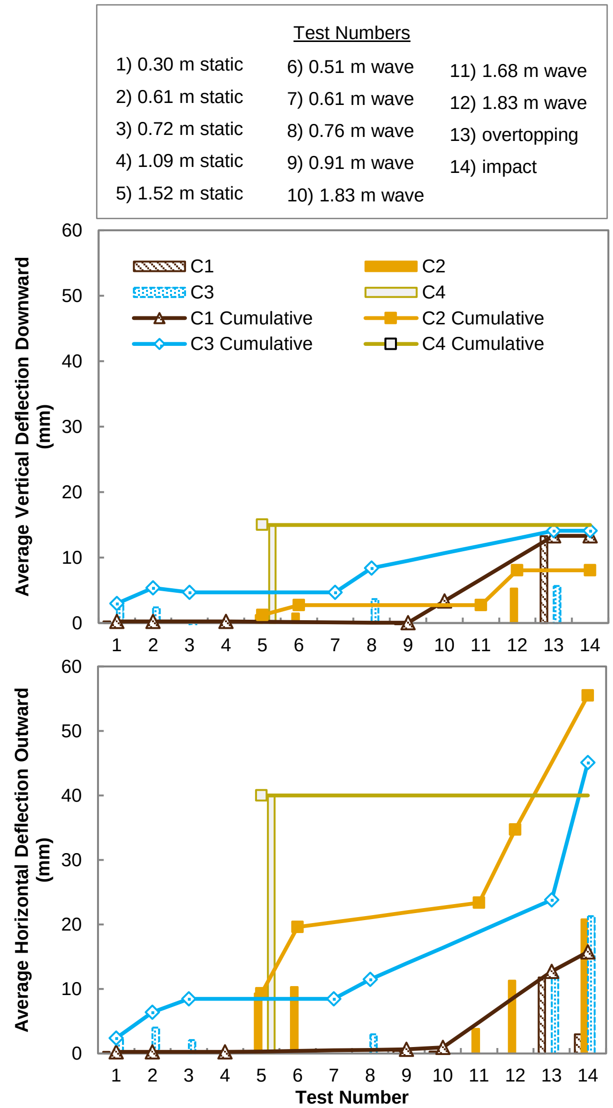

Figure 10. Summary of average displacements

The grey shaded area in Figure 11 represents the zone between the upper and lower bounds of seepage rates. This shaded band is a function of the degree of densification of the sand fill, and serves as a range of seepage rates that may be anticipated in future installations. It is important that these seepage rates be taken in context as the seepage rates are also a function of the permeability of the ground underneath the product.

The seepage rates measured in this research are in the range of other sand-filled geotextile TFPP seepage rates reported in the literature. Pinkard *et al.* (2007) and Ward (2005) summarize the results of the STP on a variety of products including the Hesco Barriers (another sand-filled geotextile TFPP) and traditional sandbags. Two sets of seepage tests were run on the Hesco Barriers, with the only difference being the method employed to seal the product to the wing-walls. As shown in Figure 12, interface seepage had a significant effect on the Hesco Barrier seepage rates, which varied greatly between the two tests. Krahn (2005) conducted a series of hydrostatic loading tests on a variety of traditional sandbag dike configurations. Seepage rates from some of those tests are also shown on Figure 12 along with the shaded region from Figure 11 as a reference.

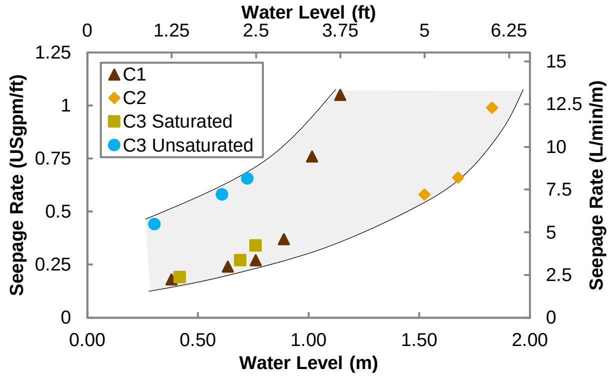

Figure 11. Normalized seepage rates measured during hydrostatic loading

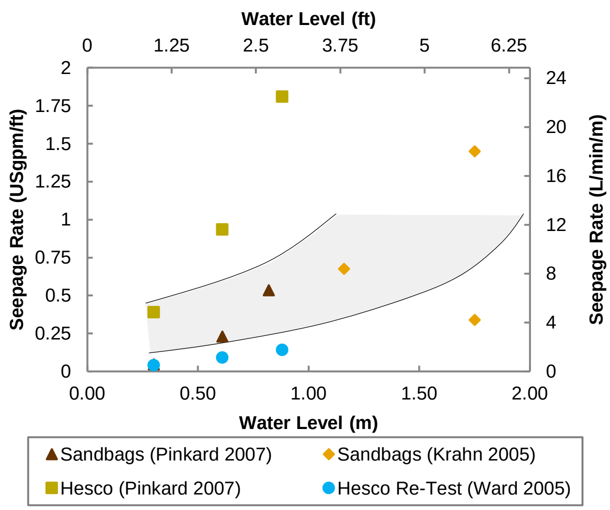

Figure 12. Seepage rate comparison

It is apparent from this and other similar testing that seepage trends can be identified, but there is significant scatter in the data associated with the inevitable variability of installation quality and location. Therefore, it is recommended that a conservative interpretation of these results be implemented in design of seepage management systems for future installations.

7 DURABILITY

The physical condition of the products (*i.e.* the geotextile fabric itself) in each configuration was visually monitored throughout each test to identify any damage. There was no visible damage to any of the configurations resulting from tests 1 through 13.

Test 14, the debris impact test, was the most severe loading condition in terms of durability testing that was administered. Configurations C1, C2 and C3 were all Wave Breaker configurations, and therefore had the same geotextile (the 4x6 WPP fabric). In all cases the debris impact made a dent on the interior face of the product as the sand fill within the chamber was displaced. However, the geotextile itself remained un-damaged when inspected with the naked eye.

The Wave Breakers also proved resistant to the elements; configuration C1 was tested and then left outdoors over winter in Winnipeg, Manitoba, after which it was inspected to determine its suitability as a foundation layer for C2 testing the following year. Upon visual examination there was no noticeable UV degradation or difference in colour between the C1 fabric and new 4x6 WPP fabric.

8 CONCLUSIONS

Several conclusions have been drawn regarding the specific products tested, along with sand-filled geotextiles in general used as temporary flood protection products.

8.1 Constructability

Large sand-filled geotextile containers can be installed much more quickly than traditional sandbags, provided there is proper equipment access. The 0.91 m Wave Breaker tested in configuration C3 was installed using 12% of the labour required to build a comparable traditional sandbag dike.

In order to maximize the installed height of the product, adequate tension must be applied to the sides of the empty chambers as they are filled. Steel frames proved more effective at applying tension to the products as they were filled compared with a spring-loaded PVC frame.

8.2 Stability

Configurations C1, C2 and C3 were shown to be stable when subjected to the gamut of modified STP tests. The deflections measured in these configurations were permanent and are associated with the densification of the sand fill as it saturated during testing.

Configuration C4 was shown to be unstable, as three bags on wall 1 toppled over just as the first hydrostatic load test was beginning. This failure showed the importance of having a wider product as the foundation layer to ensure the walls of the base layer product remain in tension.

The maximum cumulative horizontal deflection of all configurations was 55.5 mm measured for C2, and the maximum vertical deflection was 15 mm downward for C3. In all cases the deflections were permanent, and essentially a measure of the bulging of the outer product face and the settling of the product associated with the densification of the sand fill. Once the product had densified under a given hydraulic loading condition, repeating the same loading condition again did not result in any further deflections. Repeated impact testing would have presumably resulted in additional deflections; however, what was deemed a reasonable number of impacts were performed, which went beyond the requirements of the STP.

8.3 Seepage

The seepage rates measured during hydrostatic loading on configurations C1, C2 and C3 ranged from 2.24 L/min/m to 12.3 L/min/m at impounded water depths of 0.33 m and 1.83 m, respectively. These seepage rates were found to be heavily influenced by the level of compliance between the product and the wing-walls. Compliance was observed to improve as the products saturated during testing and the associated deformations resulted in a better seal between the product and the wing-walls. In the case of configuration C3 where two sets of seepage tests were performed, improved compliance resulted in an approximate 50% reduction in seepage.

For future installations, it is recommended that sand-filled geotextiles be filled with dry sand, and then that the sand be saturated manually at any chambers abutting a vertical surface. This will improve compliance and pre-emptively reduce seepage.

The relationship between water depth and seepage rate has been illustrated for this research and compared with other sand-filled geotextile products. This relationship is meant to be a tool to assist in the design of seepage management systems for future installations. However, the values should be used bearing in mind the conditions under which they were measured, and therefore used only where deemed appropriate.

8.4 Durability

The Wave Breaker material remained visually undamaged throughout testing and exposure to the elements. Additional laboratory testing would have to be performed to quantify the strength of the material before and after the testing.

8.5 Appropriate Applications

Large sand-filled geotextile temporary flood protection products are best-suited to long and relatively straight installations to accommodate the equipment required to fill the products. Corners and short segments of product were constructed as part of this research, but greater improvements over traditional flood protection would be realized in situations where there is ample equipment access, a nearby stockpile of fill material, no abrupt changes in direction and where interfaces with vertical surfaces can be minimized.

8.6 Future Work

Further field testing can be done to investigate additional stacked configurations of these products. In both stacked configurations presented in this research, the foundation layer had been tested previously, and therefore the sand fill had already undergone some densification and associated deflection. Beginning with dry fill material on both layers may result in a higher degree of densification in the foundation layer. In light of the performance of configuration C4 either a double-wide bottom layer of 0.91 m Wave Breakers, or a wider 0.91 m Wave Breaker could be tested to verify the capacity of this product to support Super Sandbags provided the outer product walls remain in tension.

This testing was performed with the products on relatively level ground. Testing the products on a slope would provide greater insight into the limits of the stability of sand-filled geotextiles. This could be valuable information to use when planning an installation along a ditch or dike, for example.

The data accumulated during this research will provide a back-analysis case for future modelling. Once a working model has been established that can duplicate the product behaviour observed during this testing, additional configurations can be modeled and the performance of future and untested installations can be anticipated.

ACKNOWLEDGEMENTS

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