ERDC Report to Sponsor

US Army Corps
of Engineers®
Engineer Research and
Development Center

Evaluation of 4-Foot Muscle Wall Flood Fighting Barrier

Efrain Ramos-Santiago, Curtis Blades, James D. Gutshall

May 2020

Executive Summary:

The 4 ft. Muscle Wall flood fighting barrier by Muscle Wall Holdings LLC., consists of a 6-foot-long, hollow plastic Muscle Wall. A unit has an "L" shape design measuring 6 ft. in length, 2.5 ft. base width and 0.68 ft. top width. Adjacent Muscle Walls are joined together through a male-to-female connector, and the resulting barrier is filled with water. For the tests reported herein, the barrier was covered with two sheets of plastic liner from the front (water side), across the top, up to the rear side (dry side). Metal 4-foot-long clips and heavy-duty adhesive tape were used to hold the liners in place. An additional rough orange base liner was used to promote friction.

The units can stack together for shipping, and the entire 74.5-ft-long barrier was shipped on a two pallets. Installation of the roughly 74.5-ft-long barrier took a crew of 4 men 7.5 man-hrs. Construction of a similarly-sized sandbag barrier took more than 200 man-hrs.

Static water seepage rates at basin depths of 1 ft., 2 ft., and 3.94 ft. were 0.026, 0.058 and 0.135 gpm/ft., respectively. At each depth the seepage rate was significantly lower than that of a comparably sized sandbag barrier.

The barrier was undamaged by waves, overtopping, debris impact, or riverine current.

The units are designed for easy disassembly and can be recovered.

Contents

Figures and Tables

Figures

Tables

Unit Conversion Factors

Multiply	**By**	**To Obtain**
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
squared feet	0.0929	squared meters
gallons (U.S. liquid)	0.003785412	cubic meters
gallons (U.S. liquid) per minute per foot	0.00020699	cubic meters per second per meter
pounds (mass)	453.59237	grams
pounds (force)	4.448222	Newtons

1 Introduction

Background on Testing Program

Early in 2004, Congress tasked the U.S. Army Engineer Research and Development Center (ERDC) to “devise real-world testing procedures for … promising alternative flood-fighting technologies…”. Through the General Investigation Research and Development Program, ERDC conducted research and developed a laboratory procedure for the prototype testing of temporary barrier-type flood-fighting structures intended to increase levels of protection during floods.

The test facility was laid out along the perimeter wall of a reservoir with dimensions of 115 ft. by 185 ft. by 4 ft. deep (Figure 1). The test facility was reconfigured specifically for innovative flood-fighting experiments by allowing levees to be constructed against two wall abutments with a 30-ft. opening between the walls (Figure 2). A geometric testing zone footprint was laid out on the concrete floor and all levees are required to be constructed within this given footprint. One side of the footprint abuts the concrete wall at a 90-deg angle, and the other side abuts the concrete wall at a 63-deg angle (Figure 3). The purpose for having two different angles is to simulate real-world geometric variability and demonstrate constructability and geometric flexibility of each vendor’s product. Additionally, the unsymmetrical geometry allows wave loading variability during hydrodynamic testing, and causes an apparent current along the 63-deg wall.

Inside the test area (leeward side of the levee), an 8-ft. diameter by 8-ft.-deep circular pit was installed to catch any seepage or overflow water from the structure (Figure 3). Two 4-in.-diam pumps were installed in the seepage pit to pump the accumulated water back into the wave basin. Two 12-in.-diam pumps (12 in. intake and 10 in. output) were also installed to pump excess water out of the seepage pit when the capacity of the 4-in. pumps was exceeded.

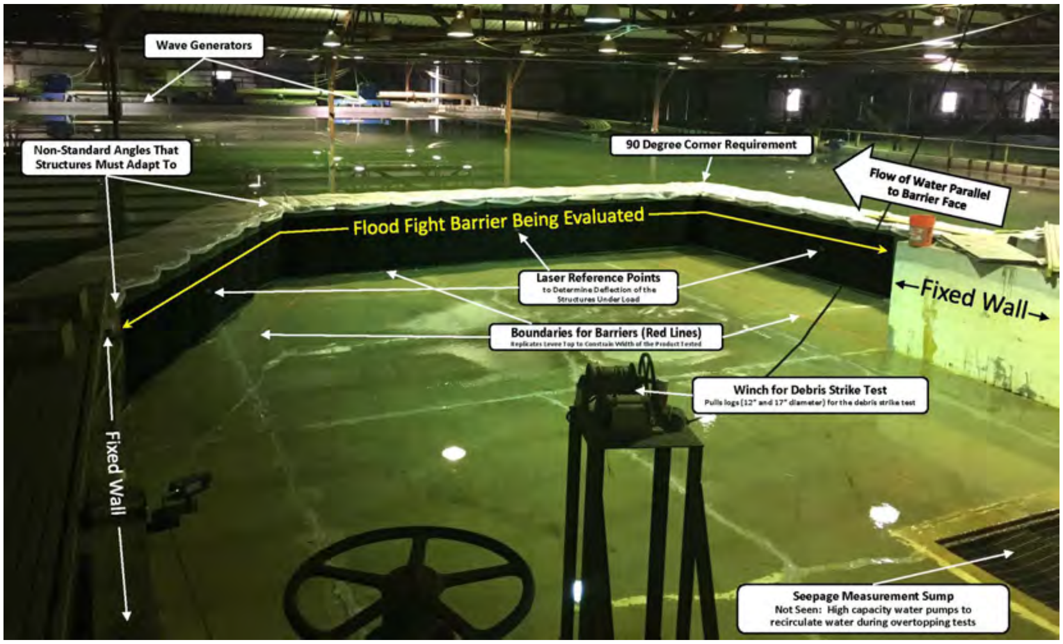

Figure 1. Looking into the research basin from the test area. The wave machines are at the far end of the basin, the winch for the debris impact test is front left, and the front edge of the sump for measuring seepage is to the lower right.

Figure 2. Looking into the test area of the research basin. The vertical white pipes extend down into the seepage pit. Barrier is not from actual test.

Evaluation of 4-Foot Muscle Wall Flood Fighting Barrier, US Army Engineer Research and Development Center Coastal and Hydraulics Laboratory, Efrain Ramos-Santiago, Curtis Blades and James D. Gutshall, May 2020.

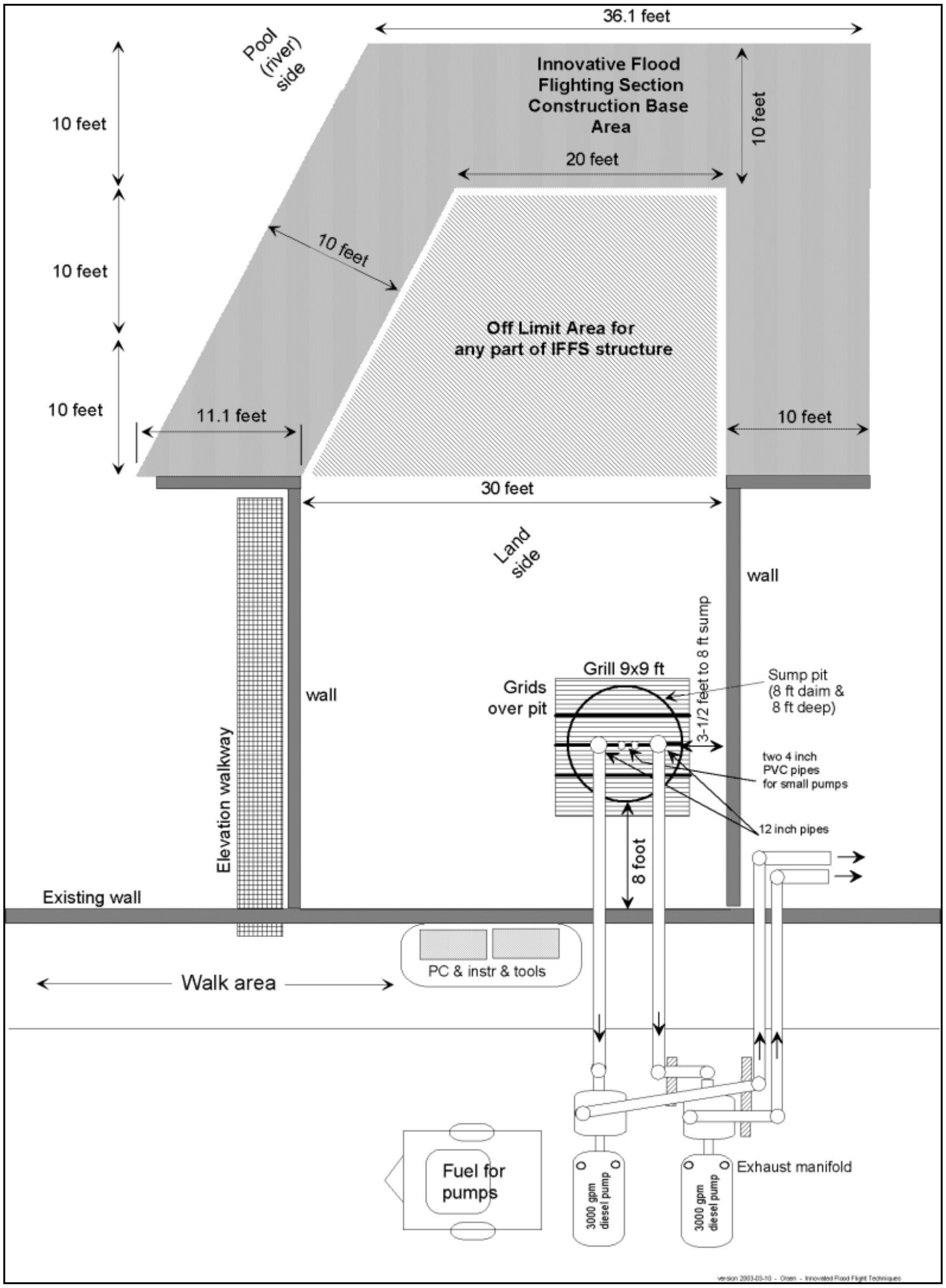

Figure 3. Layout of test area within research basin.

The test area was instrumented with a series of lasers to measure any movement of the flood-fighting barrier, a laser to measure changes in water surface elevation within the seepage pit, and an additional laser to measure water surface elevation within the basin.

In the research basin tests, products were tested in a controlled laboratory setting but under conditions that emulated an impending flood overtopping a levee along a riverbank with moderate flow. Vendors were required to arrive at the test facility with all equipment and supplies required to erect their product prior to testing. The Vendor could use his own people or ERDC personnel (after receiving training from the vendor) to construct the barrier. The ERDC testing engineer did not assist with the construction but observed and documented the selected protocol-defined metrics associated with the construction including time required to install the test walls and any special equipment requirements. After construction, the Vendor was not allowed to adjust the structure during any of the tests specified in the protocol. The protocol does allow the Vendor access to the structure a maximum of three times between tests for a limited length of time if such access is required. Any such access to the structure was recorded.

A copy of the standard testing protocol can be requested to the author of this report.

4-Foot Muscle Wall Product Description

A Muscle Wall is a portable, low-density polyethylene hollow plastic barrier (Figure 4). The 4-Foot high Muscle Wall has an "L" shape design measuring 6 ft. wide, 2.5 ft. deep at the base and 0.68 ft. deep at the top. The unit is portable and can be filled with water through filling holes located on the top side for extra weight. A releasable bung-plug cap is located near the bottom of the rear side for draining. In addition, 7 holes or kiss-throughs are distributed along the 4 ft. arm of the wall (3 near the top and 4 close to the center) that are used for the installation of the safety straps and as hand-holds. The hinge-like male to female connector in each unit enables joining two units together and allows a range of motion up to 22 degrees. The connections between units are secured by the use of safety straps. This flood barrier also can be configured to make 90-degree or greater turns through the use of a reversible corner unit. An orange base liner material is used to promote friction between the wall and the underlying floor surface. A second liner material is used as a cover, which is hold in place by installing a 4-foot clip that extends all the way down to the toe of the wall. This liner cover avoids water leakage throughout the flood barrier.

Figure 4. 4-Foot Muscle Wall barrier: front side (top left), perspective view (top right), female connector (bottom left) and male connector (bottom right).

Delivery

All the units required for the test barrier were shipped to ERDC in a Semi Truck on several pallets along with rolls of fabric that was used to seal off the barrier. The pallets were offloaded and moved into the basin facility by an ERDC employee using a Bobcat™.

2 Testing Procedure and Results

Assembly

The 4-Foot Muscle Wall units were shipped to ERDC on two pallets, with tools and supplies arriving in a pickup truck with Muscle Wall personnel. The ERDC Coastal and Hydraulics Laboratory (CHL) staff provided to the Muscle Wall personnel a Bobcat™ skid-steer loader equipped with forks. The barrier was constructed by a crew of four men on the 25 February 2020. Starting time was 07:00.

A barrier unit would be lifted from the pallet and moved to the working site by two men to be installed (Figure 5). The crew started assembling the flood barrier from the basin left wingwall all the way to the right wingwall.

Figure 5. Crew moving a wall unit.

The orange base liner material was firmly placed in the floor (Figure 6), on top of which a barrier unit will be standing. These orange base liners are tied to a wood stick to align it with the wall base rear end (Figure 7).

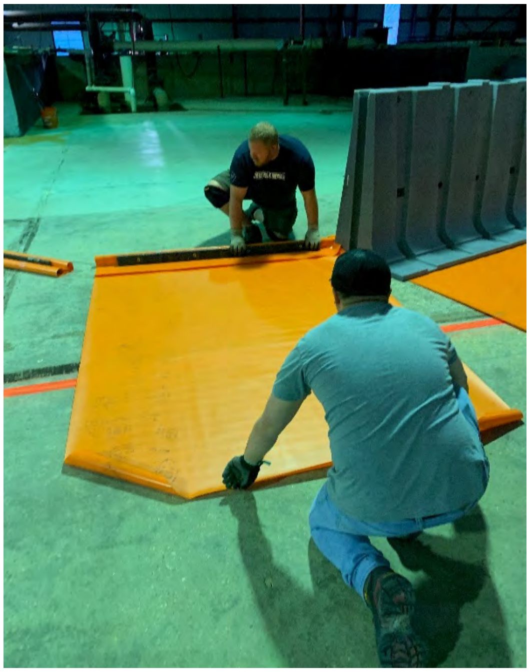

Figure 6. Placement of the orange base liner material.

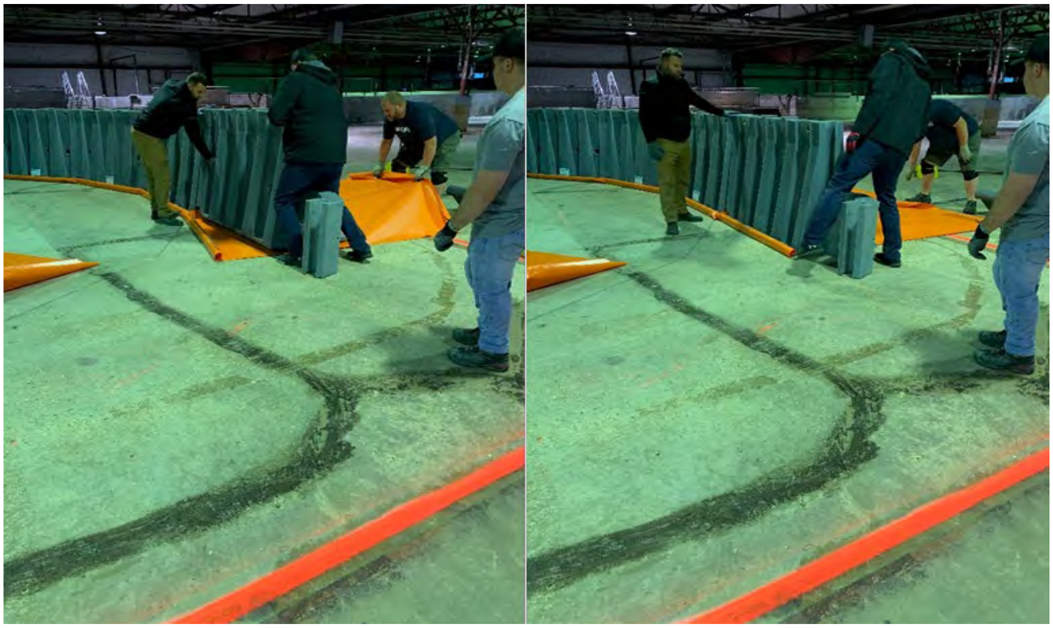

Figure 7. Crew aligning the orange base liner material with the wall unit.

Evaluation of 4-Foot Muscle Wall Flood Fighting Barrier, US Army Engineer Research and Development Center Coastal and Hydraulics Laboratory, Efrain Ramos-Santiago, Curtis Blades and James D. Gutshall, May 2020.

Two wall units are joined together by sliding the side male-to-female connectors. The barrier was also enabled to turn 90 degrees by placing a small corner unit.

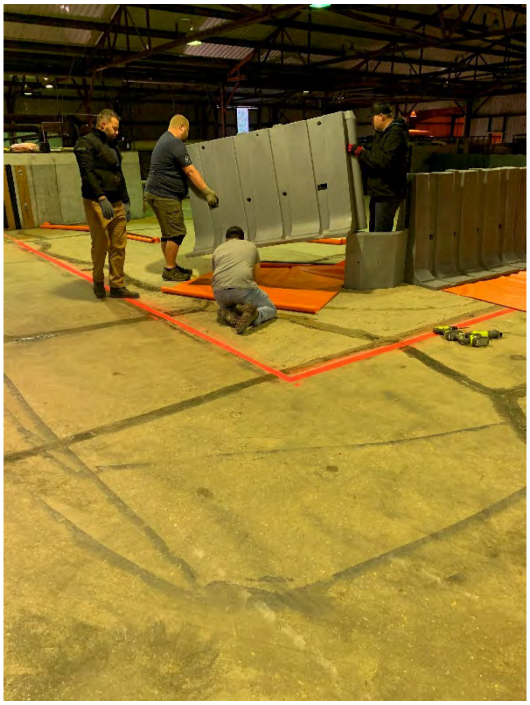

Figure 8. Crew joining a wall unit with the 90° corner unit. The basin right wingwall can be seen in the background to the left.

After the three barrier sections (left, center and right) were assembled, ratchet straps were used to cinch the wall units together (Figure 9) and with the wingwalls (Figure 10). The straps were passed throughout the Muscle Wall kiss-throughs. At this point only the straps on the top were tightened.

Two 4 ft. long, wood support beam pieces of 2 in. x 8 in. were attached to the face of each wingwall. The support beams were adhered with construction adhesive and gorilla tape. The tape was then heated for a better bond. These support beams were installed the day before official assembling of the flood barrier (Figure 11).

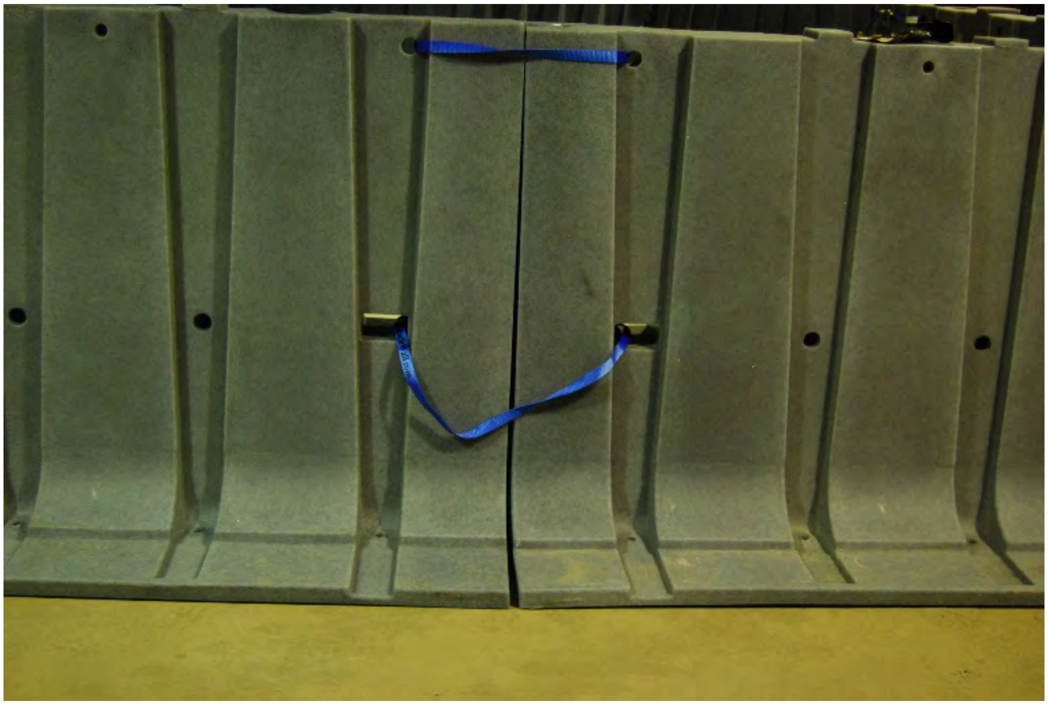

Figure 9. Placement of ratchet straps to cinch two units together.

Figure 10. Placement of ratchet straps to cinch the barrier with the basin right wingwall.

Figure 11. Installation of support boards in the wingwall.

The crew then proceeded to fix the orange base liners to the floor with a clear adhesive tape and heat was applied to improve bonding (Figure 12).

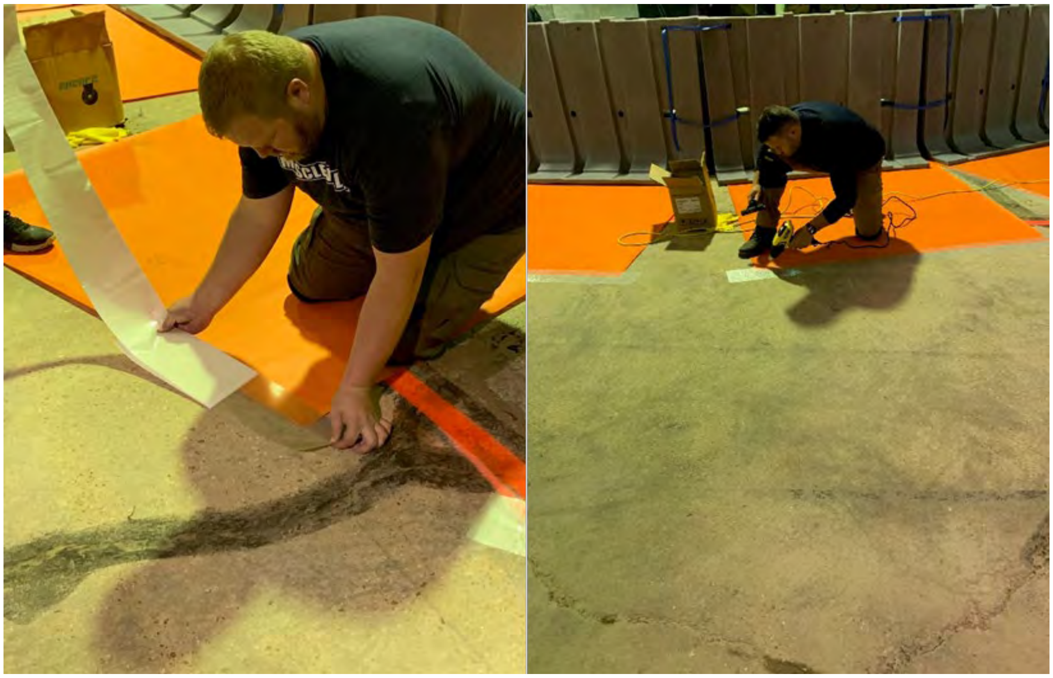

Figure 12. The orange base liner being taped to the floor and application of heat.

Having all the orange base liners in place, the second 90 degree corner unit was installed into the barrier and secured with ratchet straps (Figure 13).

Figure 13. Crew installing the top 90° corner unit.

The setup of the wall units was completed and the crew proceeded to fill the walls with water and install the liner cover. This liner was rolled out and placed over the wall. Multiple 4-foot long metal clips were also installed to hold the liner in place (Figure 14). Gorilla tape was used to bond together the excess liner at the 90 degree turn. The liner was also extended over the floor about 8 ft. toward the front of the barrier. A strip of an adhesive tape material was rolled out to adhere the liner to the concrete floor. Also, a heat gun was then used ensure the bond to the floor. The liner was cut at the point where the barrier meets the wingwalls and adhesive stripping was applied and heated. Another 2 x 8 support board was fastened over the liner to the previous 2 x 8's on the wingwall. This is to secure the liner to the wall on both sides. The excess liner was then trimmed on the ends and bonded to the wall with adhesive tape. A heat gun was then used to ensure the bond.

A second layer of liner was added and the installation process repeated. At the end, another piece of liner was added to the floor area where the left and center barrier segments joined. This was done as a safeguard, to cover a few floor cracks the crew decided to seal. The last step of the liner setup was to put masonry blocks along the tape strip bonding the liner to the floor. The crew borrowed a pallet of blocks from the basin facility to do this, and moved it into the basin with a forklift. The assembled 4-Foot Muscle Wall flood barrier is shown in Figure 15.

Figure 14. Muscle Wall metal liner clip.

Figure 15. Front (top) and left (bottom) views of the assembled 4-Foot Muscle Wall flood barrier.

The barrier had a total length of 74.5 ft., measured along the centerline on top of the barrier.

The barrier was constructed by 4 men over a total assembly time of 7.5 man-hrs. Time taken for breaks is not included in the total in order to fairly compare construction times for barriers constructed in cool weather to those constructed in the heat of summer where additional breaks are required for safety.

Equipment used during the assembly included a Bobcat™ skid-steer frontend loader, a pallet jack truck, an electric fan blower, a heat gun, a power drill, a reciprocating saw, a manual applicator gun, a smooth carpet seam roller, power cords, water hoses, measuring tape and a broom. Supplies used included the masonry or construction blocks, heavy-duty construction tape, and heavy-duty glue.

Hydrostatic Tests

One Foot Depth

Seepage

The pumps were turned on at 16:30 on 25 February 2020 and a depth of one foot in the basin was reached at 21:00. This prolonged filling time (4.5 hours) was caused by having the basin drain valve open unnoticeably. This valve was designed to drain the test basin at a rate of 8 in. per hour when fully opened and is located outside the facility. The one foot hydrostatic test officially began at 21:00, and the seepage and movement data was collected for the next twenty-two hours. The average seepage of the test was 0.0257 gpm/ft. (Figure 16), which included some minor floor crack leaks. Actual measurements of the floor crack leaks were not taken at this depth as they were visibly minor. Still, it can be reasonably assumed that there was at least a small increase in seepage due to water intrusion from beneath the basin floor.

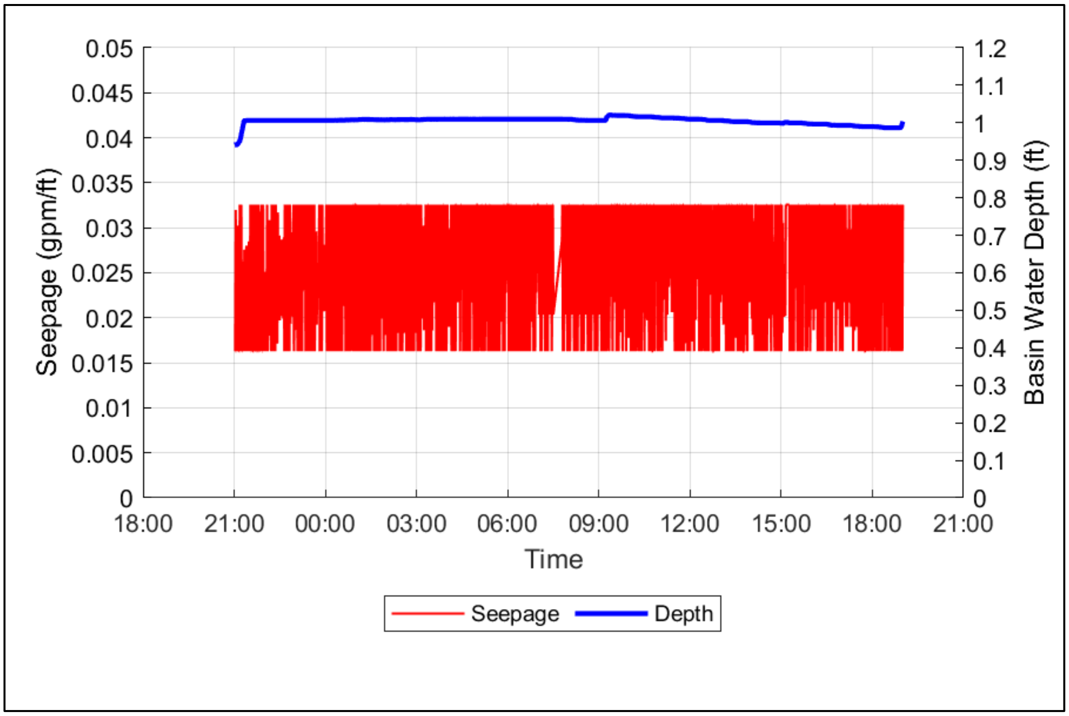

Figure 16. Seepage rates of the one-foot depth hydrostatic test.

Movement

Distance-measuring lasers were aimed near the center (vertically and horizontally) of each of the three walls of the barrier to record any movement of the barrier. Minor movement is usually expected: as the basin depth increases, water pressure on the barrier walls can cause the wall to lean inward, or water pressure can cause the wall to slide. The lasers cannot differentiate the cause of the movement; they only record if the inside wall of the barrier has moved. In the movement figures, distance to the barrier is subtracted from the original (pre-flooding) location of the barrier. Movement into the test area will therefore yield a positive value while movement out into the basin will yield a negative number.

A correction for the laser distance measurements was also computed for the three sides of the flood barrier due to the gap between wall surface and liner cover. The original (pre-flooding) location of the barrier was measured with the laser system after straightening the liner cover and pushing it against the wall surface. These distances were also confirmed manually using a plastic measuring tape. The corresponding pre-flooding location of the liner surface at the center wall target was also obtained with the laser system. These results are presented in Table 1, with the largest correction being about 29/32 in. (0.91 in.) at the center barrier wall.

Table 1. Pre-flooding distance correction factors.

Barrier side	Pre-flooding location (ft.)		Correction	
	Wall surface	Liner surface	ft.	in.
Left	38.04	38.03	0.01	0.17
Center	51.43	51.36	0.08	0.91
Right	42.27	42.21	0.06	0.73

The correction factors were then added to the laser movement measurements. The barrier movement was computed by subtracting the corrected laser distance measurements to the barrier pre-flooding location. The results for the one-foot depth hydrostatic test are illustrated in Figure 17. By the end of the test, there was no significant measurable movement from the pre-flood location.

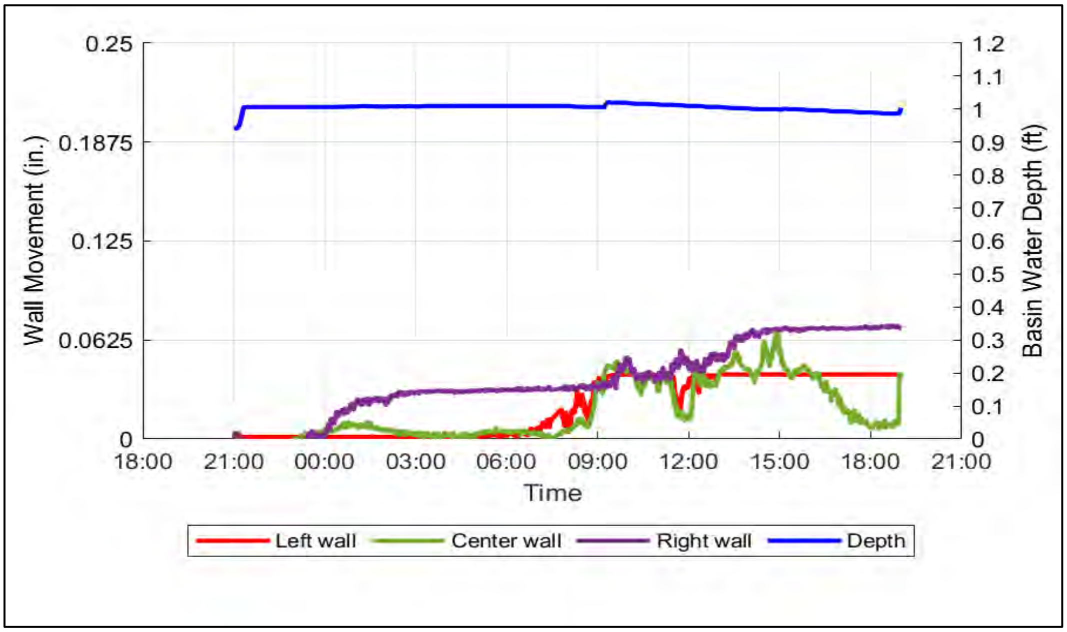

Figure 17. Movement of barrier walls during the one-foot depth hydrostatic test.

Two Foot Depth

Basin Floor Seepage

Cracks in the basin floor were last cleaned and sealed in December 2018 and again in February 2019. Prior to this test, no other attempt was made in this regard due to time constraints. Seepage through some of the floor cracks was observed when test basin had a water depth of 2 ft. or greater (Figure 18). These were measured with a calibrated cylinder as accurately as possible, then adjusted to account for smaller seepage holes that were observed but too small to measure. The adjusted floor crack seepage rates are shown in Table 2. The measured rates for a similar hydrologic test performed on March 2018 are also presented for comparison. Total seepage through the floor at a basin depth of 3.94 ft. was estimated at 0.006 gpm/ft. In this report, floor seepage at a basin depth of 1 ft. will be neglected, floor seepage at a depth of 2 ft. will be estimated at 0.0002 gpm/ft.

Table 2. Floor crack seepage rate estimates.

Basin Water Depth		**Rates** (gpm/ft.; Feb. 2020)	**Rates** (gpm/ft.; Mar. 2018)
Condition	**feet**		
-	2.00	0.0002	0.0510
66.7% h	2.63	0.0020	NA
80.0% h	3.15	0.0040	NA
95.0% h	3.80	NA	0.0100
100.0% h	3.94	0.0060	NA

Floor seepage rates were used to adjust the actual seepage collected.

Figure 18. Upward flow through cracks within the test area (1 ft. basin water depth).

Seepage

The pumps were turned on again at 19:00 on 26 February 2020, right after ending the first hydrostatic test, and a depth of 2 ft. in the basin was reached at 20:45. Seepage increased as the water level in the basin was raised from one foot to two feet. The average seepage of the test was 0.058 gpm/ft., after removal of the floor crack seepage. The time series for the two-foot hydrostatic test is shown in Figure 19. A small drop in basin water depth occurred overnight even though the automatic water valve was open. This valve has the size of a garden hose (~5/8 in.). When the CHL staff arrived next day at 07:00, the pumping system from the main reservoir was turn on to quickly refill the basin.

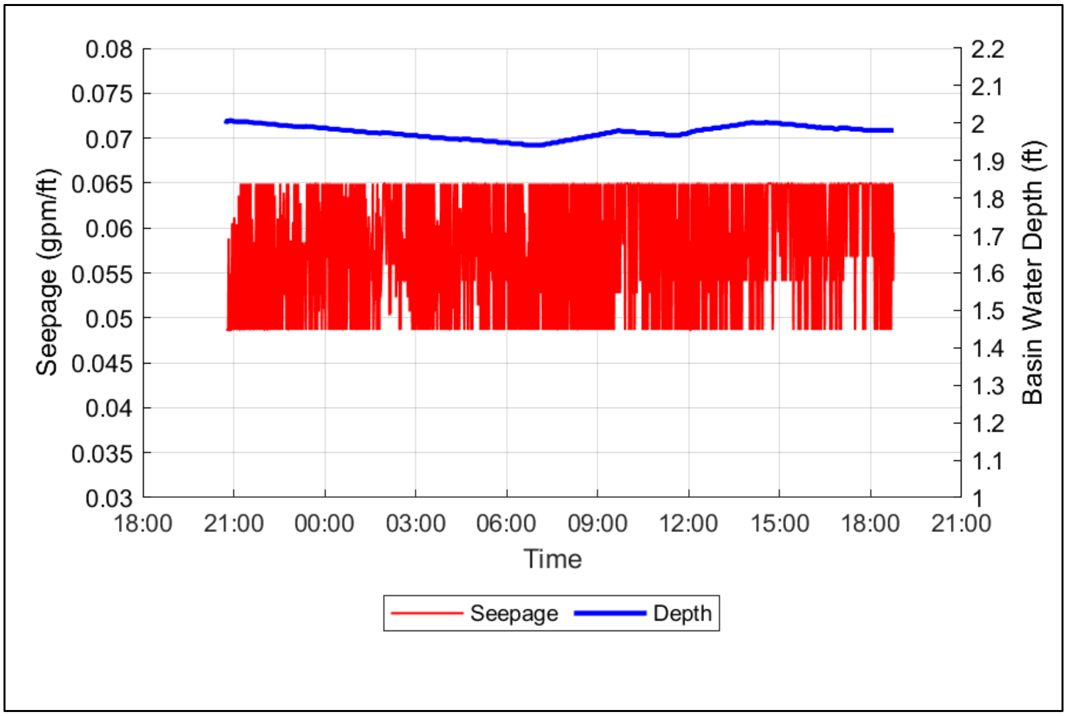

Figure 19. Seepage rates during the two-foot depth hydrostatic test.

Movement

The flood barrier movement time series for the two-foot hydrostatic test is illustrated in Figure 20. As with the previous test, no significant displacement of the three walls was observed (< 1/8 in.).

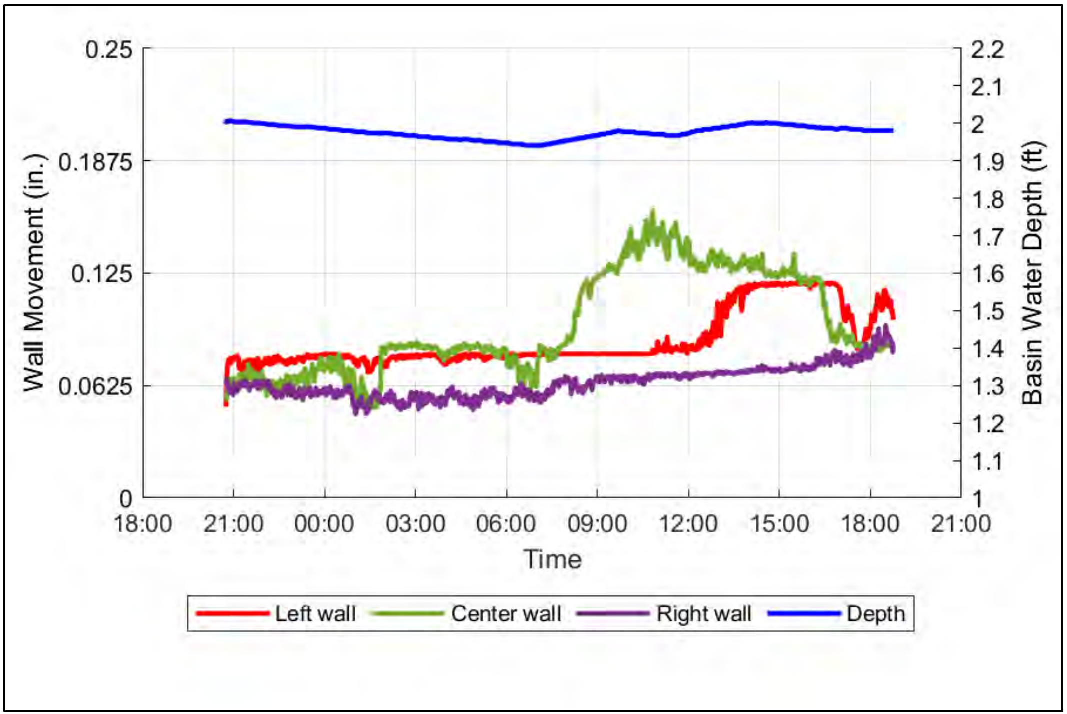

Figure 20. Movement of barrier during final two hours of two-foot hydrostatic test.

100% Depth

Seepage

A third static water test was conducted at a basin depth of 100% of the structure design height. Even though the 4-Foot Muscle Wall is designed for a working height of 3.96 ft. (47.5 in.), it was decided to use a maximum structure height of 3.94 ft. (47.25 in.). The pumps were turned on again at 19:05 on 27 February 2020, after ending the second hydrostatic test. At 22:14, the pumps were turned off since a water depth of 3.95 ft. (47- 7/16 in.) was reached. At this depth water overtopped the flood barrier at multiple spots of the center and left walls. According to the FM 2510 Standards, Chapter 4, a ±0.5 in. water depth margin is permitted. Therefore, the basin water depth was reduced to the lower allowed margin of 3.89 ft. (46.75 in.) in order to avoid overtopping. This was attained at 22:33 when the 22-hour test officially started. A picture of the flood barrier under this condition is shown in Figure 21.

Figure 21. Barrier holding back water at 100 percent of structure height.

Seepage increased as the water level in the basin was raised from 2 ft. to 3.89 ft., as expected. The average seepage of the test was 0.135 gpm/ft., after subtracting the 0.006 gpm/ft. floor crack seepage (see Table 2). A segment of the seepage time series for this test is shown in Figure 22. After completion of this test, the drain valve was opened at 20:45 to lower the basin water depth. At 22:30 the drain valve was closed, the water depth was 3.46 ft., and the basin was left to drain overnight through floor crack seepage as shown in Figure 23. The average seepage rate dropped during this time (22:30 28 Feb to 08:00 29 Feb) to 0.117 gpm/ft., after removing the effects of floor crack outflow and outliers introduced by the seepage pit pumps.

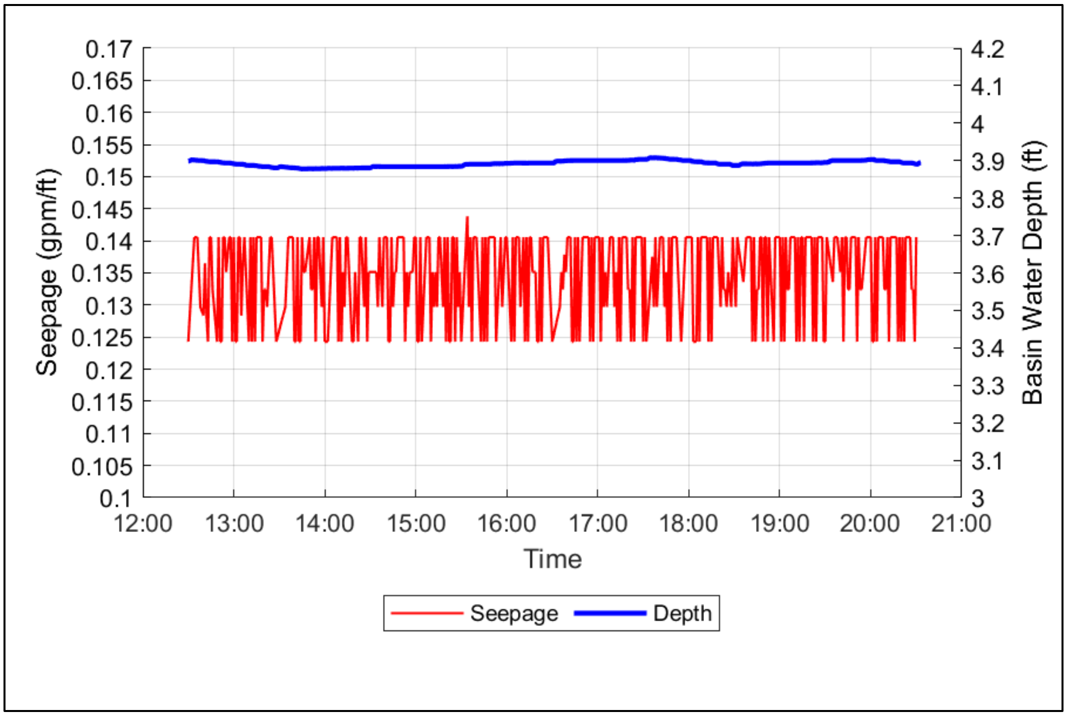

Figure 22. Seepage rates during final eight hours of the 100 percent depth hydrostatic test.

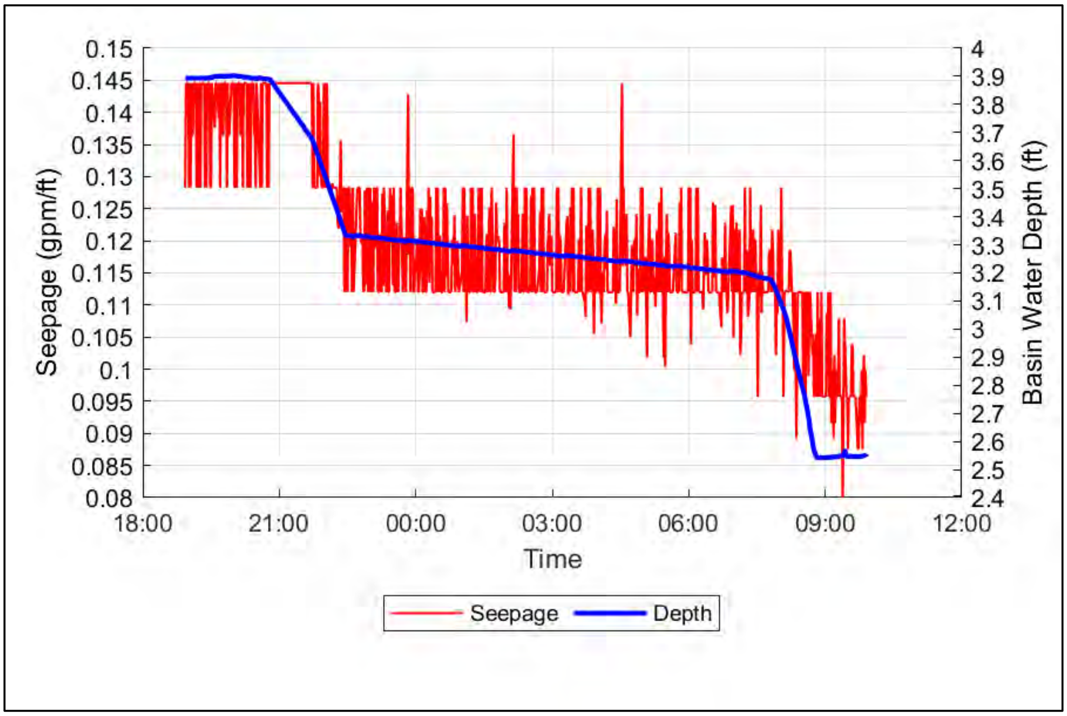

Figure 23. Seepage rates between 22:30 28 Feb and 08:00 29 Feb.

Movement

The flood barrier movement time series for the final 8 hours of this hydrostatic test is illustrated in Figure 24. It was found that all three sides of the flood barrier moved inward or into the basin's dry-zone. The left wall moved 3.86 in.; the center wall moved 3.37 in., and the left wall moved 2.70 in. However, this data does not provide the base to conclude that the flood barrier either slipped or tipped at any of these locations. The laser system is not equipped to measure additional parameters other than distance.

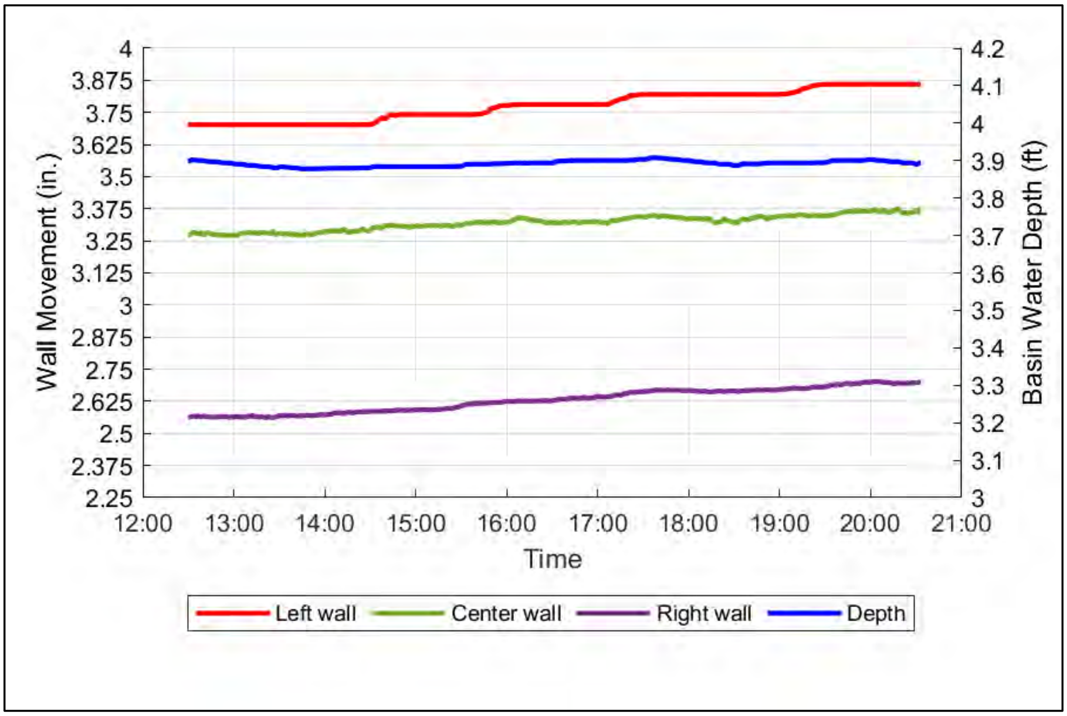

Figure 24. Movement of barrier during final eight hours of 100 percent depth hydrostatic test.

As mentioned before, after concluding the 100% depth hydrostatic test, the basin was left to drain overnight. In the following morning, 08:00 29 Feb, the drain valve was fully opened again to take the water depth to 66.7% of the structure design height required for the wave test. From the laser data shown in Figure 25, it was observed that all three walls of the flood barrier had a rebound of nearly an inch after draining. These measurements are summarized in Table 3 along with the results obtained for the 100% depth hydrostatic test. The negative sign of the total movement results indicates that the motion was in fact towards the basin's wet-zone. This is an indication of the Muscle Wall ability to bend without significantly slipping its base, a combined effect of the hollow plastic structure with the orange base liner.

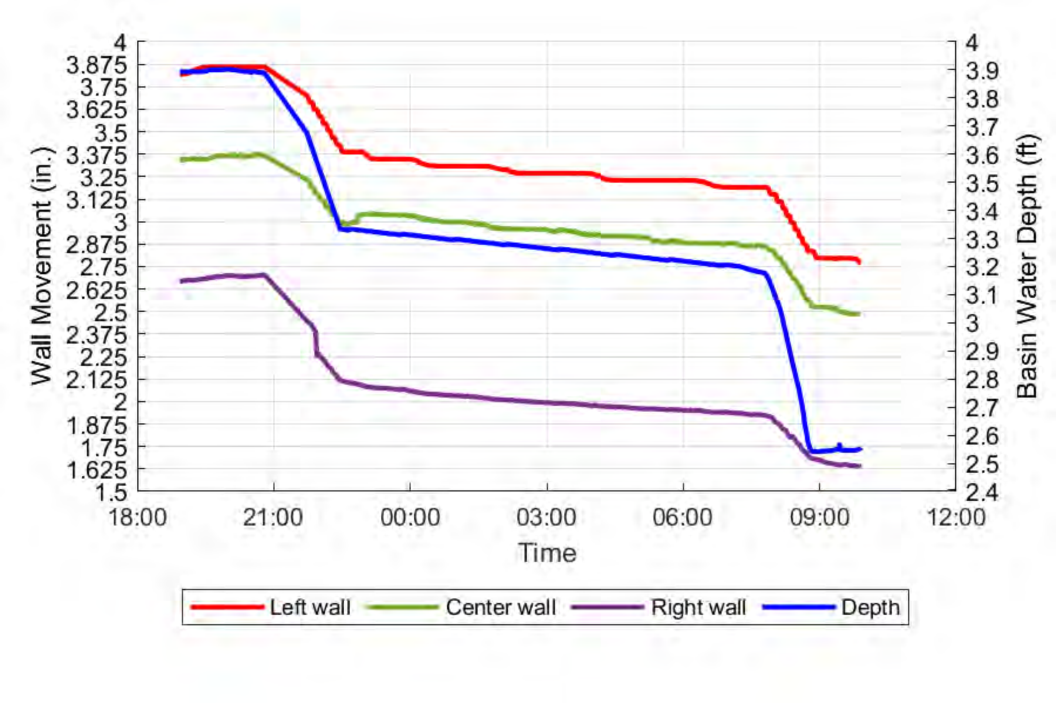

Figure 25. Movement of barrier between 22:30 28 Feb and 08:00 29 Feb.

Table 3. Flood barrier movement after the 100 percent depth hydrostatic test.

Wall	Position (in.)			Total movement (in.)
	end of hydrostatic test (20:33 28 Feb)	03:00 29 Feb	09:00 29 Feb	
Left	3.86	3.27	2.8	-1.06
Center	3.37	2.95	2.52	-0.85
Right	2.7	1.99	1.68	-1.02

Hydrodynamic Tests

Hydrodynamic tests included tests with waves and an overtopping test. The wave tests included small (2- to 3-in.), medium (6- to 8-in.), and large

(10- to 12-in.) wave heights, all with a 2-sec wave period. All wave heights were run at low water (66.7% of structure design depth) and repeated at high water (80% of structure design depth). For the 4-Foot Muscle Wall, 66.7% of structure design height was 2.63 ft. (31.5 in.), and 80% was 3.15 ft. (37.8 in.).

There are instances when tests produce wave-induced resonance in the basin which subjected the structure to much higher wave energies and much higher overtopping than structures which had been tested previously. Every basin has a natural frequency that is a function of depth and length. In the test basin, there is a natural frequency based on depth and the distance between the barrier and the wave generator. In some instances, incident and reflected waves can combine to produce very sharp wave crests and high overtopping rates.

Placement of the barrier in this test was such that the incident waves (2 sec period or 0.5/sec frequency) were a harmonic of the natural frequency, which initially resulted in resonance. There is evidence in internal reports of the occurrence of this wave phenomena during past flood barrier performance tests.

During the 80% depth wave testing some resonance appeared to be producing waves larger than 2”. Adjustments were made to the wave program to reduce the board stroke for the 6” and 11 inch waves, thereby correcting the issue.

The minor variabilities had no noticeable effect on the performance of the structure.

Low water, small waves

The small, 2 in. wave height test started was done on the 29 February 2020. Started at 09:54 and run for a total of seven hours at a basin water depth of 2.63 ft. or 66.7% the structure design height. This test was interrupted by a power outage at 16:41 that lasted a few seconds, and 9 minutes later the test continued. No damage or malfunction was observed in the equipment used in this test. The test successfully concluded at 17:05.

The seepage rates time series for this test is presented in Figure 26. The trend appears to have an inflexion point near the hour 13:00. This seems to be a continuation of the decreasing trend observed in Figure 23. Since the water depth was reduced by 8 in. in about an hour (between 08:00 and 09:00), it is possible that the floor crack outflow needed more time to stabilize and reflect the rate corresponding to the new water level. The mean seepage rate for the first three hours (09:54 to 13:00) was 0.087 gpm/ft., and 0.078 gpm/ft. for the remaining part. The total mean seepage rate was 0.082 gpm/ft. (all values adjusted for floor seepage of 0.002 gpm/ft.).

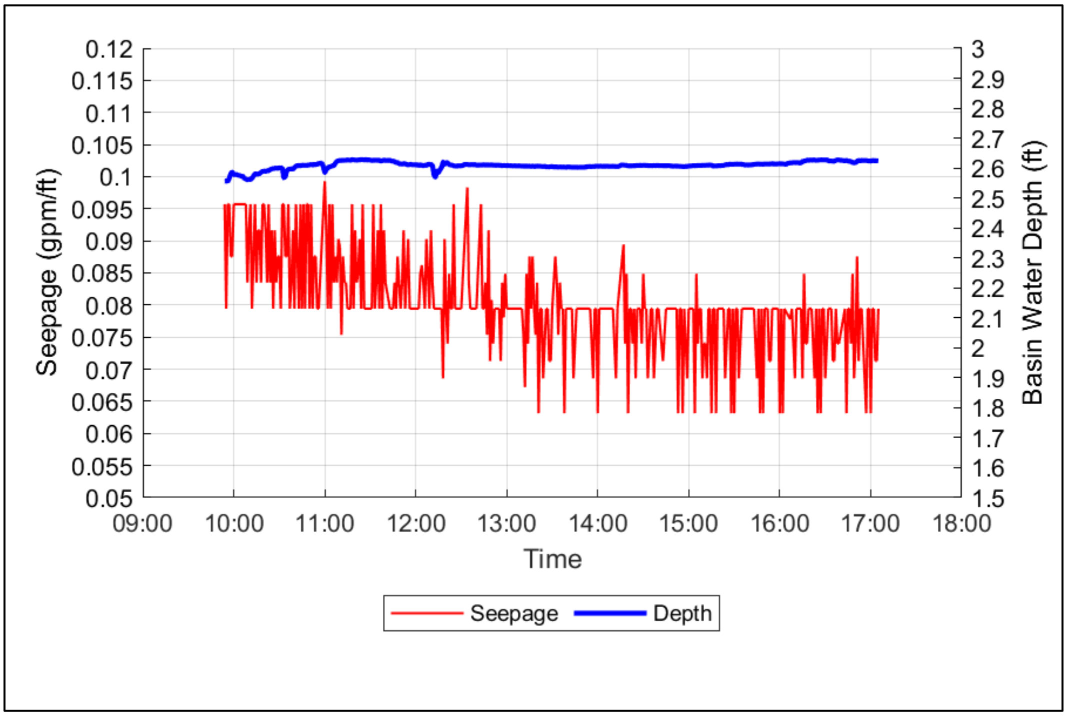

Figure 26. Seepage rates during test with small waves at low water depth.

There was no overtopping. The movement of the structure was minimal, as shown in Figure 27.

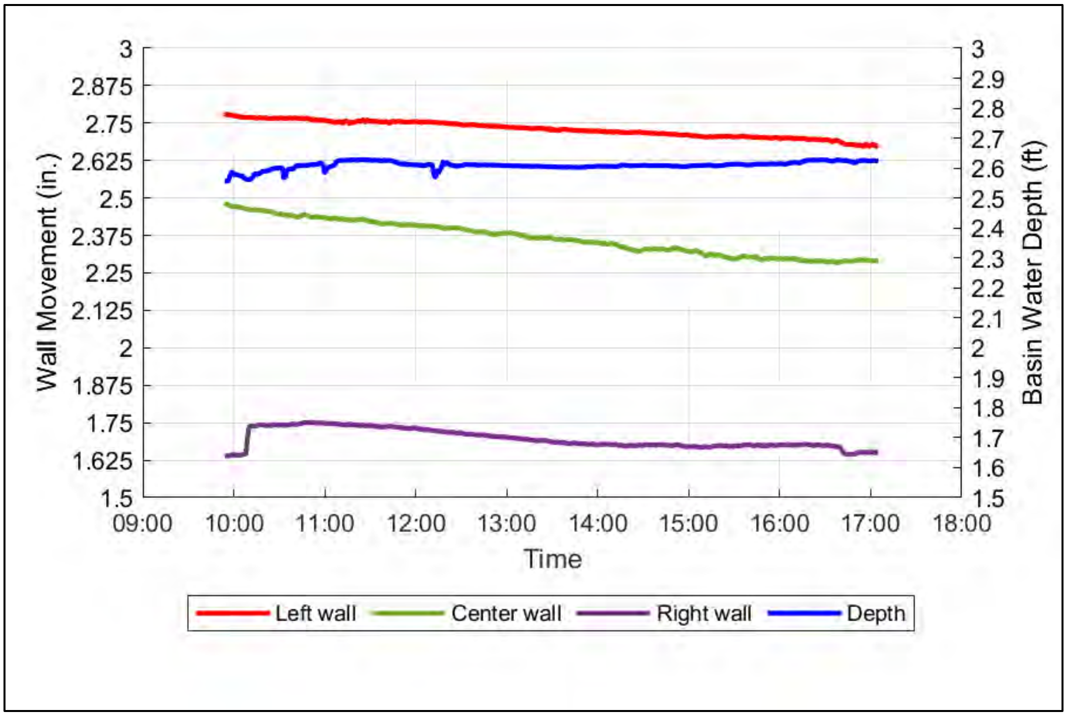

Figure 27. Movement of barrier during test with small waves at low water depth.

Low water, medium waves

The medium, 6- to 8-in. wave height test was conducted on 02 March 2020 (two days after the small waves test). Started at 08:03 and lasted about an hour. The basin water depth was 2.63 ft. (66.7% the structure design height). The medium waves were generated for three 10-minute runs with a stilling period between runs to allow the wave energy to dissipate and minimize wave energy buildup.

The seepage rates time series for this test is presented in Figure 28. The mean seepage rate was 0.066 gpm/ft., after adjusting for floor seepage of 0.002 gpm/ft. No overtopping was observed during this test. No significant movement of the structure was found from the laser data (see Figure 29.

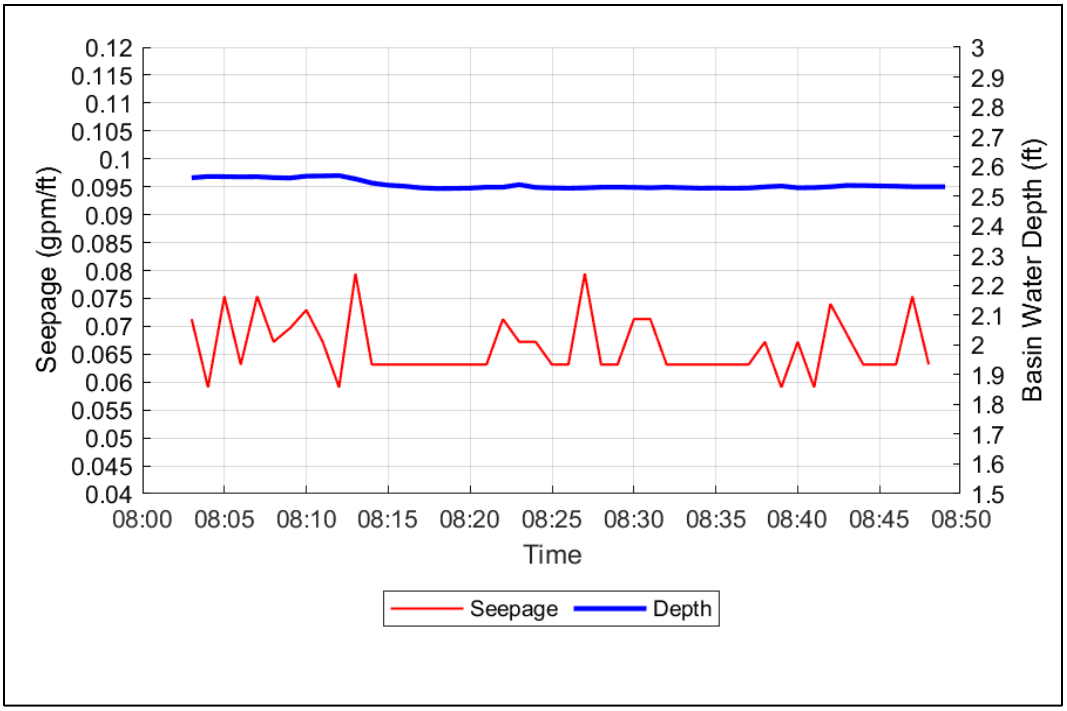

Figure 28. Seepage rates during test with medium waves at low water depth.

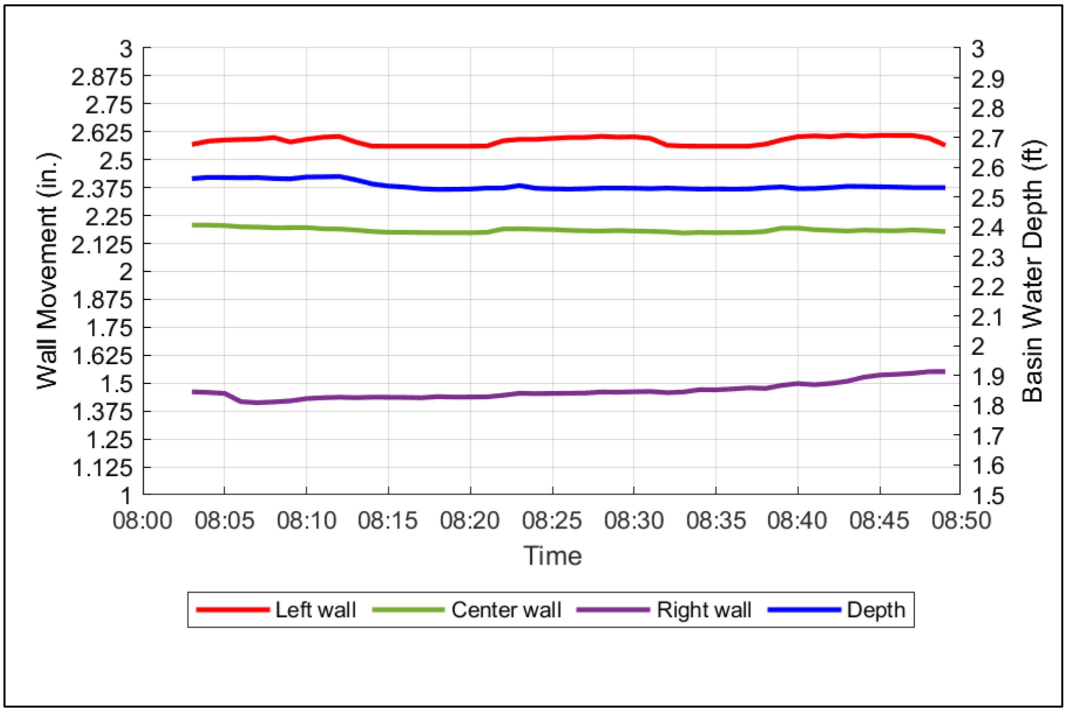

Figure 29. Movement of barrier during test with medium waves at low water depth.

Low water, large waves

The large waves were generated for a single 10-min run starting at 08:58. Waves overtopped the left wall near its center and near the wingwall; no overtopping of the right and center walls was observed (Figure 30). Average seepage rate (including overtopping) were 0.100 gpm/ft., adjusted for floor seepage (Figure 31). There was no noticeable movement of the flood barrier walls (Figure 32).

At the end of the test the basin water level was raised to 80% of the barrier height.

Figure 30. Overtopping during the test with large waves at low water.

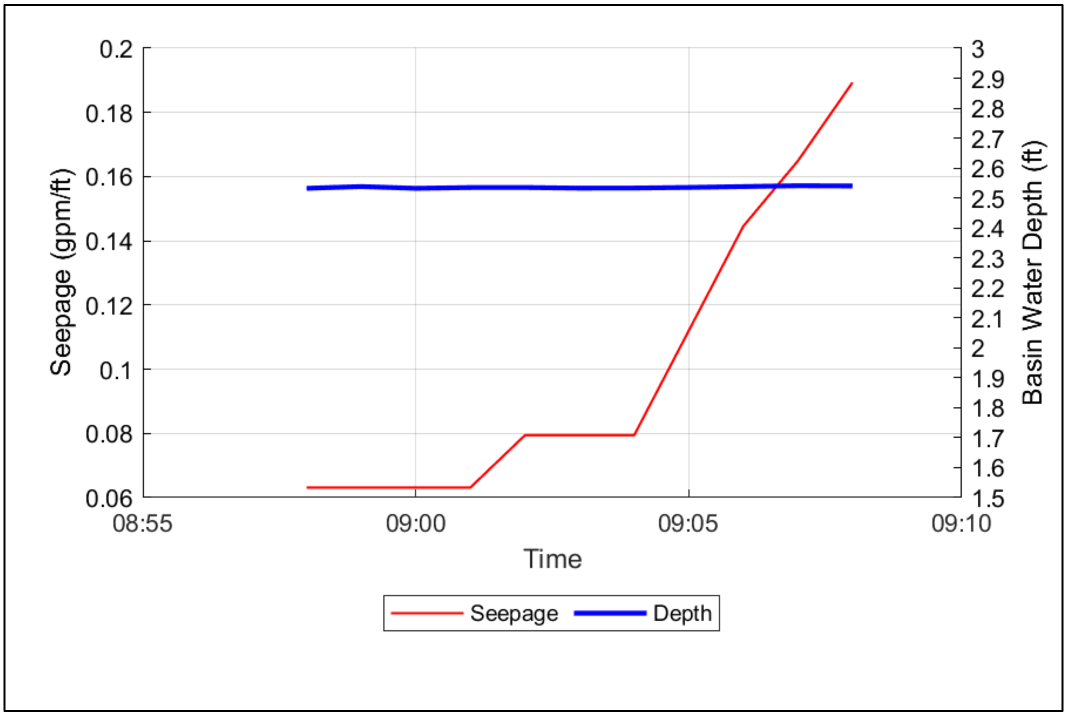

Figure 31. Seepage rates during test with high waves at low water depth.

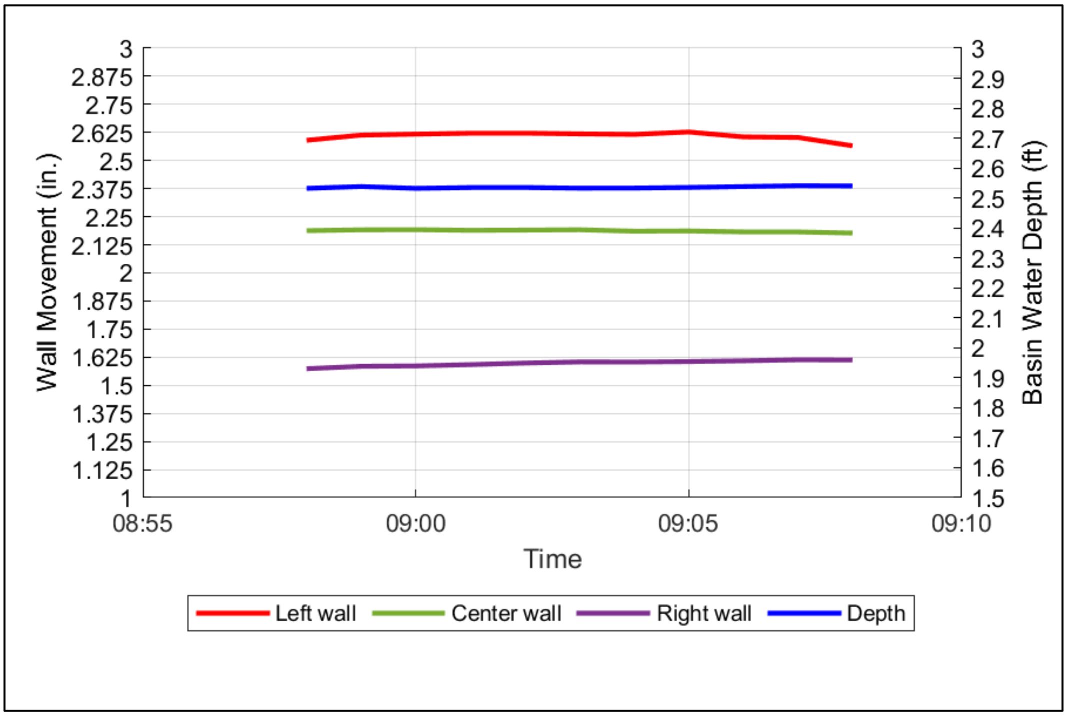

Figure 32. Movement of barrier during test with high waves at low water depth.

High water, small waves

The water level was raised to the 80% structure height of 3.15ft or 37.8 in. on 02 March 2020. High water tests were included in the protocol to insure that there would be some overtopping of the structure due to the wave action. The original protocol called for the small waves to be run for another 7 hours (as they were for the low water level), but this seemed unnecessary for structures that were not affected by the small waves. The protocol was therefore modified such that small waves at high water would be run for a minimum of one hour, and could be run for up to seven hours at the discretion of the testing engineer. If the engineer had any questions about the effects of the small waves on the structure, he could continue the tests for up to the full 7 hours. However, if the waves were having no effect on the structure, he could end the test after a minimum of one hour. For the 4-Foot Muscle Wall, the small waves had no noticeable effect on the structure and the test was run for only one hour.

The pumps were turned on at 09:15 to raise the basin water depth. The small waves test started at 10:50. Average seepage rate was 0.066 gpm/ft. (adjusted for floor seepage; see Table 2) for the time series shown in Figure 33. According to the laser measurements, the flood barrier walls moved about 0.25 in. while the basin was being filled. However, there were no significant effects found in the data not observed during the test execution. The wall movement is summarized in Table 4, and the time series per wall are illustrated in Figure 34 for the basin filling time period and the test duration.

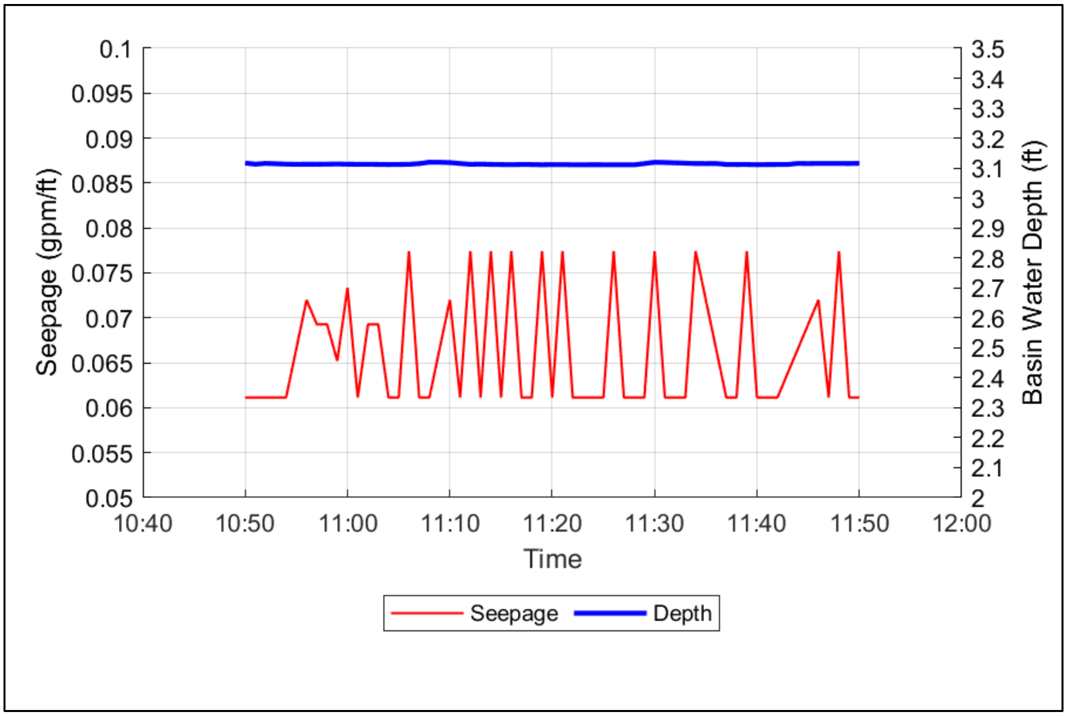

Figure 33. Seepage rates during test with small waves at high water.

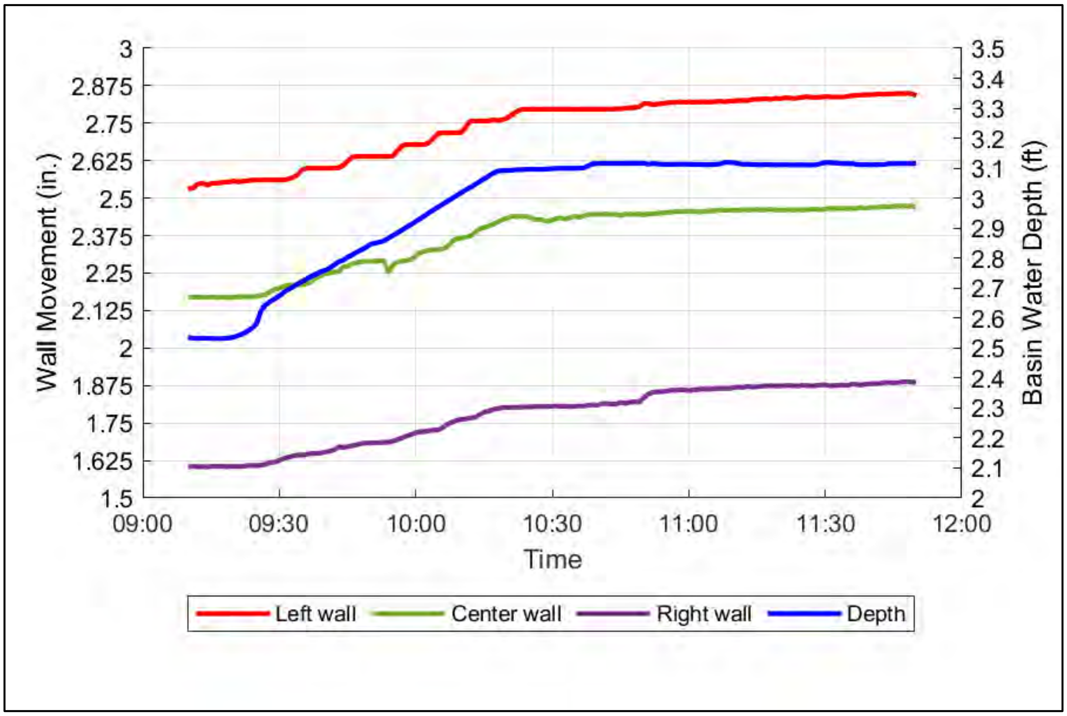

Figure 34. Movement of barrier during filling of basin and test with small waves at high water.

Table 4. Summary of barrier movement during test with small waves at high water.

Wall	Position (in.)			Total movement (in.)
	09:15	10:50	11:50	
Left	2.55	2.82	2.84	0.29
Center	2.17	2.44	2.47	0.30
Right	1.61	1.83	1.89	0.28

High water, medium waves

The three runs of medium waves (6- to 8-in. wave height) were run for 10 minutes each with an approximate 6 minute stilling period between each Figure 35. The test started at 12:41 02 March 2020.

Overtopping was observed near the center of the left wall. The peak measured overtopping rates (one-minute average) was 0.16 gpm/ft. and the average overtopping rates for the 10-min runs was 0.12 gpm/ft.

Figure 35. Flood barrier during the test with medium wave heights at high water.

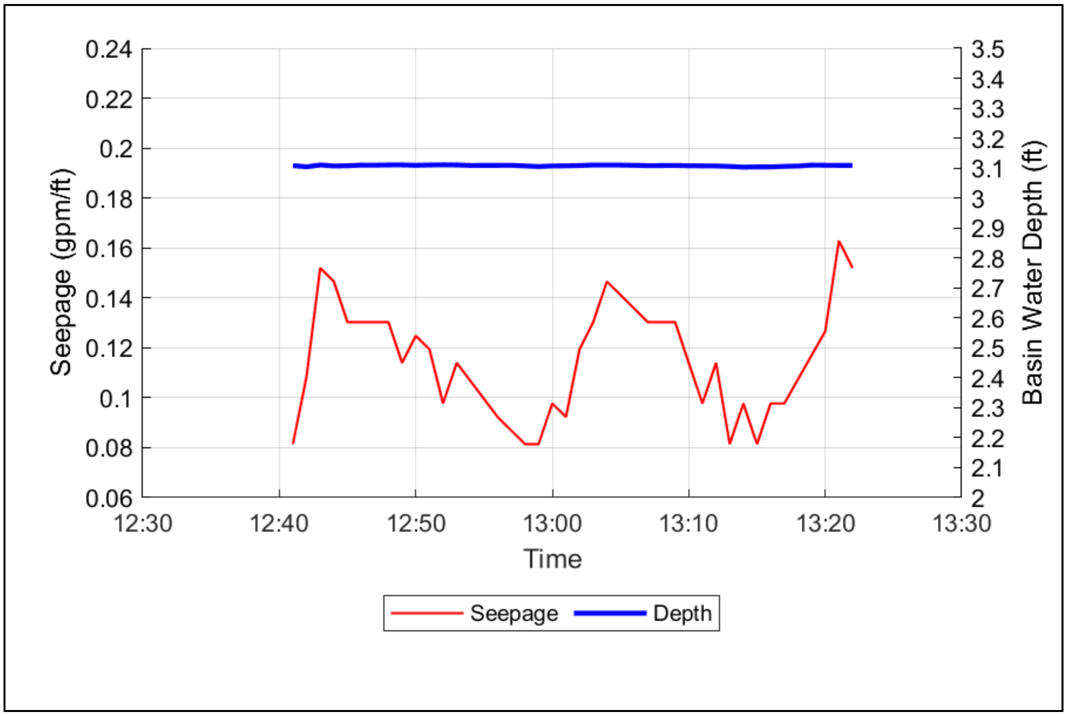

Figure 36. Seepage rates during test with medium waves at high water.

Although no movement of the barrier was observed during the tests, the data show a slight movement inward for the right wall (about 0.25 in.). The medium waves had little effect on the left or center walls (Figure 37).

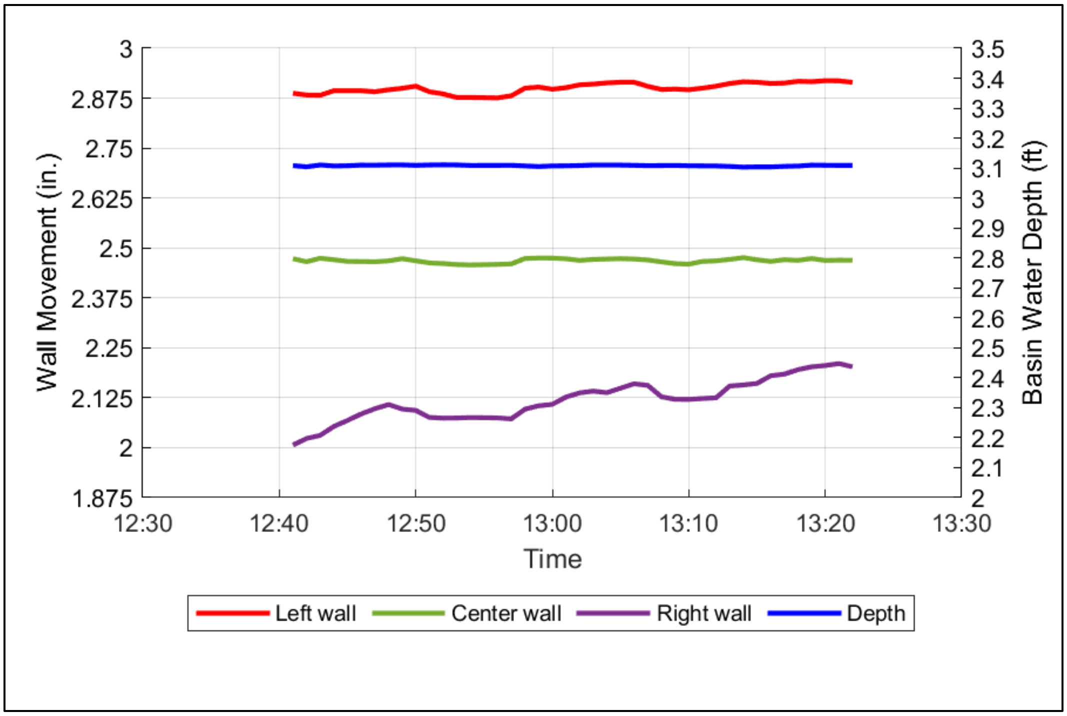

Figure 37. Movement of barrier during test with medium waves at high water.

High water, large waves

The 10-minute large waves test started at 13:32. Overtopping occurred at the center of the left side wall and at its connection with the wingwall. The waves were also splashing the right side wall near the wingwall. The overtopping reached a peak of over 1.011 gpm/ft. and averaged 0.639 gpm/ft. (Figure 38). No significant wall movement was observed (Figure 39).

Evaluation of 4-Foot Muscle Wall Flood Fighting Barrier, US Army Engineer Research and Development Center Coastal and Hydraulics Laboratory, Efrain Ramos-Santiago, Curtis Blades and James D. Gutshall, May 2020.

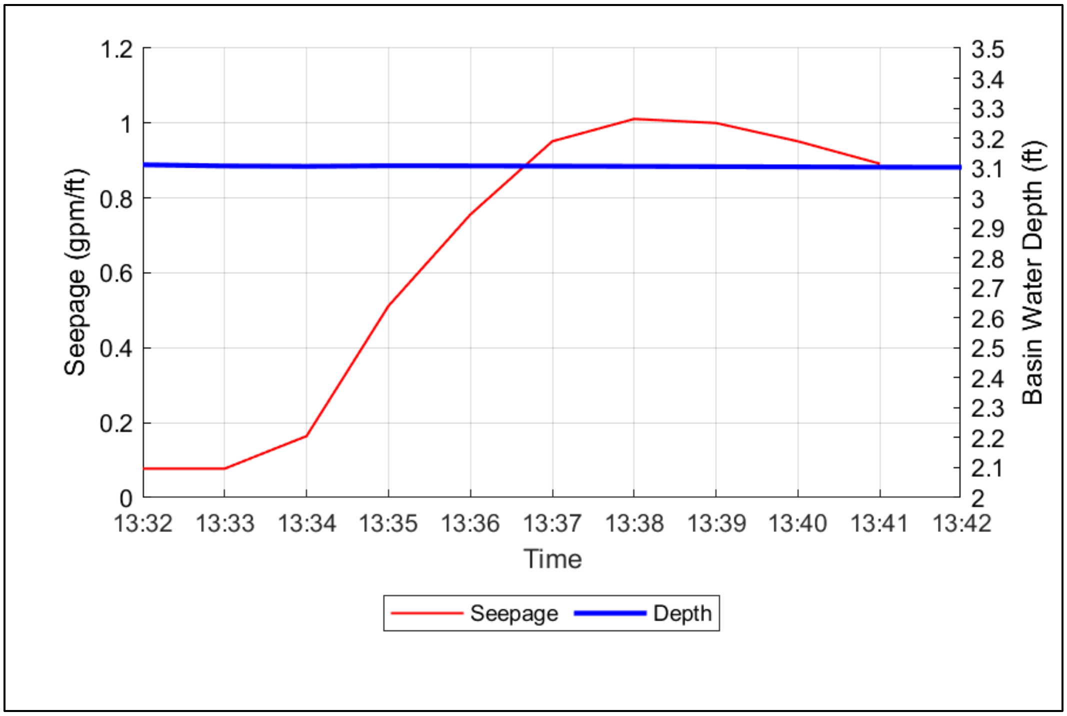

Figure 38. Seepage rates during test with large waves at high water.

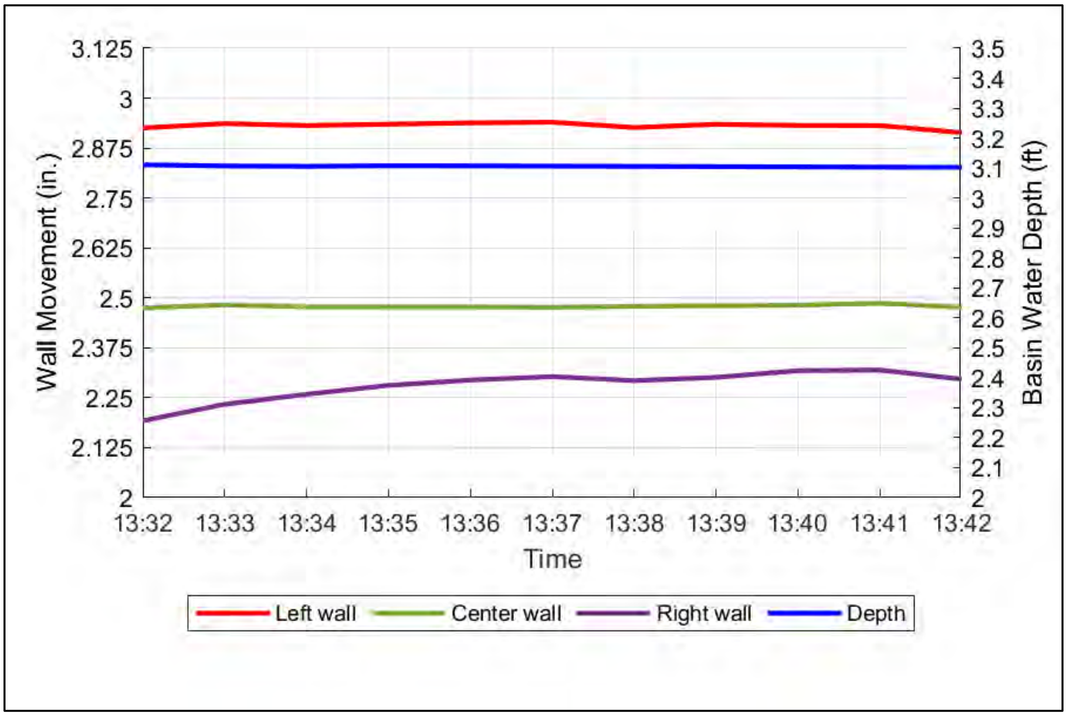

Figure 39. Movement of barrier during test with large waves at high water.

Overtopping

The overtopping test was conducted by raising the water level in the basin until water was flowing over the barrier at an average depth of 1 in. Because the liner cover was not tighten up to the barrier's top side, the crest elevation of the flood barrier varied which caused some areas of overtopping to be greater than others, while some areas had no overtopping. The test engineer estimated when the overtopping reached an average depth of 1 in., then stopped filling the basin and allowed the water to overtop the barrier for one hour before opening the drain and lowering the water level in the basin (Figure 40).

An average of one inch overtopping was estimated to be reached at 13:35 at a basin depth of 4.1 ft. The test was successfully conducted. The seepage pit pumps were turned off in order to use the diesel pumps. No problem arose with the diesel pump system that recirculates the water to the basin. The laser system continued to collect wall movement data (Figure 41). The maximum inward movement of the each wall recorded by the lasers was as follows: 4.73 in. at left wall, 4.36 in. at center wall, and 4.45 in. at right wall. This quantities are a total respect to the pre-flood wall position measured the first day of this study.

Throughout the test, the 4-Foot Muscle Wall retained structural integrity and suffered no noticeable damage.

Figure 40. Overtopping of 4-Foot Muscle Wall during overtopping test.

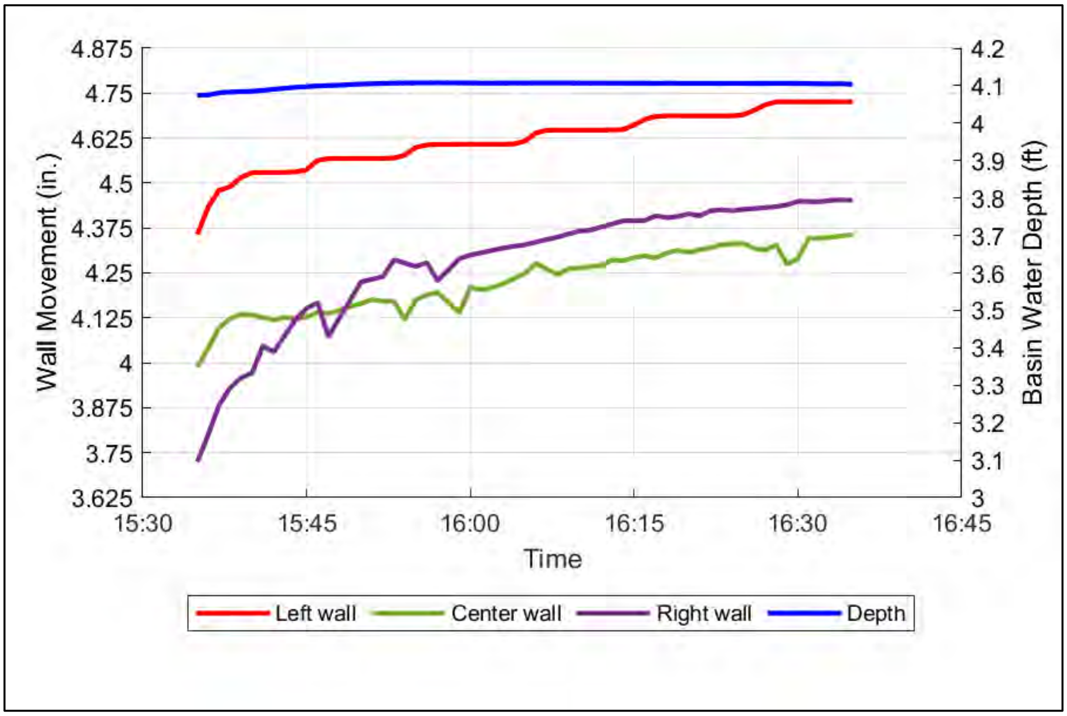

Figure 41. Movement of barrier during overtopping test.

The test basin was drained after this test was concluded at 16:45 04 March 2020. This was a necessary action in order to setup the test basin to perform the debris impact test and the riverine current test. The setup was done during the morning of 05 March and pumps started filling the basin around 12:20. Therefore, the 4-Foot Muscle Wall had another rebound due to the lack of hydrostatic pressure. The recorded outward movement (into the basin wet-zone) of the barrier is summarized on Table 5. Again, the total movement values are negative since the walls moved outward the dry-zone.

Table 5. Summary of barrier movement before impact test.

Wall	**Position (in.)**		**Total movement (in.)**
	16:35 02 Mar	07:40 04 Mar	
Left	4.73	2.86	-1.87
Center	4.36	2.17	-2.19
Right	4.45	2.41	-2.04

Debris Impact Test

To test flood fighting structures for their ability to withstand impact from debris carried by the current in an actual flood, a debris impact test is included as part of the Standardized Testing Protocol. The debris impact test involves towing two logs into the barrier with a winch located inside the test area (Figure 42). On 04 March 2020, the logs were towed in at a 20-deg angle at a speed of 5 mph (7 ft./sec), and power to the winch was cut just prior to impact with the structure. Both logs were 10-ft-long and cut from a creosote-coated telephone pole. The smaller log was 12 in. diameter and weighed 610 lbs. dry; the larger log was 16.5 in. diameter and weighed 790 lbs. dry. Both logs had been soaking in water for 1-1/2 weeks prior to testing and undoubtedly had increased in weight. A piece of plywood was placed on top of the barrier to protect the plastic and fabric from being torn by the cable (Figure 43).

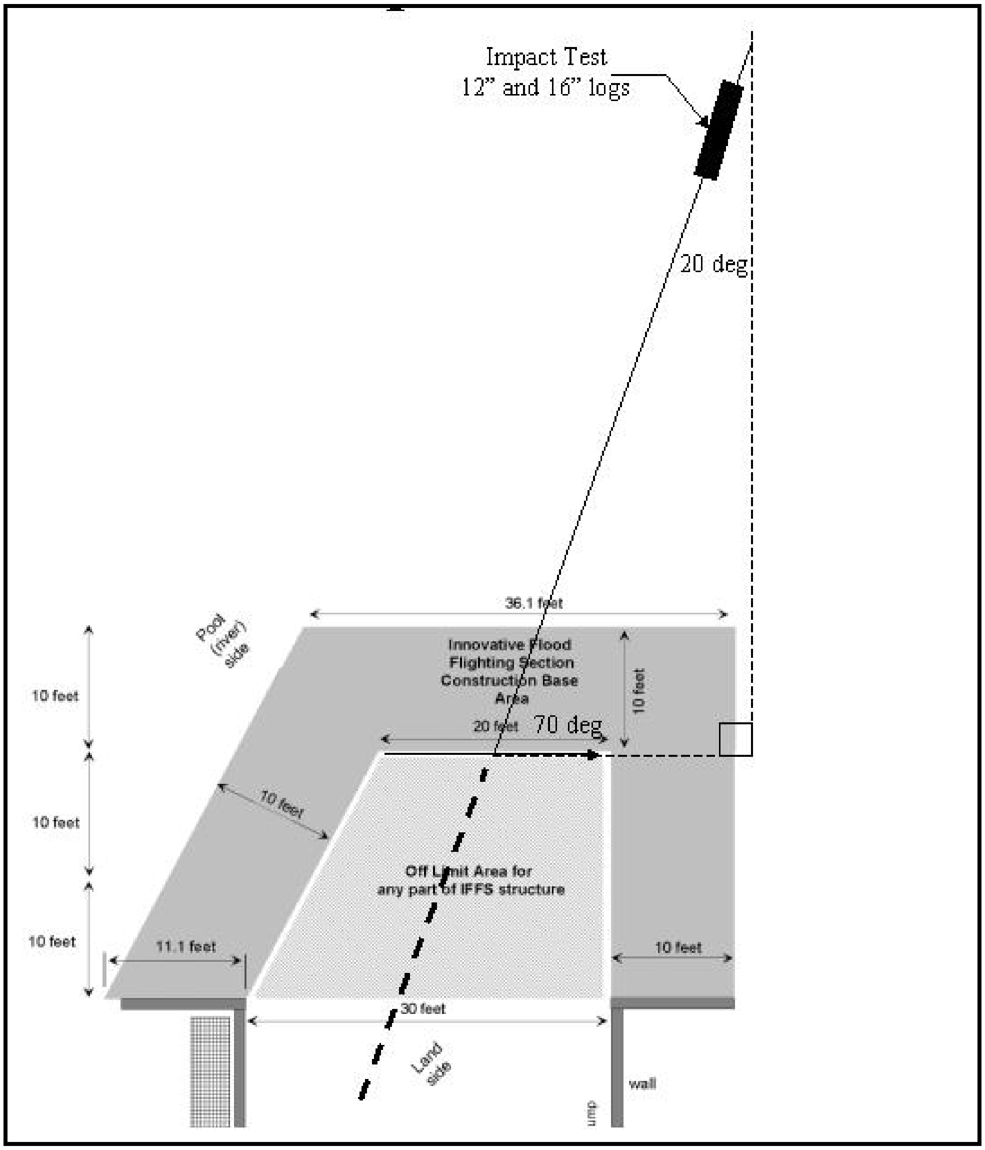

Figure 42. Setup for debris impact tests.

Figure 43. Plywood setup for liner cover protection at center wall.

Figure 44. Snapshot of the large log impacting the center wall.

The two logs were towed into the structure one at a time, the smaller log first. This test was conducted from 08:26 to 08:52, taking about 26 minutes since there were two unsuccessful impacts with the small log (the winch stopped with log around 6 ft. from the wall). An acceptable impact is obtained when the log is pulled to about a foot from the barrier's center wall. Afterwards, the test was conducted successfully and neither log caused any noticeable damage to the liner cover or to the structure. The debris impact tests were conducted at a water depth of 66.7% of structure design depth. During this test, it went unnoticed that the laser stopped measuring the basin water depth. The foam buoy got stuck when the basin was completely drained and the laser signal was lost. Meanwhile, a wooden ruler was used to check the water depth.

The average seepage rate recorded by the laser system was 0.186 gpm/ft., after removing the estimated 0.002 gpm/ft. floor crack outflow (refer to Table 2). This high seepage rate was due to a technical error, since the seepage pit pumps were not turned on after the overtopping test concluded. Hence, there is no clear idea of how this was affected during test, even though the mean value is still below the 0.25 gpm/ft. maxima required by the FM 2510 Standard, Chapter 4.

The movement values measured with the lasers for this test are summarized in Table 6. The center wall appears to have moved inward about a quarter of inch during this test.

Table 6. Summary of barrier movement during impact test.

Wall	**Position (in.)**		**Total movement (in.)**
	07:40 04 Mar	08:52 04 Mar	
Left	2.86	2.87	0
Center	2.17	2.40	0.23
Right	2.41	2.40	0

Riverine Current Test

Channel Setup

As explained before, the basin was drained overnight after the overtopping test. On the morning of 03 March, the Bobcat™ skid-steer loader entered the basin to install a guide vane along the right wall of the barrier. The guide vane was installed to direct water flow from a manifold over to within 6 in. of the right wall of the barrier to concentrate the flow and increase the flow velocity through the reduced cross section.

The initial setup of the 4-Foot Muscle Wall included extending the liner cover an additional 8 ft. from barrier toe into the wet-zone floor, along the barrier perimeter. The outward end of the liner was taped to the floor and covered with masonry blocks. The line of blocks in front of the right wall was partially removed and three heavy duty foam boards were placed over the liner (Figure 45). Small rectangular concrete blocks, 1.5 in. thick, were placed on top of the boards to support the metal frames. The guide vane was then placed in order to get within 6 in. of the barrier (Figure 46). Two additional metal frames were placed on top of the guide vane to hold it down (Figure 47). The materials used for this setting were provided by the CHL staff. The masonry blocks were borrowed from the basin facility.

Once the setup was completed, the pumps were turned on to start filling the basin.

Figure 45. Placement of foam boards.

Figure 46. Placement of the guide vane.

Figure 47. Placement of additional metal frames to hold down the guide vane.

Test execution

After ending the debris impact test on 04 March, around 09:00 the diesel pumps used for generating the riverine current were turned on. The necessary valves were opened to allow flow from and to the basin, and prime the pumps. Afterwards, these were engaged and slowly increased the engine's revolutions per minute (RPM) to generate the 7 ft. /sec channel flow velocity. A Valeport™ Model 802 EM Flow Current Meter was used to monitor the water velocity at the end of the channel. At 09:56, the required flow velocity was reached with the pumps set at the maximum 2000 RPM. The current was maintained for one hour. The riverine current test is shown in Figure 48.

Figure 48. Snapshot of the riverine current test (taken from on top of the right wingwall).

The average seepage rate recorded by the laser system was 0.186 gpm/ft., after removing the estimated 0.002 gpm/ft. floor crack outflow (refer to Table 2). This is the same rate recorded during the debris impact test earlier that day. The seepage pit pumps were still off. No significant changes in leakage through the wall was observed inside the dry-zone, compared to what was seen when the impact test was performed. Still, the mean value is still below the 0.25 gpm/ft. maxima required by the FM 2510 Standard, Chapter 4.

The movement values measured with the lasers at the end of test are summarized in Table 6, along the values reported for the debris impact test. The right wall appears to have moved inward about a quarter of inch during this test. No damage to the barrier was observed during the current test.

Table 7. Summary of barrier movement during riverine current test.

Wall	**Position (in.)**		**Total movement (in.)**
	08:52	10:56	
Left	2.87	2.87	0
Center	2.40	2.44	0.04
Right	2.40	2.67	0.27

Post Hydrostatic Test

The FM 2510 Standards required this test to be run for 22 hours. However, if the structure does not underperforms during the first hour, the engineer is provided the opportunity to end the test. For the 4-Foot Muscle Wall, the hydrostatic forces had no noticeable effect on the structure and the test was run for only one hour. The ERDC Standard Testing Protocol does not requires the engineer to perform a post hydrostatic test.

The pumps were turned on again at 11:30 on 04 March 2020 and a water depth of 3.94 ft. was reached at 13:25. The test concluded at 14:25. Average seepage rate was 0.085 gpm/ft. (adjusted for floor crack outflow; see Table 2) for the time series shown in (Figure 49). The wall movement is summarized in Table 8, and the time series per wall are illustrated in Figure 50 for the test duration. As expected, the barrier walls moved significantly compared to the position recorded by the end of the riverine current test, but did not surpassed the 6 in. maximum permanent deflection required by the Standards.

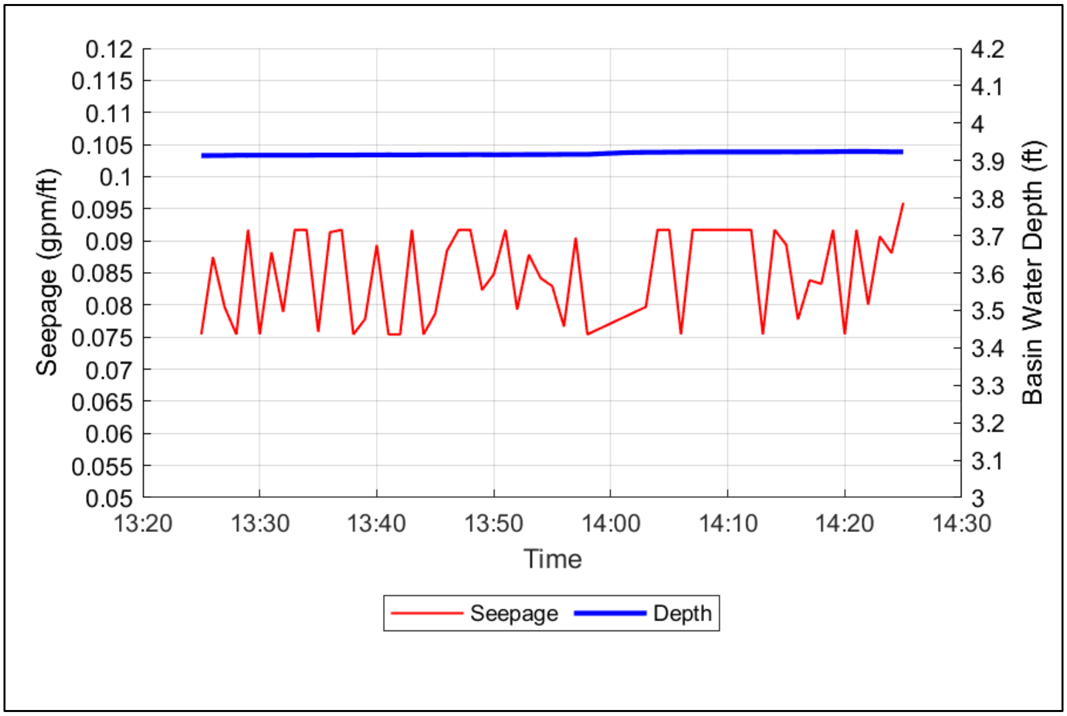

Figure 49. Seepage rates during post hydrostatic test.

Table 8. Summary of barrier movement during post hydrostatic test.

Wall	Position (in.)		Total movement (in.)
	13:25	14:25	
Left	4.41	4.57	0.16
Center	4.06	4.22	0.16
Right	3.75	3.93	0.18

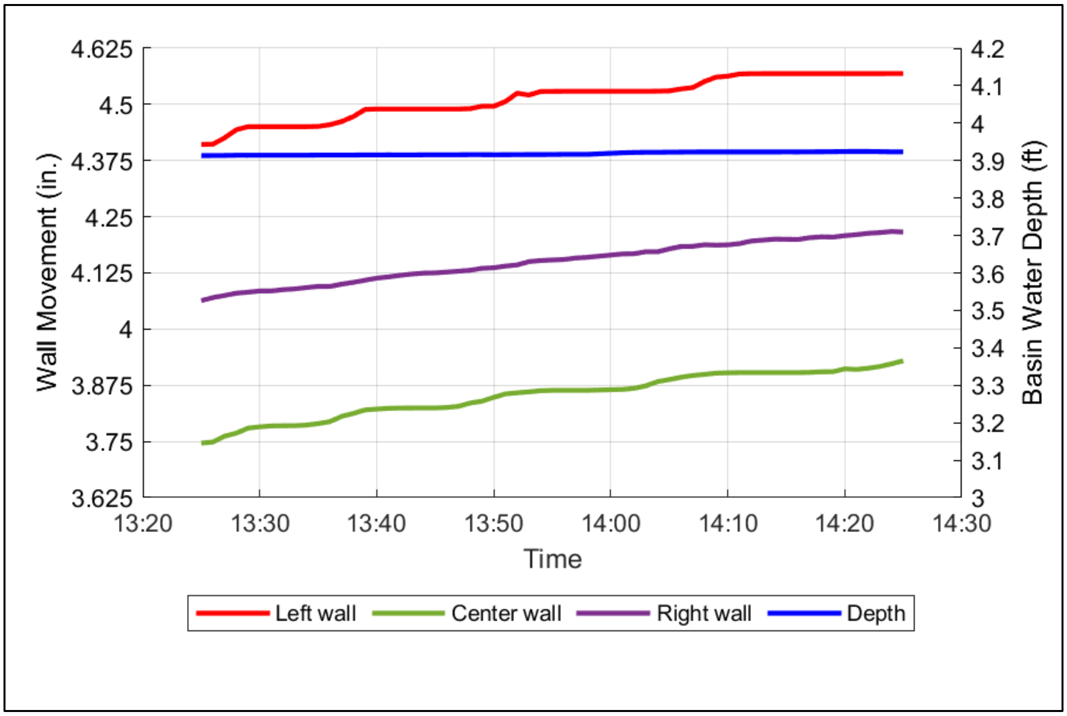

Figure 50. Movement of barrier during post hydrostatic test.

Disassembly

The removal of the 4-Foot Muscle Wall was originally scheduled for the 17 March 2020. Due to the CoVID-19 pandemic situation on spring 2020, a travel ban was imposed to all USACE facilities until 01 May 2020. Therefore, the disassembly of the flood barrier was postponed until further notice.

3 Summary

Construction Times and Seepage

Times for construction, repair and disassembly, and seepage rates are shown in Table 9.

Table 9. Summary of Tests with 4-Foot Muscle Wall flood fighting barrier.

Test	**Measurements**
Construction/Repairs/Disassembly	
Construction (man-hrs)	7.5
Disassembly (man-hrs)	TBD
Hydrostatic Seepage Rates (gpm/ft)	
1 ft. Head	0.026
2 ft. Head	0.058
100%H Head (3.94 ft.)	0.135
Post, 100%H Head (3.94 ft.)	0.085

The seepage rates listed are the average over the full duration of the hydrostatic tests.

Other Factors

Constructability and Re-usability

No large power equipment was needed to assemble the barrier, indicating that it is suitable for areas where heavy equipment may not have access. The only power equipment used for assembly or disassembly was a Bobcat™ skid-steer loader. Other equipment were hand power tools like an electric fan blower, a heat gun, a power drill, and a reciprocating saw; and manual hand tools like a pallet jack truck, a manual applicator gun, a smooth carpet seam roller, measuring tape and a broom. Supplies used included the masonry or construction blocks, heavy-duty construction tape, and heavy-duty glue.

The barrier is designed to be largely recoverable. This will have to be further evaluated after the barrier is finally disassembled.

The barrier was constructed on a flat concrete floor. In a real application, the wall units will have to rotate or turn to conform to irregularities in the ground.

The barrier was able to easily handle a 90 degree angle and a 63 degree angle in planform, and to abut perpendicularly to a vertical wall and to abut at an angle to a vertical wall.

Environmental

Because the main parts of the barrier are recoverable, the environmental impact is minimal.

Additional Information

The unit tested at ERDC was a 48-in.-high hollow plastic wall called the 4-Foot Muscle Wall. Muscle Wall units are also available in 2 ft. x 6 ft., 3 ft. x 6 ft., and 8 ft. x 4 ft. Additional information is available on the Vendor's website at www.musclewall.com .

Comparison to Sandbags Baseline Data

Table 10 compares measured parameters from the 4-Foot Muscle Wall flood fighting barrier tests reported herein to baseline data collected in 2004 with a sandbag barrier following the same protocol. The sandbags took 27 times the man-hrs to construct and had 4 times the seepage at the deepest depth tested (hydrostatic tests). In addition, sand was washed out of the sandbags during the waves test causing significant damage that had to be repaired, then the sandbags failed during the first minutes of the overtopping test when the top layer of bags was washed off the crest of the barrier then damage progressed further down into the sandbag mound with additional bags being washed off into the test area (Pinkard et al., 2007). In contrast, the 4-Foot Muscle Wall withstood all tests without damage.

Damage and Seepage

There was no damage to the barrier during any of the tests.

Maximum seepage rate during hydrostatic testing was 0.135 gpm/ft. at a basin depth of 3.94 ft. None of the dynamic tests (waves, overtopping, debris impact, riverine current) appeared to have any effect on the rate of seepage under or through the barrier.

Table 10. Comparison of 4-Foot Muscle Wall Flood Protection Barrier to sandbag baseline data.

Install/Remove	**4-Foot Muscle Wall**	**Sandbags**
	Man-hrs	
Construction	7.5	205.1
Repair 1	N/A	2.0
Repair 2	N/A	2.0
Repair 3	N/A	2.0
Disassembly	TBD	9.0
Depth (ft)	**Seepage (gpm/ft)**	
1.0	0.026	.05
2.0	0.058	.23
3.94	0.135	.53

4 Conclusions

The 4-Foot Muscle Wall barrier system proved to be an expedient and effective flood barrier. Compared to the baseline sandbag barrier of comparable length and height, the 4-Foot Muscle Wall barrier system was faster to construct and remove with fewer people and less equipment, had less seepage, and was more resilient to waves and overtopping. Under the conditions required by the Standard Testing Protocol, the 4-Foot Muscle Wall outperformed or met the performance of the baseline sandbag test in every way.

Tests were conducted on a flat, even surface. Use of the 4-Foot Muscle Wall on an irregular or sloping surface was not tested.

5 References

Pinkard, F., et al. 2007. "Flood Fighting Structures Demonstration and Evaluation Program: Laboratory and Field Testing in Vicksburg, Mississippi," ERDC Technical Report TR-07-3, July 2007. 306 pp. https://erdclibrary.on.worldcat.org/oclc/164815737

Wibowo, Johannes L., and Donald L. Ward. 2016. "Evaluation of Temporary Flood-Fighting Structures." *3rd European Conference on Flood Risk Management (FLOODrisk 2016)* 7: 10. https://doi.org/10.1051/e3sconf/20160703017.