2 Laboratory Testing and Evaluation of Expedient Flood-Fighting Barriers

Introduction

This section of the report documents the laboratory testing and performance of selected commercial vendor-furnished flood-fighting barrier products. Three selected commercial products and a USACE sandbag barrier were tested and evaluated by identical protocol in a controlled laboratory setting. Each of the four barriers (USACE sandbag levee, Hesco Bastion levee, RDFW levee, and Portadam levee) were constructed, tested, and evaluated by ERDC personnel in an ERDC laboratory. Each given barrier was constructed, tested using controlled hydrostatic wave-induced (hydrodynamic) and impact loadings, and removed from the laboratory prior to beginning the same sequence for the next barrier. All tests were conducted and evaluated using one common protocol (Appendix C) in the most objective manner possible, under full oversight and agreement of the respective vendor's representative(s).

Experiment Overview

The four full-scale flood-fighting barriers (levees) were constructed, tested, and evaluated in a controlled laboratory setting by personnel from ERDC's Geotechnical and Structures Laboratory (GSL), Coastal and Hydraulics Laboratory (CHL), Information Technology Laboratory (ITL), and Directorate of Public Works (DPW). Each levee was constructed in a testing zone within a 30-ft length opening inside the wave basin enclosed by the CHL Jay V. Hall steel hangar (Bldg. 6006). Each levee was constructed within a common geometric testing zone laid out on a smooth concrete floor. Fresh clean water was impounded against each levee for specified common test configurations simulating floodwater conditions. At test conclusion, the water was drained and each levee was disassembled for removal from the testing zone.

The levees were built to a height of 3 ft on a finished concrete floor to eliminate foundation settlement, seepage, and scour variables present at actual field sites. The levees were constructed with a 20-ft length wing wall on one side to test the 90-deg corner connection and a 22-ft wing wall on the other side to test the 63-deg corner connection. The levee face parallel to the wave machine was 30 ft long. Hydrostatic testing was performed at various water levels and hydrodynamic testing was performed with wave action of increasing magnitude. In addition, impact testing during hydrostatic loading was conducted to simulate effects of floating debris during flood conditions. No capability existed in the test basin to generate large steady-state currents along the face of the levees, thus the effects of floodwater currents were not evaluated. When waves pass by the side with a 63-deg corner, the water has an apparent current. During each test, the respective barriers were instrumented and monitored for seepage rate and lateral deflection. Visual observations of material loss, structure response, and failure patterns also were made for each levee.

Visual observations were noted for several criteria in addition to test performance. These observations included constructability concerns (geometric footprint constraints, ease of construction, manpower and equipment requirements, time and cost requirements); sustainability concerns (maintenance and repair during testing); disassembly and storage concerns (manpower, equipment, time, and cost); and environmental concerns (material safety and decontamination aspects).

Testing Equipment and Procedure

Test facility layout and construction

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. 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 2-1). A geometric testing zone footprint was laid out on the concrete floor and all levees were 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. 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 it causes an apparent current along the 63-deg wall.

On the protected side of the levee, a circular pit with an 8-ft diam by 8-ft-deep circular pit was designed and constructed to catch any seepage or overflow water from the structure. Two 4-in.-diam pumps are installed in the 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 pit when the capacity of the 4-in. pumps was exceeded.

The walls were constructed of concrete masonry blocks as shown in Figure 2-1 with concrete knee braces added on the pool side. The walls and knee bracing were locked in place with rebar grouted into the floor of the wave basin and into the knee braces to prevent the walls from moving. The knees were placed on the outside of the wall due to physical constraints of the equipment storage and instrumentation requirements. Aluminum walkways were placed on the block walls.

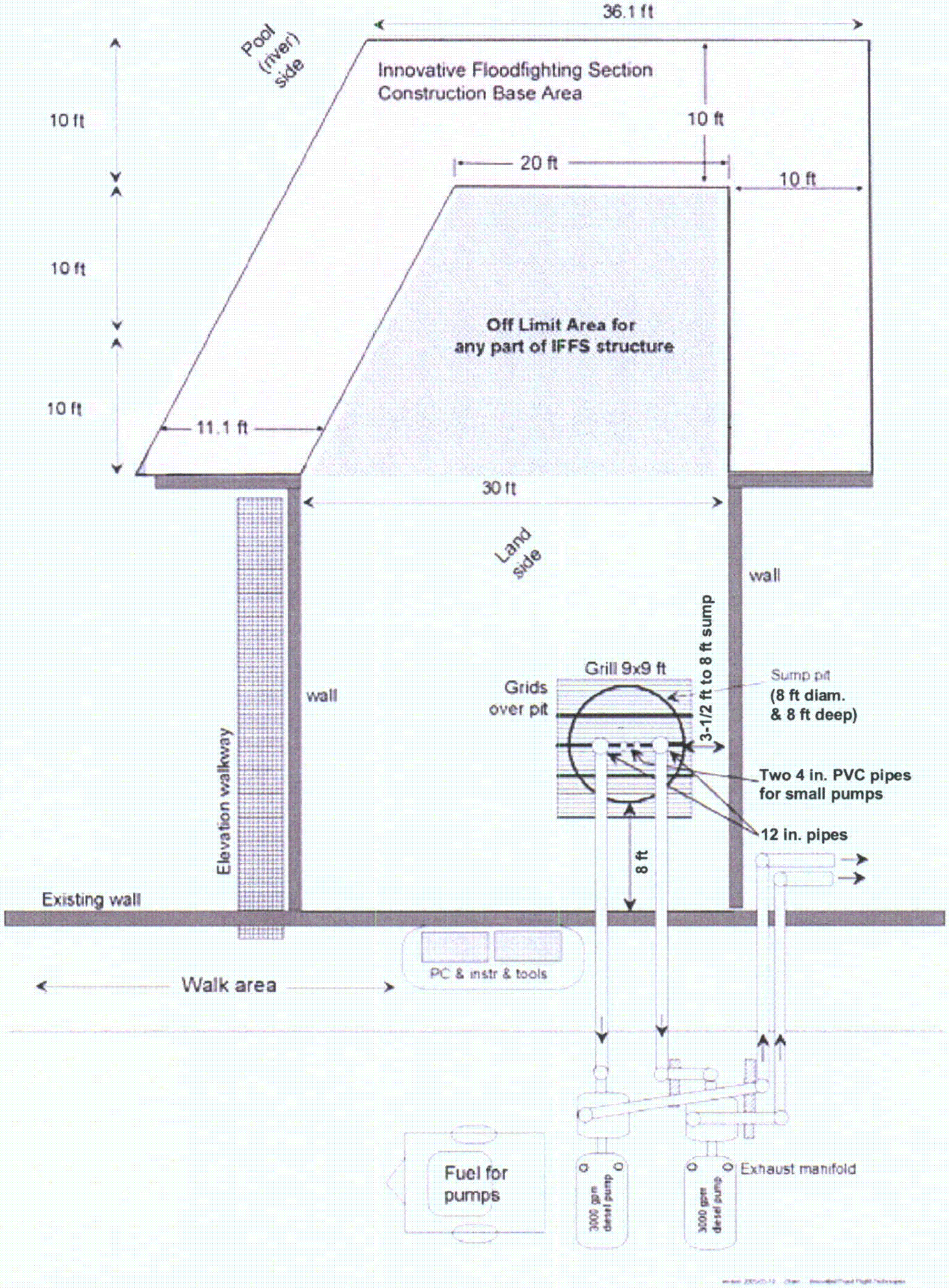


Figure 2-1. Layout of laboratory test facility

The 8-ft-diam circular sump was manufactured from an 8-ft-long corrugated steel culvert with a welded steel bottom and was placed in an excavated hole 9 ft below floor grade. A 1-ft-thick reinforced concrete slab was poured in the bottom of the hole, the vertical cylinder was installed, and a 1-ft-thick concrete mass was placed on the bottom of the cylinder. Concrete was placed around the cylinder's periphery and formed to fit the lattice steel walkway at the top of the culvert.

Two 4-in.-diam pumps were installed in the sump pit bottom. The two pumps are switched on as the water level reaches its upper float elevation (limit) and off as it reaches a lower float elevation (limit). The float with switching equipment work to control the pumps. The system with pumps, switch controls, manifolds, valves, and flow meters is shown in Figure 2-2. Each pump has a maximum flow capacity of 326 gpm against a 12-ft head, which is sufficient for all projected seepage rates (except levee overtopping).

Figure 2-2. Sump pit containing two 4-in. pumps. Top left: top of sump pit. Top right: power control panel. Bottom left: 4-in. pumps in pit. Bottom right: 4-in. valves and flow meters

Two diesel-powered 12-in.-diam pumps were installed to meet the highest pump capacity requirements during levee overtopping (~3000 gpm each). Associated plumbing for the pump system was also installed in the facility. The system with pumps, manifolds, and flow meters is shown in Figure 2-3.

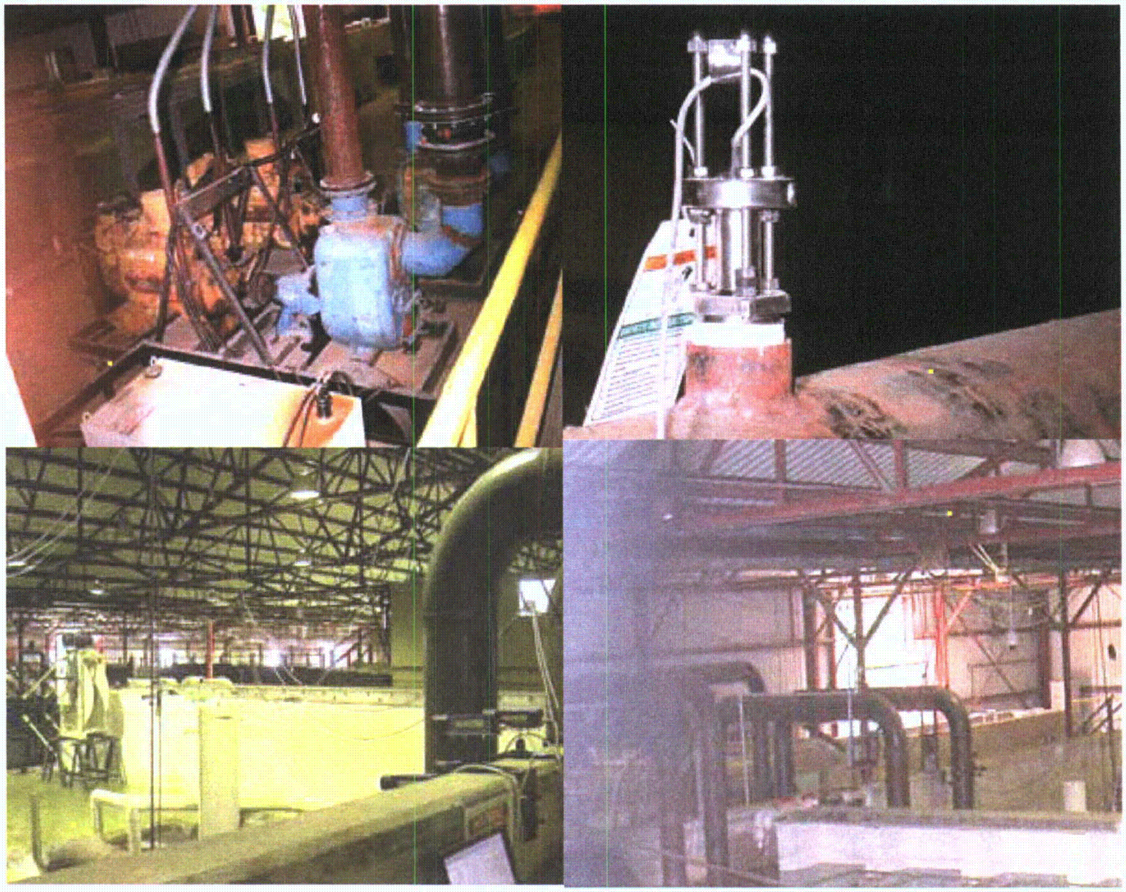


Figure 2-3. Pumping system used for overtopping, 12 in. diam. Top left: diesel pumps. Top right: flow meter. Bottom left: pipes leaving basin to pumps. Bottom right: pipes from basin to pumps and back to basin

Test facility instrumentation

The instrumentation station is mounted just behind the pool wall directly facing and parallel to the wave machine. For uniformity and ease of understanding, looking at the inside of the levees from the instrumentation station will be called the center of the levee. Right and left of the instrumentation station will be the right and left side of the levee as shown in Figure 2-4. The letters from "a" to "i" are used to show relative location on the structure. All letters are assumed to be on the center of the levee. The letter "a" is at the right wing wall, "b" is at the center of the first levee wall, "c" is at the corner of the two adjoining levee walls, "d" is 5 ft in from the right corner, "e" is 10 ft in from the right corner, "f" is 15 ft in from the right corner or 5 ft from the left corner, "g" is the left corner, "h" is at the center of the diagonal levee wall, and "i" is at the left wing wall.

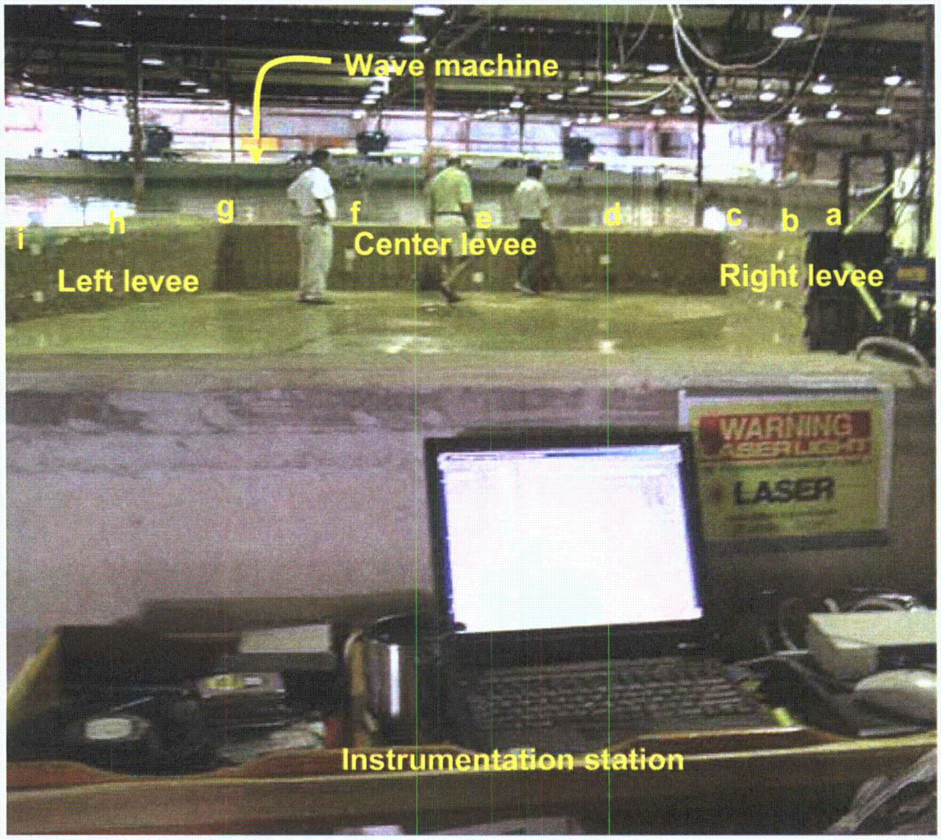


Figure 2-4. Laboratory setup

Instruments are used to measure flow rate from the 4-in. pumps (water volume/time) and water level inside the pit. Distances from the outer reservoir to two points on each longitudinal dry side levee wall (top and bottom) are monitored via eight laser-beam transducers to determine horizontal levee wall displacement during testing. Horizontal displacement of the center section is measured at a point near the center. The onsite computer recorded all input data (seepage flow rate, water level, and displacement). Wave basin data (reservoir height, wave generation, and hydraulic parameters) were monitored separately. The data acquisition system was placed on the outside of the pool wall behind the test section as shown in Figure 2-5.

The water level inside the pit from bottom of the sump pit (elevation zero) to a maximum elevation of about 48 in. above the top of the pit is measured with a laser float system (Figure 2-5). A 12-ft-long stilling pipe (12-in.-diam PVC) with holes around the bottom is placed in the pit to calm the water running into the pit. The depth of the float placed in the 12-in. pipe is measured by a laser pointed at the center of the float. The water depth or elevation relative to the bottom of the pit is recorded every second during any given test.

The outflow from the sump pit (through the two 4-in. pumps) is measured with Omega flow meters (Figure 2-6). The data acquisition computer (programmed in Visual Basic®) records the flow meter data. The pit water level and pump flow rate as functions of time calculate the water inflow rate (seepage rate) into the pit.

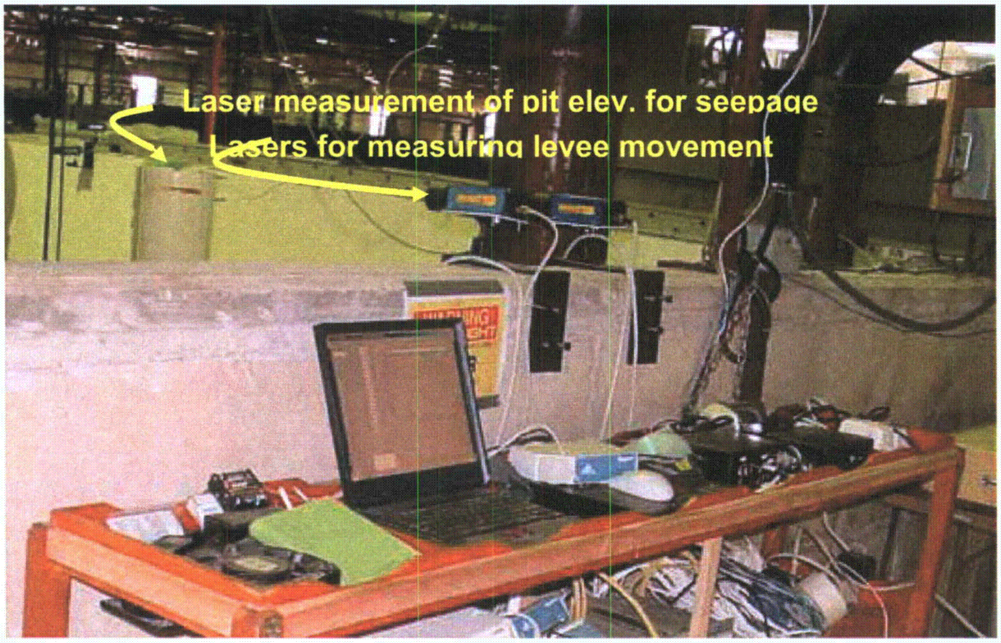


Figure 2-5. Seepage and displacement data retrieved by data acquisition system

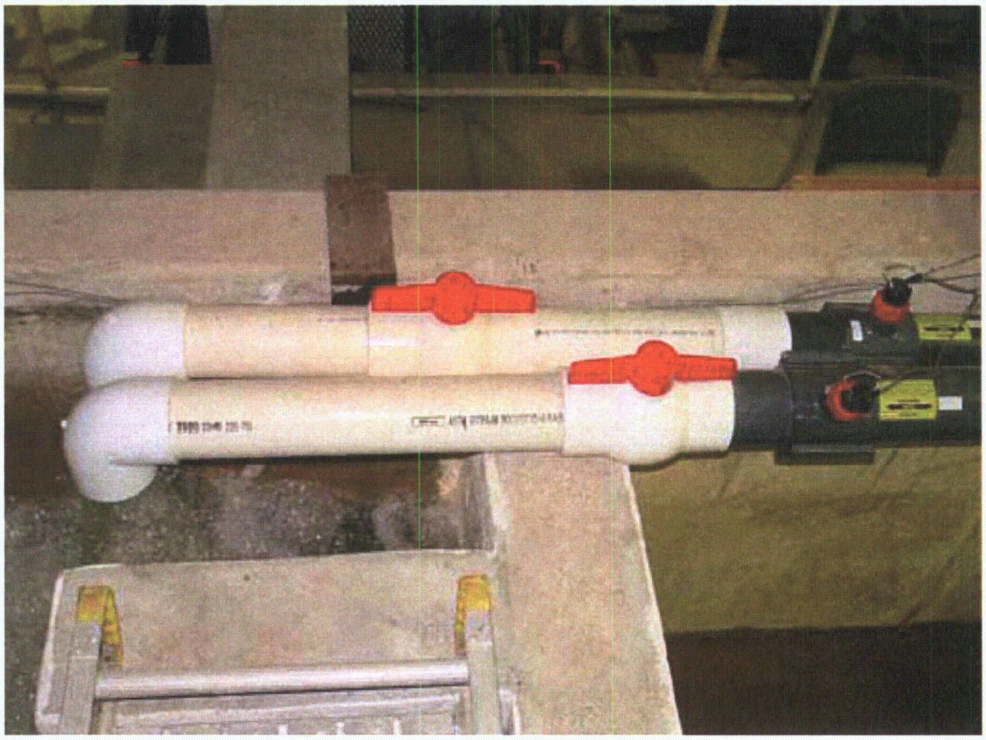


Figure 2-6. Sump pit outflow pipes and flow meters

The displacement (horizontal and overturning) of the protective side of the levee was measured with optical lasers having a maximum range of 50 m and an accuracy of ±3 mm. Movement was measured with the lasers at the top and bottom of each levee wall section at its longitudinal center, and movement is monitored at either end of the center section. The lasers reflected off white standoff targets attached to the levee. These standoff targets were placed approximately 12 in. in front of the levee to allow uninterrupted laser measurements during water overtopping (Figure 2-7).

Figure 2-7. Lasers and laser targets. Left side, top to bottom: three pictures of lasers. Top middle: laser targets on Portadam. Top right: laser targets on sand bags. Bottom middle: laser targets on Hesco Bastion. Bottom right: laser targets on RDFW

The sketch in Figure 2-7a contains the position of each of the eight lasers used and location on the levee at which it records any movement. These lasers record movements with an accuracy of ±3 mm. The laser targets were placed on the levees at points B, D, E, F, and H as seen on the Figure 2-7a. At points B, E, and H the one laser is aimed at a target placed within 3 to 8 in. from the top of the levee, and a second is placed the same distance from the bottom of the levee. Laser lines D and F are aimed at a single target placed at the center of the elevation of the levee at each of these two locations.

The use of lasers resulted from prior testing of a product that moved forward and rotated during testing (static and dynamic testing). During the 2004 tests, any movement during testing was less than the minimum measurable value with this system (±3 mm). Example test results (one plot for each laser, Figures 2-7b through 2-7i) follow. The results from a dynamic high wave test with pool elevation equal to 80 percent of the pool height (80%h) displaced no more than ±3 mm.

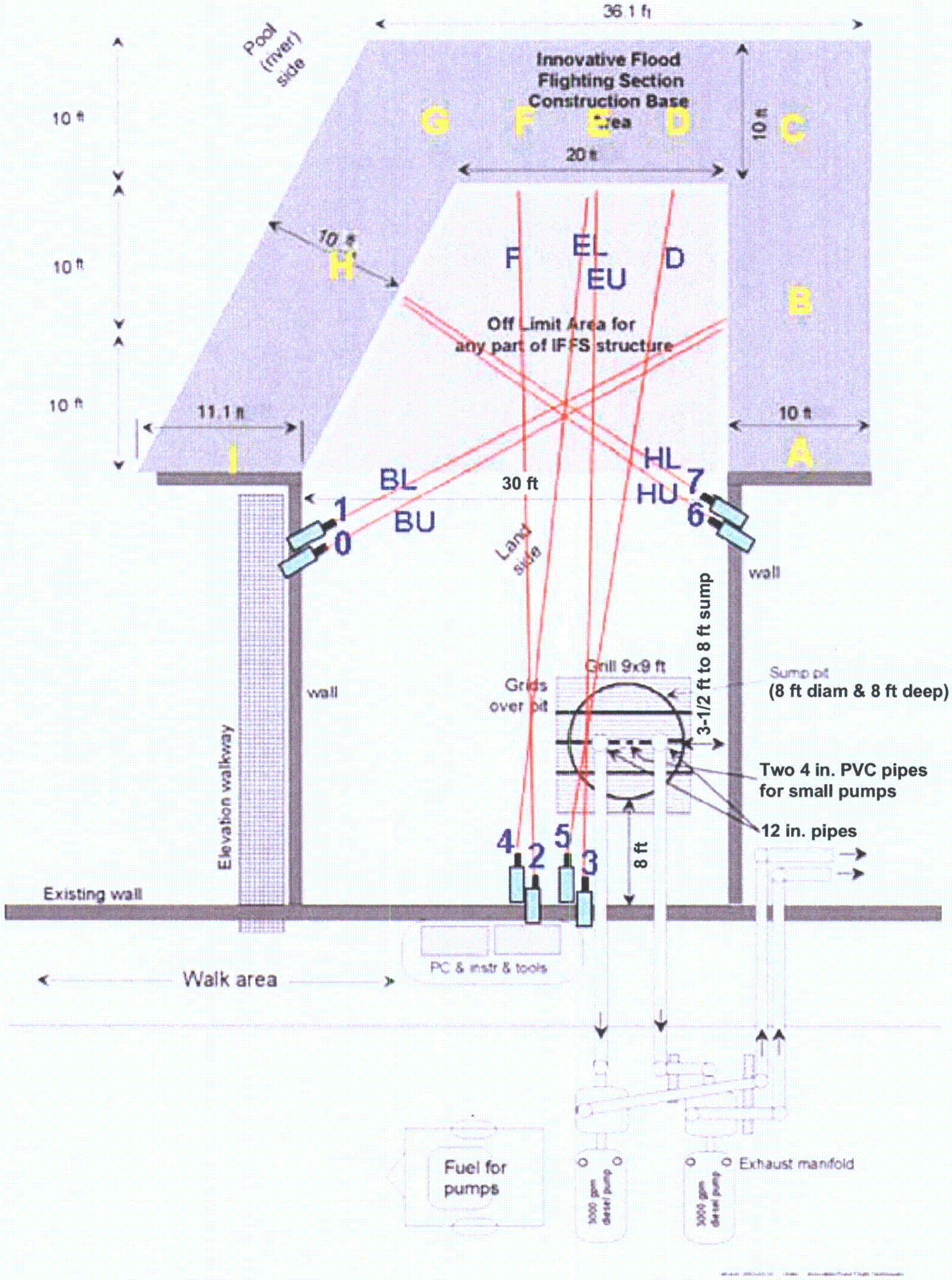


Figure 2-7a. Lasers and their targets on levee

Visual monitoring of the levee along the top and along the longitudinal center of the levee was accomplished where possible using a yellow stationary cable suspended about 1 to 2 in. above the levee and a blue strip painted directly on top of the levee. This stationary cable provides qualitative monitor of movement if large movements occur during testing. Video cameras recorded movement along the levee's parallel and perpendicular axes during the tests. The relative movement system is shown in Figure 2-8.

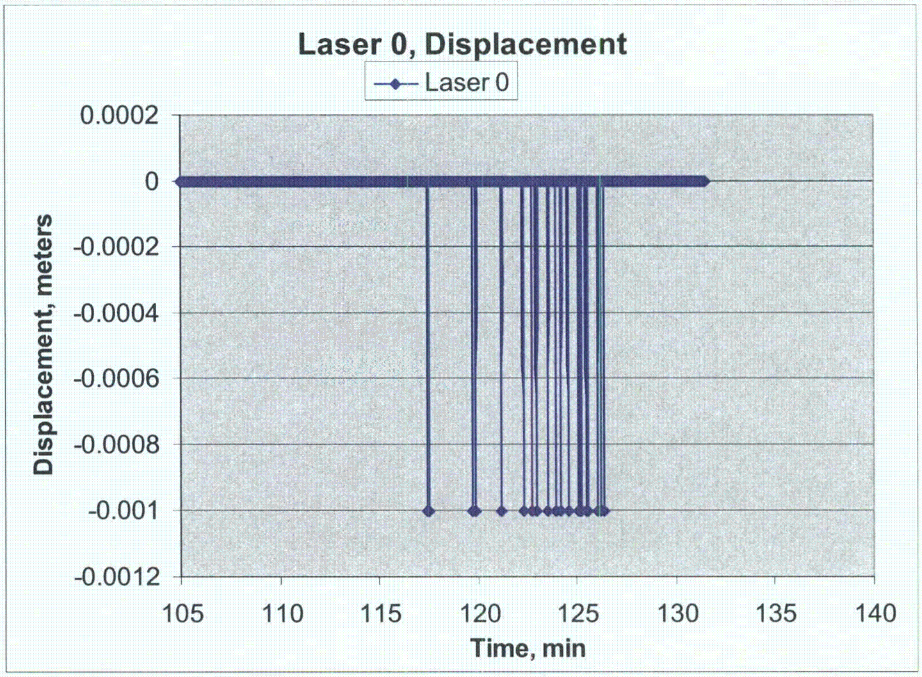


Figure 2-7b. Displacement data from laser 0

A floating-debris (log) impact-test apparatus was designed, constructed, and installed specifically to retract a wire cable attached to the log. The apparatus consists of an electric motor geared to a cable spool with remote control and safety trip wire capabilities. The apparatus is mounted on a steel frame attached to the test basin floor. The apparatus is installed and remotely controlled to provide a log impact speed of 5 mph at an approximate angle of 70 deg with the horizontal.[1] As the log is pulled into the levee, a trip wire switches off the winch just inches from the levee. This keeps the log from being pulled by the cable after impact. The complete system is shown in Figure 2-9.

[1] Horizontal equal to a line parallel to the wall where the computer acquisition system is stationed.

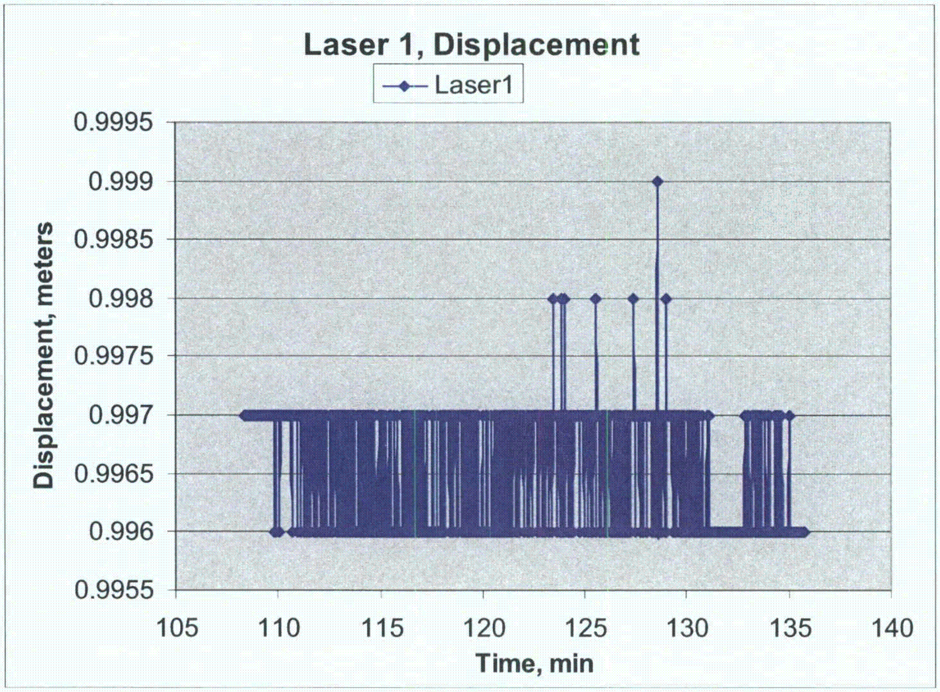


Figure 2-7c. Displacement data from laser 1

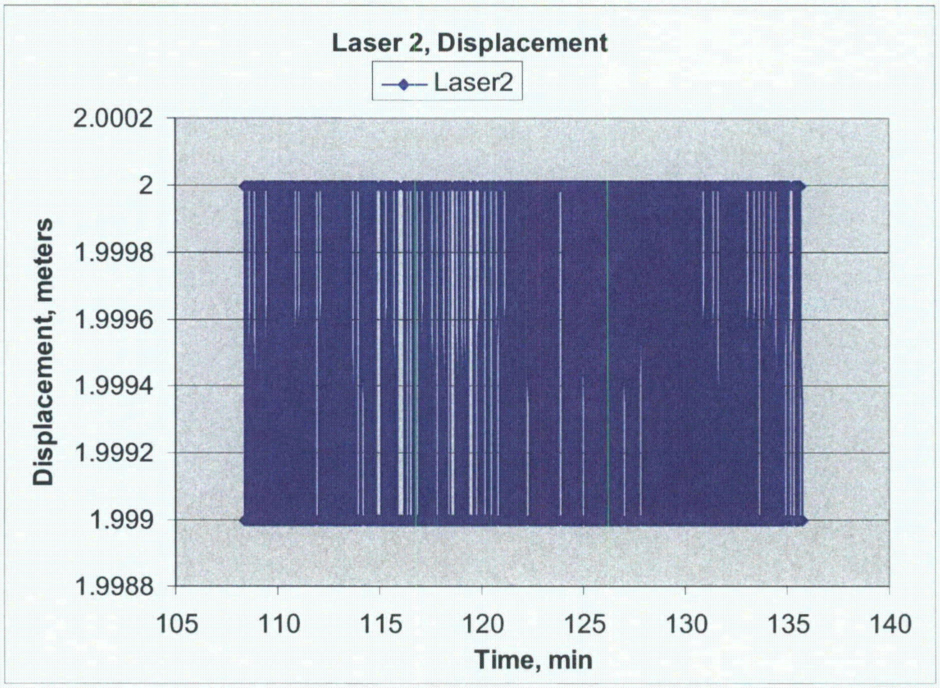


Figure 2-7d. Displacement data from laser 2

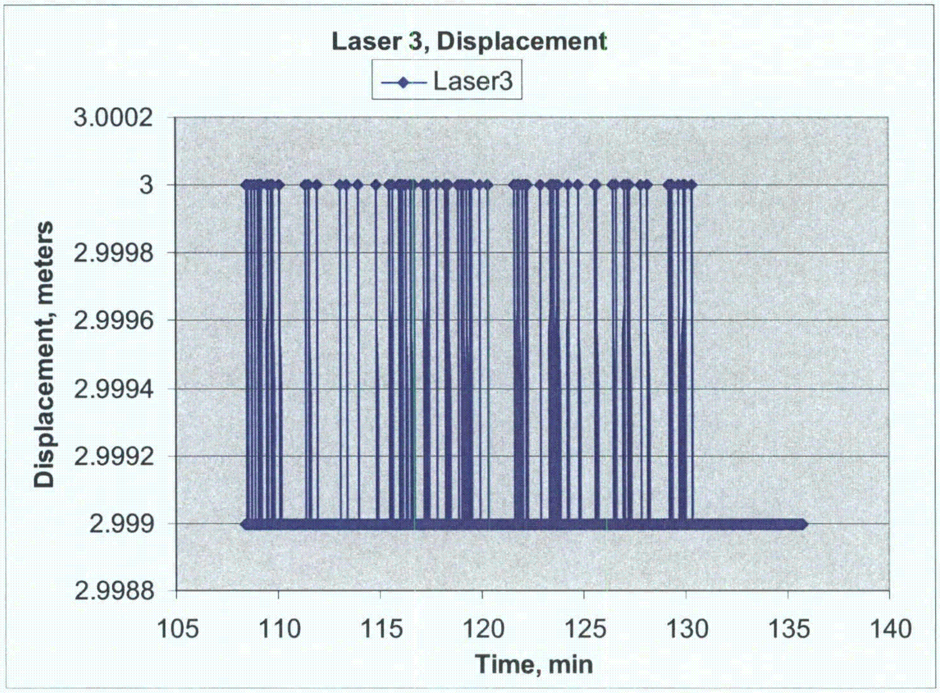


Figure 2-7e. Displacement data from laser 3

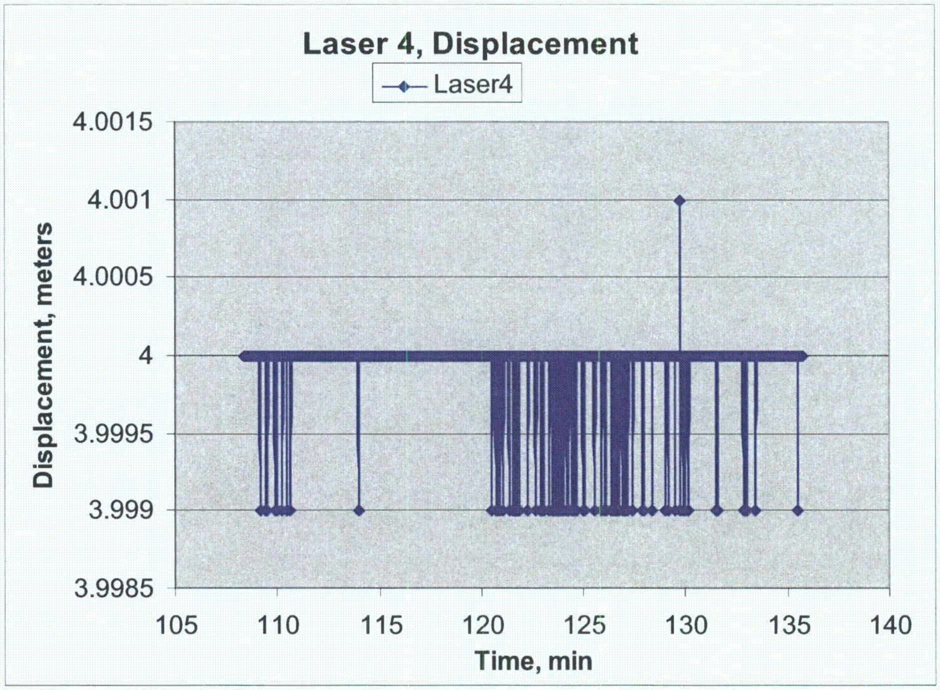


Figure 2-7f. Displacement data from laser 4

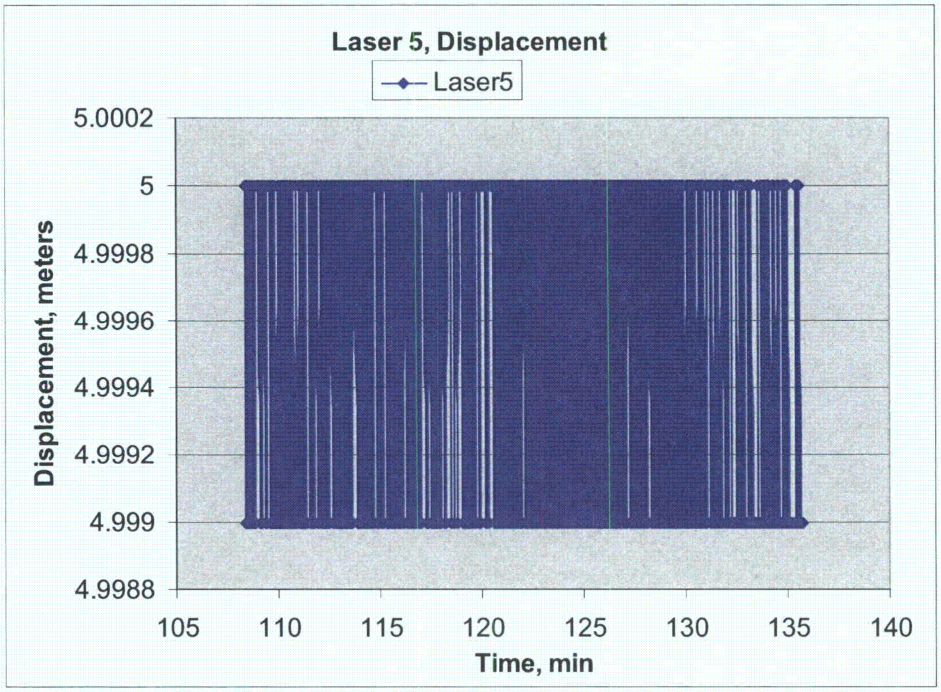


Figure 2-7g. Displacement data from laser 5

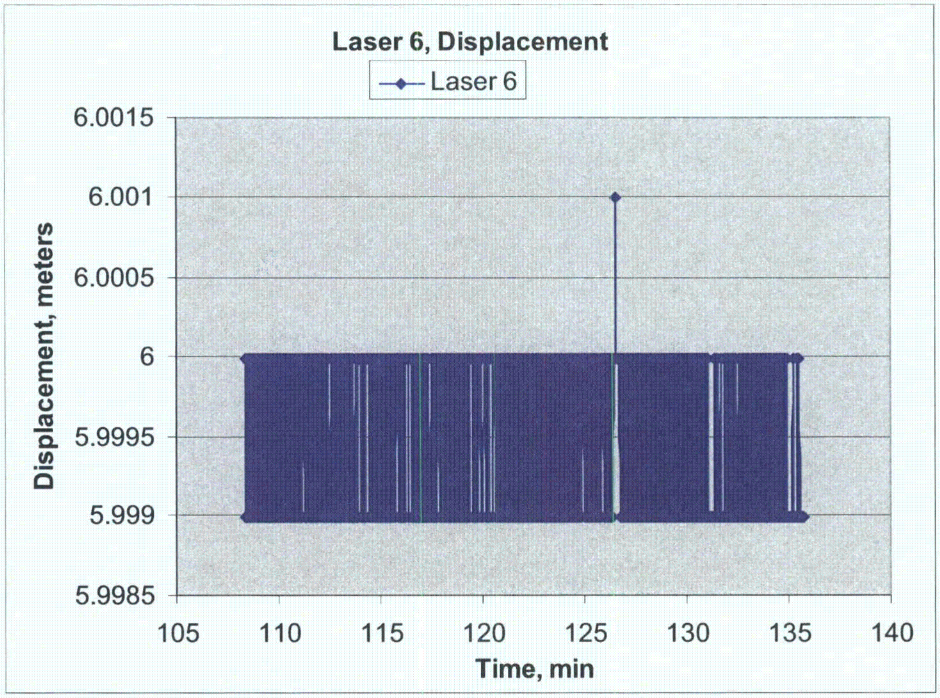


Figure 2-7h. Displacement data from laser 6

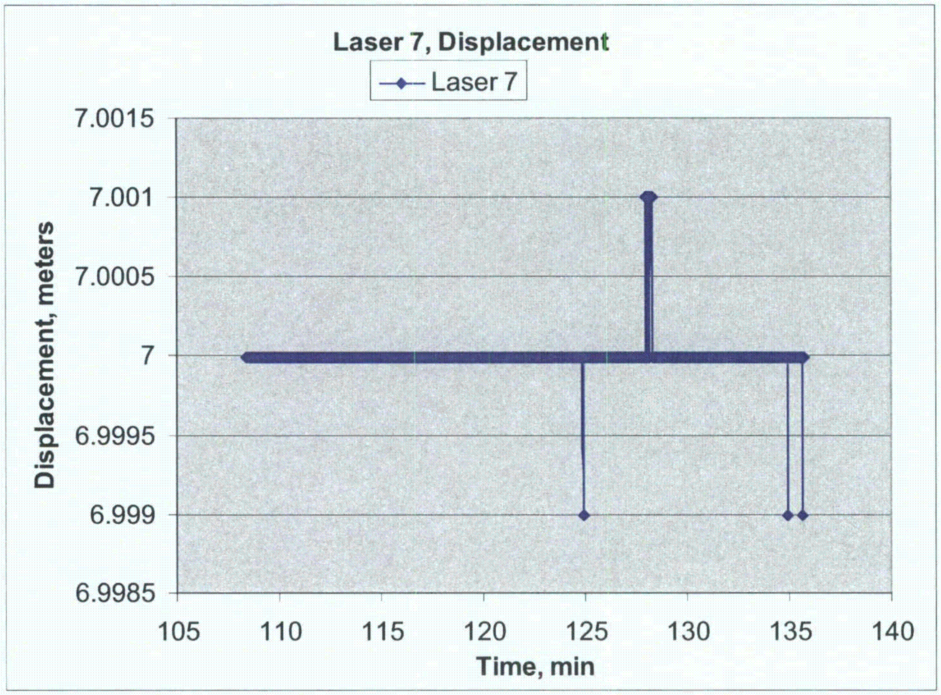


Figure 2-7i. Displacement data from laser 7

Figure 2-8. Relative movement and video monitoring system

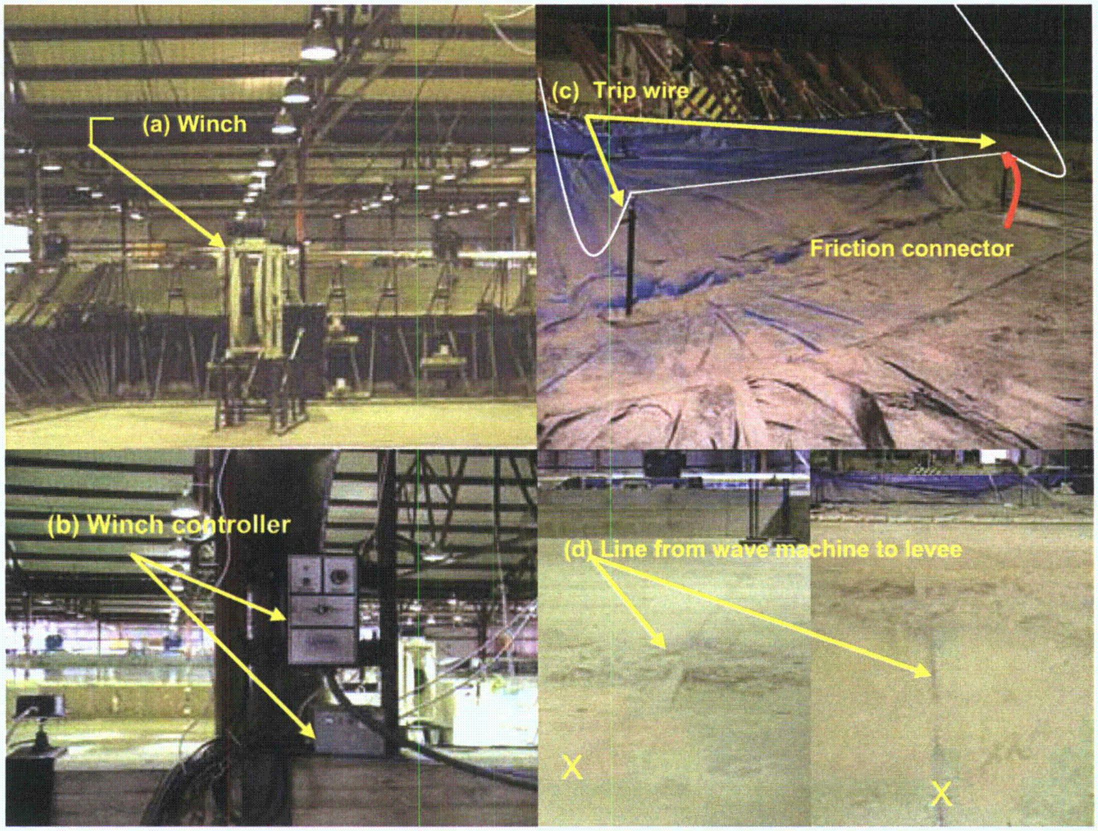


Figure 2-9. Debris impact test setup (a) Winch (b) Controller (c)Trip wire, (d) Desired path for log being towed

The pool is filled from a large sump, which when completely full contains enough water to fill the reservoir to an elevation of 3 ft. The two pumps are switched on and off at a point near the sump. The water can be pumped into and out of the pool area with the valves and pumping manifold. The two pumps are capable of filling the reservoir to an elevation of 1 ft in 1.5 hr. The system is shown in Figure 2-10.

A constant reservoir pool height is maintained with an electronically controlled elevation system as shown in Figure 2-11a. Reservoir water-level measurement is monitored with a laser float system similar to that used for pit elevation monitoring. The major difference is that a 4-in. pipe is used as the stilling basin and the float is much smaller. The data acquisition system records these data once every second as is done with all data recorded. The laser and stilling basin for the pit elevation is shown in Figure 2-11b.

CHL personnel operated and maintained the wave generation system and measured the wave heights and periods during the hydrodynamic tests. The wave machine may be seen in Figure 2-12a and 2-12b. The wave gages were placed at desirable distances from the levee and the wave generator, shown in Figure 2-12c and 2-12d.

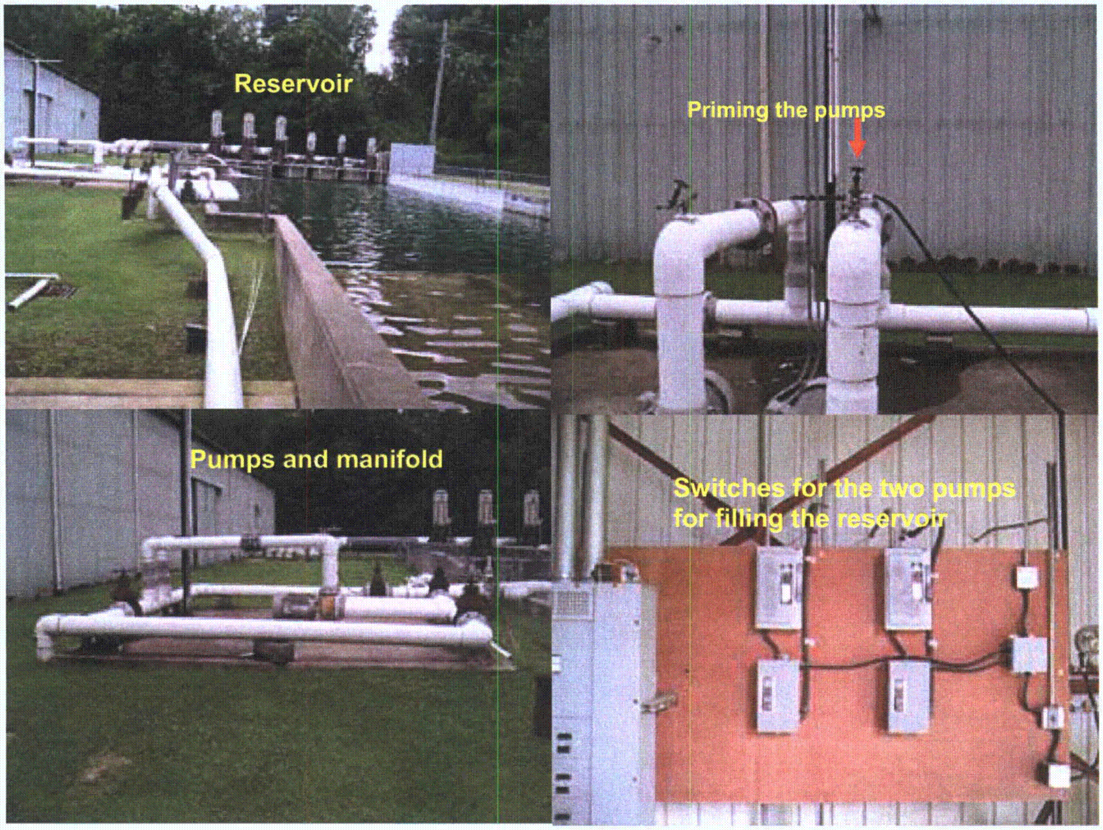


Figure 2-10. Reservoir-filling system

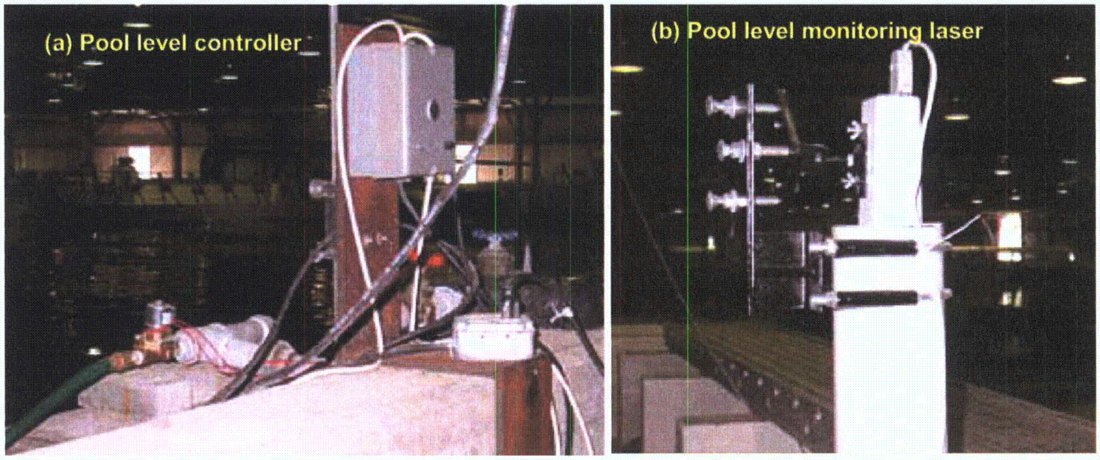


Figure 2-11. Pool level equipment (a) Controller (b) Monitoring laser

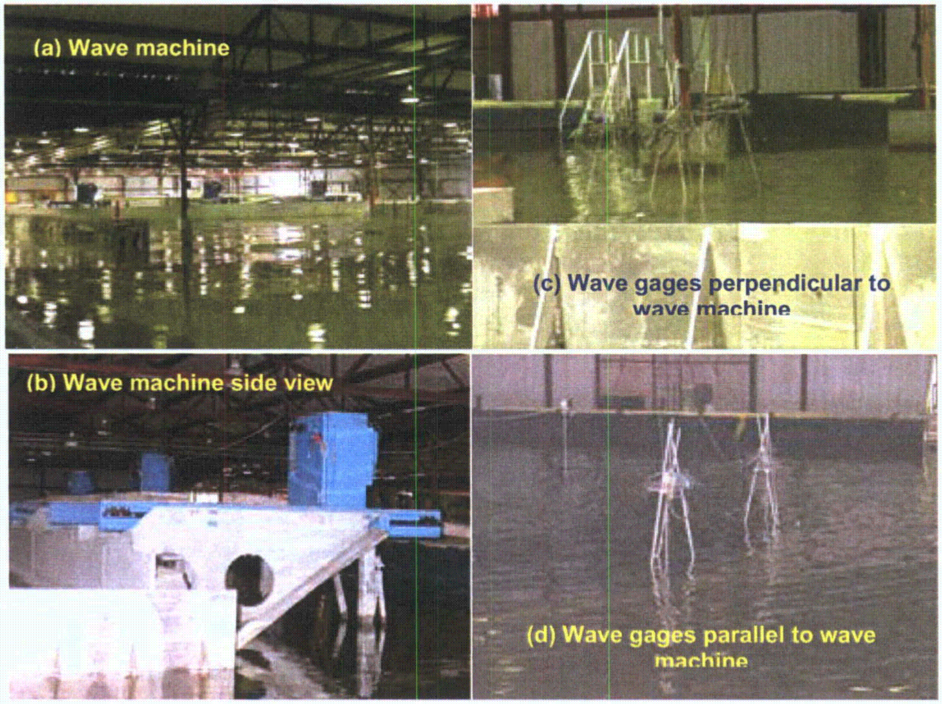


Figure 2-12. Wave generator and equipment (a) Wave machine, (b) Wave machine side view, (c) Wave gages perpendicular to wave machine, (d) Wave gages parallel to wave machine

An attempt was made to capture the wave height and period data and correlate it to the seepage and displacement data recorded by the separate data acquisition systems. A separate wave gage was used to capture these data as the waves were hitting the levees as shown in Figure 2-13.

Testing protocol

The Standard Testing Protocol (STP), referenced in Appendix C of this report, is briefly described as follows. The STP is applicable to all levee structures tested in the laboratory and documented in this report.

For a commercial product to be tested it must meet all of the criteria listed in the STP. The product is to have an engineering-based study performed to establish structural stability, with calculations presented for water pressure at all elevation up to 100 percent of the product height, and must have previously completed manufacturers' testing.

The testing protocol requires hydrostatic and hydrodynamic conditions, levee overtopping, and impact tests to be performed. For the hydrostatic tests, the pool elevation in front of the dam is raised to three different elevations (33 percent, 66 percent, and 95 percent of levee height) for a minimum of 22 hr at each elevation. It was later decided that the first two elevations should be 1 ft and 2 ft to ensure hydrostatic comparability regardless of levee height. During the testing period, levee movement and seepage values are recorded. During and after each test the levee is inspected for weakness and/or failure before the pool elevation is raised to the next level.

Figure 2-13. Separate wave conductivity rod, correlating waves with seepage

Hydrodynamic tests are performed at two different pool elevations (66 percent and 80 percent of levee height). At 66 percent height, 3-in. waves (measured from trough to crest) are generated continuously for a period of 7 hr. Waves ranging from 7 to 9 in. are then allowed to impact the structure a total of 30 min (three 10-min intervals). Next, wave heights ranging from 10 to 13 in. are allowed to impact the structure for 10 min. The water is then to be raised to a level of 80 percent levee height and the tests repeated. At the end of each 10-min increment of wave testing (excluding the 7 hr of 3-in. waves), the testing basin is to be stilled for 15 min between each test interval to allow the waves to dissipate.

Seepage and displacement measurements are to be taken and digital tapes record test data. During and after testing at each pool elevation, the levee is visually inspected for weakness and/or failure before the pool elevation is to be raised to the next level.

Overtopping is accomplished by raising the water level while allowing it to spill over the top of the levee into the test area. At first, the 4-in. pumps are used to pump the water out of the sump back into the pool. When the 4-in. pumps can no longer keep up, the 12-in. pumps are engaged one at a time with the engines running at a low rpm. The test begins when either the pool water level reaches 1.5 in. above the average levee height or the pumps are pumping at their maximum rpm and the water level in the pit is at a constant elevation, whichever comes first. Once the test begins, the pumps circulate the water at that constant pool water elevation for a period of 1 hr or until levee failure.

A total of three minor repairs are to be allowed during the testing operation. These repairs are limited not only in time but in man-hours and materials (see Appendix C for detailed information).

The final tests performed are the two separate impact tests. Two different-sized logs impact the structure at 5 mph. The logs are nominally 12-in. and 16-in. in diameter and 12 ft in length. The logs are cut perpendicularly to their length with a chain saw and left rough with sharp edges. After testing, the levee is inspected (where possible) for weakness and/or failure before the second impact test is performed. Displacement measurements are digitally recorded and the tests videotaped.

USACE Sandbag Levee Tests

Design

The first sandbag levee built on the innovative flood-fight project was in 2002 and was based on the U. S. Army Engineer District, Seattle sandbag-levee-construction protocol shown in Figure 2-14. In this protocol, the sandbag levee is constructed using off-the-shelf materials and readily available equipment. Materials include the sandbags and sand. Hand filling requires manual laborers with shovels. Alternatively, sandbags may be filled on or offsite with sandbag filling machines. The sandbag filling machines may have small or large spouts; they may contain motor driven augers; and they often have vibrators to keep the sand moving into the spouts. There are various companies that sell mechanical sandbag fillers and others that sell ready-filled sandbags. A front-end loader is generally used where sandbags are being filled. If the bags are filled offsite, then a truck is needed to convey the bags to the point where they will be deployed.

The Seattle District protocol allows the use of sandbags filled to two-thirds full and the bags occupy a space of 10 in. wide by 12 in. long by 4 in. high. The weight of a bag filled two-thirds full is determined by the density of the fill material. The bags filled in the 2002 test were 45 lb ±3 lb. The bags used to construct the sandbag structure were filled with a sandbag filling machine manufactured by Hogan Manufacturing Co. The Hogan machine uses a fixed volume auger and produces sandbags with constant volume (machine shown in Figure 2-15).

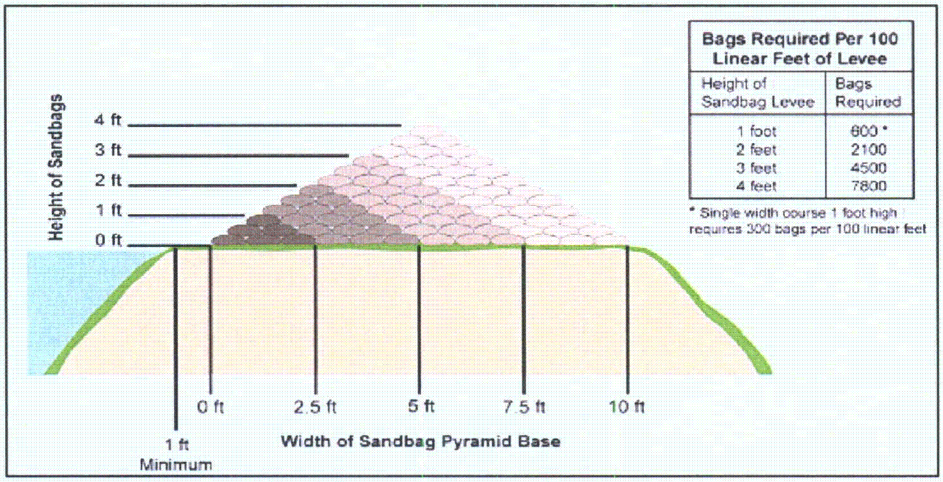
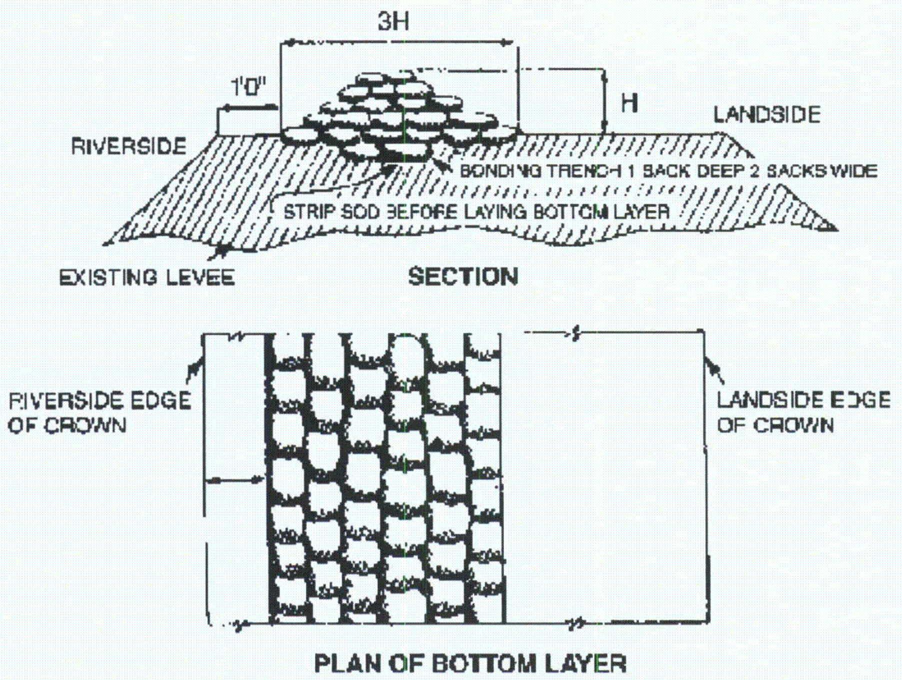


Figure 2-14. Seattle District standard sandbag levee design

Figure 2-15. Hogan Manufacturing Co. sandbag filling machine used to build pretest sandbag levee

According to the Seattle District protocol, a 3-ft-high sandbag levee having one sandbag on top will require a base 9 bags wide (90 in. or 7.5 ft) and uses 4,500 sandbags per 100 ft as can be seen from Figure 2-14. A 3-ft-high sandbag structure with two sandbags on top will be 10 bags wide (100 in. or 8.33 ft) and uses 5,300 sandbags per 100 ft. Note that the U. S. Army Engineer District, Walla Walla uses a base width three times that of the height as its minimum width criteria as shown in Figure 2-16. Seattle District also allows the use of this criterion.



BAGS REQUIRED PER 100 LINEAR FEET OF LEVEE	
HEIGHT ABOVE	BAGS
LEVEE	REQUIRED
1 FOOT	800
2 FEET	2000
3 FEET	3400

Figure 2-16. Walla Walla District standard sandbag levee design

Both the U. S. Army Engineer Districts, Walla Walla and Seattle show that the sandbags are folded under and the weight of the bag rests on the fold. The open end (not sewed) of the sandbag faces the current. Both districts also indicate that a sandbag in the same line and the same level is placed upon the end of the last sandbag (Figure 2-17).

The 2002 sandbag levee was built without any instruction or supervision from a person with field experience. The as-built structure is shown in Figure 2-18.

The sandbags were placed too high upon the preceding sandbags and did not lie flat on the concrete floor like those in Figure 2-17. This made each layer higher than it was supposed to be.

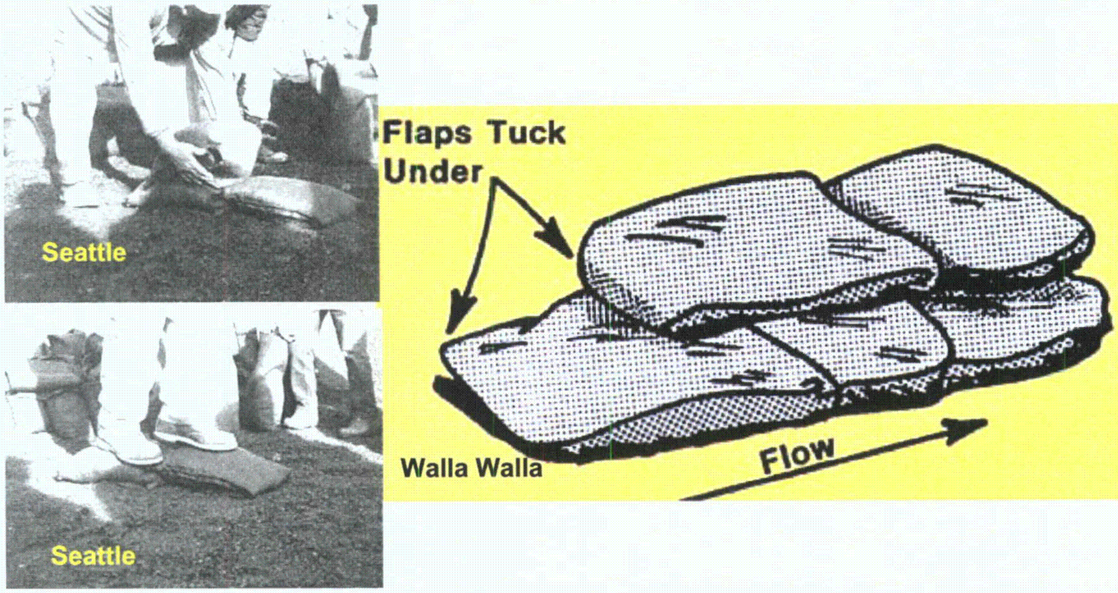


Figure 2-17. Walla Walla and Seattle Districts' design for placing sandbags

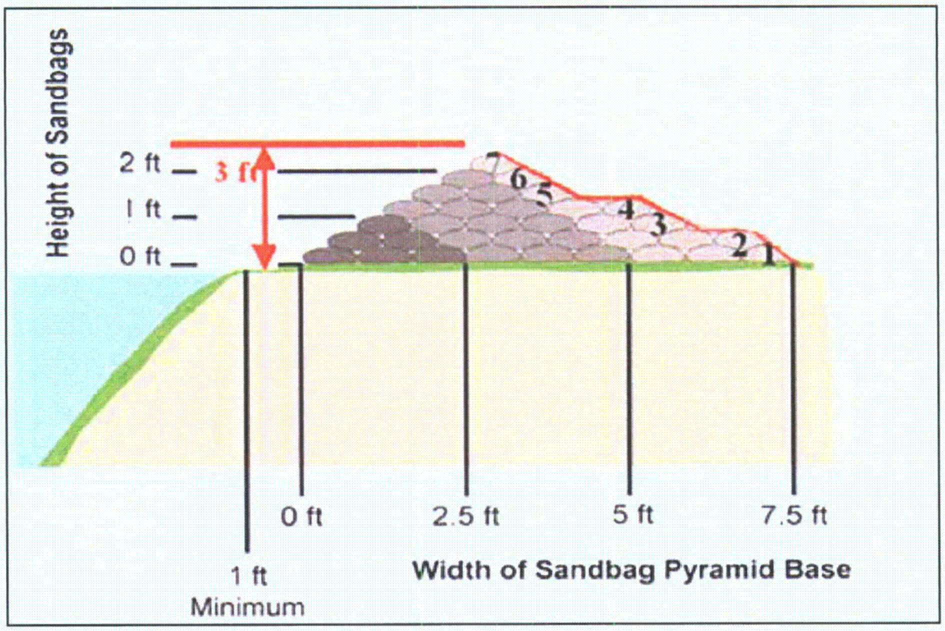


Figure 2-18. 2002 levee, as-built

The structure did not appear as the Seattle District's design because of the stacking problem, and it also had a void between each connecting bag. The resulting voids caused the pretest sandbag levee to seep excessively (7 gal/ft of levee at a water elevation of 95 percent times the height of the structure). A safety analysis of the as-built structure was performed with the following results. For the sandbag levee with water at 3-ft elevation on the poolside, the factor of safety against sliding was calculated to be 1.75 (friction factor of 0.45), and the factor of safety against overturning was calculated to be 2.49.

Another sandbag levee was constructed as part of the 2004 series of tests. Because of the massive seepage through the 2002 sandbag structure, experienced personnel supervised the construction of the sandbag levee in the 2004 tests. The U. S. Army Engineer District, Vicksburg's Emergency Management (EM) supervisors came to the ERDC Laboratory with laborers from the Vicksburg District to build the sandbag levee using the District EM protocol. Major changes from the 2002 levee were that in the 2004 test the bags were filled only one-third to two-thirds full, and the resulting 25-lb bags were not folded.

Construction

The laboratory sandbag levee for the current project was constructed in March of 2004. Although, the temperature inside the enclosed metal hangar ranged from 55 to 70 deg, providing pleasant working conditions, the work was fast-paced and fatiguing due to filling, stooping, lifting, carrying, and placing sandbags. Fans were placed in the work area, and water and electrolytic fluids were made available to all workers. The 17 full-time workers and four part-time workers were closely watched to ensure no one was overstressed or fatigued.

The construction team arrived on 15 March 2004, 0730 hr, and the sandbag levee construction began. Five of the 21 laborers were stationed at the manual sandbag filling machine (Kanzler Sandbagger®) which is shown in Figure 2-19. Two three-man teams manually filled sandbags with shovels. One of the manual teams is shown in Figure 2-19. A front-end loader with operator kept the sandbagger hopper full, supplied sand to the manual sandbaggers, and carried filled bags to the levee for placement (Figure 2-19). The remainder of the laborers carried and stacked sandbags during the construction of the levee (Figure 2-19).

Six thousand sandbags were brought to the site and 5,500 were filled and placed as per the Vicksburg District method. The time required to construct the 62 lft of levee (measured along the protected toe) was 11.5 hr. The construction required 205 man-hours or 3.3 man-hours per linear foot of levee. The level of difficulty is classified as "simple," meaning no special training or skills were required to do any of the jobs with the exception of the front-end loader operator.

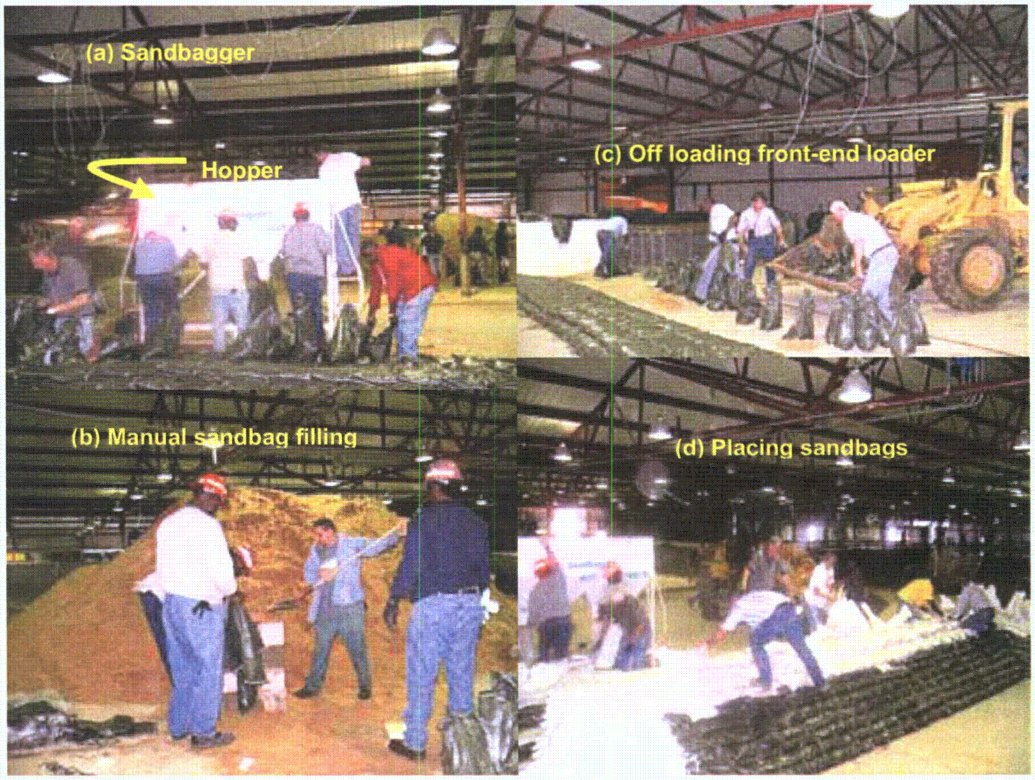


Figure 2-19. Sandbagging operation

The sand was from a commercial source with which District personnel were familiar. It was poorly graded (SP of Unified Soil Classification System) with approximate moisture content 8 percent as shown in Figure 2-20. Each woven plastic sandbag (flat dimensions 14 in. × 24 in.) was fairly uniform and weighed about 25 lb (±2 lb). Bags were filled using the manually operated sandbag filler provided by the Vicksburg District or manually filled by shovels. Sandbag weight was checked periodically.

The sandbag levee was built to the geometry shown in Figure 2-14. The goal was to have nine layers of sandbags at 4-in. height per each layer or 36 in. high (3 ft) as per the Seattle District design. In theory, a base 10 bags wide (about 100 in.) and nine layers high would make a sandbag levee 36 in. high with two sandbags on top. The Seattle District folds the bags under and each folded end leaned on the end of the preceding sandbag. During sandbag levee construction, the Vicksburg District laps their bags, which means the open end of the bag lies flat and the next bag lays on top of the preceding bag's flap and the sewed end of the bag being placed pushes tightly against the open end at the filled portion of the preceding sandbag as shown in Figure 2-21. The bags are then walked on to compact even tighter and flatter.

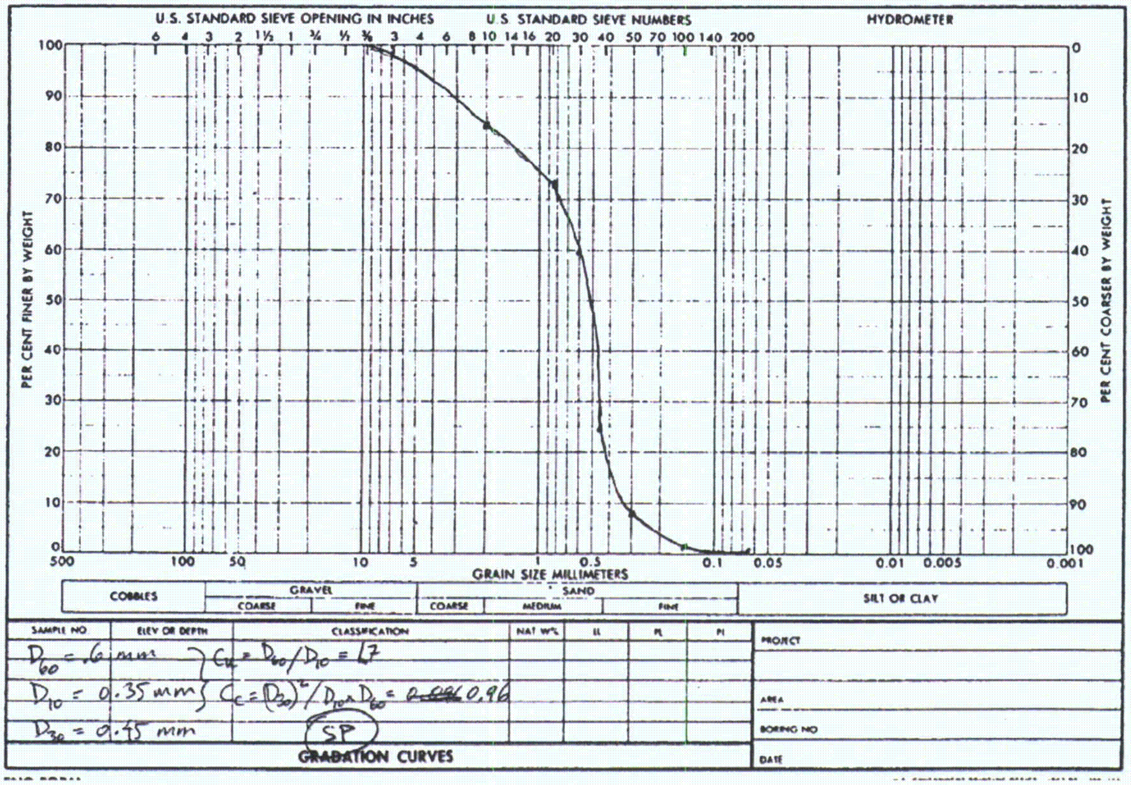


Figure 2-20. Gradation of sand used for filling sandbags

Figure 2-21. Lap stacking sandbags during construction

The 25-lb sandbags filled by the Vicksburg District when laid flat were about 10 in. wide, 12 in. long, and 3 in. high. The maximum base allowed by the testing protocol is 10 ft wide or 12 bags wide (120 in.). To have two sandbags on top would require only 11 layers or 33 in. high. One more 2-wide layer (layer 12) was placed on top of layer 11 to reach the 36-in. height. Since not all of the sandbags were 3 in. thick, there were high and low places on the levee. Various sandbags were laid alongside the top layers on either side of the levee; however, they were not tied into the main sandbag structure. This made a weak zone that was discovered during hydrodynamic testing. The finished levee and partial crew is shown in Figure 2-22.

The average height of the sandbag levee as-built was 2.997 ft (low point 2.805 ft and high point 3.115 ft). Prior to filling the reservoir to begin the hydrostatic tests, laser targets were positioned in the sandbags (Figure 2-23). The representative USACE personnel reached verbal agreement that the levee had been constructed adequately and was ready for testing.

Performance

Testing began after construction of the barrier was completed. Three minor repairs were allowed within seven windows of opportunity during the tests, as noted in Appendix C. Before the initial overtopping test, the barrier failed when subjected to large waves used to calibrate the structure for the sandbags and subsequent structures. The outer sandbag layer parallel to the wave machine was removed. Tied sandbags weighing 45 to 50 lb were placed from the floor to the top of the sandbag levee to replace those removed. An attempt was made to level the top of the levee.

Disassembly and removal of the barrier was performed after testing was completed and the test basin was drained. An environmental evaluation was also performed for the barrier system, to include environmental hazards aspects of construction and disposal.

Hydrostatic head tests

The pool elevation was sequentially raised to three different levels for a minimum of 22 hr at each predetermined elevation. During the testing period, levee displacement and seepage flow rates collected at the sump pit were recorded. During and after each test, the levee was inspected for weakness and/or failure before the pool elevation was raised to the next level.

Figure 2-22. Complete sandbag levee with partial construction crew

Figure 2-23. Sandbag levee with three of eight targets ready to test

Hydrostatic-head test, 1-ft reservoir (33 percent height). Water was first raised to the 1-ft level on the 3-ft-high sandbag levee, or approximately one-third the height of the levee. About 5 hr were required for filling the reservoir. The water was allowed to stand at that level for approximately 17 hr. The instrumentation recorded levee displacement and inflow from seepage through the levee. The levee was videotaped during all of the static testing. The range of seepage flow rate per linear foot of center-line length was 0.046 to 0.053 gpm/lft. The graph of seepage per linear foot with time can be seen in Figure 2-24. The most seepage (leakage) occurred at the block wall/sandbag interface and at the two sandbag corners.

The data in the graph (Figure 2-24) appears erratic. The large pumps used to fill the basin quit working and the data files were interrupted with some lost time. This was the first test and the data acquisition system stopped taking data 15 times, but the problems were resolved before the next tests. The plot shows the elevation with time and the seepage per linear foot. The seepage per linear foot starts high after filling and drops off with time. The water level increases with time from 12.24 to 12.28 in., but was controlled well by the automatic water-level system.

Hydrostatic-head test, 2-ft reservoir. Water was raised to 2 ft on the 3-ft-high sandbag levee (approximately two-thirds of the total levee height). The water was allowed to stand at that level for approximately 22 hr. The instrumentation recorded levee displacement and inflow from seepage through the levee. The levee was videotaped during all of the static testing. The range of seepage flow rate of center-line length was 0.20 to 0.25 gpm/lft. The graph of seepage per linear foot with time can be seen in Figure 2-25. The majority of seepage (leakage) continued at the block wall/sandbag interface and at the two sandbag corners.

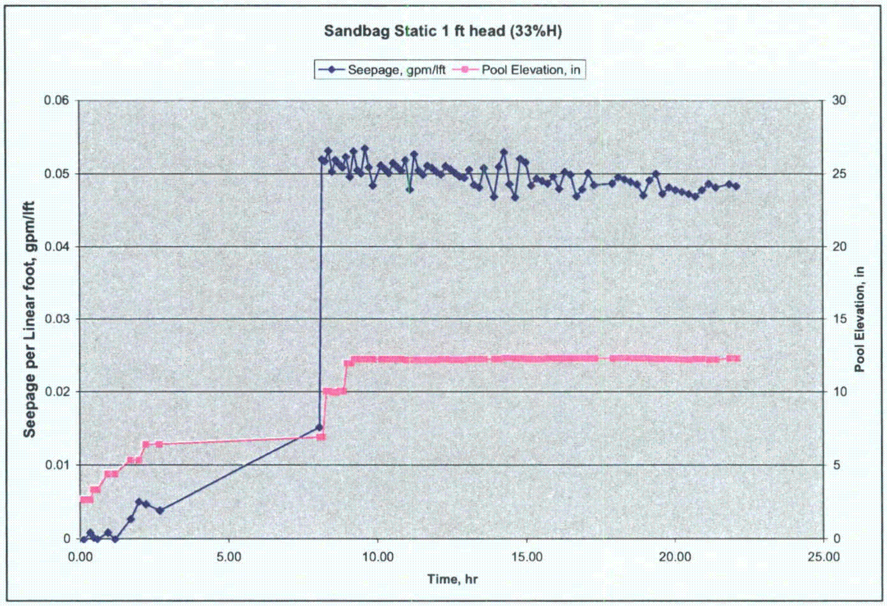


Figure 2-24. Seepage per linear foot at 1-ft head and under static conditions

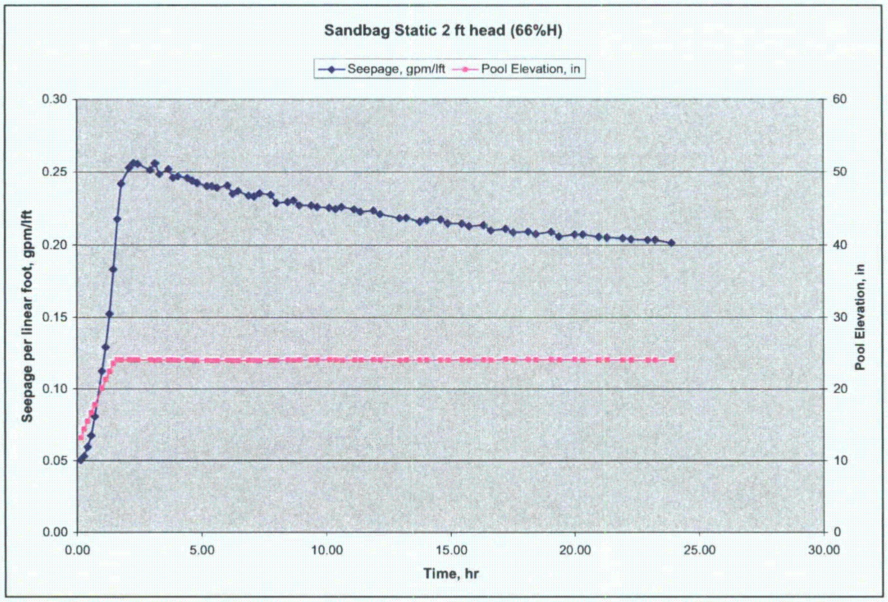


Figure 2-25. Seepage per linear foot at 2-ft head and under static conditions

The plot of seepage per linear foot shows seepage rates during filling and then runs the full 22 hr. The seepage per linear foot and water level both decrease (Figure 2-25).

Hydrostatic-head test, 3-ft reservoir. Water was raised to a height of slightly less than 34.2 in. or approximately 95 percent of the total levee height. The water began to overtop the levee so the water level was lowered to 32.4 in. or 90 percent of the average height of the levee, and allowed to stand at that height for 22 hr. The instrumentation recorded levee displacement and inflow from seepage through the levee. The levee was videotaped during all of the static testing. The range of seepage rate of center-line length was 0.45 to 0.63 gpm/lft. The graph of seepage per linear foot with time can be seen in Figure 2-26. Again, there was no displacement during this test, and most seepage (leakage) occurred at the block wall/sandbag interface and at the two corners. The large seepage at the beginning is a result of the overtopping resulting from the low points in the levee. The water was lowered and the maximum seepage afterward was 0.55 gpm/lft. When the water level was lowered to 90 percent of the height (32.4 in.) the seepage gradually decreased with time, however the water level also decreased slightly with time.

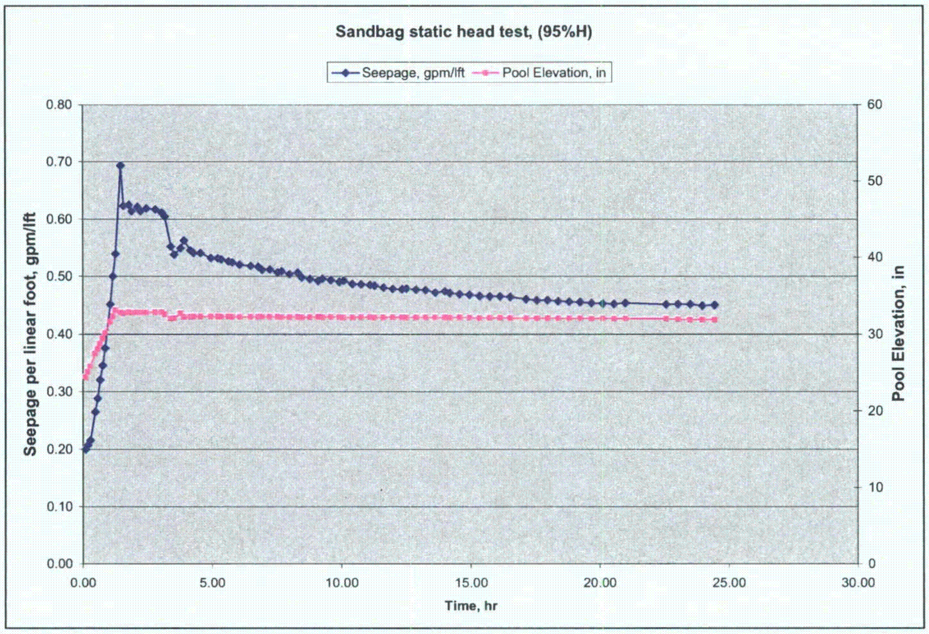


Figure 2-26. Seepage per linear foot at 32.4 in. (95% H) of head and under static conditions

Hydrodynamic tests

The testing protocol specified that packets of monochromatic waves with a wave period T = 2.0 sec be generated to impact the sandbag levee hydrodynamically. Hydrodynamic tests were performed at two different pool elevations (66 percent and 80 percent of levee height). At the 66 percent height, 3-in. waves (measured from trough to crest) were generated continuously for a period of 7 hr. Waves ranging from 7 to 9 in. were then allowed to impact the structure a total of 30 min (three 10-min intervals with 15-min calming periods between). Next, wave heights ranging from 10 to 13 in. were allowed to impact the structure for 10 min. The water was then raised to a level of 80 percent levee height and the preceding tests were repeated. At the end of each 10-min increment of wave testing (excluding the 7 hr of 3-in. wave test), the testing basin was stilled for up to 15 min to allow the waves to dissipate.

Following construction of the sandbag levee, the wave machine was calibrated. Damage to the sandbag structure during calibration was not expected based on the results of previous sandbag structure tests. The wave machine was calibrated (2004 sandbags test) for the small 3-in. waves, which were to run for 7 hr. We tried the calibration of the 3-in. waves and noticed that a large amount of material was washing out of the structure coloring the water red from the fines leaching out of the sand. During the calibration of the 7-in. waves, more discoloration of the water was noticed. Sandbags were washed away from the side and the top of the center of the structure. Figure 2-27 shows that sandbags moved between point c and point g. The structure was rebuilt and the top of the levee was leveled. Because this happened in calibration of the wave machine prior to the actual testing, it is called a rebuild. This calibration was for all products to follow and was not part of normal testing. Total rebuild time was 11 hr with four people or 44 man-hours. The levee after the rebuild is shown in Figure 2-28.

3-in. wave test, reservoir level at 66 percent levee height. The water level in the reservoir on the pool side of the sandbag levee was lowered from 90 percent of levee height to a pool height of 24 in. within an interval of about 2 hr. The wave generator was activated and the waves began to impact the levee. No overtopping was observed, the seepage rate ranged from 0.25 gpm/lft to 0.29 gpm/lft, and no displacement was observed. The 3-in. waves removed no bags. The seepage during this is documented in Figure 2-29.

7- to 9-in. wave test, reservoir level at 66 percent levee height. This test was actually performed after the 10- to 13-in. wave test (due to operator error). The water level in the reservoir on the pool side of the sandbag levee was held at 24 in., and the wave heights were increased from 7 in. to 9 in. for a period of 10 min. The test was then stopped for about 15 min between each of the three test increments to allow stilling of the basin. Seepage flow rates ranged from 0.23 to 0.32 gpm/lft and no displacement was observed during the tests. No major overtopping occurred, however, the seepage did increase slightly during each 10-min test as is shown in Figure 2-30. Two sandbags were displaced into the pool from the middle of the structure.

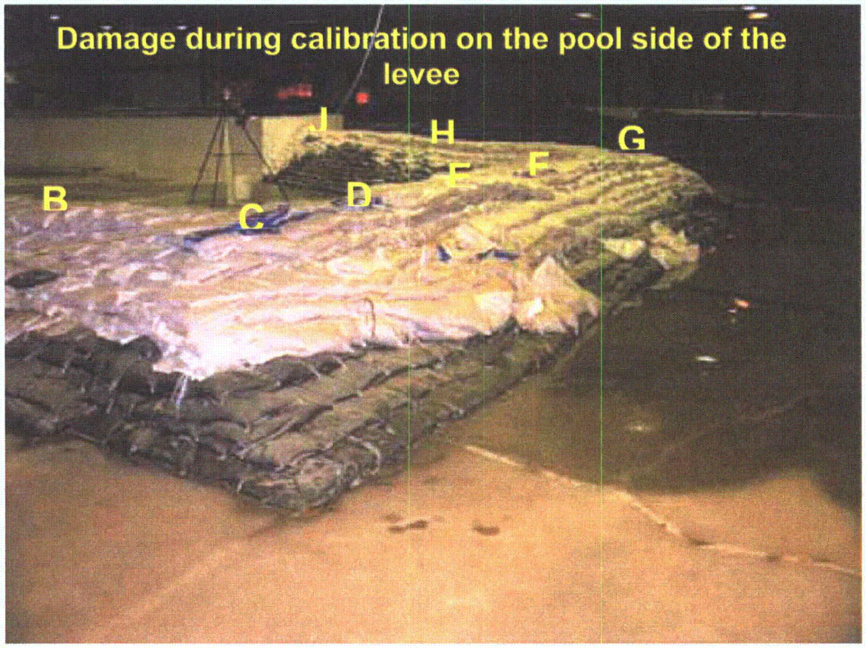


Figure 2-27. Damage done during calibration of wave machine

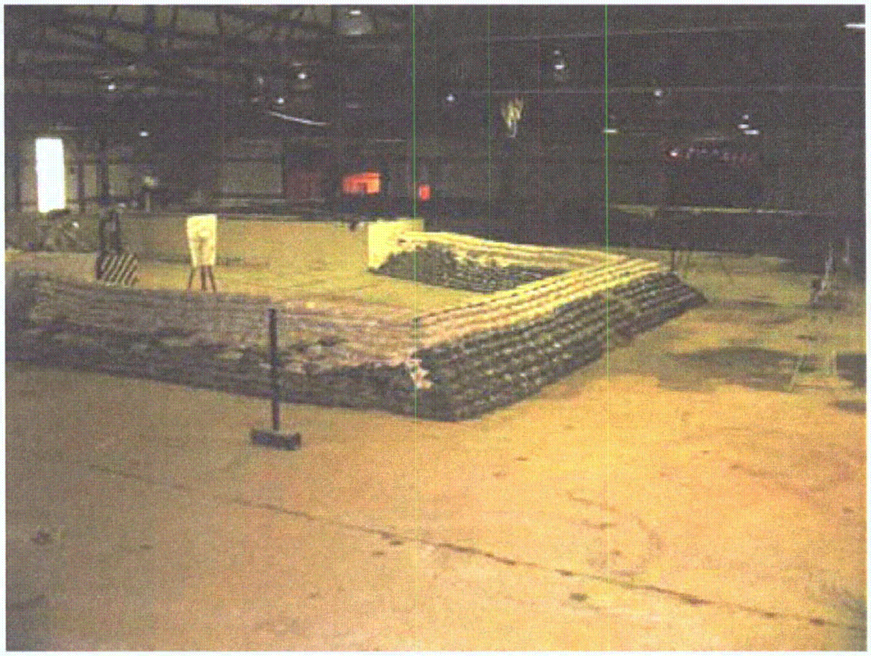


Figure 2-28. Sandbag levee after repair

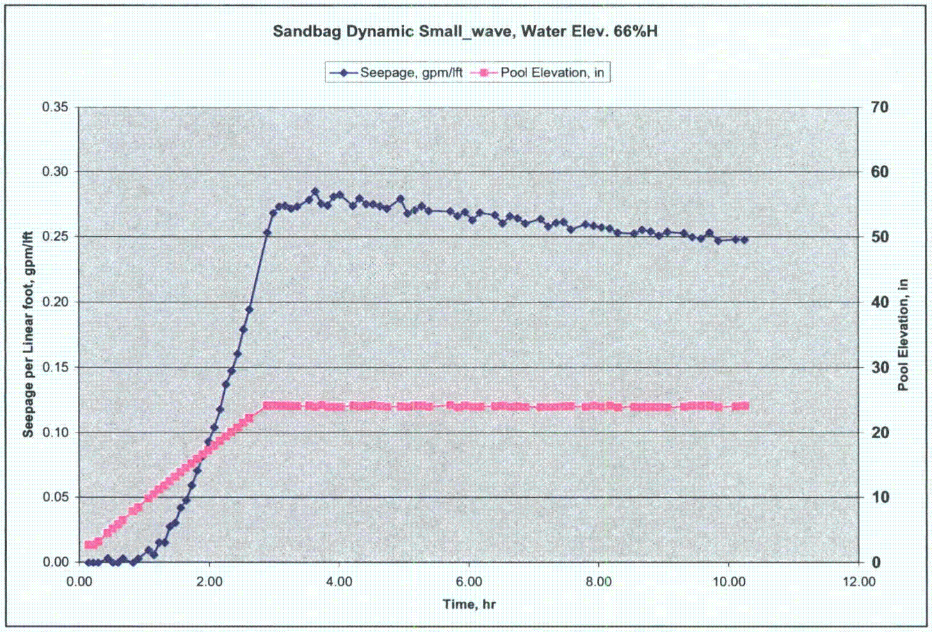


Figure 2-29. Seepage with dynamic testing at 66 percent levee height and 3-in. waves for 7 hr

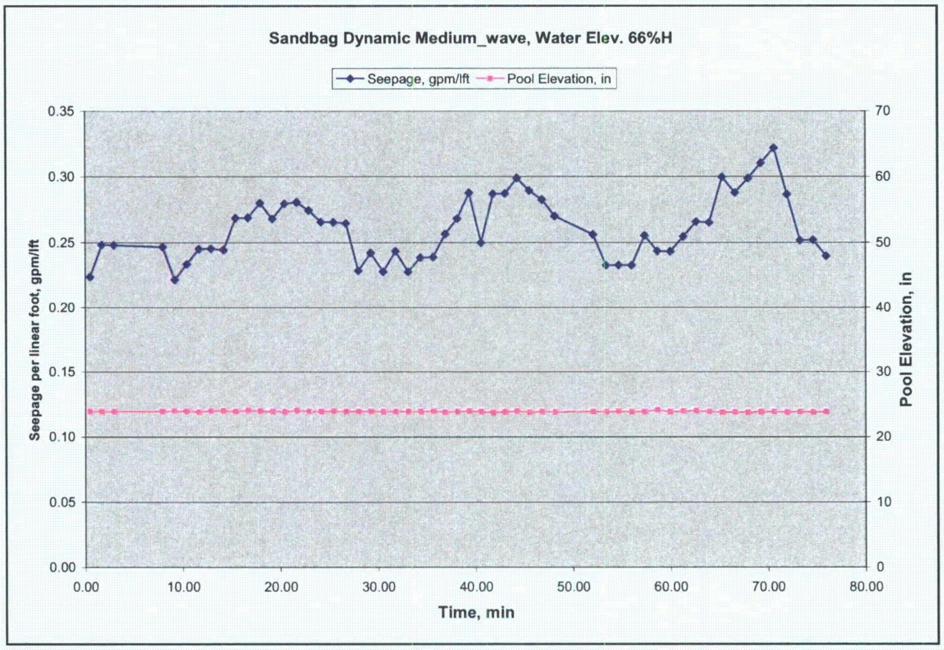


Figure 2-30. Seepage with dynamic testing at 66 percent levee height and 7- to 9-in. waves

10- to 13-in. wave test, reservoir level at 66 percent levee height. The water level in the reservoir on the pool side of the sandbag levee was held at a height of 24 in., and wave heights were generated from 10 to 13 in. for a period of 10 min. Wave overtopping occurred at each wave front, which significantly increased the observed flow rate in the sump pit from 0.23 gpm/lft up to 3.19 gpm/lft. The seepage plot is shown in Figure 2-31. Nearly all of this is overtopping, not seepage through the levee. No displacement was observed. Damage occurred during this test requiring Repair 1. Repair 1 is discussed in the maintenance section of this chapter.

3-in. wave test, reservoir level at 80 percent levee height. The water level in the reservoir or the pool side of the sandbag levee was raised to a height of 28.8 in., and 3-in. waves were generated in packets of 10 min each. The test was then stopped for about 15 min to allow stilling of the basin. This sequence was repeated three times for this test. Seepage flow rates were observed to range from 0.38 to 0.4 gpm/lft and no displacement was noted. No wave overtopping occurred. The seepage data are shown in Figure 2-32. The test was uneventful, looking much like a seepage test except there is no decrease in seepage with time.

7- to 9-in. wave test, reservoir level at 80 percent levee height. The water level in the reservoir on the pool side of the sandbag levee was held at a height of 28.8 in., and wave heights were generated in packets of 7 to 9 in. for a period of 10 min. This sequence was repeated three times.

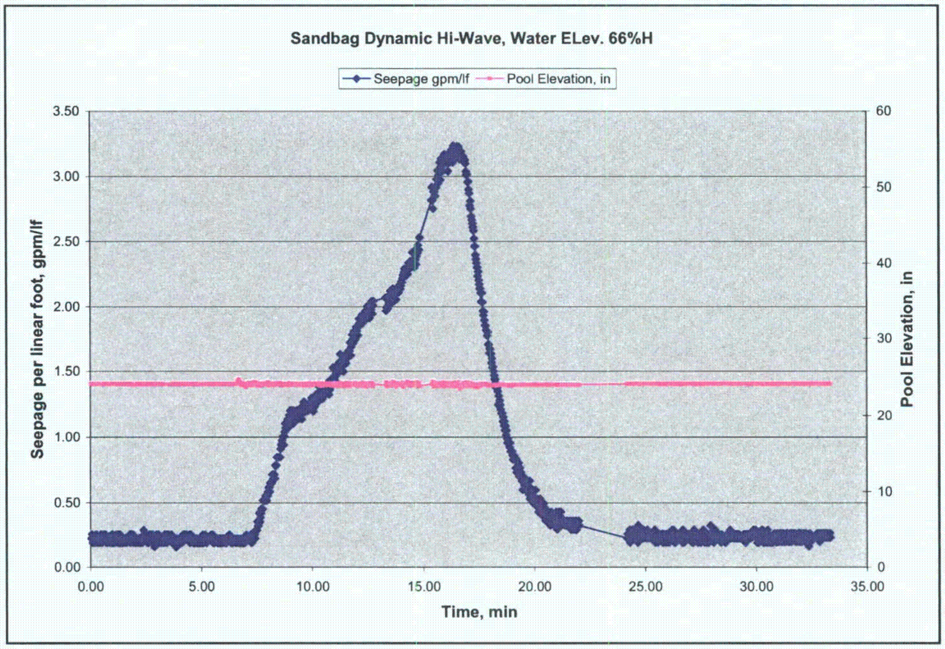


Figure 2-31. Seepage with dynamic testing at 66 percent levee height and 10- to 13-in. waves

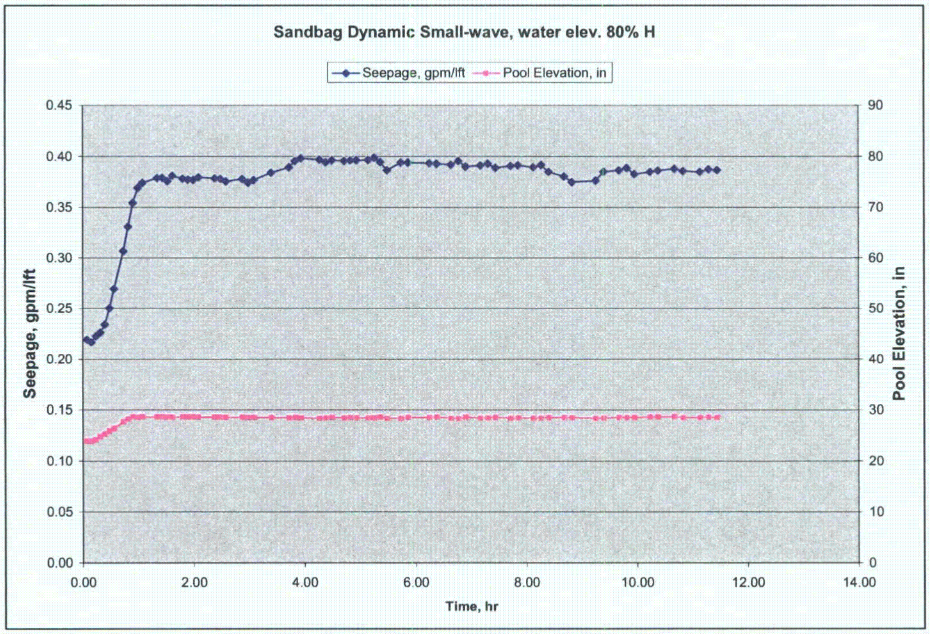


Figure 2-32. Seepage with dynamic testing at 80 percent levee height and 3-in. waves for 7 hr

Flow rate significantly increased from 0.38 to 7.42 gpm/lft due to overtopping of each wavefront. No displacement was observed. The amount of water going through and over the barrier is shown in Figure 2-33.

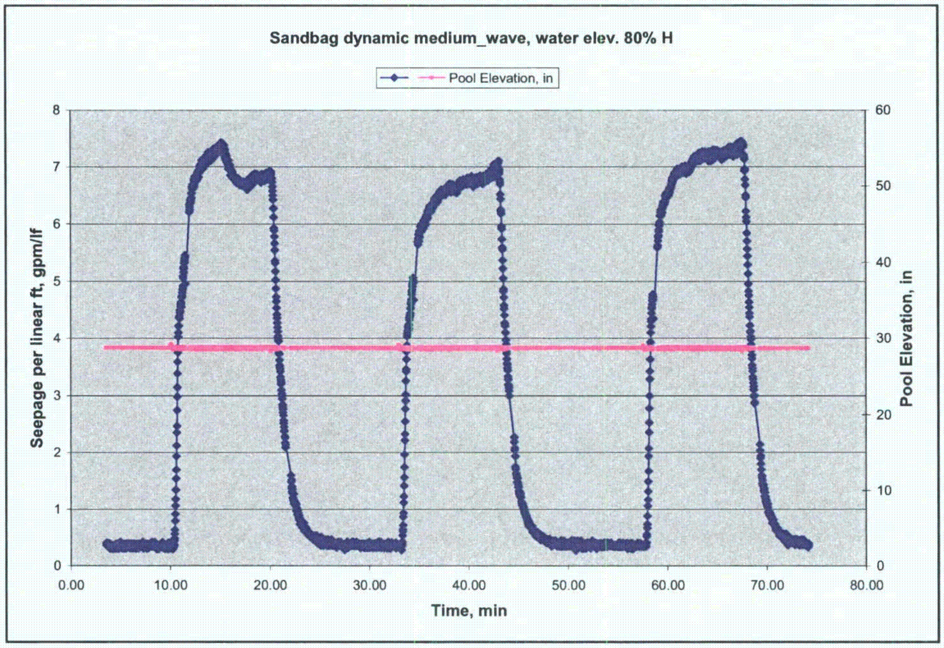


Figure 2-33. Seepage with dynamic testing at 80 percent levee height and 7- to 9-in. waves

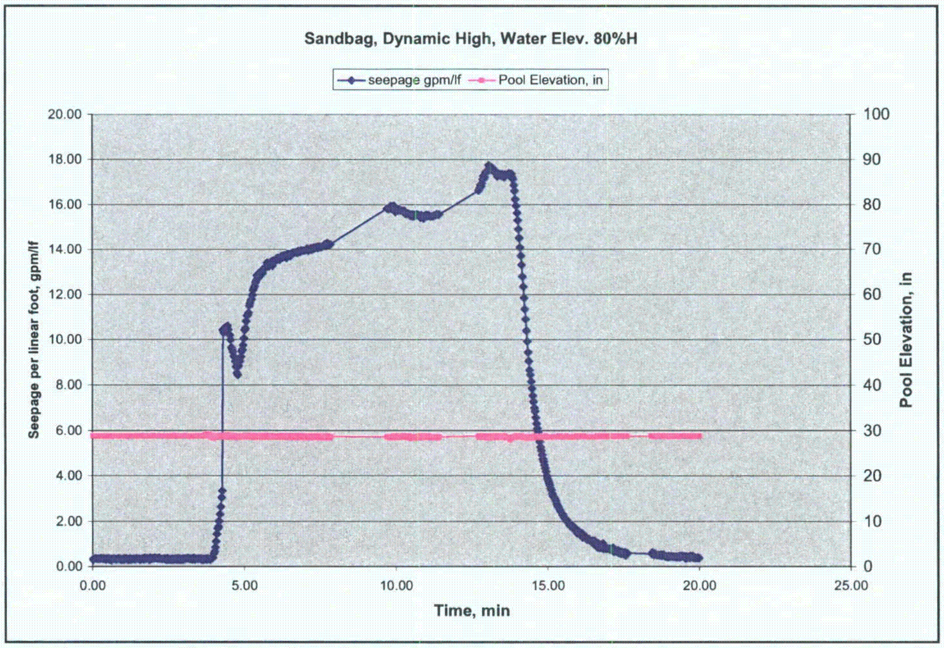


Figure 2-34. Seepage with dynamic testing at 80 percent levee height and 10- to 13-in. waves

10- to 13-in. wave test, reservoir level at 80 percent levee height. The water level in the reservoir on the pool side of the sandbag levee was held at a height 28.8 in., and wave heights were generated in packets of 10 to 13 in. for a period of 10 min.

Flow rate significantly increased from 0.37 to 17.52 gpm/lft due to overtopping of each wave front. No displacement was observed. Figure 2-34 shows extensive damage occurred during this test requiring Repair 2. Repair 2 is discussed in the maintenance section of this chapter.

Debris impact test

During flood conditions, a levee may sustain damage from floating debris such as tree stumps, trees, houses, etc. Surviving impacts without immediate or progressive levee failure is vitally important. To simulate the effects of floating-debris impact, wood logs were mechanically rammed against the levee's outer (poolside) surface at a speed of 5 mph. The test protocol (overtopping test followed by impact tests) was modified for the sandbag levee to allow repairs due to significant levee damage during an initial overtopping test. After the barrier was repaired (Repair 1), the impact tests were completed prior to subsequent wave tests with pool at 80 percent of levee height.

Two separate impacts at 5 mph were conducted. The first test impacted a 12-in.-diam log 12 ft long against the levee during a static water level held at 66 percent of the levee height, and the second test impacted a 16-in.-diam log 12 ft long against the levee also at the 66 percent height.

The locations of impact are shown in Figure 2-35. The impact occurred at "e" for the 12-in. log and at "f" for the 16-in. log. No damage occurred from either log test, although the larger log left a small indention on the barrier's front face. No permanent lateral displacement was observed during either test, and no vertical deformation was noted.

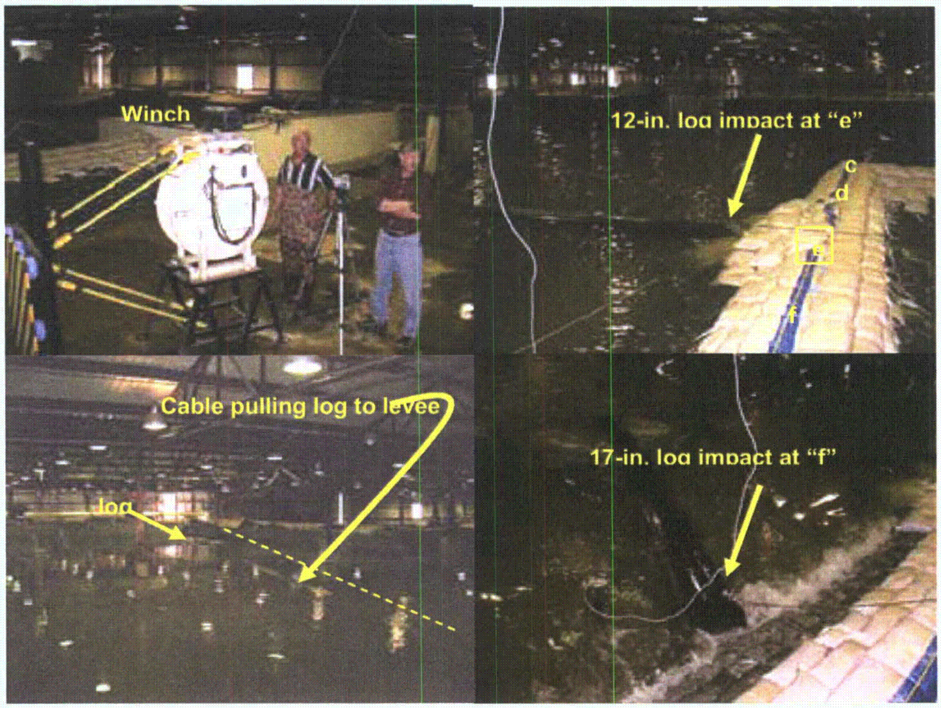


Figure 2-35. 12- and 16-in. logs at point of impact

Levee-overtopping test

To observe levee behavior where the floodwaters overtop and inundate the levee, an overtopping test was conducted. The reservoir pool height was raised beyond the height of the levee to allow overtopping to take place. During rising of the pool, numerous low spots along the crest allowed overtopping to occur in an uneven fashion. Water was to be raised to an elevation of 37.5 in., or until the pumps were unable to keep up.

However, the pool overtopped the levee at an elevation of 37 in. (approximately 1 in. above the crest), and continued for a period of 5.7 min. Progressive levee failure occurred as the total flow rate increased from 30.3 to 96.0 gpm/lft. A total flow rate of 2450 to 7,760 gpm is shown in Figure 2-36. Failure and results of failure are shown in Figures 2-37 through 2-40.

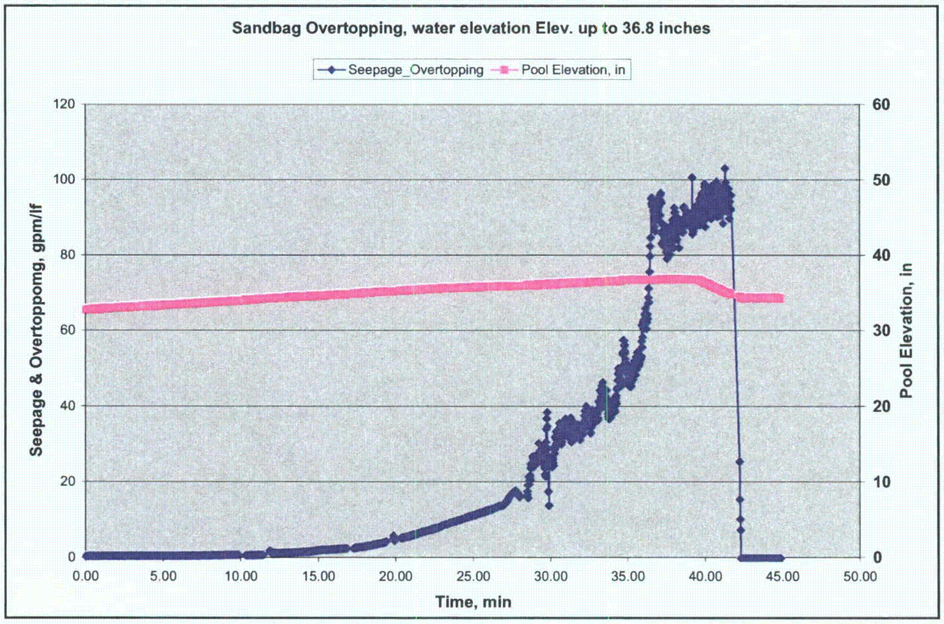


Figure 2-36. Seepage and overtopping

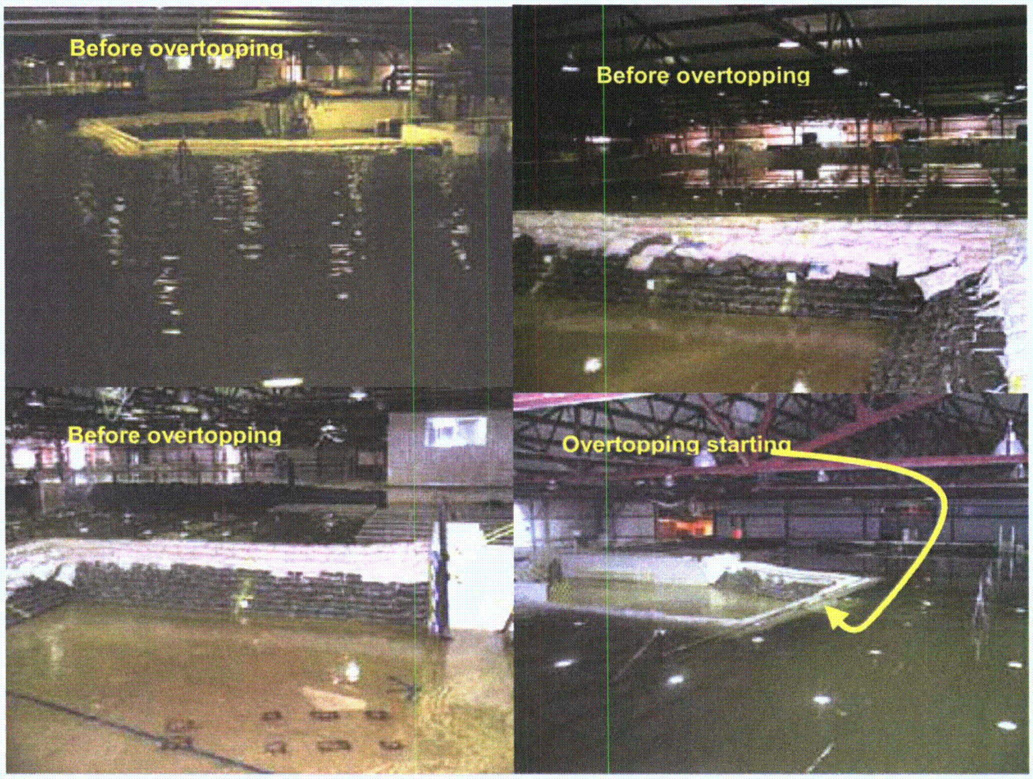


Figure 2-37. Sandbag levee prior to overtopping

The levee failed during overtopping before the pool elevation reached 37.5 in. The pumping rate continually increased until failure occurred. Thus, the structure failed before the test criterion was reached. Figure 2-37 shows the structure prior to testing. Figure 2-38 shows the progressive failure during overtopping. Figure 2-39 shows the sandbag levee after failure. The autopsy of Figure 2-40 shows that the bags became filled with water by the wave action and emptied as the sand flowed out like water (liquefaction). The wave action caused the untied bags to empty. Once the sandbags became light enough, the waves washed the bags from the levee causing failure. Some of the bags found on the landside were completely empty.

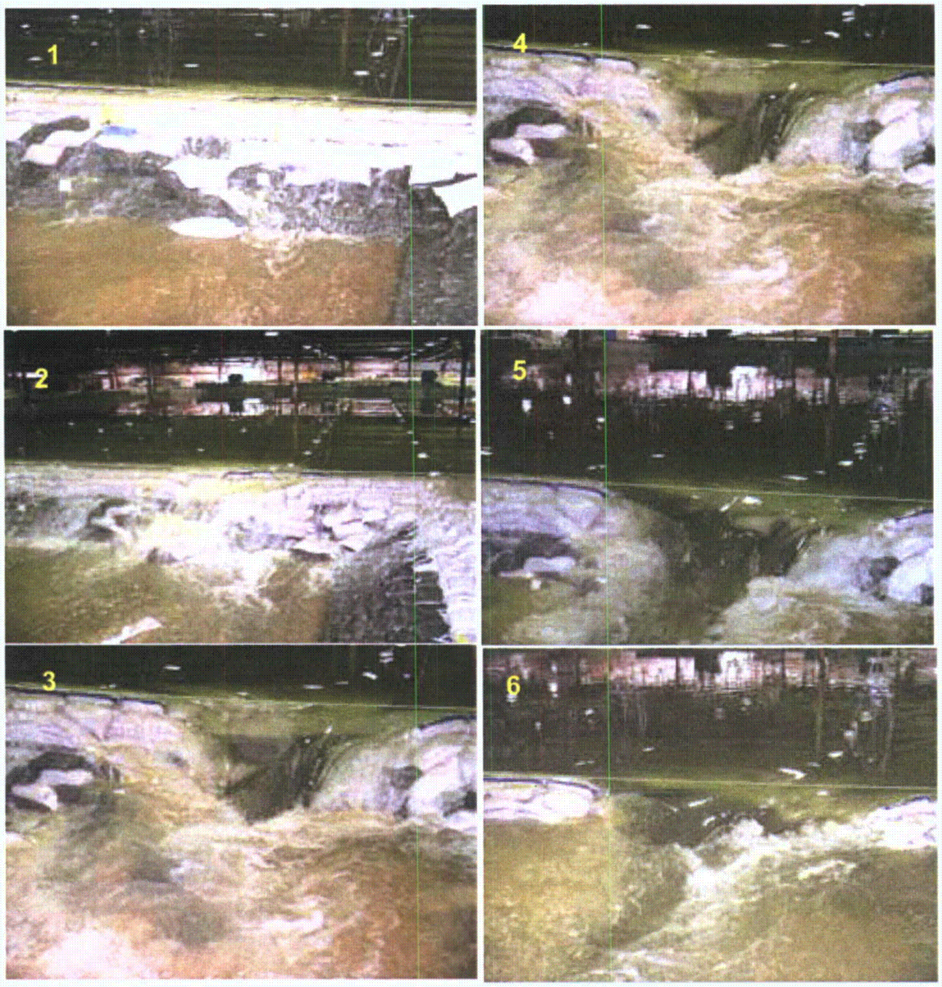


Figure 2-38. Sandbag levee progressive failure while testing

Figure 2-39. Sandbag levee after failure

Figure 2-40. Sandbag levee autopsy after overtopping

Maintenance and repair

Repair 1 was required to repair damage from the dynamic high-wave test performed with the pool at 66 percent of levee height. A four-man crew took 30 min (total time 2 man-hours) to remove damaged sandbags, reposition existing sandbags, and fill and place new sandbags on the pool side of the barrier. A Bobcat® with operator transported the new sandbags from the sand pile to the barrier.

The levee experienced damage at the center section. Sandbags were pulled back into the pool as the waves overtopped and water rushed back into the pool as the waves moved back toward the wave machine. Figure 2-41 shows the levee during the test, the damage after the test, and the levee after Repair 1.

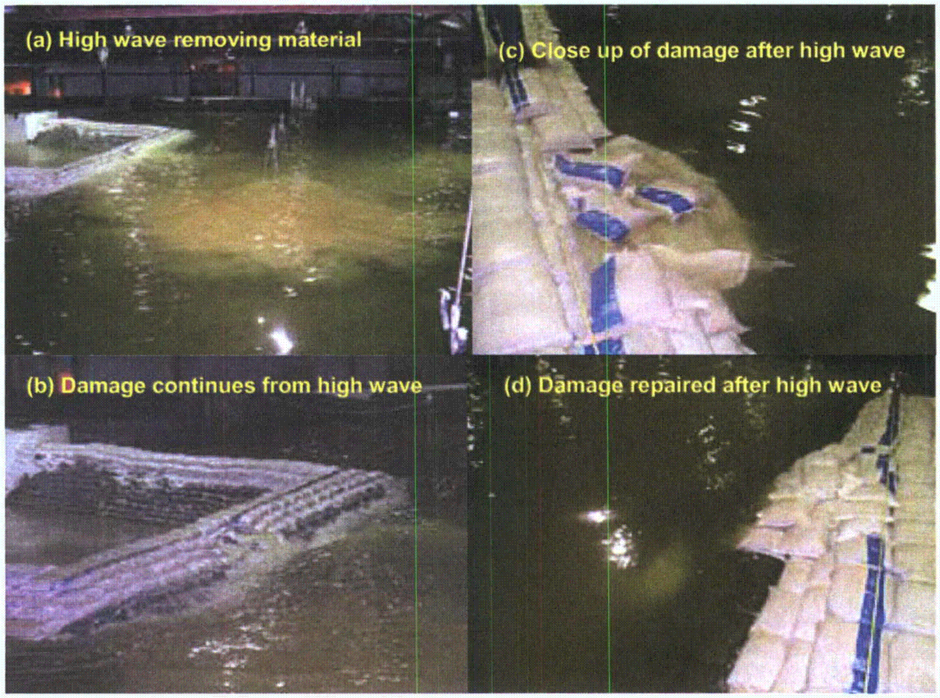


Figure 2-41. Sandbag levee damage and levee after field repair 1

Repair 2 was needed after testing with the pool at 80 percent of levee height and 10- to 13-in. waves. A four-man crew took 30 min (total time 2 man-hours) to remove damaged sandbags and repair the barrier.

Overtopping caused by the 10- to 13-in. waves resulted in movement of individual sandbags in both directions from the crest of the structure. Figure 2-42a-d shows the progressive movement of sandbags during and after this test.

Figures 2-27 and 2-28 and accompanying text show and explain the failure that required rebuild. A four-man crew took 11 hr (total 44 man-hours) to repair the damage. The rebuild was required from calibration needed to establish the limiting wave forces for all future tests. For this reason, the rebuild is not considered part of the test repairs.

Figure 2-42. Damage to levee during the 10- to 13-in. waves, water at 80 percent of barrier height

Disassembly and reusability

After all tests were completed and the reservoir was drained, the levee was disassembled. Disassembly consisted of removing the sandbags and required a two-man crew with shovels, brooms, and a Cat® 916 front-end loader working a total of nine man-hours.

The sandbags were broken and torn during removal and were not fit to be used again. The sandbags were piled into one large stack, similar to that seen in real-world flood fights. The equipment and sandbag pile can be seen in Figure 2-43.


Figure 2-43. Heavy equipment used to disassemble sandbags and waste sandbags

Environmental aspects

The only material used (sand) is considered to be nonhazardous and nontoxic, so there were no exposure hazards during these tests.

If the floodwater is contaminated with bacteria or pollutants, the sand fill inside the bags also may be contaminated. The sandbag itself should provide some filtering protection, especially for nonwater-soluble and small contaminants such as floating oil, but water-soluble contaminants would likely seep into the sand fill.

Hesco Bastion Concertainer® Levee Tests

Design

Hesco Bastion Concertainer® (hereinafter referred to as "Hesco®"), listed under U.S. Patents 3333970, 5472297, and European Patent 046626, is a structural system of linked baskets containing fill material. Hesco® systems have been used around the world for military operations as well as for combating natural disasters (Hesco 2004). The corporate Web site is http://www.hesco-usa.com.

The units (Figure 2-44) are manufactured in various sizes and are made of welded galvanized steel mesh that is assembled with coiled joints. A polypropylene nonwoven geotextile liner retains the fill material (sand, gravel, or other fill) that is dumped into the open (top and bottom) basket using minimal labor and commonly available equipment. The baskets are flat-packed on pallets, extended and joined with joining pins, filled with fill material, and stacked in various configurations depending on the end-use. The units are lightweight, portable, and are easily handled.

Engineering analysis of the system was provided by Hesco®, and listed the ability of the structure to withstand hydrostatic and uplift forces. The ability of the structure to resist lateral forces was analyzed based on the assumption that the structure will respond as a rigid body to hydrostatic forces. A free-body diagram of the hydrostatic forces showed the resistance to lateral sliding on a concrete floor with a given water height of 3 ft and a coarse-grained fill material.

A test-condition analysis for a 3-ft by 3-ft unit on a concrete floor subjected to a 3-ft-high flood was given for various load cases with given basket and fill weights, given sand unit weight, vertical and horizontal reaction forces, hydrostatic pressure force, and uplift force. Assuming an interface coefficient of friction between coarse sand and concrete floor of 0.45, the safety factor against lateral sliding was calculated to be 1.13 (Load Case 5). No floor anchoring system was accounted for, and no floor anchoring was planned for the ERDC tests.

Figure 2-44. Hesco Bastion Concertainer® basket units, assembled and empty

For the ERDC tests, the Hesco® Flood Unit system (General Services Administration (GSA) No. GS-07F5369P) was furnished, with unfolded unit dimensions of 3 ft height by 3 ft depth by 12 ft width, and commercial price of $295 per unit (approximately $25 per linear foot). End panels (3 ft × 3 ft × 3 ft), connecting joining pins (3 ft) and connecting coil hinges (3 ft) were also furnished. The wire mesh, joining pins, and coil hinges were manufactured from 8-gauge steel and coated with a proprietary galvanizing. Wire mesh size was 3 in. by 3 in. The nonwoven geotextile liner was GEOTEX® 641. Fill sand was provided by ERDC (delivered price of $7 per cubic yard) and was classified as poorly graded sand (USCS "SP") with approximate moisture content of 6 percent.

Construction

Layout of the Hesco® levee built at the ERDC test facility is shown in Figure 2-45.

The stacked units were shipped to the laboratory on a wooden pallet. Construction commenced on 4 May 2004. Relatively cool ambient air temperatures (approximately 60 to 70 deg) provided comfortable working conditions inside the hangar.

Personnel needed to construct the levee included a Hesco® supervisor and four laborers unfamiliar with the product. A 5-min training session commenced (Figure 2-46), the supervisor handed out gloves to the workers, and they began unloading and expanding the units onto the concrete floor (Figure 2-47).

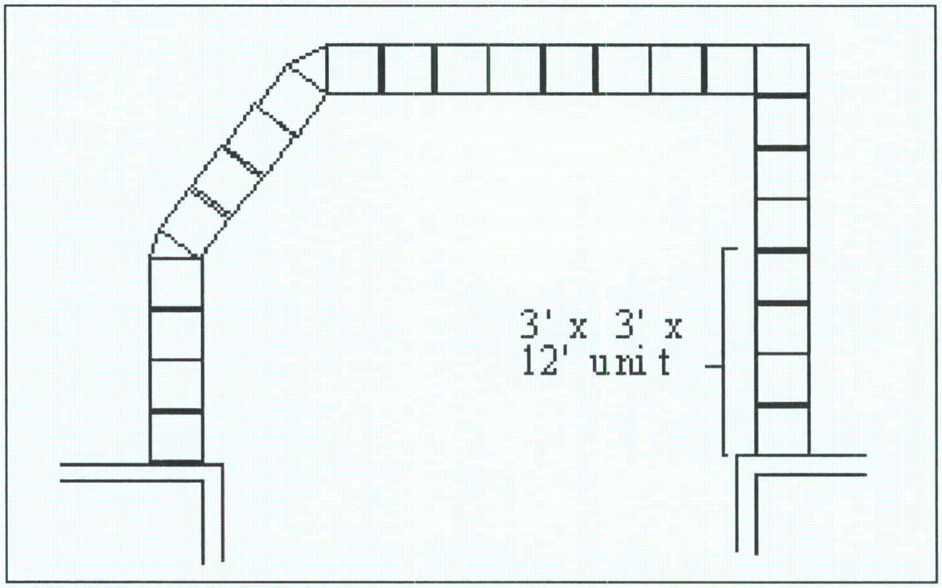


Figure 2-45. Hesco® levee layout

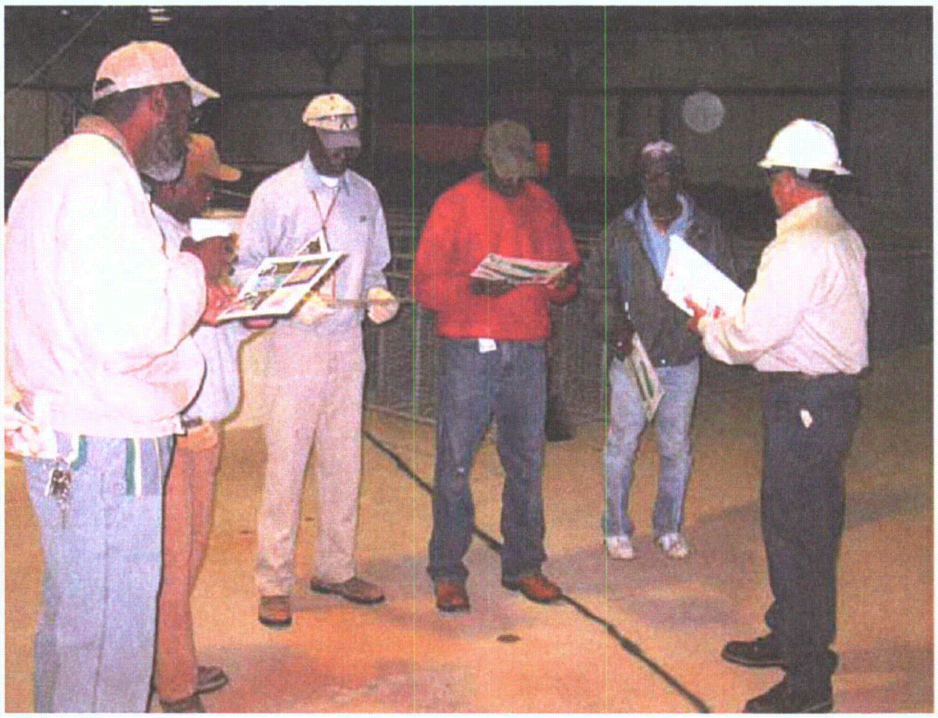


Figure 2-46. Training session for Hesco® assembly team

Figure 2-47. Expanding and positioning units

The expanded units were sequentially positioned on the layout footprint, and the coil hinges were fastened together with the joining pins (Figure 2-48). At angled connections (the intersection of the left and center walls), the supervisor folded and attached end panels to achieve proper unit geometry (Figure 2-49), and the workers continued pinning the units together. Nylon cable ties were also used for securing units together at critical locations determined by the supervisor (Figure 2-50). Initial treatments at concrete wall abutments were also installed (Figure 2-51). Total installation time for offloading, laying out, aligning, and connecting the levee structure was 60 min (approximately 1 lft/min).

The next construction phase consisted of filling the units with sand and completing the installation. The bottom flaps were flattened against the concrete floor (Figure 2-52). A front-end loader top-dumped sand into each unit (Figure 2-53). The supervisor and four workers continued securing the units, filling with sand, compacting, and leveling sand within the units with shovels while the sand-fill operation was ongoing, until all units were full and leveled (Figures 2-54 through 2-57). Approximately 24 cu yd of sand was required to fill the units.

No floor anchoring system was used at the concrete wall abutment connections. To seal the joint between the unit and the concrete wall abutment, expandable foam was dispensed into the joint by the supervisor (Figures 2-58 and 2-59).

Total installation time for the Hesco® levee was 3.5 hr (approximately 3.4 min per linear foot of levee). Labor required was a six-man crew (total 20.8 man-hours), and equipment required was a Cat® 916 front-end loader, sand, and aerosol foam. On a linear foot basis, the construction required 20.8 man-hours per 62 lft (measured along the protected toe), or 0.3 man-hours per linear foot.

Figure 2-48. Pinning units together

Figure 2-49. Top view of angled unit at intersection of left and center walls

Figure 2-50. Cable ties at joint connections

Figure 2-51. Right concrete wall abutment

Figure 2-52. Securing flaps against concrete floor. Note center coils which are prefastened at factory

Figure 2-53. Filling with sand

Figure 2-54. Shoveling sand into unit

Figure 2-55. Leveling and compacting sand within each unit

Figure 2-56. Filled with sand, view from left concrete wall abutment

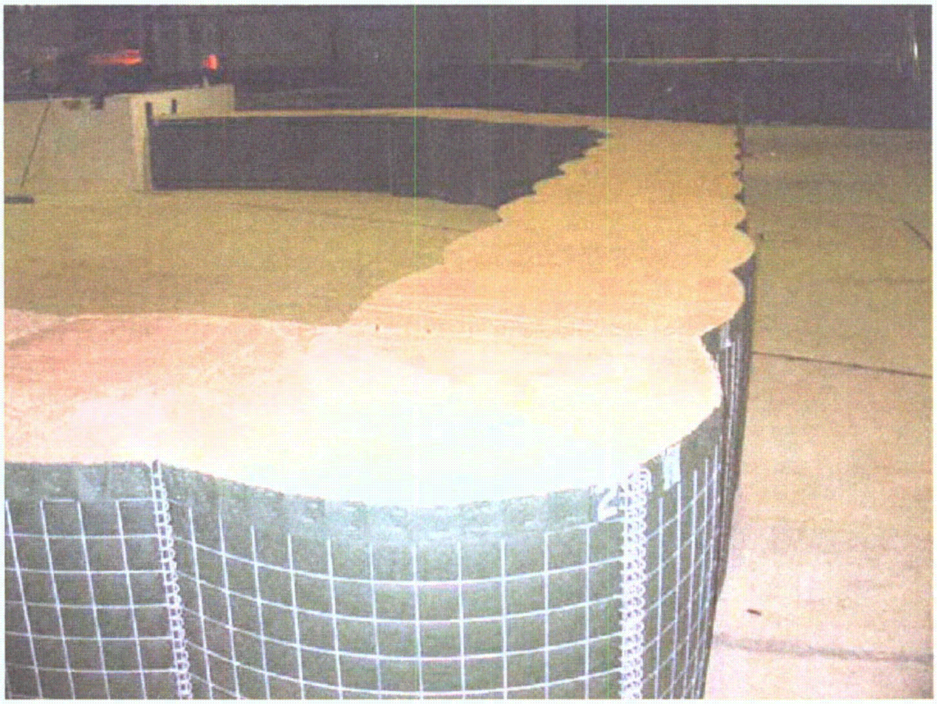


Figure 2-57. View from pool side

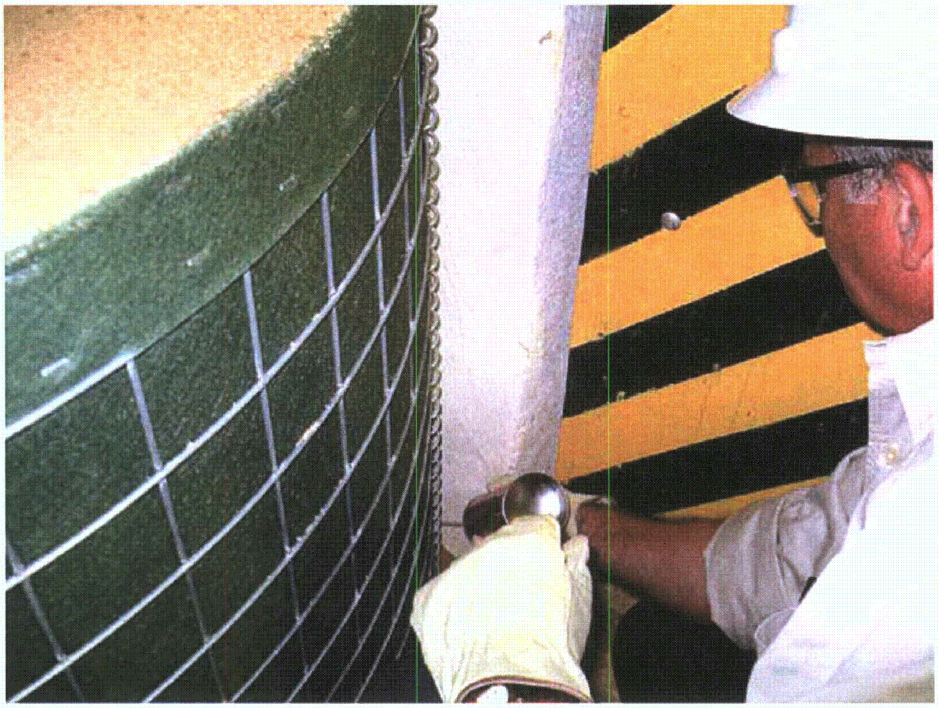


Figure 2-58. Sealing concrete wall abutment with aerosol foam

Figure 2-59. Expanded foam at abutment with concrete wall

Prior to filling the reservoir to begin the hydrostatic tests, laser targets were positioned in the levee walls and sealed with expandable foam (Figure 2-60). The completed structure was instrumented with the center-wall displacement monitoring system and was readied for static testing (Figure 2-61). The vendor representative agreed in writing that the levee had been constructed properly and was ready for testing.

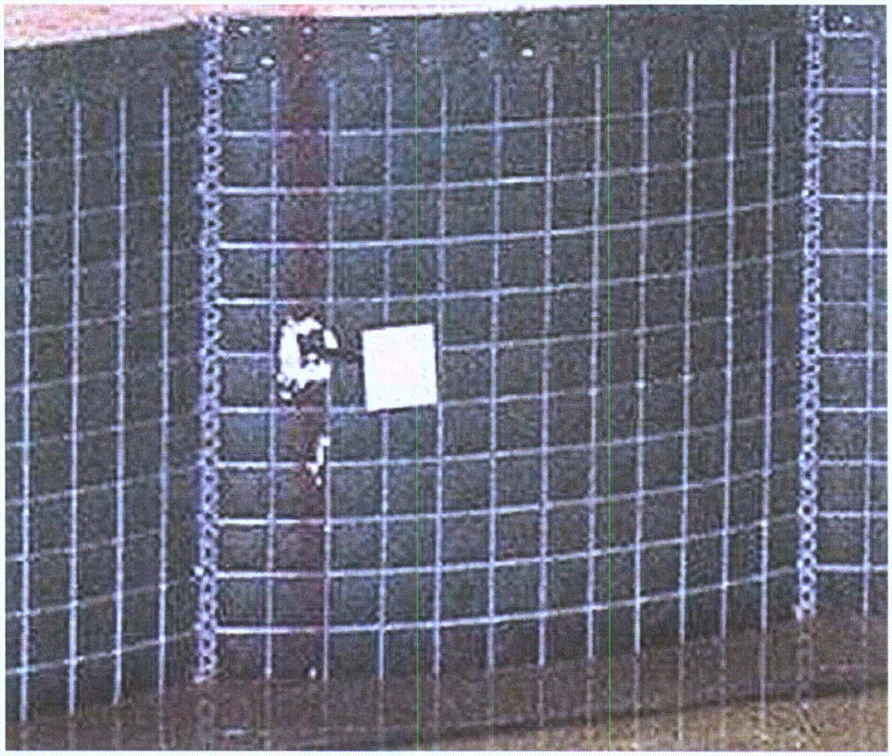


Figure 2-60. Laser target

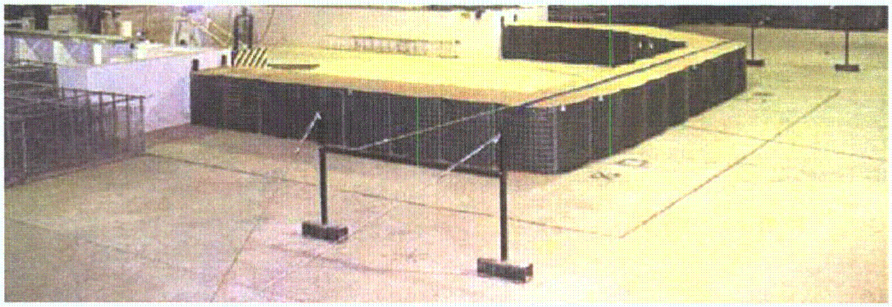


Figure 2-61. Center wall displacement monitoring system

Performance

Testing of the Hesco barrier began after construction was completed and was documented in the same manner as testing of the sandbag structure. Three minor repairs were allowed within seven windows of opportunity during the tests, as described in Appendix C. After the overtopping test, one final repair (or rebuild) was allowed prior to the impact tests.

Disassembly and removal of the barrier was performed after testing was completed and the test basin was drained. An environmental evaluation was also performed for the barrier system, to assess environmental hazards of construction and disposal.