U.S. Army
Corps of Engineers

- EXECUTIVE SUMMARY -

TESTING AND EVALUATION OF A NEW EXPEDIENT STRUCTURE FOR FLOOD FIGHTING – RAPIDLY DEPLOYED FORTIFICATION WALL (RDFW)

George F. Turk, P.E.

Historically, expedient flood fighting solutions to raising levees and impounding infrastructure against rising floodwaters have been primarily limited to those involving sandbagging operations. In a period between 1981 and 1985, the U.S. Army Corps of Engineers conducted extensive research on a number of expedient levee-raising structures under the Improvements of Operation and Maintenance Techniques Civil Works Research Program. Those tested showed limited degree of effectiveness. Major flood events plagued the 1990's. The Great Flood of '93 was the largest and most devastating event. Flooding caused loss of life and extensive damage. In 1993, at the direct request of Dr. Robert B. Oswald, then USACE Director of Research and Development, Waterways Experiment Station (WES) fielded a two-man team, Dr. Victor H. Torrey III and Mr. George F. Turk to collect data on expedient methods used to fight floods. The team was looking for innovative expedient methods, but found sandbag levees still the primary flood-fighting tool. In many cases, labor-intensive sandbagging operations often yielded poorly constructed ineffective structures.

The Corps of Engineers encourages product innovation in the field of expedient flood fighting. The U.S. Army Corps of Engineers entered a Cooperative Research and Development Agreement (CRDA) with A.M. Arellanes and Sons and Associates, Inc. on 16 March 2000. The purpose of the CRDA was to test and evaluate one such innovative product. The expedient flood fight product is called Rapidly Deployed Fortification Wall (RDFW) (Figure 1a). The RDFW is constructed from an assembly of Sand Confinement Grids (SCG). ERDC's Structures and Geotechnical Laboratory originally invented and patented several variations of SCG. In 1996, WES licensed SCG to the Native-American 8-A company, A.M. Arellanes and Sons and Associates, of Mountain View, CA. Mr. Al Arellanes, Owner, working closely with WES engineers, produced a "second-generation" rectangular-cell SCG product. Mr. Arellanes called the product RDFW.

The primary purpose the CRDA investigation was to test and evaluate the effectiveness of RDFW when configured as a wall structure, and subjected to hydrostatic and wave-induced dynamic loads. The scope of work called for the RDFW to be rigorously tested. During the testing the wall was inspected for seepage, lateral deflection, sand loss, and material failure. A secondary purpose was to develop a protocol for testing and evaluating future expedient flood fight structures. By developing a testing protocol a variety of expedient structures can be evaluated under the same controlled laboratory conditions. The Coastal and Hydraulics Laboratory tested the RDFW at full scale. Limitations exist in the laboratory. For this particular test series, the RDFW wall was 50 ft in length and 4 ft in height and buttressed against impermeable vertical concrete walls. The structure was founded on a concrete floor; thus stability against foundation scour was not evaluated. No capability existed in the test basin to generate large steady-state currents along the face of the RDFW, thus their effects were not evaluated. The report entitled, "Testing and Evaluation of a New Expedient Structure for Flood Fighting – Rapidly Deployed Fortification Wall (RDFW)" serves to document testing of the RDFW structure, which was subjected to hydrostatic loads and wave action of increasing magnitude.

The primary building block of a RDFW wall is the RDFW grid. The grids are laid side-by-side and interlocked with each other. Subsequent lifts of connected grids are stacked on lower lifts until the desired height is reached. The grid forms the skeleton, which is then filled with sand. Sand, once confined in the cells exhibits a tremendous increase in compressive strength. The sand also provides the mass for the structure, which resists sliding forces and overturning moments. This research effort used a RDFW wall that had a base-to-height ratio of approximately one. The four foot wide, four-foot tall, sand-filled RDFW wall has a dry weight of 1800 LB per linear foot. One significant observation of the wall construction process pertains to consistency and repeatability. Sandbag levees are the most used of any type of expedient structure. However, it takes training and diligence to build a sandbag levee with consistency. Rotation in crews, fatigue, and adverse conditions often lead to substandard levee construction. From observations of the construction process in building the RDFW wall, it appears the wall is relatively easy to construct. It seemed the untrained laborers quickly understood the construction process. As long as the walls are properly interlocked, filled and compacted it is anticipated there will be very little deviation in the integrity between construction of various RDFW walls.

The testing protocol for the hydrostatic head test consisted of flooding the basin on the upstream side (or riverside) of the wall and on the downstream (or "dry") side of the wall, taking measurements of the response (seepage and deflection) to rising waters. Three water levels were used for the testing, 50%, 67%, and 83% of the height of the wall. For the RDFW wall with a height of 48 in, this corresponds to 24 in, 32 in, and 40 in. At each increment, the water level is held at this stage, at least once, for a minimum of 12 hours. The RDFW wall was subject to over 128 hours of hydrostatic head levels between 2.0 ft and 3.33 ft. During this time a minimal amount of sand fill was lost from the 50-ft wall. There was no lateral deflection associated with these loads and no damage was observed. The wall essentially remained unchanged for the duration of the test series. There was no observable through-seepage, but there was under-seepage. The highest head level was $d = 3.33$ ft or 83% of the total wall height. Under this condition, the maximum-recorded under-seepage rate was 22.8 gallons of water per linear foot of wall per hour. While the RDFW wall was founded on a concrete surface, this is typical of a foundation condition that typically exists in an urban flood fight scenario. Placement of the RDFW wall on a soil foundation may yield different results. On a soil foundation, placing and keying a RDFW wall in a shallow trench may eliminate under-seepage. From the under-seepage rates given in Table 1, a field engineer has some guidance on anticipated amount of water that may become impounded on the dry side of the wall due to under-seepage, as a function of time and wall length. The engineer can then select the appropriate pump size for draining impounded water. For example, under idea field conditions with proper drainage gradients for impounded water for the greatest recorded rate of 18.7 gal/LF/hr, a small a 3-hp, 150 GPM gasoline-powered water pump typically used in flood fights should be able to drain more than 400 linear foot of wall.

The purpose of wave-induced dynamic load testing is to provide both an evaluation of the performance of the structure and to observe structural response to severe loading conditions. Insight is gained into any failure mechanism, be it fill loss, material failure, wall sliding, overturning, or deforming. The protocol calls for running four one-hour packets of monochromatic waves with a wave period of, $T = 2.0$ sec. With each successive set of four hours of wave action, barring failure or extensive damage, the wave heights are incrementally increased. The test series was conducted for two different water depths. Observations of the wall's condition and response were made during the run. At the end of each run the basin was stilled for 10-15 minutes to allow the waves to dissipate. The RDFW was subjected to incident wave heights, which were estimated to range from 0.42 ft to 1.52 ft. Waves were run at two water depths, $d = 2.0$ ft and $d = 2.67$ ft. The wall was exposed to a total of 72,000 waves within the 40-hour duration of wave action. From observations and photographic documentation much of the wave runs the wave action was severe (Figure 1b).

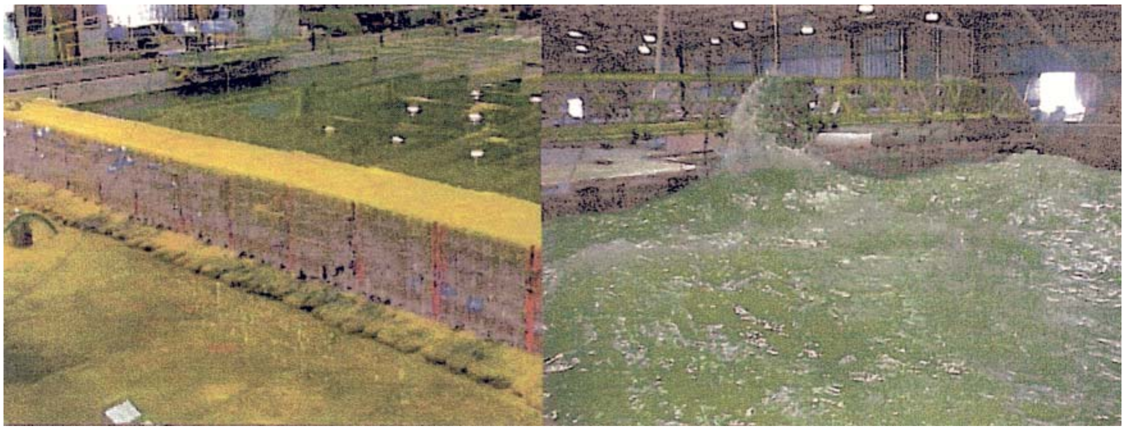
The structure was exposed to incrementally increasingly wave attack. Damage to the structure occurred at three locations along the wall. When damage at one location was deemed excessive, the wall was repaired, and wave runs continued. At the two damage locations adjacent to abutments, it appeared the abutments concentrated wave loads and accelerated damage progression. For a typical structure used in the field, the dry-side may have abutments to support the wall but it is doubtful abutments would be needed on the riverside, except at a closure. So abutment-related wave load concentrations will not occur in the field. However, in a flood there is the possibility that debris may become trapped against the wall and similar concentrated loads may occur. Damage at the wall mid-span did not occur until Hour 37. By Hour 40 the wall had sustained significant damage and the tests terminated. In observations of the deterioration of the RDFW wall, it appears the wall has more of a ductile failure mode rather than a brittle failure mode. That is, the failure comes on slowly, rather than quickly and catastrophically. In an actual flood fight under similar conditions, it appears there could be adequate time to make repairs before significant damage occurs, if manpower were available and trained.

The wave field generated in the basin was extremely complex and energetic. New methods were developed to quantify performance in terms of power exposure, as opposed to wave height and wave attack duration alone. Test results were used to generate estimated durability of RDFW for idealized wave height and water depth combinations (Table 2). These estimates should be used with discretion, for preliminary planning and maintenance schedules until validated with actual field experience.

In conclusion, the RDFW wall performed well during the investigation. The tests showed:

- The RDFW wall construction process lends itself to consistency and repeatability.
- The RDFW wall was subject to over 128 hours of hydrostatic head levels without damage.
- The maximum-recorded under-seepage rate was 22.8 gallons of water per linear foot of wall per hour.

- The wall was exposed to a total of 72,000 waves within the 40-hour duration of wave action.
- The wall has a ductile failure mode rather than a brittle failure mode.
- Repairs to the wall were relatively easy to make.



(a) (b)

Figure 1. (a) RDFW wall after 42.5 hrs of 3.33 ft of head (b) Wave action on wall, H = 1.46 ft, d = 2.67 ft

Table 1
Hydrostatic Head Tests and Underseepage Rates

Head (ft)	Elapsed Time (hr)	d_backside start (ft)	d_backside end (ft)	d_backside differential (ft)	Seepage Volume (ft^3)	Volume/LF (ft^3/ft)	Vol/LF/hr (ft^3/LF/hr)	Vol/LF/hr (gal/LF/hr)
2.00	4.25	0.07	0.16	0.09	96.2	1.9	0.5	3.4
2.00	42.50	0.17	0.70	0.53	1781.0	35.6	0.8	6.3
2.00	3.12	0.07	0.15	0.08	81.3	1.6	0.5	3.9
2.00	4.50	0.19	0.25	0.06	54.8	1.1	0.2	1.8
					HEAD, H = 2.0 ft, Average Rate -			3.8
2.67	5.75	0.12	0.30	0.18	276.8	5.5	1.0	7.2
2.67	14.30	0.30	0.60	0.30	648.8	13.0	0.9	6.8
2.67	18.00	0.30	0.50	0.20	328.3	6.6	0.4	2.7
2.67	12.00	0.07	0.50	0.43	1221.0	24.4	2.0	15.2
					HEAD, H = 2.67 ft, Average Rate -			8.0
3.33	12.00	0.08	0.50	0.42	1170.8	23.4	2.0	14.6
3.33	12.50	0.03	0.58	0.55	1905.5	38.1	3.0	22.8
					HEAD, H = 3.33 ft, Average Rate -			18.7

Table 2
Estimated Durability of RDFW for Idealized Wave and Water Depth Conditions

Water Depth (ft)	Mean Wave Height (ft)	Estimated 1-hr Power (kwh)	RDFW Test Duration (hr)	RDFW Test Cumm. Power (kwh)	Equivilent Duration (hr)	Equivilent No. of Cycles
2.00	0.50	2.87	23	158	55	99,094
2.00	1.00	8.27	23	158	19	34,389
2.00	1.50	16.83	23	158	9	16,898
2.00	2.00	27.36	23	158	6	10,395