Keystone Retaining Wall Systems, Inc.

Report of Tests

Product Evaluation for High-Velocity Flow Effects, Wave Action, Inundation and Sudden Drawdown, and Manning's *n* Determination

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C. Earl Israelsen
Gilberto Urroz

Utah Water Research Laboratory
Utah State University
Logan, UT 84322-8200

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Introduction

The Keystone Retaining Wall System is a gravity retaining wall that utilizes its weight and deep embedment shape (3:1 depth to height ratio) to resist lateral earth pressure. The mortarless, pinned connection of units allows for a structurally interlocked network while providing free drainage of the hydrostatic loads behind the wall units.

Although there are many field installations of Keystone blocks that are performing satisfactorily in a variety of uses, there have been few laboratory-type tests made of performance characteristics that would assist designers who may use the blocks. Because of the large-capacity hydraulic testing facilities in existence at the Utah Water Research Laboratory, and experienced personnel to operate them, Mr. John C. Potter, Vice President of Operations for Keystone Retaining Wall Systems, Inc. contracted with the UWRL to perform the tests described in this report.

Facilities, Procedures, and Test Results

General Description

All of the tests were conducted in an indoor concrete flume at the UWRL. The flume, which is 8 feet wide, 6 feet deep, and 570 feet long, is supplied with water under 35 feet of head from a nearby reservoir through a 4 foot diameter pipe.

The particulars of each test are presented separately, together with a computer sketch of the block configuration. In addition, a narrated, non-edited VHS video tape describing each test and its results is presented as part of this report. The video should be consulted when reading the report.

Determination of Manning's *n* Value

Initially, a 30-foot section of the concrete channel was lined with Keystone blocks. This length proved to be inadequate so it was extended to 45 feet. Six rows of compac blocks were laid longitudinally along the floor of the channel with their rough sides uppermost. Two rows of compac blocks were laid on their sides on either side of these six rows, to carry the blocks forming the side walls of the channel. Next, three rows of standard blocks were laid to form the side walls (refer to Figure 1 and the video).

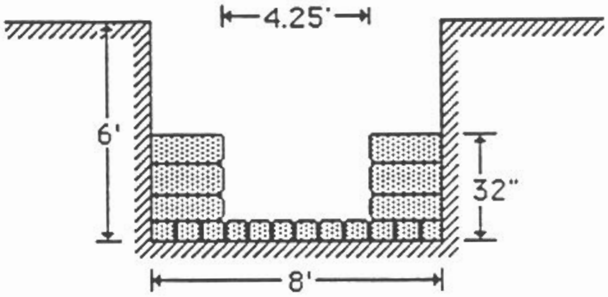

Figure 1. Cross section of channel for determining Manning's *n*.

Discharges of 10 cfs, 20 cfs, and 30 cfs were run through the channel and depth and velocity measurements were made at 1 foot intervals across the channel and at 5 foot intervals along the channel for each flow. Measurement details are presented in the appendix.

The average Manning's *n* value determined from these measurements was 0.023.

The blocks in the channel floor were removed in an attempt to gather a second set of data that could be utilized for determining a roughness coefficient for the side walls only, but this did not prove feasible. The width of the flow was so great compared to its depth that it behaved as though the channel were smooth throughout.

Attempts were made also to gather depth and velocity measurements during the high-velocity flow tests but this too proved to be impossible because of the overpowering force of the jet. Depth and velocity probes could not be inserted into the flows. However, it is believed that the *n* value of 0.023 derived as explained above is a fair representation of block roughness.

Test of Inundation and Sudden Drawdown

Blocks for this test were laid seven rows high in the configuration shown in Figure 2, and gravel was compacted in and behind them. Measurements were taken at several locations before and after the test runs of the distance between individual blocks in the wall and the concrete wall of the flume to determine whether or not there was any movement of the blocks as a result of the sudden drawdowns. A solid bulkhead was installed downstream from the wall and the channel was filled with water to a depth to cover the wall. When the wall and embankment were completely saturated, the bulkhead was raised suddenly with a crane, and the water was allowed to flow rapidly from the channel. **There was no detectable movement of any of the blocks**, even though those on the bottom row were not fastened to the floor in any way. This test shows up well on the video, and the measurements taken are recorded in the appendix.

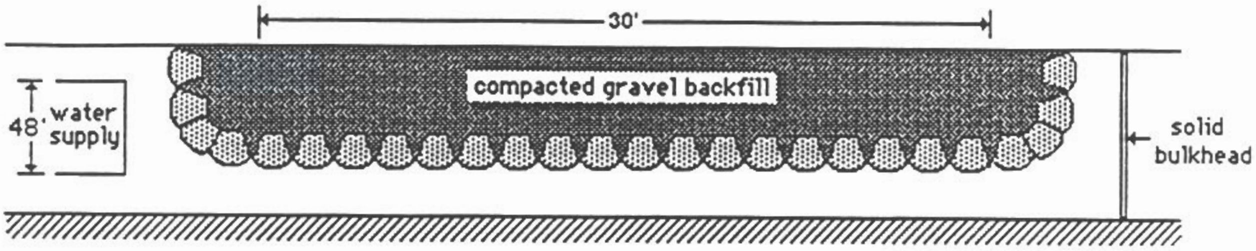

Figure 2. Block configuration for test of inundation and sudden drawdown.

Effect of High-Velocity Flows

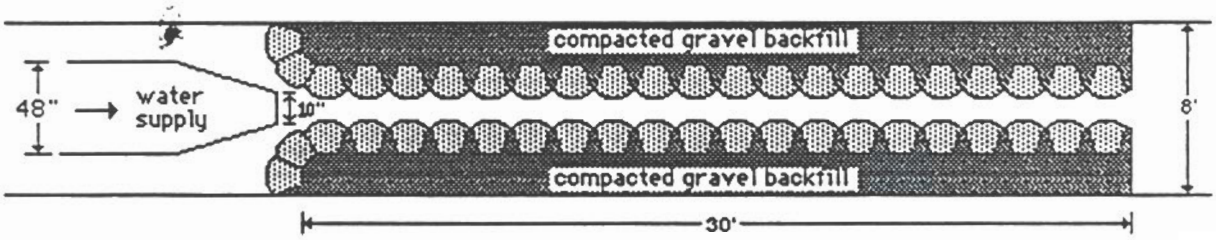

Figure 3. High-velocity flow channel.

Figure 3 shows the block configuration for the high-velocity flow test. The upstream ends of the walls were curved into the sides of the channel. When initially constructed, the downstream ends were left free but a test run showed that a bulkhead would be necessary to hold the gravel in place. A 3½-foot-wide piece of steel was installed on one side and a similar width of plywood on the other. Another test run showed that these pieces bowed and again allowed the gravel to wash out. Next, a solid steel bulkhead was installed with a 15 inch wide opening in the middle for the water to flow through. The high-velocity flow caused a pressure buildup behind the block walls, against the solid steel bulkhead. This pressure forced the ends of both walls towards the center, and again the gravel washed out. The bulkhead that finally worked was slotted so water could pass through freely from the gravel backfill. A fine-mesh wire screen was installed on the upstream side of the slotted bulkhead to retain the gravel.

Flows of 60 cfs and 80 cfs were run through the channel for approximately 15 minutes each, which produced velocities of approximately 18 and 24 feet per second, respectively. The valve was then opened fully, which allowed 90 cfs to flow at a velocity of approximately 27 fps, and this was allowed to run for 30 minutes. This is the maximum flow we could get with the present nozzle configuration.

The velocity of 18 fps was measured with a Montedero-Whitney electromagnetic velocity probe, which has a full scale range of 0–20 fps with an accuracy of ±1 percent and a resolution of 0.01 fps. The higher velocities could not be measured either with a propeller meter or with a pitot tube because the force of the 4 foot deep jet was too great and bent whatever rod that was placed in it. Therefore these velocities were calculated from the known discharge and the outlet dimensions of the nozzle. Discharge was measured with a Nusonics Ultrasonic Flowmeter which has an advertised accuracy of ±2 percent of reading for flows between 1 and 10 cfs, and ±1 percent of reading for flows over 10 cfs.

Measurements were made before and after the test runs of distances between the faces of opposing blocks in the channel in the bottom row, the third row, and the fifth row at the 1/4, 1/2, and 3/4 distances along the channel. **No movement at all of the blocks could be determined as a result of high-velocity flows.** The distance measurements appear in the appendix. The small differences in before-and-after values can be attributed to inaccuracies in measuring on the irregular faces of the blocks.

Effect of Wave Action

Preliminary trials of the wave action test indicated that it would not be possible with the method originally proposed to generate waves severe enough to possibly do any damage to a Keystone block wall. With telephone concurrence from Mr. Potter, the following configuration was constructed and utilized instead.

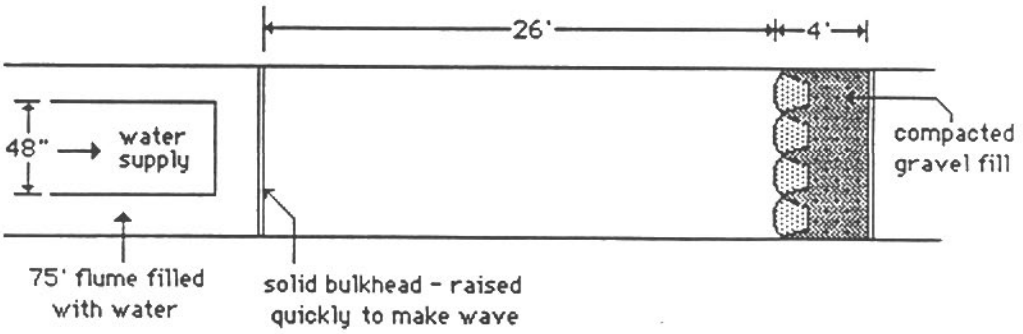

Figure 4. Plan view of wave-action test facility.

A slotted bulkhead was installed, similar to the one utilized in the high-velocity flow tests, and again it was covered with a fine-mesh wire screen to prevent gravel from going through it. In front of this, compac blocks were placed on their sides on the floor against both walls and at the 1/4, 1/2, and 3/4 points of the channel width for a distance of 4 feet upstream from the slotted bulkhead. Next, a 4 ft × 8 ft piece of plywood was laid over the blocks, and a block wall approximately 5 feet high was constructed across the channel as shown in Figure 4. Gravel was compacted in and behind the blocks. After each wave strike, the water drained rapidly from the channel through the holes beneath the block wall.

The face of the block wall was approximately 26 foot downstream from a solid steel bulkhead. The channel upstream from the bulkhead was filled with water, after which the bulkhead was raised suddenly to release a high-velocity wall of water against the blocks. These destructive waves were formed repeatedly over a period of several hours, and some of them were recorded on the video. Several measurements were made before and after the tests from points on the face of the wall to fixed locations upstream to see if any movement of blocks could be detected as a result of the force of the waves against them.

As nearly as could be determined from the measurements taken, and by visual observation, there was no movement of the blocks in the wall due to wave action. Over a period of time, the waves did, however, remove the gravel backfill from the top layer of blocks.

Summary

Four of the five tests proposed by the UWRL have been completed and are described in detail in this report and in the accompanying unedited VHS video. The tests included one for determining a Manning's n value for Keystone blocks; a second one for determining effects, if any, of inundation and sudden drawdown of water on the blocks; a third one was for determining the effect of high-velocity water flows parallel to a block wall; and the fourth was to determine the effect of severe wave action on a block wall. Test results show a Manning's n value of 0.023. They show also that the blocks are not adversely affected by inundation and sudden drawdown, by high-velocity flows, or by wave action.

The fifth test proposed was to determine the effect on the blocks of repeated cycles of freezing and thawing over an extended period of time. The UWRL is prepared to conduct this test whenever the client gives approval.

Appendix

Calculation of Manning's Resistance Coefficient (Manning's *n*).

The equation of gradually varied flow (GVF) for a prismatic open channel with zero bed slope is given by (1)

$$d_i + \frac{V_i^2}{2g} = d_{i+1} + \frac{V_{i+1}^2}{2g} + S_f \Delta x \tag{1}$$

where g = acceleration of gravity, d = flow depth, V = mean flow velocity, S_f = mean energy slope, and Δx = distance between stations i and $(i+1)$. The variables are presented in Figure A.5.

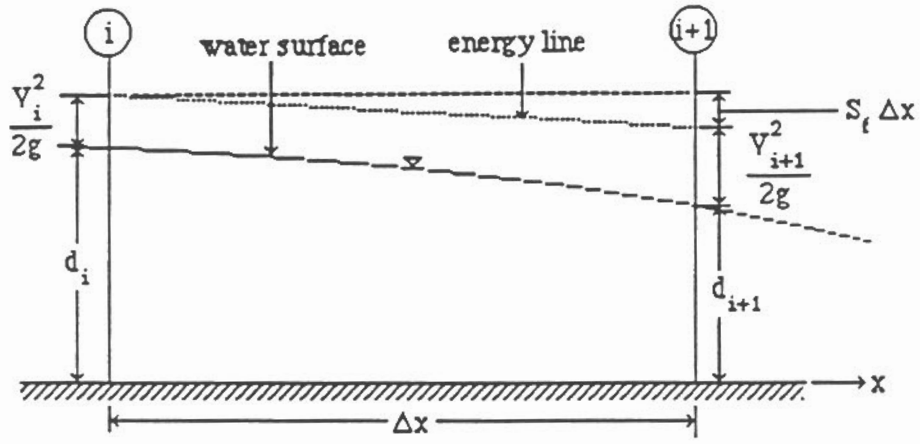

Figure A.5. Gradually varied flow in an open channel with zero bed slope.

From Equation (1), the mean energy slope is estimated as

$$S_f = \frac{1}{\Delta x}\left[d_i - d_{i+1} + \frac{V_i^2 - V_{i+1}^2}{2G}\right] . \tag{2}$$

This value of S_f is then used in Manning's equation to obtain an estimate of Manning's n between sections i and $(i+1)$,

$$n_i = \frac{1.49 R^{2/3} S_f^{1/2}}{V} \tag{3}$$

where R = average hydraulic radius for sections i and $(i+1)$ and V = average velocity for sections i and $(i+1)$.

The hydraulic radius for a rectangular cross-section is given by

$$R_i = \frac{A_i}{P_i} = \frac{B d_i}{B + 2d_i} \tag{4}$$

where A_i = cross-sectional area at section i, P_i = wetted perimeter at section i, B = channel width, and d = flow depth. The data collected in the flume consisted of flow depths (d_1, d_2, d_3) and velocities (V_1, V_2, V_3) at three positions equally spaced at any cross section. For each discharge used, those measurements were taken at 8 cross sections located every 5 feet along the channel. These cross sections are labeled from zero (0) through 35 feet. Table A.1, below, shows the data collected and the mean flow depth and velocity computed for each cross section from the three depth and velocity measurements. These mean flow depths and velocities were then used to compute Manning's n between selected cross sections for each flow.

Table A.1 Flow depths and velocities

Discharge	Sect. (ft)	d_1 (inch)	d_2 (inch)	d_3 (inch)	V_1 (fps)	V_2 (fps)	V_3 (fps)	d (ft)	V (fps)
Q1	0	12.5	12.5	12.5	2.22	2.39	2.25	1.04	2.29
Q1	5	12.0	11.5	11.5	2.70	2.83	2.67	0.97	2.73
Q1	10	11.0	11.5	11.5	2.80	2.94	2.72	0.94	2.82
Q1	15	9.5	10.5	10.0	3.12	3.28	2.93	0.83	3.11
Q1	20	10.5	10.5	10.0	3.39	3.59	3.24	0.86	3.41
Q1	25	10.0	11.0	10.0	3.40	3.65	3.54	0.86	3.53
Q1	30	9.0	9.5	9.0	3.71	4.05	3.70	0.76	3.82
Q1	35	7.5	7.5	7.0	4.00	4.40	4.38	0.61	4.26
Q2	0	13.0	12.5	13.3	5.18	5.40	5.40	1.08	5.33
Q2	5	14.0	14.0	14.3	4.90	4.80	5.00	1.17	4.90
Q2	10	14.0	14.5	14.5	4.80	4.50	4.70	1.19	4.67
Q2	15	16.0	15.3	15.3	4.70	4.30	4.50	1.29	4.50
Q2	20	16.3	16.0	16.0	4.30	4.30	4.50	1.34	4.37
Q2	25	17.5	16.5	17.0	4.40	4.10	4.20	1.42	4.24
Q2	30	17.3	16.5	17.0	4.40	3.80	4.10	1.41	4.10
Q2	35	16.7	17.0	17.0	4.20	4.10	3.70	1.41	4.00
Q3	0	22.0	22.0	22.0	6.10	6.00	5.10	1.83	5.73
Q3	5	21.5	20.0	21.5	6.00	5.80	5.60	1.75	5.80
Q3	10	20.5	20.5	21.0	5.80	5.80	5.80	1.72	5.80
Q3	15	19.0	20.0	18.5	5.40	6.20	6.10	1.60	5.90
Q3	20	18.0	19.0	19.0	5.50	6.50	5.70	1.56	5.91
Q3	25	18.5	18.5	18.5	5.50	6.60	5.50	1.54	5.87
Q3	30	17.5	17.0	18.0	6.10	6.80	5.90	1.46	6.26
Q3	35	16.0	15.5	15.0	6.40	7.30	6.30	1.29	6.67

Calculations of Manning's n were performed between sections separated by 5, 10, 15, 20, 25, 30 and 35 feet. **The 84 values so obtained ranged from 0.007 to 0.477, with an average value of 0.023 and a standard deviation of 0.007.**

Table A.2 Sudden drawdown test

	distance to flume wall (inches)		
Location	before	after 6 tests	difference
East-top	32.9	32.8	0.1
East-bottom	29.8	29.8	0.0
West-top	32.0	31.9	0.1
West-bottom	28.6	28.6	0.0
W. Corner-top	83.3	83.3	0.0
W.Corner-bottom	83.6	83.6	0.0

Table A.3 High velocity test

	distance between walls (inches)		
Station	before	after 3 tests	difference
U/S top	12.9	12.9	0.0
U/S middle	11.4	11.4	0.0
U/S bottom	10.4	10.3	0.1
Center top	14.7	14.7	0.0
Center middle	12.3	12.2	0.1
Center bottom	10.2	10.2	0.0
D/S top	13.6	13.6	0.0
D/S middle	12.3	12.2	0.1
D/S bottom	9.8	9.8	0.0

Discharge (cfs)	Velocity (fps)	Test Duration (min)
60	18.0	15
80	24.0	15
89	26.7	30

A.4 Wave test

	distance to flume wall (inches)		
Location	before	after	difference
North-top	133.8	133.8	0.0
North-bottom	133.2	133.1	0.1
Center-top	141.4	141.3	0.1
Center-middle	139.1	139.1	0.0
Center-bottom	139.6	139.6	0.0
South-top	133.3	133.2	0.1
South-bottom	132.8	132.8	0.0