UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 427

Hydraulic Stability of Cable Tied Concrete Block Revetment System During Overtopping Flow

by

Scott C. Morgan, Julie A. Tank, and Richard L. Voigt, Jr.

Prepared for

RUDLOFF BRICK & TILE SALES, INC.
Brenham, Texas 77834

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Last Revised: 8/17/98
Disk Locators: RUDLF427.doc; PR427cov.doc & figures.wmf
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ACKNOWLEDGMENTS

The authors thank the entire shop staff of the St. Anthony Falls Laboratory, University of Minnesota, who assisted with the project. In particular, Jason MacDonald, Jason Rysavy, Chris Huntley, Dan Lanske, Jerad Bankston, and Rick Hauck who assisted with data acquisition and Patricia Swanson who edited this report.

DISCLAIMER

These tests were carried out under controlled laboratory conditions. The selection and installation of any of these products at any project site will of necessity incorporate site specific concerns, and therefore must be reviewed by and be the responsibility of a qualified, registered engineer on an individual project basis.

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INTRODUCTION

The St. Anthony Falls Laboratory (SAFL) was contracted by Rudloff Brick and Tile Sales, Inc. to perform hydraulic testing of their cable tied concrete block revetment system. The testing was performed during July 1998 in SAFL's largest flume, measuring 6 feet high x 9 feet wide x 253 feet long, with a maximum discharge capacity of 300 ft^3/s. The tests were undertaken to evaluate block performance and to provide information regarding failure thresholds under controlled laboratory conditions.

The testing was conducted in a manner to replicate as close as practical, the testing performed by Simons, Li and Associates, Inc., for the Federal Highway Administration's overtopping embankment studies. A detailed description of the test setup is included later in this report. The embankment was constructed at the downstream end of the channel, extending into the tailgate pit. This allowed construction of an embankment 5.5 feet high and a maximum overtopping depth of 3.5 feet. The 2:1 downslope followed a 24 feet level section; both the embankment and level section were installed to the full 9 feet width of the channel. The full width was chosen to minimize sidewall effects.

TEST PLAN

A testing program was designed to perform the testing necessary to evaluate hydrodynamic performance of the block revetment system during overtopping conditions of various depths.

Specifically:

1. Create a suitable embankment for testing.
2. Install blocks using typical field techniques.
3. Subject block systems to varying levels of overtopping (1, 2, 3, 3.5 feet) each for a period of four hours.
4. Obtain data on block position, water surface elevation, and velocity during and after completion of each test run.

Specific information on the blocks can be found in the Appendix of this report starting on page 12.

TEST FACILITY

The test facility consisted of a large concrete flume 6 feet high x 9 feet wide x 253 feet long, with a single supply gate under gravity head. Discharge was controlled by opening or closing the supply gate. The additional elevation necessary to conduct the overtopping tests was obtained by lowering the flume's tailgate to the bed elevation and extending the sloped portion of the embankment into the tailgate pit. As shown in Figure 1, this allowed construction of an embankment of 5.5 feet net height and a maximum overtopping capability of 3.5 feet. The 2:1 downslope followed a 24-foot level section; both were installed to the full width of the 9-foot channel. Discharges during testing were well within maximum facility capability of 300 cfs.

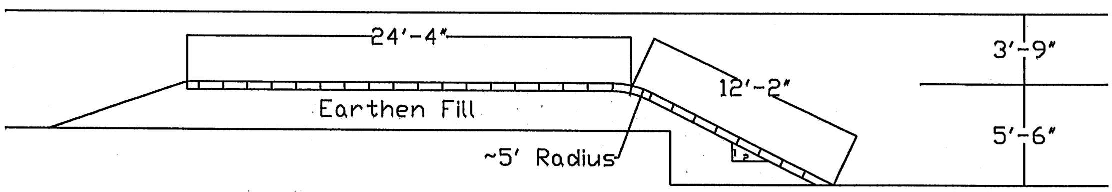


Figure 1. Elevation view of test section.

The soil used to construct the embankment was a silty clay with low plasticity, designated as CL under the Unified Soil Classification System. Of the soils available for testing purposes, this was most similar to that used in the U.S. Federal Highway Administration's previous tests. Soil properties are provided in the Appendix. The soil was compacted to 90 percent, ±5 percent of standard Proctor density in lifts of approximately 6 to 10 inches.

The blocks were installed from downstream to upstream on top of a non-woven, needle punched polypropylene 6.1 oz/yd^2 geotextile filter fabric; specific information on the geotextile fabric can be found in the Appendix. The lower 16 lineal feet of block revetment system was placed on top of a layer of 7020 Enkamat which in turn was placed on top of the geotextile filter and embankment soil. A 5-foot radius was used to transition from the flat area to the embankment slope. This is typical of a field installation. The upstream lip of the test section and the blocks immediately adjacent to the sidewall of the test section were grouted in place. Of particular concern were the vortices associated with the corners of the test channel and turbulence related to the channel's turning vanes located immediately downstream of the test section. Therefore, the most downstream row of the blocks was secured with a steel bar to prevent uplifting from localized effects.

Instrumentation included a standard water surface point gage for measuring elevations and a Prandtl tube for velocity determination. All flow rates were determined from measurements taken in the SAFL Volumetric tanks.

Photos 1 and 2 show the facility prior to testing the blocks.

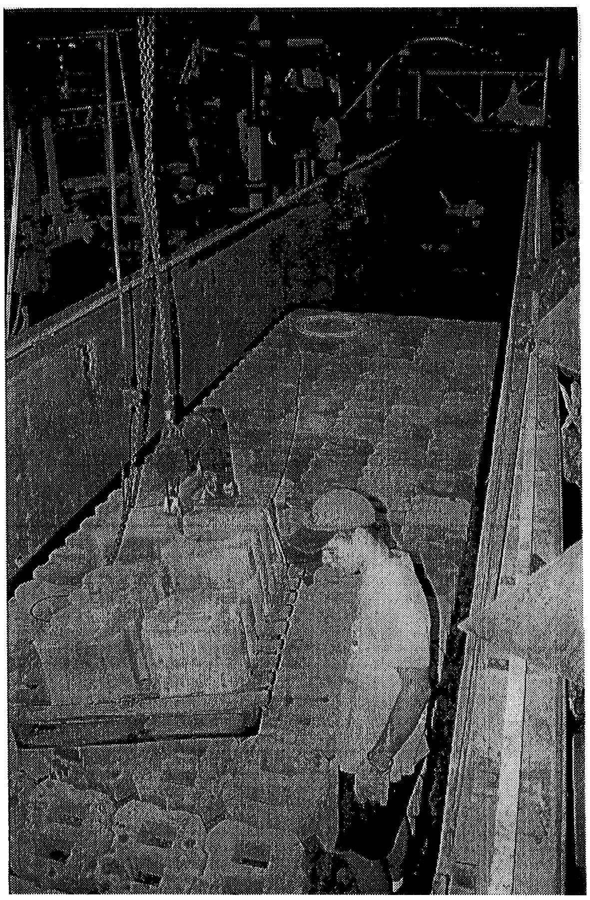


Photo 1. Installation of blocks prior to testing.

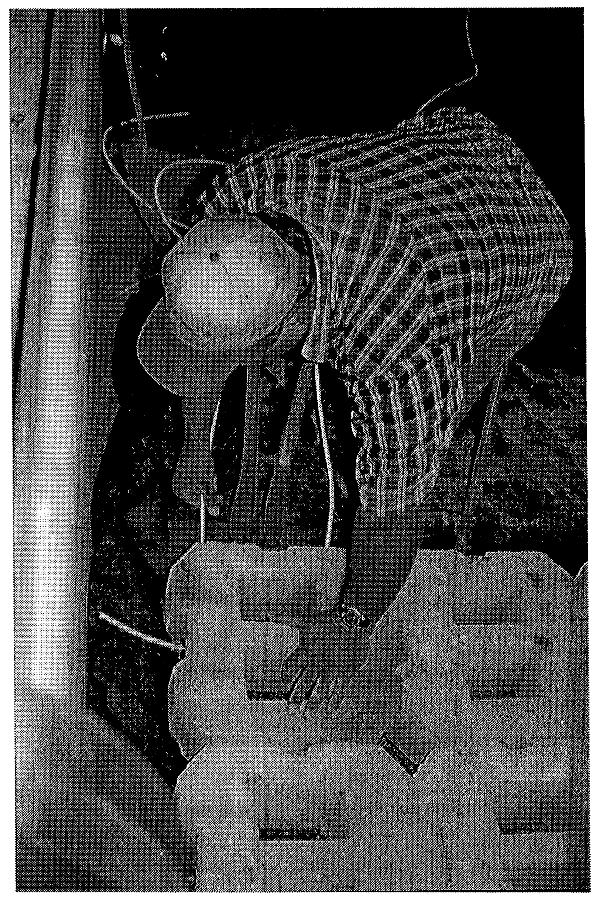


Photo 2. Installation of cables prior to testing.

TESTING PROGRAM

The testing program summary has been divided into two parts: first, a summary describing the conditions of each individual test and second, a comprehensive summary of the hydraulic analysis. All runs were conducted with a 2:1 downstream embankment slope. A data summary for each run can be found in the Appendix.

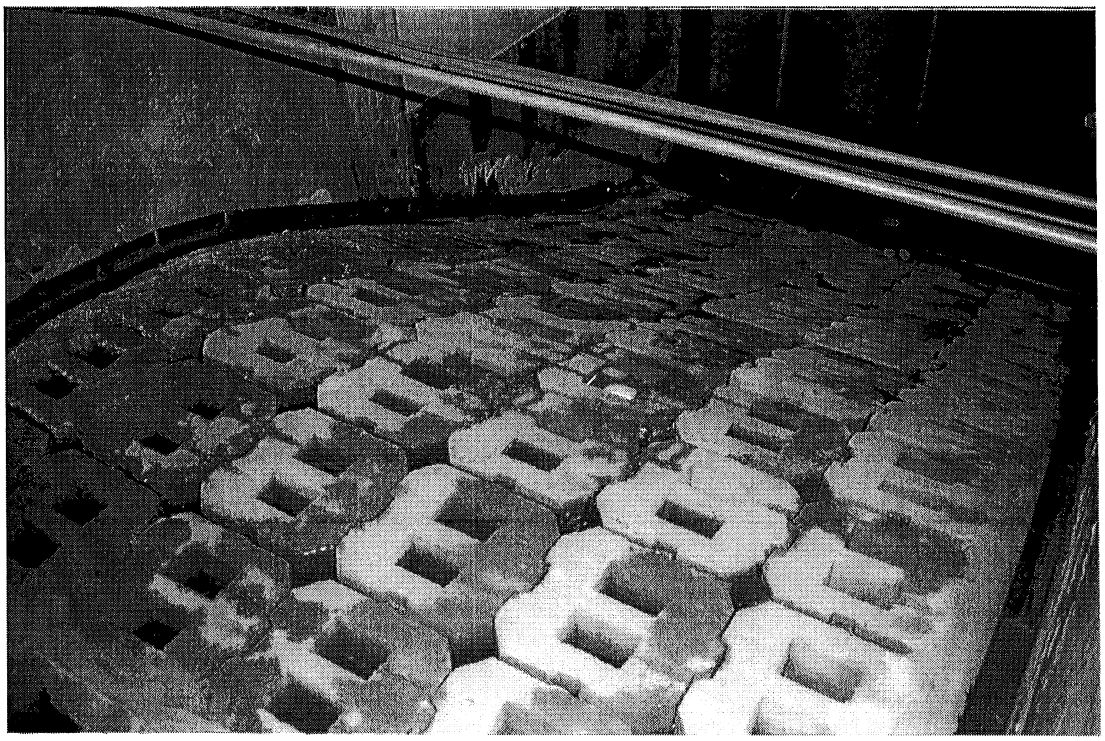


Photo 3. Completed installation of blocks prior to testing.

Summary of Individual Tests

Test Run 1

Test Run 1, consisting of a 1-foot overtopping condition and discharge of 24 cfs, was conducted on July 21, 1998. In an attempt to simulate field conditions for channel installation, this test run was performed without installation of the 7020 Enkamat drainage layer used in the FHWA tests.

After approximately 15 minutes, a region of blocks near the toe of the slope began to upwell. The inflow was shut down and the region inspected. The upwelling was found to relate to water trapped beneath the geotextile fabric. Observations indicated that the source of infiltrated water appeared to be the blocks in the radial portion of the embankment. Water passing over the blocks was being driven down along the leading edge of the blocks which, due to the radius, had a slightly upward vertical offset. The blocks on the sloped section were removed, and a layer of 7020 Enkamat was placed on top of the geotextile on the lower 16 feet of the embankment.

Following reinstallation of the blocks, Test Run 1 was conducted in its entirety on July 23, 1998 with no further problems. The run consisted of repeating the 1-foot overtopping condition, with a discharge of 24 cfs, for a period of four hours. After completion of this run, the discharge was stopped and block elevation measurements were taken.

Test Run 2

After completing Test Run 1, Test Run 2 was conducted on July 23, 1998. This run consisted of a 2-foot overtopping condition, with a discharge of 73 cfs, for a period of four hours.

Photo 4. Three-foot overtopping condition (Test Run 3).

Test Run 3

Test Run 3 was performed for a period of four hours on July 28, 1998. See Photo 4 above. The run consisted of a 3-foot overtopping condition, with a discharge of 147 cfs.

Test Run 4

Test Run 4 was performed on July 28, 1998, after completing Test Run 3. This final run consisted of a 3.5-foot overtopping condition for a period of four hours, with a discharge of 185 cfs.

HYDRAULIC ANALYSIS

A detailed hydraulic analysis was made to summarize the velocities and the shear stresses obtained during the test runs. The shear stress was calculated using the principle of conservation of momentum on a control volume in the direction of the flow;

$$\sum \boldsymbol{F} = \Delta(\rho \boldsymbol{VQ})$$

According to Clopper (1989) *corrected 1998*, this equation, for the case studied here, takes the form:

$$\tau_o = \frac{\gamma}{2}(d_1 + d_2)\sin\theta + \frac{1}{L}\left(\frac{\gamma}{2}\frac{1}{\cos\theta}\left(d_1^2 - d_2^2\right) - \rho q^2\left(\frac{1}{d_2} - \frac{1}{d_1}\right)\right)$$

where

τ_o	=	bed shear stress, lb/ft^2
d_1, d_2	=	depths of flow at the upstream and downstream ends of the control volume, respectively, in feet.
v1, v2	=	flow velocities at the upstream and downstream ends of the control volume, respectively, in feet.
L	=	length of control volume in ft
θ	=	slope angle in degrees
γ	=	unit weight of water in lb/ft^3 = 62.427 lb/ft^3
ρ	=	density of water in slugs/ft^3= 1.94 slugs/ft^3
q	=	unit discharge in cfs/ft

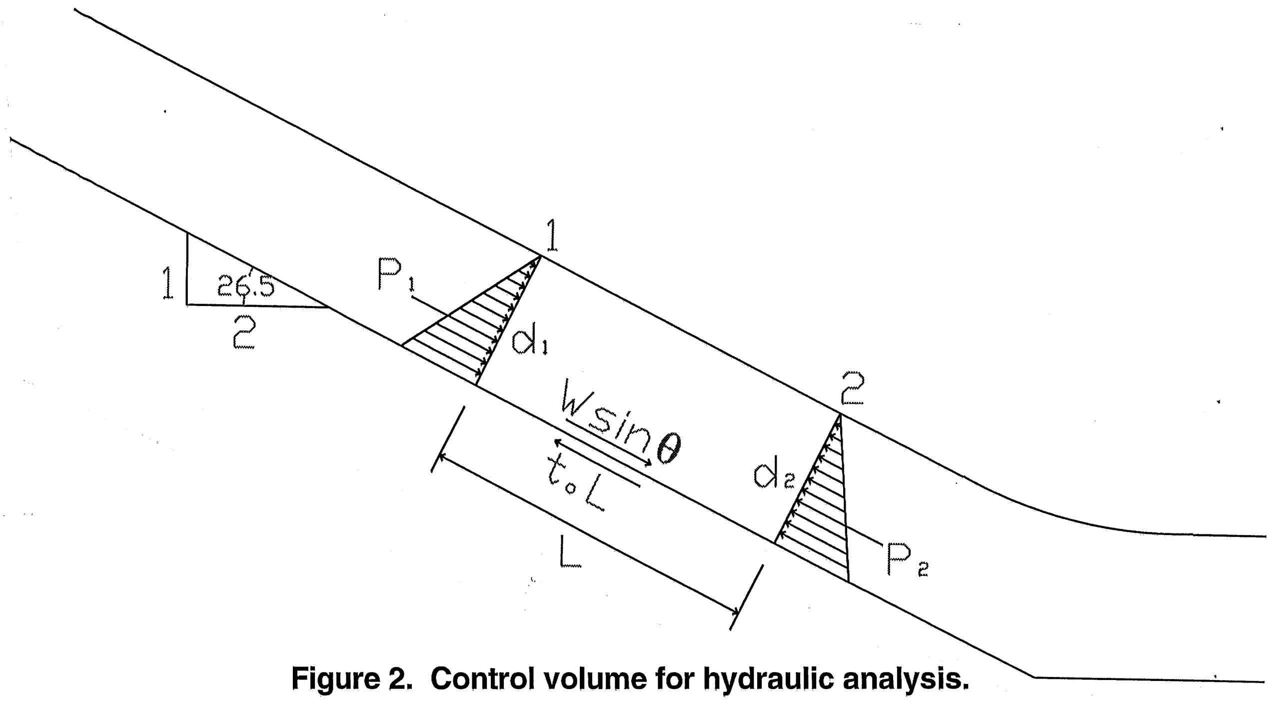


Figure 2. Control volume for hydraulic analysis.

It is important to note here the sensitivity of this formula with small variations of water depth. A simple variation of ± 1/4" on the water depth on a flow 1.05 feet deep (3-1/2 ft overtop) can change the calculated value of shear from 18.1 lb/ft^2 to as high as 19.2 lb/ft^2 or as low as 17.0 lb/ft^2.

For this reason and because of the roughness of the water surface and its effect on water surface measurement accuracy, the actual measurements obtained during experiments for the block surface and water surface elevations were fitted to smooth curves. This data was then used to calculate shear stresses at various locations along the test section.

Care should be undertaken when using the results of these tests. One must understand the inherent variability in the results obtained in such a test and use an adequate factor of safety when providing designs based on test results.

The mean water velocity may also provide an indicator of block system performance, but again results must be used with good engineering judgment.

SUMMARY AND CONCLUSIONS

The cable tied concrete block revetment system was tested for hydrodynamic stability and performance characteristics under controlled laboratory conditions. Overtopping discharges of up to 3.5 feet approach head were experienced by the blocks. The revetment system was installed on a test embankment consisting of highly erodible soil with a 2:1 downstream slope.

- The revetment system performed well up to and including maximum facility capabilities. The highest shear stress and velocity obtained were 18.1 lb/ft^2 and 18.9 ft/s, respectively. These are the average values for the most downstream individual blocks on the slope.
- The revetment system was not tested for sideslope conditions. When placed on a sideslope, maximum permissible shear stress and velocity should be reduced.
- The revetment system was installed in accordance with general field installation procedures. Vertical interblock offset was typically less than 1/4 inch. No testing was done with blocks artificially offset by larger amounts.
- The tests were performed using a non-woven, needle punched polypropylene 6.1 oz/yd^2 geotextile filter fabric for soil retention purposes. Field installation must incorporate appropriately specified geotextile filter fabric to be effective.
- Variation in subgrade conditions with the potential for unpredictable settlement could lead to failure and should be addressed with caution by reducing allowable shear stresses. Likewise, inadequate subgrade preparation leading to similar situations could lead to failure.
- It was not possible to test the undermining potential of scour migration from unprotected regions surrounding the revetment system or any potential associated problems. Proper measures must be undertaken to ensure that surrounding conditions do not detrimentally affect block performance.
- Increasing block thickness and hence unit weight may lead to increased stability for each of those designs tested.

References

Clopper, Paul E. *Hydraulic Stability of Articulated Concrete Block Revetment Systems during Overtopping Flow.* U.S. Department of Transportation, Publication No. FHWA-RD-89-199, November 1989.

APPENDICES

A: Experimental Data

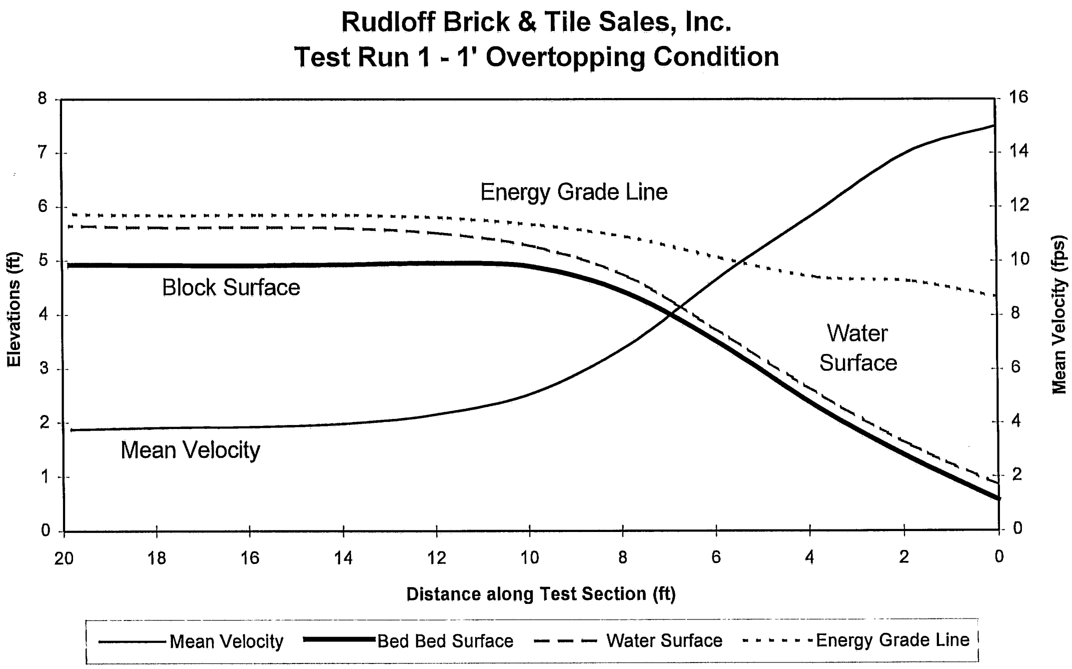
B: Embankment Soil Properties

C: Block Description

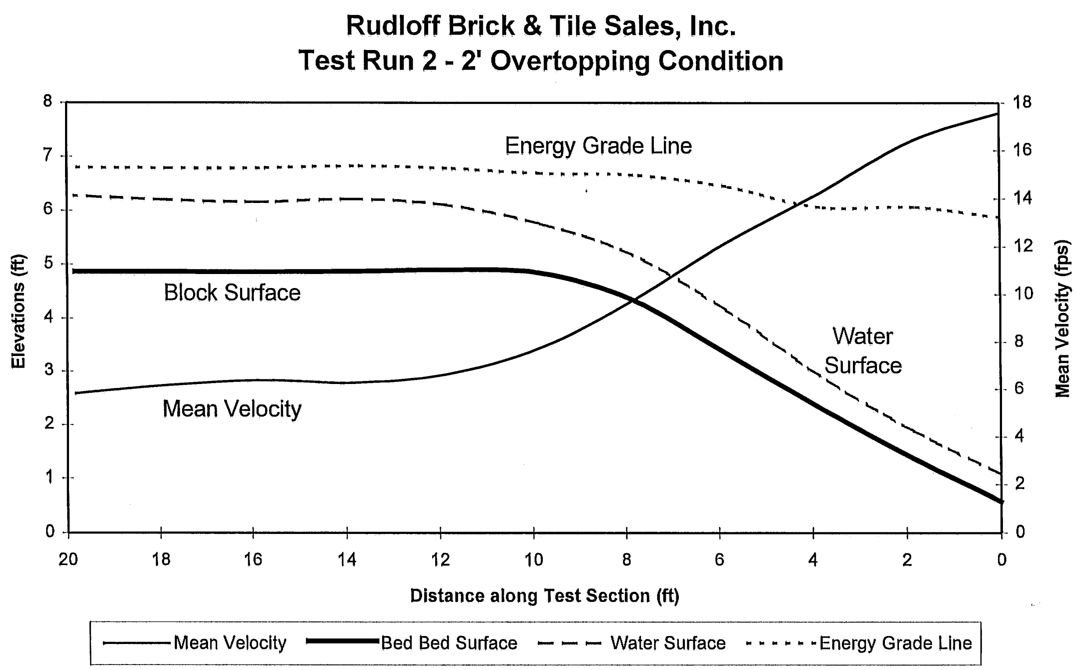
D: Geotextile Fabric Specifications

Appendix A - Experimental Data

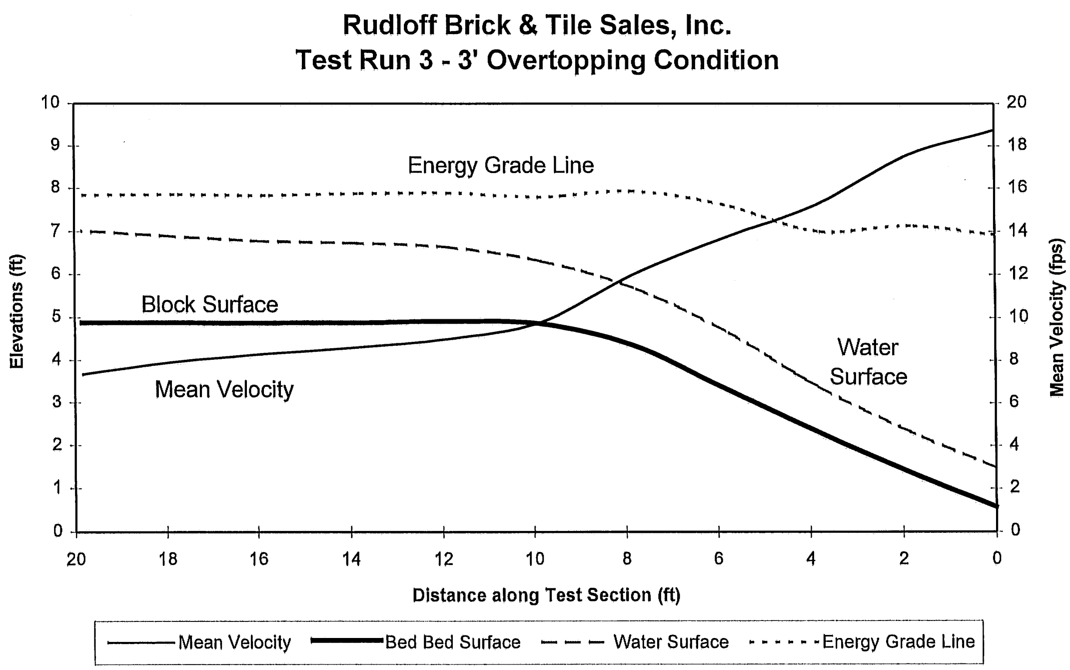
Test Run 1 - Experimental Data from 1 foot Overtopping Flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.6	0.8	4.3	15.0
2	1.8	1.3	1.6	4.6	14.0
3	3.8	2.3	2.6	4.7	11.7
4	5.8	3.5	3.7	5.0	9.5
5	7.8	4.4	4.7	5.4	6.9
6	9.8	4.9	5.3	5.7	5.1
7	11.8	5.0	5.5	5.8	4.3
8	13.8	4.9	5.6	5.8	4.0
9	15.8	4.9	5.6	5.8	3.8
10	17.8	4.9	5.6	5.8	3.8
11	19.8	4.9	5.6	5.9	3.7



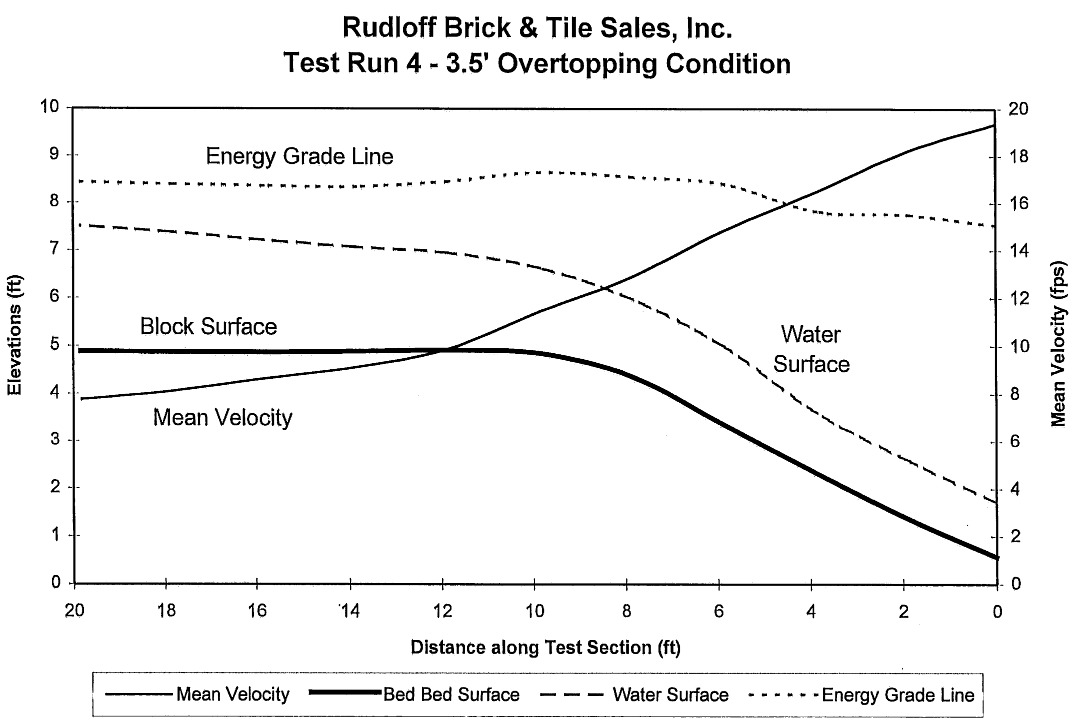
Test Run 2 - Experimental Data from 2 foot Overtopping Flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.6	1.1	5.9	17.6
2	1.8	1.4	1.9	6.1	16.4
3	3.8	2.3	2.9	6.1	14.2
4	5.8	3.3	4.2	6.4	12.1
5	7.8	4.3	5.2	6.7	9.7
6	9.8	4.8	5.8	6.7	7.7
7	11.8	4.9	6.1	6.8	6.6
8	13.8	4.9	6.2	6.8	6.3
9	15.8	4.9	6.2	6.8	6.4
10	17.8	4.9	6.2	6.8	6.2
11	19.8	4.9	6.3	6.8	5.8



Test Run 3 - Experimental Data from 3 foot Overtopping Flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.6	1.5	6.9	18.7
2	1.8	1.4	2.3	7.1	17.6
3	3.8	2.3	3.4	7.0	15.2
4	5.8	3.3	4.7	7.6	13.7
5	7.8	4.4	5.7	7.9	12.0
6	9.8	4.9	6.3	7.8	9.8
7	11.8	4.9	6.6	7.9	9.0
8	13.8	4.9	6.7	7.9	8.6
9	15.8	4.9	6.8	7.8	8.3
10	17.8	4.9	6.9	7.9	7.9
11	19.8	4.9	7.0	7.8	7.3



Test Run 4 - Experimental Data from 3.5 foot Overtopping Flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.6	1.7	7.5	19.4
2	1.8	1.4	2.6	7.8	18.2
3	3.8	2.3	3.6	7.8	16.5
4	5.8	3.3	5.0	8.4	14.8
5	7.8	4.4	6.0	8.6	12.9
6	9.8	4.8	6.6	8.7	11.4
7	11.8	4.9	6.9	8.5	9.9
8	13.8	4.9	7.1	8.3	9.1
9	15.8	4.9	7.2	8.4	8.6
10	17.8	4.9	7.4	8.4	8.1
11	19.8	4.9	7.5	8.4	7.7



Appendix B - Embankment Soil Properties

The soil used to build the test embankment was a silty clay, having a designation of CL under the Unified Soil Classification System. The soil was obtained from Dale Green, Inc. of Minneapolis, MN.

Percent Sand: 36

Percent Silt: 36

Percent Clay: 28

Atterberg limits:	Liquid limit:	28.50
	Plastic limit:	19.61
	Plasticity Index:	8.88

Specific Gravity: 2.54

Standard Proctor Density: 105 lb/ft^3 @ 10% moisture (1.7 g/cm^3)

Unified Soil Classification: CL

AASHTO Group Designation: A-4

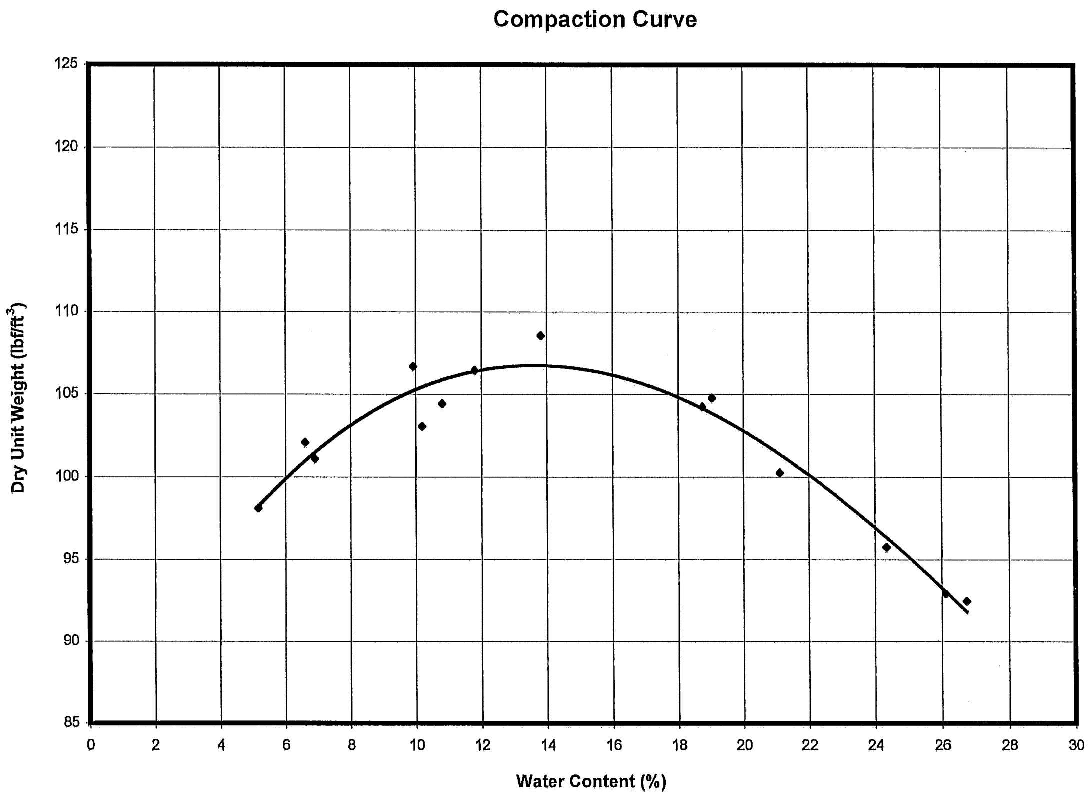
The soil was compacted in horizontal lifts, each 6 to 10 inches in height, using a vibrating plate tamper. Two to four passes of the plate brought the compaction to the required 90 percent ± 5% of standard Proctor density.

The grain size distribution and compaction curves of the test soil are shown on the following page.

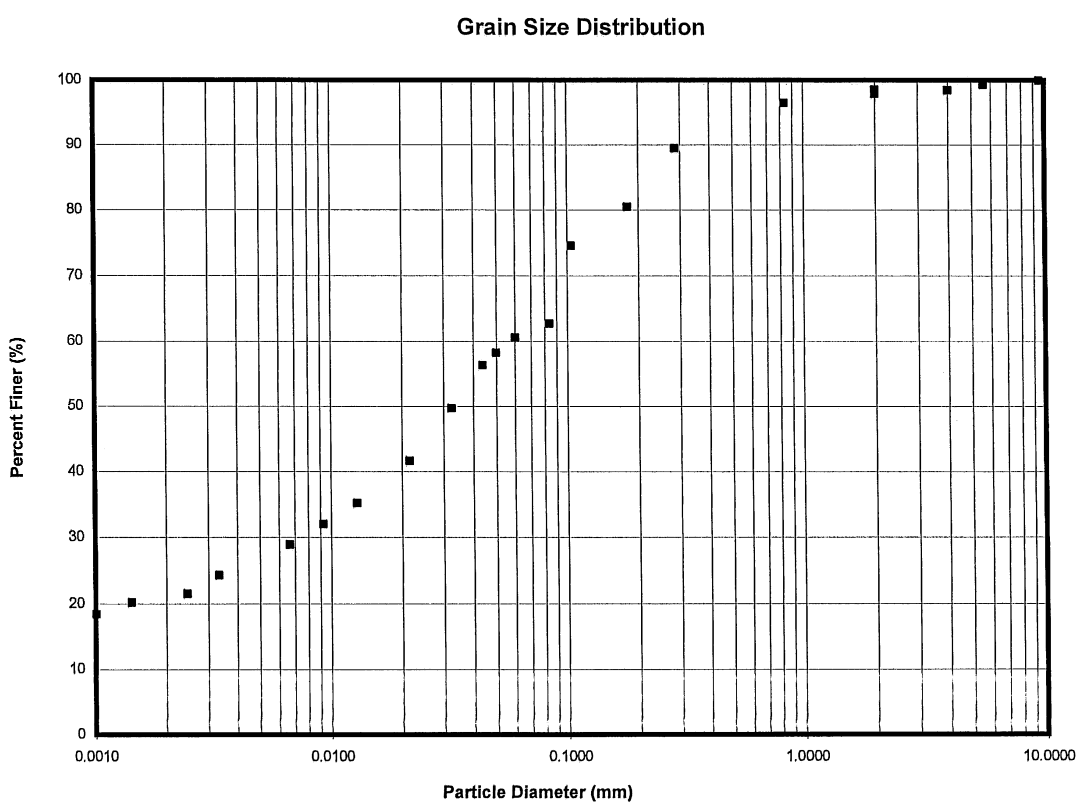
References

1. Holtz, Robert D., and William D. Kovacs. *An Introduction to Geotechnical Engineering.* Prentice-Hall, Englewood Cliffs, NJ 1981.

2. United States Department of the Interior Bureau of Reclamation. *Earth Manual.* United States Government Printing Office, Washington 1960.



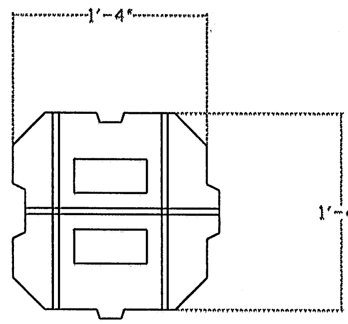
Compaction Curve
Dry Unit Weight (lbf/ft^3)
Water Content (%)



Grain Size Distribution
Percent Finer (%)
Particle Diameter (mm)

Appendix C - Block Description

The cable tied block revetment system blocks are octagonal in shape, with interlocking connectors on four of the sides. Each block weighs approximately 72 pounds and covers 256 square inches. A top view of a typical block can be seen below.



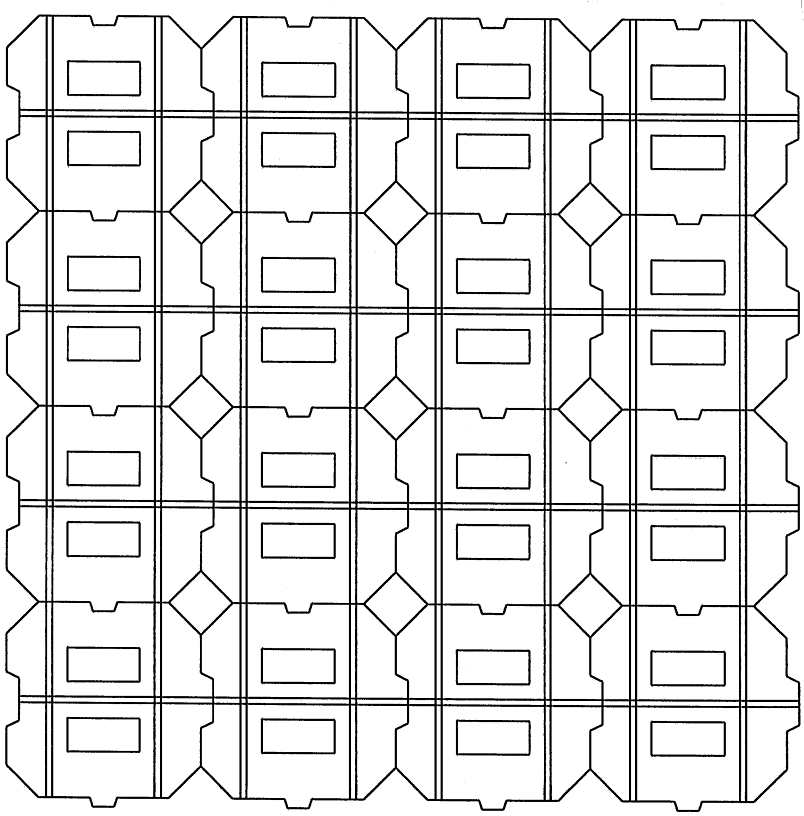


Figure 3. Schematic diagram of assembled cable-tied block system.

Appendix D - Geotextile Fabric Specifications

The geotextile used in the overtopping test was a woven needle punched polypropylene 6.1 oz/yd^2 geotextile filter fabric. The fabric's specifications are listed below.

Tensile Strength	MD 395 lbs
	XD 260 lbs
Elongation	24%
Puncture	150 lbs
Mullen Burst	480 psi
Trapezoidal Tear	MD 95 lbs
	XD 55 lbs
Permeability	.01 cm/s
AOS	.212 mm
POA	4%
Thickness	13 mils