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

Project Report No. 434

Hydraulic Stability of Cable Concrete Revetment System During Overtopping Flow

by
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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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LIST OF FIGURES AND PHOTOS

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 Cable Concrete block revetment system using typical field techniques.
3. Subject Cable Concrete block revetment system to varying levels of overtopping (1, 2, 3, 3.5 feet) each for a period of four hours.
4. Obtain data on individual block position, water surface elevation, and velocity during and after completion of each test run.

Specific information on the Cable Concrete block revetment system can be found in the Appendix of this report starting on page A-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 horizontal 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.

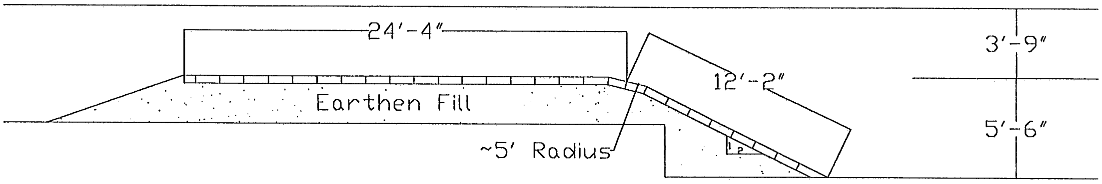


Figure 1. Elevation view of test section.

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 Cable Concrete block revetment system was installed from upstream to downstream 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 the Cable Concrete 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 horizontal 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.

Photo 1 shows the facility prior to testing the CC 35 System.

Photo 1. Installation of CC 35 System prior to testing.

TESTING PROGRAM

The testing program summary has been divided into three parts: first, two summaries describing the conditions of each individual test for both types of cable concrete systems, and lastly, 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.

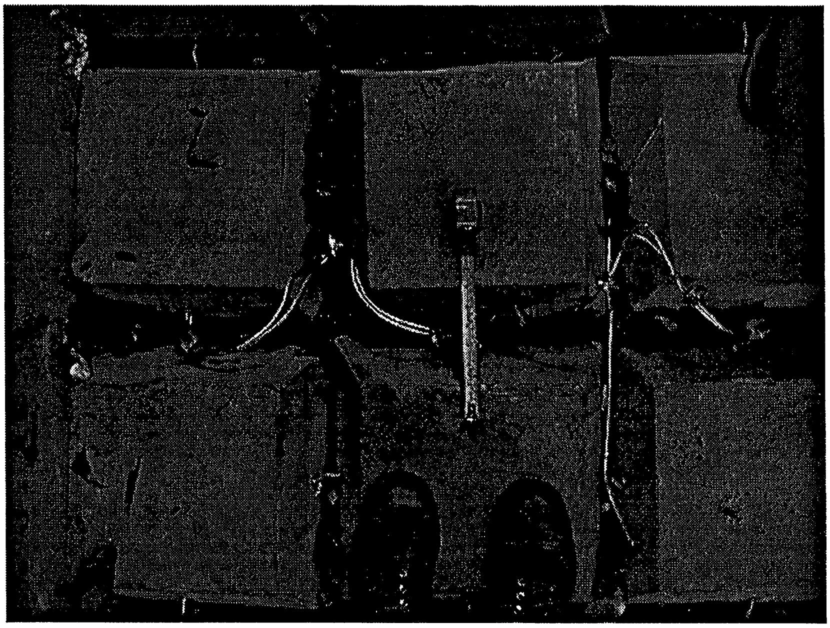


Photo 2. Post run detail of CC 35 System.

Two sizes of Cable Concrete block revetment systems were to be tested, CC 35 and CC 45 OS. The CC 35 system was installed first and tested in runs 1-4. Testing of the CC 45 OS system occurred in runs 5-8. Prior to each run, a measurement was made of the block elevations along the length of the test section. During the overtopping test, four sets of measurements of water elevation and velocity were recorded. Each measurement set consisted of measurements at 1/4, 1/2, & 3/4 channel widths and 11 stations at 2' intervals. In between runs 4 & 5, the slope was inspected for erosion or displacement. None was found, and the CC 45 OS system was installed.

Summary of Individual Tests (CC 35 Cable Concrete System)

Test Run 1

Test Run 1, consisting of a 1-foot overtopping condition and discharge of 24 cfs, was conducted on November 11, 1998. This overtopping condition was maintained 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 November 12, 1998. This run consisted of a 2-foot overtopping condition, with a discharge of 78 cfs, for a period of four hours.

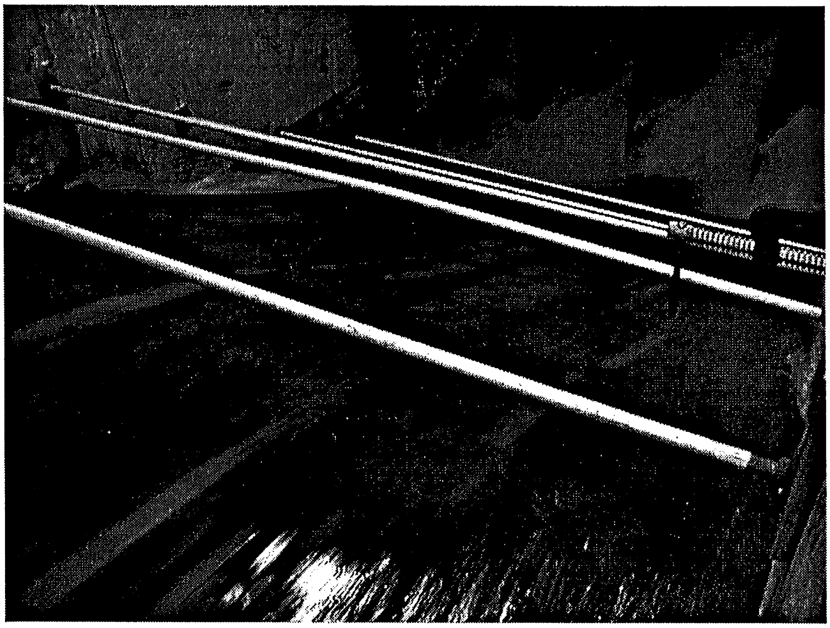


Photo 3. Three-foot overtopping condition, CC 35 (Test Run 3).

Test Run 3

Test Run 3 was performed for a period of four hours on November 17, 1998. See Photo 4 above. The run consisted of a 3-foot overtopping condition, with a discharge of 152 cfs.

Test Run 4

Test Run 4 was performed on November 20, 1998, after completing Test Run 3. This run consisted of a 3.5-foot overtopping condition for a period of four hours, with a discharge of 198 cfs.

Summary of Individual Tests (CC 45 OS Cable Concrete System)

Test Run 5

Test Run 5, consisting of a 1-foot overtopping condition and discharge of 26.5 cfs, was conducted on December 14, 1998. The run consisted of a 1-foot overtopping condition, with a discharge of 26.5 cfs, for a period of four hours. After completion of this run, the discharge was stopped and block elevation measurements were taken.

Test Run 6

After completing Test Run 5, Test Run 6 was conducted on December 15, 1998. This run consisted of a 2-foot overtopping condition, with a discharge of 74 cfs, for a period of four hours.

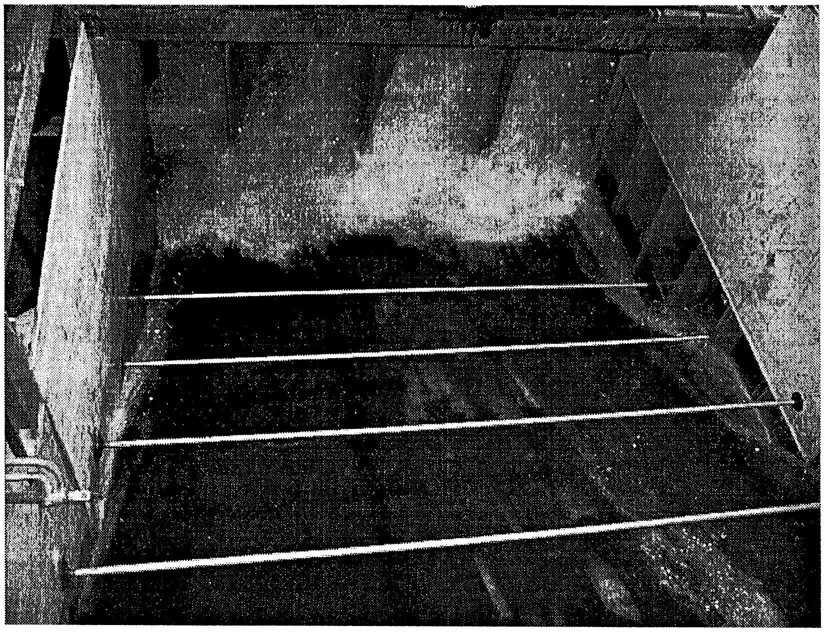


Photo 4. Three-foot overtopping condition, CC 45 OS (Test Run 7).

Test Run 7

Test Run 7 was performed for a period of four hours on December 16, 1998. See Photo 4 above. The run consisted of a 3-foot overtopping condition, with a discharge of 147 cfs.

Test Run 8

Test Run 8 was performed on December 18, 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.

Additional Inquiry

Some additional work was performed at the request of the client after the completion of Test Run 8. The client was interested in the performance of the blocks with the cable clamps normally securing the Cable Concrete mats together removed. Due to the complexities and costs of making experimental observations, the client decided to merely watch the test facility and make a few simple measurements of intermat spacing. This data is shown in the Appendix. While the blocks did move, the movement is slight. The measurements taken can not be used to predict the behavior of the Cable Concrete Mat system, as this was not a scientific test. The data was simply measured and the duration of the overtopping flow was only one hour. The results from this additional work shall not be taken to imply that the Cable Concrete Mats shall be installed in any manner other than that specified by the manufacturer.

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;

$$\sum F = \Delta(\rho V Q)$$

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

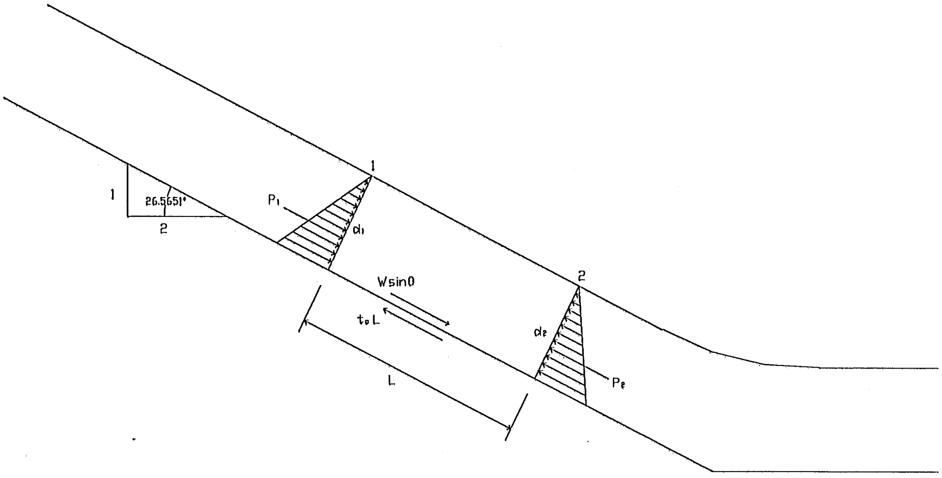


Figure 2. Control volume for hydraulic analysis.

It is important to note here the sensitivity of this formula with small variations of water depth. A ± 1/4" variation in a single measurement of the water surface elevation of a flow 11 inches deep (3 ft overtop) can change the calculated value of shear from 38.5 lb/ft^2 to as high as 39.3 lb/ft^2 (+2%) or as low as 37.8 lb/ft^2(-2%). ± 1/4" variations in four measurements of the water surface elevation of a flow 11 inches deep (3 ft overtop) can change the calculated value of shear from 38.5 lb/ft^2 to as high as 45.92 lb/ft^2 (+19%) or as low as 31.0 lb/ft^2(-19%).

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.

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

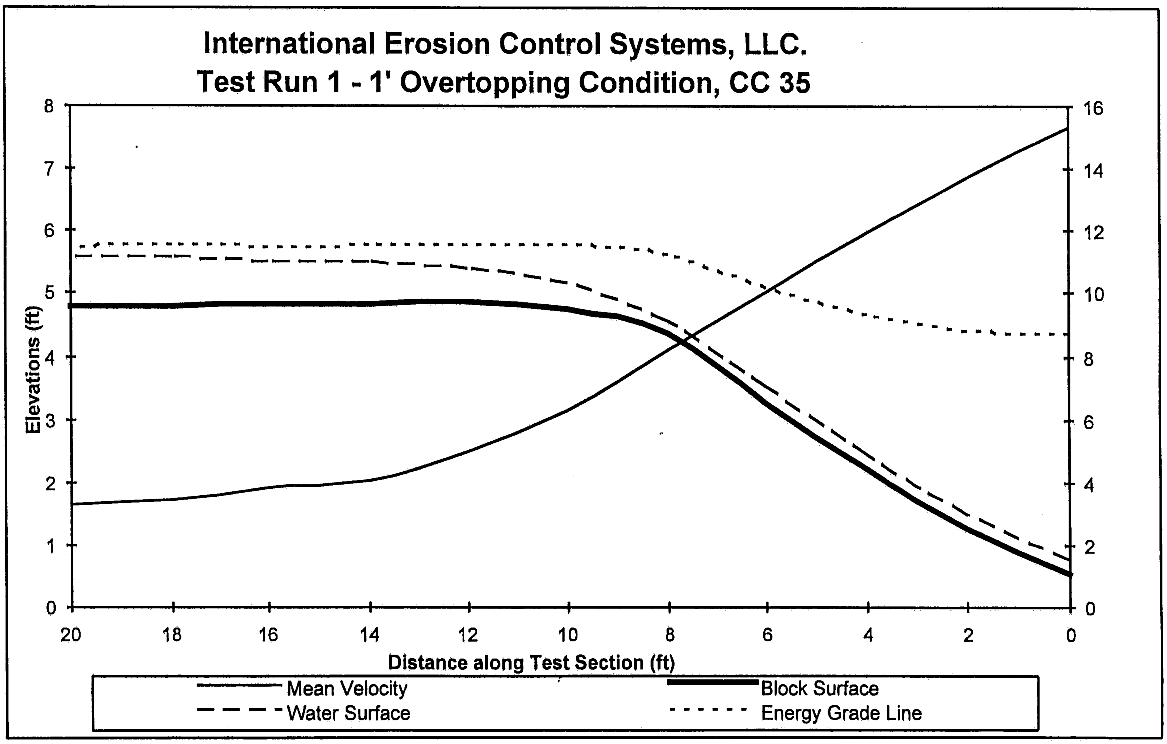
D: Geotextile Fabric Specifications

E. Cable Concrete Mat Displacement after Interconnecting Cables are Removed.

Appendix A - Experimental Data

Test Run 1 - IECS CC 35, 24 CFS
Experimental Data from 1 foot overtopping flow

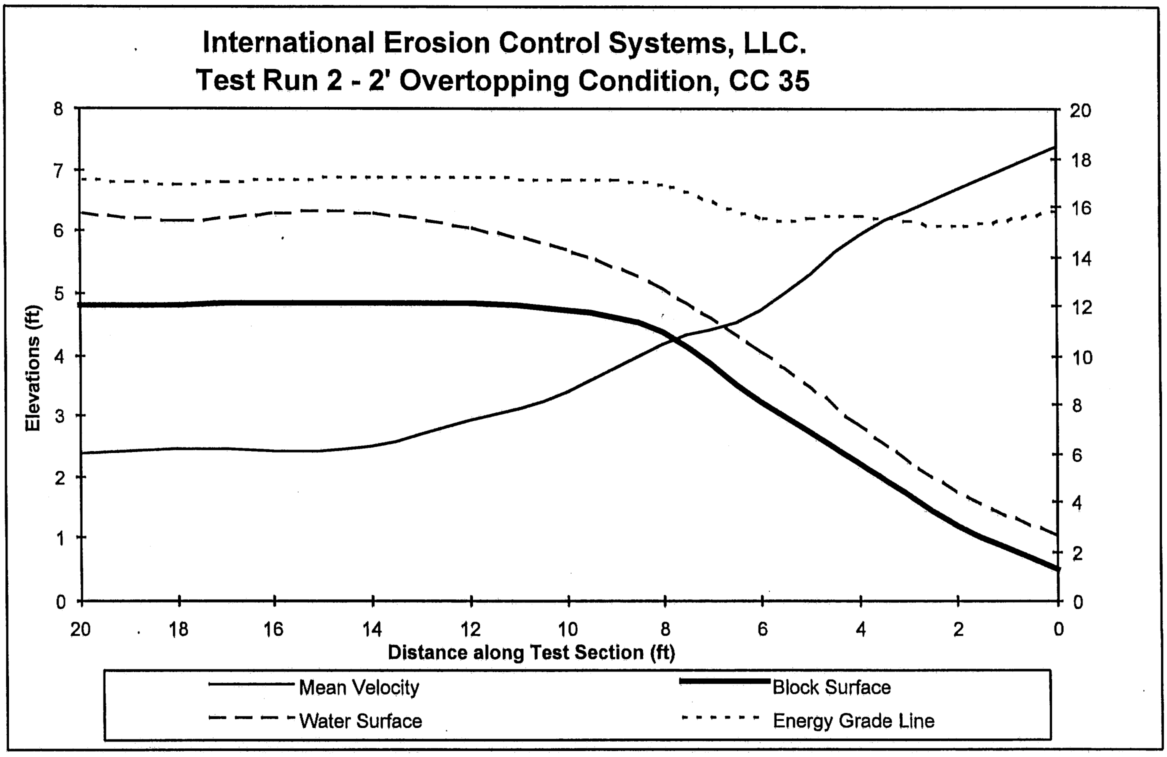
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.5	0.8	4.4	15.3
2	2.0	1.3	1.5	4.4	13.7
3	4.0	2.2	2.5	4.7	11.9
4	6.0	3.3	3.5	5.1	10.1
5	8.0	4.4	4.6	5.6	8.2
6	10.0	4.8	5.1	5.8	6.3
7	12.0	4.8	5.4	5.8	5.0
8	14.0	4.8	5.5	5.8	4.1
9	16.0	4.8	5.5	5.8	3.8
10	18.0	4.8	5.6	5.8	3.5
11	20.0	4.8	5.6	5.8	3.3


International Erosion Control Systems, LLC.
Test Run 1 - 1' Overtopping Condition, CC 35

Test Run 2 - IECS CC 35, 78 CFS

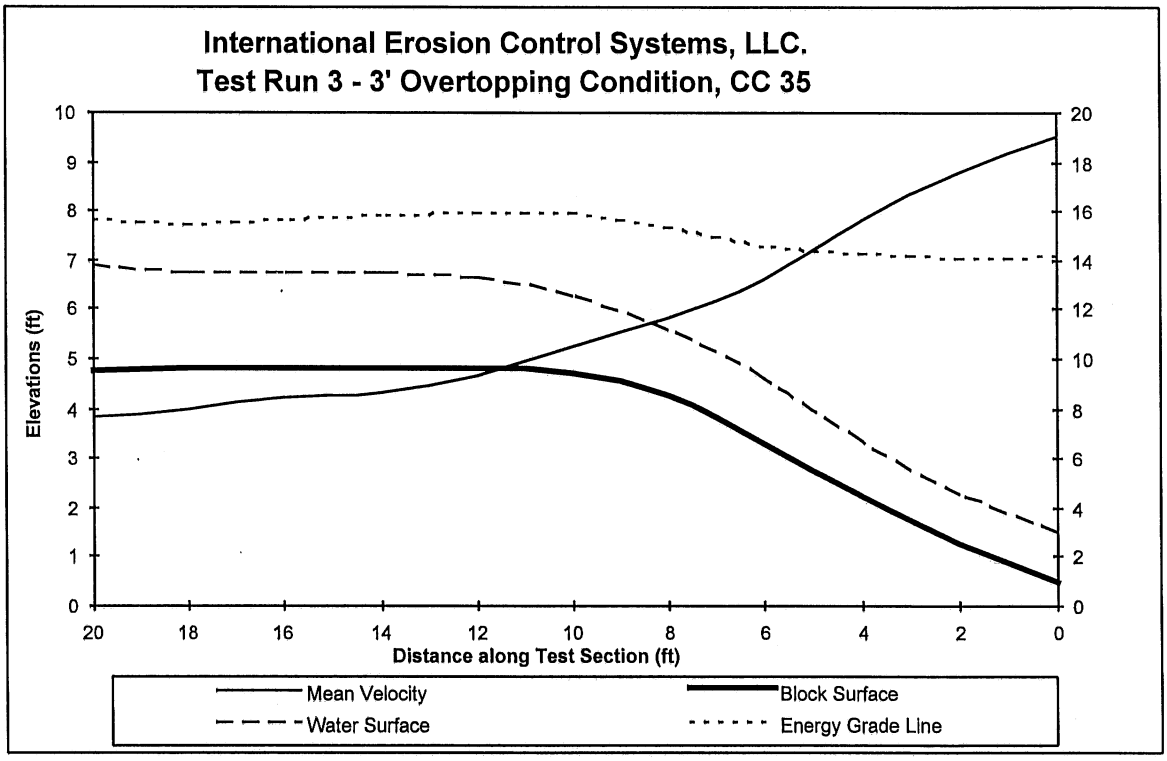
Experimental Data from 2 foot overtopping flow

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	0.5	1.1	6.3	18.4
2	2.0	1.2	1.8	6.1	16.6
3	4.0	2.2	2.8	6.2	14.8
4	6.0	3.2	4.0	6.2	11.8
5	8.0	4.4	5.1	6.8	10.4
6	10.0	4.7	5.7	6.8	8.5
7	12.0	4.8	6.0	6.9	7.3
8	14.0	4.8	6.3	6.9	6.3
9	16.0	4.8	6.3	6.8	6.0
10	18.0	4.8	6.2	6.8	6.2
11	20.0	4.8	6.3	6.8	5.9

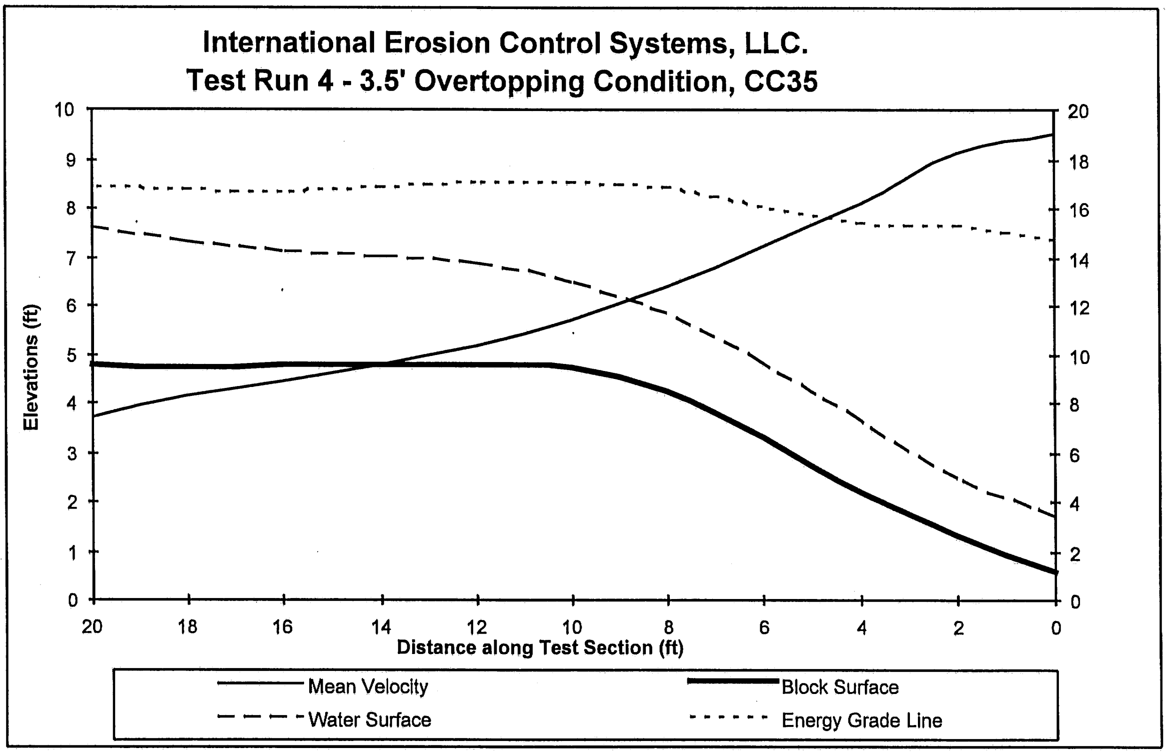


Test Run 3 - IECS CC 35, 152 CFS
Experimental Data from 3 foot overtopping flow

Station Number (ft)	Distance along Test Section (ft)	Block Surface Elevation (ft)	Water Surface Elevation (ft)	Energy Grade Line (ft)	Mean Velocity (fps)
1	0.0	0.5	1.5	7.1	19.0
2	2.0	1.3	2.3	7.0	17.5
3	4.0	2.2	3.3	7.1	15.6
4	6.0	3.3	4.6	7.3	13.2
5	8.0	4.3	5.6	7.7	11.7
6	10.0	4.7	6.2	8.0	10.5
7	12.0	4.8	6.6	8.0	9.3
8	14.0	4.8	6.7	7.9	8.6
9	16.0	4.8	6.7	7.8	8.4
10	18.0	4.8	6.8	7.7	7.9
11	20.0	4.8	6.9	7.8	7.7



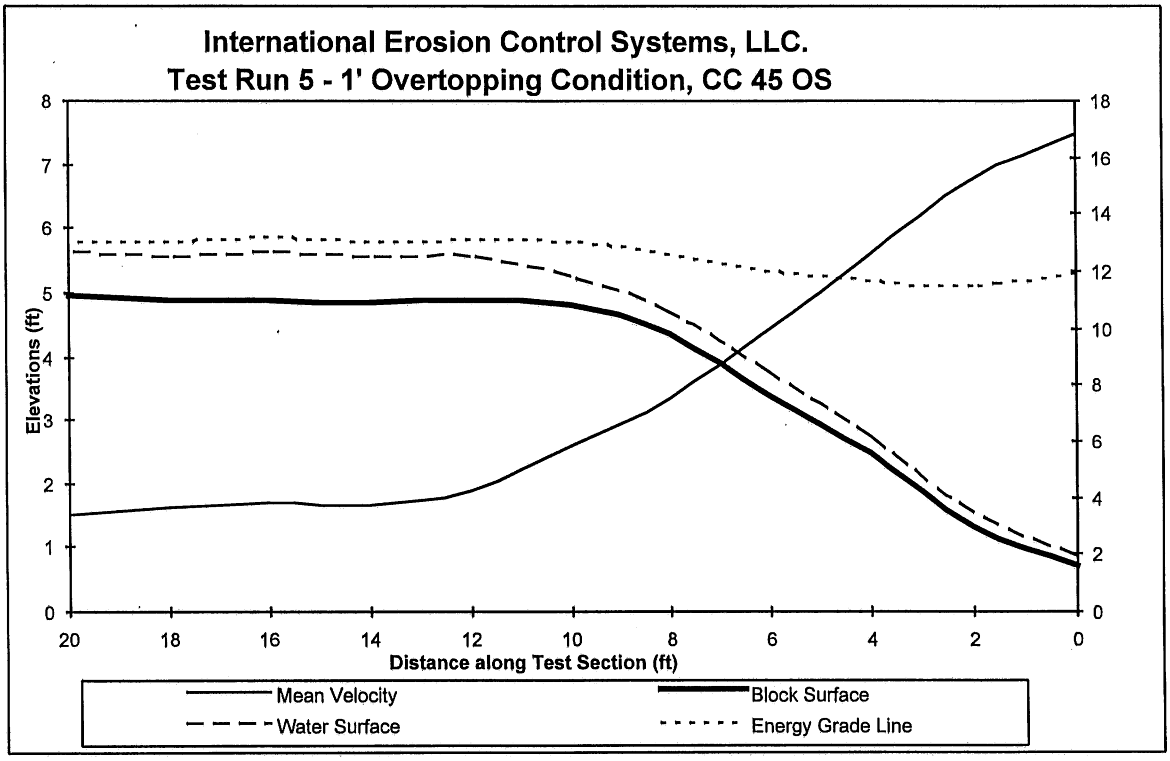
Test Run 4 - IECS CC 35, 198 CFS Experimental Data from 3.5 foot overtopping flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.6	1.7	7.4	19.1
2	2.0	1.3	2.5	7.6	18.2
3	4.0	2.2	3.7	7.7	16.2
4	6.0	3.3	4.8	8.0	14.4
5	8.0	4.3	5.9	8.4	12.8
6	10.0	4.7	6.5	8.5	11.5
7	12.0	4.8	6.9	8.5	10.4
8	14.0	4.8	7.0	8.4	9.5
9	16.0	4.8	7.1	8.3	8.9
10	18.0	4.8	7.3	8.4	8.3
11	20.0	4.8	7.6	8.5	7.5



Test Run 5 - IECS CC 45 OS, 26.5 CFS

Experimental Data from 1 foot overtopping flow

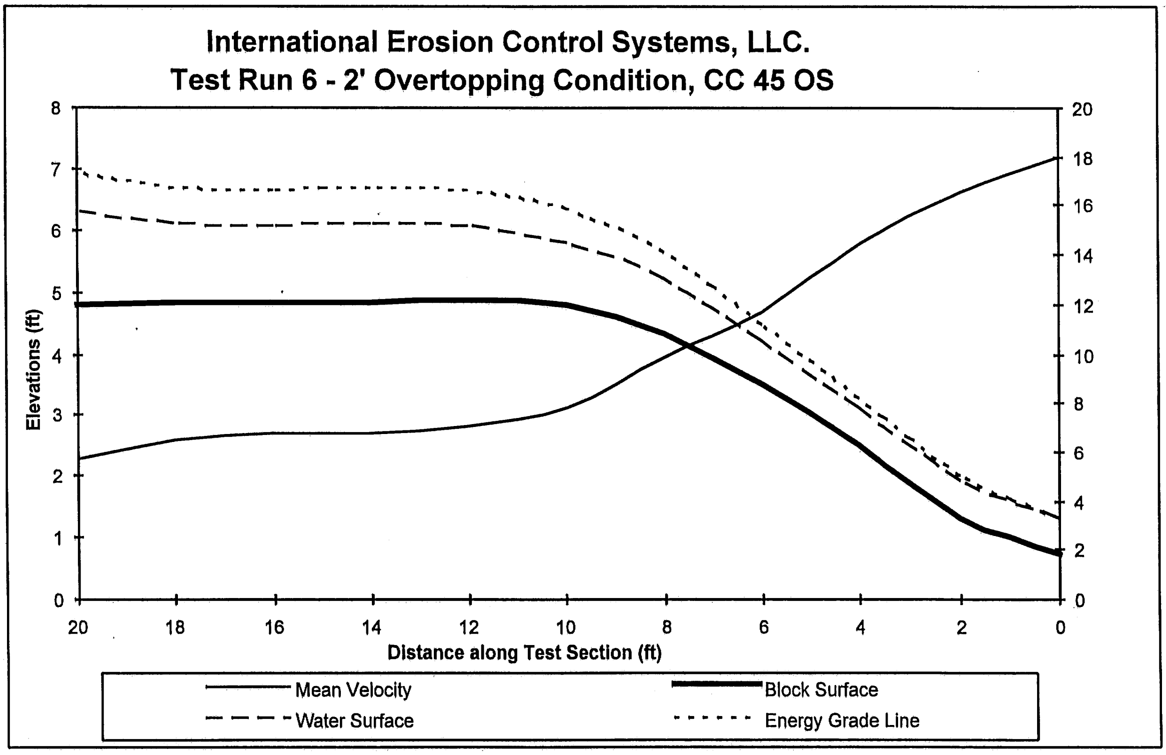
Station Number (ft)	Distance along Test Section (ft)	Block Surface Elevation (ft)	Water Surface Elevation (ft)	Energy Grade Line (ft)	Mean Velocity (fps)
1	0.0	0.7	0.9	5.3	16.8
2	2.0	1.3	1.5	5.1	15.2
3	4.0	2.5	2.7	5.2	12.6
4	6.0	3.4	3.8	5.3	10.0
5	8.0	4.3	4.7	5.6	7.5
6	10.0	4.8	5.3	5.8	5.8
7	12.0	4.9	5.5	5.8	4.2
8	14.0	4.8	5.6	5.8	3.8
9	16.0	4.9	5.6	5.8	3.8
10	18.0	4.9	5.6	5.8	3.6
11	20.0	4.9	5.6	5.8	3.4



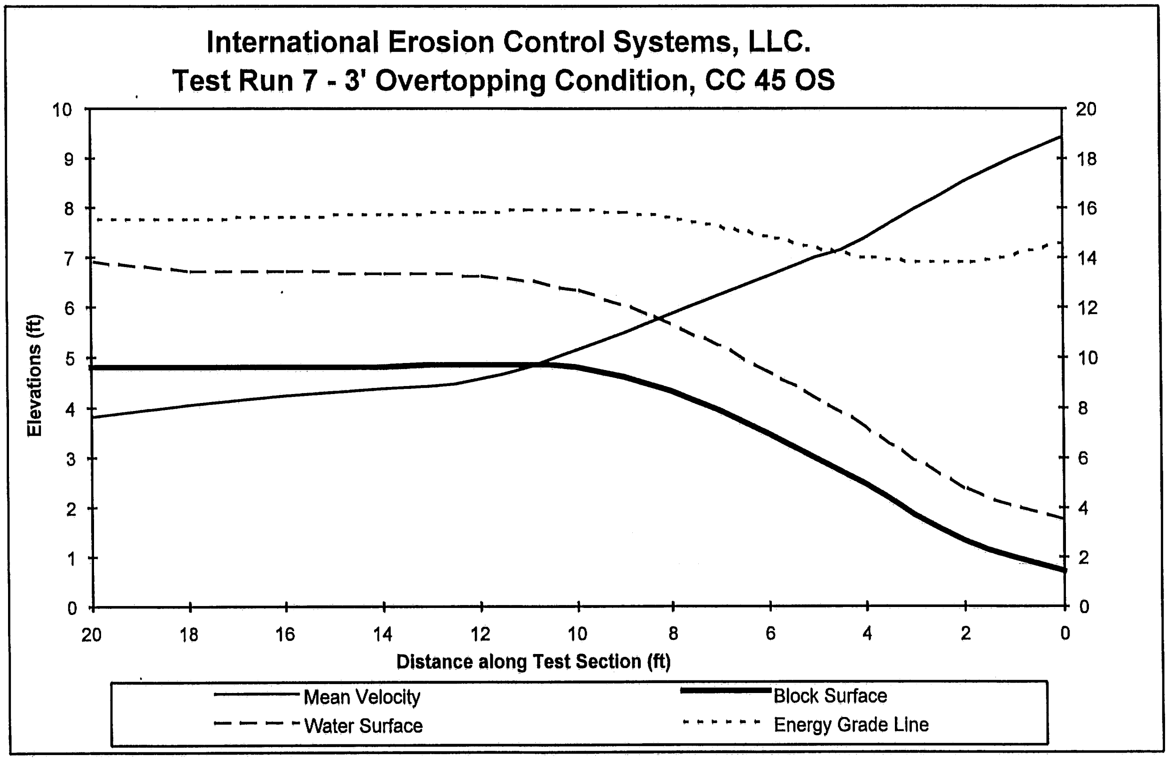
International Erosion Control Systems, LLC.
Test Run 5 - 1' Overtopping Condition, CC 45 OS

Test Run 6 - IECS CC 45 OS, 74 CFS
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	0.7	1.3	1.3	18.0
2	2.0	1.3	1.9	2.0	16.5
3	4.0	2.5	3.1	3.3	14.4
4	6.0	3.5	4.2	4.5	11.7
5	8.0	4.3	5.2	5.6	9.9
6	10.0	4.8	5.8	6.3	7.9
7	12.0	4.9	6.1	6.6	7.0
8	14.0	4.8	6.1	6.7	6.8
9	16.0	4.8	6.1	6.6	6.8
10	18.0	4.8	6.1	6.7	6.5
11	20.0	4.8	6.3	6.9	5.7


International Erosion Control Systems, LLC.
Test Run 6 - 2' Overtopping Condition, CC 45 OS

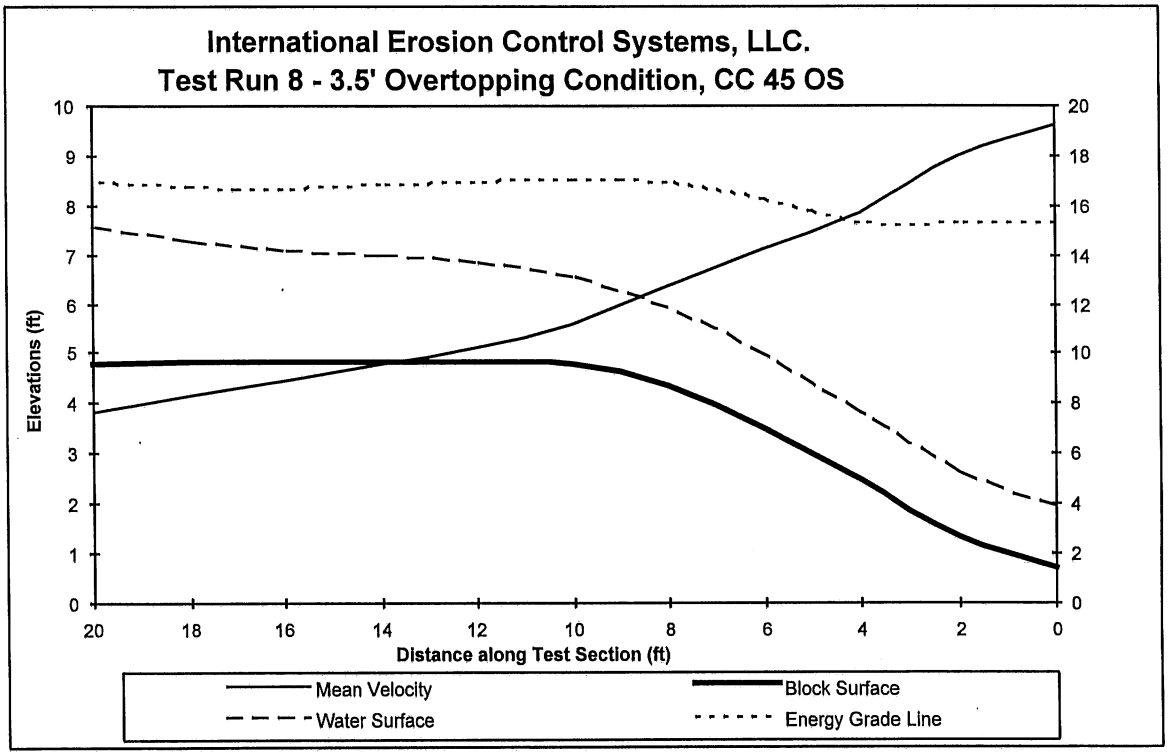
Test Run 7 - IECS CC 45 OS, 147 CFS Experimental Data from 3 foot overtopping flow					
Station Number	Distance along Test Section	Block Surface Elevation	Water Surface Elevation	Energy Grade Line	Mean Velocity
(ft)	(ft)	(ft)	(ft)	(ft)	(fps)
1	0.0	0.7	1.8	7.3	18.9
2	2.0	1.3	2.4	6.9	17.1
3	4.0	2.5	3.6	7.0	14.8
4	6.0	3.5	4.7	7.4	13.2
5	8.0	4.3	5.7	7.8	11.8
6	10.0	4.8	6.3	8.0	10.3
7	12.0	4.8	6.6	7.9	9.1
8	14.0	4.8	6.7	7.9	8.7
9	16.0	4.8	6.7	7.8	8.5
10	18.0	4.8	6.7	7.7	8.1
11	20.0	4.8	6.9	7.8	7.6


International Erosion Control Systems, LLC.
Test Run 7 - 3' Overtopping Condition, CC 45 OS

Test Run 8 - IECS CC 45 OS, 185 CFS

Experimental Data from 3.5 foot overtopping flow

Station Number (ft)	Distance along Test Section (ft)	Block Surface Elevation (ft)	Water Surface Elevation (ft)	Energy Grade Line (ft)	Mean Velocity (fps)
1	0.0	0.7	1.9	7.7	19.2
2	2.0	1.3	2.6	7.6	18.0
3	4.0	2.5	3.8	7.6	15.7
4	6.0	3.5	5.0	8.1	14.3
5	8.0	4.3	5.9	8.5	12.7
6	10.0	4.8	6.6	8.5	11.2
7	12.0	4.8	6.9	8.5	10.2
8	14.0	4.8	7.0	8.4	9.5
9	16.0	4.8	7.1	8.3	8.9
10	18.0	4.8	7.3	8.4	8.3
11	20.0	4.8	7.6	8.5	7.6



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)

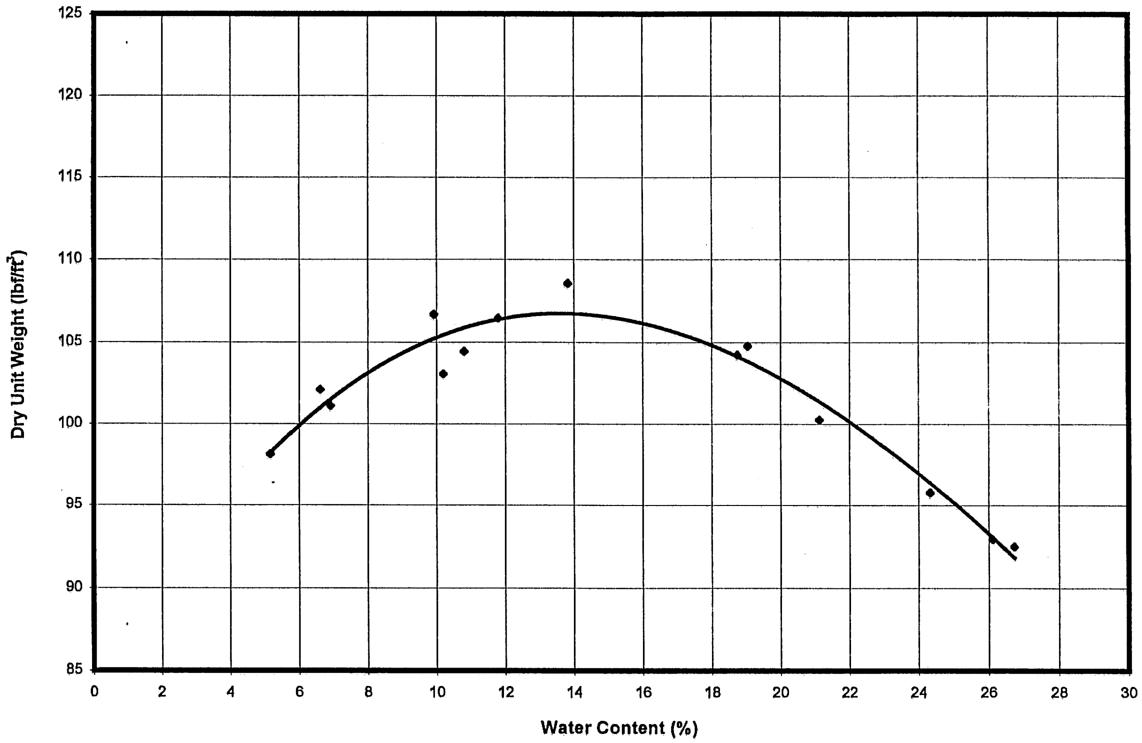
Unified Soil Classification: CL

AASHTO Group Designation: A-4

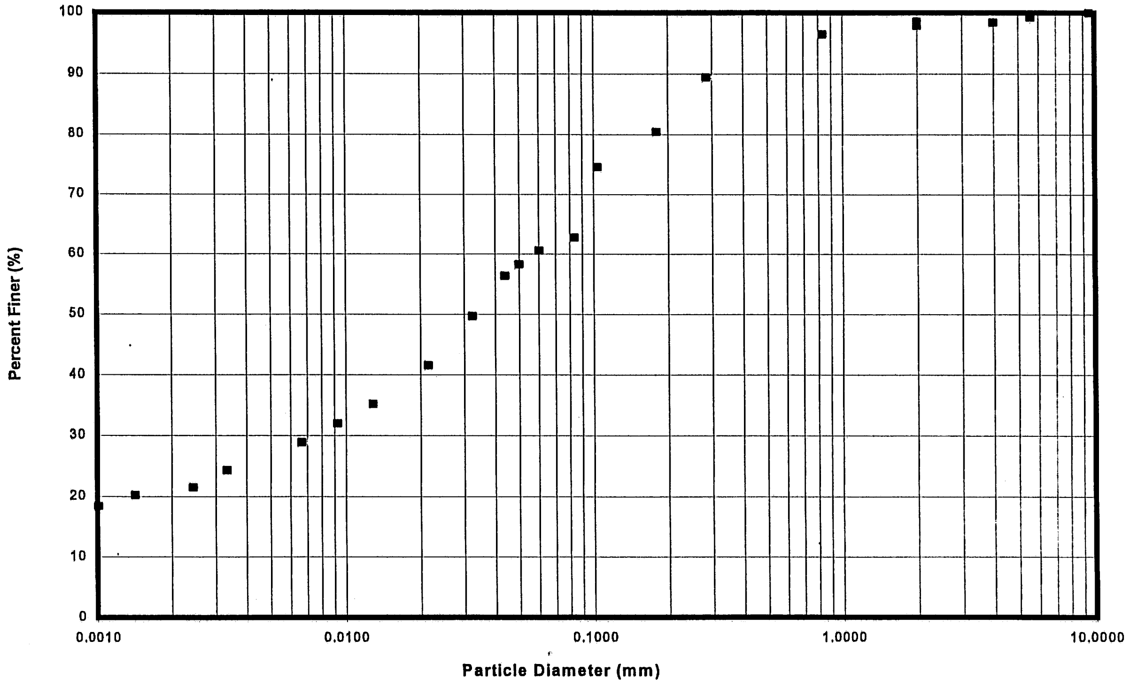
The soil was compacted in horizontal lifts, each 6 to 10 inches in height, using a vibrating plate tamper. Two to four passes of the plate brought the compaction to the required 90 percent ± 5% of standard Proctor density.

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

Compaction Curve



Grain Size Distribution



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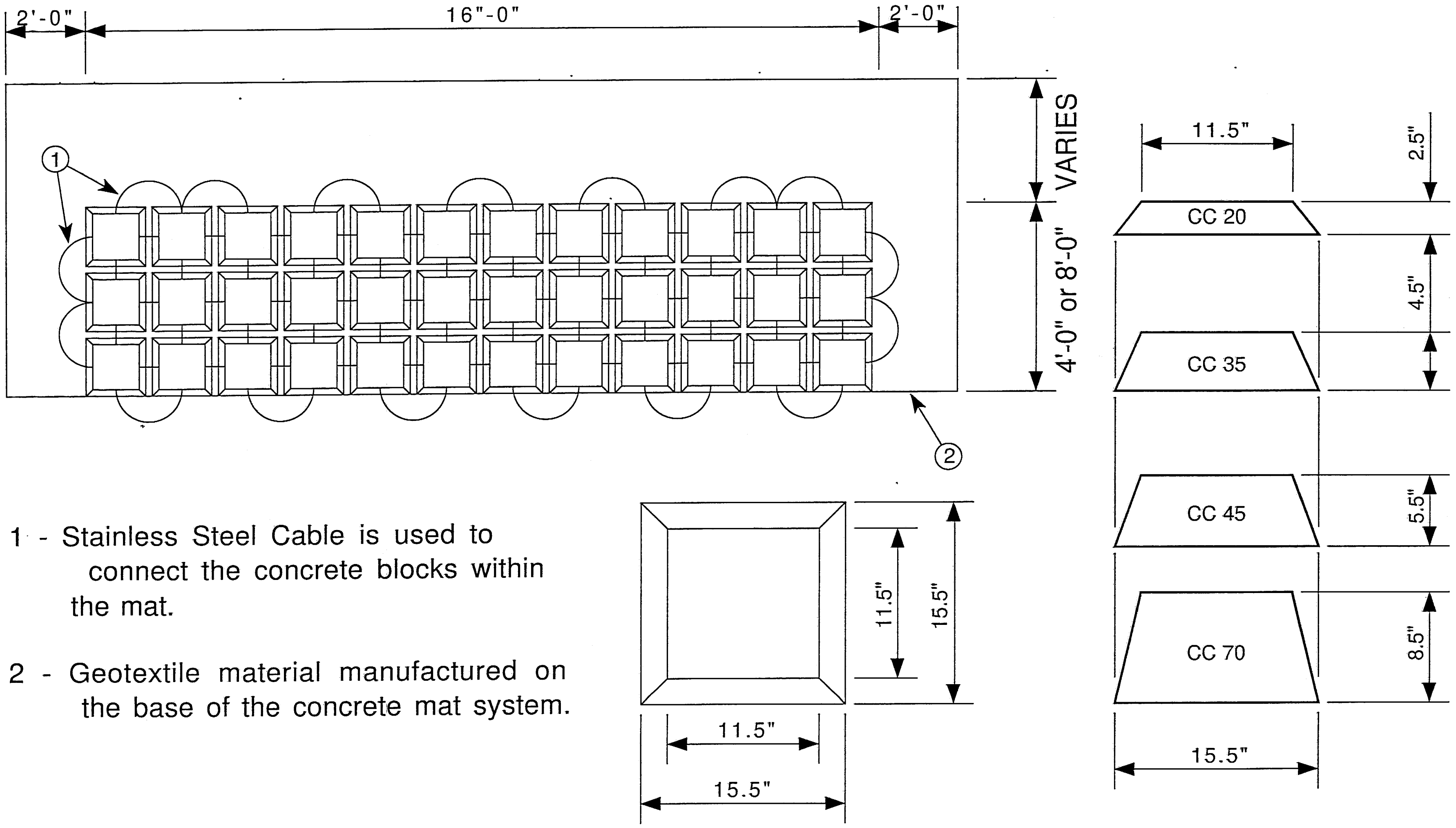
1. Holtz, Robert D., and William D. Kovacs. *An Introduction to Geotechnical Engineering.* Prentice-Hall, Englewood Cliffs, NJ 1981.

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

Appendix C - Cable Concrete Block Specifications

		CC 20 20 lbs./s.f.		CC 35 35 lbs./s.f.		CC 45 45 lbs./s.f.		CC 70 70 lbs./s.f.	
MAT	AREA	64 s.f.	128 s.f.						
	WEIGHT	1280 lbs.	2560 lbs.	2240 lbs.	4480 lbs.	2880 lbs.	5760 lbs.	4480 lbs.	8960 lbs.
	BLOCKS/MAT	36	72	36	72	36	72	36	72
BLOCKS	SPACING@BASE	0.5 in.		0.5 in.		0.5 in.		0.5 in.	
	SPACING@TOP	4.5 in.		4.5 in.		4.5 in.		4.5 in.	
	WEIGHT	35.6 lbs.		62.2 lbs.		80.0 lbs		124.4 lbs.	
CABLE		LENGTH	WIDTH	LENGTH	WIDTH	LENGTH	WIDTH	LENGTH	WIDTH
	DIAMETER	1/8 in.	1/8 in.	5/32 in.	5/32 in.	5/32 in.	5/32 in.	3/16 in.	5/32 in.
	CONSTRUCTION	1 x 19	1 x 19	1 x 19	1 x 19	1 x 19	1 x 19	1 x 19	1 x 19
	BREAKING STRENGTH	2100 lbs.	2100 lbs.	3300 lbs.	2100 lbs.	3300 lbs.	2100 lbs.	4700 lbs.	3300 lbs.

CC 35 CABLE CONCRETE MAT DESIGN

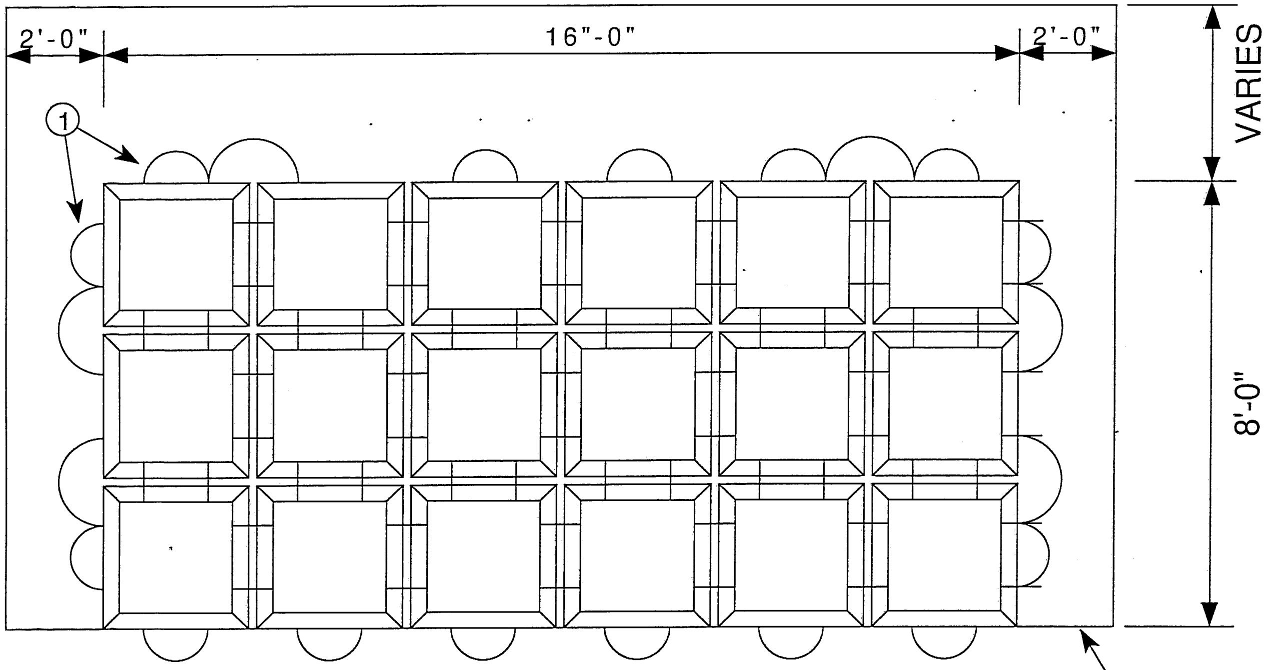


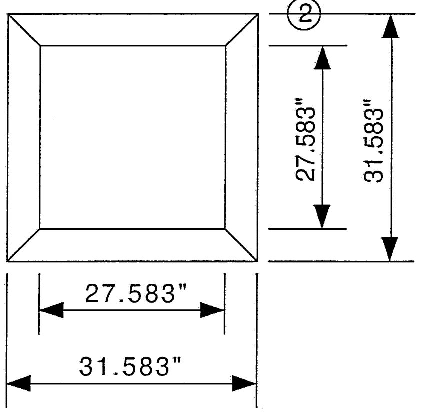
1 - Stainless Steel Cable is used to connect the concrete blocks within the mat.

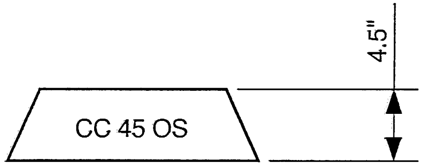
2 - Geotextile material manufactured on the base of the concrete mat system.

Figure 3. Drawing of CC 35 Cable Concrete system and individual blocks.

CC 45 OS CABLE CONCRETE MAT DESIGN







1 - Stainless Steel Cable and/or polypropylene rope is used to connect the concrete blocks within the mat.

2 - Geotextile material may be attached or unattached to the base of the concrete mat system.

3 - Gap between blocks at the bottom of the system shall be one half inch. The base of the blocks shall be 31 7/12" square, and the top of the blocks shall be 27 7/12".

WHOLE BLOCK WEIGHT = 330#

18 BLOCKS PER MAT
18 * 330# = 5940#/MAT
4482#/128 = 46.4#/SF

Figure 4. Drawing of CC 45 OS Cable Concrete system and individual blocks.

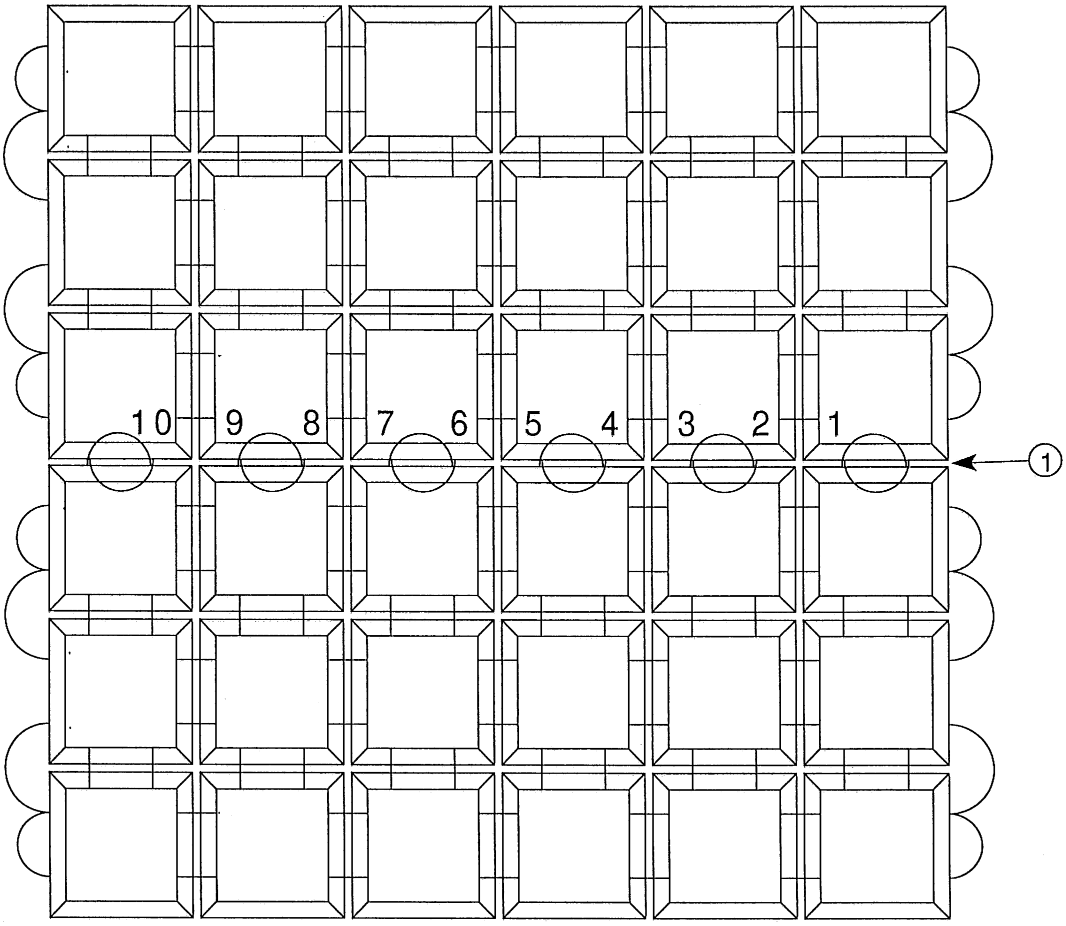
Appendix D - Geotextile Fabric Specifications

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

Appendix E – Cable-Concrete-Mat Displacement after Interconnecting Cables are Removed

Upstream



Downstream

1 - The cables connecting the mats were removed, and the distance between the upper edges of the blocks measured. Measurements were taken at points 1 - 10 as pictured above.

Figure 5. Position of block movement measurements.

	Position of measurement									
Spacing at top of block (inches)	1	2	3	4	5	6	7	8	9	10
Initial Spacing @ 1' overtopping	5 3/8	4 7/8	5 1/8	5 5/16	5 9/16	5 3/8	5 3/8	5 5/16	4 11/16	4 3/4
Movement during 1' overtopping	0	0	0	0	0	1/16	1/16	0	1/16	0
Initial Spacing @ 2' overtopping	5 3/8	4 7/8	5 1/8	5 5/16	5 9/16	5 7/16	5 7/16	5 5/16	4 3/4	4 3/4
Movement during 2' overtopping	0	0	0	1/16	0	1/16	1/16	1/16	1/8	1/16
Initial Spacing @ 3' overtopping	5 3/8	4 7/8	5 1/8	5 3/8	5 9/16	5 1/2	5 1/2	5 3/8	4 7/8	4 13/16
Movement during 3' overtopping	0	0	0	1/16	0	1/8	1/8	1/16	3/16	1/16
Final Spacing @ 3' overtopping	5 3/8	4 7/8	5 1/8	5 7/16	5 9/16	5 5/8	5 5/8	5 7/16	5 1/16	4 7/8
Total Movement	0	0	0	1/8	0	1/4	1/4	1/8	3/8	1/8

Table 1. Distances moved by Cable Concrete Mats when not cabled together.