

# DESIGN CRITERIA FOR ROUNDED/ANGULAR ROCK RIPRAP IN OVERTOPPING FLOW

by

Humberto A. Gallegos,<sup>1</sup> and Steven R. Abt<sup>2</sup>

## ABSTRACT

A series of 9 overtopping tests were performed in a physical model of an embankment to determine design criteria for rounded/angular rock riprap in overtopping flow. A predictive equation was derived as a function of the embankment slope, coefficient of uniformity, percent rounded, failure unit discharge and the median stone size. In addition, it was determined that the hydraulic roughness, Manning's  $n$ , for rounded rock riprap on steep slopes was 25 to 28 percent smaller compared to angular rock riprap.

**KEYWORDS:** Riprap, linear regression, coefficient of uniformity, coefficient of gradation, scaled model, Colorado State University, overtopping flow, embankment, hydraulic roughness, median, empirical design equation, hydraulic resistance, alluvial material, rounded riprap, angular riprap, interstitial discharge, percent rounded.

## 1. INTRODUCTION

In the construction of new dams, rehabilitation of existing dams, and the protection of the public health and environment from the potential hazards of waste materials, rock riprap is usually the most economical material for protection. Currently, available design criteria require the use of angular stones for all riprap revetments. However, in remote locations, the cost of shipping angular riprap from the quarry to the project site may increase the project cost significantly. Large quantities of alluvial material may be locally available, but stones are often rounded in shape. Only limited design criteria have been proposed to allow the utilization of rounded rock riprap for overtopping protection. The objectives of this investigation were: (1) develop design criteria for rounded rock riprap in overtopping flow; (2) expand the database of rounded rock riprap to include higher embankment slopes; (3) increase the understanding of the behavior of rounded rock riprap in overtopping flow; and (4) analyze the hydraulic roughness of rounded rock riprap on steep slopes.

## 2. TEST FACILITY

A physical model of an embankment was constructed in the Hydraulics Laboratory at the Colorado State University Engineering Research Center. The testing flume consists of a wooden head box, variable slope flume (25% variable), and tailbox. The testing flume is 1.22 m (4 ft) wide, 1.17m (3.85 ft) deep, and 12.60 m (32.0 ft) long (see Figure 1). The test matrix consisted of nine overtopping tests. Median rock sizes of 3.23 cm (1.27 in) to 9.91 cm (3.9 in) were placed on embankment slopes of 35, 40, and 45%.

## 3. BACKGROUND

Abt et al. (1987 and 1988<sub>a</sub>) conducted an extensive testing program to devise a waste stabilization design procedure and method. The test consisted of 52 flume tests in which riprap-covered embankments were subjected to overtopping flows. Embankment slopes of 1, 2, 8, 10, and 20% were protected with riprap containing median stone sizes of 2.54, 5.08, 10.16, 12.7, and 15.24 cm

<sup>1</sup> Grad. Res. Asst., Dept. of Civil Engr., Colo. State Univ., Ft. Collins, CO 80523

<sup>2</sup> Prof., Dept. of Civil Engr., Colo. State Univ., Ft. Collins, CO 80523

(1, 2, 4, 5, and 6 in). Riprap layer thickness ranged from 1.5 D<sub>50</sub> to 4 D<sub>50</sub>. The empirical design equation for angular rock riprap is expressed as follows:

$$D_{50} = 5.23S^{0.43}q_{design}^{0.56} \quad (1)$$

$$q_{design} = 1.35q_f \quad (2)$$

The rounded riprap required oversizing of about 40% to provide the same level of protection as the angular riprap. Ullman (2000) developed a design criteria for rounded riprap in overtopping flow by conducting a series of 12 flume tests in which rounded riprap of median stone diameter ranging from 2.39 cm (0.94 in) to 9.91 cm (3.9 in) were placed on embankment slopes of 20, 25 and 30% and subjected to overtopping flow conditions. The design equation for rounded rock riprap in overtopping flow is:

$$\frac{D_{50}}{C_u^{0.25}(1.12\%R + 0.39)} = 6.48S^{0.43}q_f^{0.56} \quad (3)$$

#### 4. ROUNDED/ANGULAR ROCK RIPRAP ANALYSIS

The test findings from this study, Ullman (2000) and Abt et al. (1988<sub>a</sub>) are presented in Table 1.

**Table 1: Test Results**

		D <sub>50</sub> (cm)	D <sub>50</sub> (in)	C <sub>u</sub>	Rounded %	S decimal	q <sub>f</sub> m <sup>3</sup> /m	q <sub>f</sub> ft <sup>3</sup> /ft	Mode Of Failure	
Current Study	1	Round	5.87	2.31	1.21	79	0.35	0.042	0.465	Exposure
	2	Round	3.23	1.27	1.32	80	0.35	0.014	0.154	Catastrophic
	3	Round	0.91	3.90	1.24	82	0.35	0.006	0.305	Exposure
	4	Round	5.87	2.31	1.21	79	0.40	0.031	0.335	Channel
	5	Round	3.23	1.27	1.32	80	0.40	0.014	0.157	Channel
	6	Round	0.91	3.00	1.24	82	0.40	0.051	0.552	Exposure
	7	Round	3.23	1.27	1.32	80	0.45	0.012	0.131	Exposure
	8	Round	5.87	2.31	1.21	79	0.45	0.006	0.304	Catastrophic
	9	Round	0.91	3.90	1.24	82	0.45	0.005	0.703	Exposure
Ullman (2000)	10	Round	2.39	0.94	1.24	85	0.20	0.019	0.20	Channel
	11	Round	2.39	0.94	1.24	85	0.30	0.015	0.16	Channel
	12	Round	3.23	1.27	1.32	80	0.20	0.020	0.33	Channel
	13	Round	3.23	1.27	1.32	80	0.25	0.021	0.22	Channel
	14	Round	3.23	1.27	1.32	80	0.30	0.019	0.21	Channel
	15	Round	4.00	1.77	1.33	78	0.20	0.005	0.38	Channel
	16	Round	4.50	1.77	1.33	76	0.25	0.035	0.38	Channel
	17	Round	4.50	1.77	1.33	76	0.30	0.029	0.32	Channel
	18	Round	5.87	2.31	1.21	79	0.20	0.053	0.53	Catastrophic
	19	Round	5.87	2.31	1.21	79	0.30	0.048	0.53	Catastrophic
	20	Round	5.87	2.31	1.21	79	0.25	0.052	0.57	Catastrophic
	21	Round	9.91	3.90	1.24	86	0.30	0.046	1.04	Catastrophic
Abt et al. (1988 <sub>a</sub> )	22	Round	10.42	4.10	2.12	95	0.20	0.087	0.95	Unk. no. n.
	23	Round	10.42	4.10	2.12	95	0.20	0.087	0.95	Unk. no. n.
	24	Round	10.42	4.10	2.12	95	0.10	0.183	1.90	Unk. no. n.
	25	Round	10.42	4.10	2.12	95	0.10	0.192	2.09	Unk. no. n.
	26	Round	5.21	2.05	2.14	95	0.10	0.093	0.89	Unk. no. n.
Abt and Johnson (1981)	1	Angular	2.59	1.02	1.75	0	0.02	0.102	1.11	Unk. no. n.
	2	Angular	2.59	1.02	1.75	0	0.01	0.158	1.50	Unk. no. n.
	3	Angular	2.59	1.02	1.75	0	0.10	0.033	0.36	Unk. no. n.
	4	Angular	2.59	1.02	1.75	0	0.10	0.031	0.34	Unk. no. n.
	5	Angular	2.59	1.02	1.75	0	0.10	0.028	0.31	Unk. no. n.
	6	Angular	2.59	1.02	1.75	0	0.10	0.059	0.42	Unk. no. n.
	7	Angular	5.08	2.00	2.40	0	0.10	0.078	0.85	Unk. no. n.
	8	Angular	5.08	2.00	2.40	0	0.10	0.062	1.00	Unk. no. n.
	9	Angular	5.08	2.00	2.40	0	0.10	0.102	1.11	Unk. no. n.
	10	Angular	5.59	2.20	2.09	0	0.10	0.103	1.12	Unk. no. n.
	11	Angular	5.59	2.20	2.09	0	0.10	0.115	1.25	Unk. no. n.
	12	Angular	5.59	2.20	2.09	0	0.10	0.115	1.25	Unk. no. n.
	13	Angular	5.59	2.20	2.09	0	0.08	0.166	1.91	Unk. no. n.
	14	Angular	5.59	2.20	2.09	0	0.02	0.416	4.53	Unk. no. n.
	15	Angular	5.59	2.20	2.09	0	0.20	0.046	0.50	Unk. no. n.
16	Angular	10.16	4.00	2.30	0	0.10	0.322	3.51	Unk. no. n.	
17	Angular	10.16	4.00	2.30	0	0.10	0.348	3.79	Unk. no. n.	
18	Angular	10.16	4.00	2.30	0	0.10	0.378	4.12	Unk. no. n.	
19	Angular	10.41	4.10	2.15	0	0.20	0.166	1.81	Unk. no. n.	
20	Angular	12.95	5.10	1.82	0	0.20	0.327	3.56	Unk. no. n.	
21	Angular	15.75	6.20	1.69	0	0.20	0.407	4.43	Unk. no. n.	

Equation 1 developed by Abt et al. (1988<sub>a</sub>) was used as the basis for the analysis of the rounded and angular rock riprap data. To adjust the data for rock riprap gradation, the median rock riprap size was divided by C<sub>u</sub><sup>0.25</sup>. The adjustment collapsed the data set for the current, Ullman (2000) and the Abt et al. (1988<sub>a</sub>) data into a single relationship. The riprap sizes used in this study and the Ullman (2000) study indicate that the percent rounded rock increases with median stone size (see Table 1). Equation 4 is used to adjust the difference observed in percent rounded as median stone diameter increases:

$$\frac{D_{50}}{C_u^{0.25}(1.0805 \cdot \%R + 0.4428)} = 5.23S^{0.43}q_f^{0.56} \quad (4)$$

Equation 4 is plotted for all data presented in Table 1 to produce Figure 2. Safety factors were included in Equation 4 to account for the scatter in Figure 2 and the maximum expected unit discharge was multiplied by a factor of 1.35 to reduce movement of stones that would compromise the riprap stability. The recommended design equation is:

$$\frac{D_{50}}{C_u^{0.25}(1.0805\%R + 0.4428)} = 6.58S^{0.43}q_f^{0.56} \quad (5)$$

Equation 5 was developed from a database with the following constraints: (1) embankment slopes of 10 to 45 percent, (2) median rock sizes of 2.39 cm (0.94 in) to 15.24 cm (6 in), (3) rounded rock 55 to 95 percent rounded (4) riprap layer thickness of 1.5D<sub>50</sub> to 3D<sub>50</sub> and (5) coefficient of uniformity from 1.21 to 4.

## 5. HYDRAULIC ROUGHNESS ANALYSIS FOR ANGULAR/ROUNDED ROCK RIPRAP IN OVERTOPPING FLOW

To calculate the hydraulic resistance the Manning equation was used:

$$n = \frac{k}{V} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (6)$$

To determine Manning's n, the surface flow was utilized. The interstitial velocity through the riprap layer was estimated using Equation 7 developed by Abt et al (1988<sub>a</sub>):

$$V_i = 0.23\sqrt{gD_{10}S} \quad (7)$$

The surface discharge is the difference between the total and the interstitial discharge. The average surface flow velocity was obtained by dividing the surface flow discharge by the surface flow area. The surface flow depth was inserted in the hydraulics radius term in Manning's equation. The Abt et al (1988<sub>b</sub>) data for Manning's n using angular and rounded rock riprap and the rounded rock riprap data for Manning's n from the current and the Ullman (2000) study are presented in Table 2.

**Table 2: Manning's n data**

Manning's n data from Abt et al. (1988 <sub>a</sub> )					
Test #	D <sub>50</sub> (in)	D <sub>50</sub> (cm)	S (%)	n	D <sub>50</sub> S (in)
24	1.02	2.59	1	0.024	0.010
10	1.02	2.59	2	0.024	0.020
25	1.02	2.59	10	0.034	0.102
6	2.2	5.59	2	0.025	0.044
32	2.02	5.13	8	0.036	0.162
31	2.2	5.59	10	0.036	0.220
18	2.2	5.59	20	0.035	0.440
7	4.1	10.41	20	0.043	0.820
10A	5.1	12.95	20	0.044	1.020
15	6.2	15.75	20	0.055	1.240
21	4	10.16	20	0.022	0.800
22	4	10.16	20	0.033	0.800
36	4	10.16	10	0.041	0.400
38	4	10.16	10	0.049	0.400
46	2	5.08	10	0.048	0.200
Manning's n data from Ullman (2000)					
4	1.27	3.23	20	0.041	0.254
5	2.31	5.87	20	0.048	0.462
6	1.77	4.50	20	0.034	0.354
7	0.94	2.39	20	0.029	0.188
8	2.31	5.87	30	0.052	0.693
9	1.77	4.50	30	0.034	0.531
10	3.9	9.91	30	0.058	1.170
11	1.27	3.23	30	0.031	0.381
12	0.94	2.39	30	0.012	0.282
13	1.27	3.23	25	0.030	0.318
14	1.77	4.50	25	0.021	0.443
15	2.31	5.87	25	0.041	0.578
Manning's n data from current study					
1	2.31	5.87	35	0.012	0.809
2	1.27	3.23	35	0.121	0.446
6	3.9	9.91	40	0.015	1.560
8	2.31	5.87	45	0.047	1.040
9	3.9	9.91	45	0.048	1.755

Abt et al. (1988<sub>b</sub>) found that combining the median stone size and the embankment slope in one parameter reduces the data scatter observed when Manning's n values are plotted against the median stone size. The Manning's n values are plotted against the product of the median stone size and embankment slope in Figure 3. Figure 3 presents the best-fit lines for angular and rounded stones. The power equations for angular and rounded riprap are:

$$y = 0.0457x^{0.1579} \quad (\text{Angular}) \quad (8)$$

$$y = 0.0328x^{0.0973} \quad (\text{Rounded}) \quad (9)$$

Equation 9 provides smaller Manning's n values for a specified median stone size and embankment slope for rounded rock riprap. Manning's n values for rounded rock riprap were 25 to 28 percent smaller compared to angular rock riprap.

## 6. CONCLUSIONS

The recommended design relationship for rounded/angular rock riprap in overtopping flow is:

$$\frac{D_{50}}{C_u^{0.25}(1.0805\%R + 0.4428)} = 6.58S^{0.43}q_f^{0.56} \quad (10)$$

It was found that Manning's n values for rounded rock riprap were 25 to 28 percent smaller compared to angular rock riprap.

## 7. ACKNOWLEDGMENT

Information presented herein was obtained from the research conducted under Abt et al. (1987, 1988<sub>a</sub>, and 1988<sub>b</sub>) and Ullman (2000). The Colorado State Agricultural Experiment Station funded the study.

## 8. REFERENCES

Abt, S.R., Khattak, M.S., Nelson, J.D., Ruff, J.F., Shaikh, A., Wittler, R.J., Lee, D.W., and Hinkle, N.E. (1987). Development of riprap design criteria by riprap testing in flumes: Phase I. NUREG/CR-4651, U.S. Nuclear Regulatory Commission, Vol 1.

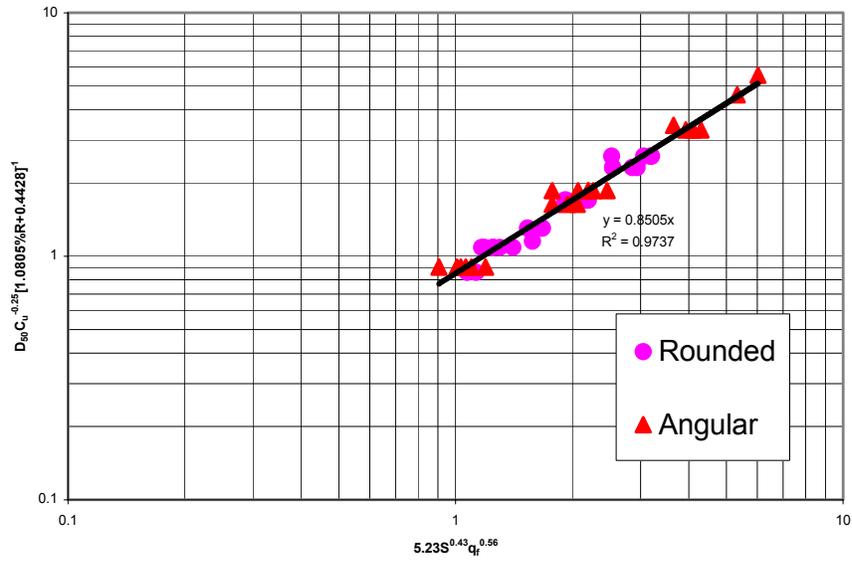
Abt, S.R., Wittler, R.J., J.D., Ruff, LaGrone, D.L., Khattak, M.S., Nelson, J.F., Hinkle, N.E., and Lee, D.W. (1988<sub>a</sub>). Development of riprap design criteria by riprap testing in flumes: Phase II. NUREG/CR-4651, U.S. Nuclear Regulatory Commission, Vol 1.

Abt, S.R., Wittler, R.J., Ruff, J.F., and Khattak, M.S. (1988<sub>b</sub>). Resistance to flow over riprap in steep channels. Water Resources Bulletin, 24 (6), 1193-1200.

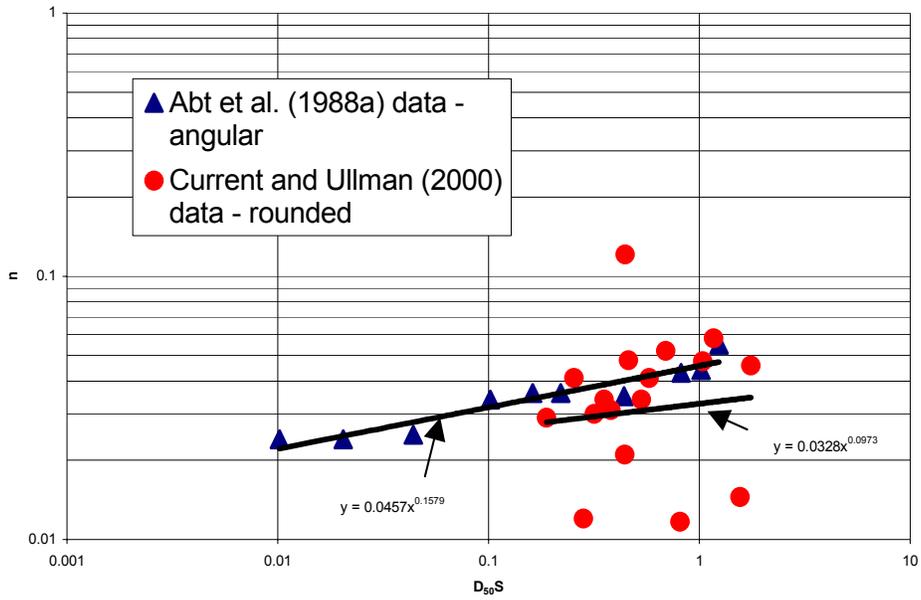
Ullman, C. (2000). Rounded riprap in overtopping flow. Masters Thesis, Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.



**Figure 1: Testing Flume**



**Figure 2: Rounded and angular rock riprap data adjusted for  $C_u$  and percent rounded rock**



**Figure 3: Manning's n values for angular and rounded riprap with best-fit lines**