Design of Rock Chutes

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Abstract. *Rock chute design information is consolidated from several sources to provide a comprehensive design tool. The rock slope stability, boundary roughness, and outlet stability of rock chutes are each discussed. Tests were performed in three rectangular flumes and in two full size structures. Angular riprap with a median stone size ranging from 15 to 278 mm was examined on rock chutes with slopes ranging from 2 to 40%. The typical mode of channel failure is described. An empirical prediction equation is presented relating the highest stable discharge on a rock chute to the median stone size and the bed slope. A boundary roughness relationship is also presented that relates the Manning roughness coefficient to the median stone size and bed slope. These tests also suggest that the riprap size required for stability on the slope will remain stable in the outlet reach even with minimal tailwater. This article contains information needed to perform a rock chute design.*

Keywords. *Rock chutes, Riprap, Channel design, Hydraulics, Stability, Roughness, Grade control.*

Rock chutes or loose-riprap-lined channels are used to safely convey water to a lower elevation. These structures provide an alternative method of protecting the soil surface to maintain a stable slope and to dissipate a portion of the flow energy. Watershed management applications for this type of structure are numerous such as channel stabilization, grade control, and embankment overtopping. Depending on the availability and quality of accessible rock materials, rock chutes may offer economic advantages over more traditional structures. Flow cascading down a rock chute is visually pleasing, and these structures offer aesthetic advantages for sensitive locations. Construction of these chutes can be performed with unskilled labor and a comparatively small amount of equipment. A typical rock chute profile is shown in figure 1.

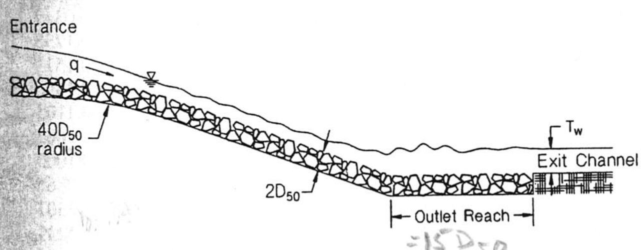

Figure 1–Typical rock chute profile.

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Rock chute structures have been the subject of several recent investigations. The objective of this article is to present pertinent information from several sources to provide the designer with a comprehensive design tool.

Related Work

Rock chutes in various forms have been used for many years. Isbash (1936) examined the ability of flowing water to move rocks. The shape of a rock fill cross-section was described while stone of a known size and weight was deposited in flowing water. Isbash developed a relationship describing the minimum velocity necessary to move stones of a known size and specific gravity. Anderson et al. (1970) developed a design procedure for riprap-lined drainage channels by testing rounded stone on relatively flat slopes. Uniformly sized riprap materials remained stable at higher flow rates than non-uniform materials. The non-uniform materials enhanced the protection of the filter material below the rock layer. Wittler and Abt (1990) found that the stone gradation has a significant influence on chute performance. The uniformly sized riprap withstood higher flow rates than non-uniform material of the same D_{50}. The uniform material did fail more suddenly than the non-uniform materials once the slope became unstable.

Abt et al. (1987) and Abt and Johnson (1991) tested both angular and rounded stone and found that the rounded stone failed at a unit discharge of approximately 40% less than angular shaped stones of the same median stone size. These researchers developed design criteria for median stone sizes between 25 and 152 mm on slopes ranging between 1 and 20%.

Maynord (1988) developed a riprap sizing method for stable open channel flows on slopes of 2% or less. This design method, based on the average local velocity and flow depth, used the D_{30} as the characteristic rock size. The effects of riprap gradation, thickness, and shape were also examined. Maynord (1992) extended this design method to slopes between 2 and 20% for nonimpinging flows. Frizell

for RX<6"

and Ruff (1995) examined riprap with a D_{50} of 380 mm on 2:1 slopes (horizontal:vertical). These researchers investigated riprap for embankment overtopping protection.

Mannings

Anderson et al. (1970) developed a relationship for the boundary roughness of rock-lined channels. The Manning roughness was described as a function of the stone size only. Abt et al. (1987) also developed a relationship that predicts the Manning roughness as a function of the bed slope and stone size.

Rock chutes testing performed at the USDA-ARS Hydraulic Engineering Unit is the primary source of information for this report. These tests focused on three specific areas: rock slope stability, roughness, and outlet stability. Robinson et al. (1995) reported an empirical rock slope stability relationship for rock sizes ranging from 15 to 145 mm on slopes of 10 to 40%. This stability relationship predicts rock size as a function of the discharge and channel slope. Robinson et al. (1997) revised this design relationship in an attempt to better represent the data base. Rock chutes were tested to failure in three different flumes as well as full-size prototype structures for slopes of 8 to 40% and median rock sizes up to 278 mm. Rice et al. (1996) examined six design procedures and compared their results for a range of discharges and bed slopes. Rice et al. (1998a) developed empirical relationships to predict the Manning roughness coefficient as a function of stone size and bed slope. These roughness relationships allow calculation of the flow depth in a rock chute. Rice et al. (1998b) conducted tests to examine the rock size necessary to maintain stability of the rock chute outlet.

Riprap Properties

Distribution

The rock chutes testing described in this article was performed using predominantly angular crushed limestone with a D_{50} of 15 to 278 mm. The rock layers in all tests were $2D_{50}$ thick. The D_{50} is the particle size for which 50% of the material sample is finer. The median stone diameter and the D_{50} are considered equal. Rock used in this study displayed a coefficient of uniformity ($C_u = D_{60}/D_{10}$) of 1.25 to 1.73. The specific gravity of the stones ranged from 2.54 to 2.82. The geometric standard deviation ($\sigma_g = D_{84.1}/D_{50} = D_{50}/D_{15.9}$) ranged from 1.15 to 1.47 with all but one rock sample ranging between 1.31 and 1.47. The length to width ratio (L/B) ranged from 1.98 to 2.36. The geometric stone properties were similar for all rock sizes, and the gradations exhibited by these materials were more uniform than well graded.

Sufficient quantities of each material were sampled to accurately represent each rock size. ASTM (1996) Standard D5519 suggests that a sample size should be large enough to ensure a representative gradation and to provide test results to the desired level of accuracy. The specimen size should be large enough that the addition or loss of the largest stone in the sample will not change the results by more than a specified amount. For this study the largest element in each test material represented 0.7% to 3.1% of the sample weight.

Results and Discussion

Rock Slope Stability

Rounded Low Slopes

Rock chute stability tests were performed in three separate flumes with widths of 0.76, 1.07, and 1.83 m (2.5, 3.5, and 6.0 ft). Two full size prototype structures were also constructed and tested to failure. These large-scale chutes were constructed with a 2.74-m (9-ft) bottom width and 2:1 side slopes. A total of 38 rock chute stability tests were performed on slopes ranging from 2 to 40% for median rock sizes of 15 to 278 mm. Rock chutes testing was initially limited to slopes between 10 and 40%. However, interest was expressed in slopes below 10%. Eleven tests were conducted on slopes ranging from 2 to 8%. Four of these tests were conducted with bed slopes ranging from 2 to 6% with 2:1 side slopes. Table 1 lists the test results for this study. The tests were performed by introducing a base flow in the rock chute, then increasing the flow incrementally. Orifice plates and air-water differential manometers were used to measure flow in the two smaller models, while Parshall flumes were used to measure flow in the larger models. Rock slope stability was observed at each flow rate, with particular attention directed to stone movement on the slope. The flow rate was increased until the rock chute was judged to be unstable.

A

Table 1. Test results $\frac{D_{60}}{D_{10}}$

Run No.	Flume Width (m)	D_{50} (mm)	Specific Gravity	Geometric Std. Dev.	Coef. of Uniformity	Slope (%)	Max. Stable q ($m^3/s/m$)
1	1.07	15	2.76	1.42	1.65	10	0.00578
2	1.07	15	2.76	1.42	1.65	12.5	0.00529
3	1.07	15	2.76	1.42	1.65	16.7	0.00378
4	1.07	15	2.76	1.42	1.65	22.2	0.00314
5	1.07	33	2.70	1.42	1.65	10	0.0248
6	1.07	33	2.70	1.42	1.65	12.5	0.0235
7	1.07	33	2.70	1.42	1.65	16.7	0.0186
8	1.07	33	2.70	1.42	1.65	22.2	0.0147
9	0.76	46	---	1.15	1.25	40	0.0381
10	1.07	52	2.82	1.46	1.72	10	0.0762
11	1.07	52	2.82	1.46	1.72	12.5	0.0624
12	1.07	52	2.82	1.46	1.72	16.7	0.0578
13	1.07	52	2.82	1.46	1.72	22.2	0.0483
14	0.76	52	2.82	1.46	1.72	40	0.0349
15	1.07	89	2.54	1.41	1.58	10	0.1738
16	1.07	89	2.54	1.41	1.58	12.5	0.1514
17	1.07	89	2.54	1.41	1.58	16.7	0.1596
18	1.07	89	2.54	1.41	1.58	22.2	0.1105
19	1.83	89	2.54	1.41	1.58	12.5	0.1663
20	1.83	89	2.54	1.41	1.58	22.2	0.1003
21	1.83	89	2.54	1.41	1.58	40	0.0865
22	1.83	145	2.55	1.35	1.54	12.5	0.3307
23	1.83	145	2.55	1.35	1.54	22.2	0.2239
24	1.83	145	2.55	1.35	1.54	40	0.1951
25*	2.74	188	2.58	1.47	1.73	16.7	0.4385
26*	2.74	278	2.59	1.31	1.47	33.3	0.6726
27	1.83	188	2.58	1.47	1.73	8	0.7525
28	1.83	188	2.58	1.47	1.73	22.2	0.5416
29	1.83	188	2.58	1.47	1.73	40	0.3279
30	1.07	52	2.82	1.46	1.72	6	0.1858
31	1.07	33	2.70	1.42	1.65	6	0.0892
32	1.07	33	2.70	1.42	1.65	4	0.1830
33	1.07	15	2.76	1.42	1.65	2	0.0427
34	1.83	192	2.61	1.35	1.58	6	1.5258
35*	1.07	52	2.82	1.46	1.72	6	0.2025
36*	1.07	52	2.82	1.46	1.72	4	0.2546
37*	1.07	33	2.70	1.42	1.65	4	0.1096
38*	1.07	33	2.70	1.42	1.65	2	0.2518

* Tested with 2:1 side slopes.

Failure was defined as the flow condition that exposed the underlying geofabric or bedding material. As the slope decreases, however, the chute surface can become quite ragged without exposing the geofabric. Therefore, some subjectivity was involved in the determination of a highest stable discharge. The same procedures were followed in each test to minimize this subjectivity. The variability associated with the highest stable discharge determination is expected to increase as the chute slope decreases. The rock chute surface typically experienced the greatest damage just downstream of the crest on the sloping section. Test configurations used a $40D_{50}$ radius to improve the flow transition between the horizontal approach section and the sloping chute (see fig. 1). While this radius provides improved flow conditions for the larger slopes, the influence of this radius diminishes as the slope decreases. While flow in these chutes tends to transition to normal depth relatively rapidly, the area most subject to failure is the upper reach of the chute just below the crest.

Slope Transition

The rock chute stability tests failed in a relatively consistent manner. Typically as the flow rate was increased, smaller stones were repositioned or removed from the slope. This initial stone movement was generally observed at flow rates well below the design discharge. As the flow rate increased, additional stone movement occurred. Even though a small amount of material was repositioned and/or removed, the entire chute remained stable. As the flow rate reached the highest stable discharge, larger stones were observed to vibrate, move on the slope, and/or tilt up into the flow. At higher discharges numerous larger stones would tilt into the flow and be transported downslope. These stones often caused a chain reaction by dislodging additional material. Channelization and/or scour holes were then observed in the rock layer, and the chute was considered to have failed.

Rock chutes become more stable as the stone size increases and/or the slope decreases. A plot of the highest stable unit discharge (q) in $m^3/s/m$ versus the product of the median stone size (D_{50}) and the bed slope (S_o) in decimal form provides a convenient means of data separation (fig. 2). A two-stage prediction equation was developed from the stability tests as follows:

$\frac{1}{1.89} = 0.529$

$$q = 9.76E - 7\ D_{50}^{1.89}\ S_o^{-1.50} \qquad S_o < 0.10 \qquad (1)$$

S_o

Highest Stable Discharge?

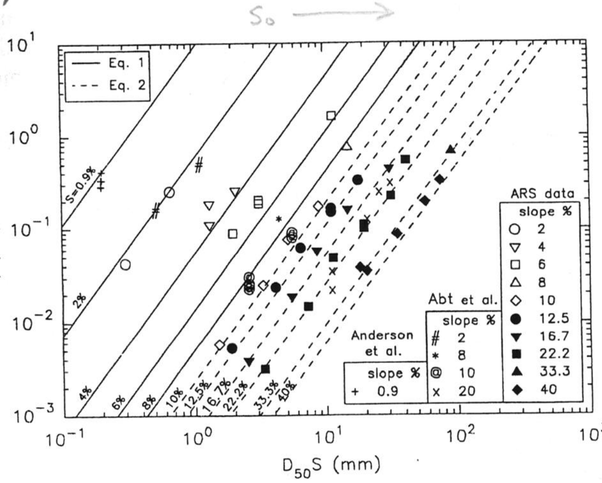

Figure 2–Rock chute stability data.

$$q = 8.07E - 6\ D_{50}^{1.89}\ S_o^{-0.58} \qquad 0.10 \le S_o \le 0.40 \qquad (2)$$

where

q = highest stable unit discharge ($m^3/s/m$)

D_{50} = particle size for which 50% of the sample is finer (mm)

S_o = decimal slope (dimensionless)

Equations 1 and 2 apply only to rock chutes constructed with angular riprap with a rock layer thickness of $2D_{50}$. These equations have not been verified for slopes less than 2% or greater than 40%. These equations were developed for a rock specific gravity ranging between 2.54 and 2.82, and a geometric standard deviation ranging from 1.15 to 1.47.

Lim Hutins

These empirical functions, shown graphically in figure 2, envelope all of the ARS test data above a slope of 10% and most of the ARS data below 10%. Both equations produce the same results with minor roundoff error at a slope of 10%. Fit constants for these equations were determined graphically while maintaining the same slope in log-log space. The highest stable discharge determination was more difficult as the rock chute slope decreased; therefore, the variability associated with the lower slope data is expected to increase. The increased difficulty in determining the highest stable discharge for slopes less than 10% suggested that an enveloping relationship for these data would be overly conservative.

Data taken from Abt and Johnson (1991) are also plotted on figure 2 after converting their failure discharges to a highest stable discharge. This data agrees very well with the ARS data. Data from Anderson et al. (1970) for a slope of just under 1% is also plotted to show how well this relationship matches previous work at very low slopes. It should be noted that the tests of Anderson et al. (1970) were performed with rounded stone, so failure at a lower discharge would be expected. The data of Anderson et al. (1970) were converted to angular riprap values assuming that the rounded stone fails at a unit discharge of 40% less than the angular stone as suggested by Abt and Johnson (1991). With this conversion the data of Anderson et al. (1970) are reasonably predicted by equation 1.

Equation 1 and 2 are simple and easy to apply. Appropriate engineering judgment and an appropriate safety factor should be applied when using these equations. Caution should be exercised if equation 1 or 2 are applied outside the data base from which they were developed. Equation 2 should not be used for slopes greater than 40%.

Boundary Roughness

An estimate of the boundary roughness is necessary to effectively design a rock chute. The Manning equation is the most commonly used equation for expressing flow resistance in open channels.

$$n = \frac{R^{2/3}\ S^{1/2}}{V} \qquad (3)$$

where

n = Manning roughness coefficient

R = hydraulic radius (m)

$$D_{50} = \left(\frac{q\ S^{1.5}}{9.76e^{-7}}\right)^{1/1.89}$$

V = average flow velocity (m/s)
S = energy gradient

Rice et al. (1998a) developed an empirical relationship to predict the Manning roughness coefficient as a function of the median stone size (D_{50}) and the bed slope (S_o). The Darcy-Weisbach friction factor was also predicted as a function of the relative submergence (d/D_{84}) where d represents flow depth and D_{84} is riprap size for which 84% of the material is finer. Tests were conducted in a 1.07-m wide flume and two 2.74-m wide field-scale structures using angular riprap with median diameters ranging from 52 to 278 mm. The bed slopes examined ranged from 2.5 to 33.3%.

Rice
mean

Bed elevations were obtained along the channel centerline for each test condition. Discharge and flow depths were measured at each incremental test flow. Due to the extreme turbulence and air entrainment at the flow surface, the water surface elevations could not be accurately measured. The depth of flow was measured with piezometers placed in the bedding material.

Flow resistance is a function of the flow depth above the effective top-of-riprap elevation. While there is no recommended procedure for determining the effective top-of-riprap elevation, an accurate value is necessary to determine the Manning roughness coefficient. An error in the flow depth translates into a much larger error in the Manning coefficient. For example, a 10% error in the flow depth translates into a 17% error in the n value. The effective top-of-riprap elevation was determined using the measured unit discharge through the riprap, measured flow depths, and the Stephenson (1979) empirical equation for velocity through rock material:

$$V_m = n_p \left(\frac{S_o g D}{K'}\right)^{1/2} \tag{4}$$

where
V_m = velocity through rock (m/s)
n_p = porosity
g = gravitational acceleration (9.81 m/s^2)
K′ = a dimensionless friction factor
D = representative rock diameter in m (use D_{50} in m)

Abt et al. (1987) presented values for n_p of 0.44 to 0.46 for angular riprap. The factor K′ is defined by Stephenson (1979) as:

$$K' = K + \frac{800}{R_e} \tag{5}$$

where
K = 4 for crushed rock
R_e = Reynolds number ($dV/n_p\nu$)
ν = kinematic viscosity

The values of $800/R_e$ were small (< 0.01); therefore, it was assumed that K′ = K = 4 . Using the measured flow depths at different percentage water coverage of the riprap, equation 4 was used to calculate the velocity through the rock materials. The calculated unit discharge through the riprap or mantle flow (q_m) was compared with the measured discharge. The maximum flow depth with good agreement between calculated q_m and measured q_m

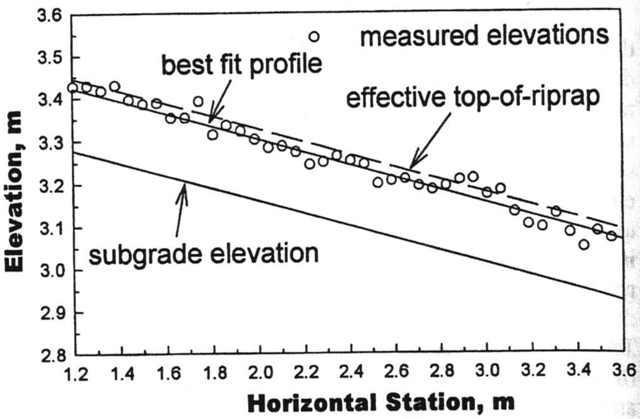

Figure 3–Top-of-riprap elevation.

occurred at about 95% coverage of the riprap. The effective top-of-riprap elevation was selected as the flow depth for which 95% of the riprap was covered. A plot of the bed surface elevation versus the horizontal station (fig. 3) illustrates that the effective top-of-riprap falls between the maximum top-of-riprap elevation and the least squares fit of the measured elevation. For practical design purposes, the effective top-of-riprap elevation is considered to be at the top of the $2D_{50}$ thick layer.

The Manning n was calculated using the surface discharge and average depths measured in the middle third of the slope length. The stable discharges near failure of the riprap were used in the analysis, since these discharges should result in the highest flow resistance. Using the wide channel assumption where the hydraulic radius R = d and with $V = q_s/d$, and $S = S_o$ equation 3 can be used to calculate n. With these substitutions equation 3 becomes:

$$n = \frac{d^{5/3}\, S_o^{1/2}}{q_s} \tag{6}$$

where
d = flow depth above the effective top-of-riprap
q_s = surface unit discharge ($q_t - q_m$)
q_t = total unit discharge
q_m = unit discharge through the riprap

The data of Rice et al. (1998a) and Abt et al. (1987) both show a strong tendency for n to increase as the channel slope increases. Rice et al. (1998a) combined the two data bases and developed the following roughness relationship:

$$n = 0.0292\,(D_{50}\; S_o)^{0.147} \tag{7}$$

Rice

This relationship was developed for angular riprap on slopes between 2.8 and 33.3%. Rice et al. (1998a) also expressed the combined data bases in terms of relative roughness $(8/f)^{1/2}$ and relative submergence (d/D_{84}):

Rice

$$\left(\frac{8}{f}\right)^{1/2} = 5.1 \log\left(\frac{d}{D_{84}}\right) + 6 \tag{8}$$

Solve for f

from Rice et al 1998

Equation 8 should provide reasonable estimates of the Darcy-Weisbach friction coefficient (f) for loose, angular riprap.

Outlet Stability

The riprap size required for outlet stability was also examined in two separate flumes and two field-scale structures (Rice et al., 1998b). Angular riprap with a D_{50} ranging from 52 to 278 mm was tested at slopes ranging from 8 to 40%. For a specific discharge, rock size, and slope, the movement of riprap in the outlet section was observed for a range of tailwaters. An overflow tailgate was used to adjust the tailwater elevation in the 1.83- and 1.07-m wide flumes. It was assumed that the worst case condition for outlet stability would occur at the maximum stable unit discharge predicted for a given riprap size and bed slope. The tailwater elevation could be controlled with the flume tests but not with the field-scale structures. The field-scale structures were evaluated at the stable discharge and at two lesser discharges. The flume tests were performed at tailwater (T_w) to median stone size (D_{50}) ratios of 3.0, 2.0, and the minimum resulting from the horizontal riprap section and downstream channel resistance.

The centerline bed surface profiles were measured before and after each test flow. The water surface profiles were measured on the chute and the outlet section. Air entrainment and turbulence made these measurements difficult at times. Typical water surface profiles in the outlet reach (fig. 4) show that without a forced tailwater, the water surface stabilizes at a tailwater elevation slightly less than $2D_{50}$ due to the outlet reach and downstream channel resistance. While some minor shifting of the riprap along the slope was noted, no movement of the riprap was observed in the outlet reach. Notable movement of riprap in the outlet reach of the chute was not observed for any test. These tests provide evidence that the riprap size required for stability along the bed slope will be stable for the outlet reach. Also, the results show that the minimum tailwater that occurs as a result of the outlet reach and downstream channel resistance is sufficient to ensure stability of the riprap in the outlet reach.

Observations were made during each test to establish the required length of horizontal riprap downstream of the sloping section. For most tests, the primary attack on the riprap in the outlet reach extended to $12D_{50}$ downstream of the sloping section. In a limited number of tests, this attack continued to approximately $14D_{50}$ downstream. Therefore, a horizontal reach length of $15D_{50}$ or more is recommended downstream of the sloping chute (Rice et al., 1997b). The elevation of the top of riprap at the exit of the outlet reach should be at or below the downstream channel bed elevation to prevent unraveling or sloughing of the riprap. Unraveling of the riprap in the outlet reach could result in failure of the rock chute. The potential for bed degradation downstream of a chute should be considered when establishing the riprap elevation.

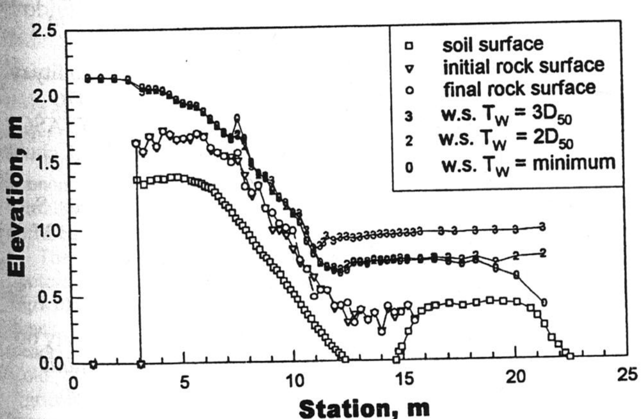

Figure 4–Bed and water surface profiles, 22.2% slope, D_{50} = 188 mm, and q = 0.351 $m^3/s/m$.

Related Design Topics

Numerous design considerations other than rock slope stability, roughness, and outlet stability can have a major influence on rock chute performance. The following topics are listed to identify a few of those potential problem areas. These related topics were not the primary focus of this study, and traditional design techniques should be fully exploited to address these issues.

- Provide seepage collection and relief
- Use appropriate filters and cutoffs
- Sample riprap to determine a characteristic size and gradation
- Be aware of rock quality and durability problems
- Rounded rock fails more quickly than angular rock
- Channel side slopes must also remain stable
- Prevent rock size classification during handling and placement
- Avoid flow concentrations
- Provide adequate freeboard
- Use an appropriate safety factor
- Provide for routine inspection and maintenance

Example Design

To reinforce the application of this design information, an example design is presented. In most cases the design discharge is known, and the bed width is varied to accept this flow. The bed slope can also be adjusted to obtain a desired stone size.

Given:

Energy slope (S) = Bed slope (S_o) = 0.20
Channel bottom width (B) = 5 m
Channel side slopes (Z) = 2:1
Total discharge (Q) = 3.0 m^3/s

Find:

Required median stone size (D_{50})
Mannings roughness coefficient (n)
Unit discharge through the rock mantle (q_m) and surface unit discharge (q_s)
Flow depth (d)

The design is applicable for angular crushed limestone placed in a $2D_{50}$ thick layer. The effective top-of-riprap is assumed to be $2D_{50}$ above the subgrade. Equation 2 is used to determine the stone size required for rock slope stability.

The unit discharge (q) is 0.6 $m^3/s/m$. Since the channel is trapezoidal, the unit discharge will actually be slightly less. Rearranging equation 2 to solve for D_{50} yields the following expression:

$$D_{50} = \left[\frac{\left(qS^{0.58}\right)}{8.07E-6} \right]^{1/1.89} \tag{9}$$

11.75'

If $q = 0.60\ m^3/s/m$ and $S = 0.20$, then $D_{50} = 231$ mm. Substituting $D_{50} = 231$ mm and $S_o = 0.20$ into equation 7 yields a Manning roughness coefficient of $n = 0.051$. The surface flow unit discharge $q_s = (q_t - q_m)$. The total unit discharge (q_t) is 0.60 $m^3/s/m$, and the unit discharge through the mantle $(q_m) = V_m\ (2D_{50})$. The velocity through the rock mantle (V_m) is determined from equation 4. With $n_p = 0.45$, $S_o = 0.20$, $g = 9.81\ m/s^2$, $D = 0.231$ m, and $K' = 4$, V_m is calculated to be 0.151 m/s. Therefore, q_m = (0.151 m/s) (2) (0.231 m) = 0.070 $m^3/s/m$. Therefore, q_s = 0.60 $m^3/s/m$ - 0.070 $m^3/s/m$ = 0.53 $m^3/s/m$. Rearranging equation 6 to calculate the flow depth above the effective top-of-riprap (d) yields:

$$d = \left(\frac{n\ q_s}{S_o^{0.5}} \right)^{3/5} \tag{10}$$

Using equation 10 the flow depth (d) = 0.186 m.

Summary and Conclusions

Rock chutes were examined using three flumes and two field-scale structures. Angular limestone was tested in sizes ranging from 15 to 278 mm on slopes ranging from 2.0 to 40%. All tests were conducted using a horizontal approach, a sloping chute, and a horizontal escape reach. The rock layer was $2D_{50}$ thick for all tests. Tests were performed to improve prediction of rock slope stability, boundary roughness, and outlet stability of rock chutes. This article presents pertinent information from several sources to provide a comprehensive design tool.

Empirical relationships are presented that describe the highest stable discharge as a function of the median stone size and bed slope. The stability relationship was developed by determining a highest stable discharge for 38 combinations of stone size and bed slope. The chutes typically failed just downstream of the horizontal crest on the sloping section by removing sufficient stone to expose the geofabric and/or filter material. The stability increased as the stone size increased and/or the slope decreased.

An empirical relationship is presented to predict the Manning roughness coefficient as a function of the median stone size and the bed slope. The Darcy-Weisbach friction factor was also predicted as a function of relative submergence. Once the roughness is determined, the flow depth in a rock chute can be calculated. A procedure was developed to determine the effective top-of-riprap elevation, thereby determining the portion of the flow volume that is contained in the rock mantle.

The stability of rock chute outlets was examined in two separate flumes and two field-scale structures. Tailwater to median stone size ratios were examined at values of 3.0, 2.0, and the minimum resulting from the horizontal riprap section and downstream channel resistance. These tests suggest that the riprap size required for stability on the slope will also be stable in the outlet reach. A horizontal outlet reach length of $15D_{50}$ is recommended downstream of the sloping chute. The elevation of the top of riprap at the exit of the outlet reach should be at or below the downstream channel bed elevation. The potential for bed degradation downstream of a chute should be considered when establishing the riprap elevation.

These design relationships apply to angular riprap on slopes between 2 and 40% with a rock mantle thickness of $2D_{50}$. Appropriate engineering judgment. should be applied when extending this design information beyond the data base from which it was developed.

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