Rock Chute Outlet Stability

C. E. Rice, K. C. Kadavy, K. M. Robinson, K. R. Cook

Abstract. *Rock chutes, rock riprap on steep slopes, are used as grade control structures to safely conduct a water flow to a lower elevation. Previous studies have reported relationships to predict the highest stable unit discharge on the sloping face as a function of the material D_{50} and the bed slope. However, the studies do not report the riprap size required for stability at the toe of the chute. The riprap size required for outlet stability was examined in two separate flumes and two field-scale structures. For all tests, the D_{50} size predicted for stability on the sloping bed was also stable at the toe of the chute. The tailwater elevation resulting from the outlet reach and downstream channel resistance was sufficient to prevent movement of the riprap in the outlet reach.* **Keywords.** *Riprap, Rock chute, Grade control, Hydraulic structures.*

Gradient control structures are used to locally drop the channel bed level and decrease the channel grade to a stable gradient between structures for man-made or naturally occurring channels. One type of grade control structure is a rock chute. Rock chutes can be used in many situations to stabilize steep reaches of the channel. Depending on site conditions and stone availability, rock chutes may offer economic advantages over the more traditional grade control structures.

The rock chute is formed by lining the channel with a geotextile and riprap. The riprap serves to stabilize the chute and dissipate a portion of the flow energy. In order to function properly, the chute must have a stable outlet. For ease of construction, it is desirable to use the same size of rock and diameter distribution for the outlet as is used on the chute slope.

Background

Procedures for sizing riprap for overtopping flows and embankment slopes have been presented by Isbash (1936), Abt and Johnson (1991), Stephenson (1979), and Robinson et al. (1997). These procedures may not be applicable for riprap placed at the toe of rock chutes to ensure stability as the flow transitions from the embankment to the toe and the downstream channel.

The U.S. Bureau of Reclamation presented a procedure for sizing riprap at the exit of stilling basins (Peterka, 1964). A curve (Figure 165, Peterka, 1964) gives the individual minimum stone size (diameter and weight of spherical specimen) for a range of bottom velocities up to 17 ft/s (presented in English units). If the bottom velocity cannot be determined, the local velocity may be substituted. This procedure for sizing riprap has been presumed to be conservative.

Robinson et al. (1997) presented the following equation to relate the maximum recommended unit discharge, stone size, and bed slope (NOTE: The second equation is in English unit):

$$q = \left(D_{50}S\right)^{\left(1.40+0.213/\sqrt{S}\right)} \exp\left(-11.2 + 1.46/\sqrt{S}\right) \quad (1a)$$

$$q = \left[10.76\left(305D_{50}S\right)^{\left(1.40+0.213/\sqrt{S}\right)} \exp\left(-11.2 + 1.46/\sqrt{S}\right)\right] \quad (1b)$$

where q is the unit discharge, $m^3/s/m$ ($ft^3/s/ft$); D_{50} is rock size for which 50% of the sample is finer by weight, mm (ft); S represents slope, m/m (ft/ft), dimensionless; and exp is the exponential. Equation 1 is not a curve fit to the data, but a curve enveloping the data. Thus, the predicted values should be somewhat conservative.

Previous studies do not address the stability of riprap at the toe of the chute (chute outlet). This article extends the research by Robinson et al. (1997) by examining the stability of riprap at the chute outlet.

Experiments

A schematic drawing describing the test variables is presented in figure 1. Table 1 presents the range of flume/chute dimensions used in the study. Two three-dimensional field-scale chutes, with 2.74 m (9.00 ft) wide bottoms and 2:1 side slopes were tested. Figures 2, 3, and 4, respectively, present the 1.07 m (3.51 ft) wide flume, the 1.83 m (6.00 ft) wide flume, and the 16.7% slope field structure prior to testing (The flume slopes are variable). The properties of the riprap used in the tests are presented

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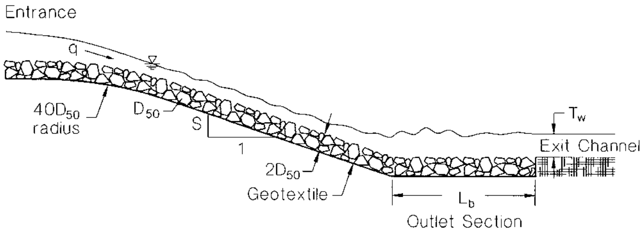

Figure 1–Definition sketch of the study rock chute.

Table 1. Range of flume and chute dimensions used in the study

Facility	Slope %	q $m^3/s/m$ ($ft^3/s/ft$)	D_{50} mm (ft)	L_b/D_{50}	T_w/D_{50}
1.07-m flume (3.51-ft)	10-22.2	0.030-0.11 (0.323-1.18)	52-89 (0.171-0.292)	17-24	0.54-3.0
1.83-m flume (6.00-ft)	8-40	0.27-0.75 (2.91-8.09)	188 (0.617)	15	1.75-3.0
Field chute	17-33	0.38-0.71 (4.09-7.64)	188-278 (0.617-0.912)	16-24	1.35-2.3

Figure 2–The 1.07 m (3.51 ft) wide flume with D_{50} = 89 mm (0.292 ft) and S = 22.2%.

Figure 3–The 1.83 m (6.00 ft) wide flume with D_{50} = 188 mm (0.617 ft) and S = 8%.

in table 2. To provide a reasonable contact between the riprap and the channel bed, each flume and field chute had

Figure 4–The field chute with D_{50} = 188 mm (0.617 ft) and S = 16.7%.

Table 2. Riprap properties used in the study

D_{50} mm (ft)	C_u	G_s	σ_g	L/W
52 (0.171)	1.72	2.82	1.46	2.10
89 (0.292)	1.58	2.54	1.41	2.04
188 (0.617)	1.73	2.58	1.47	2.20
278 (0.912)	1.47	2.59	1.31	1.98

C_u = coefficient of uniformity, D_{60}/D_{10}.
G_s = specific gravity.
σ_g = geometric standard deviation, $D_{84.1}/D_{50}$.
L/W = length to width ratio.

a subgrade treatment. The solid floor of the 1.07-m (3.51 ft) wide flume was covered with a carpet pad and a nonwoven geofabric. The carpet pad provided a base similar to that of a concrete sand layer. The compacted cohesive soil subgrade for the 1.83-m (6.00 ft) flume and the field chutes was covered with a 50-mm (0.164 ft) thick layer of concrete sand and a nonwoven geofabric. All tests were conducted with a riprap layer thickness of two D_{50} measured normal to the bed slope. The riprap materials used in each test were predominantly angular, crushed limestone. All tests were conducted using clear water.

At the exit of the sloping bed, a horizontal riprap section two D_{50} thick and 15 to 24 D_{50} long was constructed (L_b in fig. 1). An end sill with height equal to the thickness of the riprap layer was placed at the downstream end of the horizontal riprap section for the 1.07-m (3.51 ft) wide flume and the field-scale chutes. For the 1.83-m (6.00 ft) wide flume, a 4.57 to 6.10 m (15 to 20 ft) length of compacted cohesive soil layer was placed downstream of the horizontal riprap section to restrain the riprap.

Orifice plate flow meters were used to measure discharge in the 1.07-m (3.51 ft) wide flume and Parshall flumes measured the flow in the 1.83-m (6.00 ft) flume and the field-scale structures.

The worst case condition for stability was assumed to occur at the toe of the chute at the maximum allowable unit discharge predicted by equation 1 for a specified riprap size and bed slope. The tests were performed by introducing a base flow into the flume or chute and incrementally increasing the flow slowly to the maximum discharge. After the maximum flow was continued for approximately 30 min, the flow was shut off, the water drained off, and the outlet section inspected. Our experience with previous riprap studies at stilling basin exits has shown that riprap, if not stable, will move within 5 to 10 min after introduction of flow through the structure.

The riprap stability after each test was evaluated by observing riprap movement on the outlet section and comparing the *before* and *after* measured centerline elevations of the outlet reach riprap. Centerline elevations of the riprap were taken before and after each test sequence. Centerline elevations of the water surface were taken during each test.

The tailwater elevation, T_w, could be controlled with the flume tests but not with the field-scale structures. For the flume tests, T_w/D_{50} was equal to 3.0, 2.0, 1.0, and the minimum tailwater caused by the toe riprap resistance. The tailwater for the field-scale structures was the minimum resulting from the resistance of the horizontal riprap section.

RESULTS

Figures 5 and 6, respectively, present typical flow conditions for the 1.83-m (6.00 ft) wide flume and the 16.7% slope field chute. The tailwater for each is a minimum. The water surface is very rough for both flows down the slope and in the outlet section. Waves and significant turbulent activity were observed in the outlet section but no movement of the riprap occurred.

Figures 7 and 8, respectively, present typical centerline bed, riprap, and water surface profiles, before and after a test flow, for the 1.83-m (6.00 ft) wide flume at slopes of 8 and 22.2%. The water surface profiles in the outlet reach for both slopes show that without a forced tailwater elevation, the water surface for both chutes stabilizes at a tailwater elevation of approximately $2(D_{50})$ due to the outlet section resistance. For the 8% slope, there is no observed difference in the riprap placement on either the bed slope or the outlet reach after the test flow. For the 22.2% slope, there was minor shifting of the riprap along the bed slope, but no movement of the riprap in the outlet reach.

The results observed in figures 7 and 8 are typical of every test conducted. There was minor shifting of the riprap during some tests but no transport of riprap from the outlet section during any test. These results provide evidence that the riprap size required for stability along the

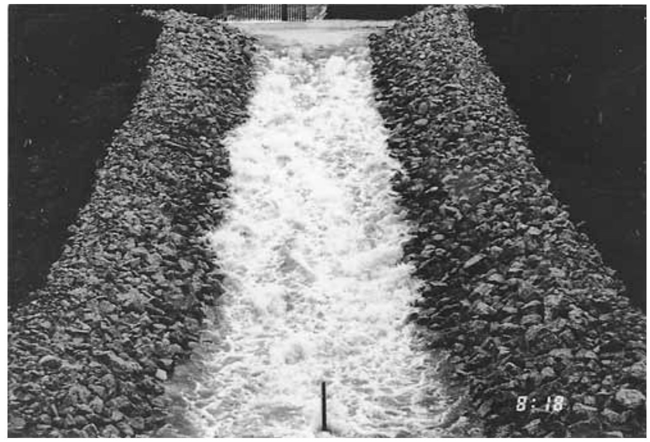

Figure 6–Flow in the field flume: q = 0.44 m³/s/m (4.74 ft³/s/ft); D_{50} = 188 mm (0.617 ft); S = 16.7%.

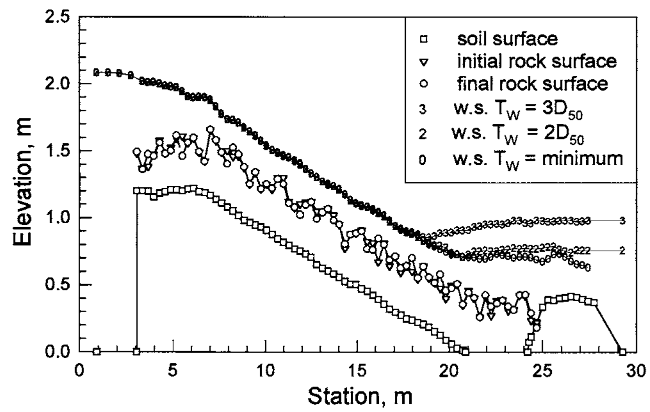

Figure 7–Bed and water surface profiles: 1.83 m (6.00 ft) wide flume; q = 0.752 m³/s/m (8.09 ft³/s/ft); D_{50} = 188 mm (0.617 ft); S = 8%. (water surface at the tailwater).

Figure 5–Flow in the 1.83 m (6.00 ft) wide flume: q = 0.69 m³/s/m (7.43 ft³/s/ft); D_{50} = 188 mm (0.617 ft); S = 8.0%.

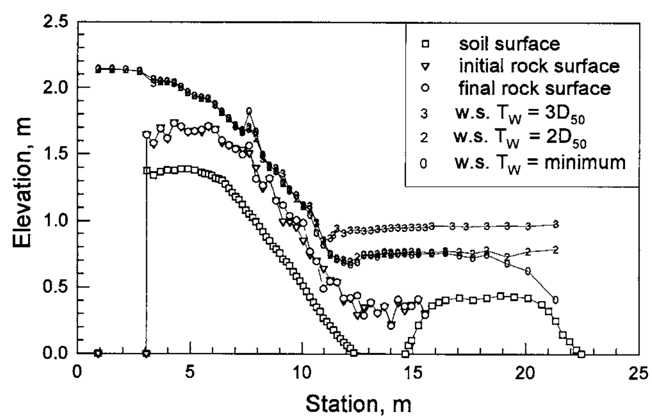

Figure 8–Bed and water surface profiles: 1.83 m (6.00 ft) wide flume; q = 0.35 m³/s/m (3.77 ft³/s/ft); D_{50} = 188 mm (0.617 ft); S = 22.2%. (water surface at the tailwater).

bed slope predicted by equation 1 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.

Observations were made during each test to establish the required length, L_b, of the horizontal riprap at the toe of the chute. For all tests, the waves and significant turbulent activity in the outlet reach did not continue beyond 14 D_{50} downstream of the sloping bed. It is recommended that $L_b/D_{50} \geq 15$ for the outlet section downstream of the toe. 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 or sloughing of the riprap in the outlet reach could result in failure of the chute structure.

Summary and Conclusions

Studies reported in the literature relative to rock chutes predict conservative riprap size required for stability on the sloping bed of the chute but do not address the stability of riprap at the toe of the chute. This article extends the research studies on rock chutes reported in the literature by examining the stability of riprap at the chute outlet.

Tests were conducted in two flumes and two field-scale structures at slopes ranging from 8 to 40%, riprap ranging from 52 to 278 mm (0.171 to 0.912 ft), and discharges ≤ 0.752 $m^3/s/m$ (8.09 $ft^3/s/ft$) to develop criteria for the size of riprap required for stability at the toe of the chute. Results of the study show that the riprap size required for stability on the sloping bed of the chute using equation 1 will be stable for the outlet reach. Movement of the riprap in the outlet reach was not observed in any of the tests even with the worst case conditions.

The length L_b of the outlet section downstream of the toe of the chute should be ≥ 15 D_{50}. The elevation of top of riprap at the exit of the outlet reach should be at or slightly below the downstream channel bed elevation to prevent unraveling or sloughing of the riprap in the outlet reach which could result in failure of the chute structure.

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Notation

The following symbols are used in this article:

- C_u = coefficient of uniformity, D_{60}/D_{10}
- D_{10} = riprap size for which 10% is finer by weight, mm (ft)
- D_{50} = riprap size for which 50% is finer by weight, mm (ft)
- D_{60} = riprap size for which 60% is finer by weight, mm (ft)
- $D_{84.1}$ = riprap size for which 84.1% is finer by weight, mm (ft)
- G_s = specific gravity
- L = length of stone, m (ft)
- L_b = length of outlet riprap section, m (ft)
- q = unit discharge, $m^3/s/m$ ($ft^3/s/ft$)
- S = bed slope, expressed as a decimal
- T_w = tailwater depth, relative to top of riprap, m (ft)
- W = width of stone, m (ft)
- σ_g = geometric standard deviation, $D_{84.1}/D_{50}$