Livebed Scour at Bendway Weirs and Rock Vanes Formed of Loose Rock

Robert Ettema, Prof., Colorado State University, Ft. Collins, CO, Robert.Ettema@colostate.edu
Alex Wittmershaus, Engineer, Northwest Hydraulic Consultants, Bellingham, WA, AWittmershaus@nhcweb.com
Parker Maddocks, Engineer, Halff Associates Inc., Bentonville, AR, pMaddocks@halff.com
Christopher I. Thornton, Assoc. Prof., Colorado State University, Ft. Collins, CO, Christopher.Thornton@colostate.edu
Nathan Holste, Hydraulic Engineer, Bureau of Reclamation, Tech. Service Center, Denver, CO, nholste@usbr.gov
Drew Baird, Hydraulic Engineer, Bureau of Reclamation, Tech. Service Center, Denver, CO, dbaird@usbr.gov
David R. Varyu, Hydraulic Engineer, Bureau of Reclamation, Tech. Service Center, Denver, CO, DVaryu@usbr.gov
Ari J. Posner, Physical Scientist, Bureau of Reclamation, Area Office, Albuquerque, NM, aposner@usbr.gov
Robert S. Padilla, Hydraulic Engineer, Bureau of Reclamation, Area Office, Albuquerque, NM, RPadilla@usbr.gov

Abstract

Presented here are findings from curved-flume experiments to investigate how livebed scour at bendway weirs and rock vanes may destabilize these loose-rock structures. In accordance with this aim, experiments sought to develop and confirm design dimensions enabling bendway weirs and rock vanes to perform as required when subject to livebed scour. It was found necessary to use a *Hydrograph Procedure* to simulate discharge increases associated with the rising limb of a hydrograph of flow to avoid the false influence that dunes may exert on the performance of bendway weirs and rock vanes. Findings from the flume showed that bendway weirs and rock vanes experienced rock dislodgement primarily via contraction scour, which undermined the toe of the tip of these instream structures. Relatively modest scour caused the rock to destabilize and dislodge from the tip slope into the scour region along the channel's establishing thalweg. Rock partially armored the zone of contraction scour (then along the re-establishing thalweg). As flow depth increased above the mean elevation of the bendway weirs or rock vanes, the flow field at each bendway weir or rock vane changed and velocity across the tip slope increased. These changes caused contraction scour to reduce as flow depth exceeded tip elevations, but to extend further along the curved channel. Additionally, scour and tip-slope reduction shortened the crest of bendway weirs and rock vanes. Recommended design dimensions, given here, accommodate crest shortening but ensure that bendway weirs and rock vanes perform as required.

Introduction

Bendway weirs and rock vanes are transverse (across channel), instream structures primarily used to establish the thalweg alignment of flow and bed-sediment movement along the outer bank of a curved, alluvial channel. In doing so, these structures are considered to serve an outerbank-protection role. Typically built from loose quarry rock, bendway weirs and rock vanes seek to direct flow away from a channel's outer bank by scouring the channel's alluvial bed so that the thalweg moves and establishes itself in a path along the ends (tips) of these instream structures.

This study involved series of experiments to investigate how bendway weirs and rock vanes perform subject to livebed-scour (active bed-sediment transport). Ironically, bendway weirs and rock vanes may fail owing to scour. The study sought to recommend and confirm design dimensions of individual bendway weirs and rock vanes so that these instream structures could accommodate some structural failure (and concomitant loss of rock) owing to livebed scour yet continue performing as required. Wittmershaus (2022), Maddocks (2022) and Ettema et al. (2022) document the experiments discussed here. The last two references also describe preliminary experiments conducted with two straight flumes that led to preliminary designs for individual bendway weirs and rock vanes.

The Bureau of Reclamation's (BOR's) Albuquerque Office (AO-BOR) and BOR's Denver-based Technical Service Center (TSC-BOR) funded and guided this study. Accordingly, the study's focus was on the Middle Rio Grande and curved channels approximately comparable in size and bed-sediment composition to those forming the Middle Rio Grande. Bendway weirs were considered because their level crest is considered attractive by AO-BOR, as this feature makes the bendway weir less visually intrusive in a natural channel. In comparison, a rock vane has a sloped crest, with the top of the slope being essentially at a level taken as the top of the channel's outer bank. Figure 1 illustrates bendway weirs in the Middle Rio Grande near Bernalillo, NM, and Figure 2 shows transverse profiles indicating the difference between bendway weirs and rock vanes. A useful review regarding the use of transverse, rock structures is given by Baird et al. (2015). The literature on scour or flow fields at bendway weirs and rock vanes otherwise is not elaborated here, due to space limitation and because the literature largely contains findings from studies that treat rock structures as being of fixed form, not as assemblages of loose rock.

Figure 1. A series of bendway weirs in the Middle Rio Grande, Bernalillo, NM (Source AO-BOR)

Other names and variations in form exist for rock structures used as transverse, instream rock structures. The barb form, for example, typically has a crest with two slopes: the crest slope of a bendway weir for the portion protruding into the channel (flat crest slope); and a somewhat steeper crest slope than a rock vane (crest slope nearest the bank being commensurate with the slope of the riprap cover used to protect the stream bank). Also, to be mentioned are spur dikes, guide bunds, and bridge abutments are transverse instream structures, but they differ in several ways from bendway weirs and rock vanes insofar that they extend to (and possibly above) the top of bank, and therefore, generate slightly different flow fields than do bendway weirs and rock vanes. As Figure 2 illustrates, bendway weirs and rock vanes become fully submerged as flow stage increases as a major hydrograph passes along a channel. Nonetheless, an important aspect of scour at these structures is that the manner of structural failure owing to scour may be similar for them all: *scour triggers geotechnical instability and direct entrainment by flow, which then cause these structures to fail*.

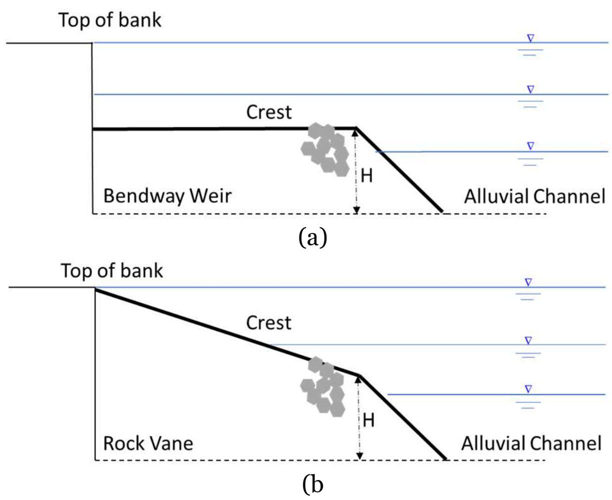


Figure 2. Cross-section profiles of (a) bendway weirs; and (b) rock vanes. These two profiles are transverse across channel and reflect the main difference between the two rock structures. Three flow depths are indicated.

Objectives

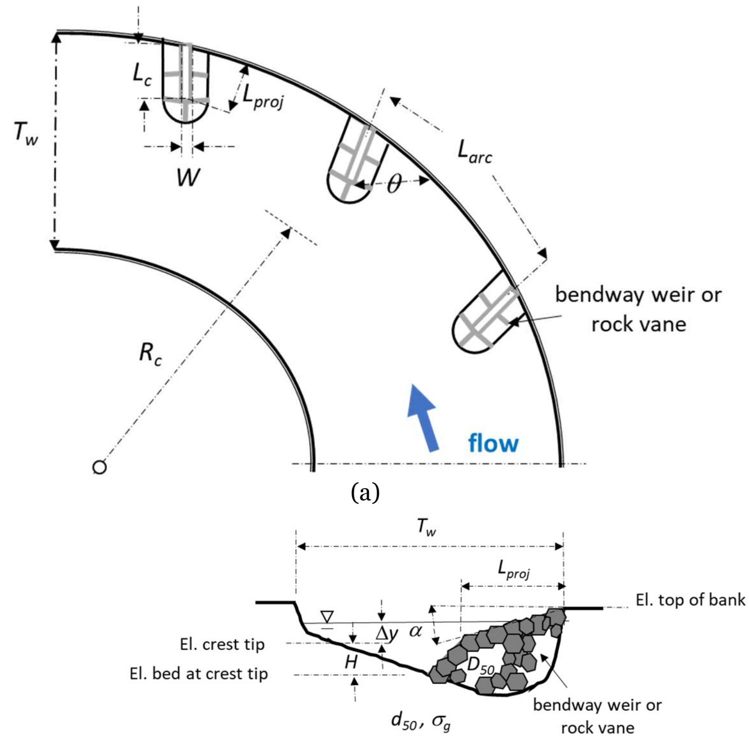
The study focused on bendway weirs and rock vanes, and it sought to produce and confirm designs for these rock structures to ensure continued structure performance under livebed conditions in alluvial channels. Accordingly, the study involved the following sequence of objectives:

1. Determine the main modes whereby livebed scour may induce bendway weirs and rock vanes to fail.
2. Ascertain how the maximum depth of livebed scour at bendway weirs and rock vanes varies with flow stage (water level) relative to average crest height of bendway weirs or rock vanes in channel bends.
3. Set and confirm design recommendations for bendway weirs and rock vanes subject to livebed scour.

These objectives focused primarily on a relationship entailing the variation of the two dependent parameters indicated in the following functional equation:

$$\Pi = \varphi\left(\frac{(\Delta y + H)}{H}, \frac{D_{50}}{d_{50}}\right) \tag{1}$$

Where Π = maximum depth of scour normalized with, H = crest-tip height of bendway weir or rock vane; Δy = water-surface height above tip; D_{50} = median diameter of quarry rock forming a bendway weir or rock vane; and d_{50} = median diameter of bed sediment at the location of a bendway weir or rock vane. Figure 3 shows these variables for a series of rock vanes. The study indicated little need to extend Equation (1) to include more variables, because only modest scour caused bendway weirs or rock vanes to fail. The series was configured as recommended by Siefken et al. (2021) in a series of numerical experiments completed as part of an overall study for AO-BOR.



(a)

(b)

Figure 3. Variables used for the dimensional analysis leading to Equation (1). The indicated flow direction concurred with the direction used for the experiments.

Also, to attain the objectives mentioned above, a curved flume was built whose geometry was typical of curved channels along the Middle Rio Grande. While conducting the experiments, it was found that the sequence of flows must replicate the low-flow conditions usually prevailing when building bendway weirs and rock vanes at field sites, followed then by the flow conditions associated with the rising limb of a flow hydrograph at a field site. This procedure was needed because a concern quickly arose during initial tests with the flume regarding the influence dunes and a point-bar may exert on the performance of bendway weirs and rock vanes. Therefore, the parameter $(\Delta y+H)/H$ was varied by increasing Δy from -0.25H to H, where H is the height of the tip (Figure 3). Also, two values of d_{50} were used (a medium sand and a very-coarse sand) though D_{50} for the rock was kept constant.

Experiments

Experiment Layout

The livebed experiments were performed using a curved flume, which had a trapezoidal cross-section geometry, a 1.22-meter-wide bed, sideslopes set at 1.5H:1.0V, and a 0.25-meter-thick, layer (initial) of bed sediment. A view of the completed flume is shown in Figure 4. The bed's slope was deemed negligible relative to other factors affecting bed elevation. The flume's layout was based on channel-bend dimensions given by AO-BOR and was representative of alluvial bends comprising the Middle Rio Grande. Steady discharges of water and steady rates of sediment transport through the model were handled by means of the layout, which was used for all the experiments. It was assumed that the headbox and the sediment hopper at the upstream end of the model were sufficiently far upstream of the actual curved channel that accumulation of sediment would not influence the experiments. Ettema et al. (2022) documents the design and construction of the curved flume, the experiment layout used, experiment procedure followed, and the program of experiments conducted.

Figure 4. View of the curved flume fitted with six bendway weirs on the bed of medium sand, and $(\Delta y + H)/H \approx 1.25$

The experiments had the following principal features:

- Water discharge, Q, passed through a closed-loop flow path, whereas the rate of sediment transport, G_S, occurred through an open-loop flow path. Water was pumped from the laboratory's sump beneath the flume, passing through the flume, and then returning (sediment-free) to the sump. Water temperature and its range were 10°C ± 1°C.
- The bed sediment comprised of very coarse sand (median diameter, d_{50} = 1.3 mm, geometric standard deviation, σ_g = 1.3) or medium sand (d_{50} = 0.38 mm, σ_g = 1.5). Both sands comprised less than about 1% by weight of magnetite.
- The sediment sizes were within the capacity of available water discharge to create livebed conditions for all (but one) four values of $(\Delta y+H)/H$ used for the tests; $(\Delta y+H)/H$ = 0.75-2.0. The experiments begun with flow commensurate with the condition $(\Delta y+H)/H$ =1.25, but no rock structures were present. Water and sediment discharges increased as $(\Delta y+H)/H$ increased.
- Bed-sediment was fed into the headbox at a prescribed rate by means of a hopper, and a motor-driven auger, whose rate of rotation was adjusted to vary the rate of bed-sediment feed into the model. The sediment-feed rate was pre-estimated and checked by weighing samples taken over a given period. A diffuser panel spread sediment across the flume's bed. The bottom end of the angled board was 0.92 m wide. At the flume's downstream

end, a bed-sediment trap captured the bed sediment that had passed fully along the curved flume.
- Water and sediment inflows entered the flume's headbox, then moved around the curved flume. These inflows were managed so as not to alter the bathymetry of the curved flume.

The rock used to construct bendway weirs and rock vanes was sized using the methods outlined in Ettema et al. (2020). For this rock, d_{50} = 12.5 mm, $d_{100} \approx$ 25 mm, and σ_g = 1.60. The rock consisted of typical crushed rock. Heaped, the rock stood at an angle of approximately 42°. The dimensions of bendway weirs and rock vanes were scaled in accordance with Siefken et al. (2021):

- Bendway weirs (BW): height at tip, H =7.6 cm; projected length, L_{proj} = 0.52 m; crest width, W = 7.6 m; angle to bank, sideslope = 1.5H:1.0V; and θ = 60°.
- Rock vanes (RV): height at tip, H =7.6 m; projected length, L_{proj} = 0.52 m; crest width, W = 7.6 m; sideslope = 1.5H:1.0V; crest slope = 11.3° (20%); angle to bank, and θ = 60°.

Program of Experiments

An important step in conducting the experiments entailed doing a series of *Initial Tests* with the curved flume to determine an appropriate procedure for conducting the *Main Tests* (Ettema et al. 2022).

Table 1. Program of the main experiments conducted in the present study (0 means no rock structure, and 6 means a configuration of six rock structures)

BW or RV	d_{50} (mm)	Q (m³/s)	y (cm)	Shear stress ratio τ_o/τ_c	$(\Delta y+H)/H$	L_{proj} (cm)	H (cm)
0 BW	1.3	0.07	9.53	1.6	1.25	52.1	7.62
6 BW	1.3	0.04	5.72	0.9	0.75	52.1	7.62
6 BW	1.3	0.07	9.53	1.6	1.25	52.1	7.62
6 BW	1.3	0.10	15.2	2.5	2.0	52.1	7.62
0 RV	1.3	0.07	9.53	1.6	1.25	52.1	7.62
6 RV	1.3	0.04	5.72	0.9	0.75	52.1	7.62
6 RV	1.3	0.07	9.53	1.6	1.25	52.1	7.62
6 RV	1.3	0.10	15.2	2.5	2.0	52.1	7.62
0 BW	0.38	0.07	9.53	4.8	1.25	52.1	7.62
6 BW	0.38	0.04	5.72	2.9	0.75	52.1	7.62
6 BW	0.38	0.07	9.53	4.8	1.25	52.1	7.62
6 BW	0.38	0.08	15.2	7.7	2.0	52.1	7.62
0 RV	0.38	0.07	9.53	4.8	1.25	52.1	7.62
6 RV	0.38	0.04	5.72	2.9	0.75	52.1	7.62
6 RV	0.38	0.07	9.53	4.8	1.25	52.1	7.62
6 RV	0.38	0.08	15.2	7.7	2.0	52.1	7.62

The *Initial Experiments* were necessary because tests soon revealed that bedform (dunes and point-bar) development could significantly affect the performance of bendway-weirs and rock-vanes built in alluvial bends. Recall that the maximum height of a dune exceeds about a third of the nominal depth of flow, Y (e.g., Raudkivi 1990); and the crest of a bendway weir is in the range 0.33 to $0.5Y$. This paper does not document the *Initial Experiments*; interested readers are directed to Ettema et al. 2022). Table 1 lists the program of main experiments. Consequent to findings from the *Initial Experiments*, the experiments were done using the *Hydrograph Procedure*, in which the water discharge was increased for each test in a series of experiments, thereby mimicking the progress of a hydrograph passed the configurations of bendway weirs or rock vanes.

Instrumentation Methods

Pertinent parameters (and associated variables) were measured and managed by means of several instrumentation methods. The methods include LiDAR scans, Large-Scale Particle Image Velocimetry (LSPIV), Acoustic-Doppler-Velocimeter (ADV), structure-dimension measurements (obtained using a tape measure), and water-surface elevations (obtained using Massa acoustic probes) and bed-surface elevations (obtained using Massa acoustic probes, tape measure, and LiDAR).

For example, LiDAR scans of the bathymetry of the curved flume's bed were collected using a TOPCON Laser Scanner. The flume's bed was scanned before and after each experiment to compare the changes in bend bathymetry. The LiDAR scanner was placed at two different locations, one position at the upstream end of the flume, and the other position was downstream near the riprap region at the exit of the flume. This arrangement enabled complete coverage of the bed and rock structures. The scanner's positions were surveyed into the Hydraulics Laboratory's electronic coordinate system to avoid geometric distortion in the results and facilitate the melding of data from the two scanning positions. Data from the scanner were transferred to a computer via an SD card and post-processed in the computer program Magnet Collage, whereupon output data were sent to an Autodesk Recap file for viewing.

Procedure

Figure 5 shows the *Hydrograph Procedure* used for the bed formed of very coarse sand and medium sand, respectively. The *Procedure* entailed first forming the bathymetry of the curved channel. Then, an experiment was conducted at a reduced flow until equilibrium conditions prevailed. The subsequent experiments entailed increasing the flow stage and concomitantly the flow discharge and sediment feed rate. The procedure for each experiment entailed the following steps:

1. Before the initial bed-forming flow was run, the bed was refilled with sediment and leveled. The sediment trap was emptied, and the hopper refilled with dry sand.
2. The pump was turned on at a lower discharge than desired to slowly fill the flume. When the flume was filled, the pump was set to the discharge for the initial bed forming flow conditions ($[\Delta y+H]/H = 1.25$), the sluice and overshot gates were opened and adjusted to maintain the appropriate flow depth. Additionally, the hopper was turned on and set to the feed-rate required for bed-sediment transport proportionate with the flow conditions.
3. The water-surface elevation was monitored and recorded for the selected five points along the flume throughout the duration of the experiment.

4. The experiment then was allowed to proceed until equilibrium conditions prevailed in the flume. Equilibrium was judged to prevail when no further bed-deepening occurred.
5. Near the end of the experiment, before the experiment was ended, LSPIV data were collected regarding flow velocities at the water surface.
6. After running the flume 4 hours (usual period) to reach bedform equilibrium, the sluice gate was closed, and pump and hopper were shut off. Closing the sluice gate allowed the flume to slowly drain and prevent bedforms from washing out. Additionally, a sump pump placed in the headbox was used to drain the flume from the headbox as well. The flume was drained from each end to reduce to negligible any flow velocities along the flume while the flume was draining.
7. Rock structures were installed in the flume and the bed was LiDAR scanned.
8. In recommencing an experiment, the pump was restarted at a lower flow rate than desired to slowly fill the flume to inhibit mobility of bed sediment. Once the flume was filled, the pump was set to the discharge corresponding to the flow condition $(\Delta y+H)/H = 0.75$ in the flume. The sluice and overshot gates were opened and adjusted to maintain the appropriate flow depth. Additionally, the hopper was turned on and set to the sediment feed-rate associated with $(\Delta y+H)/H = 0.75$.
9. The water-surface elevation was monitored and recorded for the selected five points along the flume throughout the duration of the experiment. Photos were also taken of the channel during the experiments.
10. Near the end of the experiment, and before the experiment ended, LSPIV data on water-surface vectors were collected.
11. After running the flume for 4 hours to reach bedform equilibrium, the sluice gate was closed, and the pump and hopper were shut off. Closing the sluice gate enabled the flume to slowly drain and prevent bedforms from washing out. Additionally, the sump pump in the headbox drained the flume from the upstream end.
12. The bed was LiDAR scanned, and structure measurements and photographs of the channel were taken.
13. The hopper was refilled with dry sand.
14. Steps 7-12 were repeated for the next two flow conditions: $(\Delta y+H)/H = 1.25$ then 2.0.

Results

The writers consider the observations and data presented here to be representative of bendway weirs and rock vanes subject to live-bed scour.

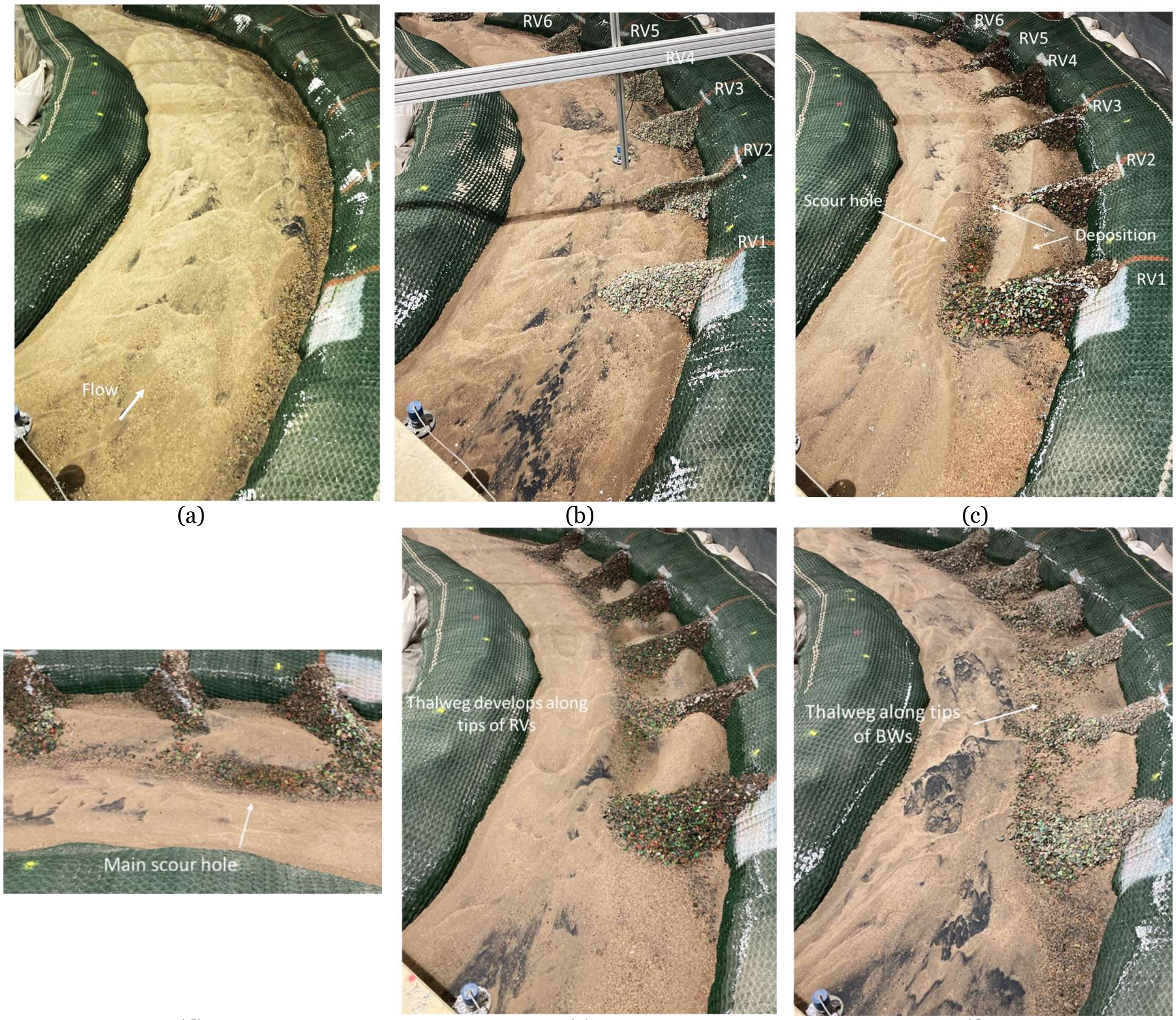
Observations

The following principal observations concern live-bed scour, and consequent scour-induced failure, of rock vanes and bendway weirs. Figure 5 illustrates the experiment with the series of six rock vanes on the bed of very coarse sand. Practically the same live-bed scour processes were observed for bendway weirs, and for rock vanes and bendway weirs on medium sand. The main observations were as follow:

1. With no rock vanes in the channel, and $(\Delta y+H)/H \approx 1.25$, flow altered the channel's initially flat bathymetry such that the channel's thalweg lay along the outer bank of the channel (Figure 5a). The six rock vanes then were built in the channel (Figure 5b).
2. When the experiment was continued at $(\Delta y+H)/H \approx 0.75$, a region of relatively deep scour formed due to flow contraction around the tip of rock vane 1 (Figure 5d) but this scour region did not extend from rock vane 2 to rock vane 6. The scour region (or scour hole) was the deepest of all contraction scour conditions. Figure 5d shows, in detail, the

region of deepest scour. The base of the scour region was covered with rock displaced from rock vane 1.

3. For $(\Delta y+H)/H \approx 1.25$, the scour region shallowed but lengthened downstream along the ends of all the rock vanes, thereby forming and delineating the shifted thalweg (Figures 5e&f). The tips of all the rock vanes failed, so that the top layer (or more) of rock of each tip face slid into the contraction scour region. Except near rock vane 1, the channel remained deep along the outerbank.



(a) (b) (c) (d) (e) (f)

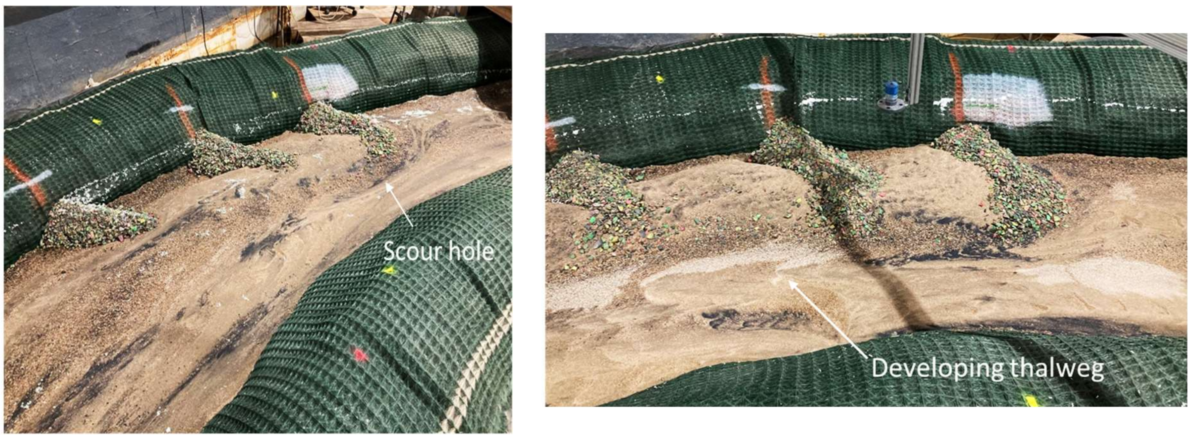
Figure 5. Scour, thalweg development, and failure modes of six rock vanes on the bed of very coarse sand: (a) no rock vanes, Q = 2.5 cfs (0.07 m^3/s); (b) newly built rock vanes before experiment; (c) $(\Delta y+H)/H \approx 0.75$ (after experiment); (d) a detail view of (c); (e) $(\Delta y+H)/H \approx 1.25$ (after experiment); (f) $(\Delta y+H)/H \approx 2.0$ (after experiment)

4. Subsequently for $(\Delta y+H)/H \approx 2.0$, the lengthened region of scour extended along the ends of all the rock vanes but shallowed slightly in several locations (Figures 6a&b). However, the tip slopes of the rock vanes became flatter, causing the crests of the rock vanes to shorten further. The larger values of flow velocity across the tips of the rock vanes at times dislodged rocks not well seated on each tip. Also, because the flow was deeper and less blocked by the rock vanes, the depth of contraction scour (and the

thalweg) became even shallower than when $(\Delta y+H)/H \approx 1.25$. Also, more bed sediment accumulated between the rock vanes than was observed when $(\Delta y+H)/H \approx 0.75$ and 1.25.

5. The upstream slope of the first rock vane (RV1) was prone to fail, owing to scour development at the rock-vane tip.

The series of six bendway weirs experienced the same sequence of livebed development and failure as listed above for the series of six rock vanes. For example, Figures 6a&b illustrate the initial deep scour region developed at the lead bendway weir when $(\Delta y+H)/H \approx 0.75$, then the extension of this region when $(\Delta y+H)/H = 1.25$.

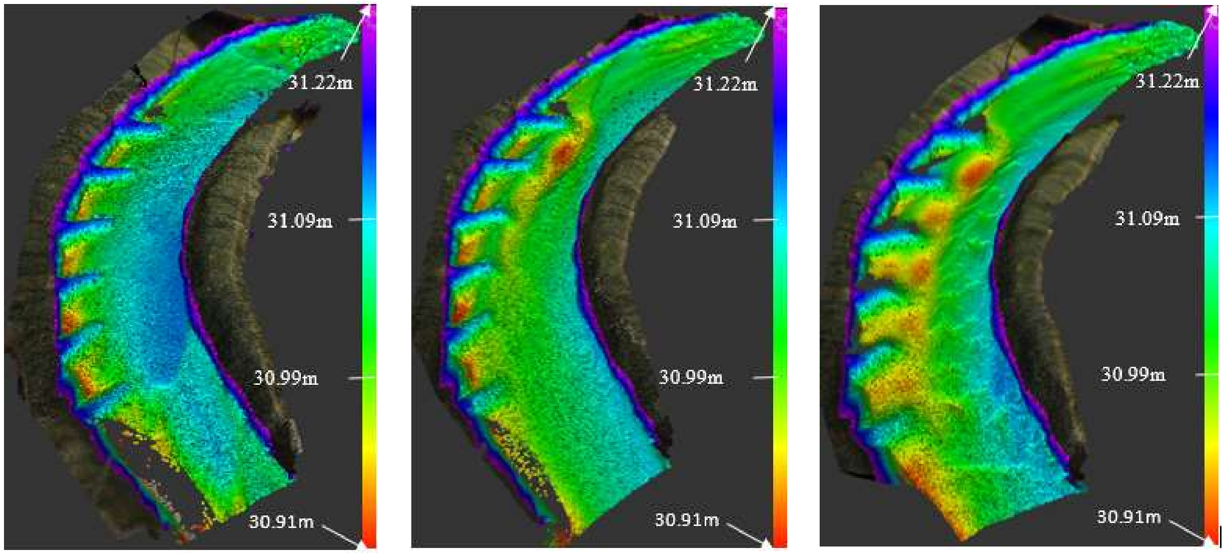


(a) (b)

Figure 6. Scour region observed for the six bendway weirs: (a)$(\Delta y+H)/H \approx 0.75$; and (b) $(\Delta y+H)/H \approx 1.25$

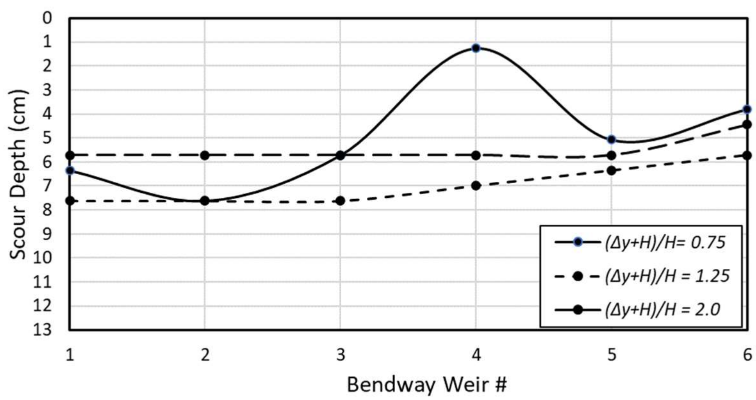
The rock vanes or the bendway weirs did not breach. However, in some experiments, accumulated bed sediment reached the top of a bendway weir. Not elaborated here, but evident in the LiDAR scans (Ettema et al. 2022), is the suggestion that the variation of $(\Delta y+H)/H$ also influenced the bathymetry of the curved channel, and thereby also affected bendway-weir performance. Included in the bathymetry is the channel's point bar, which evolved to an extent during the experiments. Figure 7 gives three LiDAR scans of the bed after the experiments with six bendway weirs on the very coarse sand. Figure 8 indicates scour depths at the crest tips of the bendway weirs and rock vanes. The following observations concern live-bed scour of the medium sand, though the main findings are essentially the same as the findings listed above for the bendway weirs and rock vanes on the very coarse sediment:

1. Larger values of shear stress ratio were attainable for the medium sand.
2. The deepest scour occurred for the six bendway weirs and rock vanes on the very coarse sand, because rock from the bendway weirs or rock vanes did not embed or armor as effectively as when the rock landed on the medium sand. Evidence for this point is in Figure 5f, which shows rock slightly upstream of the first rock vane. Rock from the failed tip rolled on the coarser fraction (fine gravel) before partially armoring the bed surrounding the tip of each rock vane.
3. Small dunes were a pronounced feature of the bendway weirs and rock vanes on the bed of medium sand, and often formed against the leading face of bendway weir 1 or rock vane 1. However, using the hydrograph procedure ensured that the dunes did not affect the performance of the configuration of bendway weirs or rock vanes. In particular, the volume of bed sediment accumulated between the bendway weirs did not change appreciably.

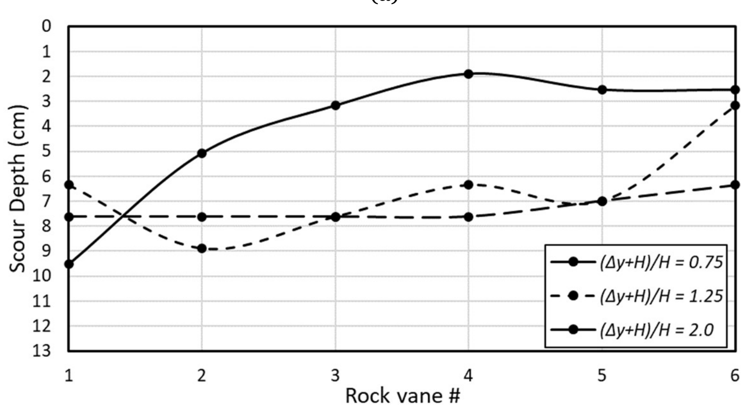


(a) (b) (c)

Figure 7. LiDAR scans for six bendway weirs on the bed of very coarse sand in the curved flume under the following flow-hydrograph conditions: (a) initial bed formed for $(\Delta y+H)/H \approx 1.25$ and with bendway weirs newly placed; (b) $(\Delta y+H)/H \approx 0.75$; and (c) $(\Delta y+H)/H \approx 1.25$ (1.00 m ≡ 3.28 ft)



(a)



(b)

Figure 8. Scour depth at tips of bendway weirs and rock vanes on very coarse sand: (a) bendway weirs; and (b) rock vanes. Structures are numbered from upstream to downstream (see Figure 5).

Thalweg Depths

The experiments yielded thalweg depths that, as $(\Delta y+H)/H$ increased, became approximately the same along the ends of the six bendway weirs and rock vanes, for both the very coarse sand and the medium sand. Figure 8 shows the thalweg depths for the tests involving the variation of $(\Delta y+H)/H$ for each rock structure on the very coarse sand. The thalweg usually was deepest in the vicinity of bendway 2 or rock vane 2. Overall, however, the thalweg was deepest at rock-vane 1 for the bed of medium sand.

These measurements of thalweg depth accompany the series of photographs in Figures 5 and 6 and the LiDAR scans in Figure 7. Essentially, thalweg formation began as the contraction scour formed at or between bendway weirs or rock vanes 1 and 2, then extended along these rock structures as the flow discharge and, thereby, $(\Delta y+H)/H$ increased. As the thalweg extended, the thalweg's depth shallowed at bendway weir 1 and rock vane 1 for both sands, and for bendway weir and rock vane 2 on the very coarse sand.

Scour Depths

For all experiments, the maximum scour depth (essentially contraction scour, though increasingly complicated by flow over the structure) along the thalweg of the channel occurred when $(\Delta y+H)/H = 0.75$. Subsequently, scour depth successively decreased when $(\Delta y+H)/H$ increased to 1.25 and 2.0, as Figure 9 indicates. This result is attributable to widening of the flow cross-section, as the failure of the tip slope, which spilt dislodged rock on to the scour surface (and thalweg) and armored that surface.

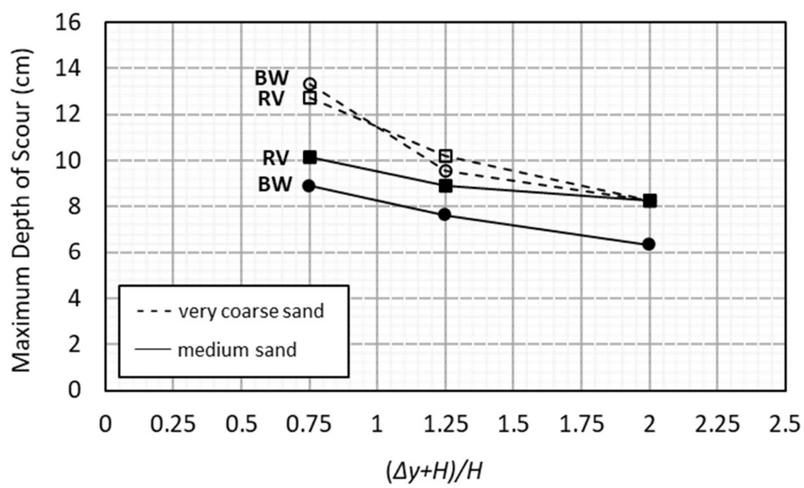


Figure 9. Maximum depth of scour versus $(\Delta y+H)/H$ for bendway weirs (BW) and rock vanes (RV) on beds of very coarse sand or medium sand.

The results prompt the ensuing two questions:

- What minimum value of scour depth at the slope's toe is needed to cause the tip slope to fail?
- What maximum depth of scour in the bed sediment could occur?

These questions are pertinent for structures formed of loose rock. Of great importance is the scour depth at the toe of a slope of piled rock. Once the slope fails and the rock tumbles into the scour zone (also the thalweg) the depth of maximum depth of scour becomes difficult to estimate accurately because of the armoring effect of the rock and the reduced length of the bendway weir or rock vane. Also, to be considered is the height, H, of the bendway weir or rock vane at its tip. The answer to the first question can be formulated approximately and shows that only modest scour is needed to destabilize the rock layer. For the experiment, only a scour depth of about 3 cm was needed. Figure 10 is a sketch associated with the analysis.

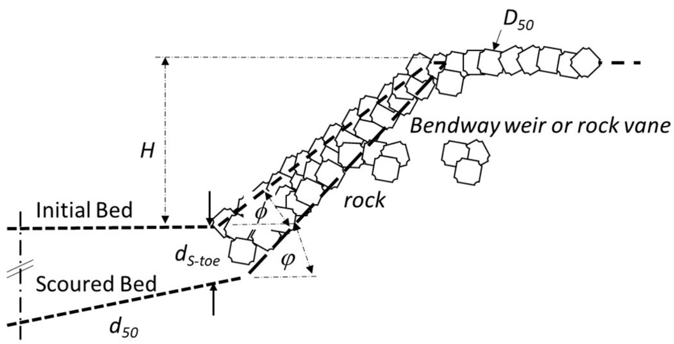


Figure 10. Scour at the toe of a rock pile may destabilize the toe; scour depth at toe = $d_{S\text{-}toe}$. Here, α = built slope of tip face, and φ = equilibrium slope of rock loosely piled. This figure assumes no crossflow of water across the tip face

The loose-rock construction of bendway weirs and rock vanes complicates estimation of the potential maximum scour depth. Once rocks moved from the tip slope and landed in the scour region (the developing thalweg) those rocks partially armored the scour region. Additionally, the crest length of the bendway weir or rock vane decreased, thereby affecting scour depth. The extent of bendway-weir or rock-vane failure varied owing to the seating of rock on the tip slope, influenced the number of rocks tumbling into the scour region and, thereby, caused some variability in scour depth. The experiments suggest that the deepest scour at the toe occurred when $(\Delta y + H)/H = 0.75$, the least value of $(\Delta y + H)/H$ used; the tip slope failed at this value. Figure 10 suggests that, for the present experiments, the maximum depth of scour depth occurred approximately for $(\Delta y + H)/H = 0.75$, because this scour depth was sufficient to fail a bendway weir or rock vane, causing these rock structures to shorten. Bendway weir 1 and rock vane 1 would have failed when d_S reached about about 3 cm. Lesser values of d_S may occur as a hydrograph produced lesser values of $(\Delta y + H)/H$.

The values of $d_{S\text{-}MAX}$ for bendway weirs and rock vanes were about the same when $(\Delta y + H)/H = 0.75$, except a shallower scour depth occurred for the bendway weirs on the medium sand. The difference, though, is attributable to the disposition of rock on the scour bed. The difference indicates the range of variability in scour-depth data, as rock disposition differed depending on the extent to which rock in the scour zone (developing thalweg) rested on sand or rock. The variability is within about half the diameter of the median size of rock on the tip slope: D_{50} = 12.5 mm (0.5 in). This difference is evident for the medium sand, in which the values of scour depth were less for the bendway weirs than for the rock vanes. Bendway weir 1, adjacent to the scour region, shortened more than did the rock vane 1 (see the next sub-section), thereby more rock from the bendway weir spilt into the scour zone.

The maximum scour depths at the bendway weirs and rock vanes were larger in the bed of very coarse sand compared to the bed of medium sand. The value of D_{50}/d_{50} was greater for the bed of medium sand, such that dislodged rock from the bendway weirs or rock vanes moved further on the bed before armoring the bed. This process enabled the bed to scour more before rock dislodgement occurred and the channel became armored, preventing further scour. Bendway weirs and rock vanes placed on the bed of very coarse sand experienced nearly identical values of maximum scour depth, whereas there was about 1 cm difference in maximum depth of scour in medium sand for the corresponding flow conditions. This aspect requires further investigation, as the manner whereby dislodged rock moved on the sand bed differed somewhat for the two bed sediments. Also, as mentioned above, some variation could occur, depending on uncertainties in how the dislodged rock landed.

Recommended Layout

The present study focused especially on the design of bendway weirs and rock vanes to function as required after live-bed scour (scour generally) had triggered the structural failure of the bendway weirs and rock vanes. The crest of the first bendway weirs or rock vane should be widened to accommodate failure of the upstream slope of these rock structures.

The layout for a bendway weir is given by Ettema et al. (2022), who also discuss the recommended layout for a rock vane. Figure 11 shows the layout (a similar layout was developed for rock vanes).

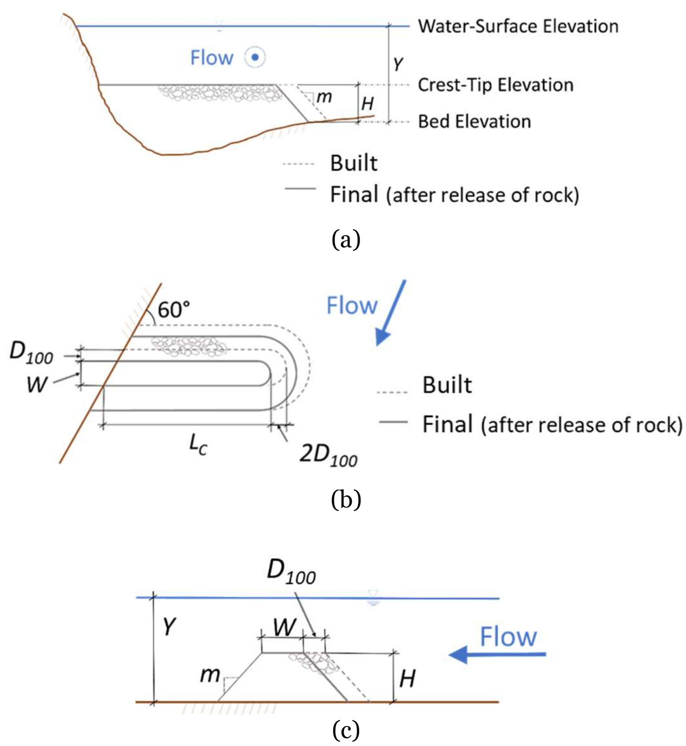


Figure 11. Recommendation for the design of a bendway weir: (a) streamwise, cross-section view of the design recommendation; (b) plan view of the design recommendation (widened for the upstream rock structure only); and (c) centerline elevation view (looking toward outer bank) of the design recommendation. A design alternative is to face the tip of final shape with a double layer of rock larger than the median size of rock used to build the bendway. The basic top width, $W \approx 2D_{100}$, as recommended by Lagasse et al. (2009).

The same lengthening and widening of crest are recommended for rock vanes as for bendway weirs. The layout includes a volume of rock that livebed scour and tip-slope would launch. Note that D_{100} is the largest diameter of rock used in building the bendway weir or rock vane. Also, m = 1.5H:1.0V. The "Built" layout includes a volume of rock that livebed scour releases. The "Final" layout enables the bendway weir to perform as design requires.

Conclusions

For rock structures like bendway weirs and rock vanes, scour need only get sufficiently deep that the side slope of a face becomes undermined and fails geotechnically. Thereafter, scour likely will not deepen because the local flow area has increased, and the scour region becomes partially armored with rock dislodged from the bendway weir or rock vane.

The sequence of bendway weir or rock vane failure owing to live bed scour can be summarized as follows:

- First, when $(\Delta y+H)/H \approx 0.75$, scour caused only the tip slope of the first rock vane to fail.
- Then, when $(\Delta y+H)/H \approx 1.25$, scour caused all the tip slopes of all the bendway weirs and rock vanes to fail.
- Finally, when $(\Delta y+H)/H \approx 2.0$, swifter flow displaced unstably seated rock and, thereby, decreased the slope of the failed tips for all the rock vanes, thereby caused the rock vanes to shorten.

Figure 11 shows the recommended design layout of a bendway weir. The same lengthening and widening of crest (first structure only) are recommended for rock vanes (Ettema et al. 2022).

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