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STREAM RESTORATION IN THE VICINITY OF BRIDGES[1]

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ABSTRACT: The number of stream restoration and enhancement projects being implemented is rapidly increasing. At road crossings, a transition must be created from the restored channel through the bridge or culvert opening. Given conflicting design objectives for a naturalized channel and a bridge opening, guidance is needed in the design of the transition. In this paper we describe the use of vanes, cross vanes, and w-weirs, commonly used in stream restoration and enhancement projects, that may provide an adequate transition at bridges. Laboratory experiments were conducted on vanes and cross vanes to provide a transition for single span bridge abutments and on w-weirs to provide a transition for double span bridges which have a pier in mid-channel. The results of the experiments provided design criteria for transitions using each of the three structures. Prior field experience provided guidance on appropriate applications in terms of the stream and bridge characteristics.

(KEY TERMS: erosion; sedimentation; aquatic ecosystems; stream restoration; vanes; weirs; bridges, bridge scour; hydraulics.)

INTRODUCTION

Stream restoration and other enhancement projects are proliferating around the country to stabilize and naturalize streams disturbed by highway construction, urban development, and channel modifications such as straightening and dredging. It is not unusual in most parts of the country for a stream to intersect a roadway in a given project reach, particularly in urban settings. Therefore, it is critical to the success of the restoration project, as well as the safety of the bridge, that the intersection of the roadway and stream be appropriately incorporated into the design.

Design parameters and concepts are significantly different for stream restoration and bridge foundation protection. Most bridge openings are designed to convey a design storm, typically sized between the 25- and 100-year floods, depending on the type of bridge. The bridge is expected to resist scour (erosion at the bridge) for the 100-year storm; thus, the bridge must be protected for the 100-year flood. At many bridges, a large portion, if not all, of the overbank flow during a flood will be forced to return to the main channel to be conveyed under the bridge. The flow returning from the floodplain often approaches the main channel and bridge at a high angle, causing local and contraction scour around the structure and erosion of the approach fill.

By contrast, the basis of most channel restoration, naturalization, and enhancement designs is the bankfull discharge. The channel is typically designed to convey the bankfull discharge with higher flood flows conveyed out of banks along the flood plain. Structures placed at channel bends to protect eroding banks or across the bed to protect against bed degradation and local bank erosion are sized to withstand higher flood flows, although the discharge of those floods are rarely specified.

Where a channel restoration project meets a road crossing, the design of the restored channel must often be disrupted so that all or part of the flow returns to the channel or near the channel, depending on the configuration of the bridge approaches and abutments. Thus, a transition must be created that: (1) conveys flood flows up to the design standard for the bridge, (2) conveys sediment flow without causing additional scour at the bridge piers and abutments, and (3) does not produce aggradation beneath the

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bridge. Ideally, the restoration design should provide a more effective conveyance channel that actually promotes water and sediment flow through the bridge opening. In this paper, the adaptation of several stream restoration techniques will be described for the purpose of creating such transitions at bridges.

PROBLEMS AT BRIDGES

Bridge scour is the erosion of stream channel bed material in the vicinity of abutments or piers. It is categorized as: (1) local scour, which occurs at the abutments or piers, caused by the obstruction to flow; (2) contraction scour, which occurs under and near bridge openings and generally lowers the channel bed, due to flow constriction; and (3) channel degradation, which is a lowering of the entire channel bed and which would occur whether or not a bridge was in place. Guidance on predicting the various types of scour is given in Richardson and Davis (1995), although many other prediction methods exist in the literature. The three scour components are typically thought to be independent so that the total scour at a bridge is simply the sum of the local scour, contraction scour, and degradation.

Scour can compromise the safety of a bridge; thus, mitigation measures are often employed to protect the bridge foundation. Local and contraction scours are typically treated using armor, most commonly riprap. Riprap is designed to withstand the forces associated with the 100-year flood or greater. Design charts for sizing and placement of riprap are available in HEC-23 (Lagasse *et al.,* 1997). Other armor protection for local and contraction scour includes precast concrete units, grout filled bags, foundation extensions, and concrete aprons. Several techniques to break up the vortices that cause scour have been installed at bridges and in laboratories with limited success. These include sheet and cylindrical piles placed upstream of piers (sacrificial piles), circular shields around the piers, and hydrofoils placed upstream of piers.

Channel bed degradation can be estimated using mathematical models or years of data showing trends in channel bed changes. Many alluvial channels experience long-term degradation (100+ years); however, a bridge engineer is concerned primarily with that which occurs over the life of the bridge. The long-term degradation process can be accelerated considerably by human activities, such as channel straightening and urbanization. This often causes the channel to become unstable and incise. It is difficult to control channel degradation locally at a bridge. Mitigating against degradation typically requires stabilization of the entire stream reach, including the bridge. Common measures for halting or retarding degradation include check dams and weirs. The use of check dams and weirs must be properly designed to maintain the stable slope, width/depth ratio, and sediment competence of the channel.

In addition to the scour processes listed above, bridge foundations can also be affected by channel widening and lateral migration. These processes have proven to be even more difficult to predict than channel degradation, especially as the latter can occur on rivers that are essentially in regime. Although the existence of a bridge is rarely the cause of channel widening or lateral migration, these processes can threaten the safety of bridge foundations located in the floodplain or overbank area. As the channel widens or moves laterally, it encroaches on piers with shallower foundations or abutments on the floodplain. Mitigation measures for bank failure include armoring, such as riprap and other revetments, vegetation, and vanes.

Excessive aggradation in a bridge reach can also affect the ability of a bridge opening to convey water and sediment. Aggradation is the deposition of channel material in a particular reach or cross section resulting when the sediment load supplied to a reach of river from upstream exceeds the reach's capacity to transport sediment. This often occurs as a result of flow contraction at the bridge during floods, which reduces velocities in the backwater reach leading to aggradation upstream of the bridge. A reduction in the design flood capacity of the bridge due to aggradation increases hydraulic loadings on the bridge superstructure and promotes further sedimentation and flooding in the elevated backwater. Even when a bridge is seriously affected by aggradation, it is rare for sediment to totally block all the spans. As bed material transport preferentially follows the locus of the maximum velocity filament, there will be some parts of the cross section where bed material load is minimal. These sections will still be prone to bed scour, particularly where increased backwater exacerbates contraction effects. Mitigating aggradation is a difficult problem. For severe cases, such as those that occur in some of the mid-Atlantic states, dredging has been the solution for many years.

USE OF RESTORATION MEASURES AT BRIDGES

Ideally, a stream restoration project should attempt to consider the flow and sediment dynamics at bridges in the project reach. Three structures commonly used in restoration designs that may also be useful in directing flows efficiently through bridge openings are vanes, cross vanes, and w-weirs (see Figures 1, 2, and 3). They are typically constructed from rock that is large enough to resist movement under shear stresses expected for the design flow, although other materials can be used. Each of these structures locally protect river banks by diverting flow away from them, creating quiescent conditions at the bank toe while the faster overspilling flow is directed into the mid channel. When properly positioned, vanes, cross vanes, and w-weirs induce secondary circulation in the flow and promote the development of scour pools in zones where surface flows converge and cause downwelling.

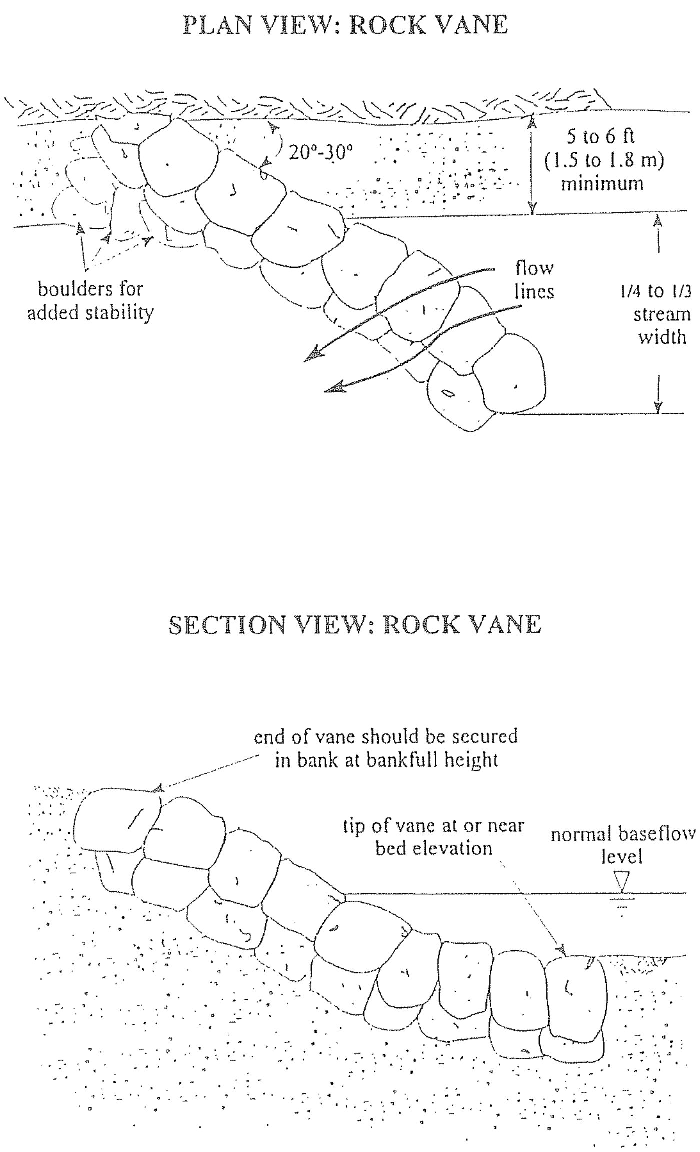


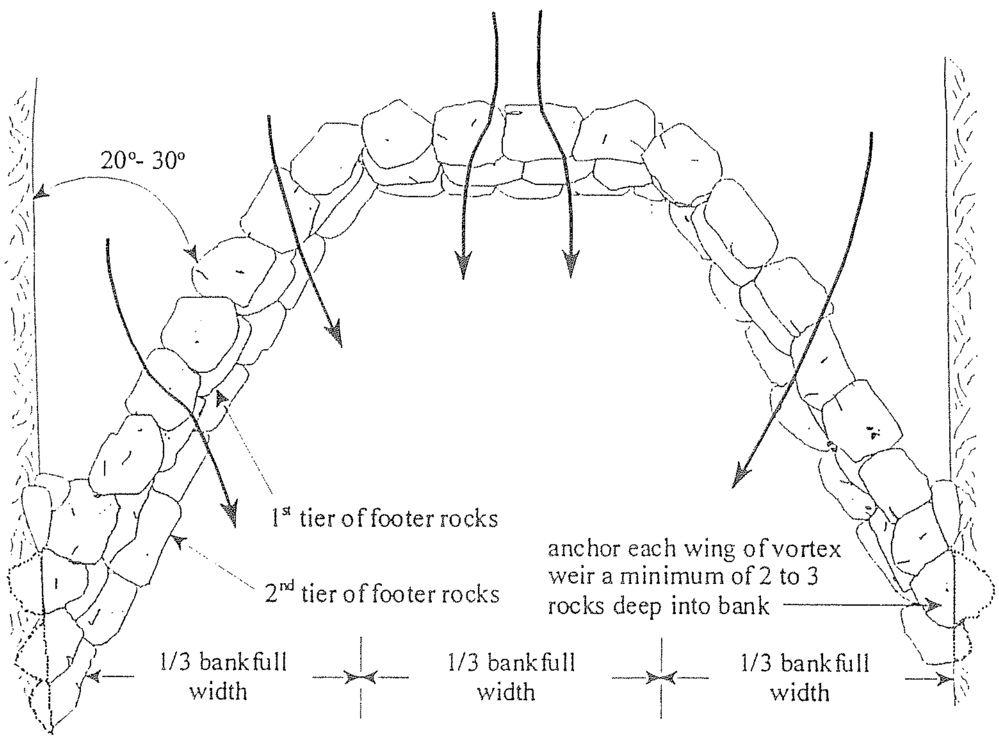
Figure 1. Rock Vane Design (Rosgen, 1996; Brown and Johnson, 1999).

The three structures vary somewhat in purpose. Vanes are single-arm structures angled to the flow and pitch from floodplain level at the bank into the streambed such that the tip of the vanes are submerged even during low flow (Figure 1). They are primarily used to control bank erosion and to redirect the flow away from the bank where they are located. Cross vanes are used to divert erosive flow away from banks while providing some level of grade control via a central section that crosses the stream either at the bed level or at the required bed level if grade control is required (Figure 2). W-weirs are a special case of cross vanes with the arms adjacent to the banks designed similarly to vanes and cross vanes. The central apex of the 'W' is typically about one-half of the bankfull height. Two scour pools are formed downstream of either upstream apex, as shown in Figure 3.

Very few vanes, cross vanes, and w-weirs have been installed in the field for the purpose of improving flow through bridge openings. As one example, vanes and cross vanes were installed at a small single-span bridge over Bear Creek in the Tiadaghton State Forest in central Pennsylvania during the fall of 1999. Bear Creek is located about 20 miles north of Williamsport, Pennsylvania, near Barbours. The second-order stream is a tributary to Loyalsock Creek, which is a tributary to the West Branch of the Susquehanna River. The bed sediment is characterized by a fairly uniform distribution, ranging from medium gravel to medium boulders, with a median sediment size, D50, of 94 mm. Characteristic dimensions are given in Table 1. At the left bridge abutment, erosion was threatening the integrity of the bridge. A vane was installed upstream of the affected abutment. Immediately, the vane caused the flow to be diverted away from the bank and the abutment, significantly reducing erosive forces adjacent to it. Within a three-week period, the quiescent waters just upstream of the vane and through the bridge opening allowed sediment to deposit along the toe of the bank, thus providing additional protection to the abutment. Immediately downstream of the bridge, a cross vane had been constructed to provide additional channeling of the flow into the center of the channel and assist in pooling flow in the near bank region.

The purpose of the flume experiments described below was to identify hydraulic characteristics and performance of the structures under varying conditions of flow and design.

PLAN VIEW: CROSS VANE



SECTION VIEW: CROSS VANE

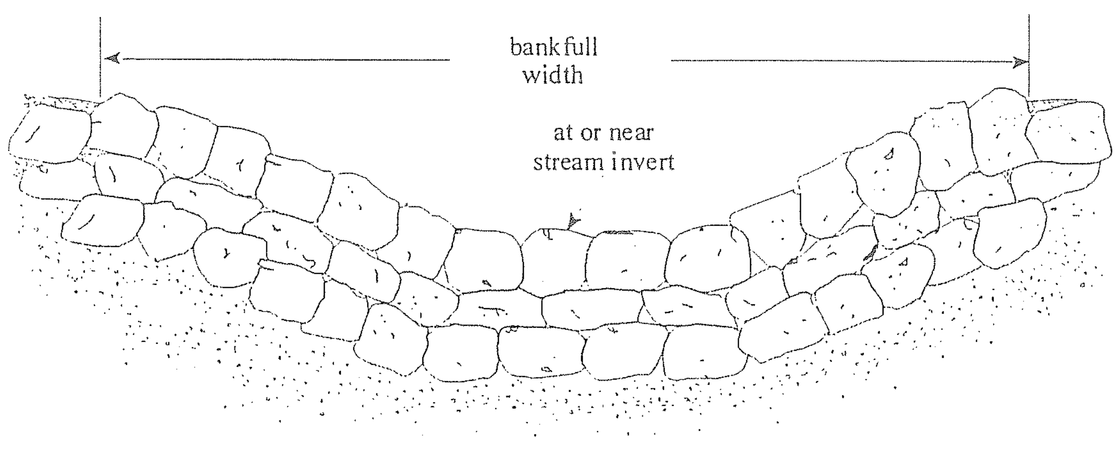


Figure 2. Cross Vane Design (Rosgen, 1996; Brown and Johnson, 1999).

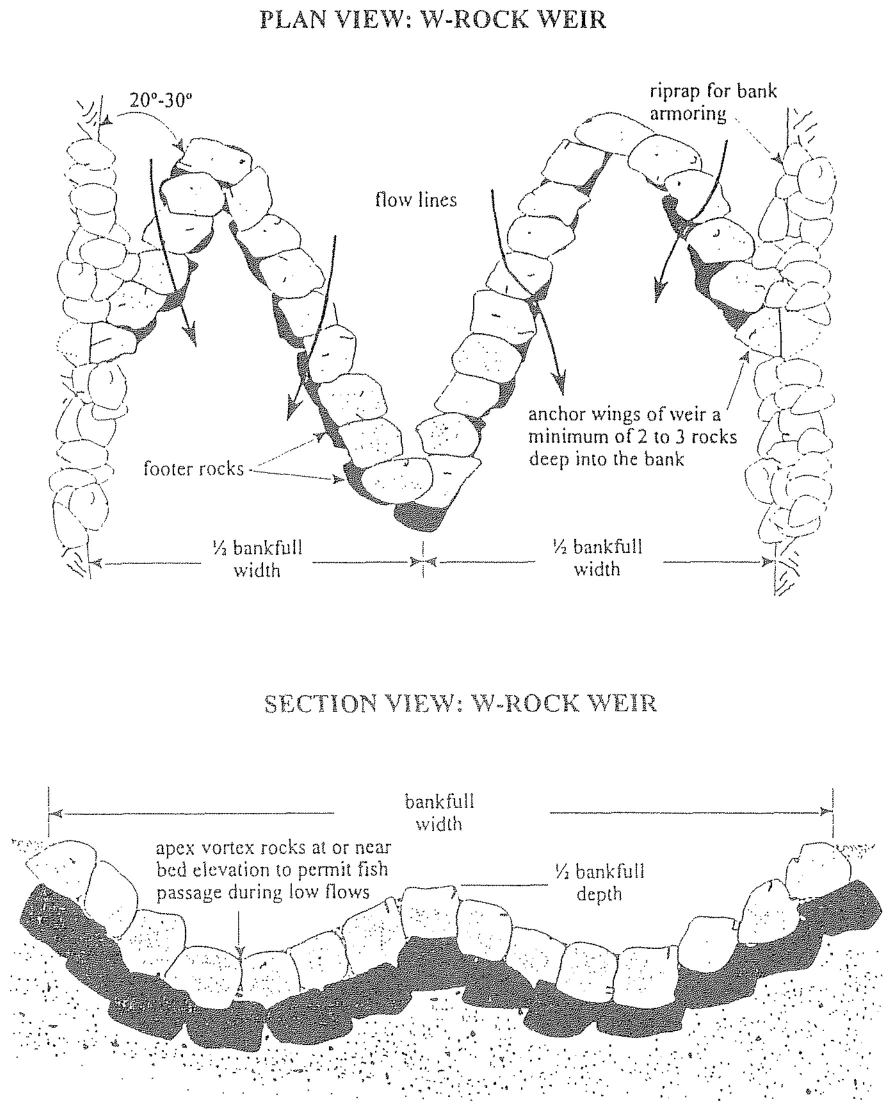


Figure 3. W-Weir Design (Rosgen, 1996; Brown and Johnson, 1999).

EXPERIMENTAL EVIDENCE FOR USE OF VANES, CROSS VANES, AND W-WEIRS AT BRIDGES

Experimental Program

Experiments on the effect of vanes, cross vanes, and w-weirs at bridges were conducted at the Pennsylvania State University in a 15 meter (50 ft) long, 1.5 meter (5 ft) wide, 0.9 meter (3 ft) deep recirculating flume to simulate flow patterns and the resulting scour at bridge piers and abutments. A venturi meter and manometer were used to provide discharge measurements and a point gage was used to measure flow depths in the flume. Flow velocity was measured with an acoustic doppler velocity meter attached to an overhead carriage. The experiments were conducted to determine the effects of: (1) vanes at bridge abutments, (2) cross vanes at abutments, and (3) w-weirs at bridge piers.

TABLE 1. Bear Creek Channel Characteristics.

Parameter	Observed Value
Average Bankfull Width	43.0 ft
Average Bankfull Depth	3.90 ft
Width/Depth Ratio	11.03
Slope	0.022
Sinuosity	1.1

Tests on scour at bridge abutments were carried out by modeling the channel (76 cm; 2-1/2 ft) and one floodplain (76 cm; 2-1/2 ft) to maintain sensible scaling (see Table 2). Although the floodplain would have limited width, it was relatively smooth and could transmit discharges comparable to a wider, rougher, floodplain. Consequently, return flows to the river at the bridge abutment, due to the embankment contracting the flow, would be representative of field conditions. The model abutment was a vertical wall type with set-back from the channel representative of typical field sites and aligned with the flow. The floodplain and channel bank were rigid with a mobile channel bed. Sediment size was chosen such that bedforms would be minimized and the sediment would approximately scale to field size. All flows were run at the incipient velocity for sediment motion to provide maximum scour conditions and a consistent velocity ratio from one experiment to the next. The tests were run at the approximate bankfull condition and for a range of flood flows to determine peak flow effects.

TABLE 2. Model Dimensions.

Variable	Abutment Model (1:18)	Pier Model (1:9)
Channel Width (cm)	76	152
Bankfull Depth (cm)	10	15
Sediment Size (mm)	1	1
Floodplain Width (cm)	76	–
Abutment Setback (cm)	25	–
Pier Diameter (cm)	–	8

Generalized scaling of bridge, flow, and sediment characteristics was accomplished based on the Froude number ($F_r = V/(gy)^{1/2}$, where V = flow velocity, g = gravitational constant, and y = flow depth), the flow distribution between the channel and overbank area, and geometrical similarity. Froude number similarity is important in any open channel flow problem. Although it is usually impossible to preserve similarity between multiple similarity parameters, the parameters can be maintained within an acceptable range that supplies typical values in the field and that provides the appropriate flow conditions. In the case of mobile bed studies, the Froude number is kept within an acceptable range so that the velocity ratio can be maintained at the desired value. Table 2 provides the dimensions of the two models used for vanes and cross vanes (abutment model) and w-weirs (pier model). When modeling the effectiveness of W-weirs in controlling pier scour, the full 1.5-m width of the flume was used to model channel width.

A total of 76 experimental runs were conducted, with each run lasting four hours. Although this length of time at incipient motion does not yield the maximum scour depth, it does provide approximately 75 percent of the total scour based on the Laursen (1963) equation as recommended in Umbrell *et al.* (1998). Since the objective of the experiments was to determine the change in the scour pattern with the use of vanes and weirs rather than the determination of the maximum scour depth, it was decided that a four-hour time interval provided a consistent and adequate time period.

Six initial runs were conducted with the abutment in place, but with no vanes or cross vanes upstream, over a range of flow conditions to determine the location and extent of scouring that would occur without these measures. For the w-weirs, this process was repeated; five runs were conducted over a range of flows with no w-weir in place so that scour at the unprotected pier could be measured to use as a comparison. The orientation of the structures relative to the bank (i.e., the angle from the bank), the location of the structures with respect to the bridge, the number of vanes required to reduce scour, and the height of the w-weir apex were varied and tested over a range of flows to assess the ability of the structure to modify flow at the channel bed and reduce scour under flood conditions. The resulting scour depths and channel bed topography were measured and recorded at the end of each four-hour period. A summary of the ranges of values for the experimental runs are given in Table 3.

TABLE 3. Summary of Experimental Data.

Structure	Angle at Bank (degree)	Interior Angle (degree)	Number of Structures	Distance From Structure to Abutment or Pier	Discharge (m^3/s)	Flow Depth (cm)
Vane	20-30	N/A	1-3	0-2W	0.021-0.084	15-28
Cross Vane	25	N/A	1	2W	0.031-0.072	19-28
W-Weir	25	30-40	1	0.3W	0.066-0.209	15-43

Results

The results, given in Table 4, showed that the following configurations produced the lowest scour depths at the bridge foundations.

Vanes. Vanes should be orientated upstream at 30 degrees to the bank (see Figure 4), which yields a scour reduction ranging from 64 to 90 percent for flow depths ranging from 15 to 28 cm (corresponding to the bankfull to 100-year events), respectively. The vane should extend about one-third of the bankfull channel width into the channel from the bank (Rosgen, 1996; Brown and Johnson, 1999). At the bank, the height of the vane should be at the bankfull elevation, pitching down to the channel invert at its tip. This pitch from the horizontal should not exceed about 7.5 percent on low to moderate slopes less than about 0.02 (scour depths increase with larger pitch angles because the overtopping flow is drawn over the structure quite abruptly). This geometry dictates that in order to achieve a 7.5 percent pitch with a 30 degree orientation to the bank, the channel must have a width to depth ratio of at least 20. If this cannot be met, then for a width to depth ratio of 17 or more, a 25 degree orientation to the bank can be used. The orientation should not be reduced below 25 degrees as lower angles were shown to be less effective at moving scour away from the bridge abutment and banks. On higher slopes, 0.02 up to about 0.045, a higher pitch can be used, on the order of 12 to 14 percent. A series of two or more vanes placed upstream from the abutment provides slightly more flow and scour control than just one, resulting in a scour reduction of about 15 percent over the one-vane case. The vane should be placed upstream from the abutment such that $1.5W \leq d \leq 2W$, where W is the channel width and d is the projected distance along the bank from the upstream corner of the abutment to the upstream tip of the vane (with $d \geq 0$). This assures that the bridge abutment will be within the zone of separation caused by the vane. Vanes placed just upstream of the bridge abutment or attached to the wing wall do a poorer job in terms of reducing scour than when the vane is placed further upstream. There are two reasons for this. First, during an overbank flow, the shear stresses are highest at the upstream corner of the abutment due to the obstruction to the flow and the overbank flow returning to the channel to pass under the bridge. A vane located in the zone where the shear stresses and flow accelerations are already high may actually cause additional acceleration of flow over the vane. If a second vane is used, the spacing between the vanes should be based on the same calculation as the spacing between the bridge and the vane except that the distance will be measured from the upstream tip of the first (downstream) vane to the upstream tip of the second (upstream) vane. Figure 5 shows the design parameters for vanes upstream of abutments.

Cross Vanes. Cross vanes are designed similarly to vanes except that the connecting central portion (the center one-third of the channel) is placed at the channel invert. The arms of the cross vane are designed the same as for vanes with one vane on each side of the channel. Figure 6 shows the design parameters for cross vanes upstream of abutments.

W-Weirs. W-weirs are placed upstream of bridge piers such that the flow is diverted around the pier. At the banks, the weir height is at the bankfull elevation to maintain the proper horizontal pitch from the bank to the channel bed (see discussion under *Vanes*). At the central apex, the weir height is about three-quarters of the bankfull elevation and the two upstream apexes are at the channel invert. This height provided the optimum deposition zone upstream of the pier in that the pier was located in the deposition zone and the scour depth with respect to the original channel bed was minimal. The angle at the bank, θ, should be 25 degrees while the angle in the central apex, α, should be about 40 degrees (see Figure 7). This configuration provides a low horizontal pitch (about 4 degrees or less) of the weir arms (L in Figure 8) from the downstream apex to either upstream apexes and permits optimal flow over the weir. Other configurations, particularly those that yield a higher pitch, result in too much water flowing over the apex which, in turn, causes additional scour at the pier. To investigate this, a set of five experiments were conducted with the pitch set at 9.5 degrees. The results showed that scour in excess of that which would occur with no w-weir in place, occurred for at least one flow depth. In addition, several supplementary experiments were conducted with a central apex angle of 30 degrees, yielding a relatively shallow pitch. The results showed that too shallow a pitch provides very little benefit to the bridge pier in terms of diverting flow and reducing scour. Based on the depositional pattern observed when only the w-weir was placed in the flume, it was shown that the w-weir should be placed 0.3W upstream from the pier, where W is the bankfull channel width. Figure 8 shows the design parameters for the placement of a w-weir upstream of a bridge pier. An additional benefit of w-weirs that became apparent during the experiments was that a w-weir placed upstream of a bridge effectively produces uniform flow conditions across the cross section. If the flow entering the weir has higher velocities in one part of the channel than another, at the exit of the weir, the velocities will be

TABLE 4. Experimental Data for Vanes, Cross Vanes, and W-Weirs.

Run Number (1)	Structure (2)	Height (3)	Angle (4)	Number of Structures (5)	Distance (m) (6)	Discharge (m^3/s) (7)	Flow Depth (cm) (8)	Scour Depth at Abutment or Pier (cm) (9)	Percent Reduction in Scour at Abutment or Pier (10)
1	None	–	–	–	–	0.017	9	0	
2	None	–	–	–	–	0.03	15	1.4	
3	None	–	–	–	–	0.037	19	1.4	
4	None	–	–	–	–	0.053	22	3.5	
5	None	–	–	–	–	0.057	25	6.9	
6	None	–	–	–	–	0.064	28	8.6	
7	Vane	Bankfull	20	1	0.094	0.021	15	2	-42.9
8	Vane	Bankfull	20	1	0.094	0.044	19	0.9	35.7
9	Vane	Bankfull	20	1	0.94	0.057	22	1.1	68.6
10	Vane	Bankfull	20	1	0.94	0.068	25	3	56.5
11	Vane	Bankfull	20	1	0.94	0.084	28	3.3	61.6
12	Vane	Bankfull	25	1	0.94	0.024	15	0.5	64.3
14	Vane	Bankfull	25	1	0.94	0.057	22	1.9	45.7
15	Vane	Bankfull	25	1	0.94	0.067	25	2.7	60.9
16	Vane	Bankfull	25	1	0.94	0.07	28	3.6	58.1
17	Vane	Bankfull	30	1	0.94	0.026	15	0.5	64.3
18	Vane	Bankfull	30	1	0.94	0.035	19	0.5	64.3
19	Vane	Bankfull	30	1	0.94	0.057	22	0.8	77.1
20	Vane	Bankfull	30	1	0.94	0.059	25	1.3	81.2
21	Vane	Bankfull	30	1	0.94	0.067	28	0.9	89.5
22	Vane	Bankfull	25	1	0.41	0.047	22	1.1	68.6
23	Vane	Bankfull	25	1	0.41	0.062	25	5.2	24.6
24	Vane	Bankfull	25	1	0.41	0.081	28	6.7	22.1
25	Vane	Bankfull	25	1	1.25	0.047	22	0.2	94.3
26	Vane	Bankfull	25	1	1.25	0.061	25	0.5	92.8
27	Vane	Bankfull	25	1	1.25	0.054	28	1.7	80.2
28	Vane	Bankfull	25	2	0.94/0.94	0.049	22	0.8	77.1
29	Vane	bankfull	25	2	0.94/0.94	0.069	25	1.7	75.4
30	Vane	Bankfull	25	2	0.94/0.94	0.079	28	2.5	70.9
31	Vane	Bankfull	25	2	1.25/1.25	0.07	28	0.4	95.3
32	Vane	Bankfull	25	3	1.25*3	0.072	28	0.8	90.7
38	Cross Vane	Bankfull	25	1	1.25	0.031	19	0	100
39	Cross Vane	Bankfull	25	1	1.25	0.041	22	2	42.9
40	Cross Vane	Bankfull	25	1	1.25	0.061	25	5.8	15.9
41	Cross Vane	Bankfull	25	1	1.25	0.072	28	5.9	31.4
42	None	–	–	–	–	0.92	15	N/A	
43	None	–	–	–	–	0.13	22	N/A	
44	None	–	–	–	–	0.18	29	N/A	
45	None	–	–	–	–	0.208	36	N/A	
46	None	–	–	–	–	0.25	43	N/A	
47	W-Weir	Bankfull	50	1	2.38	0.091	15	N/A	-24.7
48	W-Weir	Bankfull	50	1	2.38	0.176	22	N/A	33.3
49	W-Weir	Bankfull	50	1	2.38	0.229	29	N/A	40.7
50	W-Weir	Bankfull	50	1	2.38	0.232	36	N/A	40.9
51	W-Weir	Bankfull	50	1	2.38	0.231	43	N/A	18.6
52	W-Weir	+2 cm	50	1	2.38	0.269	43	N/A	26.3
53	W-Weir	-2 cm	50	1	2.38	0.26	43	N/A	20.3
54	W-Weir	Bankfull	35	1	2.38	0.229	43	N/A	21.2

TABLE 4. Experimental Data for Vanes, Cross Vanes, and W-Weirs (cont'd.).

Run Number (1)	Structure (2)	Height (3)	Angle (4)	Number of Structures (5)	Distance (m) (6)	Discharge (m^3/s) (7)	Flow Depth (cm) (8)	Scour Depth at Abutment or Pier (cm) (9)	Percent Reduction in Scour at Abutment or Pier (10)
55	W-Weir	Bankfull	20	1	2.38	0.237	43	N/A	46.6
56	W-Weir	Bankfull	20	1	2.38	0.104	15	N/A	51.5
57	W-Weir	Bankfull	20	1	2.38	0.207	29	N/A	1.6
58	None	–	40	1	–	0.067	15	N/A	
59	None	–	40	1	–	0.098	22	N/A	
60	None	–	40	1	–	0.135	29	N/A	
61	None	–	40	1	–	0.178	36	N/A	
62	None	–	40	1	–	0.204	43	N/A	
63	W-Weir	7.5	40	1	–	0.075	15	N/A	
64	W-Weir	7.5	40	1	–	0.104	22	N/A	
65	W-Weir	7.5	40	1	–	0.143	29	N/A	
66	W-Weir	7.5	40	1	–	0.176	36	N/A	
67	W-Weir	7.5	40	1	–	0.203	43	N/A	
68	W-Weir	7.5	40	1	0.46	0.079	15	N/A	18.8
69	W-Weir	7.5	40	1	0.46	0.105	22	N/A	7.7
70	W-Weir	7.5	40	1	0.46	0.143	29	N/A	14.3
71	W-Weir	7.5	40	1	0.46	0.174	36	N/A	29.7
72	W-Weir	7.5	40	1	0.46	0.199	43	N/A	32.1
73	W-Weir	11.25	40	1	0.46	0.106	22	N/A	75.0
74	W-Weir	15	40	1	0.46	0.102	22	N/A	91.3
75	W-Weir	7.5	30	1	0.46	0.105	22	N/A	-6.7
76	W-Weir	7.5	30	1	0.46	0.139	29	N/A	-3.8

NOTES: Column 2. Runs 63-67 were run with w-weir only and no pier.
Column 4. Runs 47-57 angle is inside angle of W; Runs 47-57 bank angle = 25 degrees.
Column 6. Distance for vanes measured from upstream corner of the abutment to the upstream tip of the vane.
Distance for w-weirs measured from tip of vane end (upstream vertex) to center of pier.

approximately uniform across the cross section. In situations where the bed levels vary across the section, the two inverts can be set at different levels. Equally, flows through the one span can be increased by locating its invert further upstream and at a lower elevation.

APPLICABILITY

It is anticipated that vanes, cross vanes, and w-weirs will not be acceptable solutions at all bridges. Certain stream and bridge types will not be amenable to the use of these structures. Based on the experimental work as well as previous use of these structures in the field for stream restoration purposes (e.g., see Anacostia Restoration Team, 1992; Haltiner, 1995; Rosgen, 1996; and Brown and Johnson, 1999), it is likely that they will be best suited to stream channels with the following characteristics:

- Gravel-Bed Streams – Stream bed material with a median sediment size in the gravel to cobble range is most appropriate. Installation in silt or fine sand bed material can be difficult and excessive erosion may occur; thus it is necessary for the installation to be accompanied by the use of geotextiles to promote stability of the structure.

- Bankfull Channel Width Greater Than 12 m (40 feet) – A channel width of at least 12 meters is desirable for w-weirs so that the appropriate angle at the banks and pitch of the structures can be obtained. Cross vanes and vanes can be constructed in narrower channels; however, this requires a lower bank angle (down to 20 degrees) which was shown in the laboratory to be less effective in moving scour away from the abutments than the 25- to 30- degree angles.

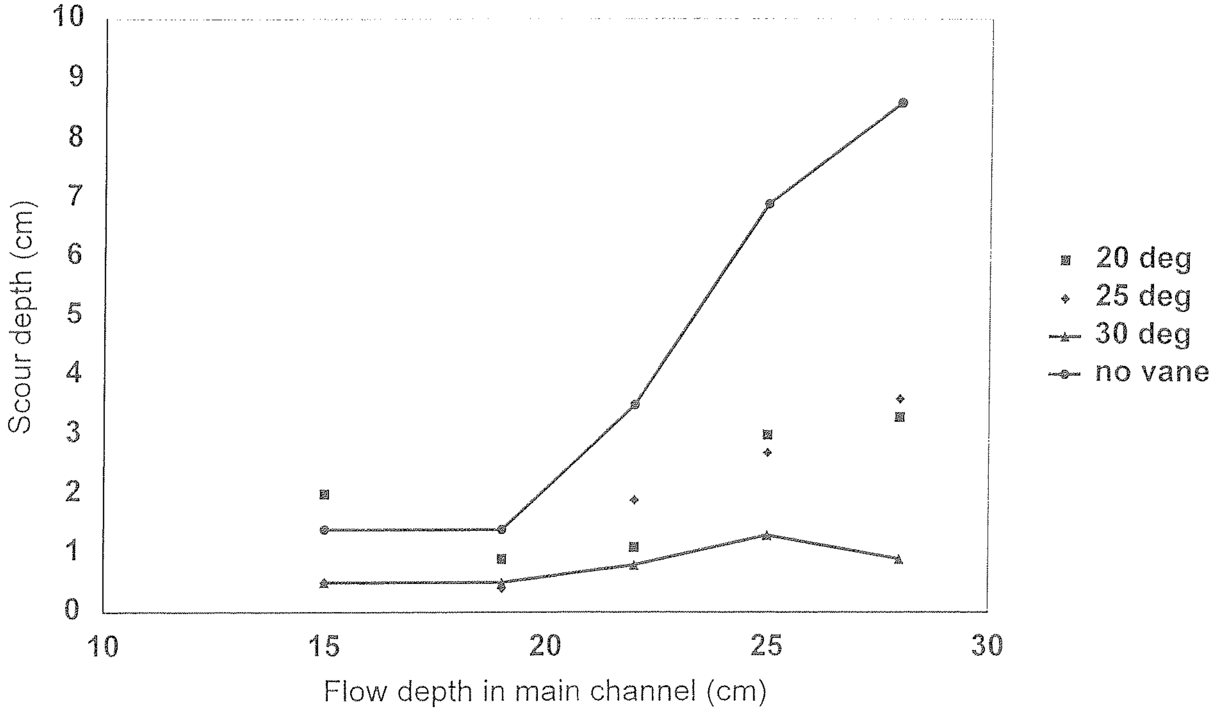


Figure 4. Effect of Vane Angle on Scour Depth.

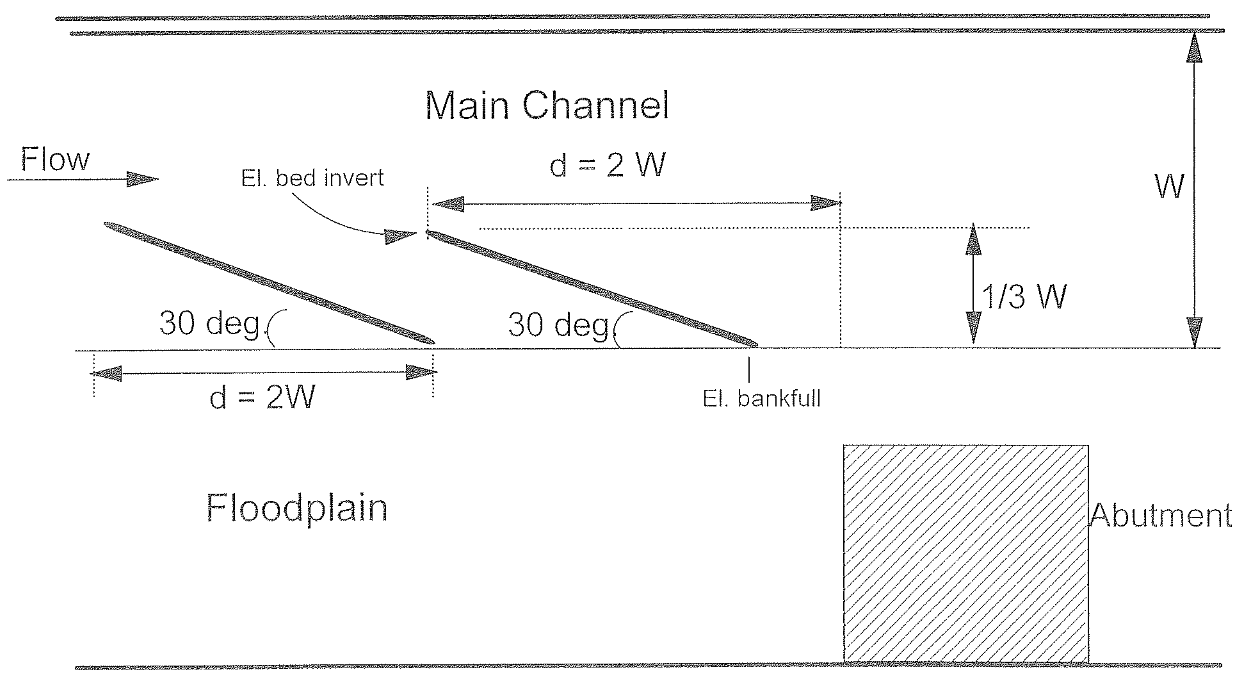


Figure 5. Design Configuration for Vanes.

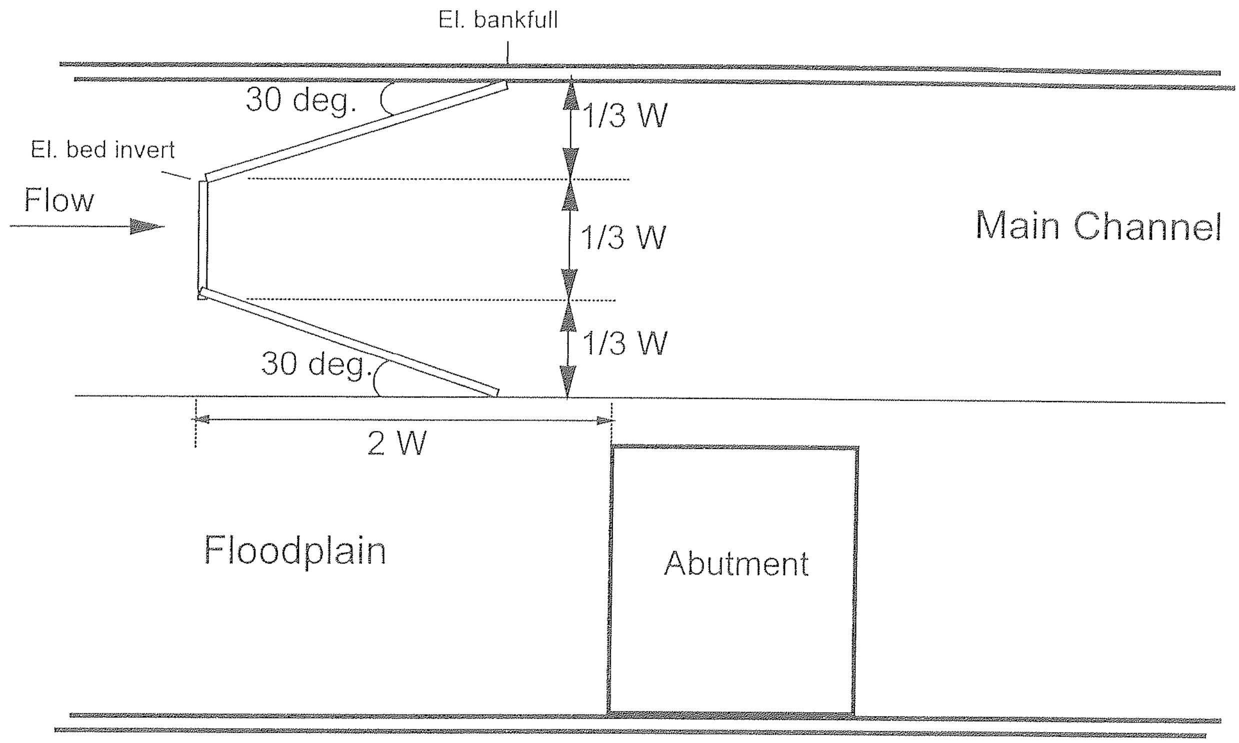


Figure 6. Design Configuration for Cross Vanes.

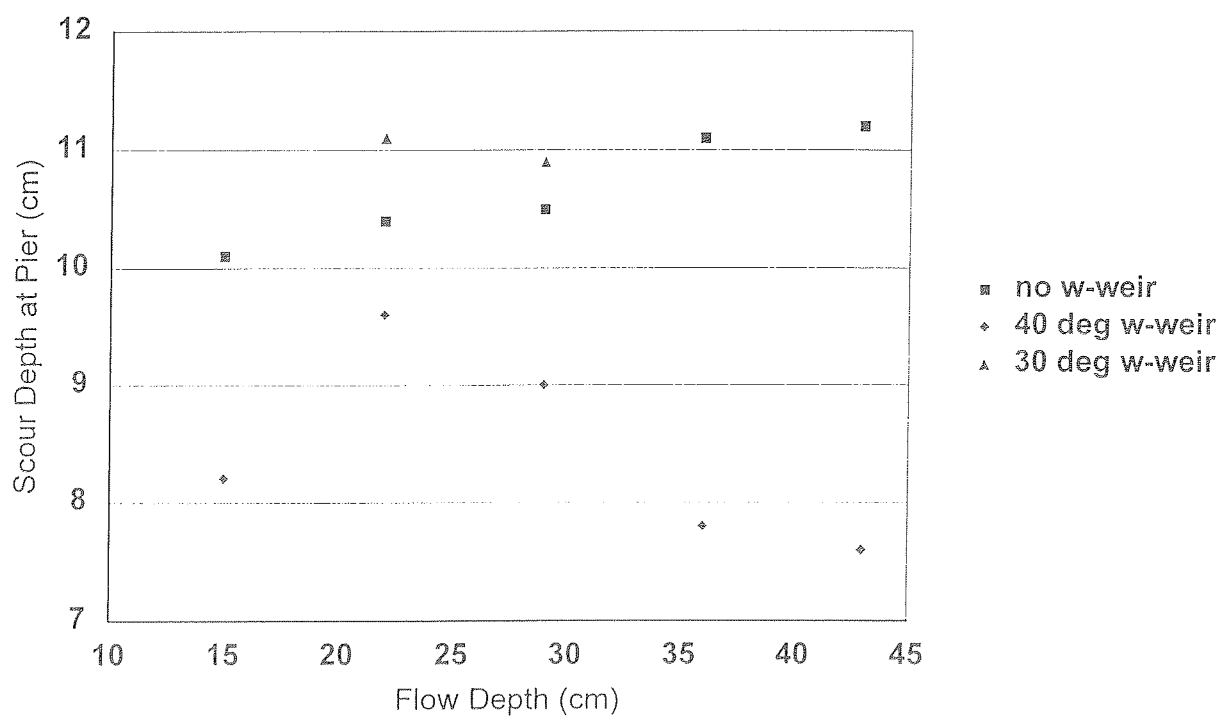


Figure 7. Scour Depth as a Function of W-Weir Central Apex Angle of 30 and 40 Degrees.

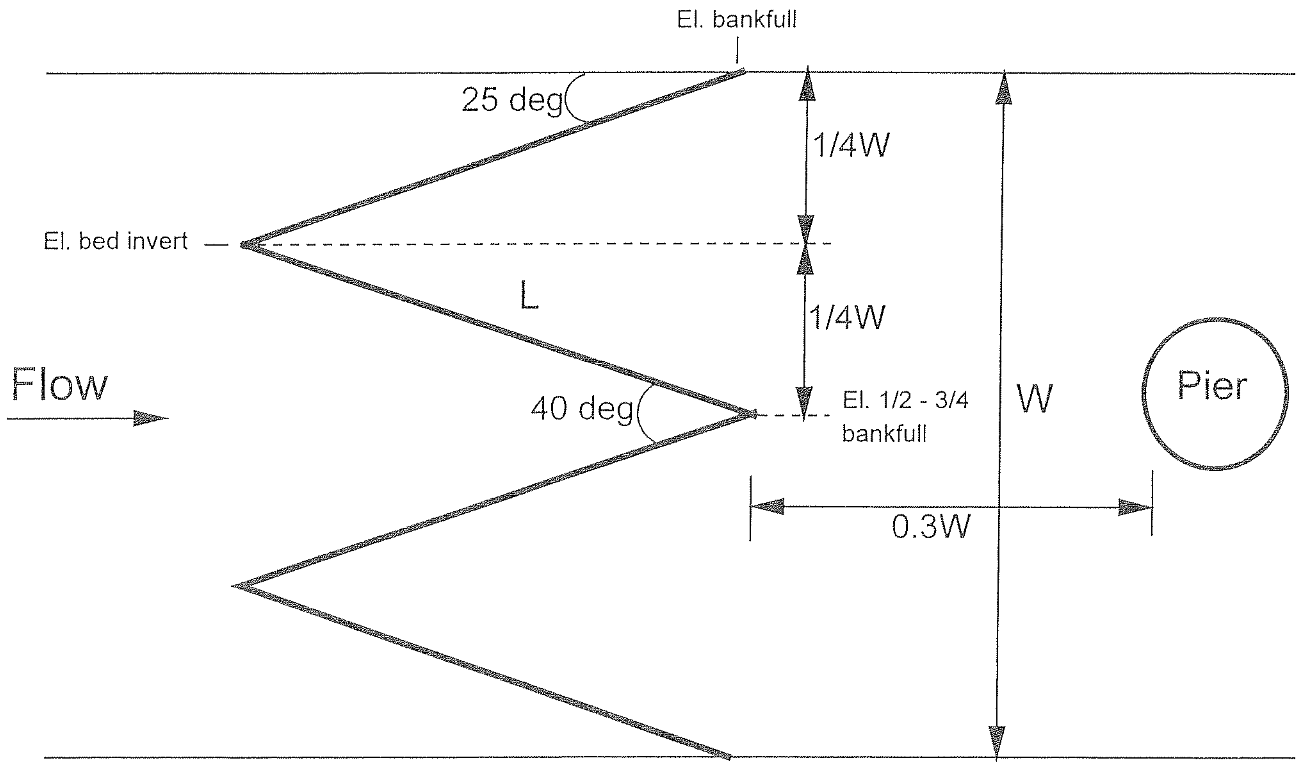


Figure 8. Design Configuration for W-Weirs.

- Moderate Bankfull Width-to-Depth Ratio – A low width to depth ratio will not provide adequate space for the correct angle and pitch of the structures. The width to depth ratio should be at least ten. A reduced angle can be used to accommodate vanes and cross vanes in lower width/depth channels, as described above.

- Channel Pattern – A straight channel or mild to moderate sinuosity is acceptable. Installation of these structures in a braided channel should be avoided.

- Moderate to High Flow Velocity – Slow flow, pooled reaches, and backwater areas are not appropriate because the structures will not have the intended influence upon the flow field.

In addition to the stream channel characteristics listed above, vanes, cross vanes, and w-weirs can be used in streams with a relatively high bedload transport since the higher local velocities encountered in the vicinity of the structure permit passage of bedload. Urban streams which experience "flashy" flows can also be acceptable environments for these structures, provided that the other characteristics listed above are present.

The limitations and recommendations for appropriate stream characteristics lead to the following bridge characteristics that are recommended for these structures:

- Single Span Bridge – For single span bridges, vanes or cross vanes will provide flow transitions through the span and reduce shear stresses and scour along the abutments.

- Double Span Bridge – For two-span bridges, w-weirs will provide flow transition through the bridge opening and will reduce shear stresses and scour at both the abutments and center pier.

- Blocked Floodplain – For bridges where the floodplain is blocked or partially blocked by the bridge approach or embankments, vanes, cross vanes, and w-weirs can be particularly effective in providing a smoother transition from the upstream floodplain through the bridge opening.

- Span Width – As stated above, the bankfull channel width must be at least 12 meters to accommodate w-weirs. Therefore, the span width should also be approximately 12 meters or greater. For vanes, and cross vanes, a smaller span width may be acceptable.

In addition to the structures placed upstream of the bridge, additional structures may be placed just downstream of the bridge opening to maintain a smooth transition throughout the bridge opening and back into the natural channel.

Bridge inspections are required every two years; thus, if the vanes, cross vanes, or w-weirs are part of the bridge system, they will likely need to be inspected every two years as well. Monitoring only after overbank flood events may not be sufficient, as scour can occur during a flood event and refill during the receding flood, leaving minimal evidence that undermining may have occurred. In addition, because the bridge must withstand the 100-year flood, the structures must be monitored to assure that the footing and rock size are adequate to withstand such high shear stresses. The Federal Highway Administration (FHWA) provides guidelines for the selection of rock size for a wide range of flow conditions (Lagasse *et al.,* 1997). It is recommended that the footing consist of one to two layers of footer rocks, depending on the size of the footer, the bed substrate, and the predicted maximum scour depth. In addition, the footing depth should be at least as deep as the deepest scour observed along the thalweg upstream and downstream of the bridge over a reach length no less than 20 times the channel width. Finally, monitoring programs following the construction of stream restoration projects typically have durations of three to five years. Where a bridge is located in the reach and is part of the restoration design, the monitoring duration for the structures at the bridge may need to be considerably longer to capture high flow events.

CONCLUSIONS

Small scale laboratory studies have shown that three rock structures commonly used in stream restoration projects, vanes, cross vanes, and w-weirs, can be effectively used to create flow transitions from the restored stream through bridge openings. This treatment is particularly effective where the floodplain is partially or fully blocked by the roadway embankment. During overbank flood flows, the flow in the overbank area approaching the bridge will be forced to contract just upstream and under the bridge opening. The use of vanes, cross vanes, and w-weirs creates a smoother transition from the floodplain flow to the contracted bridge flow. In addition, the smoother transition and the creation of depositional zones along the banks and, in the case of w-weirs, in mid-channel, prevents undesirable scour from occurring along the abutments and at the piers.

ACKNOWLEDGMENTS

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