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Report No. UT-15.04

ROCK STREAM STABILTY STRUCTURES IN THE VICINITY OF BRIDGES

Prepared For:

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Research and Development Division

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16. Abstract

This report was sponsored by the Utah Department of Transportation (UDOT) to determine if rock stream stability structures could be used as scour countermeasures and to protect streambanks. Traditional scour countermeasures, such as rock riprap, are effective in minimizing erosion but may not provide the best aquatic habitat. UDOT is interested in finding countermeasures that are effective in minimizing erosion at design flows and also benefit the aquatic habitat.

David Rosgen, a specialist in fluvial geomorphology, has developed restoration structures that are friendly for aquatic habitat and also provide streambank protection and stream stability. These structures are the J-Hook Vane, Cross-Vane and W-Weir. Based on the findings outlined in this report, Cross-Vanes and W-Weirs can help protect bridges because they will protect both sides of a streambank while also providing grade control of the streambed.

For stream stability structures to withstand design flows and shear stresses experienced near bridges, they should follow the design guidelines specified in this report. One of the most important design guidelines is that the structures discussed in this report have an attached portion of floodplain where the structure meets the streambank. This portion of floodplain area can help to disperse the energy of the flow, thereby reducing shear stresses at abutments.

Cross-Vanes and W-Weirs can help protect bridges and other infrastructure against scour by reducing shear stresses at piers and abutments at the design flood event. To further investigate their use as a scour countermeasure, it is recommended that this type structure be installed near a bridge following this report's design criteria.UDOT believes that Cross-Vanes and W-Weirs should not be used as a primary scour countermeasure and that rock riprap (or other equivalent structural countermeasure) should be used as the primary protection for bridge foundations, abutments and piers.

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EXECUTIVE SUMMARY

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For stream stability structures to withstand design flows and shear stresses experienced near bridges, they should follow the design guidelines specified in this report. One of the most important design guidelines is that the structures discussed in this report have an attached portion of floodplain where the structure meets the streambank. This portion of floodplain area can help to disperse the energy of the flow, thereby reducing shear stresses at abutments. However, in the vicinity of some bridges, a natural floodplain area may not be feasible.

Cross-Vanes and W-Weirs can help protect bridges and other infrastructure against scour by reducing shear stresses at piers and abutments at the design flood event. To further investigate their use as a scour countermeasure, it is recommended that this type structure be installed near a bridge following this report's design criteria.

1.0 INTRODUCTION

1.1 Objective

The objective of this research project is to determine if rock stream stability structures can be used as scour countermeasures and to protect streambanks near state bridges and highways. The Utah Department of Transportation (UDOT) is responsible for over 1800 bridges; more than 800 of these bridges span over water (Zundel, Fazio, 2006). UDOT is responsible for bridge safety and protection against scour. Thus, any scour countermeasure that is used must be able to protect the bridge structure, including piers and abutments, at the design flow.

Many different forms of scour countermeasures exist. Some are highly effective in preventing erosion but may not provide the best aquatic habitat. Countermeasures have been developed that are good for aquatic habitat but appear to be more prone to failure. UDOT is interested in finding scour countermeasures that are effective in minimizing scour while benefitting aquatic habitat.

Stream stability countermeasures made from large rocks are more natural than concrete structures and may provide more environmental benefits. However, depending on their design and placement, many of these structures have not performed well during design flood events. A common issue at bridges with little or no floodplain is contraction of flow through the bridge section which can increase shear stresses and scour. This increase in shear and presence of contraction scour has caused a number of stream stability structures near bridges to fail (Dahle, 2008).

1.2 Scope

The stream stability structures studied in detail in this report are rock cross-vane type structures. This report provides design guidelines for rock cross-vane structures that will help prevent failure during the design flood event. Actual field installation and observance of these structures under various flow conditions will depend on future funding and is not part of this project.

1.3 Report Outline

The following sections are presented:

- A literature review of different scour countermeasure practices near bridges
- Proposed design guidelines for rock stream stability structures that are also able to withstand design flows
- The effectiveness of stream stability structures during design flows
- Conclusions and Recommendations

2.0 LITERATURE REVIEW

The literature review includes a description of the scour that occurs near bridges and various scour countermeasure methods.

2.1 Scour at Bridges

Scour near bridge piers and abutments occurs due to converging flow. The converging flow on piers and abutments produces a recirculating current. The recirculating current begins to scour the streambed around the pier or abutment, exposing the footings (Figure 2-1). The exposed footings put the bridge at risk of failure (Arneson et al., 2012).

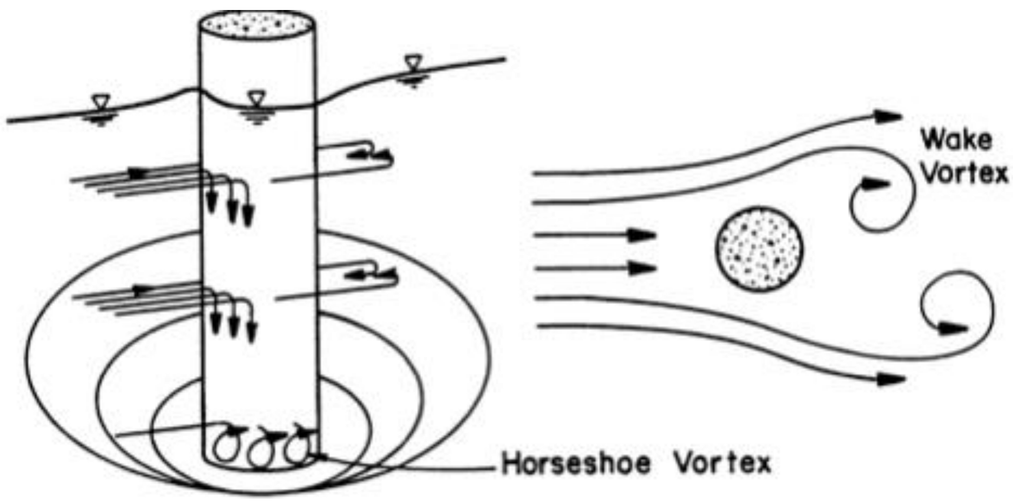

Figure 2-1: Recirculating Current at a Bridge Pier (Arneson et al., 2012).

When bridges are constructed, floodplains are often eliminated to reduce the bridge span. The elimination of floodplains decreases the effective flow area, which forces the stream's flow to be confined to the main channel as it passes under the bridge (Figure 2-2). The smaller effective flow area increases water velocity and the shear stress in the channel, which in turn increases scour; this is known as contraction scour (Arneson et al, 2012).

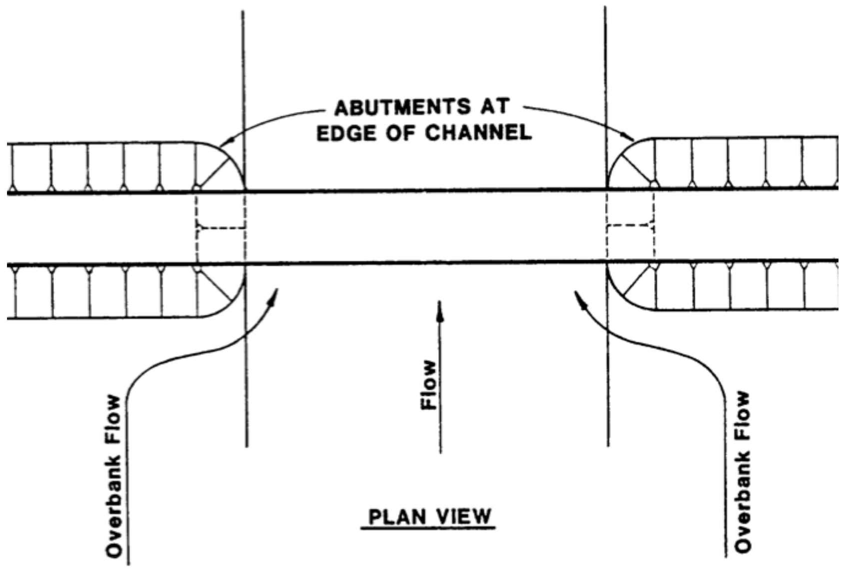

Figure 2-2: Restricted Effective Flow Area Due to Bridge Abutments (Arneson et al., 2012).

2.2 Riprap

The most common practice for protecting streambanks and infrastructure from scour is the use of riprap (Lagasse et al., 2009a). Riprap armors the area where scour is a concern with larger rocks that will resist the scouring flows; this is used along streambanks, bridge piers and bridge abutments (Figure 2-3). This is a popular method because it is cost effective and has in many cases, provided reliable protection (Grinderland, 2013).

Figure 2-3: Riprap Used to Protect a Bridge Abutment. Flow from Left to Right (Photo by Evan Cope).

Rock riprap is generally well graded to help the riprap layer to interlock, creating a stronger and more resistant revetment. Well-graded riprap also has fewer void spaces than uniformly graded riprap; the decreased void space reduces the passing of underlying finer bed material through the riprap layer (Lagasse et al., 2009a).

When using rock riprap, it is important to armor the bank to a depth deeper than the maximum scour near the toe of the riprap revetment. If scour occurs and undermines the toe of the riprap revetment, the riprap will begin to slide down the slope of the streambank into the scour hole. An effective solution is to place a greater volume of riprap at the toe of the abutment to allow the natural replacement of rock if it becomes dislodged due to scour. It is also important to provide a filter beneath the riprap layer to prevent fines from migrating out of the embankment and side slopes. Filters can consist of geo-separation fabric or a carefully designed granular layer. The riprap surface should have a smooth transition from native streambank to riprap revetment. An abrupt change can cause scour to occur at the transition’s location and will begin to undermine the riprap layer (Figure 2-4), potentially causing failure (Grinderland, 2013).

Riprap can be very effective in protecting bridges and other infrastructure from scour, but does not eliminate scour. The area that is armored with riprap is protected, but scour may occur elsewhere where riprap armoring is not present (Lagasse et al., 2009a); scour may occur on the streambank or in the streambed near the riprap or downstream from the riprap (Figure 2-4) (Grinderland, 2013).

Figure 2-4: Abrupt Change from Riprap to Streambank, Causing Downstream Scour. Flow from Top to Bottom (Photo by Evan Cope).

2.3 Stream Stability Structures

Rock vane type structures provide protection against streambank erosion by redirecting the flow away from the streambank and towards the center of the channel. They do not eliminate erosion but tend to move erosive forces towards the center of the channel instead of along the streambank (Johnson et al., 2001). These structures can reduce the need for riprap along the streambank as the flows are directed away from the banks (Sotiropoulos, 2013). Rock vane type structures are favored by natural resource agencies because they provide aquatic habitat in the stream channel. The stream stability structures researched for this report are constructed from large rock and are designed to be keyed into the channel and submerged in lower flows.

While natural resource agencies may be in favor of these structures, their ability to protect bridges is questionable. Bridges are generally designed for the 50-year flood event and must withstand scour forces from the 100-year flood event. In the past, stream stability structures have been designed for lower flows (not exceeding 5-year); but they must also withstand erosive and scour forces from higher design flows in order to function long term. Failure of these structures in higher flows has prevented their use as stand-alone scour countermeasures.

2.3.1 Bendway Weirs

Bendway weirs are small weirs comprised of rock riprap (Figure 2-5) that extend into the channel no more than one third of the channel width. They are designed to be submerged during seasonal mean stream flows. They are built at an upstream angle of 60 to 80 degrees from the streambank tangent line (Figure 2-6). Bendway weirs realign flow and reduce velocities near the streambank (Lagasse et al., 2009b).

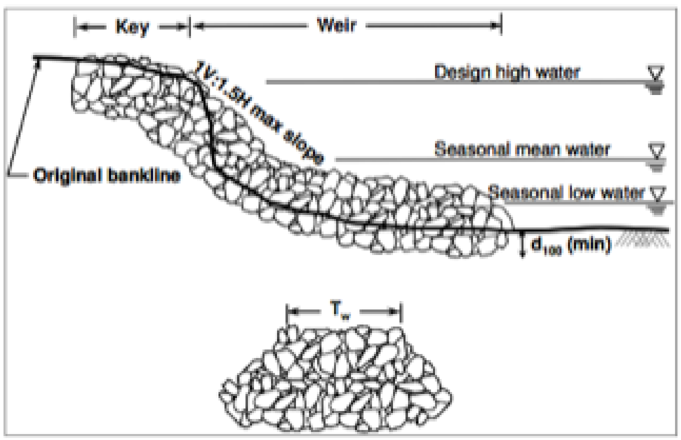

Figure 2-5: Bendway Weir Cross Section (Lagasse et al., 2009b).

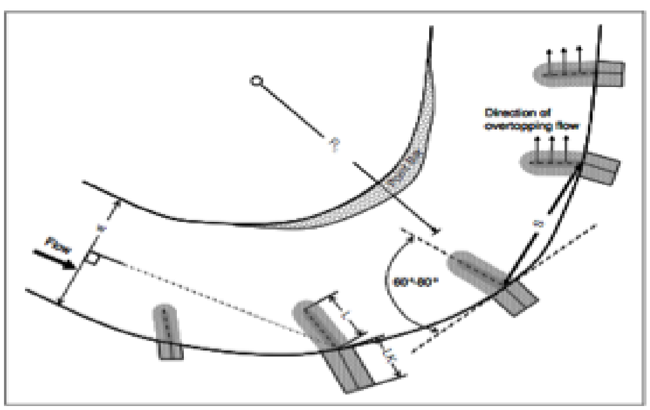

Figure 2-6: Bendway Weir Plan View (Lagasse et al., 2009b).

Bendway weirs create smaller scour pools than rock vane type structures but the scour is higher near the end of the structure; this must be considered when designing footer rocks (Sotiropoulos, 2013). Due to the smaller scour pool in the center of the channel created by bendway weirs, they do not create as much aquatic habitat. Bendway weirs were initially intended to scalp point bars and relocate the thalweg to the inside of the bend. It was later observed that they also induced sediment deposition near streambanks. The large angle of bendway weirs from the streambank tangent line can create a recirculating current which can cause erosion at the upstream side of the structure where the structure meets the streambank (Rosgen, 2006).

2.3.2 Rock Vane Structures

Rock vane type structures include the J-Hook Vane, Cross-Vane and W-Weir. These structures redirect flows towards the center of the channel, thereby protecting the streambank. They facilitate the development of scour pools at the center of the stream which provide fish habitat (Rogen, 2006). Rock vane structures should be constructed at an angle between 20 and 30 degrees from the streambank tangent line to eliminate recirculating eddies behind the structure which may cause streambank erosion. They should be built sloping down from the top of the bank between two and seven percent.

The J-hook Vane is a rock vane structure with a hook near the center of the channel. The vane portion extends 1/4 to 1/3 across the channel width with the next third being “hooked” to create a scour pool for fish habitat (Figure 2-7). The J-hook Vane is used to protect the streambank on one side of the channel by decreasing the bank slope, stream velocity, and shear stress (Rosgen, 2006).

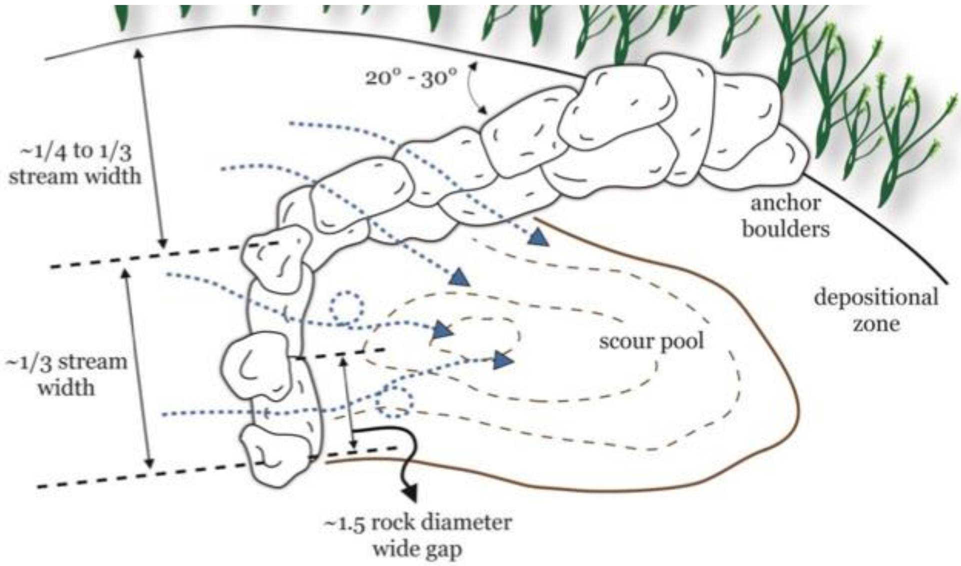

Figure 2-7: J-hook Vane (Sotiropoulos, 2013).

The Cross-Vane consists of two rock vanes, one on each side of a stream each extending into 1/3 of the channel width that connect together near the center of the channel (Figure 2-8). Cross-Vanes are effective when the streambanks on each side of the stream must be protected such as in the vicinity of bridges. They provide grade control of the streambed and reduce bank erosion by directing flow to the center third of the channel (Rosgen, 2006).

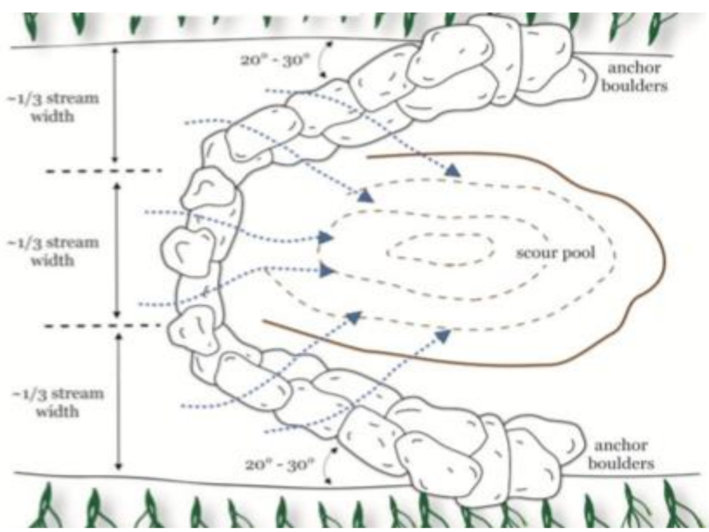

Figure 2-8: Cross-Vane (Sotiropoulos, 2013).

The W-Weir is similar to a Cross-Vane, but consists of a rock Cross-Vane on each half of the stream channel. The rock Cross-Vanes are connected in the center and result in a W-shaped structure (Figure 2-9). The purpose of the W-Weir is to minimize scour along the streambanks and the center portion of the streambed; two scour pools are created, one on each side of the centerline of the channel. The W-Weirs have been recommended for stream bank protection when there are bridge piers in the center of the channel that need scour protection (Rosgen, 2006, Figure 3-1).

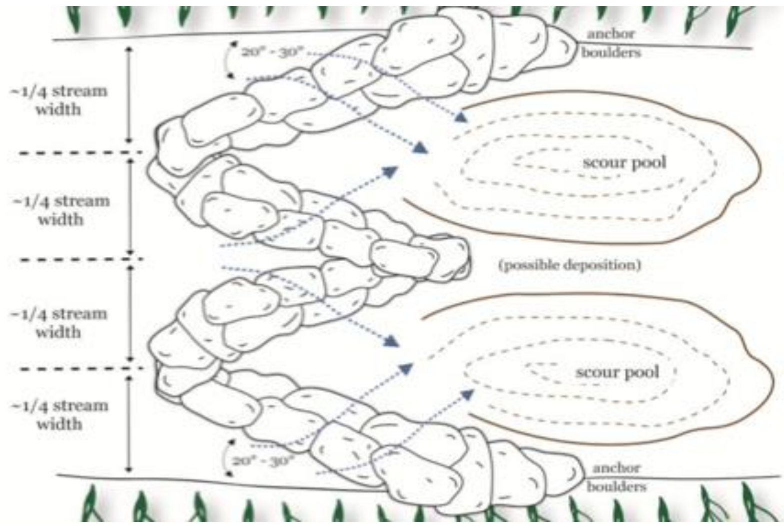

Figure 2-9: W-Weir (Sotiropoulos, 2013).

3.0 DESIGN GUIDELINES

This section describes design guidelines for rock Cross-Vane and W-Weir structures. Based on literature reviews, these two structures best satisfy the study objectives of this report to help protect streambanks, bridge piers and bridge abutments while providing better aquatic habitat. Design guidelines are provided to help prevent failure at design flows for bridge scour, such as the 100-year flood.

3.1 Determine Bankfull Conditions

The stream stability structures considered in this report are designed and constructed to bankfull height. The bankfull condition as the elevation at the top of the streambank where flooding begins. The term "bankfull" is primarily used for rivers that have an attached floodplain (Rosgen, 1996) but can, with care, be identified for incised channels where the original floodplain is more commonly called a terrace. Stream stability structures are generally constructed to bankfull height at the streambank location. When the stream flow depth is greater than bankfull height, energy dissipation occurs on the floodplain. At higher flows, this reduces shear stresses in the main channel, thereby reducing scour at bridge piers and abutments.

Bankfull flows range anywhere from the 1-year to the 5-year flood event (Lave, 2008; Zundel, 2006). The bankfull flow corresponds to the discharge at which the stream channel is most effective at moving sediment, forming and removing bars (Dunne, Leopold, 1978). Identifying a preferred method for determining the bankfull discharge is beyond the scope of this project. Whatever method is used, however, a submerged structure is desired to keep a more natural appearance and to keep from damming the stream upstream from the structure.

For stream stability structures to function properly, a floodplain should be present at the determined bankfull height. Stream stability structures that are constructed without a floodplain at the top of the structure are susceptible to greater flow convergence and erosion where the structure meets the streambank. The higher converging flow and shear stresses can lead to scour at bridge piers and abutments. A connected floodplain, such as a bench, at the top of the structure where the structure meets the streambank allows a portion of the stream energy to be dissipated, thereby reducing erosive forces (Figure 3-1).

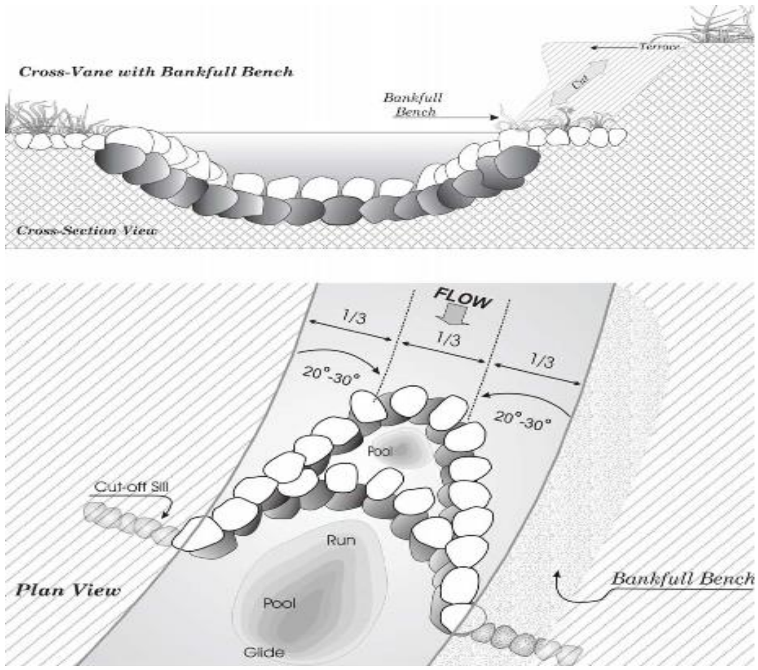

Figure 3-1: Excavated Bankfull Bench for a Stream Stability Structure (Rosgen, 2006).

Proposed guidelines for sizing an excavated bankfull bench are shown in Table 3-1.

Table 3-1: Guidelines For Sizing a Bankfull Bench.

Bankfull Channel Width (ft.)	Minimum Bankfull Bench Width (% of Channel Width)
< 20 ft.	75%
20 – 50 ft.	50%
> 50 ft.	25%

In some cases such as near a bridge, a floodplain cannot be implemented. Bridges are constructed with shorter spans to keep construction costs down, frequently eliminating floodplains. A proposed solution for scenarios where floodplains cannot be implemented is the use of culverts at bankfull elevation constructed as shown in Figure 3-2. These culverts mimic a floodplain.

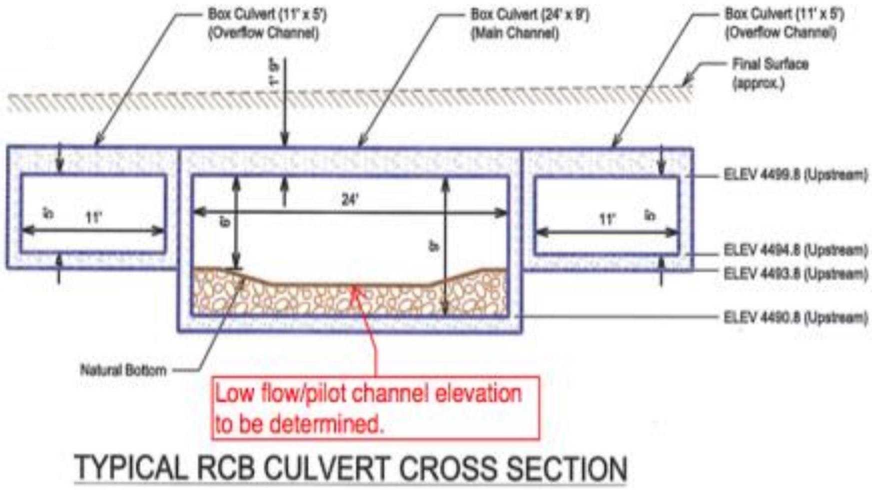

Figure 3-2: Cross-Section Drawing of Overflow Culverts (From Hobble Creek and I-15 Plan Set)

3.2 Rock Sizing

Unlike rock riprap or bendway weirs, rock vane type structures do not have interlocking rock; they require larger rock than riprap or bendway wiers (Sotiropoulos, 2013). The riprap equations that yield the largest sized riprap for bridges are found in Hydraulic Engineering Circular 23 (HEC-23) Volume 2. These equations are specifically designed to size riprap for bridge piers and abutments and yield larger rock sizes compared to other riprap equations due to the greater shear stresses at bridges. HEC-23 also recommends using a 20% factor of safety when using these riprap equations for stream stability structures such as bendway weirs. The formulas give the D50 diameter, which is then doubled to yield the D100 diameter (Lagasse et al., 2009b).

Empirical data provided by David Rosgen to relate shear stress to rock size has been used to create a best-fit equation for rock size (Figure 3-). To validate that stream stability structures require larger rock than the HEC-23 equations, data were analyzed from the Division of Natural Resources (DNR). Cross-sections, channel gradients and Manning's coefficients were provided for the Spanish Fork River near Thistle, Utah. The provided data were used for sizing rock with HEC-23 and with the empirical data provided by David Rosgen. The results for all equations were plotted (Figure **3**) and show clearly that rock vane type structures require larger rock.

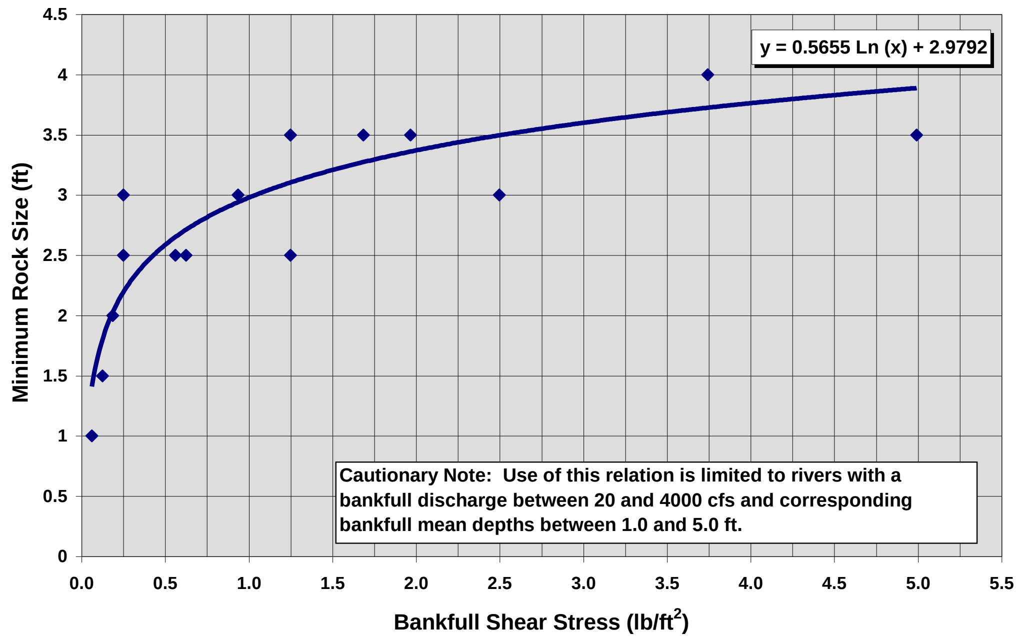

Figure 3-3: Rock Sizing Based off of Shear Stress (Chart by David Rosgen).

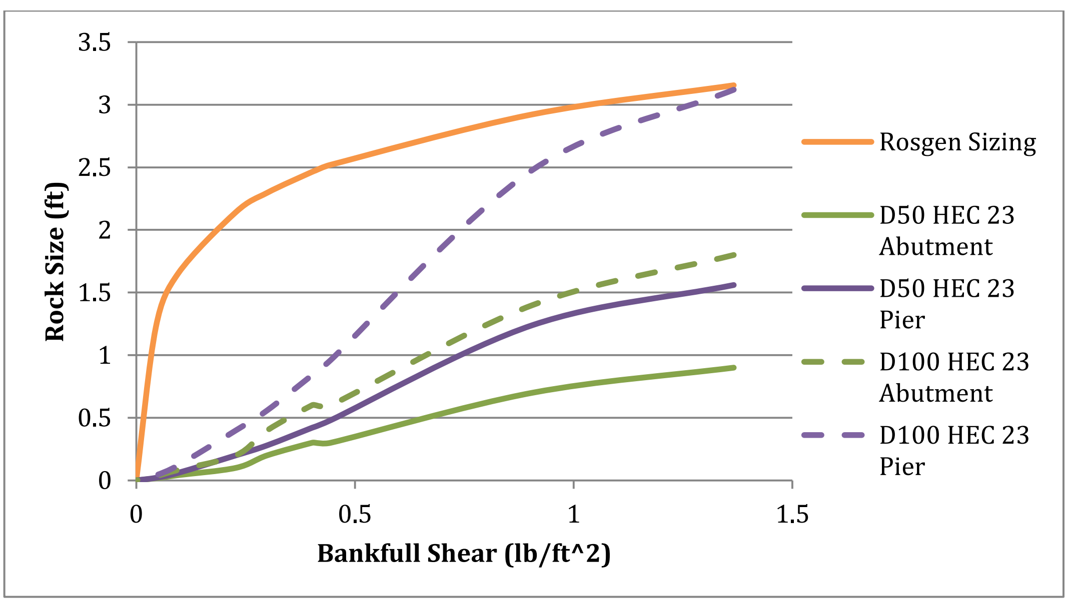

Figure 3-4: Rock Sizing Equations vs. Shear Stress.

To implement rock vane type structures near bridges, rock sizing should be done with the shear stress calculated from a 100-year flow. Sizing rock for a 100-year flow will allow stream stability structures to be built to withstand the higher flows without failure; this enables stream stability structures to be more reliable because the rocks can resist the shear stresses present (Johnson et al., 2002).

3.3 Angle of Structure from Bank

If the angle of a stream stability structure from the tangent line of the streambank is too large, recirculating eddies occur where flow converges with a stream stability structure and the streambank (Rosgen, 2006). The recirculating eddies can actually cause greater bank erosion and eventual failure of the structure (Figure 3-5). The angle from the tangent line of the streambank must be small to eliminate the recirculating eddies. The optimum angle range for rock vane type structures to prevent the recirculating eddies is between 20 and 30 degrees from the streambank tangent line (Figure 3-) (Johnson et al., 2001).

Figure 3-5: Large Vane Angle that Created a Recirculating Eddy and has Actually Increased Streambank Erosion. Flow from Right to Left. (Photo by Evan Cope).

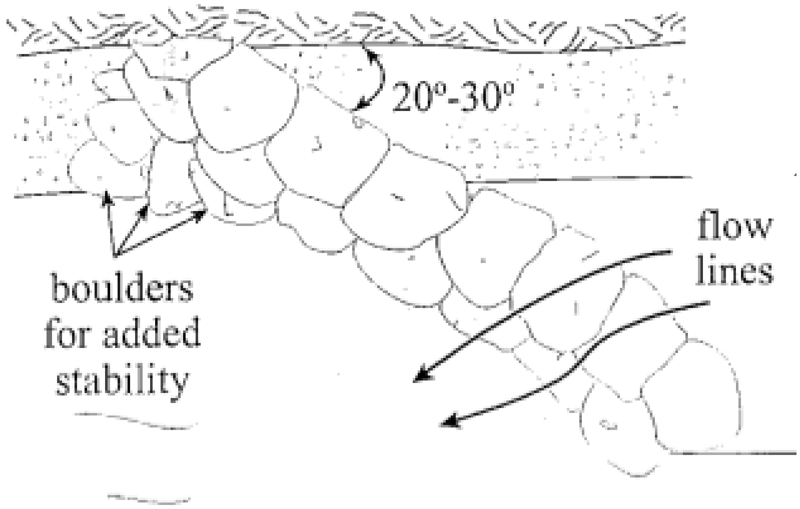

Figure 3-6: Optimum Angle Range from Streambank Tangent Line for Vanes (Johnson et al., 2001).

A 20-degree angle is recommended for the greatest length of bank protection. The smaller angle allows for the construction of a longer stream stability structure because it leaves the streambank and enters the stream more gradually. The longer structure protects a greater amount of streambank (Figure 3-) (Rosgen, 2006). The 20-degree angle also minimizes scour at the end of the structure, providing greater protection to the stream stability structure and its footer rocks (Sotiropoulos, 2013).

Figure 3-7: Tight Vane Angle Protected and Stabilized the Streambank. Flow from Right to Left (Photo by Evan Cope).

3.4 Vane Slope

To best redirect flow towards the center of the channel, the vane must slope upstream. The adverse slope help direct the flow away from streambanks, preventing erosion. The vane slope should be between 2 and 7 percent (Figure 3-, Rosgen, 2006). If slopes are too steep, the vane can actually cause greater streambank erosion (Figure 3-).

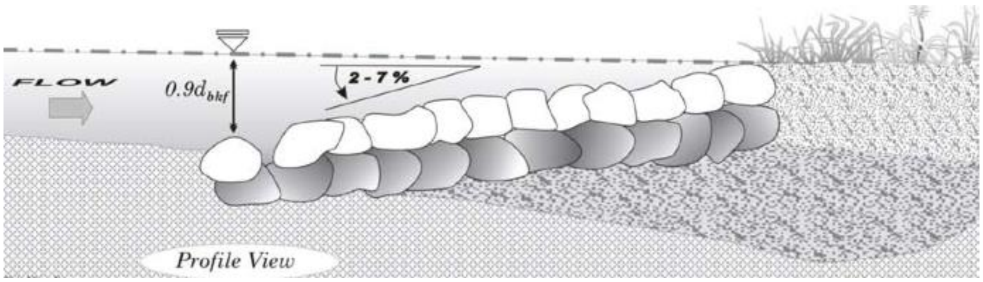

Figure 3-8: Vane Slope (Rosgen, 2006).

Figure 3-9: Steep Vane Slope has Increased Steambank Erosion. Flow from Right to Left. (Photo by Evan Cope)

3.5 Footer Rocks

Footer rocks must be set deeper than the maximum scour hole depth to prevent structure failure. One method proposed for Cross-Vanes and W-Weirs is to have footers that are two to three times deeper than the maximum scour hole present in a structure-free channel

(Sotiropoulos, 2013). Recommended guidelines suggest for the footer rocks to be three times deeper than the rock vane structure's protrusion height above the streambed for gravel streambeds; for sand streambeds, the depth should be doubled to six times (Figure 3-, Rosgen, 2006).

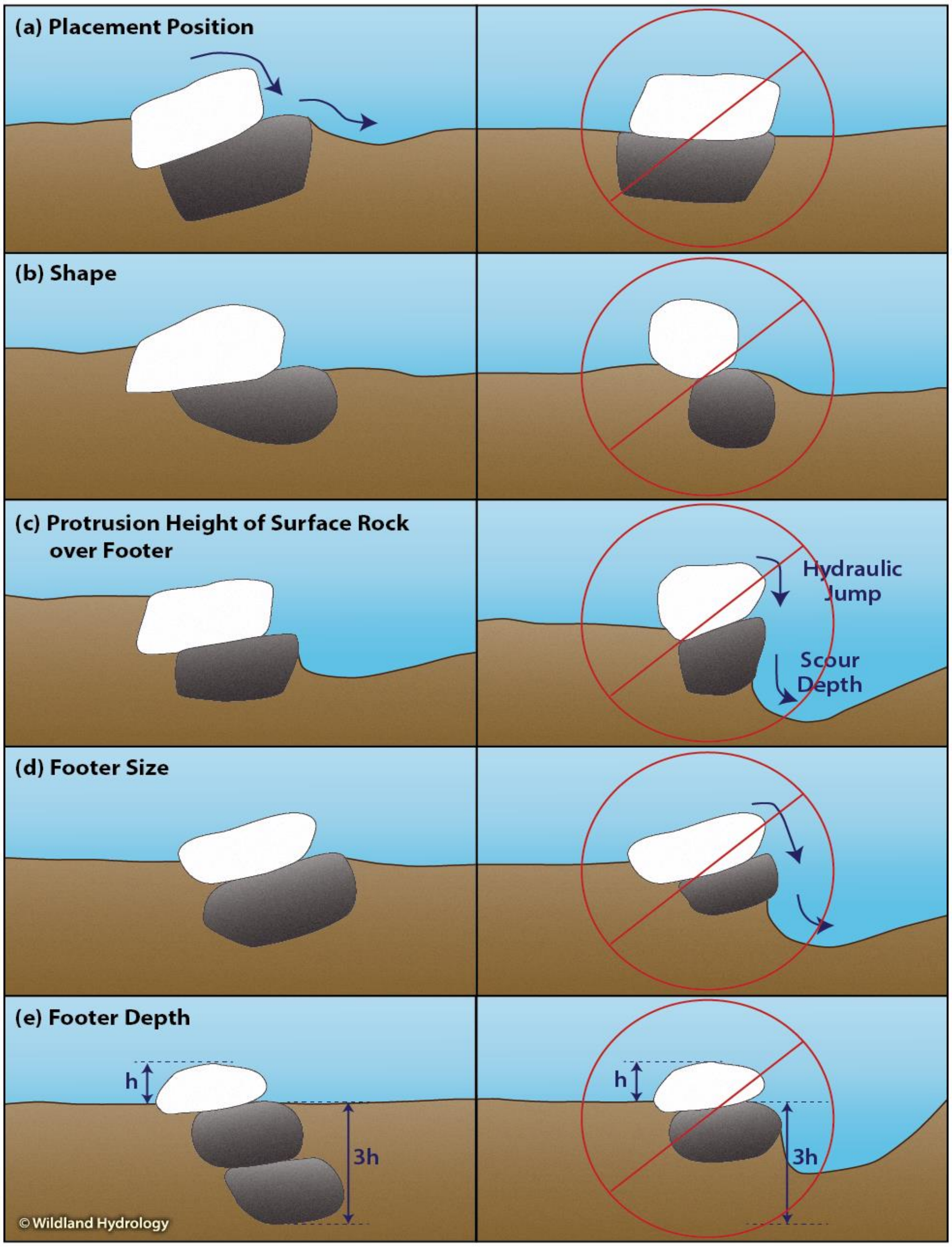

Figure 3-10: Footer Design and Installation. Flow Left to Right (Image from David Rosgen).

In addition to being placed deep, the footer rocks must be designed and installed correctly. The footer rocks must be angled back to the flow so that the protruding rocks can lock into the footer rocks below, giving the rock vane structure greater strength. The footer rocks are placed farther forward than the rocks placed above so that a hydraulic jump is not created and so scour is reduced. Flat rocks are better so that there is more contact surface between the footer rocks and protruding rocks. Footer rocks should be larger or at least equal in size to the protruding rocks (Figure 3-). Following these guidelines protect the footers from scour and being undermined, thereby reducing failure of the stream stability structure (Rosgen, 2006).

3.6 Rock Step

To prevent the downstream scour pool from getting too deep for Cross-Vanes and W-Weirs, a rock step can be installed within the vane arms (Figure 3- and Figure 3-). This creates a series of stream stability structures thereby reducing the size of the scour pool (Sotiropoulos, 2013). This provides additional protection so that the structure's footer rocks will not be undermined and also to contain lateral scour (Rosgen, 2006).

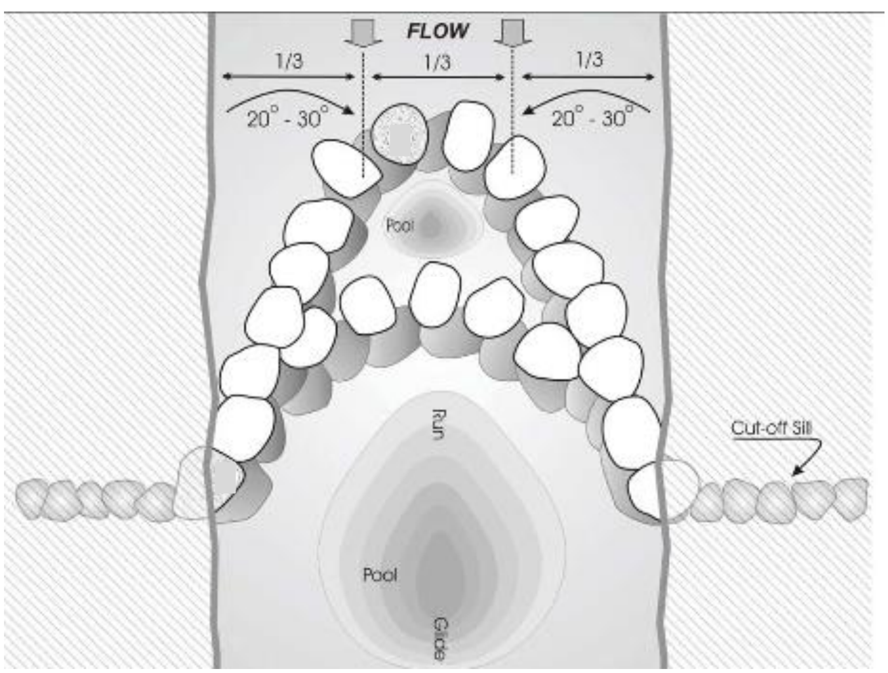

Figure 3-11: Plan View of Rock Step (Rosgen, 2006).

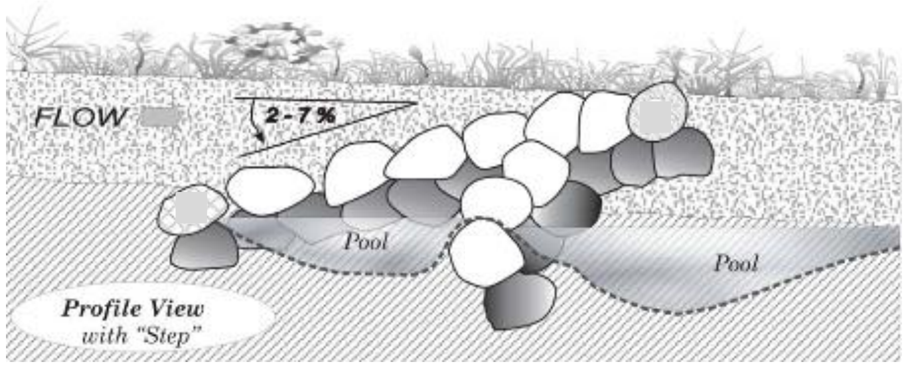

Figure 3-12: Profile View of Rock Step (Rosgen, 2006).

3.7 Upstream Distance from Infrastructure

Written literature recommends placing stream stability structures two channel widths upstream from any bridge or infrastructure that is to be protected (Johnson et al., 2001; Sotiropoulos, 2013) measured from the infrastructure to the crest of the Cross-Vane or W-Weir (Figure 3-). The maximum scour zone exists within one channel width downstream of a stream stability structure; thereby they shouldn't be placed any closer than one channel width upstream from infrastructure (Sotiropoulos, 2013).

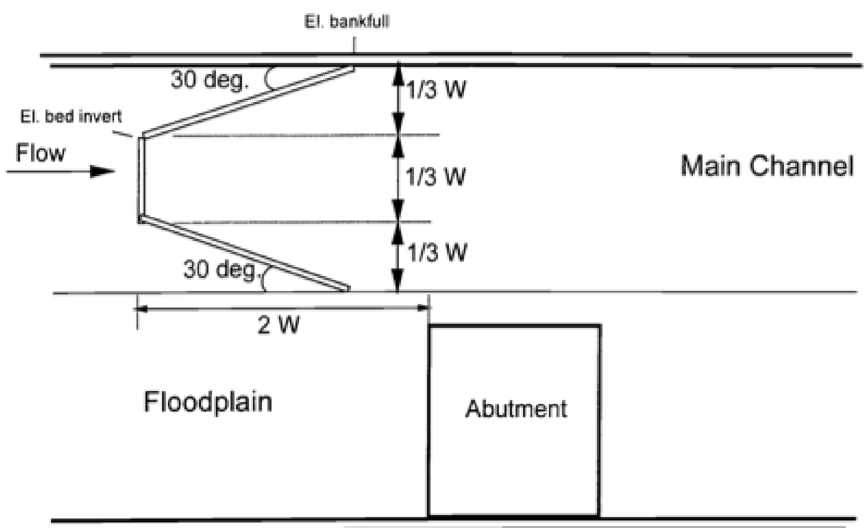

Figure 3-13: Cross-Vane Placed 2 Channel Widths Upstream of Bridge Abutment (Johnson et al., 2002).

There have been disagreements about the claim of placing stream stability structures two channel widths upstream of infrastructure. The stream stability structures are said to have the greatest impact on the flow immediately downstream and so they need to be placed closer to the bridges being protected. The high scour area is contained inside of the arc of a Cross-Vane or W-Weir, which is within one channel width from the structure's crest.

To investigate whether stream stability structures should be placed closer to bridges, a two-dimensional (2-D) model was created using Surface-Water Modeling Software (SMS) and Sedimentation and River Hydraulics- 2D (SRH-2D). SMS was used to prepare a 2-D mesh for SRH-2D. The stream created was a straight trapezoid channel with a connected floodplain at the bankfull height. The designed channel was 40 feet wide with an attached floodplain at 2.5 feet above the streambed. A Cross-Vane was placed inside the stream to see how far downstream the impacts from the Cross-Vane cease (Figure 3-). The cross vane was placed at the bankfull height which was 2.5 feet and gradually sloped down towards the center of the channel at a five percent slope. The arms perpendicular to the bank were each one third the channel width and were connected to the central portion of the structure in the middle third of the channel.

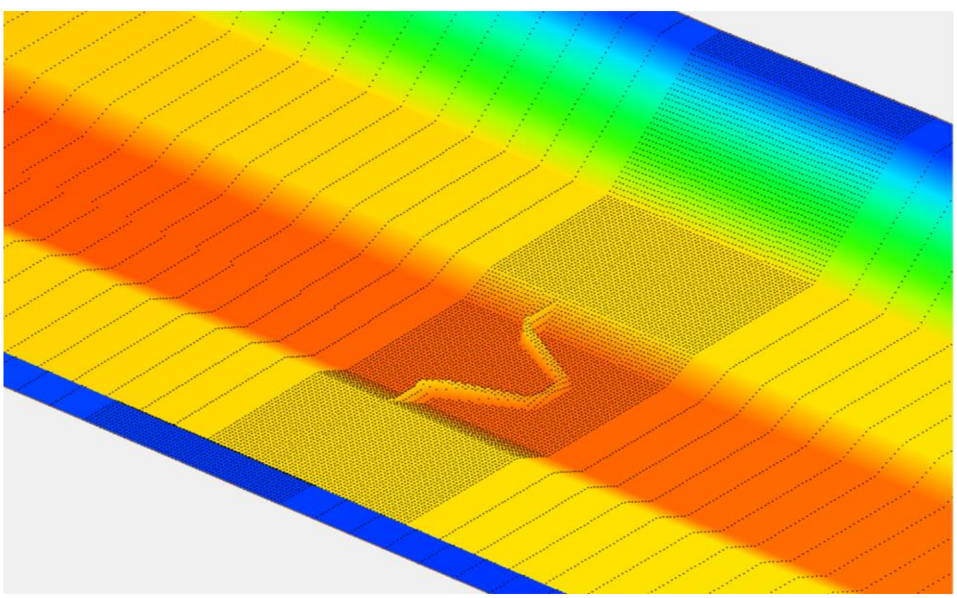

Figure 3-14: 2-D Mesh of River with Cross-Vane (Created with SMS). Downstream is to the left.

To determine how far downstream rock vane type structures have an impact on streambank erosion, the calculated shear stress along the streambank were examined for various flows with a bankfull flow of 400 cubic feet per second (cfs) and a bankfull depth of 2.5 feet. Streambank shear stresses were plotted for different channel widths downstream from the Cross-Vane (Figure 3-).

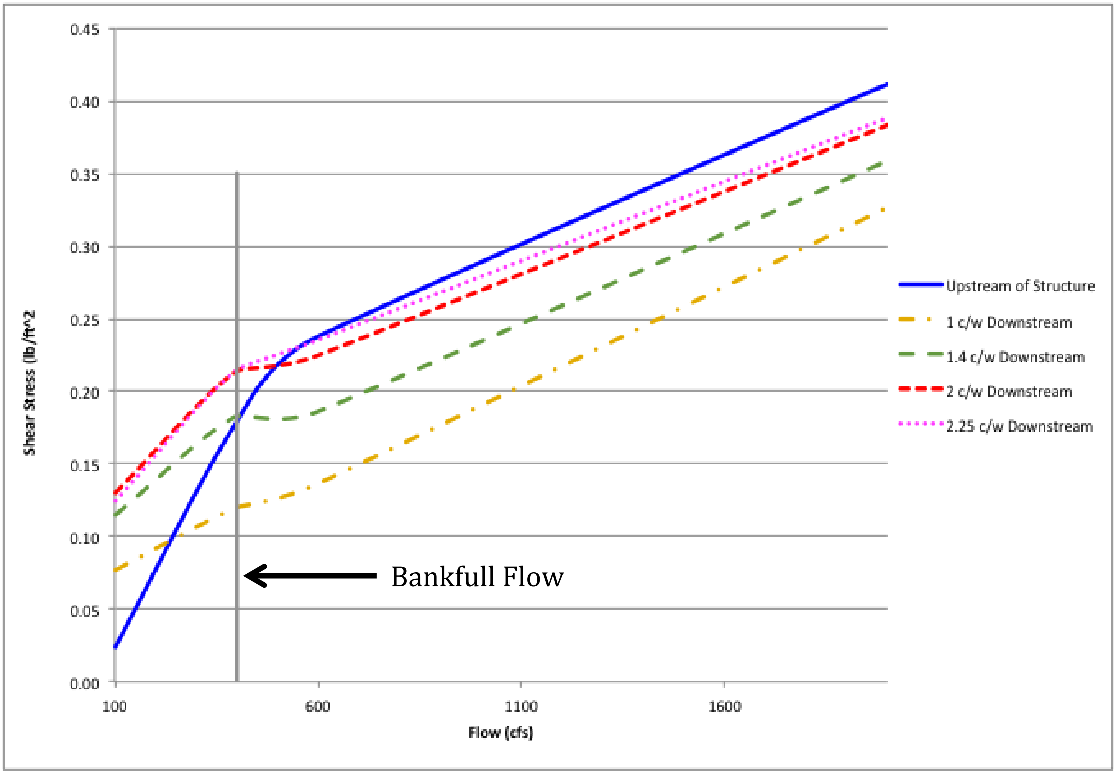

Figure 3-15: Bank Shear vs. Flow for Different Channel Widths Away from Cross-Vane.

For flows near the bankfull flow, the bank shear stress would return to the same shear stress that was upstream of the structure once the flow was two channel widths or greater downstream from the crest of the Cross-Vane. For example, if a Cross-Vane was located 1 channel width upstream from a bridge, shear stress at the bridge would be reduced by about 1/3 for bankfull flows. For larger than bankfull flows, the shear stress 2 channel widths downstream of the Cross-Vane is only slightly less than those measured upstream. Using a location of one channel width upstream from the bridge for larger than bankfull flows, shear stress at the bridge is reduced about 50% due to the Cross-Vane. When looking at Figure 3-, the shear stress at 1 (dash and dot yellow line) and 1.5 (long dashed green line) channel widths downstream from the Cross-Vane is lower than it is upstream (solid blue line) of the Cross-Vane at bankfull and greater flows. In Figure 3- the blue line also shows the bank shear stress without a Cross-Vane structure to help illustrate the difference in shear stress with and without a Cross-Vane Structure.

Based on this model, it is best to place a rock stream stability structure between 1 and 1.5 channel widths upstream of the bridge to be protected; at these locations the streambank shear stresses are still lower than without a Cross-Vane.

4.0 EFFECTIVENESS AT DESIGN FLOWS

Stream stability structures can be built to withstand design flows, but their impact on the design flows is questioned. As stream stability structures become a smaller portion of the total flow depth, their impact diminishes (Sotiropoulos, 2013). Arguments have been made claiming that stream stability structures are still effective at design flows while others claim the contrary. An analysis of a stream stability structure's impact on design flows will be considered in the sections that follow. Although not recommended as a stream stability structure, a labyrinth weir will be included in the discussion to illustrate the impact of flow depth over a structure to downstream changes in velocity.

4.1 Modeling vs. Field Observations

It is important to understand the limits of modeling because models require assumptions. The assumptions that are made must be clearly understood because poor assumptions will result in poor results (Lagasse et al., 2012). Due to the limitations of models, they can have different outcomes than what is actually observed in the field. This creates a difference of opinions, regarding the need for stream stability structures.

A 2-D model performed at Brigham Young University by Ben Dahle demonstrated that at higher flows, stream stability structures become ineffective in their purpose to protect streambanks. The 2-D model was performed by using survey and flow data for Thistle Creek in Thistle, Utah. The surveyed data was loaded into SMS to create a mesh and prepare data for a 2-D model in Finite Element Surface Water Modeling System (FESWMS). The model was calibrated using known flow parameters for the area to create the most accurate model possible (Dahle, 2008).

The flow direction and velocity were checked at different locations along the stream stability structure in Thistle Creek and then compared to a location upstream of the stream stability structure. The flow direction and velocity at the different locations along the structure were compared to the upstream location to analyze the difference created by the structure. The difference for each location along the structure was plotted against different flow depths to show the change of direction and velocity. (Figure 4-1 and Figure 4-2).

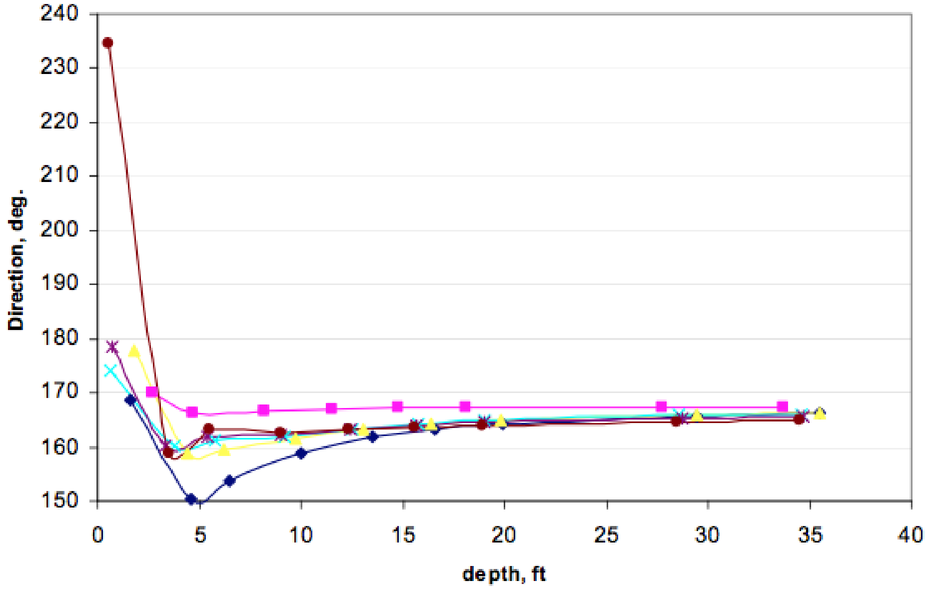

Figure 4-1: Cross-Vane Effective Depth from Change in Flow Direction (Dahle, 2008).

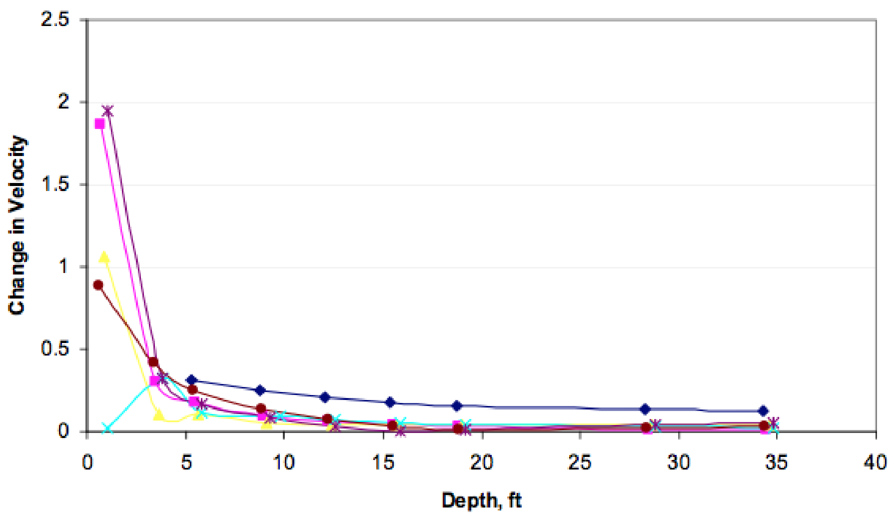

Figure 4-2: Cross-Vane Effective Depth from Change in Velocity Magnitude (Dahle, 2008).

The model showed that the Cross-Vane placed on Thistle Creek was effective in changing the flow direction and water velocity if the flow was less than four feet deep. Once the flow depth exceeded four feet, the change in direction and velocity was very small. This stream has a base flow of less than one foot but a greater depth of flow can be rapidly reached on Thistle Creek, meaning that the Cross-Vane was not an effective scour countermeasure (Dahle, 2008).

Actual field observations have shown that even when the flow is much higher than the bankfull elevation, stream stability structures still have an effect on the flow. There are claims that 2-D models do not very accurately reflect the impact on the water surface above bankfull flow; some field observations on stream stability structures show that they continue to have an effect on the water surface above bankfull flow. A 2-D model can be too limited to capture and simulate what is actually happening on the water surface. Two dimensional models have shown that when a restoration structure is exposed to deep flows, the water surface is not impacted. Photographs of Cross-Vanes on the Batavia River in New York at base flow (Figure 4-3) and later above bankfull flow (Figure 4-4) visually show that even under design flow conditions, the water surface was impacted by the Cross-Vanes.

Figure 4-3: Batavia at Base Flow with Floodplain. Flow from Top to Bottom (Photo by David Rosgen).

Figure 4-4: Cross-Vane Effecting Higher than Bankfull Flow on Batavia River. Flow from Top to Bottom (Photo by David Rosgen).

4.2 2-D Model

The 2-D model used for analysis in Section 3.7 was used to analyze a Cross-Vane's impact on flow as the water depth increases. This was done to see if a 2-D model could support what has been observed visually in the field. Flow values less than, equal to and greater than bankfull were used; bankfull for the model was 2.5 feet. As expected, when depth increased, the redirection of flow decreased when observing the flow vector arrows. Flows below bankfull showed significant redirection when passing over the Cross-Vane (Figure 4-5). Bankfull flow was also redirected as water passed over the Cross-Vane (Figure 4-6), but when the flow was more than double the bankfull height, the flow was not very effectively redirected (Figure 4-7).

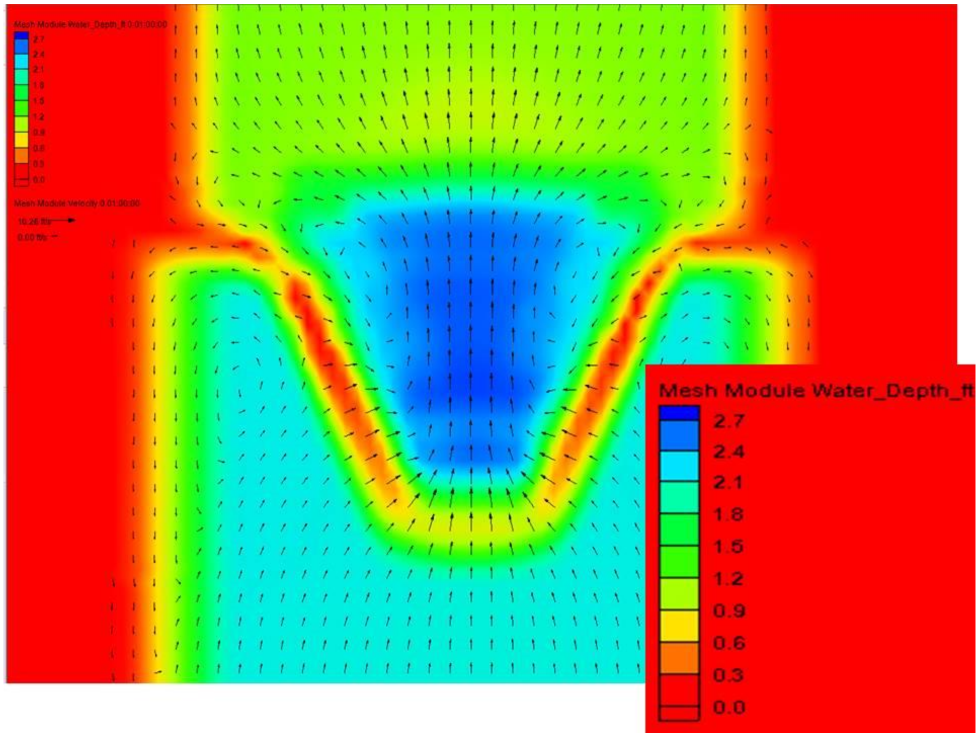

Figure 4-5: Flow Vectors Below Bankfull. Flow Depth = 1 Foot (Image from SMS).

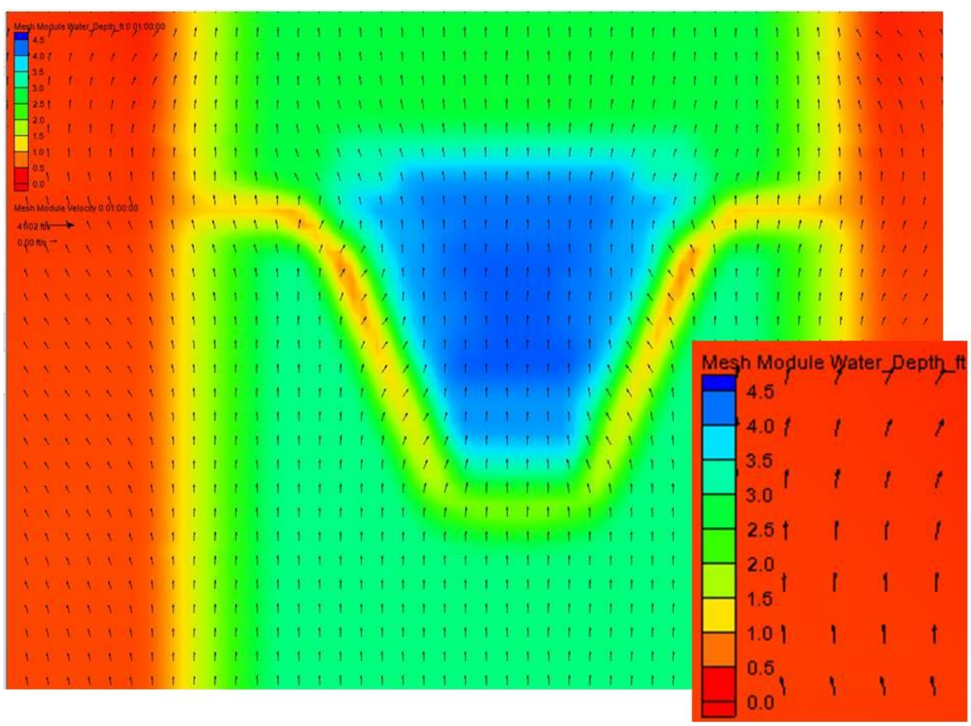

Figure 4-6: Flow Vectors At Bankfull. Flow Depth = 2.5 Feet (Image from SMS).

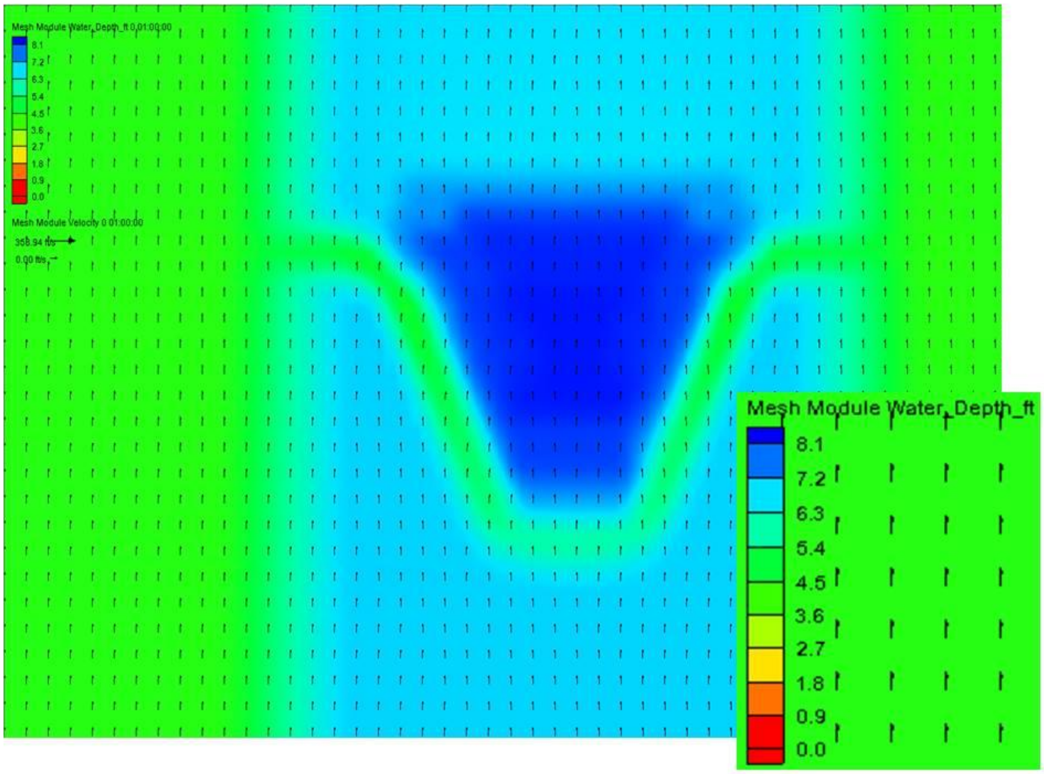

Figure 4-7: Flow Vectors Above Bankfull. Flow Depth = 6.5 Feet (Image from SMS).

According to the 2-D model created, design flows may not be redirected by a stream stability structure. In addition to the flow direction, the water surface elevation was analyzed for flow values less than, equal to and greater than bankfull flow. The model showed that water surface elevation was impacted as the water passed over the Cross-Vane for flows less than, equal to and greater than bankfull flow (Figure 4-8, Figure 4-9 and Figure 4-10). This shows that stream stability structures do have some impact on water surface even if flows aren't redirected, supporting visual observations made in the field.

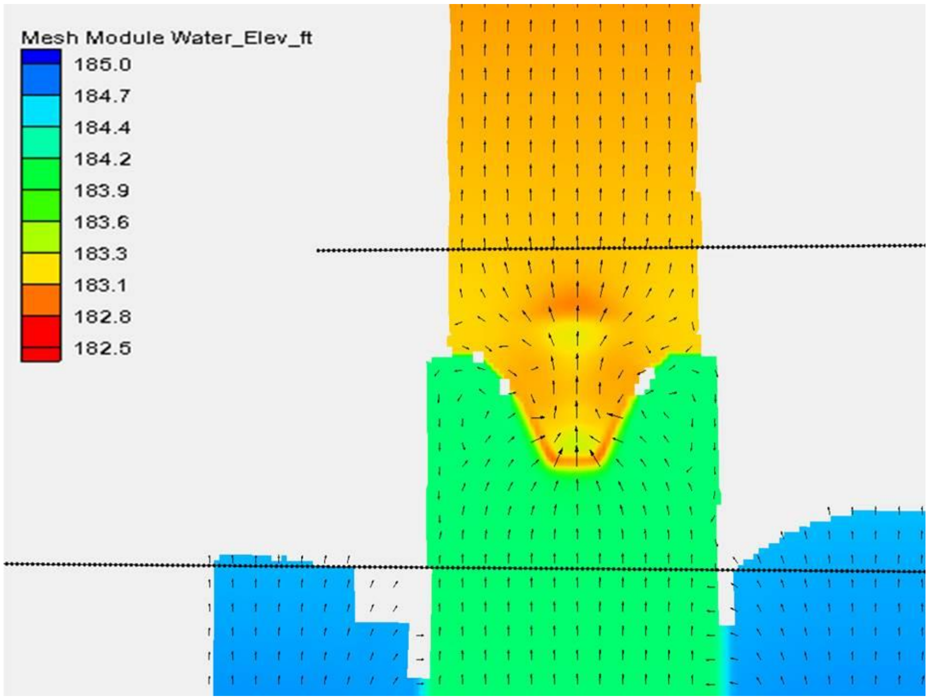

Figure 4-8: Water Surface Elevations Below Bankfull Flow. Flow Depth = 1 Foot (Image from SMS).

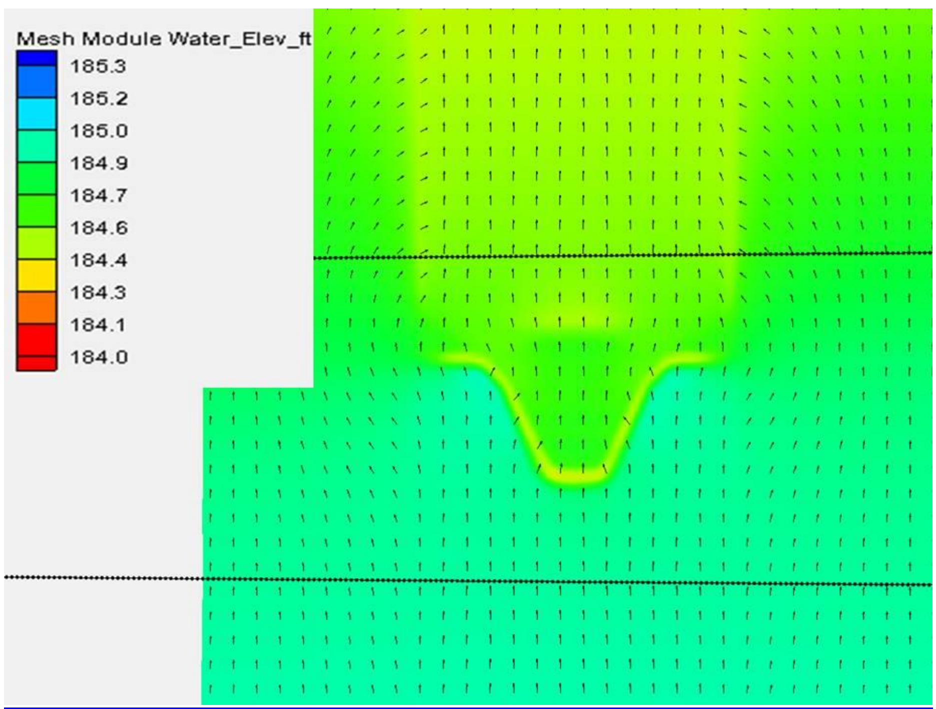

Figure 4-9: Water Surface Elevations for Bankfull Flow. Flow Depth = 2.5 Feet (Image from SMS).

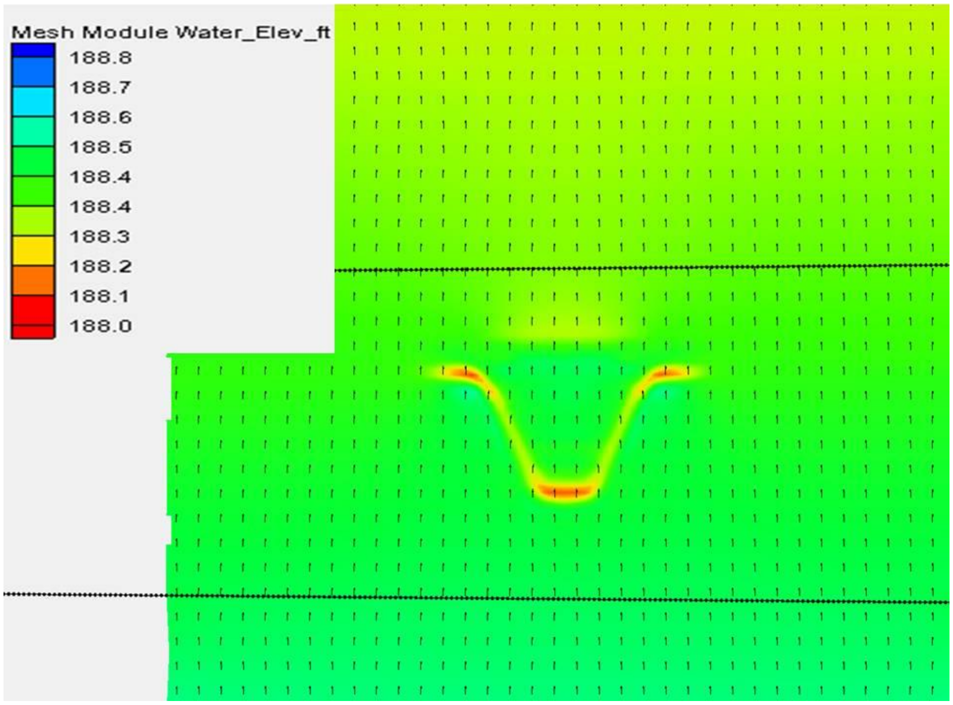

Figure 4-10: Water Surface Elevations for Above Bankfull Flow. Flow Depth = 6.5 Feet (Image from SMS).

In Section 3.7, bank shear stress in the model was analyzed under different flows at different locations downstream from a Cross-Vane. The same shear stress data were used to plot bank shear vs. flow depth. The flow depths analyzed began at the bankfull flow of 2.5 feet and go up to 10 feet deep, 4 times the bankfull flow depth (**Figure 4-11**). Based on the results from this model, even at higher flows, the Cross-Vane still helped to decrease the streambank shear stress. The decrease in shear stress at 1 channel width downstream of the Cross-Vane was greater near bankfull flows and less at high flows, but the shear stress is still decreased overall for all flows. The shear stress analysis in the model helps support field observations that stream stability structures do have an impact on design flows.

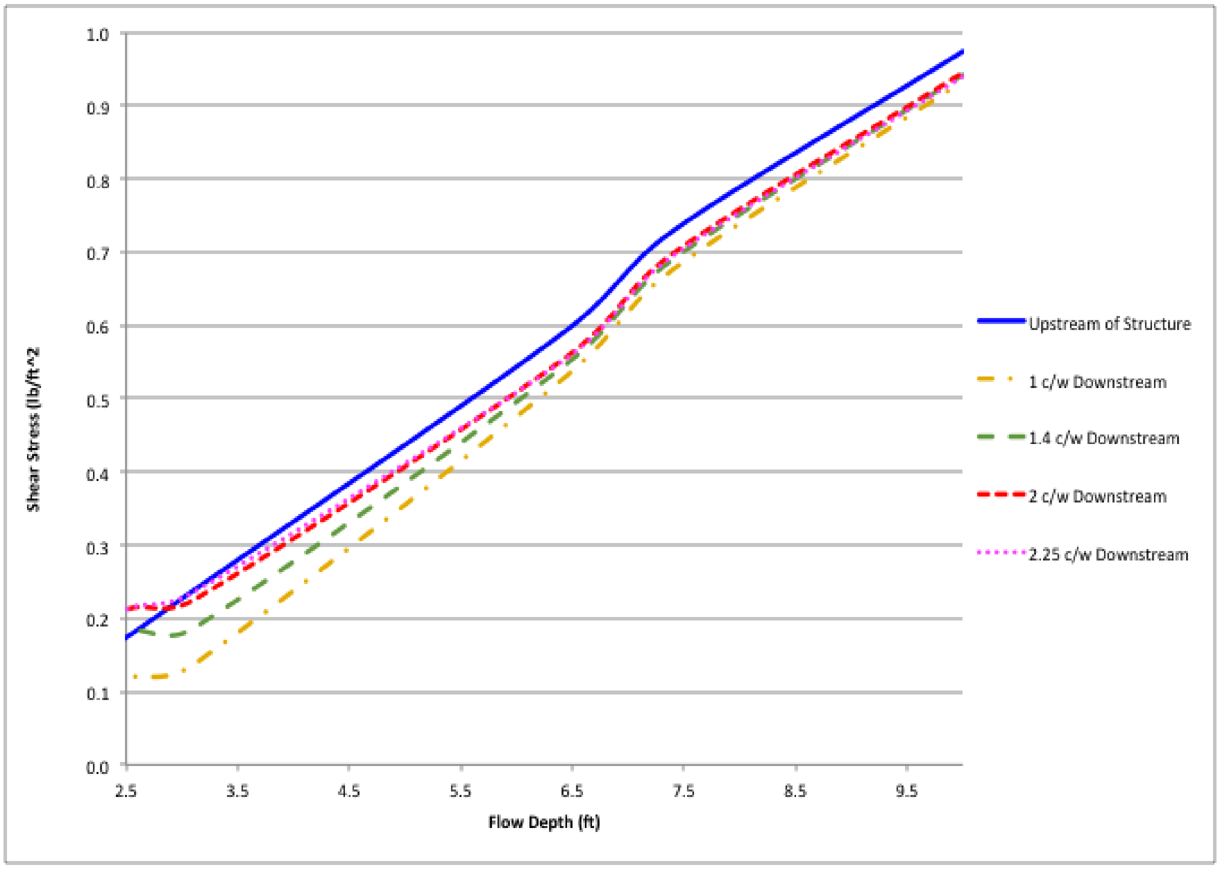

Figure 4-11: Bank Shear vs. Flow Depth for Different Channel Widths Away from a Cross-Vane.

4.3 Labyrinth Weir Comparison

To further investigate whether rock stability stream structures continue to redirect water velocities as water depth increases, an analogous hydraulic structure was investigated – the labyrinth weir. Labyrinth weirs increase the flow capacity of spillways by redirecting water velocities for relatively low overflow depths. They have a longer effective length per unit width than a linear weir due to the zigzag-like configuration (Figure 4-12). The greater length per unit width of a labyrinth weir promotes higher flow than that of a linear weir. Stream stability structures were compared to labyrinth weirs to help determine if they are effective at design flows. Studies have been performed to determine if labyrinth weirs should be used when flows get deeper – that is, to determine if the redirecting nature of a labyrinth weir (and therefore a stream stability structure) decreases as water depth increases over the weir.

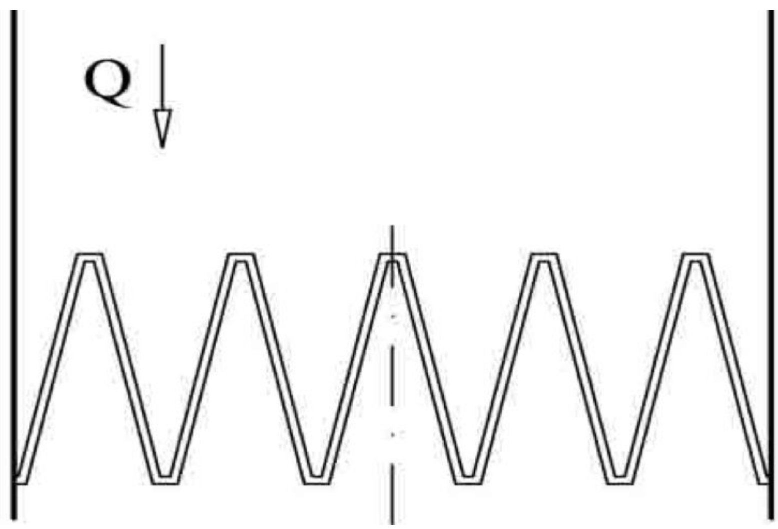

Figure 4-12: Labyrinth Weir Configuration (Crookston, 2010).

The flow that passes over a weir is represented by the weir equation. The equation is the general equation used for both labyrinth and linear weirs. The differences in calculated flow between a labyrinth and linear weir are resultant of the length of the weirs and the different weir coefficients used (Tullis et al., 1995).

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_T^{3/2}$$

Where

Q = Flow, L^3T^{-1}

C_d = Dimensionless weir coefficient, 1

L = Effective weir length, L

g = Acceleration due to gravity, LT^{-2}

H_T = Total head above the weir crest, L

The effective weir length differs between a linear and a labyrinth weir. For a linear weir the effective length is the actual length of the weir. The effective length of a labyrinth weir is different due to the zigzag configuration, which means that the effective length must be calculated using an effective length equation for a labyrinth weir (Figure 4-13).

$$L = 2N(A+L2)$$

Where

L = Effective weir length, L

N = Number of cycles (4 shown in Figure 4-13), 1

A = Inner apex width, L

L2 = Effective length of side leg, L

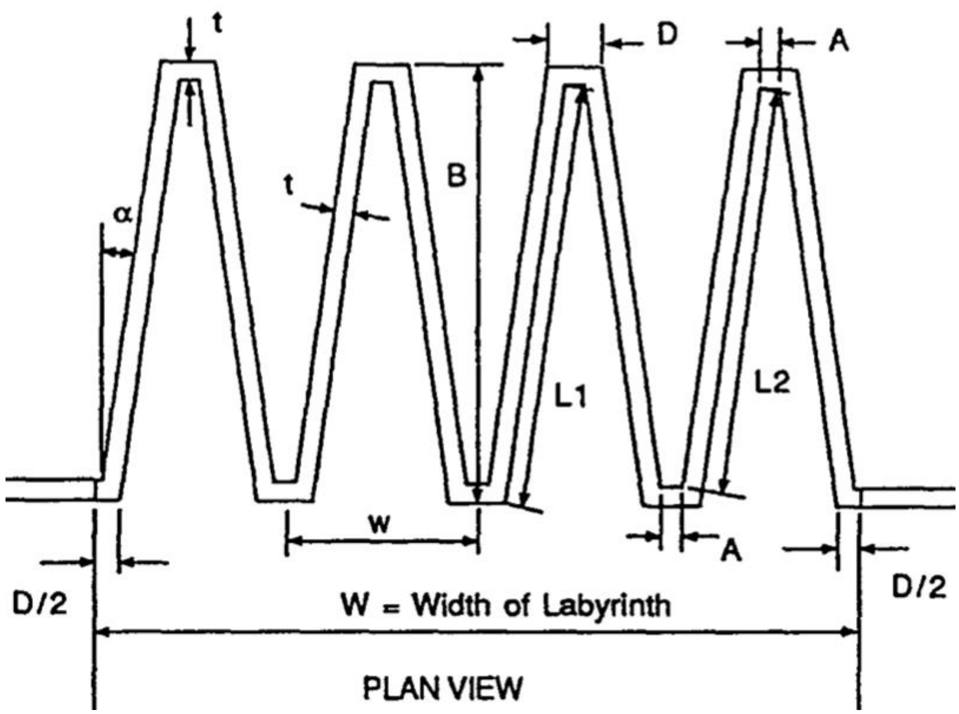

Figure 4-13: Effective Length Variables (Tullis at al., 1995).

The total upstream head (H_T) is the water depth and velocity head above the crest of the weir, calculated by summing the upstream piezometric head (h) and the average upstream velocity head (V^2/2g) (Figure 4-14).

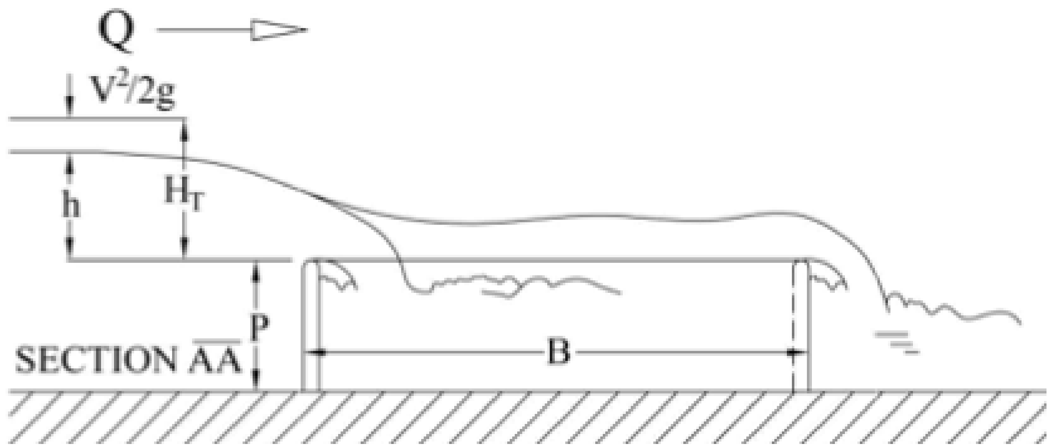

Figure 4-14: Labyrinth Weir Variables (Crookston, 2010).

Weir coefficients are used to compensate for viscosity, energy, momentum, weir geometry and crest shape (Crookston, 2010). Weir coefficients are provided for several different types of weirs and have been established with laboratory testing. As the total upstream head increases for a labyrinth weir, the weir coefficient begins to decrease, showing that the overall performance of the weir decreases (Figure 4-15). The effectiveness of a labyrinth weir is correlated with the ratio of the total upstream head (H_T) divided by the weir height (P) (Figure 4-14). Labyrinth weirs are more efficient when the headwater ratio is less than 0.9 (Crookston, 2010).

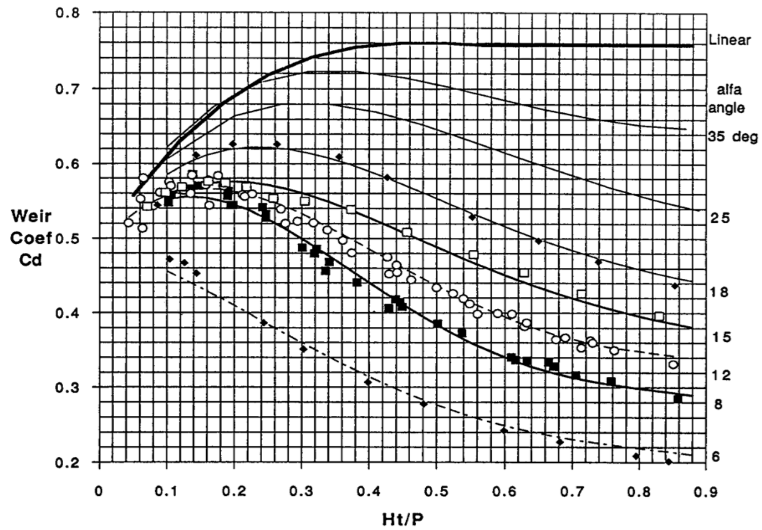

Figure 4-15: Weir Coefficients for Headwater Ratios Lower than 0.9 (Tullis et al., 1995).

Laboratory studies and 3-D numerical models were performed to verify the performance or labyrinth weirs with headwater ratios greater than one (Crookston et al. 2012). This was done to test the values presented by Brian Mark Crookston in 2010 and to see if labyrinth weirs were still effective at increasing flows at headwater ratios greater than one. Testing reflected that for headwater ratios greater than one, the labyrinth weir coefficients follow the Crookston values (Figure 4-16). The recommendation for labyrinth weirs is to maintain a headwater ratio under 0.9 but they will still accommodate more flow than a linear weir at greater headwater ratios (Crookston et al. 2012). Although a labyrinth weir serves a different purpose than a stream stability structure, stream stability structures are most effective at lower flow depths but still have some influence on deeper flows much like the labyrinth weir. Labryinth weirs are not employed to decrease shear stress downstream, so no shear stress comparisons were attempted.

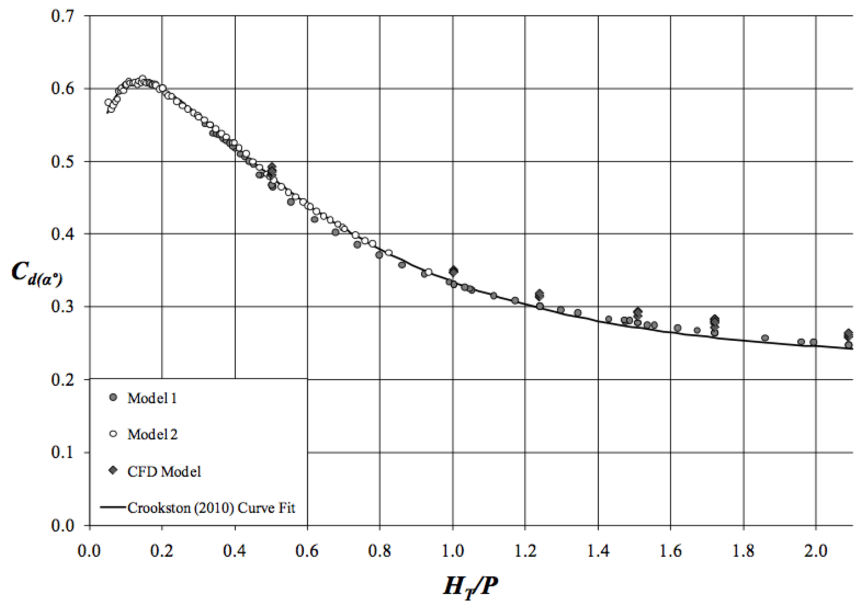

Figure 4-16: Coefficients for a 15-degree Labyrinth Weir (Crookston et al., 2012)

5.0 CONCLUSIONS

Based on a literature review, Cross-Vanes and W-Weirs were determined to be the best stream restoration structures for protecting bridges while promoting fish habitat. To eliminate the failure of Cross-Vanes and W-Weirs at higher flows near bridges, certain design criteria must be followed. There must be a floodplain present at the bankfull height to disperse the energy of higher than bankfull flows. The suggested design criteria are shown in Table 5-1 below.

Table 5-1: Summarized Design Guidelines of Cross-Vanes and W-Weirs at Bridges.

Design Guideline	**Comments**
Floodplain	Must be present at the bankfull height. Must begin upstream of structure and extend downstream of the structure through the bridge If no attached floodplain is present, one must be excavated (Figure 3-1) or floodplain culverts should be installed (Figure 3-2).
Rock Size	Use the100-year shear stress and the Rosgen chart (Figure 3-) to size rock. Floodplains are essential to help to reduce shear on rocks.
Angle from Bank Tangent Line	20 to 30 degree angle, 20 degree protects more streambank (Figure 3-).
Vane Slope	2 to 7 percent slope (Figure 3-).
Footers	3 to 6 times the height of structure above the streambed. Placement is important (Figure 3-).
Rock Step Inside Vane Arms	Regulates the size of the scour hole and protects the footers from being undermined (Figure 3- and Figure 3-).
Upstream Distance from Infrastructure	1 to 1.5 channel widths upstream, this is measured from the crest of the Cross-Vane or W-Weir (Figure 5-1).

Modeling illustrated that stream stability structures do perform better at lower flows, but they can still effect design flows; this was also reflected when comparing a stream stability structure's effectiveness to that of a labyrinth weir.   The decrease in bank shear stress occurred at all flows, meaning that even at design flows, stream stability structures can still decrease scour. Illustrations demonstrating the implementation of stream stability structures near bridges can be seen in Figure 5-1 and Figure 5-3 below.

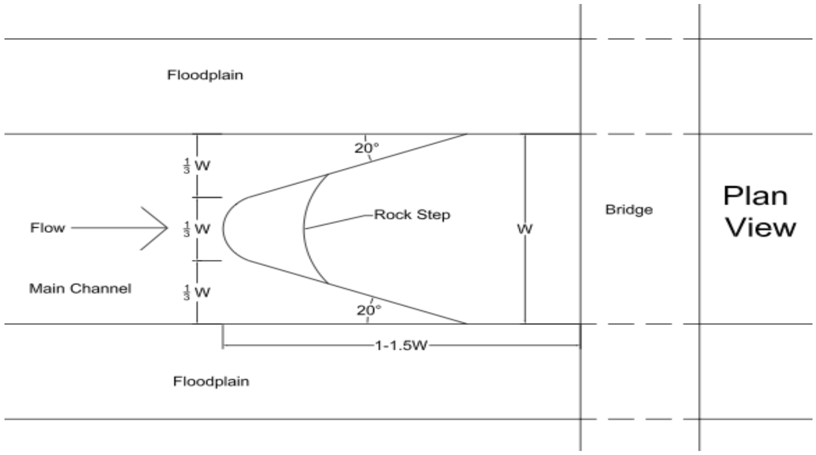

Figure 5-1: Plan View for Implementing a Restoration Structure Near a Bridge.

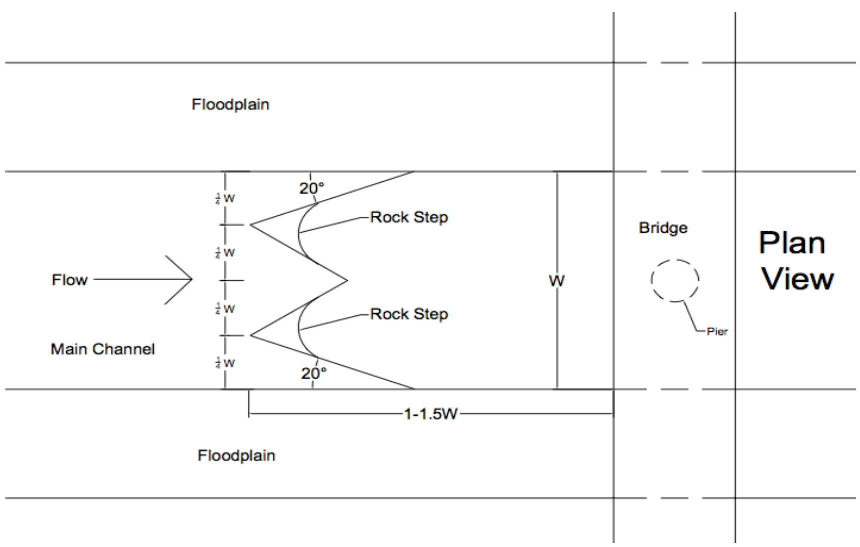

Figure 5-2: Plan View for Implementing a W-Weir Near a Bridge.

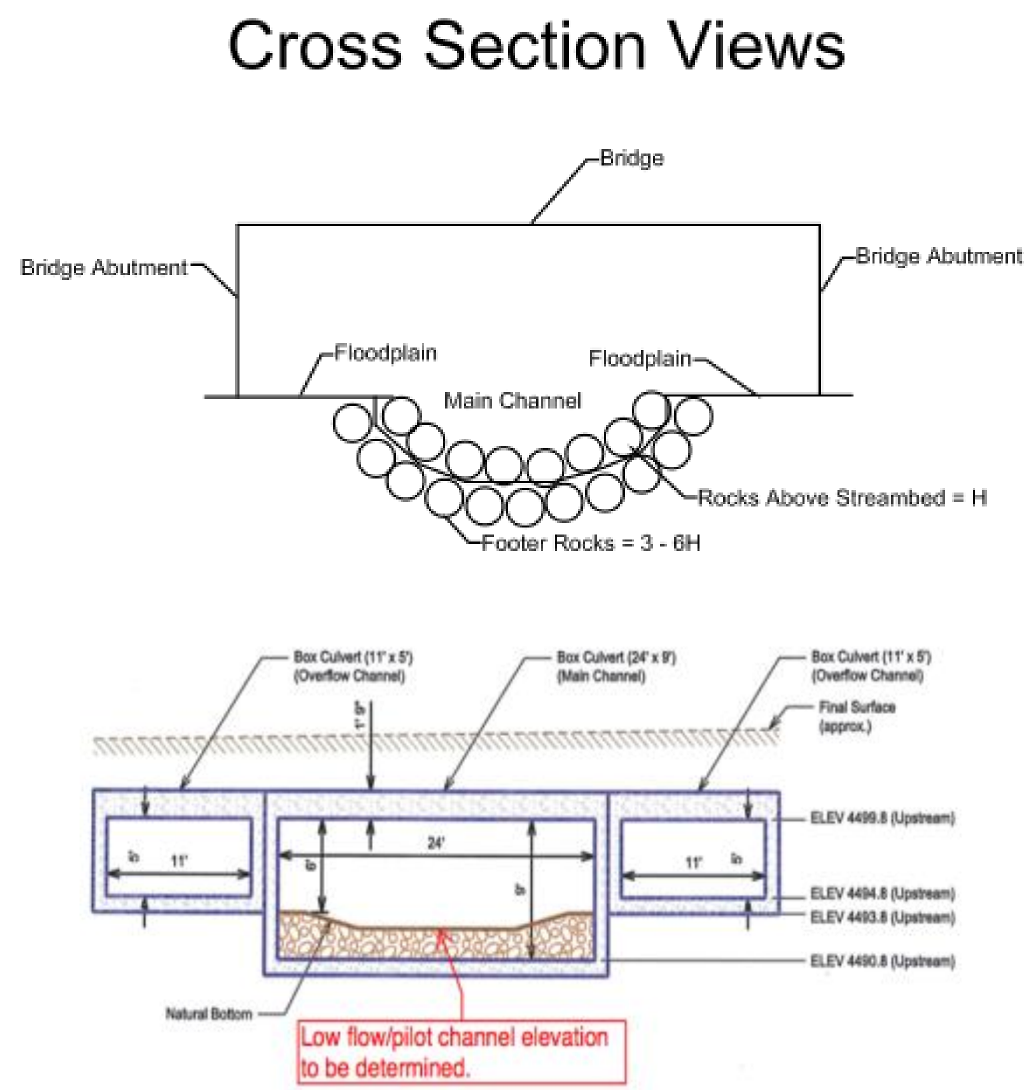

Figure 5-3: Cross Section Views for Implementing a Restoration Structure Near a Bridge. Top with Attached Floodplain at Bankfull. Bottom with Floodplain Culverts at Bankfull

6.0 RECOMMENDATIONS

Based on the research and modeling done for this report, Cross-Vanes and W-Weirs appear to hold promise for use as scour countermeasures in the vicinity of bridges when the correct design procedures are followed. It is important to recognize that models are limited by the assumptions made while creating the model and that field observations are also important and must be taken into account to ensure greater confidence. We recommend a Cross-Vane or W-Weir be placed at a bridge location that is already protected by riprap to measure changes in shear stress and erosion potential at the bridge abutments and piers.

When implementing a Cross-Vane or W-Weir, some important things to consider are impact of floating debris on the structure, inspections after flooding events, and using trained personnel to install and maintain the structures. As this report mentions, a floodplain must be present for a stream stability structure to properly function.

UDOT believes that Cross-Vanes and W-Weirs should not be used as the primary scour countermeasure for bridges. Stream and river systems are dynamic; to address unanticipated future conditions at bridges, rock riprap (or other equivalent structural countermeasure) should always be used as the primary scour countermeasure to protect bridge foundations and abutments.

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