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RESEARCH REPORT

Evaluating the Success of Meeting Design Objectives on Previously Constructed OOS Stream Stability Projects

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16. Abstract

The ability to detect failure or impending failure of a stream stabilization project or its components is important to assuring that the bridge will be protected during high flow events. The objectives of this project were to assess the degrees of success of stream channel transition designs through bridge reaches and the suitability of these projects to transport sediment through the bridge opening.

In addition to creating a methodology for assessing existing transitions, a methodology was developed that guides the design type selection process at new bridges or new channel transition projects. This process uses a rapid channel stability assessment to initially assess a site for instabilities that need to be addressed by the design. Two design checks are included as part of the method. The first check is the V/Vc analysis for assessing general trends in sediment mobilization through the bridge opening. Due to the use in this study of one dimensional HEC-RAS models to provide inputs for channel depth and velocity, the V/Vc results provide only an average-based mobilization. The second design check is the Failure Modes and Effects Analysis. This requires the designer to systematically analyze all the potential failure modes of the design and to consider solutions that reduce the risk priority numbers of design components. Incorporating these checks in the design process should help increase the likelihood of a successful channel transition design. Several observations and recommendations were made based on field observations at a limited number of sites, comparisons of imagery, and analyses described in this report.

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C = consequence rating in FMEA
D = sediment size
D_f = detection rating in FMEA
D_{50} = median sediment size
n = Manning’s roughness coefficient
O = occurrence rating in FMEA
RPN = Risk Priority Number
S = slope
S_s = specific gravity of sediment
V = flow velocity
Vc = critical flow velocity
y = flow depth

γ = specific weight of water
γ_s = specific weight of sediment
θ_c = dimensionless critical shear stress
τ_c = critical shear stress
τ_o = average boundary shear stress
ω = streampower

Glossary

The terms in this glossary are defined as they are used or as provided in Chapter 14: Stream Morphology.

Abutment - The structure supporting the ends of a bridge and retaining the embankment soil. In scour analysis, the end of roadway embankments in addition to the supporting structure is referred to as the abutment.

Aggradation - The general increase in the elevation of the streambed or floodplain caused by sediment deposition.

Bank - The rising ground, bordering a stream channel, which restricts lateral movement of water at normal water levels. The left and right banks are defined from a down-stream-facing orientation.

Bankfull discharge - The flow that just be-gins to flood the active floodplain. The active floodplain is the floodplain that is being created by the channel under the cur-rent watershed and climate conditions.

Bar - A ridge-like accumulation of sand, gravel, or other alluvial material formed in the channel.

Bed - The ground on which a body of water lies, limited laterally by a bank.

Bed control - A channel bed feature, such as a bedrock outcrop or culvert inlet invert, that holds a constant elevation in the streambed and limits degradation caused by downstream channel disturbances.

Bendway weirs – countermeasures used to improve lateral stream stability and flow alignment

Boundary shear stress - The force per unit area exerted by the flow on the channel boundary in a direction parallel to the channel boundary (bed and banks).

Channel - A discernible waterway that continuously or periodically contains moving water within a defined bed and banks.

Channelization - The artificial straightening or dredging of a stream either to relocate it or to make it deeper, straighter, or shorter.

Critical shear stress - The minimum force per unit bed area that will mobilize the bed material.

Cross vanes – countermeasures used to improve lateral stream stability, flow alignment, and grade control

Culvert - A concrete, corrugated steel, or plastic pipe, of varied size and shape, used to convey water, typically under a road. Is usually open at each end and not tied to a larger closed storm-drain network.

Degradation - The general lowering of the streambed or floodplain surface elevation caused by erosion.

Discharge - Volume of water flowing through a given stream at a given point and within a given time period, usually measured as volume per unit of time (e.g., cubic ft per second).

Entrenchment (channel entrenchment) - A measurement used to indicate the amount or degree of vertical containment of flood flows within a channel. This measurement of containment considers both vertical and lateral confinement of the channel. (Entrenchment ratio equals the width of the flood-prone area at an elevation twice the maximum bankfull depth, divided by the bankfull width.)

Floodplain - The relatively flat land bordering a stream or river channel that is formed by the deposition of sediment during floods. The active floodplain is that being formed by the current stream of the channel in the current climate.

Geocells – countermeasures used for slope protection

Lateral migration - Movement of the entire channel in a cross valley direction. This typically occurs near bends where one bank erodes and the other accretes (builds) such that the channel moves across the valley. In some cases the overall dimensions of the bankfull channel may not change substantially with this translation movement.

Meanders - Regular and repeated bends of similar amplitude and wavelength along a stream channel.

Planform or planform pattern - The form of the channel from a plan view perspective.

Pool - Portion of the stream, often deeper than surrounding areas, with reduced current velocity during normal flow periods.

Reach - Any specified length of stream.

Riffle - A shallow extent of stream where the water flows more swiftly over completely- or partially-submerged rocks to produce surface disturbances under normal flow periods.

Scour - The cumulative effect of the erosive action of water that causes an identifiable depression or cusp in a streambed, stream bank, or other channel or floodplain boundary.

Sediment - Fragmented material that originates from the weathering of rocks and de-composition of organic material and is transported in suspension by water, air, or ice to be subsequently deposited at a new location.

Thalweg - A line connecting the lowest or deepest points along a streambed or valley bottom. The stream longitudinal profile is a plot of the elevation of the thalweg versus distance along the channel.

Vanes – countermeasures used to improve lateral stream stability and flow alignment

INTRODUCTION

There are a variety of techniques available for countering stream channel instability at bridges. Countermeasures are typically categorized into three groups: armoring, hydraulic control, and grade control. The treatment of stream channel instability and selection of countermeasures are dependent on the physical conditions at the bridges, such as reach-wide channel degradation, aggradation, sediment transport, or lateral channel movement or widening. The feasibility of and confidence in each of the various components and countermeasures is a function of multiple factors, including effectiveness, cost, maintenance, constraints, and the ability to detect failure. Some countermeasures have been systematically tested, while others may have been laboratory - tested, but not field tested. Others cannot be used effectively within existing right-of-ways. There is a wide range of costs associated with the initial design and construction of the stabilization measures as well as the maintenance costs. The ability to detect failure or impending failure of a stream stabilization project or its components is important to assuring that the bridge will be protected during high flow events. In addition, movement of sediment through the bridge opening is important to avoid deposition that limits flow or changes the direction of flow.

The objectives of this project were to assess the degrees of success of stream channel transition designs through bridge reaches and the suitability of these projects to transport sediment through the bridge opening and to provide recommendations for improving current practices of channel design and reconstruction in the vicinity of bridges in Maryland. The objectives were met through the following tasks:

1. Evaluation of selected existing field sites to determine the stability, current damage states, and success in meeting the goals of the channel construction projects;
2. Examination of current literature and other state DOT practices for developing stable transitions at bridges;
3. Development of a method for identifying the feasibility of developing stable, resilient streams channels in the vicinity of bridges based on current practices based on the field observations and current literature, develop a method; and
4. Development of recommendations to improve upon current practices for developing and maintaining stable, resilient channels at bridges in Maryland.

LITERATURE REVIEW

Bridges over streams and rivers are susceptible to erosional processes during a wide range of flows. Local and contraction scour erodes sediment from bridge piers and abutments, potentially affecting the safety of the bridge. There has been considerable focus on assessing scour, designing countermeasures to protect bridges against scour, and designing foundations to resist scour. Stream channel instability, on the other hand, includes bank failure, lateral migration, and bed degradation, has the potential to impact safety at bridges as much or more than local and contraction scour. Figures 1-4 provide examples of unstable channels at bridges in the mid-Atlantic area. Figure 1 shows channel widening upstream of the bridge that could threaten the bridge wing walls and abutments. Figure 2 shows an example of upstream bank failures, which have resulted in unstable conditions at the bridge and significant deposition of sediment. Figure 3 provides an example of channel degradation that has exposed foundations and is causing the banks to become unstable. Deposition of sediment at bridge openings can also create unstable conditions by clogging the waterway. Aggradation can cause the restricted waterway to concentrate such that scour is increased at abutments and/or piers in the remaining opening and to develop large, mobile bars, as shown in Figure 4, that increase lateral migration of the channel. The restricted waterway might also result in increased backwater, causing flooding upstream of the bridge.

The focus of this literature review is to present the state of the art in stream channel transitions that convey the water and sediment through the bridge opening while minimizing scour and sediment deposition and to provide initial observations at the eight selected sites in Maryland. Predicting and preventing channel instability at bridges is a difficult task. The complexities and unique characteristics of bridge crossings have eluded computational modeling thus far. In addition, maintaining a safe and stable waterway opening under the conditions of an unstable stream channel has proven to be difficult for a number of reasons: (1) the bridge owner typically has a very limited right-of-way to work within; (2) creating stable channel conditions can be costly in terms of design, construction, and maintenance; and (3) bridge personnel may have limited experience in stream channel behavior and countermeasure applications.

RECENT ADVANCES IN SCOUR AND CHANNEL INSTABILITY PRACTICES

Hydraulic Engineering Circular 23 (HEC-23) (Lagasse et al. 2009) is the Federal Highway Agency manual for scour and stream channel instability countermeasures. Table 2-1 of HEC-23 provides a very good summary of the uses and applications of the countermeasures in the manual at the time of writing. The authors surveyed all of the state DOTs as well as consultants and FHWA regions to determine the experiences with the various countermeasures. HEC-23 presents general discussions and design guidelines for 19 countermeasures, ranging from riprap to soil cement to articulated concrete blocks. Biotechnical countermeasures discussed in the manual include live staking and vegetated riprap; however, the primary focus is on armoring banks, slopes, and beds. The manual is meant to provide an overview of options, but does not address common limitations, such as right of ways, and does not address specific regions of the country.

A risk-based method for selection countermeasures was proposed by Johnson and Niezgoda (2004) using a failure modes and effects analysis. The method is a relatively simple, systematic technique for assigning relative risk to scour countermeasure choices at the design phase and takes into consideration economic, environmental, and social benefits. The resulting ratings can be used to determine components of the design that require particular attention to prevent failure of the countermeasure and to adequately protect the bridge, as well as justification for decision making.

In a recent study for the National Cooperative Highway Research Program (NCHRP 24-33), Sotiropoulos and Diplas (2013) and Radspinner et al. (2010) conducted reviews of the current use of in-stream structures for stabilizing stream channels, focusing on five of the most commonly used structures: rock vanes, J-hooks, bend-way weirs, cross vanes, and w-weirs. They conducted laboratory and field experiments and computational studies in order to develop engineering guidelines, design methods, and recommended specifications for in-stream structure installation, monitoring, and maintenance. Their study provided significant results relevant to this study. The literature review, survey of practitioners, and experiments showed that a single rock vane or weir did not adequately control erosion on meander bends and that the size, angle, and spacing of these structures would require at least 100 feet of stream length, well outside of most ROWs.

Based on the demand for more environmentally sensitive, sustainable countermeasures for treating stream bank stability in the vicinity of highways, the NCHRP funded project 24-39, titled Evaluation and Assessment of Environmentally Sensitive Stream Bank Protection Measures, was recently completed. The objectives of the research were to produce guidelines for appropriate selection, design, installation, and maintenance of environmentally sensitive stream bank stabilization and protection measures (Lagasse et al., 2015). The guidelines were based on a literature review, assessments of current field installations, and laboratory testing.

Stream Stabilization Practices

The type of protection that is used at a bridge depends on the nature of the problem. Lagasse et al. (2009) provide a comparison of a selected group of countermeasures by qualitatively describing the functional application (i.e., local scour, contraction scour, and channel instability), suitable river environment (river type and size, flow conditions, and physical condition), maintenance, and installation experience. At existing bridges, the bridge engineer can choose from one of two categories of countermeasures: armor the channel bed and banks or alter the flow alignment. These methods can also be used in combination.

By far, the most common treatment for protecting bridges from scour is armor, particularly riprap. Other types of armor include precast concrete units, grout filled bags, foundation extensions, and concrete aprons. All of these measures armor the bed or bank material against erosive forces. They do not break up vortices or redirect the flow. If sized, graded, and placed well, armor can be a very effective measure for preventing scour at both piers and abutments and locally halting channel instability. However, for bridges with narrow waterway openings, armor can cause further contraction of the waterway opening and actually exacerbate scour. At vertical wall abutments, riprap and other armor may be ineffective due to the steepness of the banks. Detailed information on riprap, gabions, rock mattresses, vegetated riprap, grout bags/mattresses, and articulated concrete blocks, along with their design guidelines, can be found in HEC-23.

One armoring technique not covered in HEC-23 that is finding increasing use with some DOTs is geocells. Geocells are relatively inexpensive countermeasures used for slope protection. The cells are connected in expandable panels made from high-density polyethylene, polyester or another polymer material. When expanded during installation, the interconnected strips form the walls of a flexible, three-dimensional cellular structure into which specified infill materials, such as soil, sand, aggregate, or cement, are placed and compacted. The result is a free-draining system that prevents mass movements by providing confinement through tensile reinforcement (Geosynthetics, 2013). Geocells have been widely used for slope protection in highway applications and many others. Design and installation guidelines are provided at websites, such as Strata and other makers of geocells.

Flow altering devices can be used to realign the flow to mitigate against local and contraction scour as well as bank widening and lateral migration. These measures include submerged (Iowa) vanes, bendway weirs, rock vanes, and cross vanes and have been used for many years to deflect flows and sediment and to control spiral flow in bends and erosion at banks. Each of these flow altering devices is described briefly below.

In experimental studies, it was found that submerged vanes were effective over a wide range of flow depths from two to eight times the vane height (Odgaard, 2009). Submerged vanes are typically constructed from sheet pile or reinforced concrete founded on adequately deep pilings, but could also be made of large rocks or wood with footers of adequate depth to resist erosional forces. Odgaard (2009) provides design and construction guidelines.

Bendway weirs are low elevation stone sills, very similar to vanes, used to improve lateral stream stability and flow alignment problems (Lagassee et al. 2009). Bendway weirs are typically not visible at bankfull flow and redirect flow by causing it to pass perpendicularly over the weir. They are made from stone, tree trunks, or grout filled bags. Lagasse et al. 2009), provide design guidelines.

Vanes and cross vanes are stream restoration or stabilization structures commonly used to improve lateral stability and flow alignment and, in the case of cross vanes, provide some grade control on degrading beds. Like submerged Iowa vanes, these structures tend to be very effective in flow depths up to about five times their height. Johnson et al. (2001; 2002) tested these structures in a laboratory flume at a single span model bridge to assess their ability to move scour away from pier and abutment foundations, thereby reducing scour at bridges.
The results showed that scour at the pier or abutment was generally reduced on the order of 65–90%, depending on flow conditions and the structure configuration. The scour was moved away from the abutment or pier into the center of the channel. These structures have not yet been systematically tested in the field; however, preliminary design criteria for these structures and their appropriate applications, in terms of bridge and stream types, are given in Johnson et al. (2001, 2002).

In addition to armoring and/or instream structures, stabilization practices may include realigning the channel with the bridge opening, changing the channel width or depth upstream of the bridge, and lowering one or both floodplains to provide additional room for the river to convey or store flow and sediment. These practices typically necessitate working with local land owners and relevant state agencies to provide access to the land upstream of the bridge. As an example, Figure 5 shows the Ohio SR 412 bridge over Fuller Creek prior to and after a project in which the upstream floodplain was lowered and widened to accommodate additional flow and sediment, essentially creating a two-stage channel for a brief reach upstream.

Incorporating Stream Stabilization Practices into Bridge Countermeasures

Limited research results exist for treating unstable channel transitions at bridge waterways. Johnson (2005; 2006) developed a method for assessing stream channel stability in the vicinity of a bridge. The method consists of 13 indicators that collectively yield the relative overall stability as well as the vertical versus lateral stability. The Federal Highway Administration (FHWA) Hydraulic Engineering Circular (HEC) 20 (Lagasse et al., 2012) incorporated the Johnson (2005; 2006) method into their guidelines for assessing and protecting against stream channel instabilities. HEC-20 provides a starting point for analyzing channel instability to determine the causes of the problem and possible solutions. HEC-23 (Lagasse et al., 2009) provides guidance on design and construction of countermeasures for protecting bridge foundations against scour and channel instability. Proper use of these guidelines requires experience and the availability of equipment and sufficient right-of-way. Due to these limitations, Newlin and Johnson (2009) suggested an adaptive management approach to maintenance of stream channels at bridges, rather than a more common risk-averse management approach, to take advantage of opportunities for learning new information about stream channel response.

As described earlier, there are a variety of practices and countermeasures are available for creating stable transitions at bridges for a range of channel conditions. Johnson (2002) and Johnson et al. (2010) developed a set of scenarios and determined best or state-of-the-art practices for each of those scenarios. The scenarios included meander migration, flow contraction, poor alignment of the channel to the waterway opening in straight or meandering channels, bank instability, bed degradation, and debris accumulation. However, sediment accumulation was not explicitly addressed. Based on field observations, Johnson (2006) developed recommendations for addressing stream channel instability based on common issues in physiographic provinces across the U.S.

The problem of aggradation at bridges is not sufficiently addressed in current guidelines and is a difficult problem to mitigate. While sediment deposition in a bridge waterway is often not considered to be a condition that threatens a bridge foundation, as discussed previously, significant sediment deposition can alter the waterway, causing scour conditions and flooding. Many of the mid-Atlantic states experience severe sediment deposition (see Figure 6, for example), often with bed material comprised of unconsolidated gravel and cobbles. Poor watershed practices combined with prior channel modifications, such as straightening, and glacial deposits are often the culprits that lead to this condition. Johnson et al. (2001) developed a suite of possible solutions for dealing with chronic sediment deposition at bridges. The solutions included dredging (the current practice at many bridge locations), bar removal, upstream sediment traps, channelization, channel relocation, and bridge modification. Each of these solutions has benefits and disadvantages and requires a range of costs, including initial construction and maintenance. They examined the costs over a 50-year period and found that establishing a sediment trap that could be easily accessed for cleaning was the most cost-efficient.

In recent years, DOTs have used many of the practices described here to solve sediment accumulation and other instability problems at bridges. The use of in-stream structures, such as vanes, cross vanes, and w-weirs, and channel modifications have been considered as a way of controlling stream channel instabilities for a wide range, including sediment deposition, especially when they can be constructed within the right-of-way. For example, the Ohio Department of Transportation is experimenting with the use of in-stream structures to provide improved channel alignment with the bridge abutments, move sediment through the bridge opening, and stabilize channel banks. Figure 7 shows one example for a bridge west of Toledo, Ohio. Considerable sediment and debris upstream of the bridge were causing chronic maintenance problems, as shown in Figure 7. To alleviate these conditions, a partial w-weir was installed in the Fall of 2015 in an attempt to improve the movement of sediment and debris through the bridge opening. The weir is currently being monitored for effectiveness.

Current State Guidance for Stream Modification at Road Crossings

Few state DOTs offer guidance in their design manuals related to creating stable channel transitions at bridge crossings. Several noteworthy examples from DOT guidelines are summarized below.

WashDOT acknowledges in their Hydraulics manual (WashDOT 2015) that structures, such as bank barbs and drop structures, are largely ineffective for rivers with a large sediment load. They even discourage their use in such situations.

IDOT has a limitation for stream modification projects to not increase scour and erosion (Drainage 2011). IDOT determines that a project is reaching this goal if the average existing channel velocity is not increased beyond the permissible velocity of the predominant soil type at the project site unless it already naturally exceeds the predominant soil types scour velocity. Beyond this point, there is a 10% increase limit imposed. Illinois also acknowledges that extensive channel excavation aimed at increasing flood conveyance is an ineffective practice because the site will aggrade until the natural channel pattern is re-established. IDOT states that these limitations have resulted in a reduction of flooding due to aggradation, negative effects to the upstream floodplain, and lateral migration of the stream within the artificially widened area, which frequently leads to a skewed watercourse approach that further endangers the bridge. IDOT also discourages overbank excavation. They believe the excavations will eventually aggrade back to the original state.

After historic flooding in 2011 from hurricane Irene, Vermont's Agency of Natural Resources (ANR) has generated several river project standards to protect and enhance floodways (Kline 2015). Their Equilibrium Standard restricts changes to stream gradients that may affect sediment transport. This standard is meant to eliminate negative stream alterations, but may limit the use of grade altering designs at bridge crossings. Vermont's ANR also has a river corridor standard which requires that new development leave a meander belt for natural stream processes. This standard would require modification of bridge design practices to accommodate bank stability.

The Oregon Department of Transportation has implemented some of the most extensive standards for new bridge construction. The have created fluvial performance standards (FPS) aimed at creating sustainable, eco-friendly bridge crossings by allowing natural channel processes to take place through the bridge crossing (ODOT 2004). The primary stated requirements for new crossings are first to "promote natural sediment transport patterns for the reach, provide unaltered fluvial debris movement, and allow for longitudinal continuity and connectivity of the stream-floodplain system". This requires no fill within the "functional floodplain," defined as the width at an elevation of three times the average bankfull depth. Another requirement of the standard is that the bridge opening must be sufficiently wide to allow for the site-potential maximum length debris to pass through. Site-potential debris is determined based on maximum tree height within the basin and the transportation capacity of the stream.

Anderson (2008) conducted a review on applying Oregon's FPS to bridge design through three study crossings. Overall, Anderson asserted that the standards were a positive measure because they allowed for natural channel processes and they reduced costs through more expedient permitting. The results of the study also showed that the standards may also prevent the design of excessively constrictive bridges for smaller crossings. In that case, the fluvial standard is the governing factor in span length over hydraulic considerations. Cummings (2013) also examined the effects of the FPS on crossing maintenance. Her team did not find any correlation of reduction of maintenance cost for 57 bridges designed using the new FPS. However, she acknowledged that the oldest bridges in the study were constructed in 2007, which is not enough time to draw conclusions about maintenance reduction over the lifetime of the structures.

FIELD OBSERVATIONS

Sites to be included in this study were selected in cooperation with MDSHA personnel. The sites represent a range of problems and practices, as well as physiographic settings. Two sites, MD 7 over James Run and MD 136 over James/Broad Run, are included for the purpose of comparison. No channel stability or transition practices were used at these sites, so they are in their "natural" state. MD 136 is mistakenly and repeatedly referred to as MD 136 over James Run. However, it is actually Broad Run. In this report, we will attempt to correct this by referring to it only as Broad Run. Figure 8 shows the general location of the eight sites. Site location maps are provided in the Appendix. They are situated in three physiographic regions across the state. Table 1 provides a summary of the eight sites, including channel instability/transitions issues at each site and the measures or practices used to stabilize the transitions. Table 2 summarizes the types of information available from MDSHA at the initiation of study.

Each of the sites listed in Table 1 were visited during the period of April-July, 2016, accompanied by either MDSHA personnel or Ward Oberholtzer from Land Studies. At each site, photographs were taken and notes to provide input to stability assessments. The sites were revisited in February, 2017. This second visit was conducted to collect additional data necessary for analysis of the projects and to observe any changes that may have occurred over the winter. Additional photos were taken for comparison between visits. Bar sediment samples were collected from MD 17, MD 223, MD 25, and MD 7. Stability assessments (Johnson, 2005; Lagasse et al., 2012) were conducted at each site as a way of conducting the initial site observations systematically. Table 3 provides those results. Detailed observations on each site are provided below, progressing from west to east.

MD 36 over Georges Creek

Bridge #01013, Maryland Route 36 (MD 36) over Georges Creek, is located in Allegany County, 1.5 miles Northeast of Lonaconing, Maryland. This site lies within the Appalachian Plateau transition of the Valley and Ridge physiographic region. MD 36 at this crossing is classified as a rural-minor arterial road and, as of the year 2009, has an average daily traffic (ADT) of 7,706 (Baughn 2016). The land use within the 79.7 square kilometers (30.7 square miles) watershed upstream of the bridge is primarily agricultural, but also includes residential lots, commercial developments, pasture, and woods. In the vicinity of the MD 36 crossing, Georges Creek is a gravel-bed channel with well vegetated banks. Other reaches of Georges Creek between Lonaconing and Midland have constructed, vertical-walled banks and areas of degradation of the fractured bedrock. Woody vegetation is establishing on lateral bars throughout the reach. Degradation is the primary process within this watershed; however, sediment deposition also occurs in areas of lower energy flow, such as in backwaters caused by bridges and at slope changes. Factors affecting stability of this watershed include channelization, entrenchment, and flow constrictions from bridge crossings and flood walls. There is a railroad bridge approximately 122 meters (400 feet) downstream that likely creates a backwater condition from the rail bridge to bridge #1013.

The MD 36 crossing over Georges Creek was replaced in December 2005 due to scour damage to the existing bridge. The previous crossing was a three-span bridge 32.6 meters (107 feet) in length. The bridge had vertical abutments with a 50-degree skew to the roadway. The flow approached the crossing at approximately 25 degrees, resulting in scour. The new bridge is a double span bridge that is better aligned with the flow. Stability at this site was rated as Fair (see Table 3), implying that a "more extensive geomorphic or hydraulic study is needed to further assess the potential for adverse conditions developing at the bridge" (Johnson, 2006). The results can then be used to determine whether repair or rehabilitation is needed. In addition to the overall stability, the ratings can be separated into vertical and lateral. For MD 36, the vertical and lateral scores were similar, as shown in Table 3; thus, neither of those processes strongly dictates the instability. However, there are several indicators that stand out as having particularly high values in the "Poor" rating category. For MD 36, the indicators in the "poor" range are channel entrenchment or confinement and bank slope.

The site modifications included excavation of the floodplain on the left upstream bank and instream structures. Channel structures begin upstream with a cross vane, followed by three J-hook vanes, a series of three cross vanes, the bridge, and a downstream cross vane. The cross vanes are intended to control the grade and degradation through the reach. The J-hook vanes are intended for bank stability. Several of the J- hook vanes have rock that is fracturing and deteriorating. There is considerable deposition and vegetative growth upstream of the right span of the bridge (Figure 9). Data taken from the USGS gage 01653600 Piscataway Creek at Piscataway MD shows that this watershed experienced a 10-year, 20-year, and a 33-year return period storm since the reconstruction of this bridge in 2005. During site visits, widespread degradation and entrenchment were observed throughout the rest of the watershed, as were localized areas of deposition of large rocks.

MD 17 over Middle Creek

Bridge #10071, Maryland Route 17 (MD 17) over Middle Creek, is located in Frederick County, 2.4 kilometers (1.5 miles) northeast of Myersville, Maryland. The site and upstream watershed lie within the Blue Ridge physiographic region. MD 17 is classified as a Rural-Major Collector with an ADT of 1,951 vehicles as of 2009 (Baughn 2016). The existing land use in the 65.8 square kilometer (25.4 square mile) upstream watershed consists of pasture, cropland, forest, commercial developments, and residential lots. In the vicinity of the MD 17 crossing, Middle Creek is a gravel bed channel with well vegetated banks. Sources of potential instability in the reach include past anthropogenic activities, such as channel relocation, changing land use, presence of a downstream quarry, and confinement from abandoned abutments upstream.

The MD 17 crossing over Middle Creek was replaced in October 2005. Deposition of sediment in the left span had resulted in a scour hole forming along the right abutment. The previous crossing was a two span bridge, approximately 24.1 meters (79 feet) in length. It was replaced by a single span bridge, intended to prevent aggradation. A cross vane marks the upstream extent of the channel stabilization project associated with the bridge replacement. The cross vane was placed to control the bed elevation. A lowered floodplain was constructed for about 100 feet upstream.

At high flows, the left floodplain, which is now a substantial bar, overtops, directing the flow toward the right abutment. The deposition of the bar may have been exacerbated by the sloped left abutment. Riprap at the downstream end of the right abutment is beginning to fail. A series of three vanes were constructed upstream to redirect flow away from the steep right bank and right abutment. A cross vane was also used downstream of the project to prevent head cuts from migrating up from the downstream gravel quarry. During a site visit on May 17, 2016, aggradation of the left bank under the bridge and undermining of the riprap stabilization on the downstream right bank were observed (Figures 10 and 11). During the site visit in February, 2017, a sediment sample was collected from the large bar that has developed within the project reach (see appendices). The outside bank upstream is experiencing erosion upstream of the rock vanes, and the inside bend has had extensive deposition. The lateral bar has pushed the channel against the bridge riprap on the opposite bank and eroded some of the riprap from the toe of the abutments. The bridge is still protected from lateral migration by riprap, geotextile, and the old crossing foundations. However, the riprap erosion will require maintenance. Due to the extent and depth of the lateral bar, the conveyance of the bridge is likely reduced from the design.

MD 28 over Tuscarora Creek

Bridge #10014, Maryland Route 28 (MD 28) over Tuscarora Creek, is located in Frederick County, 4.4 kilometers (2.7 miles) west of Point of Rocks, Maryland. This site lies within the Piedmont physiographic region. MD 28 is classified as a rural-minor arterial road with an ADT of 3,212 vehicles as of 2009 (Baughn 2016). The primary land use in the 51.0 square kilometer (19.7 square mile) upstream watershed is agricultural. The remainder is a mix of residential, commercial, industrial, and institutional land use. In the vicinity of the crossing the channel is a gravel channel with significant amounts of agriculturally derived silt present in the system. The channel has well vegetated banks. The primary symptoms of instability in the reach are entrenchment and deposition of fine sediment.

The MD 28 crossing over Tuscarora Creek was replaced in 2007 because the previous bridge was scour critical and superstructure had deteriorated. The previous crossing was a two span bridge totaling 14.0 meters (46 feet) in length. The new bridge is 33.5 meters (110 feet) in length across two spans. The hydraulic structures used in the channel at this bridge include a cross vane at the upstream boundary of the project to hold the channel in place laterally and a rock vane upstream of the bridge. Although the rock vane still in place and undamaged, it is partially buried and does not appear to be effective any longer. Floodplain excavation and riparian plantings were also undertaken at this site.

Aggradation of the excavated floodplain was observed during a site visit on May 17, 2016 (see Figure 12). Judging from observations made during site visits, the floodplain elevation has increased due to deposition by approximately 1-2 ft. Also, the downstream cross vane is buried under sediment; however, burial does not affect the vanes ability to prevent upstream head cut migration. The right span is well aligned with the low flow channel.

MD 223 over Piscataway Creek

Bridge #16051, Maryland Route 223 (MD 223) over Piscataway Creek, is located in Prince Georges County, 1.9 kilometers (1.2 miles) north of Rosaryville, Maryland. This site lies within the Coastal Plain physiographic region. MD 223 is classified as a State Secondary Rural Urban OPA (Other Principle Arterials) with an ADT of 31,292 vehicles as of 2012 (Baughn 2016). Andrews Joint Airfield covers 54% of the 12.2 square kilometers (4.7 square miles) watershed upstream of the crossing. The remaining land uses include a mix of forest, open land, and residential lots. In the vicinity of the MD 223 crossing, Piscataway Creek is a gravel bed channel with well vegetated banks. There are unconsolidated lateral bars throughout the reach. Current channel conditions are likely a result of past anthropogenic activities, which included straightening, relocation, and deposition of legacy sediment from mill dams.

The MD 223 crossing over Piscataway Creek was replaced in 2012 due to frequent flooding of the roadway. The previous crossing was composed of four adjacent 2.97 meter x 2.01 meter (9.58 feet x 6.58 feet) corrugated metal arch pipes, each 55 feet in length. This configuration created a backwater condition upstream of the culverts that contributed to aggradation and flooding issues at the crossing. The replacement bridge was a single span slab bridge, 16.76 meters (55 feet) in length. For the new bridge, the primary practices used for the stream channel transition were lowering of the floodplain and clearing of debris. Although the new bridge realigned the channel and bridge opening, the bridge is still on the outside of a large meander; thus, deposition of sediment upstream of and within the bridge opening is a chronic problem, as shown in Figure 13. The upstream bar redirects the low flow such that the angle of approach to the bridge opening during low flow is increased and flow within the bridge opening is directed against the left abutment. At high flows the stream likely overtops these bars and approaches the bridge at a lesser angle. The opening beneath the bridge appears to be acting as a sediment trap. However, the observed bar downstream of the bridge opening indicates that at least a portion of the sediment is moving through the opening to the downstream channel.

The stability assessment for this site resulted in a Fair rating (see Table 3), implying adverse conditions that may require repair or rehabilitation. The vertical and lateral scores, shown in Table 3, were similar, indicating that both processes are at work and neither particularly dominates. There are, however, several categories that rated as Poor, which may warrant attention. Those indicators in the “poor” range include 5 (bed material packing and sorting), 6 (bar development), and 13 (alignment of upstream channel to the bridge opening). This is certainly not a surprising result, as it is observed that there is significant sediment accumulation that is altering the alignment of the low-flow channel, but combined with the other ratings leads to the overall “Fair” score.

MD 25 over Georges Run

Bridge #3019, Maryland Route 25 (MD 25) over Georges Run, is located in Baltimore County, 1.6 kilometers (1 mile) East of Armacost, Maryland. This site lies within the Piedmont physiographic region. MD 25 is classified as Major Rural Collector with an ADT of 4,881 vehicles as of 2009 (Baughn 2016). The primary land use in the 33.9 square kilometer (13.1 square mile) upstream watershed is agricultural with a minor percentage of forest and residential lots. In the vicinity of the MD 25 crossing, Georges Run is a gravel bed stream with well vegetated banks. Channel instability in the upstream area is likely a result of increased sediment supply from a past relocation of Peggy’s run and lateral migration of the channel upstream of the project bounds.

The MD 25 crossing over Georges Run was replaced in early 2016. Stream alterations made during reconstruction included excavation of the upstream floodplain, construction of upstream guide banks, excavation of a scour hole under the bridge (see Figure 14), and excavation of a forked channel downstream (see Figure 15). The excavation of the left floodplain was intended to provide storage for sediment. Sediment deposition in this newly excavated area was observed during visits in April and again in June, 2016. A large gravel bar extends downstream toward the bridge from the left guide bank. Debris accumulation in the upstream Peggy’s Run may help to slow the downstream migration of sediment in the future. The forked channel created downstream of the bridge opening was intended to provide relief for high flows so that high stresses against the right bank are lowered. Cross vanes upstream of the bridge were observed to be partially buried during a site visit on June 6, 2016.

Maryland Route 165

Bridge #12046, Maryland Route 165 (MD 165) over a tributary to the West Branch of Winters Run, is located in Harford County, 6.77 kilometers (4.22 miles) north of Baldwin, MD (see Appendices, Figure A6). It is a single span slab bridge, 13.72 meters (45 feet) in length. This site lies within the Piedmont physiographic region. MD 165 is classified as a rural major collector with an ADT of 7,471 vehicles as of 2009 (Baughn 2016). Residential lots are the primary land use in the 16.5 square kilometer (6.4 square mile) upstream watershed. The remainder of the watershed is a mix of pasture, forest, and cropland. In the vicinity of the crossing, the West Branch of Winters Run is a gravel bed channel.

The MD 165 crossing over West Branch tributary was replaced in 2004 due to issues with scour. It was replaced to accommodate a 25-year storm. The hydraulic modifications made during construction included realigning the channel to a previous location, the installation of a rock vane, and construction of three cross vanes to control grade through the bridge. As of a site visit on June 6, 2016, there was woody debris in the upstream channel and the channel is laterally migrating toward the left bank (see Figure 16). All instream structures upstream of the bridge are no longer functioning as intended since the channel has migrated. However, the opening itself appears to be free of debris and sediment accumulation and is aligned with the channel. Downstream of the bridge, the project included a rock wall on the right bank and a J-hook. There was significant bank erosion downstream of the rock wall (Figure 17); thus, it appears that the J-hook is not functioning as intended.

MD 136 over Broad Run

Bridge #12034, Maryland Route 136 (MD 136) over Broad Run, is located in Harford County, 2.6 kilometers (1.6 miles) northeast of Creswell, Maryland. This site lies within the Piedmont physiographic region. MD 136 is classified as a rural major collector and has an (ADT) of 6,361 vehicles as of 2009 (Baughn 2016). Agriculture is the primary land use within the 12.1 square kilometers (4.7 square miles) upstream watershed. Residential lots and forest are the next largest land uses; commercial areas and grassy lots also are present in the watershed. In the vicinity of the MD 136 crossing, Broad Run has a gravel channel bed with well vegetated banks.

The MD 136 crossing over Broad Run was rebuilt in 2006 due to deterioration of the superstructure and frequent overtopping. The existing bridge was a single span of 8.5 meters (28 feet) in length. No stream channel alterations were made at this site during reconstruction. Upstream of the bridge, the left bank is being undermined and a sediment bar has accumulated (see Figure 18). The channel is well aligned with the bridge opening and sediment accumulation does not appear to be an issue (see Figure 19).

MD 7 over James Run

Bridge #12009, Maryland Route 7 (MD 7) over James Run, is located in Harford County, 0.8 kilometers (0.5 miles) east of Belcamp, Maryland. This site lies at the transition of the Piedmont and the Coastal Plain physiographic regions, known as the Fall Zone. MD 7 is classified as an Urban Minor Arterial with an ADT of 12,500 vehicles as of 2013 (Baughn 2016). The primary land use in the 28.7 square kilometer (11.1 square mile) upstream watershed is agricultural. There also forested areas, medium density residential lots, low-density residential lots, and pasture areas.

The crossing was reconstructed in 2014. No stream alterations were made at this site during reconstruction. The stream transports a significant gravel load (see Figure 20). Sediment and debris has accumulated upstream and beneath the bridge, but appears to be moving through the opening and downstream (Figure 21). Given the unstable upstream conditions with woody debris being added to the stream, debris accumulation will likely be ongoing. The channel was well aligned with the bridge opening.

METHODOLOGY

Successful transitions can be defined by building on the definition of stable channels at bridges. Johnson (2005) defines a stable channel in the vicinity of a bridge as one in which the relationship between geomorphic process and form is stationary and the morphology of the system remains relatively constant, over a defined distance upstream and downstream from bridge, and with minimal lateral movement. In addition, channel transitions through bridge waterways should maintain the ability to convey the design flood flow and require minimum maintenance.

The method developed in this project is divided into two sections:

1. Assessing channel transition projects at existing bridges and
2. Guiding design selection of channel transitions at new bridges.

ASSESSING CHANNEL TRANSITION PROJECTS AT EXISTING BRIDGES

Existing projects at bridges are commonly described in terms of either success or failure. In this section, a method is developed to expand that description so that the projects can be described by a wider range of descriptors based on the damage to the project observed. The method is based on prior research for describing the damage states to stream modification projections, not necessarily associated with bridges (Jones and Johnson, 2015). Damage states provide a meaningful description of the state of current bridge transition projects at the selected sites and avoids the need to define failure.

Complicating the determination of damage states for existing bridge sites in this study is that several of the channel designs included a preformed scour hole beneath the bridge. It is unclear under what flow conditions through the scour holes will convey the sediment from the holes and when it will be stationary. This is a complex three dimensional sediment transport question and a potential area of future research.

The damage state factors and ratings developed for use in this study are given in Table 4. The factors are based on Jones and Johnson (2015) as well as the definition of a stable transition, areas of concern expressed by MDSHA personnel, modes of failure observed at bridges during this study, and from the rapid channel stability assessment (Lagasse et al. 2012). This table defines the level of damage to various aspects of a waterway transition post-construction. Each of the damage factors is described below.

1. *Overall impact on safety of the waterway transition***.** Unless the entire project is heavily armored, it is expected that some channel adjustments will occur over time. Although local changes may occur to various elements of the stream modification project, those changes overall may not impact the safety of the waterway transition through the bridge opening or they might negatively affect the safety of the bridge foundations. The channel adjustments might even create a more stable and safe transition. This factor describes the impact of those overall changes to the original as-built project on the safety at the bridge.

2. *Instream structure and countermeasure integrity*. Instream structure and countermeasure integrity addresses damage to components of the transition itself. Damage in this area at channels with a favorable stability rating may indicate that the channel is stable despite the damaged instream structures. This factor was included in the damage state table of Jones and Johnson (2015); however, the ratings have been modified for this study. Jones and Johnson (2015) used the median value of the damage scores that were assessed for each individual structure. Using the median has the potential to hide damage to an individual structure that is paramount to the stability of the transition. The modified ratings used in Table 4 attempt to remedy this issue.

3. *Bank stability and lateral migration*. Bank stability and lateral migration rates the damage to lateral project stability. As described by Jones and Johnson (2015), raw and failing banks can be a symptom of channel migration, widening, or degradation. These adjustments can result in endangering the bridge foundations by creating an altered flow path. The breaks in percent of total bank length given in Table 4 are those used to distinguish between conditions in the bank stability habitat parameter by Barbour et al. (1999).

4. *Project tie-ins*. The project tie-in is defined as the up- and downstream ends of the channel modification project. Destabilization of channel transitions as a result of erosion at the project tie-ins at the up- or downstream ends of the project reach can impact the entire project. If the project did not include a reach outside of the bridge right-of-way, the upstream

and downstream tie-ins are considered the riprap or wing walls immediately adjacent to the bridge.

5. *Bed degradation*. Bed degradation is evidence of damage to a project resulting from shear stresses in the channel exceeding the resistance of the bed material. Bed degradation is a concern because long-term bed degradation has the potential to endanger bridge crossing foundations. This category was adapted from the rapid channel stability assessment (Johnson, 2005; Lagasse et al. 2012).

6. *Sediment deposition and woody debris accumulation*. Sediment deposition and woody debris accumulation is evidence of a lack of channel competence and/or capacity or a bridge waterway opening that does not convey the incoming debris supply. The ratings for this damage factors were adapted from the rapid channel stability assessment (Johnson, 2005; Lagasse et al. 2012).

Table 4 defines the level of damage to various aspects of a waterway transition post-construction. After rating each category the sum of the ratings can be calculated for an overall score. The sum is then normalized by the number of factors to obtain an overall damage state. An undamaged project will mainly be composed of factors that are rated as “none” with only a few “moderate” ratings and no “extensive” or “complete” ratings. Any indicators ranked as extensive or complete should receive immediate attention to assure that the safety of the bridge is not compromised.

Evaluation of the damage states is unavoidably subjective; however, the descriptions of damage provided above and in Table 4 should help to minimize discrepancies between observers. All damage scores need to be documented with descriptions of site conditions and photographic documentation of the conditions described. It is appropriate to confirm damage scores, especially visual assessments of the likely extent of damage, with a survey of site conditions before remedial action is taken. Related to reducing subjectivity, this framework relies on the availability of information pertaining to the design and as-built condition of the project being evaluated. As-built conditions may not have been surveyed and individuals who participated in the design and construction may not be available in all situations. If this is the case, the damage assessment may not be as accurate, as assumptions would have to be made regarding the original condition of the project components.

GUIDING DESIGN SELECTION OF CHANNEL TRANSITIONS AT NEW BRIDGES

In this section, a methodology is developed for selecting a type of channel design based on site stability conditions, the ability of the channel to transport sediment through the waterway opening beneath the bridge, and relative risk of failure to the design components. Figure 22 depicts the general methodology. A rapid channel stability assessment, described in HEC-20 (Lagasse et al. 2012) and in Johnson (2005), is used to assess overall channel instability, as well as the contribution to instability from lateral and vertical factors. A suitable design type must then address each area of instability. Once an initial design type is selected, it is checked for trends in relative sediment transport capacity using a ratio of flow velocity to critical velocity (V/V_c) for a range of flows. If the analysis shows a trend toward decreasing V/V_c toward the bridge, then alternative channel geometries can are tested to see if a more desirable trend can be obtained. A desirable result is a consistent ratio throughout the reach, which is competent to support transport through the bridge opening without either aggradation or degradation. Once the analysis shows a favorable result, a Failure Modes and Effects Analysis (FMEA) is conducted to assess relative risk of the individual components of the design. Based on the results of the FMEA, if any modifications are made to the design that would affect the results of the V/V_c analysis, the analysis should be repeated. If the results of this V/V_c analysis are favorable, the design is considered to be appropriate.

Each of the components described above and shown in Figure 22 are described in more detail below.

Rapid channel stability assessments

Developed by Johnson (2005) and adopted by the Federal Highway Association in HEC-20 (Lagasse et al. 2012), the rapid channel stability assessment is a qualitative method to assess levels of stability based on thirteen independent stability indicators. These indicators include watershed wide instabilities as well as local vertical and lateral instabilities. This study uses the stability assessment unmodified from its form in HEC-20. Based on site visit observations and aerial imagery of the watersheds indicator ratings were assigned for the existing condition at each of the bridges included in this study. The ratings for each of the individual indicators were summed to compute an overall rating. The numerical sum is compared to a table to obtain a qualitative overall rating of excellent, good, fair, or poor. Vertical and lateral fractions can be calculated to indicate if the overall instability is more vertically or laterally derived. Indicators 4-6 pertain to vertical stability, and indicators 8-13 pertain to lateral stability. Vertical and lateral fractions are then calculated by summing the appropriate ratings and normalizing by the total number of points possible for each group (Johnson 2005).

The results of the rapid channel stability assessment can be used as a starting point to identify suitable design types, such as do nothing, excavated flood plain, grade control, channel relocation, etc. Based on the limited sample group of this study, do nothing is one option at sites with an overall rating of excellent and possibly good. Doing nothing should not be an automatic choice for sites with an overall rating of good, especially if there are individual indicators with poor ratings. Indicators with ratings of poor point out issues that may need to be addressed through channel modifications. If channel modifications are considered necessary or potentially necessary, then the results of individual indicators can be used as an aid at selecting potential design components.

V/V_c Analysis

Many geomorphic studies agree that streampower is a powerful indicator of channel stability. It has often been used to predict sediment transport. The streampower per unit channel width, ω, is typically assessed over an extended reach, rather than in a short reach, as in the case of transition projects at bridges. In addition, in our case, streampower is a difficult value to accurately assess for a given cross section, unless very detailed flow data are available.

An alternative is to combine shear stress with the Manning equation to yield a critical velocity that is strongly related to streampower. In this method, we set the average channel boundary shear stress to equal the critical shear stress, and solve for slope. Substitution of this slope into to Manning equation provides the critical velocity, V_c. In this manner, V_c can be shown to be related to ω, and is readily compared to cross-sectional velocities for a range of discharges at locations upstream and at the bridge. The development of the Shields-Manning equation is developed below. At critical conditions, the critical shear stress just equals the average boundary shear stress:

$$\tau_c = \tau_o \tag{1}$$

Substituting the Shields equation for τ_c:

$$\theta_c(\gamma_s - \gamma)D = \gamma y S \tag{2}$$

Solving Eq. 2 for S:

$$S = \frac{\theta_c(\gamma_s - \gamma)D}{\gamma y} = \frac{\theta_c(S_s - 1)D}{y} \tag{3}$$

Where S_s = specific gravity of sediment.

Manning's equation solved for slope, S, is given by:

$$S = \frac{V^2 n^2}{1.49^2 y^{4/3}} \tag{4}$$

Assuming $V = V_c$ at critical conditions and $S_s = 2.65$, then setting Eq. 3 equal to Eq. 4 yields:

$$\frac{{V_c}^2 n^2}{1.49^2 y^{4/3}} = \frac{\theta_c(S_s - 1)D}{y} \tag{5}$$

Solving Eq. 5 for critical velocity yields:

$$V_c = \frac{1.49}{n} y^{1/6}[\theta_c(2.65 - 1)D]^{1/2} \tag{6}$$

A number of assumptions are associated with the use of Eq. 6 to compute V/V_c. First, the values of V/V_c represent an average for the cross section; however, that value may vary significantly across the cross section, especially in meander bends unless a 2-dimensional analysis was used to determine the hydraulics. Second, partial transport studies show that at shear stresses twice the critical shear stress, partial movement of sediment can be expected (Pitlick and Wilcock, 2001). At values of three and higher, the entire bed is likely to be in motion. In this study, we assume that the same is approximately applicable for V/V_c. Third, the value of the dimensionless critical shear stress, θ_c, is assumed to be 0.03 (Parker et al., 2003; Mueller and Pitlick, 2005).

The goal of the V/V_c analysis is not to predict sediment transport, but rather to determine trends in sediment motion from upstream through the bridge opening for a range of discharges. If the ratio is high upstream and then drops significantly in the vicinity of the bridge, it can be assumed that the bridge location is a depositional one. On the other hand, if the ratio is significantly higher near the bridge, it may indicate an erosional environment. The goal is to maintain the V/V_c ratio from upstream through the bridge reach. If this is not attainable, then a different design type, such as a widened and lowered floodplain, may be more appropriate.

Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects Analyses (FMEA) has since been applied to a variety design problems in a wide variety of industries. The FMEA is a qualitative method intended to illuminate potential failure modes of individual design components and identify the impact of each failure mode on the system as a whole. It provides a systematic method for assessing relative risk of alternative designs and individual design components. FMEA has been adopted for use in stream restoration design and countermeasure selection by Johnson and Brown (2001), Johnson and Niezgoda (2004), and Niezgoda and Johnson (2007).

In an FMEA, relative values are assigned to each failure mode for the consequences of failure or severity, C, likelihood of occurrence of the failure, O, and the ability to detect failure (D_f). Rating tables for C, O, and D_f are established prior to the analysis to prevent bias in the final values. C, O, and D_f can then be multiplied together to yield a Risk Priority Number (RPN). The tables created for stream design projects are provided in the references given above. RPNs are relative values of risk associated with a failure mode of a given component. Relatively high RPNs are typically given greater attention in the final or alternative design. The goal of an FMEA as part of the design selection process is to identify high risk design components and mitigate the risks to improve the likelihood of success of the channel transition.

RESULTS

The results of the project are divided into two sections. The first section provides the damage states of the selected project sites using the method developed above. The second section provides three case studies to demonstrate the use of the methodology developed for selecting a type of channel transition design for a new project.

DAMAGE STATES OF EXISTING CHANNEL TRANSITION PROJECTS

Damage state assessments were carried out at each of the selected sites described above to assess the relative degrees of damage at the existing channel transitions. Each of the six individual ratings is out of a possible four points which correspond to none, moderate, extensive, and complete damage. The overall rating ranges from six to 24. The damage state ratings for the study bridges are shown in Table 5.

MD 36 over Georges Creek is relatively undamaged, receiving ratings of none except for two ratings of moderate for Instream Countermeasures, and Sediment and Woody Debris Aggradation. The upstream J-Hook vanes were constructed of lower quality rock that flaked; however, that has had no noticeable effect on the project as a whole. There is sediment deposition and woody vegetation growth in one span of the bridge. Also noteworthy is the damage rating of none for Degradation. During site visits, widespread degradation and entrenchment were observed throughout the rest of the watershed and localized areas of deposition of large rocks.

MD 17 received damage ratings greater than none for three indicators. Bank Erosion and Sediment Deposition were assessed a rating of extensive. This is a result of the bend upstream and under the bridge crossing. The outside bank upstream is experiencing erosion above the rock vanes, and the inside bend has had extensive deposition. The lateral bar has pushed the channel against the bridge riprap on the opposite bank and eroded some of the riprap from the toe of the abutments. The bridge is still protected from lateral migration by riprap, geotextile, and the old crossing foundations. However, the riprap erosion will require maintenance. Due to the extent and depth of the lateral bar (above the water surface elevation extending approximately 10.6 m (35 ft) out from the left abutment, extending the length of the project reach from the upstream face of the bridge, and jutting approximately 1.2-1.5 m (4-5 feet) high from the normal water surface to the maximum), the conveyance of the bridge is likely reduced from the design.

MD 28 over Tuscarora Creek received zero damage ratings higher than none. Based on photos and site observations, the floodplain has risen by deposition approximately 0.3-0.6 m (1-2 ft). It appears the majority of this deposition occurred shortly after construction. Also, the downstream cross vane is buried under sediment; however, burial does not affect the vanes ability to prevent head cut migration. This deposition did not warrant any ratings of damage for any of the indicators. The channel is well aligned with the bridge and appears to be in stable condition.

At MD 223 over Piscataway Creek, the Sediment and Woody Debris Aggradation damage indicator received a rating of complete damage. Approximately eighty percent of the widened channel area in the vicinity of the bridge has experienced deposition of gravel bars that have modified the flow approach to the bridge. At high flows the stream likely overtops these bars and approaches the bridge approximately perpendicularly. Based on the USGS 01653600 Piscataway Creek at Piscataway MD gage, with a record going back to 1966, this watershed has experienced a 33-year return period storm since the reconstruction of this bridge in 2013. Due to roadway realignment for the nearby intersection, the bridge was constructed on or just downstream of a river bend. Thus, the design conveyance is reduced and maintenance will be required.

MD 25 over George’s Run received two damage ratings of none and four ratings of moderate. This project was only recently completed in early 2016. The moderate ratings were assigned do to river adjustments at the upstream project end. Some erosion was observed on the right bank in the vicinity of the upstream tie-in and cross vane. Also, the incoming sediment, including larger gravels from Peggy’s Run, is depositing near the upstream cross vane. As of the August 2016, site visit, the floodplain near the upstream cross vane had deposition of gravel up to approximately 125 mm in diameter to a depth in excess of 20 cm. This deposition has caused the stream to approach the upstream cross vane at an angle that negates the vane’s function of aligning flow. The vane would still prevent lowering of the channel bed elevation if the stream remains within the boundary of the vane. These issues approximately 100 m upstream of the bridge crossing. There is also deposition of finer materials closer to the bridge both on the floodplain and in a bar just upstream of the bridge. The project is too young to determine longer term damage states.

MD 165 over a Tributary to the West Branch of Winters Run is straight and stable immediately around the bridge. The project as a whole has issues with lateral erosion and sediment deposition. The uppermost part of the project became buried with incoming sediment causing the circumvention of the uppermost cross vane. This issue has since been compounded by more deposition and tree fall. Downstream as the water exits the bridge it is directed at an unprotected area between the two cross vanes. This has resulted in lateral erosion that is encroaching on a private driveway. There is no foreseeable need for maintenance. However, this transition received the highest damage state rating of all the Maryland bridges included in this study, which is 12 out of a possible 24. Most of the damage is related to the cross vanes that were buried, circumvented, and direct flow toward an under-protected area of bank. While the effectiveness of the transition can be assessed as designed, it is more difficult to say how the transition would be assessed without the cross vanes.

MD 136 over Broad Run received damage ratings of extensive for the Bank Stability and Project Tie-in indicators. At this project no stream stability countermeasures were constructed. These two items are linked as they both relate to the lateral migration of the reach upstream of the bridge. The stream is not imminently threatening the infrastructure; however, it is primarily being protected by undercut trees. Without the trees there is little bank protection remaining. Toppling of the trees may not be as imminent as their precarious lean would suggest. A small black cherry tree that is undercut and overhanging the channel is visible in identical condition both in photos from post reconstruction (2006) and in a 2016 site visit. At this time, this bridge attains all three aspects of the definition of a successful transition. The possibility for future instability is present, as indicated by the results of the rapid channel stability analysis conducted. This site received a stability rating of 86, right on the border of the good and fair categories, indicating a potential for instability that may require attention.

MD 7 over James Run received ratings of moderate for the Bank Stability indicator and of extensive for the Sediment Deposition indicator. No stream stability countermeasures were used at this location. At this site the bed is composed of angular gravels (D_{50} = 33 mm), and the banks are composed of finer material (MDSHA 2004). The channel is broad and very shallow. The channel upstream appears to be widening as there are also large leaning trees on both banks. The bridge opening flood conveyance is likely compromised by sediment deposition within the span.

CASE STUDIES

In order to demonstrate the design selection methodology (Figure 22), three case studies were conducted based on the selected sites described earlier. The MD 25 over Georges Run study demonstrates the use of the entire guiding design selection methodology (Figure 22). The MD 7 over James Run site demonstrates the process for a bridge where doing nothing is a potentially viable option. MD 136 over Broad Run represents a site where no channel transition was constructed, but according to the results of a rapid channel stability analysis one might have been warranted.

In the case studies, a representative sediment size and a desired return period flow must be selected in order to compute the velocity ratio. In this report, D_{50} was selected as the representative sediment size. When D_{50} is in motion, then it can be assumed that there is significant transport occurring. The 10-year return period was selected for the flow. This return period represents a significant out-of-bank event, typically capable of moving significant sediment in natural conditions. At bridges, the 10-year flow should be able to move deposited material through the bridge opening and downstream.

As an example of calculating and interpreting V/V_c, data from MD 223 over Piscataway Creek was used based on the 10-year flow. In this example, $n = 0.045$ (MDSHA, 2010) and the dimensionless critical shear stress, $\tau^* = 0.03$ (Parker et al, 2003; Mueller and Pitlick, 2005). Table 6 provides the results beginning upstream at station 6560, working downstream toward the bridge at station 3637, and finishing further downstream at station 1000. Assuming that the partial transport concept applies here, as described in the previous section, then the calculations above show that sediment upstream of the bridge will likely be mobilized upstream during the 10-year flood event. However, at the bridge, V/V_c drops significantly, indicating that at least a portion of the sediment will likely not be transported through the bridge opening. Given that the V/V_c ratio is based on averages and is low (close to one), it is likely that on the inside of the bends, as occurs under the bridge, sediment will deposit due to V dropping below the critical value.

MD 25 over Georges Run

This case study provides an example of the selection guidance for a design type. It demonstrates how to use a rapid channel stability assessment (Lagasse et al. 2012) to identify instabilities, select a transition that addresses the instabilities, and analyze the proposed design in a way that should increase the likelihood of creating a stable transition. The overall process is shown in Figure 22 and described in the methodology section.

This is a semi-hypothetical case study based on a project that has already been constructed. Three design options were considered in this study. Design Option 1 represents the pre-existing condition of the site, Design Option 2 represents the transition that was constructed by MDSHA in 2016, and Design Option 3, a hypothetical option, represents raising the floodplain of Design Option 2 by 0.46 m (1.5 ft) in an attempt to increase the velocity to a point at which sediment would be carried through the bridge opening. Reports and photographs (MDSHA 2014) of the pre-construction conditions (Design Option 1) were used as input for the rapid channel stability assessment and instabilities that existed at that time were determined from the assessment. The design ultimately constructed by MDSHA in 2016 (Design Option 2) was used as the initial design for this case study. This design involved floodplain excavation, cross vanes upstream of the bridge, a guide bank immediately upstream of the bridge, and a forked channel downstream of the bridge. As a comparison to the existing design, Design Option 3 involved raising the bank heights of the initial designed channel (Design Option 2) as a way to increase the velocity through the bridge opening such that sediment would be transported through the opening and downstream at the same flow. Each part of this method is described in further detail in the following paragraphs.

The preliminary stability rating of the pre-existing stream channel (Option 1) of the MD 25 bridge is given in Table 7. The results indicate that this reach was experiencing significant instability both laterally and vertically. Although both the lateral and vertical instability fractions are high, the lateral is 0.84, which is significantly higher than the vertical fraction 0.63. Since the bridge received an overall rating of fair, “do nothing” is not a valid option in this case. The indicators that received the worst ratings included bar development, bank soil, bank, slope, bank protection, bank cutting, bank failure, and upstream distance to meander. The high rating for bar development indicates a tendency for deposition either due to a decrease in competence and/or an increased incoming sediment supply. The banks were approximately one meter high with an angle of 80-90 degrees. Mass wasting was evident by the scalloped bank and slumped material. Approximately 250 m (820 ft) upstream of the bridge crossing, a 200-m (650 ft) reach of a tributary known as Peggy’s Run, was straightened in the past by a landowner. It now contributes a significant portion of the local sediment load at the MD 25 bridge over Georges Run (MDSHA 2014). Any potentially successful design for the new bridge must address the two main issues of unstable banks and sediment transport and deposition from upstream.

The values of V/V_c for the pre-construction case (option 1) are given in Table 8. Recall that the goal of computing V/V_c is not to determine the precise value at which sediment moves, but rather the trend as the flow approaches the bridge. In this and all cases, $D_{50} = 16$ mm was the selected sediment size and the 10-year flow was selected as the design discharge. Table 8 shows that the velocity ratio dropped significantly just upstream of the bridge for the 10-year flow. Given that the velocity will be lower on the inside of the bend, it is likely that sediment deposition would take place. Thus, Design Option 2 is examined.

The constructed geometries from the HEC-RAS model were used to check the general trend in the ratio of V/V_c for the channel, as constructed (option 2), shown in Table 8. The velocity ratio upstream of the bridge is still lower than upstream, but higher than in the pre-constructed scenario. This suggests that deposition is still likely to occur, especially on the floodplain and at bends, although more sediment may be carried through the opening. It should be noted that it is not possible to reflect the effect of the preformed scour hole on the velocity ratio under the bridge, as this represents strongly three-dimensional flow, not captured by HEC-RAS. If the project goal is to capture sediment or to store it in a more easily accessible location for later dredging, then this ratio is acceptable.

A hypothetical alternate design (option 3) is considered in this study to determine whether it is possible that a channel with higher banks might facilitate the transport of sediment through the bridge opening. This option includes a channel with higher banks than Design Option 2. The geometry in the HEC-RAS model was adjusted by raising the excavated floodplain elevation by approximately 0.46 meters (1.5 feet). The resulting V/V_c ratios of this alternative design are given in Table 8. Raising the floodplain elevation resulted in a more consistent V/Vc ratio throughout the reach for the 10-year flood event and increased the ratio slightly upstream of the bridge. In this case, no pre-formed scour hole under the bridge was assumed. Thus, the velocity ratio indicates that some sediment is likely transported through the opening; however, given that the calculations were based on D_{50}, larger sediment, such as the D_{84}, may not be picked up and transported, especially at bends. The comparison presented here by this hypothetical design modification demonstrates how iterative changes can be made within this design selection framework (Figure 22).

After the designer determines a design geometry with an acceptable ratio of V/V_c throughout the reach, Figure 22 shows that a Failure Modes and Effects Analysis (FMEA) should be conducted. The FMEA is used to identify the project components, the potential failure mechanisms of each component and the potential for detecting a failure. Table 9 is the FMEA for Design Option 3 with higher banks than Design Option 2. Again, FMEAs for both Design Option 2 and 3 were included in this study for comparison purposes. The FMEA for Design Option 2 is available in the appendix. The FMEA highlights design components with relatively higher risk priority numbers. Components that have significantly higher RPNs may indicate weak points in the design. Such components can be redesigned more robustly or switched for other more reliable components that achieve the same function. In addition to identifying components with high RPNs, the FMEA can be used to aid in deciding between multiple potential designs that have passed the V/V_c analysis. Comparisons of total RPN can be made between the designs. If one design results in significantly lower RPNs, it should be selected. If the designs have similar total RPNs, cost can be brought into the comparison.

If any modifications to the channel geometry design are made after conducting the FMEA, the V/V_c analysis is conducted again, as shown in Figure 22, to examine any potential sediment mobilization issues. If the V/V_c results are acceptable, the type of design can be considered ready for detailed design work.

MD 7 over James Run

This case study provides an example our design selection process that results in a ‘do nothing’ option. No channel stabilization measures were constructed at this site. A rapid channel stability assessment was conducted during a visit to the site, with the results provided in Table 3. An overall rating of Good was assessed. Poor ratings of 10 were recorded for the bar development and bank protection indicators. James Run is straight for at least 90 meters (300 ft) upstream of the MD 7 crossing. Based on leaning trees on both banks, the channel appears to be widening. However, based on the overall stability rating, this site has good stability. The ‘do nothing’ design is appropriate for this location because of its good stability rating. (A V/V_c analysis was not conducted for this site because of issues with the HEC-RAS model needed for the analysis inputs.)

MD 136 over Broad Run

This case represents a bridge where no channel transition was constructed. This location received a stability rating of 86 (Table 3). This value is at the boundary between the good and fair categories. While a transition has not been necessary at this location, there is some instability within the bridge reach that may warrant future attention. The banks upstream are steeply cut by the erosive forces of the meandering channel. Undercut banks were observed and many of the trees upstream are leaning (Figure 18). The wide band of riparian vegetation composed of large trees is acting to limit instability in this reach. Without this vegetation the instability would likely be greater. Table 10 shows wide variations in V/V_c based on D_{50} = 23 mm. The ratio drops just upstream of the bridge. This decrease indicates a potential for sediment deposition, which is observed in Figure 18. While this project may have warranted additional analysis based on the high stability score and decreasing trend in the velocity ratio, the fact that it has remained stable lends an interesting aspect as a case study. Several factors lead to the observed stability of the transition. First, while the velocity ratio does drop significantly upstream of the bridge and bars have formed, the ratio increases under and downstream of the bridge likely due to a decrease in flow width. Thus, it is possible for sediment to be conveyed through the opening. Second, the foundations from the previous bridge were left in place when the new bridge was built, creating hard points for the reduced channel width beneath the bridge. It is recommended that monitoring at this site be continued, as dislodging of the upstream woody vegetation could rapidly reduce the stability of the transition upstream of the bridge.

CONCLUSIONS AND RECOMMENDATIONS

In this study, existing transitions at Maryland bridges were examined for the purpose of determining the state of those transitions as well as their usefulness in defining and recommending best practices for future projects.

Rather than label a project as a failure or success, an attempt was made to define a level of functionality by describing the state of any damage existing at a site. This method facilitates a discussion of the suitability of various design types to a variety of site conditions far better than an either/or label of failure/success. Assessing the damage state of an existing project can provide input on the ability or inability of a transition to sustainably transport both the flow and sediment presented at that site. The damage states assessment is composed of factors that are applicable to the range of channel transitions selected for this project.

In addition to creating a methodology for assessing existing transitions, a methodology was developed that guides the design type selection process at new bridges or new channel transition projects. This process uses a rapid channel stability assessment to initially assess a site for instabilities that need to be addressed by the design. Two design checks are included as part of the method. The V/V_c analysis is a useful tool for assessing general trends in sediment mobilization through the bridge opening. Due to the use in this study of one dimensional HEC-RAS models to provide inputs for channel depth and velocity, the V/V_c results provide only an average-based mobilization. Thus, at bends and scour pools, where 2- or 3-dimensional flow is prevalent, the ratio is likely higher or lower than the average. The second design check is the Failure Modes and Effects Analysis. This requires the designer to systematically analyze all the potential failure modes of the design and to consider solutions that reduce the risk priority numbers of design components. Combining this method with current design knowledge should help to further increase the likelihood of a successful channel transition design.

Several observations and recommendations are made below based on field observations at a limited number of sites, comparisons of imagery, and analyses described in this report. Although the number of sites included in the study represent a limited sample size spanning multiple physiographic regions, bridge configurations, dates of construction, and channel transition types, several general recommendations can be made.

Recommendation 1. Archive data, reports, and as-built surveys.

Assessing the suitability of a stream stabilization project at a bridge requires a holistic analysis from geomorphological, hydrological, hydraulic, and sedimentological perspectives. Much, but not all, of this information was available for the selected sites from MDSHA. Much of this information was not available for several locations. Some of the reports from MDSHA were incomplete and some were incomplete drafts with missing figures and tables. Most notably, as-built surveys were unavailable. It is strongly recommended that improved data collection and archiving be undertaken in the future.

Recommendation 2. Undertake a three-dimensional modeling exercise to better understand flow through pre-formed scour holes and other complex flows at bridges.

Pre-formed scour holes under bridges were used in the design of several stream-bridge intersections in the study to facilitate the conveyance of a design flood flow under a roadway that cannot be elevated. Wider bridge spans would be both more expensive and have the potential to reduce particle mobility, causing unintended sediment depositions. However, flow through pre-formed scour holes is a three-dimensional process and the movement of sediment into and out of these holes is a complex modeling problem, well beyond the scope of this study. Further study that includes three-dimensional modeling would greatly improve the understanding of sediment transport through these designs.

Recommendation 3. Consider excavated floodplains upstream of bridges where appropriate.

Excavated floodplain type designs observed in this project appeared to be well suited to those sites that contain legacy sediments, that are severely entrenched, that are within watersheds that have the goal of increasing flood storage capacity, and/or that are unable to convey the incoming sediment load through the bridge opening. Although both monetarily and environmentally costly, at locations where conveyance of the incoming sediment load is infeasible, sediment removal in the storage areas may be easier and less costly than under a bridge. This idea was also shown to be feasible in a previous study by Newlin and Johnson (2009) for bridges in northern Pennsylvania. MD 17 over Middle Creek, MD 28 over Tuscarora Creek, MD 25 over Georges Run, and MD 223 over Piscataway Creek all included floodplain excavation to some extent. To greater and lesser extents, all of these projects experienced depositions on the floodplain, often shortly after construction. Excluding MD 25 over Georges Run because it was recently constructed, MD 28 received the most stable overall rating of the Maryland bridges in the rapid channel stability assessments evaluated for this study. At MD 223, the excavated floodplain had less ability to control the position of the channel thalweg. One possible solution may be to bury vanes within the floodplain to maintain the stream channel at a perpendicular angle of approach to the roadway. Design and construction guidelines for this approach (referred to as floodplain log sills), as an example are provided on pages 23-24 in Philadelphia Water Department (2015).

Recommendation 4. Maintain and monitor riparian woody vegetation.

Some general characteristics describe sites where the “do nothing” option is likely to be successful. As in prior studies, wide riparian buffers of large, healthy, woody vegetation was observed to be associated with the stable sites. MD 136 over Broad Run demonstrates the power of woody vegetation at stabilizing a channel transition. Bridges located on straight reaches often had far fewer problems than bridges near meanders or on streams that were very meandering. Woody vegetation and straight channels were typical of channel transitions with the most stable transitions.

Recommendation 5. Monitor beaver activity at several sites.

Finally, although not specifically addressed in the study, Beaver activity, such as gnawing of stabilizing woody vegetation, was observed at the MD 25 and MD 28 sites during field visits. This should be monitored, as extensive removal of riparian vegetation and debris dams or dams constructed by beavers could have the potential to destabilize currently stable transitions.

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Table 1. Summary of sites included in this study.

Bridge Number	Route and Waterway	Map Location	Latitude	Longitude	County	Physiographic Region	M-B/ USACE Class*
12009	MD 7 over James Run	0.5 mi. E. of Belcamp	39.476534	-76.260441	Harford	Coastal Plain	MA
12034	MD 136 over Broad Run	3 mi. E. of Belair	39.529929	-76.262740	Harford	Piedmont	MA
12046	MD 165 over W. Br of W. Br	3 mi. S of Jarrettsville	39.556021	-76.465079	Harford	Piedmont	MA
3019	MD 25 over Georges Run	8 mil. W of Hereford, 1 mile E. of Armacost	39.615443	-76.790174	Baltimore	Piedmont	MA
10071	MD 17 over Middle Cr.	1 mi. E. of Wolfsville	39.523330	-77.548330	Frederick	Piedmont	MA
10014	MD 28 over Tuscarora Cr.	2 mi. E. of Point of Rocks	39.268700	-77.490960	Frederick	Piedmont	MA
16051	MD 223 over Piscataway Cr.	N. of Rosaryville	38.785550	-76.843779	Prince Georges	Coastal Plain	MA
1013	MD 36 over Georges Cr.	1 mile south of Midland	39.579448	-78.966752	Allegany	App Plateau	MO/MA

*C = cascade, S = step pool, P = plane bed, R = pool-riffle, D = dune-ripple, B = braided, MT = mountain torrent, MA = meandering, MO = modified, S.R = State Route, Cr. = Creek, R. = River

Table 1 (continued). Summary of sites included in this study.

Bridge Number	Route and Waterway	Land Use	Watershed Area (sq km)	Transition Issues or Problems	Primary Stabilization Practices or Measures
12009	MD 7 over James Run	mix of forest, suburban, agricultural	28.7	aggradation, bar formation	None. Comparison only.
12034	MD 136 over Broad Run	primarily agricultural with small percent forest and suburban	12.1	aggradation, bar formation	None. Comparison only.
12046	MD 165 over W. Br of W. Br	mix of forest, suburban	16.5	lateral movement	vanes, cross vanes, rock wall
3019	MD 25 over Georges Run	primarily agricultural with small percent forest and suburban	33.9	aggradation, bar formation	lowered floodplain, guidebanks, preformed scour hole under bridge, riprap banks, forked channel d/s
10071	MD 17 over Middle Cr.	primarily agricultural with small percent forest and rural	65.8	bar formation on bend	rock and cross vanes, lowered floodplain, riprap, sloped abutment
10014	MD 28 over Tuscarora Cr.	primarily agricultural	51.0	infilling/aggradation in left channel and left span	rock vane, cross vane
16051	MD 223 over Piscataway Cr.	forest and suburban	12.2	aggradation, bar formation	lowered floodplain, preformed scour hole under bridge, no structures
1013	MD 36 over Georges Cr.	mix of forest and urban with minor agricultural, and suburban, plus mining	79.7	reach wide degradation	cross vanes, lowered floodplain

Table 2. Summary of data and analyses provided by MDSHA for each site (for references see Maryland State Highway Administration reports in the reference list).

Bridge Number	Route and Waterway	As-Built Surveys	Monitoring Reports	Hydrologic Reports	Hydraulic Reports	HEC-RAS Models	Geomorphology Reports
1013	MD 36 over Georges Creek		✓	✓	✓	✓	✓
10071	MD 17 over Middle Creek	✓	✓	✓	✓	✓	✓
10014	MD 28 over Tuscarora Creek			✓	✓	✓	✓
16051	MD 223 over Piscataway Creek			✓	✓	✓	✓
3019	MD 25 over Georges Run						
12046	MD 165 over Br. W. Br. Winters Run			✓	✓	✓	
12034	MD 136 over Broad Run			✓	✓	✓	✓
12009	MD 7 over James Run			✓	✓	✓	✓

Table 3. Stream channel stability assessments at selected bridge sites based on Johnson (2005; 2006) and Lagasse et al. (2012). Descriptions and ratings for each of the 13 indicators are given in Johnson (2005; 2006).

Indicators	**Bridges**							
	MD 36 over Georges Cr. (1013)	**MD 17 over Middle Cr. (10071)**	**MD 28 over Tuscarora Cr. (10014)**	**MD 223 over Piscataway Cr. (16051)**	**MD 25 over Georges Run (3019)**	**MD 165 over W. Br of W. Br (12046)**	**MD 136 over Broad Run (12034)**	**MD 7 over James Run (12009)**
1.Watershed	9	8	8	9	7	7	7	7
2. Flow habit	8	4	4	5	2	3	3	3
3. Channel pattern	8	5	5	9	8	7	7	7
4. Entrenchment	10	6	5	5	4	5	5	4
5. Bed material	7	8	7	11	7	8	6	8
6. Bar development	6	9	5	11	9	8	7	10
7. Obstructions	4	5	5	4	2	10	5	4
8. Bank soil	9	5	5	9	5	5	5	5
9. Bank slope	11	6	3	7	5	8	10	8
10. Bank protection	6	4	9	8	3	9	10	10
11. Bank cutting	3	6	7	9	4	9	10	9
12. Bank failure	2	4	3	2	2	3	5	3
13. U/S meander	9	9	3	10	10	4	6	3
Overall Rating	92 (Fair)	79 (Good)	69 (Good)	99 (Fair)	68 (Good)	86 (Good-Fair)	86 (Good-Fair)	81 (Good)
Vertical Fraction	0.64	0.64	0.47	0.75	0.56	0.58	0.50	0.61
Lateral Fraction	0.56	0.47	0.42	0.63	0.40	0.53	0.64	0.53

Table 4. Damage state factors and ratings for existing channel transition projects.

Damage Factors	**Damage Ratings**			
	1 - None	**2 - Moderate**	**3 - Extensive**	**4 - Complete**
1. Overall impact on safety of the waterway transition	Channel adjustments in the overall project area over time are either positively impacting the bridge foundations or are not creating any safety issues.	Channel adjustments in the overall project area over time has created mild to moderate safety concerns compared to the as-built design.	Channel adjustments in the overall project area over time have created unexpected safety issues that have the potential to impact the integrity or functioning of the bridge foundations.	Channel adjustments in the overall project area over time have created safety issues that negatively impact the structural integrity of infrastructure of the bridge foundations.
2. Instream structure and countermeasure integrity, including riprap	None of the structures have been displaced and there is no visible erosion or burial by deposition. All are functioning as intended.	One or more of the structures have been displaced or circumvented so that their function is no longer fulfilled. However, the damage to these structures does not directly impact the crossing.	Structure(s) have been damaged and are nonfunctioning. Damage to these structures is causing instability within the reach that will require direct attention to prevent future risk to the crossing.	Structure(s) are displaced from as-built location and/or detached from bank such that the structure no longer functions as designed. The crossing is in immediate danger.
3. Bank stability and migration	Banks are stable and vegetation is in good condition.	Isolated instances of bank failures (mass wasting, undercut, etc.) or raw banks, affecting 5-30% of the project reach.	Bank failures or raw banks frequent, describing 30-60% of reach. Channel migration is evident in the vicinity of the bridge but thalweg is within design channel limits.	Bank failures or raw banks prevalent, describing more than 60% of the project reach. Thalweg has left design channel limits anywhere in reach.
4. Project tie-in	All tie-in locations are stable with no erosion around ends.	Tie-ins show some erosion or adjustment but are sufficiently removed from critical	Tie-ins are eroding with potential future impacts to infrastructure.	Tie-ins are exposed. Erosion around ends is excessive and imminently

		infrastructure to prevent direct impacts.		threatening project stability and critical infrastructure.
5. Bed degradation	There is evidence of higher flows accessing floodplain (e.g. debris or deposition on floodplain).	Evidence of moderate or severe entrenchment affecting 5-30% of project reach.	Evidence of moderate or severe entrenchment affecting 30-60% of project reach.	Evidence of moderate or severe entrenchment affecting >60% of reach. A head cut or knickpoint is present or began within the project reach.
6. Sediment and woody debris aggradation	Less than 1/3 of the bottom is affected by sediment deposition. Pools are not filling in and there are no unintended depositions or debris jams.	Sediment deposition is affecting less than 1/3 of the channel bottom or deposition in pools is evident. Occasional depositions or debris jams are present.	Sediment deposition is affecting 1/3 to 2/3 of the channel bottom, reducing waterway adequacy. Moderately frequent depositions or debris jams requiring occasional maintenance.	Aggradation is evident or sediment deposition affects > 2/3 of the channel bottom, severely reducing waterway adequacy. Obstructions are frequent and maintenance is required regularly
Sum of Ratings				
Average Rating				

Table 5. Damage state ratings based on Table 4 for present state of project sites. The overall rating ranges from six to 24.

Indicators	**Bridges**							
	MD 36 over Georges Cr. (1013)	**MD 17 over Middle Cr. (10071)**	**MD 28 over Tuscarora Cr. (10014)**	**MD 223 over Piscataway Cr. (16051)**	**MD 25 over Georges Run (3019)**	**MD 165 over W. Br of W. Br (12046)**	**MD 136 over Broad Run (12034)**	**MD 7 over James Run (12009)**
1. Infrastructure integrity	1	2	1	1	1	1	1	1
2. Instream structure integrity	2	1	1	1	2	2	1	1
3. Bank stability	1	3	1	1	2	3	3	2
4. Project tie-in	1	1	1	1	2	3	3	1
5. Bed degradation	1	1	1	1	1	1	1	1
6. Sediment and Debris	2	3	1	4	2	2	1	3
Overall Score	8	11	6	9	10	12	8	9

Table 6. HEC-RAS output of channel characteristics and V_c and V/V_c calculations from HEC-RAS data and Eq. 6 for MD 223.

River Station	**W.S. Elevation**	**Min Channel Elevation**	**Depth (D) (Difference)**	**Channel Velocity**	**Froude #**	**V_c**	**V/V_c**
Upstream	(ft)	(ft)	(ft)	(ft/s)		(ft/s)	
6560	197.6	190.6	7.1	4.3	0.35	1.3	3.3
6230	196.1	190.2	5.9	4.0	0.32	1.4	2.9
5825	194.6	188.1	6.6	3.9	0.28	1.5	2.6
5515	193.5	187.4	6.2	3.3	0.28	1.1	2.9
5215	192.3	187.3	5.0	3.6	0.32	1.6	2.3
4885	190.9	186.8	4.1	3.7	0.41	1.5	2.5
4695	189.4	184.8	4.6	4.5	0.45	1.5	2.9
4515	189.0	184.9	4.1	2.4	0.24	1.5	1.6
4275	188.4	182.6	5.8	4.1	0.33	1.4	3.0
4210	188.2	181.4	6.8	3.7	0.26	1.4	2.7
4120	187.7	181.3	6.4	4.5	0.37	1.4	3.2
3980	187.0	181.3	5.7	4.1	0.33	1.4	3.1
3890.01	186.3	180.7	5.6	6.0	0.49	1.4	4.3
3858.01	186.2	180.0	6.2	5.0	0.37	1.4	3.5
3756	186.2	177.0	9.2	3.2	0.19	1.5	2.2
3730	186.2	177.0	9.2	2.6	0.15	1.9	1.3
3690	186.0	177.0	9.0	3.8	0.23	2.1	1.8
3637	Bridge						
3580.01	185.8	177.0	8.8	2.8	0.18	2.1	1.4
3505.01	185.6	179.8	5.8	4.6	0.34	2.0	2.3
3275	185.2	180.5	4.7	3.4	0.29	1.9	1.8
3005	184.3	178.9	5.4	3.6	0.29	1.8	2.0
2660	182.9	178.4	4.5	4.2	0.38	1.9	2.2
2390	182.3	177.9	4.4	2.5	0.22	1.4	1.8
2250	181.9	177.2	4.7	2.8	0.26	1.3	2.2
1990	181.1	176.7	4.4	3.6	0.32	1.4	2.6
1580	179.6	176.2	3.4	3.1	0.32	1.3	2.3
1340	178.9	175.0	3.9	2.7	0.26	1.5	1.8
1000	178.1	174.3	3.8	2.6	0.26	1.4	1.9

Table 7. Rapid channel stability assessment for MD 25 over Georges Run before reconstruction by MDSHA based on reports and photos provided by MDSHA. Ratings are taken from Table 2 in Johnson (2005) or Table 5.5 in Lagasse et al. (2012). Vertical stability indicators are 4–6; lateral stability indicators are 8–13. Lateral and vertical stability scores are computed by summing the appropriate ratings, then normalizing by the total number of points possible in each category, as described in Johnson (2005) and Lagasse et al. (2012).

Stability Indicators	**MD 25 over Georges Run (3019)**
1.Watershed	7
2. Flow habit	2
3. Channel pattern	8
4. Entrenchment	7
5. Bed material	7
6. Bar development	9
7. Obstructions	2
8. Bank soil	9
9. Bank slope	11
10. Bank protection	12
11. Bank cutting	10
12. Bank failure	9
13. U/S meander	10
Overall Rating	103 (Fair)
Vertical Fraction	0.63
Lateral Fraction	0.84

Table 8. V/V_c for the 10-year flow and D_{50} = 16 mm at Georges Run case study. River Station 1 is downstream of the bridge, and river station 16 is upstream near the confluence with Peggy's Run.

River Station	**V/Vc**		
	Pre-constructed	**Constructed**	**Raised banks**
16	2.3	2.5	2.5
15	2.1	2.3	2.2
14.8	2.0	3.3	2.7
14.7	2.2	3.2	3.4
14.5	3.2	2.7	3.0
14	1.8	2.7	3.3
13	3.0	2.5	2.9
12.5	1.4	2.3	3.1
12	1.8	2.4	2.6
11.5	BRIDGE		
11	4.1	3.9	3.9
9	4.9	3.9	3.9
8.5	3.3	3.3	3.3
8	2.7	2.7	2.7
7	2.5	2.5	2.5
6	2.5	2.5	2.5
5	3.1	3.1	3.1
4	4.4	4.4	4.4
3	2.7	2.7	2.7
2	3.2	3.2	3.2
1	2.9	2.9	2.9

Table 9. FMEA Example for MD 25 over Georges Run redesigned with higher banks. The highest possible total RPN is 10*10*10 = 1,000. Thus, the highest total RPN for all components is 8*1,000 = 8,000.

Component	**Potential failure mode (s)**	**Potential effect(s) of failure on components**	**Potential effect(s) of failure on whole system**	**C**	**Potential cause(s)/ mechanism(s) of failure**	**O**	**Current design controls**	**D_f**	**RPN**
Rock linings (Rip-rap at bridge and around cross vanes)	Excessive scouring above and behind structure	Additional erosion around abutments	Bank erosion; lateral movement; infrastructure impact; sediment input	6	Design of bank stabilization measures not sufficient	4	HEC 23 guidance	6	144
	Structure displacement	Additional erosion around abutments	Bank erosion; lateral movement; infrastructure impact; sediment input	6	Improper sizing of rock	6	HEC 23 guidance	6	216
	Structure undermining	Additional erosion around abutments	Bank erosion; lateral movement; infrastructure impact; sediment input	6	Insufficient design of structure foundation to resist hydraulic forces	4	HEC 23 guidance	6	144
Cross-sectional geometry change	Rapid widening	Potential failure of adjacent measures	Sediment input; local or regional property or structural loss	6	Bankfull design sediment transport capacity to great and insufficient bank stabilization measures	4	Allowable shear stress or stream competence check	8	192
	Excessive deposition (too wide)	Burial of other measures	Increased flooding	4	Insufficient design of bankfull sediment transport capacity	8	Allowable shear stress or stream competence check	8	256
	Bed degradation (too narrow) and head cutting	Undermining of measures	Eventual bank collapse, infrastructure impacts, loss of overbank habitat	8	Designed bankfull sediment transport capacity to be too great	6	Allowable shear stress or stream competence check	8	384
Vegetative bank stabilization	Erosion of vegetation and banks	Potential failure of adjacent measures	Eventual bank collapse, infrastructure impacts, sediment input	6	Design of bankfull sediment transport capacity to be too great	8	Allowable shear stress or stream competence check	8	384
Guide bank	Erosion from lateral migration of channel and flood flow impact	None or minimal	Infrastructure impacts, sediment input	4	Insufficient bank stabilization measures	4	Allowable shear stress	8	128
							Total		**1848**

Table 10. V/V_c for the 10-year flow and D_{50} = 23 mm at MD 136 over Broad Run. River Station 16 is upstream.

River Station	**V/Vc**
16	1.6
15	1.4
14	4.3
13	1.8
12.9	2.8
12.5	3.2
12.4	2.6
12.2	2.1
12.1	1.4
12	2.4
11.8	3.6
11.5	2.4
11	2.7
10.7	1.8
10	1.3
9.5	BRIDGE
9	2.5
8.5	2.0
8	2.2
7	3.3
6	4.0
5	2.6
4	2.9

Figure 1a. Looking upstream from bridge.

Figure 1b. Looking downstream at bridge.

Figure 1. Krantz Mill Road over Big Beaver Creek, PA.

Figure 2. Looking downstream at the Hinckley Hills Road bridge over East Branch of Rocky River in Medina County, Ohio.

Figure 3. Stream channel degradation. U.S. Rt. 199 N, 0.8 km S of Gandeville, WV.

Figure 4. PA 3036 over S. Branch Sugar Creek near Troy, PA.

Figure 5a. Pre-construction.

Figure 5b. Post construction.

Figure 5. Ohio SR 412 over Fuller Creek looking upstream pre- and post-construction.

Figure 6. Severe sediment deposition at PA 287 over Mitchell Creek, north of Tioga, PA.

Figure 7a. Conditions upstream of bridge.

Figure 7b. Partial w-weir installed upstream of the bridge in Fall, 2015.

Figure 7. Instream structure constructed upstream of U.S. Route 20 over Bean Creek in Fulton County, Ohio, to control sediment and debris.

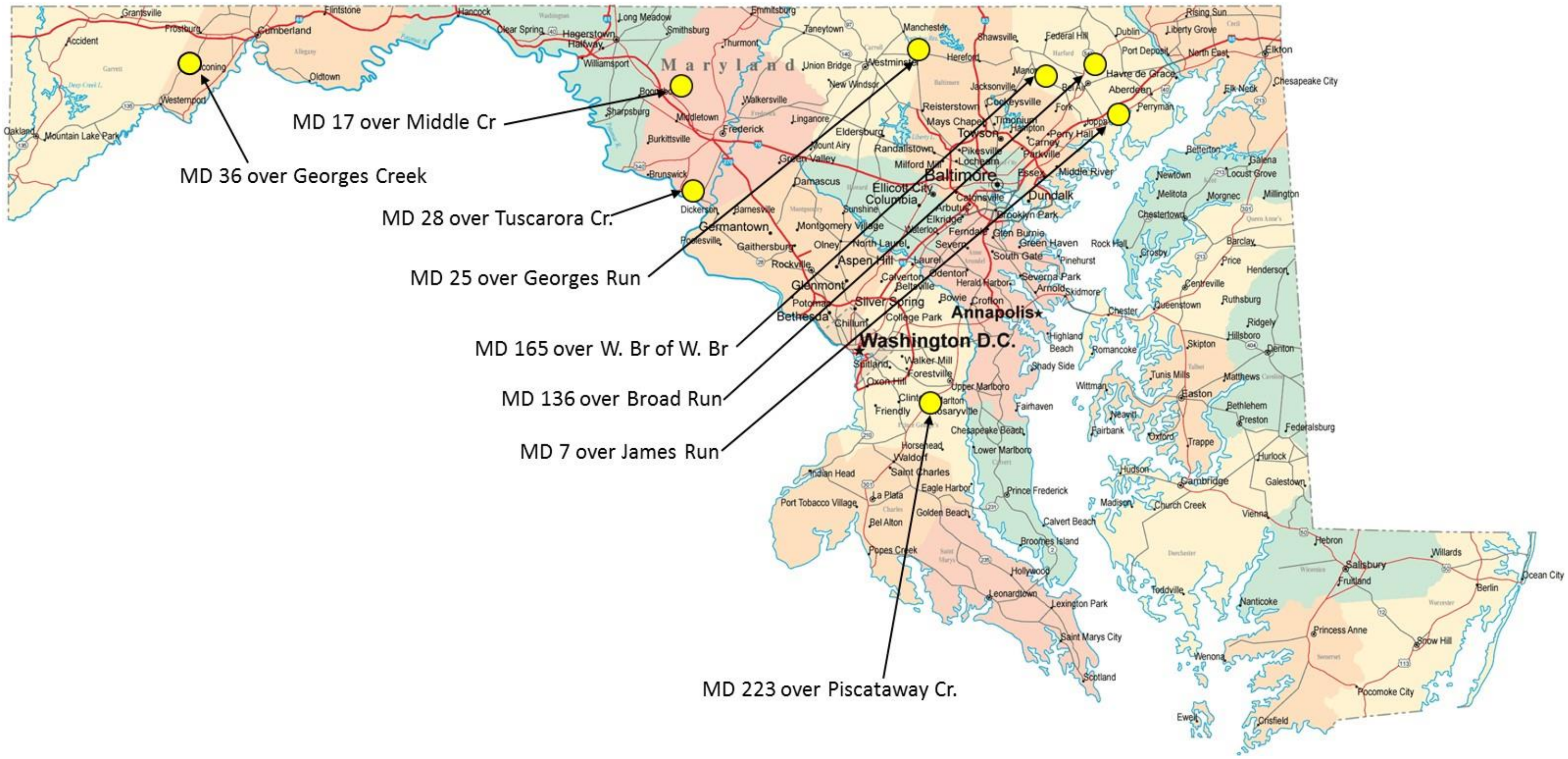

Figure 8. Location of eight bridge sites.

Figure 9. MD 36 over Georges Creek standing upstream on lowered flood plain showing aggradation and woody vegetation accumulating in right span.

Figure 10. MD 17 over Middle Creek standing upstream looking downstream showing aggradation occurring on left bank.

Figure 11. MD 17 over Middle Creek. Undermining of Riprap on downstream right bank.

Figure 12. MD 28 standing upstream showing aggradation in left span and rock vane in bottom right of picture.

Figure 13a. Bar upstream of the bridge.

Figure 13b. Looking upstream under the bridge. Note the deposition in the left of the picture.

Figure 13. MD 223 over Piscataway Creek.

Figure 14a. Photo taken in April, 2016, prior to establishment of vegetation.

Figure 14b. Photo taken in June, 2016, as vegetation becomes established.

Figure 14. Looking downstream at MD 25 at excavated floodplain on the left, guidebank further downstream on the left at the bridge. Note sediment deposition on the left.


Figure 15. Forked channel downstream of MD 25 at Georges Run.

Figure 16. MD 165 over tributary to the West Branch of Winters Run, facing downstream toward the bridge. Note the lateral erosion, poorly functioning vanes, and woody debris in the channel.

Figure 17. Downstream of MD 165 over tributary to the West Branch of Winters Run, facing upstream. Vanes in the channel have failed to control bank erosion on the right bank.

Figure 18. MD 136 over Broad Run, looking upstream from bridge.

Figure 19. MD 136 over Broad Run looking downstream at the bridge opening. The previous bridge abutments were left under the reconstructed bridge.

Figure 20. Facing upstream from MD 7 over James Run.

Figure 21. Looking downstream at MD 7 over James Run. Sediment accumulation on the right bar appears to be moving downstream through the bridge opening.

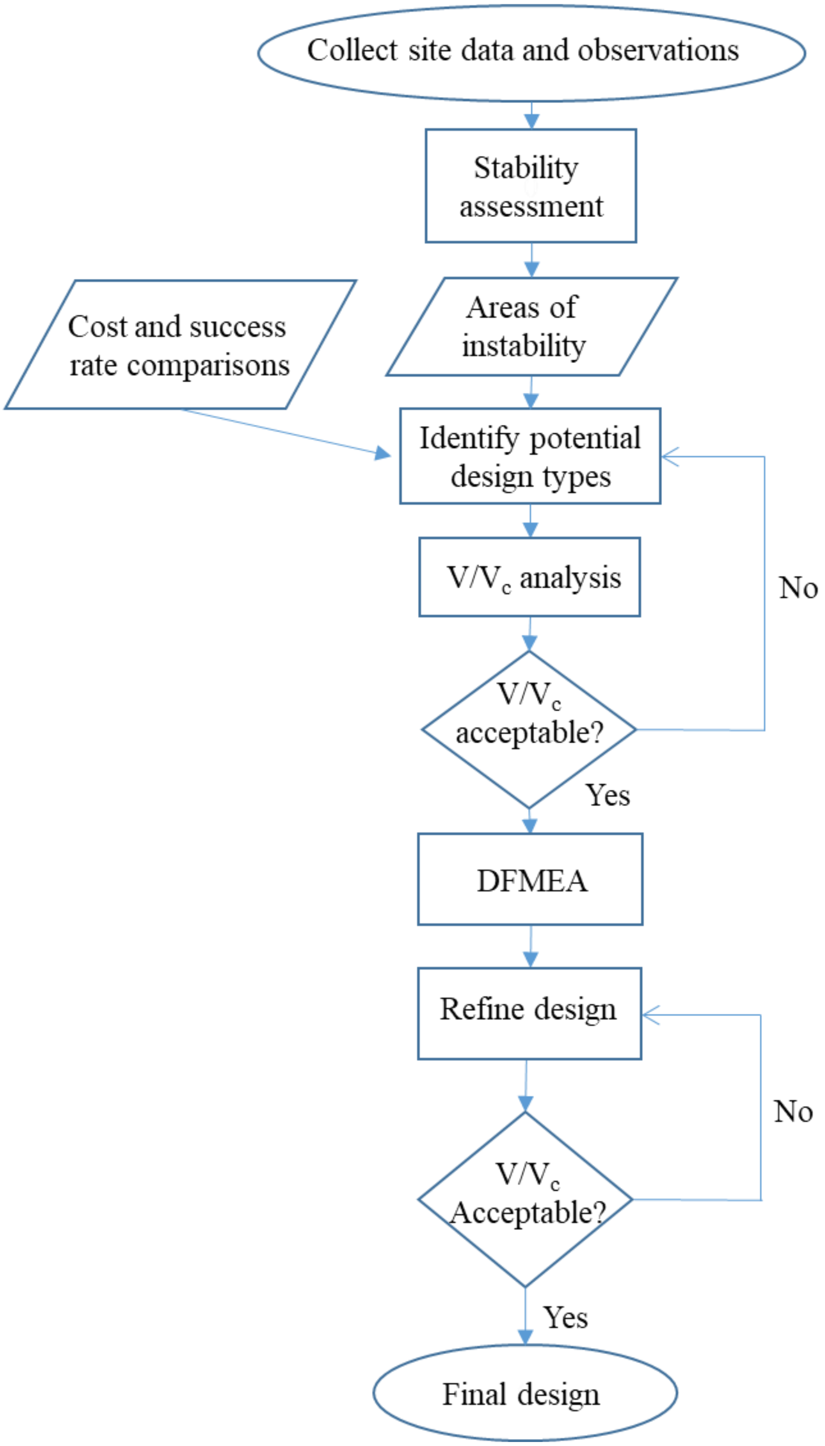

Figure 22. Site assessment, design selection, and design review process flowchart.