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Soil Saver Wall Performance and Potential Modifications for Aquatic Organism Passage

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One of the issues with RCB culverts is the potential for erosion to develop upstream of the culvert (headcutting). The Kansas Department of Transportation (KDOT) constructs soil saver walls on RCB culverts to prevent headcutting. The hydraulic efficiency of culverts with soil saver walls is usually acceptable. However, soil saver walls act as a drop inlet and can hinder AOP. Therefore, KDOT is considering modifications to the soil saver wall design to further promote AOP.

Thirty states were surveyed to evaluate current RCB culvert applications and headcutting prevention practice and how AOP was addressed. Most of these states had problems with headcutting due to box culverts. Some of these states used a soil saver wall-type structure to control headcutting in the form of a rock or gabion weir, stone wall, concrete wall, or embedment formation. These features may include a V-notch. Some states use upstream riprap. Some states are facing regulatory issues regarding AOP. Most states with upstream weirs that act as drop inlets have redesigned or are in the process of redesigning those structures to facilitate AOP.

Fifteen existing RCB culverts in Kansas with soil saver walls were surveyed; seven of these are discussed in this report. Most of these culverts were in excellent condition. There was very little to no headcutting observed and the culverts appeared to be functioning well. It did appear they could potentially act as a barrier to AOP.

Flume testing was conducted in the Water Resources Lab at the University of Kansas on models of a conventional box culvert with a standard soil saver wall configuration, a wall with a square notch, and a wall with a V-notch. It was observed that excellent performance for the control of grade was provided by the soil saver wall for both the standard and notched walls. The V-notch wall appeared to have the potential to provide for better AOP for low flows, therefore this configuration is preferred.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Reinforced concrete box (RCB) culverts are designed to provide hydraulic conveyance at peak stream discharge for low initial and long-term maintenance costs; however, these structures can pose challenges to aquatic organism passage (AOP) at some locations. A number of states are using a variety of methods for the construction of RCB culverts that facilitate the passage of aquatic organisms. Culverts constructed using stream simulation methods, roughened channels, and inclusion of baffles are some of the methods used to promote AOP.

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Chapter 1: Introduction

1.1 Background

The United States road network includes hundreds of thousands of roadway-stream crossings. Most stream crossings have traditionally been designed with a focus on roadway safety, hydraulic conveyance for a design stream discharge, and initial cost (Kosicki & Bennett, 2001). Reinforced concrete box culverts, hereafter referred to as “RCB” or simply “box” culverts, have traditionally been one of the most common types of roadway-stream crossings due to their relatively low cost of construction and maintenance as compared with other crossings, such as single- or multiple-span bridges. RCB culverts are typically square or rectangular in shape with each side consisting of concrete reinforced with steel reinforcing bars or welded wire fabric. Each box culvert may have one or more barrels, or openings, that convey the stream discharge from the upstream side of the roadway to the downstream side. Box culverts can be precast in sections, which can also speed up the installation process and often save labor costs.

Traditionally, when a box culvert is installed, it is not as wide as the channel it conveys. This creates a channel constriction. Wide RCBs typically cost more due to the requirement for more reinforcement or an increased number of walls or increased wall thickness to support the design loads, therefore minimizing culvert width generally results in lower construction costs. However, constriction of the channel causes higher flow velocities through the culvert and can potentially lead to several problems, including scour near the culvert. Box culverts are often recessed below the streambed which can lead to channel bed incision (i.e. headcutting) upstream of the culvert. The existence and degree of headcutting depends on several factors, such as culvert orientation, stream slope, and stream sediment types upstream of the culvert. Headcutting may be naturally-occurring or anthropogenic. Natural causes include: (1) base level drop due to earthquakes or tectonic processes, (2) ground water sapping due to ground water concentration or piping action, and (3) change in sediment regime due to fire, drought, or flooding. Anthropogenic causes include (1) change in sediment regime due to increased or decreased sediment input in streams, (2) change in flow regime due to increased runoff from urban areas, (3) change in base level due to changes in output elevation, and (4) constriction of flow or addition of flow barriers in streams.

The Kansas Department of Transportation (KDOT) has used a system called a soil saver wall at the upstream end of box culverts where the potential for headcutting was a concern and/or where grade changes near the culvert necessitated a grade control structure. The soil saver wall is a concrete structure spanning the width of the channel at the end of the upstream culvert apron, and is designed to retain the streambed material to prevent headcutting. Soil saver walls in combination with the concrete wing walls create a drop inlet to the box culvert and have been effective at preventing headcutting in streams across the state of Kansas.

1.2 Problem Statement

The detrimental effect of some stream crossings, such as box culverts, on commercial fish migration became apparent several decades ago in parts of the United States. Migratory salmon populations in the Pacific Northwest were some of the first to be studied in regard to this problem. Over the last few decades, increased awareness of the importance of aquatic organism passage (AOP) has increasingly made it a critical design parameter in a number of states. Regulating agencies in Kansas are among those concerned that drop inlet structures such as soil saver walls may further inhibit AOP.

1.3 Research Objective

The objective of this study was to identify potential alternatives or modifications to the soil saver wall that would maintain hydraulic performance and prevent headcutting, while not restricting the upstream migration of the aquatic life in the stream. This study consisted of four phases: (1) research of previous studies involving AOP and box culverts, (2) a field survey of existing box culverts with soil saver walls in Kansas, (3) a survey of other states to determine the "state of the practice" with regard to AOP and box culverts, and (4) preliminary flume studies of potential soil saver wall modifications.

1.4 Scope of Work

KDOT has used soil saver walls upstream of box culverts for a number of years. The soil saver walls have been very effective at preventing channel incision, or headcutting, upstream of box culverts. Soil saver walls are relatively simple and inexpensive to construct as they are made with reinforced concrete. While soil saver walls are effective at preventing erosion upstream, they present a potential barrier to upstream migration of fish and other aquatic organisms that may want to move through the box culvert, and the governing regulatory agencies have required that alternatives to the traditional soil saver wall be used.

The first task of this study was to determine what other methods for headcutting prevention are available, effective, cost efficient, and do not create a potential barrier to aquatic organism passage (AOP). A review of published literature regarding AOP, headcutting, and box culverts was conducted to find alternatives to the soil saver walls. The literature review was helpful in determining the efficacy of some alternatives to the soil saver wall, as well as some other AOP methods. The literature review also provided some insight into the relative cost of some of the soil saver wall alternatives, AOP structures, and methods of culvert construction.

A survey of state transportation officials was conducted to provide further insight into possible alternatives to soil saver walls. The survey was used to determine the current "state of the practice" for box culvert installation with regard to AOP and headcutting. The survey also was used to help determine the degree of regulatory requirements other state transportation officials are experiencing in relation to AOP and box culverts.

The second task of this study was to determine the condition of existing soil saver walls installed in box culverts in the state of Kansas. The existing soil saver wall culverts were visited, photographed, and measured to evaluate their effectiveness.

The third task of this research was to identify the most promising soil saver wall alternatives. A preliminary flume study was performed to test two potential modifications to the soil saver walls, a square notch and V-notch, and to determine their effectiveness with regard to preventing headcutting upstream of box culverts. The V-notch configuration was chosen based on the 30-state survey of Departments of Transportation. The models were tested in a sand flume with various water levels and flow rates. Headcutting patterns were studied and photographed after the sand bed reached equilibrium.

1.5 Report Organization

This report is organized as follows:

Chapter 1 provides general background information and a summary of the research described in this report.

Chapter 2 contains a review of the published literature on the function of soil saver walls in RCB culverts, aquatic organisms in Kansas, the potential effect of culverts on aquatic habitats, and the design and construction of AOP-promoting culverts in the United States.

Chapter 3 contains the results of a 30-state DOT survey. States were asked about their use of box culverts, their level of problems with headcutting, specific measures applied to control headcutting, and features incorporated to enhance aquatic organism passage (AOP) through such culverts.

Chapter 4 provides an assessment of soil saver wall performance in Kansas. Fifteen sites in Kansas were visited and seven are described in detail in this chapter.

Chapter 5 contains a summary of the laboratory modeling of the soil saver wall with and without modifications for enhancing aquatic passage.

Chapter 6 provides a discussion of the conclusions reached in this study and recommendations developed based on this research.

Chapter 2: Literature Review

2.1 Reinforced Concrete Box (RCB) Culvert with Soil Saver Wall

Culverts are a cost effective, commonly used method for providing for drainage beneath roads all around the world. Culverts permit roadway traffic to cross streams without changing the roadway elevation or requiring streams to change course. Culverts can be circular, elliptical, rectangular, or in the shape of an arch.

KDOT defines a bridge as a drainage structure with a span of more than 20 ft, as measured along the centerline of the road between the inside faces of the end supports. Culverts are defined as any waterway structure not defined as a bridge. The reinforced concrete box (RCB) culvert may be constructed with single or multiple cells, along with the headwalls and wing walls to retain the fill supporting the roadway. The bottom is generally paved and incorporates toe walls at each end to prevent piping or bed scouring of the culvert. Box culverts range from 3.0- to 20.0-ft cell spans and 2.0- to 20.0-ft cell heights with a maximum fill height of 50 ft. Multiple barrel culverts are an appropriate solution for projects with limited cover or small allowable headwater and are more economic than box culverts having a single long span culvert. The drawbacks of the multiple barrel culvert include possible accumulation of sediment and debris in the widened channel section and in the culvert (KDOT, 2011). Many culverts throughout Kansas were designed using traditional methods based on hydraulic conveyance. Culvert sizes were selected to maintain an acceptable level of ponding upstream of the roadway (Schall, Thompson, Zerges, Kilgore, & Morris, 2012). Culverts can inhibit AOP because of excessive flow velocities, drops at inlets and/or outlets, physical barriers such as weirs, baffles, or debris caught in the culvert barrel, excessive turbulence at the inlet, and low flows (Kilgore, Bergendahl, & Hotchkiss, 2010).

A depressed or drop inlet in RCB culverts is generally selected for the inlet control of flow, which is hydraulically beneficial. Additionally, drop inlets are constructed to provide grade control, and right of way considerations may limit the ability to place a typical culvert inlet (Schall et al., 2012). In Kansas, a short wall (1-3 feet), commonly referred to as a “soil saver,” has often been constructed across the stream bed at the ends of the wings at the upstream entrance to the culvert. The soil saver functions as a grade control structure to aid in controlling erosion (headcutting) in the upstream drainage basin (KDOT, 2007). This drop inlet in the culvert is hydraulically beneficial because it causes the box to be governed by inlet control of flow. The soil saver wall in the present culvert system serves as a drop inlet; however, it may inhibit the movement of aquatic life by creating physical and behavioral barriers.

2.2 Potential Effect of Culvert with Soil Saver on the Aquatic Habitat

Rivers and streams provide an important habitat for many animal species, many of which depend on the ability to move freely throughout their ecosystem in order to complete their life cycles (Jackson, 2003). For long-term viability of aquatic organisms in streams, their ability to move freely is an important consideration. Culverts may act as a barrier to the free flow of water in the stream and hence may impede the free movement of aquatic life, potentially forcing them to survive independently in a small reach of stream. Smaller, more isolated populations are most likely to die of chance events (Fahrig & Merriam, 1985). After a long period of time, genetic homogeneity and natural disturbances are also likely to cause larger populations to decline (Jackson, 2003). The Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) identified the possible fragmentation of habitat and movement barriers for aquatic organisms due to culvert construction as a common problem. This is documented in the NRCS Conservation Practice Standard, “Stream Crossing” (No. 578). This standard restricts the use of general culverts in stream reaches where a very large flow of sediments or large woody material is expected, or where the channel gradient exceeds 6% (NRCS, 2011).

Culverts may create one or more types of barriers in the river, including jumps and eddies; higher flow velocity; shallow depths; an exhaustion and behavior barrier; and an upstream drop due the presence of a drop inlet. The Washington Department of Fish and Wildlife (WDFW) emphasized the need to consider the various concerns while designing AOP-promoting culverts. These concerns may dictate the siting, sizing, and design of culverts for aquatic organism passage improvement (Bates, Barnard, Heiner, Klavas, & Powers, 2003). These concerns are:

- Direct habitat loss
- Water quality degradation
- Upstream and downstream channel impacts
- Ecological connectivity
- Construction impact on river channels
- Probable future impact on the channel due to risk of culvert failure

Inclusion of a vertical drop in the culvert can serve as a barrier for AOP. Vertical drops can block use of the upper watershed and potentially access to spawning habitat. These barriers can serve as a complete barrier (blocking all fish migration at all flows) or a temporary barrier (blocking migration some of the time) that results in the loss of production by causing a delay in organism movement. Partial barriers (blocking of smaller or weaker fish within a species) can also cause problems by limiting genetic diversity of the habitat (Bates et al., 2003).

The flow depth is the major contributor to facilitate the AOP. A minimum depth of flow is needed to meet the swimming capacity of the aquatic organisms because fish submergence eliminates a fish's risk of oxygen starvation, allows the fish to create the maximum thrust, and lowers the risk of bodily injury through contact with the culvert bottom (Dane, 1978; Ad Hoc Forest Practices Advisory Committee on Salmon and Watersheds, 2000; Kilgore et al., 2010). These depths are also needed for enhancing the swimming potential of fish, reducing bodily injury of fish, and reducing predation, as well as supporting fish while resting (Kilgore et al., 2010). The minimum depths required for different types of salmonid and trout species for Washington and Oregon states are stated in different research papers. These depths are 0.59 ft for Pink Salmon, Chum Salmon, Coho Salmon, and Sockeye Salmon, and 0.79 ft for Spring Chinook Salmon, Summer Chinook Salmon, Fall Chinook Salmon, and Steelhead Trout (Thompson, 1972; Smith, 1973). The depth requirements depend on the type of species as well as their life stage.

2.3 AOP-Promoting RCB Culverts

An engineered culvert should meet the criteria of appropriate hydraulic capacity and structural integrity. For facilitating AOP (if needed), the California Department of Fish and

Game (CDFG) recommends the culvert be designed to meet the criteria of the “Active Channel Design Option,” “Stream Simulation Design Option,” or “Hydraulic Design Option” (CDFG, 2002). The Active Channel Design Option calls for making the culvert crossing sufficiently large and burying the bed of the culvert below the stream channel to permit natural movement of bedload and the formation of a stable streambed inside the culvert. This method is suitable for very low channel slopes (<3%) with a short culvert length. This method is considered suitable for all types of aquatic life and for new and replacement culverts.

The Stream Simulation Design Option calls for mimicking the natural stream processes within the culvert. The key elements used for this purpose in stream simulation design options are placement of embedded bed or no bed structures, stream sediment bed materials, and bankfull width design of the culvert. This method does not have any target species. This would essentially mean the culvert would have a natural bed and be of about the same base width as the natural channel. Aquatic organism passage, transportation of sediments, and debris and flood conveyance within the culvert are intended to function as they would in a natural channel (CDFG, 2002). This method is suitable for medium channel slopes (<6%) and moderate to long culvert lengths. This method provides for the passage for all aquatic life, however, care must be taken to ensure that ecological connectivity is maintained.

The third option for the AOP-promoting RCB culvert is the Hydraulic Design Option. This method focuses on the swimming abilities of target species and the age class of particular types of aquatic life. Determination of high and low design flows for targeted aquatic organism passage, water velocity, and water depth are required for this option.

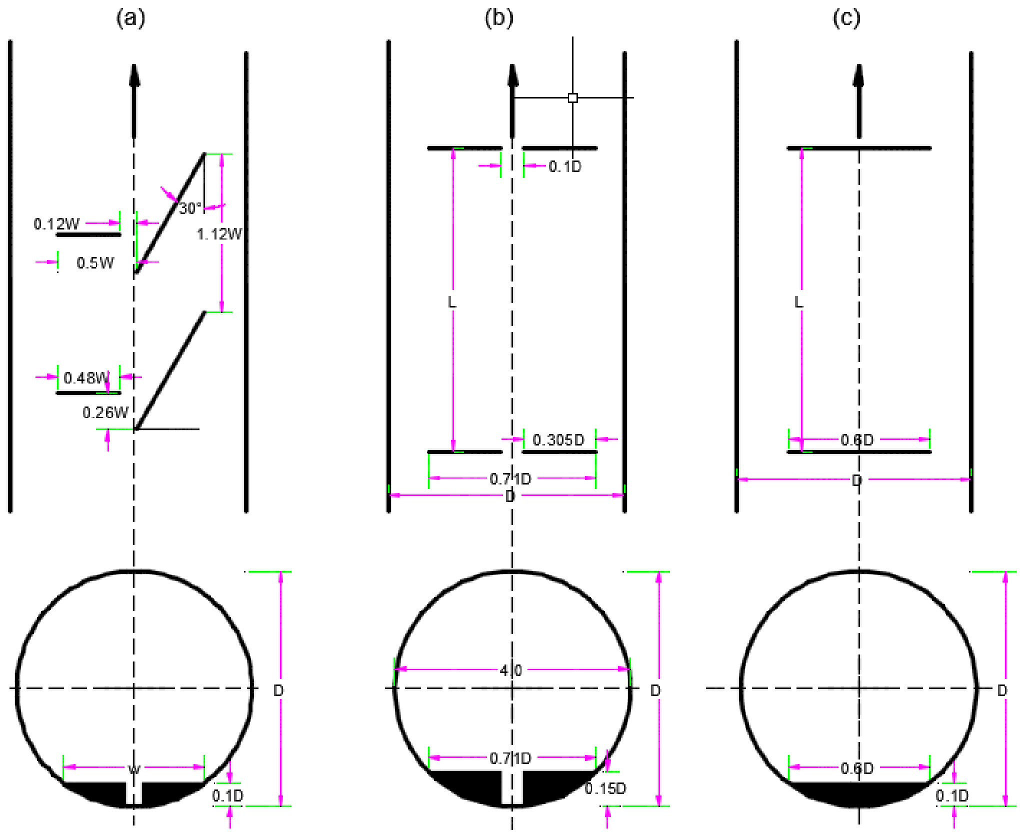
NRCS (2011) considers the ability of target organisms to swim upstream and downstream with a particular velocity. Designing stream crossings, including culvert structures, in accordance with the swimming and leaping capabilities of target species (or a similar species with comparable swimming abilities), along with utilizing hydraulic computations to satisfy the design with physiological requirements of target organisms, are fundamental to providing adequate AOP.

According to Bates (2006), culverts which fall into the category of hydraulic design (fish way, baffles, roughened channel, grade controls) or stream simulation design (grade control, regrading of the channel, or providing natural grades) can be successfully used. The design methods mentioned above are governed by project objectives, which may include one or more of the following:

- Adequate passage of fish
- Adequate passage for other AOP
- Habitat protection or restoration
- River and stream continuity
- Wildlife passage

Several techniques have been developed to improve the fish passing capacity of culverts. These techniques include the offset baffle system (McKinley & Webb, 1956); spoiler baffle system (Engel, 1974); side baffles system (Watts, 1974); fish baffles system (Rajaratnam, Fairbairn, & Katopodis, 1986); and the slotted weir culvert system (Rajaratnam, Katopodis, & McQuitty, 1989). These different types of baffles are presented in Figure 2.1.

Baffles of different shapes and orientations are viewed as one of the effective ways to make box culverts fish or AOP-promoting structures. Baffles are added within the culvert to increase the hydraulic roughness as well as extend the flow distance length, and hence decrease the sectional velocity, inside the culvert. These baffles have to be relatively close together and short in length as compared to the flow depth to create streaming flow. Another method to create a roughened channel is to place a graded mix of rock and sediment inside the culvert barrel. This creates enough roughness and hydraulic diversity to achieve fish passage. This is beneficial because increased roughness creates diverse flow velocities and patterns that provide migration paths and resting areas for a variety of aquatic organisms (Bates et al., 2003). A potential drawback of this method is that baffles installed in existing culverts may cause upstream flooding due to decreased culvert capacity. Furthermore, baffles have a tendency to catch woody debris that reduce culvert capacity. This debris may, in fact, lead to complete plugging of the culvert (Barnard et al., 2013).



(a) offset baffle, (b) slotted-weir baffle, and (c) weir baffle systems

Figure 2.1: Different Types of Baffles
Source: Rajaratnam et al. (1989); Figure redrafted by the authors.

2.4 Practical Methods at Road Crossings for AOP in the United States

2.4.1 Stream Simulation

Stream simulation seeks to replicate the natural channel within and around the box culvert such that the stream is essentially unaffected by the box culvert. This requires a hydrologic study of the channel to determine the slope of the channel far upstream and downstream of the culvert. The box culvert itself must be placed such that it does not alter this natural slope, and perhaps most importantly the culvert must be at least as wide as the bankfull width of the channel. Bankfull width culverts are believed to have minimal impact on the natural channel and aquatic organisms contained within because, by definition, the channel will only exceed the bankfull width during flood events. Thus, normal flows should not reach the walls of the culvert, and the culvert barrel, being recessed and backfilled with streambed material, should behave very similarly to the natural channel (Kilgore et al., 2010). The downside of stream simulation is a significant cost increase due to the much larger culvert width required, so these culverts are much more costly to excavate and construct than traditional box culverts that constrict the channel. Therefore, while the stream simulation method is ideal for AOP, it is often not financially feasible, and may be of little value for AOP for box culverts placed in ephemeral streams and channels that likely do not carry any migratory aquatic species.

2.4.2 Roughened Channels

Roughened channels are often created using rock riprap or other granular material that is non-erodible to protect the bed of the channel from erosion and help to retain more of the natural stream sediments. A few states such as Florida have used gabions to fulfill this purpose, but most states tend to use riprap. Roughened channels seem to be effective at preventing headcutting according to some state transportation officials surveyed (see Chapter 3). The roughened channel can also be used to slow channel flow and facilitate better AOP through the culvert (Baki, Zhu, & Rajaratnam, 2014). Roughened channels are a much more labor intensive system to install than soil saver walls and require careful placement. This method is more costly than other methods.

2.4.3 Baffles

Baffles are used in a few states, such as Pennsylvania, and are also used in conjunction with a roughened channel system to help retain the granular material. Alternating baffles could potentially be used upstream of the box culvert on a concrete apron in place of a soil saver wall to retain the soil while also creating a path for AOP. The baffles could look very similar to the soil saver wall, except that they would not be quite as wide as the culvert wing walls. A few baffles could be offset a short distance away from one another to create a long channel for AOP, while still retaining the vast majority of the upstream channel bed. This method could potentially be applied as a retrofit to existing soil walls, where the soil saver wall would be cut open at one end and one or more additional baffles be installed behind it on the upstream apron of the culvert. Though this is a promising alternative, more investigation will be necessary to ensure long term effectiveness. The potential downside to this method is maintenance. A few states, such as Minnesota, have found that baffles tend to clog with debris and must be cleaned out regularly to ensure they function properly.

2.5 Threatened and Endangered Aquatic Life in Kansas

Haslouer et al. (2005) investigated the status of native fish species in Kansas based on information from 801 stream surveys conducted by the Kansas Department of Wildlife, Parks and Tourism (KDWPT) throughout the state since 1994, data from the Natural History Museum at The University of Kansas (KU) and Fort Hays State University, published studies, and other reliable sources. Based on the recommendations provided by Haslouer et al., KDWPT developed lists of endangered species (E), threatened species (T), and species in need of conservation (SINC). The KDWPT lists of threatened and endangered species of aquatic organisms are presented in Tables 2.1 and 2.2.

Table 2.1: List of Kansas Threatened and Endangered Aquatic Species Statewide

List of Kansas Threatened	List of Kansas Endangered
A. <u>Fish</u> • Blackside Darter (Percina maculata) • Flathead Chub (Platygobio gracilis) • Hornyhead Chub (Nocomis biguttatus) • Neosho Madtom (Noturus placidus) • Plains Minnow (Hybognathus placitus) • Arkansas Darter (Etheostoma cragini) • Redspot Chub (Nocomis asper) • Shoal Chub (Macrhybopsis hyostoma) • Sturgeon Chub (Macrhybopsis gelida) • Topeka Shiner (Notropis topeka) • Western Silvery Minnow (Hybognathus argyritis) **B. <u>Invertebrates</u>** • Butterfly Mussel (Ellipsaria lineolata) • Delta Hydrobe (Probythinella emarginata) • Fluted Shell Mussel (Lasmigona costata) • Ouachita Kidney Shell Mussel (Ptychobranchus occidentalis) • Rock Pocket Book Mussel (Arcidens confragosus) • Sharp Hornsnail (Pleurocera acuta) **C. <u>Chelonia</u>** • Northern Map Turtle (Graptemys geographica)	**A. <u>Fish</u>** • Pallid Sturgeon (Scaphirhynchus albus) • Peppered Chub (Macrhybopsis tetranema) • Arkansas River Shiner (Notropis girardi) • Sicklefin Chub (Macrhybopsis meeki) • Silver Chub (Macrhybopsis storeriana) **B. <u>Invertebrates</u>** • Elktoe Mussel (Alasmidonta marginata) • Ellipse Mussel (Venustaconcha ellipsiformis) • Flat Floater Mussel (Anodonda suborbiculata) • Mucket Mussel (Actinonaias ligamentina) • Neosho Mucket Mussel (Lampsilis rafinesqueana) • Rabbitsfoot Mussel (Quadrula cylindrica) • Slender Walker Snail (Promatiopsis lapidaria) • Western Fanshell Mussel (Cyprogenia aberti)

Source: KDWPT (2015b)

Table 2.2: Federal Threatened and Endangered Aquatic Species in Kansas

List of Federal Threatened	List of Federal Endangered
A. <u>Fish</u> • Neosho Madtom (Noturus placidus) • Arkansas River Shiner (Notropis girardi) **B. <u>Invertebrates</u>** • Rabbitfoot Mussel (Quadrula cylindrica)	**A. <u>Fish</u>** • Pallid Sturgeon (Scaphirhynchus albus) • Topeka Shiner (Notropis topeka) **B. <u>Invertebrates</u>** • Neosho Mucket Mussel (Lampsilis rafinesqueana)

Source: KDWPT (2015a)

Chapter 3: State DOT Survey Results

3.1 General

The survey of other state Departments of Transportation had several goals. The first goal was to determine if states other than Kansas were experiencing headcutting problems in streams at their box culverts. The second goal was to find out what methods other states used to remedy or prevent headcutting at box culverts, and what methods, if any, the states use for AOP through box culverts. The final goal of this survey was to determine the level of regulatory concern in other states with regard to AOP and box culverts. In total, transportation authorities from 30 states responded to the survey either via e-mail or by phone. The questions asked in the survey were as follows:

1. Does your state still install box culverts for roadway stream crossings? If not, do you still have some in service and was AOP a contributing factor in stopping the use of box culverts?
2. Has your state encountered problems with channel bed incision (headcutting erosion) upstream of any culverts? And does your state install measures to prevent such erosion?
3. If your state installs measures to prevent headcutting, what types have been used? Are any of these installed to facilitate AOP, or are other measures installed for AOP?
4. Have any of the measures installed caused environmental or wildlife regulatory concerns with regard to AOP? If no measures are installed to prevent headcutting or facilitate AOP, have there been any regulatory concerns with regard to box culverts and AOP?

All of the states that responded to the survey use box culverts for roadway stream crossings. Several of the states surveyed do not install measures to prevent headcutting for a variety of reasons. Many states do not install any measures specifically for AOP in or around their box culverts for a number of reasons. Other states are pushing towards the state of the art stream simulation from the Federal Highway Administration Hydraulic Engineering Circular

Number 26 (FHWA HEC 26; Kilgore et al., 2010; Schall et al., 2012). The specific responses from each state surveyed are listed below in alphabetical order.

3.2 Details of States Survey

3.2.1 Alabama

Alabama has encountered problems with headcutting upstream of box culverts, but does not currently install measures to prevent such erosion. Alabama typically installs box culverts embedded approximately 1 foot, and allows the culverts to fill in with native streambed material. The state has encountered regulatory concerns with regard to box culverts and AOP. As of this writing, Alabama is currently in the process of reviewing and updating their box culvert design strategy to create a "more intentional and informed policy regarding aquatic species passage."

3.2.2 Alaska

Alaska has not encountered problems with headcutting upstream of box culverts; however, measures have been installed to prevent such erosion from occurring. Alaska has used weirs in the box culvert to control grade and prevent erosion for nearby utilities. The state has also used V-notched walls similar to soil saver walls for culvert inlets, though these were not used for AOP. In the southwest portion of Alaska, the culvert inverts are typically placed at the expected streambed elevation. The stream is studied so that fluctuation from the existing streambed elevation can be anticipated prior to culvert installation. The Alaska DOT often works closely with the environmental and biological regulators to determine mutually acceptable culvert designs, thus avoiding problems with obtaining permits.

3.2.3 Arizona

Arizona has encountered problems with headcutting upstream of box culverts. Arizona has used concrete walls similar to soil saver walls to prevent streambed erosion upstream of box culverts, and also uses check dams with weirs in drainage channels. Arizona has not encountered regulatory concerns with regard to AOP and box culverts because most of the streams in the state are ephemeral.

3.2.4 Arkansas

Arkansas has not encountered problems with headcutting upstream of box culverts because much of the state is rocky and does not generally have erosion problems. Arkansas has installed drop inlets in areas with large elevation changes (hilly areas). The state has used a small cutout on the inlet wall to help with low flow conditions. Arkansas has not encountered any regulatory problems with regard to AOP and box culverts.

3.2.5 California

California has encountered problems with headcutting upstream of box culverts and has installed several types of measures to mitigate this erosion. Some areas of the state have much larger elevation changes, i.e., mountainous regions where erosion is a much larger concern. California has used rock weirs upstream of the culvert in some cases to prevent headcutting, though these are more often downstream of the culvert. The state has also installed baffles in culverts to promote a more natural streambed. Baffles are sized based on fish species and life stage, as well as low and high flow (minimum and maximum) passable conditions for that species. However, stream simulation is the preferred design approach for new crossings utilizing culverts. For the stream simulation approach, the stream profile is analyzed far upstream and downstream of the proposed crossing with the intent of minimizing disturbance of the existing stream/streambed. Therefore the stream profile remains relatively unchanged well upstream and downstream from the crossing. California has encountered regulatory concerns with regard to AOP and box culverts. These concerns are more prevalent in some areas than others.

3.2.6 Connecticut

Connecticut has not encountered problems with headcutting upstream of box culverts and does not install measures specifically to prevent such erosion. Connecticut has installed several types of systems to promote AOP. The state has used rock weirs and step pools upstream of box culverts, though these are mostly used downstream of culverts. The state has used buried riprap or baffles in the culvert to stabilize a more natural streambed in their box culverts. The culvert with riprap or baffles is either actively filled in with native streambed material during construction or is allowed to fill in with material transported by the stream. The state has also used some concrete fishways. Connecticut has not encountered regulatory problems with regard to AOP and box culverts because the DOT works very closely with the environmental regulators during the design of stream crossings.

3.2.7 Delaware

Delaware has only encountered a couple instances of headcutting upstream of box culverts due to the state being mostly flat. No specific erosion control measures have been implemented to prevent headcutting. Delaware typically installs box culverts embedded 1 foot which are allowed to fill in with stream sediment. The state has installed a few fish ladders on spillways, but no specific AOP measures have been used on box culverts. Delaware has not encountered regulatory concerns with regard to AOP and box culverts.

3.2.8 Florida

Florida has not encountered problems with headcutting upstream of box culverts, but does install countermeasures to prevent such erosion when necessary. Florida has used riprap and gabion mats upstream of box culverts to prevent erosion of the streambed. As of this writing, the state is working on a revetment manual for such situations but does not have any standards yet. Florida has not encountered any regulatory issues with regard to AOP and box culverts.

3.2.9 Illinois

There have been some issues with headcutting upstream of box culverts in Illinois. Illinois installs cut-off walls upstream and downstream of the box culvert to prevent scour at the inlet and outlet of the box culvert. The box culverts are embedded approximately 3 inches to 1 foot depending on the location. The box culverts are allowed to fill in with native streambed material. The intent is that this will create a more natural channel bed through the length of the culvert. Illinois has encountered little regulatory resistance with regard to obtaining environmental permits for box culverts, and the issues encountered have been inconsistent.

3.2.10 Iowa

Iowa has encountered some problems with headcutting upstream of box culverts and has used some drop inlets structures to prevent such headcutting. The drop inlets are installed with and without notches or drain holes, and are mostly used in ephemeral or annual streams. These structures are similar to the soil saver walls used in Kansas. Iowa has not encountered regulatory problems regarding AOP because their drop inlet structures are used in streams that are not wet year-round (i.e., ephemeral or intermittent).

3.2.11 Louisiana

Louisiana has not encountered any problems with headcutting upstream of box culverts due to the state being relatively flat, and no countermeasures have been installed to prevent such erosion. Louisiana typically places the culvert invert at the expected streambed line. There have been a few AOP structures placed in the state where the culvert was embedded up to 2 feet and allowed to fill in with stream sediment to provide a more natural streambed in the culvert. Louisiana has not encountered regulatory issues with regard to AOP and box culverts.

3.2.12 Maine

Maine has encountered some problems with headcutting upstream of box culverts. Maine has utilized several different countermeasures to prevent upstream erosion of the channel bed. The state typically installs box culverts embedded 2 feet, and culverts with a streambed grade less than 3 percent are backfilled with local stream sediment. When grades are steeper than 3 percent, the streambed sediment in the culvert is sometimes stabilized with gravel and cobbles. The state has also used sediment sills and occasionally weirs in the culvert to stabilize the streambed. Maine has also armored the culvert inlets with rock when grades are too steep, and even used step pools upstream of the culvert on occasion. The Maine DOT philosophy is to create a more natural streambed channel in their culverts. Maine has not encountered regulatory issues with regard to AOP and box culverts due to active involvement with the regulatory agency in the planning phase of stream crossing projects.

3.2.13 Maryland

Maryland has encountered some problems with headcutting upstream of box culverts. Maryland has used riprap to create roughened channels upstream of some box culverts. The state has also used some pipe arch culverts (bottomless) to replace box culverts. Maryland has also used fish ladders in a few instances. The state has not encountered regulatory issues with regard to AOP and box culverts, however, the various regulatory agencies have input right from the beginning of the planning process to ensure a mutually satisfactory design is reached.

3.2.14 Michigan

Michigan has on rare occasion encountered problems with headcutting upstream of box culverts. Michigan typically uses “6A aggregate between the culvert invert and the proposed flow line to establish a consistent stream bed profile from upstream to downstream of the culvert.” Michigan’s 6A aggregate is almost entirely gravel-sized particles with 100% passing the 1½-inch sieve and 0% to 8% passing the No. 4 sieve. The state has also installed bottomless culverts in some instances. Michigan is planning to build one box culvert that will contain a series of alternating concrete baffles to provide sufficient depth for fish passage. The state faces several regulatory concerns with relation to AOP and box culverts, such as high flow velocities, low water depths under daily flow conditions, natural substrates, terrestrial passage, and perched culverts.

3.2.15 Mississippi

Mississippi has encountered some problems with headcutting upstream of box culverts, but as of this writing has not yet implemented any of the proposed countermeasures. The state typically countersinks box culverts 2 feet and allows the culverts to fill in with stream sediment. Mississippi has proposed using rock chutes, some with step pools upstream of box culverts. Mississippi has just recently encountered its first permitting issue with regard to box culverts and AOP.

3.2.16 Missouri

Missouri has not encountered any problems with headcutting upstream of their box culverts and does not implement measures to prevent such erosion. Missouri typically installs box culverts 1 foot below streambed elevation and allows the culverts to fill in with native streambed material. The intent is that this will create a more natural channel bed throughout the length of the culvert. Missouri has not encountered regulatory problems with regard to environmental permits for box culverts.

3.2.17 Nebraska

Nebraska has encountered some problems with headcutting upstream of box culverts. Nebraska has used broken back culverts and soil saver wall type structures to stabilize streams and halt further upstream headcut migration. However, the state does not use embedded culverts as AOP structures when a new structure is placed on a perennial stream. Nebraska is currently conducting research on the feasibility of using bottomless culverts in perennial streams, but has not installed any bottomless culverts at this time. The state has a significant number of stream channels with large elevation drops and active nickpoint migration (headcutting). The state has not encountered regulatory issues regarding AOP and culverts.

3.2.18 New Hampshire

New Hampshire has not encountered problems with headcutting upstream of box culverts. New Hampshire has utilized several different structures to mitigate headcutting upstream of their culverts. The state has installed baffles in culverts in a pattern perpendicular to the stream flow as well as a chevron pattern. Often the baffles increase in spacing at the culvert inlet to help with sediment deposition. New Hampshire has also used log vanes to prevent headcutting upstream of culverts, but not in situations where AOP was a concern. The overall goal for culvert design in New Hampshire is a more natural streambed which hopefully will allow for unhindered AOP. New Hampshire has not had regulatory issues with regard to box culverts and AOP because they work closely with the state regulatory agency on stream crossings to create a mutually acceptable design.

3.2.19 North Dakota

North Dakota has not encountered any problems with headcutting upstream of their box culverts. However, the state typically installs cut-off walls upstream and downstream of the culvert, as well as riprap in front of the culvert apron on the upstream side of the culvert. The riprap is intended to prevent erosion of the streambed, or headcutting, and may also provide a pathway for upstream aquatic organism passage. North Dakota has not encountered regulatory problems with regard to environmental permits for box culverts.

3.2.20 Ohio

Ohio has not encountered problems with headcutting upstream of box culverts. Ohio does, however, install countermeasures to prevent such upstream erosion. The state design procedures for box culverts include the following: bankfull discharge design, depressed culvert inverts, and paved depressed approach aprons. Although the bankfull discharge design is preferred, it may not be required on replacement culverts. Ohio also installs a cut-off wall in situations where an approach slab is utilized. When the culvert invert is placed below the streambed elevation, the culvert is allowed to fill in with stream sediment. Ohio has not encountered regulatory issues with regard to AOP and box culverts.

3.2.21 Oklahoma

Oklahoma has encountered problems with headcutting upstream of box culverts. Oklahoma has used the following structures to prevent or mitigate channel erosion upstream of the culverts: broken-back culverts, drop inlets, energy dissipaters at the outlet, cut-off walls, and gabions/riprap for bank stabilization. The state has not encountered any regulatory issues with regard to AOP and box culverts.

3.2.22 Pennsylvania

Pennsylvania has not encountered problems with headcutting upstream of box culverts. In the past, Pennsylvania used to countersink culverts 1 foot and simply allow the culvert invert to fill in with stream sediment, but this practice is no longer used. Current box culvert design practices in the state typically include baffles installed within the culvert. The baffles are most often spaced 8 feet apart along the length of the culvert, but are not the full width of the culvert. The baffle openings are alternated to create a meander within the culvert. Baffles are not always perpendicular to stream flow and occasionally baffles are placed on the inlet apron of the culvert. Different designs are used when stream grade is greater or less than 4 percent. Pennsylvania has encountered some regulatory issues with regard to AOP and box culverts. The state has been working with the fish commission to achieve suitable designs for culverts.

3.2.23 South Carolina

South Carolina has not encountered problems with headcutting upstream of box culverts; however, the state has used some countermeasures to prevent headcut erosion. South Carolina has used riprap to create a roughened channel in some cases. The state has used recessed culverts as well, and allows them to fill in with stream sediment. South Carolina has also used some three-sided culverts, otherwise known as “bottomless” culverts. The state has encountered some regulatory issues with regard to AOP and box culverts.

3.2.24 South Dakota

South Dakota has encountered some problems with headcutting upstream of box culverts. South Dakota currently countersinks box culverts 1 foot and allow the culverts to fill in with stream sediment. The state had previously encountered environmental regulatory issues and began the practice of countersinking culverts as a result.

3.2.25 Texas

Texas has encountered some problems with headcutting upstream of box culverts. Texas has occasionally used riprap at culvert entrances, but not specifically to prevent headcutting upstream. Culverts in the state are typically installed such that the invert is level with the existing streambed. Texas has not encountered any regulatory issues with regard to AOP and box culverts.

3.2.26 Vermont

Vermont has not encountered problems with headcutting upstream of box culverts; however, the state does install countermeasures to prevent such upstream erosion. The state’s box culvert design goal is to allow all culverts to have a “natural” bed to bankfull width. Vermont’s design calls for countersinking culverts several feet, installing baffles in the culvert barrel, and backfilling with 2-3 feet of riprap. The baffles and riprap create a hard barrier to help capture sediments transported from upstream of the culvert and prevent headcutting from propagating upstream of the culvert. Vermont has started placing more fines within the riprap, essentially a more well-graded material, to prevent underseepage through the riprap. Vermont has not encountered regulatory problems with regard to AOP and box culverts, although AOP has been a concern since 2006.

3.2.27 Virginia

Virginia has not encountered problems with headcutting upstream of box culverts and does not install countermeasures to prevent such erosion. Virginia countersinks the box culvert inverts 6 inches below the streambed. The state has rarely experienced much, if any, headcutting erosion upstream of its box culverts. Virginia has not encountered any regulatory issues with regard to AOP and box culverts.

3.2.28 Washington

Washington has occasionally encountered problems with headcutting upstream of box culverts, and in certain situations grade control measures are used. For a culvert where headcutting is anticipated, the culvert is either designed to prevent headcutting or the potential impacts of headcutting, and scour and profile degradation are analyzed. Roughened channel is currently the preferred method, and has been used on fish-bearing streams. Roughened channel designs include the rock sizing method or unit discharge method (D84), and are designed for 100-year stability. Washington uses a non-erodible layer below, such as granular material or large angular rock (riprap), with sediment above to provide a more natural streambed. The non-erodible layer provides stability during a large flow event, protects structures, and ideally this layer will fill back in with sediment after a large flow event. Washington has used fish ladders in the past, but would only use them now with a stipulation of strict maintenance due to their tendency to catch sediment and debris. The state requires that all four-sided box culverts be greater than 1.2 times the bankfull width plus 2 feet. Washington has also used three-sided box culverts, or so called “bottomless” culverts. The state is facing legal pressure to make all streams have the same gradient upstream, downstream, and in the culvert such that the channel flow does not experience the effects of the culvert. The idea is to make all stream crossings more “natural” and not alter the stream at all.

3.2.29 West Virginia

West Virginia has encountered problems with headcutting upstream of box culverts and has installed countermeasures to prevent such erosion. West Virginia has used a rock cross vane design recommended by Dave Rosgen for about 10-15 years (these are U-shaped weir structures that cross the stream and have a height of about 6 inches, see Figure 3.1), log weirs, and baffles installed in the culvert barrel. Sometimes notches are installed in the aforementioned structures for low flow conditions. The baffles are installed perpendicular to stream flow with the intent that stream rock and sediment will fill in between them. West Virginia has not encountered regulatory issues with regard to AOP and box culverts because the state works closely with the regulators to find mutually acceptable solutions.

3.2.30 Wyoming

Wyoming has encountered problems with headcutting upstream of box culverts and has used countermeasures to prevent such erosion. Wyoming has used rock or gabion weirs, timber cribbing (weirs), cut-off walls, and baffles in the culvert barrel. The baffles are installed perpendicular to the stream flow and have a V-notch in the center for low flow conditions. The baffles are used to retain stream sediment materials and ideally will create a more “natural” streambed. Wyoming has encountered regulatory issues with regard to AOP and box culverts.

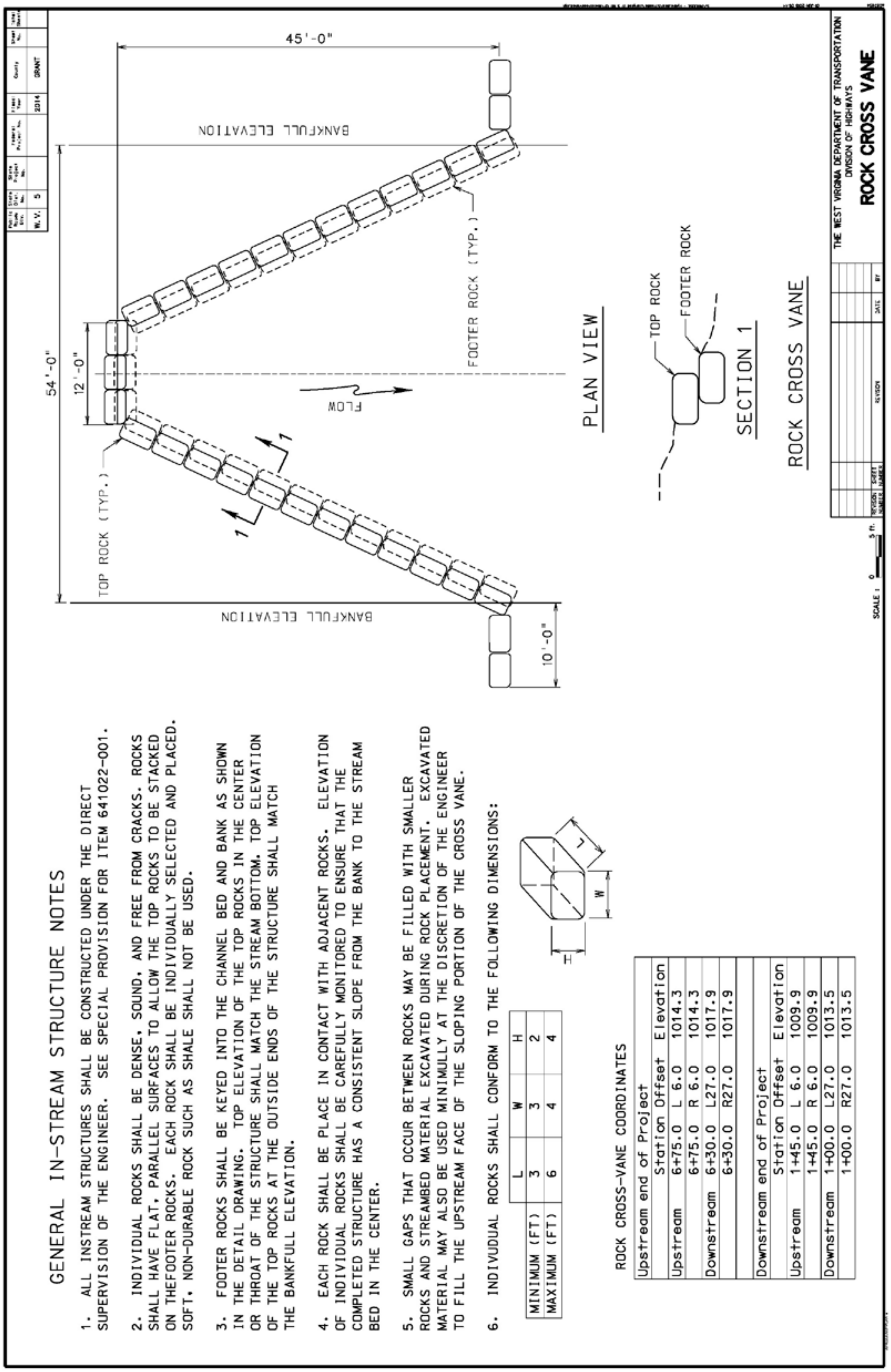


Figure 3.1: West Virginia Rock Cross Vane Design
Figure provided courtesy of the West Virginia Department of Transportation.

3.3 Comments on the Survey of States

The state surveys showed that some states do not install measures to prevent headcutting. Some of these states incorporate low height embedded inlets. Many work closely with AOP regulators within the state. Some states use soil saver wall measures, however, they do not provide any AOP facilities in or around certain box culverts since there are no regulatory concerns for various reasons, including working jointly with AOP regulators. In some states, a soil saver wall is unnecessary because the culvert is in a rocky area where erosion is not a concern. Some states are designing the culverts based on FHWA HEC 26 (Kilgore et al., 2010). Some of the states are using soil saver type structural features to prevent headcutting while incorporating AOP features. These structural features include application of notches in soil saver walls, riprap and gabion mats upstream from the culvert, baffles within the culvert, and timber cribbing weirs in culvert inlets.

3.4 Soil Saver Wall Modification to AOP Promoting Culverts

The basic function of an AOP promoting culvert is to let water flow continuously through the culvert for all flows as well as allowing the passage of aquatic organisms in the upstream direction. This precludes the use of drop structures that totally block upstream passage for lower flow regimes. Stream stability should also be considered when designing AOP promoting culverts. In this study, headcutting is the main concern. Other states which are addressing headcutting in AOP culvert design use notches in soil saver walls installed near the culvert inlet. Construction of notches on existing soil saver walls as well as new walls is a relatively easy modification. Hence, at this phase of study, placement of notches in soil saver walls was the design modification selected for further investigation.

Chapter 4: Existing Soil Saver Wall Conditions

4.1 General

KDOT has constructed soil saver walls upstream of many box culverts throughout Kansas. A map of 21 box culverts in eastern Kansas was provided by KDOT, and 15 culverts were visited and photographed as a part of this study. Descriptions of seven of the 15 culverts are presented in this report. The goal of these site visits was to determine the operating condition of the soil saver walls currently in service throughout the state. The conditions of the channels upstream of the soil saver walls also provide a good indication of the effectiveness of these structures at preventing headcutting. Additionally, the nature of the channel, whether it is a perennial stream or an ephemeral drainage channel, was assessed. The soil saver walls visited varied in height from approximately 6 inches to 3 feet. None of the culverts surveyed showed signs of significant headcut propagation upstream, but some sites had very minor headcutting just upstream from the soil saver wall unless they were riprapped. Only two of the 15 box culverts visited appeared to be in a perennial stream, i.e., where the channel flows year-round. Nine culverts were either in a channel that was completely dry upstream and/or downstream of the culvert, or were in an obviously man-made storm water drainage channel.

4.2 K-7 Highway, Wolf River Drainage, 1.56 Miles Southeast of Sparks, Doniphan County, KS

This culvert carries a tributary drainage channel of the Wolf River and crosses under K-7 Highway in Doniphan County, KS, approximately 3.5 miles north of US-36. The drainage channel flows east to west. The culvert has a soil saver wall that is 3.0 feet in height at the centerline of the culvert and slopes upward at the wing walls, as shown in Figures 4.1 and 4.2. The following figures show the soil saver wall at the inlet from the upstream side and from inside the barrel of the culvert. At the time of the visit the stream depth was several inches. The culvert had water flowing through it at the time of site visit though it is an ephemeral channel. The culvert was clean at the time of site visit and functioned well for water passage.

Figure 4.1: Culvert under K-7 Highway, Facing Downstream at Inlet

Figure 4.2: Culvert under K-7 Highway, Facing Upstream at Inlet from Culvert Barrel

4.3 US-73, Spring Branch Drainage, 3.25 Miles North of US-36, Brown County, KS

This culvert carries drainage from farm fields (west to east) under US-73, 3.25 miles north of US-36 just south of the Kansas-Nebraska border, in Brown County, KS. The drainage channel flows northwest to southeast. The culvert has a soil saver wall that is approximately 1.0 foot in height. Figure 4.3 shows the culvert inlet. At the time of the visit the drainage channel was completely dry. The major portion of the water in the culvert comes from the highway ditch as there was a defined channel at the side of the highway. There was no defined channel in front of the culvert and no headcutting was observed.

Figure 4.3: Culvert under US-73, Facing Upstream (NW) from Inlet

4.4 K-246 Highway, Terrapin Creek Drainage, 6 Miles East of US-75, Near Morrill, KS

This culvert carries drainage from farm fields under K-246 Highway, 6.0 miles east of US-75 near Morrill, in Brown County, KS. The drainage channel flows north to south from the farm field to the field adjacent to the railroad. The culvert is a two-celled box with a soil saver wall that is approximately 1.0 foot in height and has three drain holes installed. Figure 4.4 shows the culvert inlet. At the time of the visit the drainage channel was completely dry.

Figure 4.4: Culvert under K-246 Highway, Facing West Across Inlet

4.5 K-116 Highway, Elk Creek Drainage, 2.46 Miles East of K-16, Jackson County, KS

This culvert carries drainage from an Elk Creek offshoot under K-116 Highway, 2.46 miles east of K-16, in Jackson County, KS. The drainage channel flows north from a drainage channel to a farm field on the north side of the road. The culvert is a single-cell box with a soil saver wall that is approximately 3.0 feet in height. Figures 4.5 and 4.6 show the culvert inlet, and at the time of the visit the drainage channel had standing water over 1 foot in depth upstream of the soil saver wall. However, the channel was completely dry just a few feet downstream of the culvert outlet.

Figure 4.5: Culvert under K-116 Highway, Facing West Across Inlet

Figure 4.6: Culvert under K-116 Highway, Facing Downstream at Inlet

4.6 US-59, Stonehouse Creek Drainage, 1.25 Miles North of US-24, Jefferson County, KS

This culvert carries drainage from Stonehouse Creek under US-59 Highway, 1.25 miles north of US-24, near Lawrence, in Jefferson County, KS. The drainage channel flows from the wooded area to the east of the road to the drainage channel west of the road. The culvert is a double-cell box with a soil saver wall that is approximately 1.0 foot in height and slopes upward at the wing walls. Figures 4.7 and 4.8 show the culvert inlet. At the time of the visit the drainage channel was completely dry, except for a small pool of water at the outlet.

Figure 4.7: Culvert under US-59, 1.25 Miles North of US-24, Facing Downstream at Inlet

Figure 4.8: Culvert under US-59, 1.25 Miles North of US-24, Facing North Across Inlet

4.7 K-4 at Munkers Creek Drainage, 3.6 Miles East of K-180, Wabaunsee County, KS

This culvert carries drainage from farm fields under K-4 Highway, 3.6 miles east of K-180 near Alta Vista, in Wabaunsee County, KS. The drainage channel flows from the farm field north of the road to the farm field south of the road. The culvert is a single-cell box with a soil saver wall that is approximately 1.0 foot in height. Figures 4.9 and 4.10 show the culvert inlet. At the time of the visit the drainage channel was completely dry.

Figure 4.9: Culvert under K-4, 3.6 Miles East of K-180, Facing Downstream at Inlet

Figure 4.10: Culvert under K-4, 3.6 Miles East of K-180, Facing Upstream at Inlet (Overhead View)

4.8 K-4 at Munkers Creek Drainage, 3.5 Miles East of K-180, Wabaunsee County, KS

This culvert carries drainage from farm fields under K-4 Highway, 3.5 miles east of K-180 near Alta Vista, in Wabaunsee County, KS. The drainage channel flows from the farm field north of the road to the farm field south of the road. Like the culvert just a tenth of a mile east, this culvert is a single box with a soil saver wall that is approximately 1.0 foot in height. Figures 4.11 and 4.12 show the culvert inlet. At the time of the visit the drainage channel was dry; however, the culvert itself had standing water due to a blockage at the outlet.

Figure 4.11: Culvert under K-4, 3.5 Miles East of K-180, Facing Upstream at Inlet (Overhead View)

Figure 4.12: Culvert under K-4, 3.5 Miles East of K-180, Facing East Across Inlet

Chapter 5: Flume Study

5.1 General

A preliminary flume study has been performed to assist in understanding the scope of the problem of upstream headcutting of box culverts. The flume study included tests of models of a conventional soil saver wall and walls with a square notch and a V-notch. Notched walls have the potential to be more conducive to aquatic organism passage (AOP) than the existing soil saver walls. These two modifications are presented in Figure 5.1 and 5.2. The inclusion of a notch in the soil saver wall is proposed as an alternative. The modifications were selected based on the practice in other states.

5.2 Theoretical Explanation of Proposed Models

A model culvert of 1:24 scale was proposed for flume testing. The prototype square sectional area of the culvert was 10 × 10 ft. The box culvert scale model was constructed out of marine grade plywood and coated with waterproof paint. All components of the culvert were made of half-inch plywood. The wing walls were vertical and set at a 45 degree angle to the box. The outlet wing walls were identical to the inlet wing walls. The upstream and downstream aprons were 10 ft in length. The model culvert is presented in Figure 5.1.

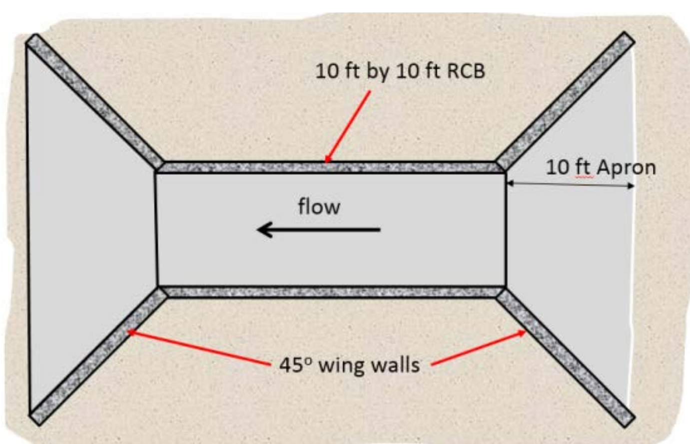


Figure 5.1: Sketch of Model Culvert Prepared at Lab

A soil saver wall was added to the front of the culvert at the edge of the inlet apron at a distance of 10 ft from the entrance of the culvert. The height of the soil saver wall was 2 ft and the length of the soil saver wall was 30 ft. This soil saver wall is modeled based on the KDOT soil saver wall design. The efficiency of this culvert was assumed to be 100%. The model culvert with traditional soil saver wall is presented in Figure 5.2.

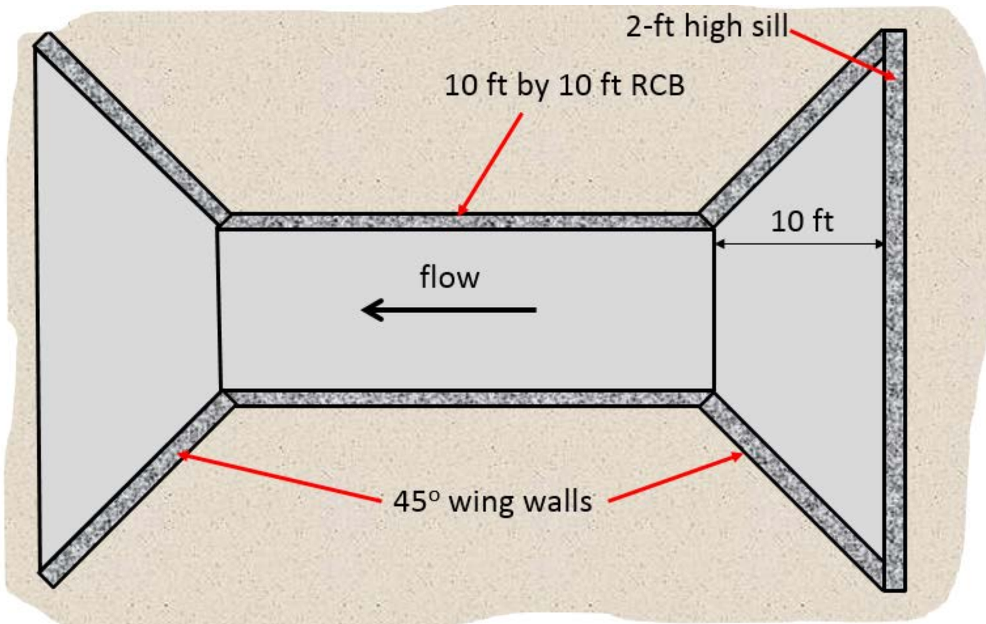


Figure 5.2: Sketch of Model Culvert with Soil Saver Wall at the Upstream End

The capacity of this model culvert is influenced by either the upstream control at the soil saver wall or at the culvert inlet itself. These capacities are presented here:

1. Upstream control (critical depth) at soil saver wall

$$q_{ss} = \frac{Q}{B} => y_{c,ss} = \left(\frac{q_{ss}^2}{g}\right)^{1/3}$$ **Equation 5.1(a)**

$$=> E_{c,ss} = \left(1.5 + \frac{K}{2}\right) * y_{c,ss}$$ **Equation 5.1(b)**

Where:

Q = Flume discharge (cfs)

B = Length of the soil saver wall (ft)

q_{ss} = Specific discharge at soil saver wall (cfs/ft^2)

$y_{c,ss}$ = Critical depth relative to top of soil saver wall (ft)

g = Gravitational constant (ft/sec^2)

$E_{c,ss}$ = Energy upstream from soil waver wall (ft)

K = Possible loss coefficient for flow to soil saver wall (typically negligible)

Some modifications will need to be made to Equations 5.1(a) and 5.1(b) to account for altered weir configuration due to the notch. Experimental data will be required to adjust the equations.

2. The inlet control (critical depth) at culvert entrance

$$q_{cv} = \frac{Q}{b} \Rightarrow y_{c,cv} = \left(\frac{q_{cv}^2}{g}\right)^{1/3}$$ **Equation 5.1(c)**

$$\Rightarrow E_{c,cv} = \left(1.5 + \frac{K}{2}\right) * y_{c,cv}$$ **Equation 5.1(d)**

Where:

b = Width of the culvert (ft)

q_{cv} = Specific discharge at culvert (cfs/ft^2)

$y_{c,cv}$ = Critical height at culvert inlet (ft)

$E_{c,cv}$ = Energy (ft)

G = Gravitational constant (ft/sec^2)

The lower discharge between Equations 5.1(a) and 5.1(b) for a given upstream energy level controls the culvert discharge.

5.3 Flume Testing Setup

Two alternative soil saver models are presented in this phase of study without changing the hydraulic design criteria of the culvert. These are:

- Soil saver wall with a square notch with a depth of 1 ft.
- Soil saver wall with a 120 degree V-notch with a width of 2 ft at the top.

These tests were performed on single-cell box culvert.

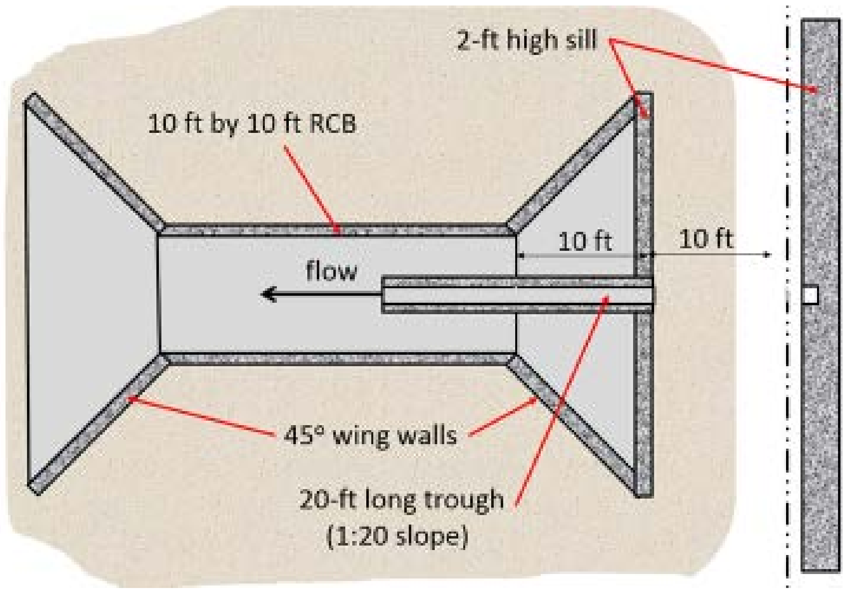


Figure 5.3: Alternative Model with Square Notch Slope Ramp

The square notch was connected to a 1-ft square ramp channel that would facilitate AOP. Figures 5.3 and 5.4 show the square notch with the ramp modification of the soil saver wall and Figures 5.5 and 5.6 show the V-notched modification of soil saver wall.

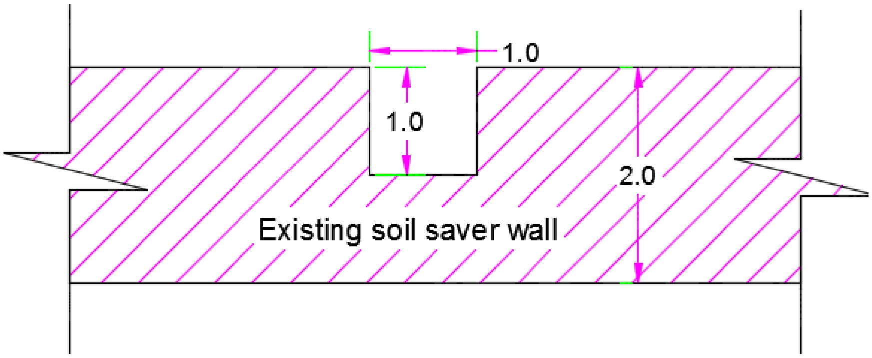


Figure 5.4: Schematic Front View of Square Notch Soil Saver Wall

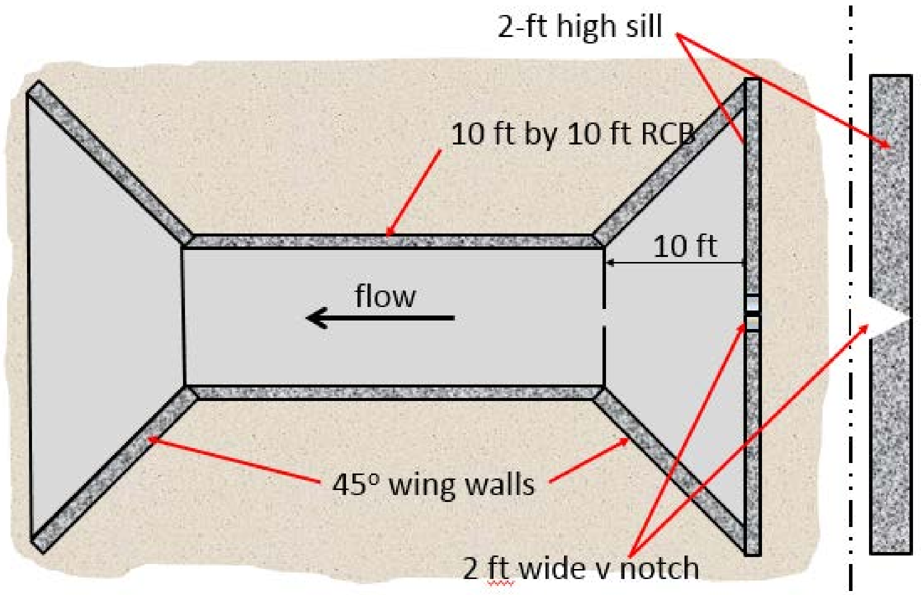


Figure 5.5: Alternative Model with V-notch

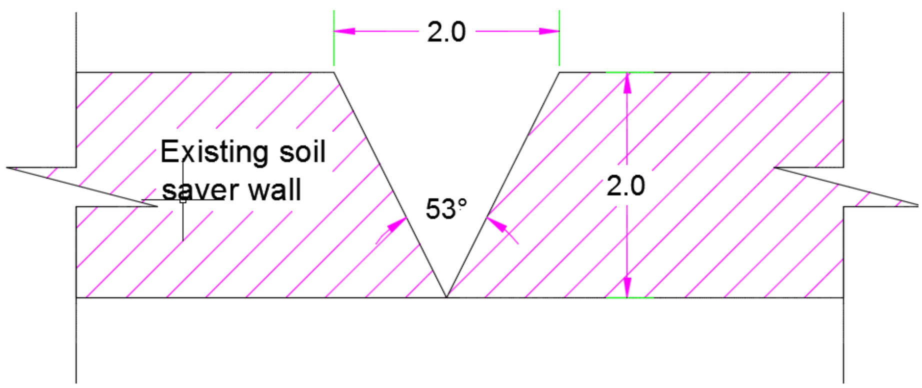


Figure 5.6: Schematic Front Elevation of V-Notch Soil Saver Wall

The model box culvert was set up in the flume at the hydraulics laboratory at the University of Kansas. The flume was 16 inches wide. The total width of the box culvert model at the end of the wing wall was just slightly less than the width of the flume. The flume was filled with a fine- to medium-grained sand to a depth between 2 and 3 inches to model the stream bed material.

Figure 5.7: Testing Flume and Box Culvert Scale Model, Overhead View

The flume was modified at one section to lower the bottom platform and deepen the section, which allows for deeper recession of the culvert model to better simulate real box culvert installations and larger headcuts. The flume and box culvert scale model are shown from overhead in Figure 5.7.

5.4 Physical Properties of Bed Materials

The bed material was uniformly distributed sand. The gradation of the sand is shown in Figure 5.8. All the particles of the bed material are smaller than 1 mm. The specific gravity of this sand is 2.67. This sand was selected because it reaches a level bed condition quickly for different discharges on the flume.

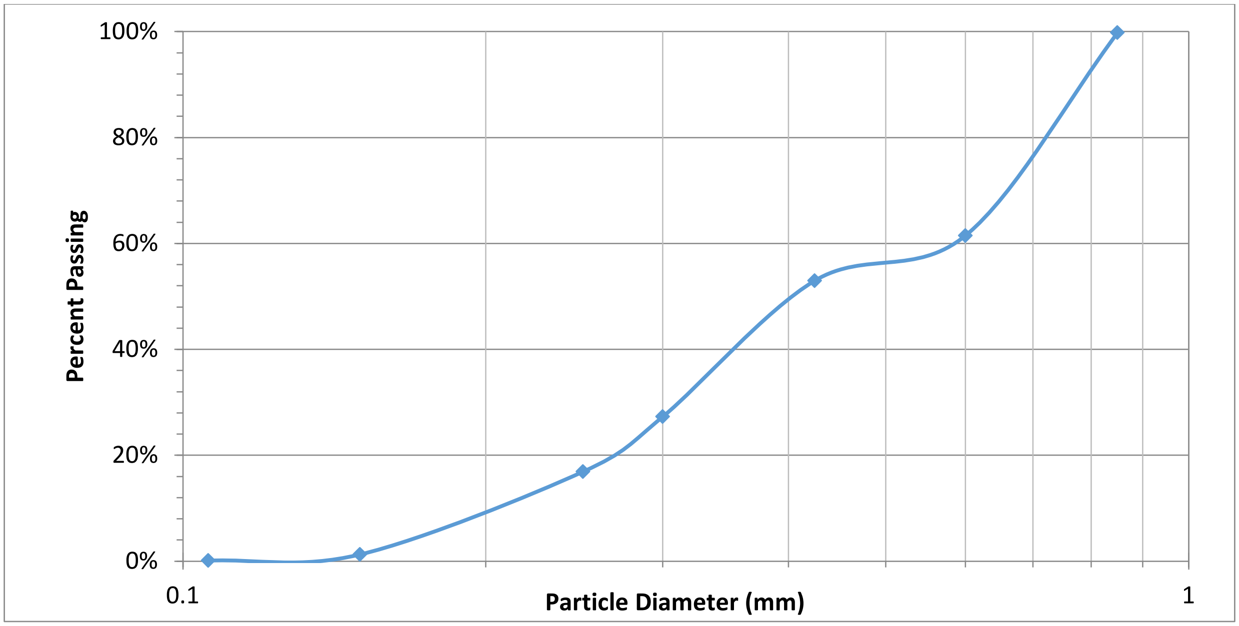


Figure 5.8: Gradation Curve of Sand Used for Flume Testing

Aggregates were used to riprap the outlet of the culvert to prevent erosion of the bed materials. The aggregate sizes ranged from one-half inch to 2 inches. The downstream riprap is shown in Figure 5.9.

Figure 5.9: Downstream Riprap by Aggregate

5.5 Procedure of Laboratory Tests

Water was added to the flume from the supply pipe and the velocity controller was adjusted to maintain the desired discharge on the culvert. This discharge was allowed to flow until the bed upstream became stable. A secondary reservoir was attached to the flume with a syphon system that added water to replace water lost from the flume due to evaporation or seepage and maintain a constant water level within the flume.

After finding the stable bed slope, the velocity of the flow was measured by recording the time required for a floating cork to travel a certain distance (10 ft for some tests and 8 ft for some tests). Also, the water surface, top of sand, and the bed of the flume were measured by the vertical measuring scale. This scale was rolled on the flume as shown in Figure 5.10.

Photographs were taken to determine the scour depth, length, and pattern of the scour made due to the different types of soil saver wall modification. Tests were conducted for a range of discharge levels to determine the effect of discharge quantity on the headcutting. After completion of each cycle the water in the flume was drained.

Figure 5.10: Water Profile Measuring Device at Lab

5.6 Test Results of Model Tests

5.6.1 Culvert with Uniform Depth Soil Saver Wall

Three consecutive tests were carried out on the uniform depth soil saver wall for different discharges. The motor speed was kept constant and the supply velocity was approximately constant for all tests. Only the water depth was changed with each test. Discharge and the upstream profiles were measured and plotted. Headcutting was observed in all three tests. Headcutting was deeper at the two sides of the culvert inlet and less pronounced at the middle part of the channel. As the discharge increased, the depth of headcutting increased. The upstream area affected by headcutting also increased as the discharge increased for the uniform depth soil saver wall. The photographs that follow contain examples of these test results.

1. Very Low Water Level Test: For the low flow condition, headcutting upstream of middle part of the soil saver wall was negligible while the sides experienced a considerable amount of headcutting. The semi-elliptical headcutting pattern is also small. Figure 5.11 illustrates the flume test results. The upstream profile of the water and bed surface is presented in Figure 5.12.

   The average depth of the flow was 1.19 inches and the flow velocity of this test was 0.64 ft/sec. The discharge was 0.085 ft^3/sec.

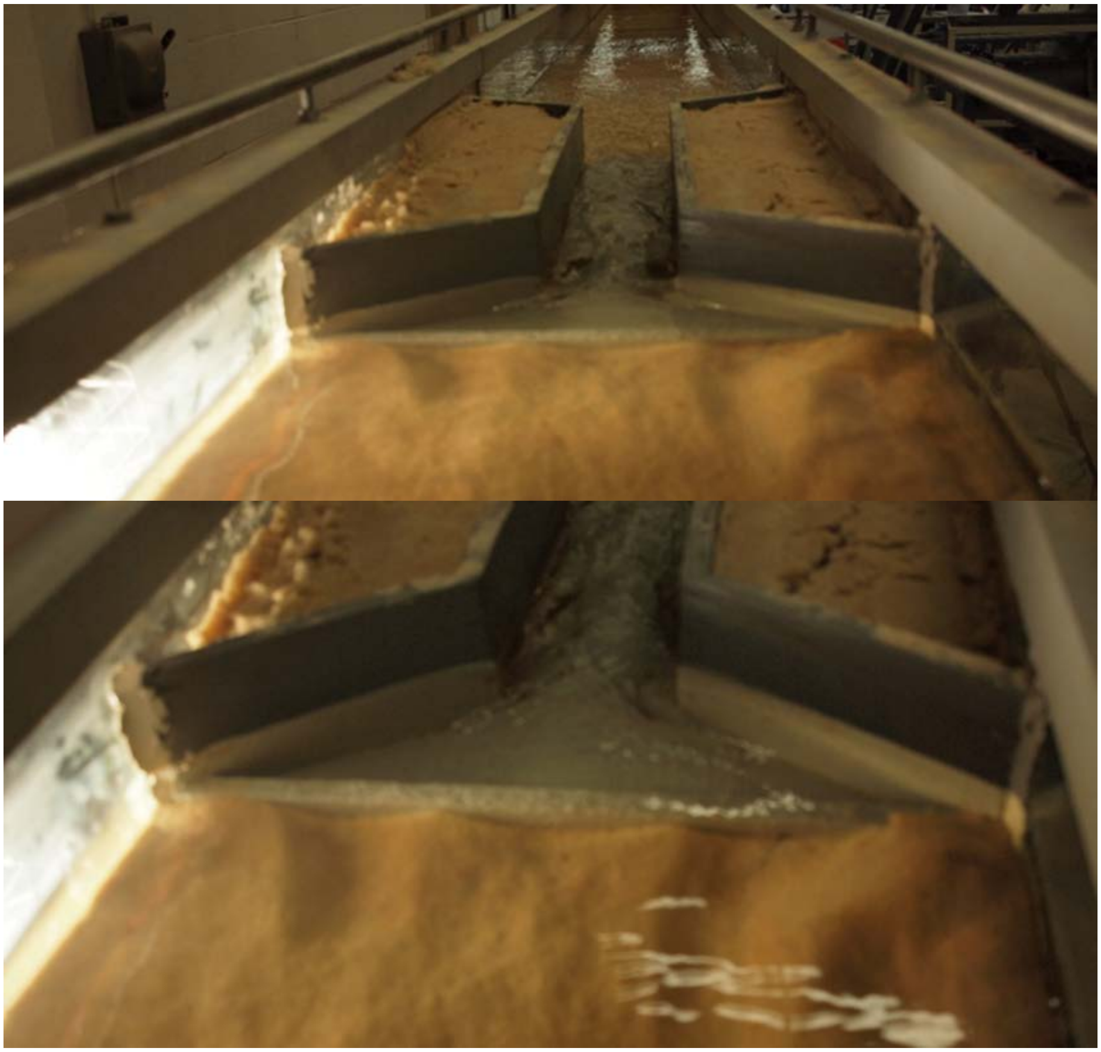


Figure 5.11: Photographs for Headcutting by Low Flow for Uniform Depth Soil Saver Wall

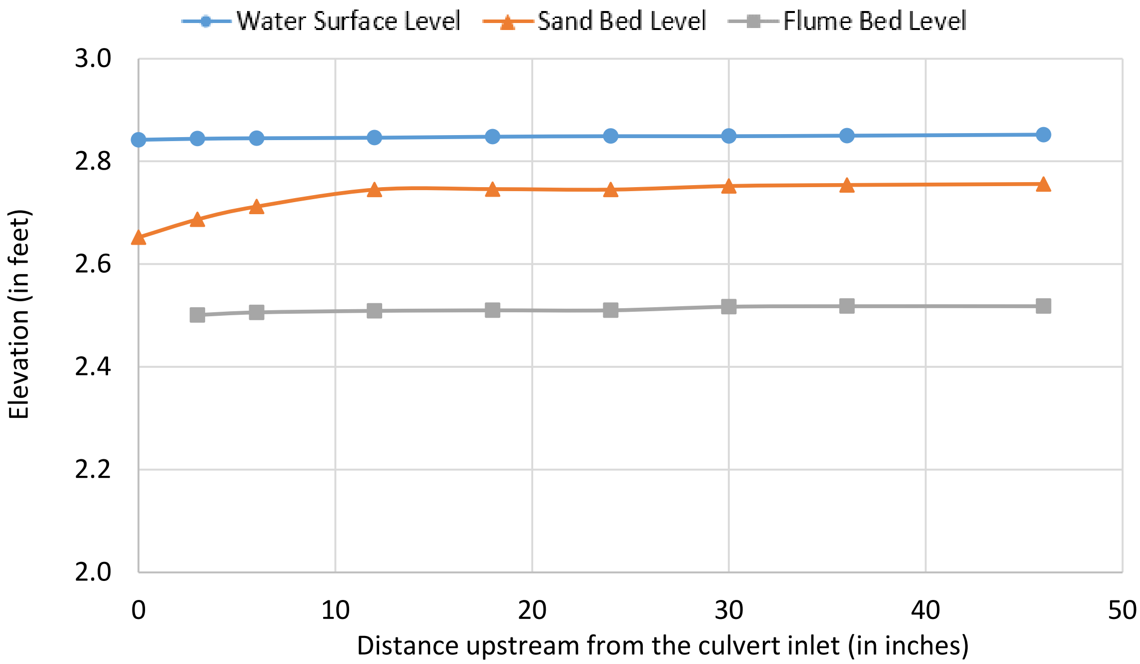


Figure 5.12: Upstream Flow and Bed Profile of the Lower Flow at Uniform Depth Soil Saver Wall

2. Intermediate Flow Test: For this test, the upstream headcutting pattern is the same as that for the lower flow; however, the upstream headcutting has expanded to a larger area. Photographs presented in Figure 5.13 illustrate the flume test results. The upstream profile of the water and bed surface is presented in Figure 5.14.

The average depth of the flow is 2.47 inches. The flow velocity for this test was 0.66 ft/sec and the discharge was 0.181 ft^3/sec.

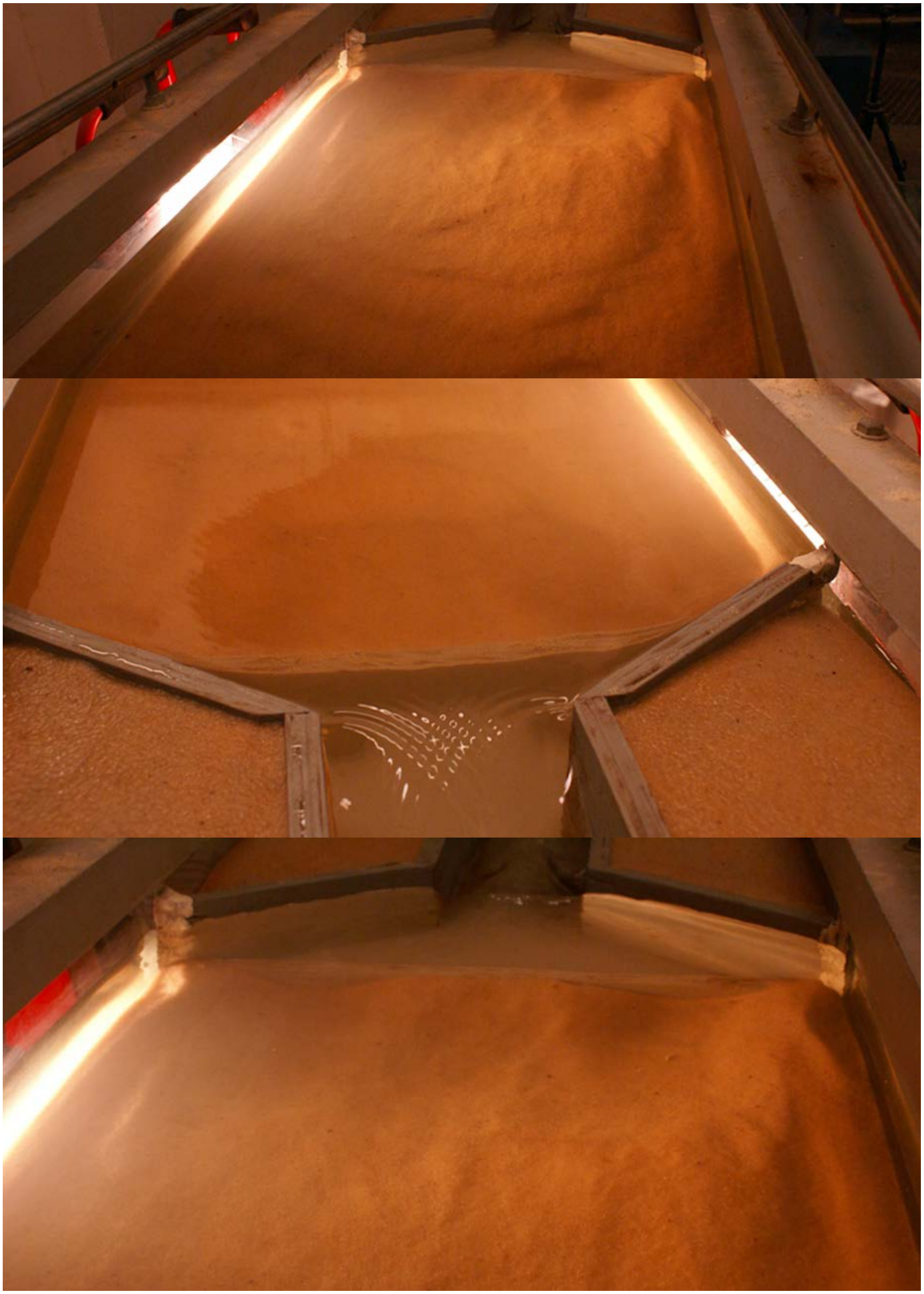


Figure 5.13: Photographs for Headcutting by Intermediate Flow for Uniform Depth Soil Saver Wall

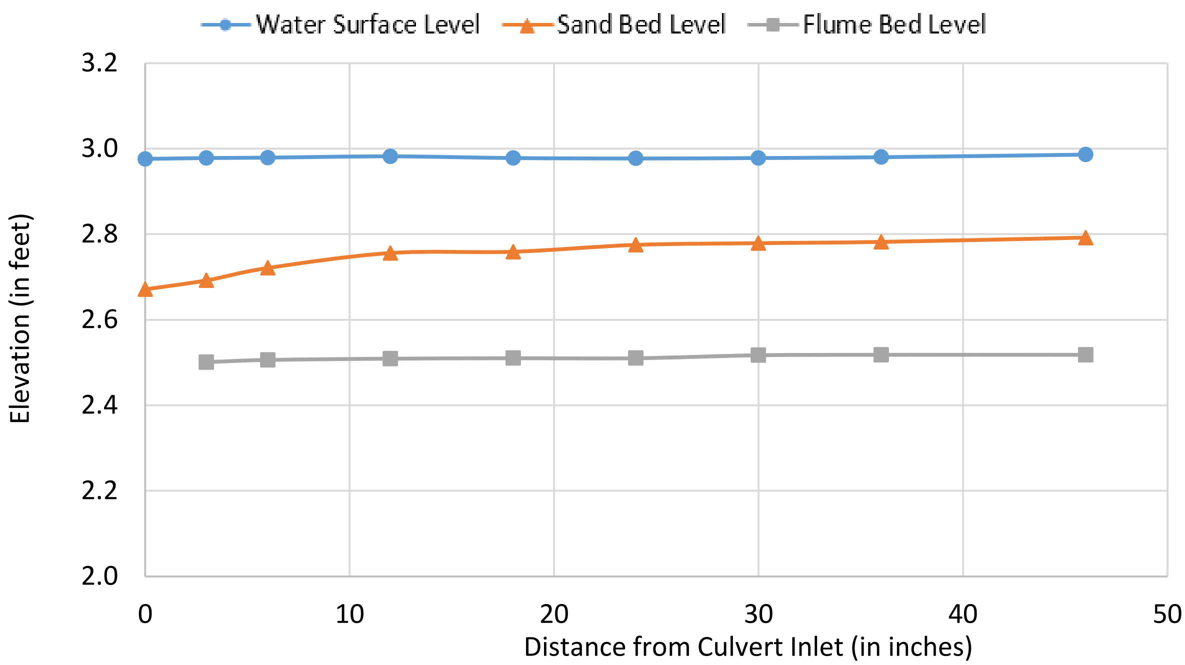


Figure 5.14: Upstream Flow and Bed Profile of the Medium Flow at Uniform Depth Soil Saver Wall

3. High Water Level Test: For high flow, the pattern of headcutting was similar to that of the first two cases; however, the extent was bigger for the two sides upstream of the soil saver wall as compared to middle of the flume, which was almost the same as the previous cases. The shape of the headcutting was very similar but was considerably larger. Also, a slight mass was deposited just upstream of the headcutting line. Photographs presented in Figure 5.15 illustrate the flume test results. The upstream profile of the water and bed surface is presented in Figure 5.16.

   The average depth of the flow was 3.07 inches. The flow velocity for this test was 0.68 ft/sec and the discharge was 0.233 ft^3/sec.

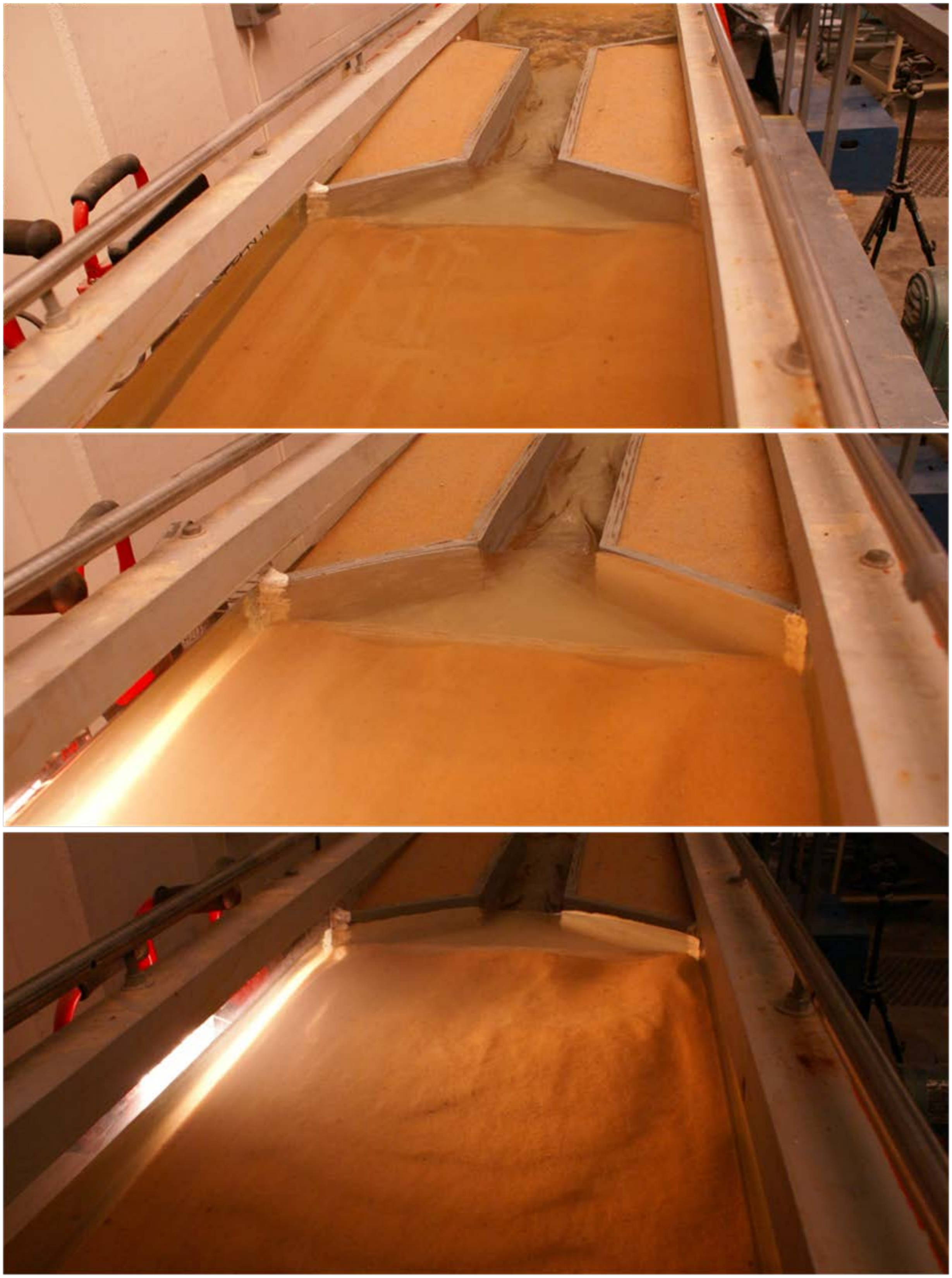


Figure 5.15: Photographs for Headcutting by Higher Flow for Uniform Depth Soil Saver Wall

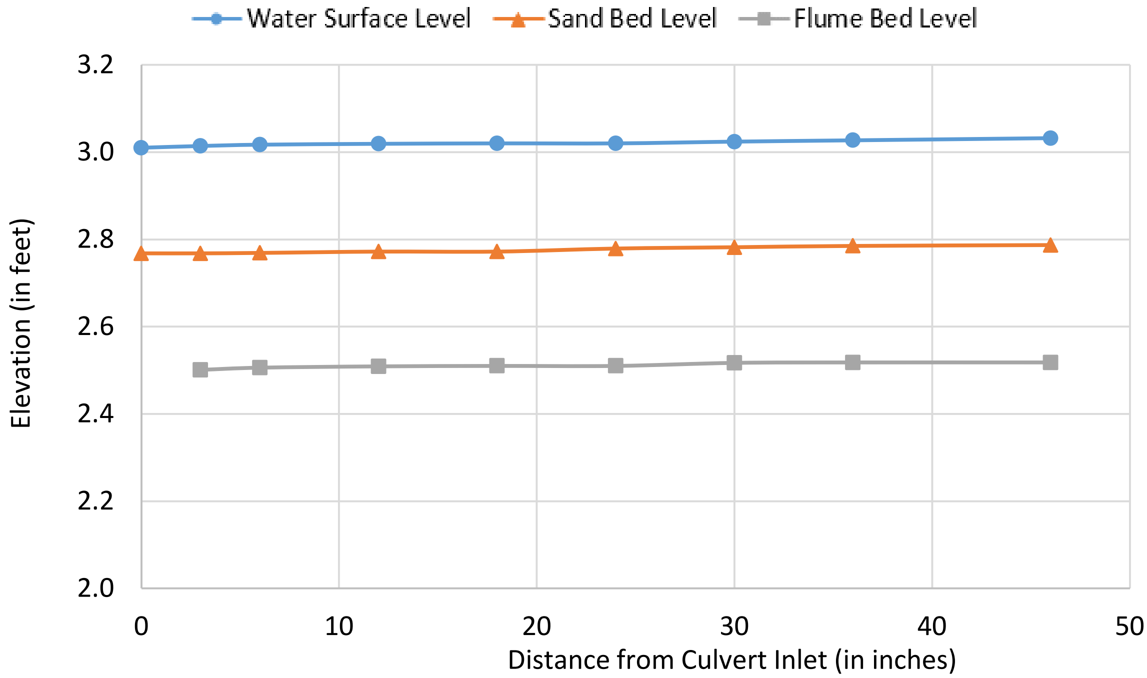


Figure 5.16: Upstream Flow and Bed Profile of the Higher Flow at Uniform Depth Soil Saver Wall

5.6.2 Culvert with Square Notch with Transition Ramp

Two tests were carried out with low flow and high flow for this set of tests. The results were similar except for the amount of scour. The headcutting above the square notch with ramp generated a different shape from the uniform depth soil saver wall. It resembled an elongated semi-ellipse with two deep scour pockets at the sides and a shallow scoured area in the middle. Also, a significant deposit was seen just beyond the boundary of the scour. The extent of the scour depth and scour area is greater for high flow as compared to low flow; however, the pattern is very similar. It was observed that the headcutting depth was slightly higher in the middle of the flume and almost the same at the sides when compared to the uniform depth soil saver wall. Therefore, only the minor local scour was caused by the notch on the soil saver wall. Figures 5.17, 5.18, and 5.19 show the lower flow and higher flow scour patterns.

Figure 5.17: Photographs for Headcutting by Lower Flow for Soil Saver Wall with Square Notch

Figure 5.18: Photograph for Headcutting by Higher Flow for Soil Saver Wall with Square Notch

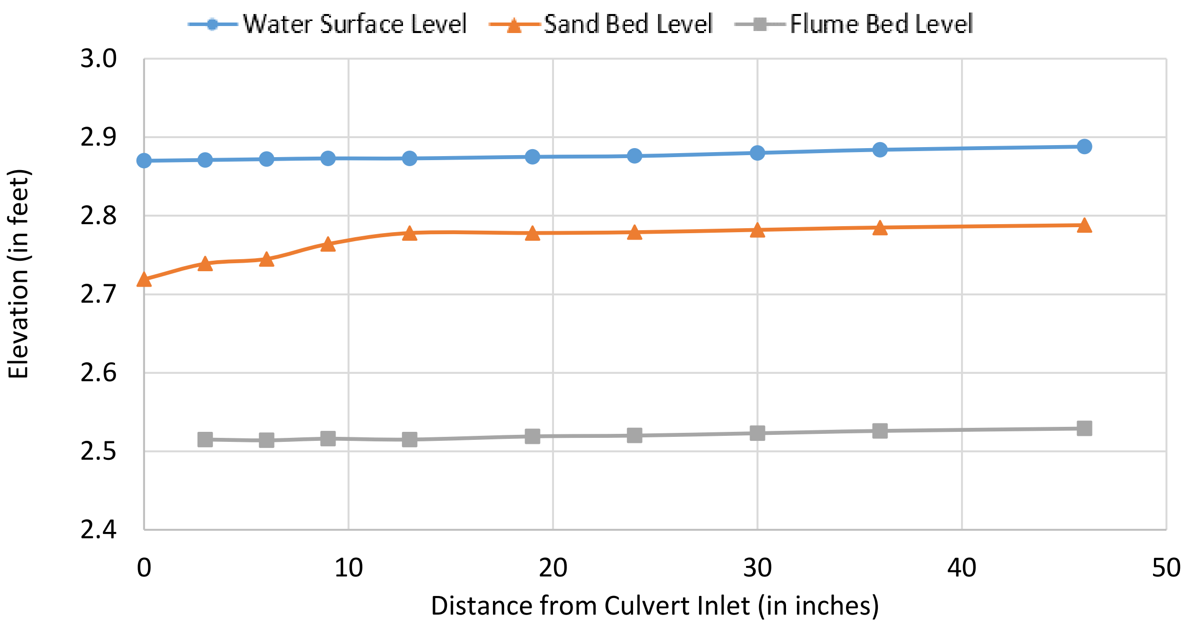


Figure 5.19: Upstream Flow and Bed Profile at Lower Flow for the Soil Saver Wall with Square Notch

For low flow, the upstream profile of the water and bed surface is presented in Figure 5.19. The average depth of the flow is 0.14 ft. The flow velocity for this test was 1.05 ft/sec and the discharge was 0.137 ft^3/sec.

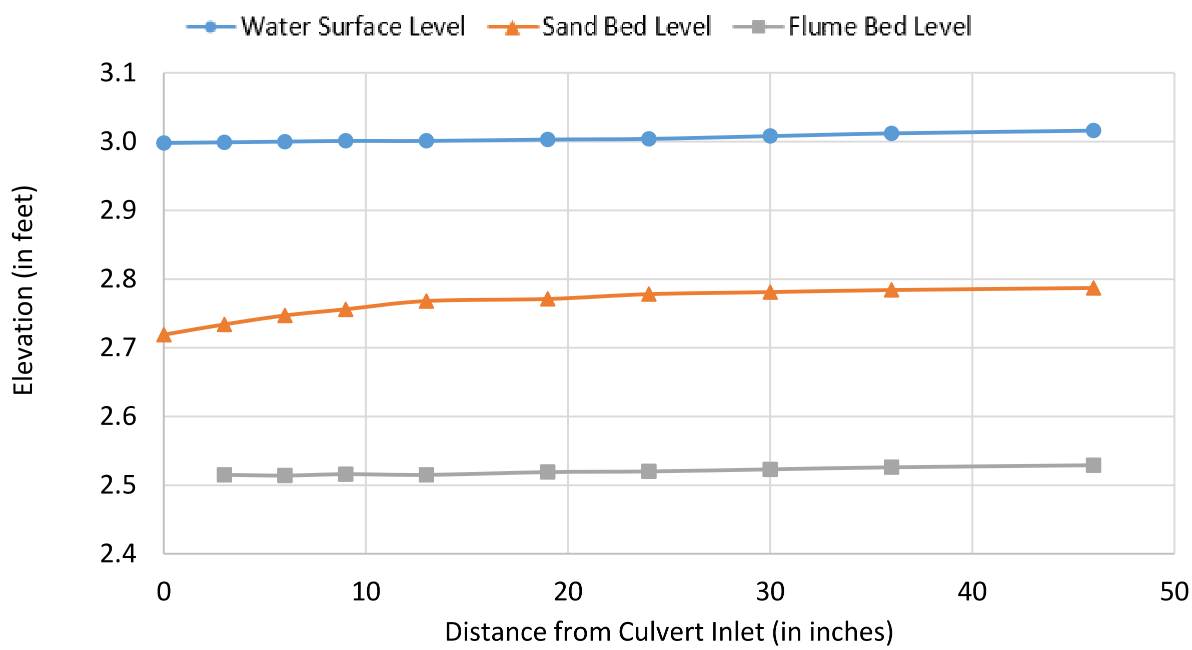


Figure 5.20: Upstream Flow and Bed Profile of the Higher Flow of Soil Saver Wall with Square Notch

For high flow, the upstream profile of the water and bed surface is presented in Figure 5.20. The average depth of the flow is 2.75 inches. The flow velocity for this test was 0.809 ft/sec and the discharge was 0.247 ft^3/sec.

5.6.3 Culvert with V-Notch

Two tests were conducted for different discharges for the soil saver wall with a V-notch. The supply velocity was held approximately constant for this set of tests, and only the water depth was changed. For these tests, the headcutting developed in a pattern that was considerably different from the patterns observed for the uniform depth soil saver wall and the square notch. The upstream bed also had a higher elevation than the previous two sets of tests. Figure 5.21 shows the intermediate flow and Figure 5.22 shows the low flow.

Figure 5.21: Photographs of Headcutting by Intermediate Flow for Soil Saver Wall with V-Notch

Figure 5.22: Photographs for Headcutting by Lower Flow for Soil Saver Wall with V-Notch

The previous photographs show that the scour pattern forms in two triangles with greater scour at the sides and less scour in the middle. Also, the depth of scour increases toward the ends of the soil saver wall and the depth is relatively shallow at the middle. An area of local scour existed at the middle due to the V-notch and was not propagated beyond its scour line.

For the lower flow condition, the upstream profile of the water and bed surface is presented in Figure 5.23. The average depth of the flow is 1.07 inches. The flow velocity for this test was 1.14 ft/sec and the discharge was 0.136 ft^3/sec.

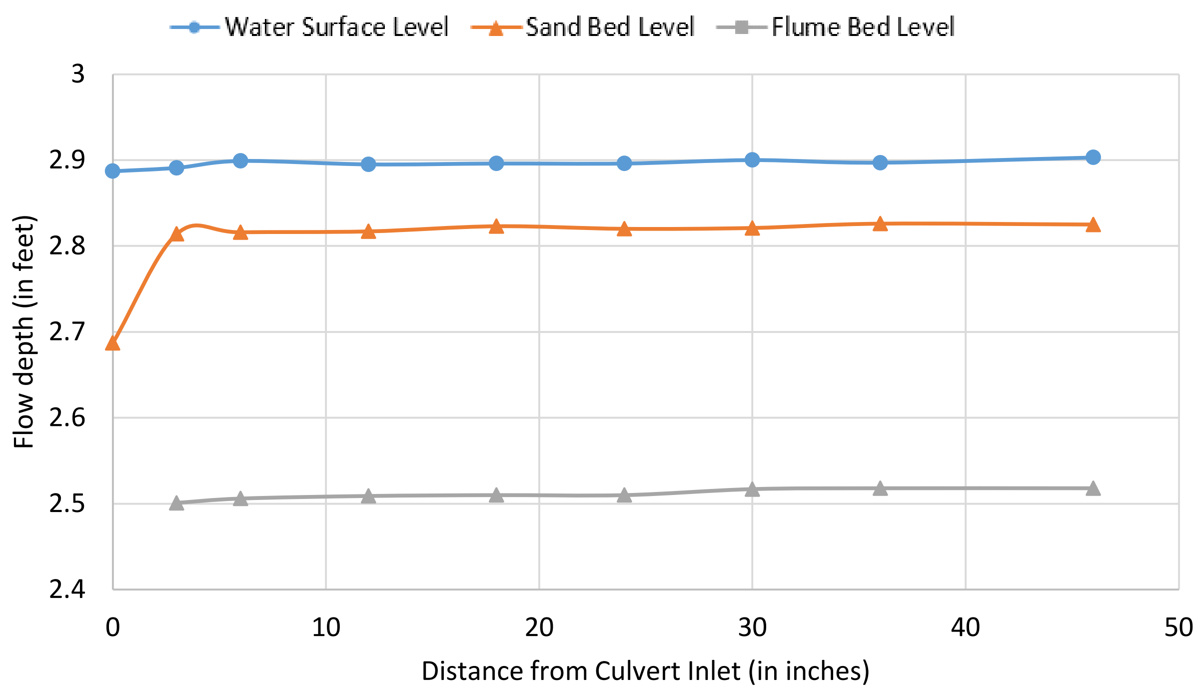


Figure 5.23: Upstream Flow and Bed Profile of the Lower Flow of Soil Saver Wall with V-Notch

For the intermediate flow condition, the upstream profile of the water and bed surface is presented in Figure 5.24. The average depth of the flow is 1.41 inches. The flow velocity for this test was 1.160 ft/sec and the discharge was 0.181 ft^3/sec.

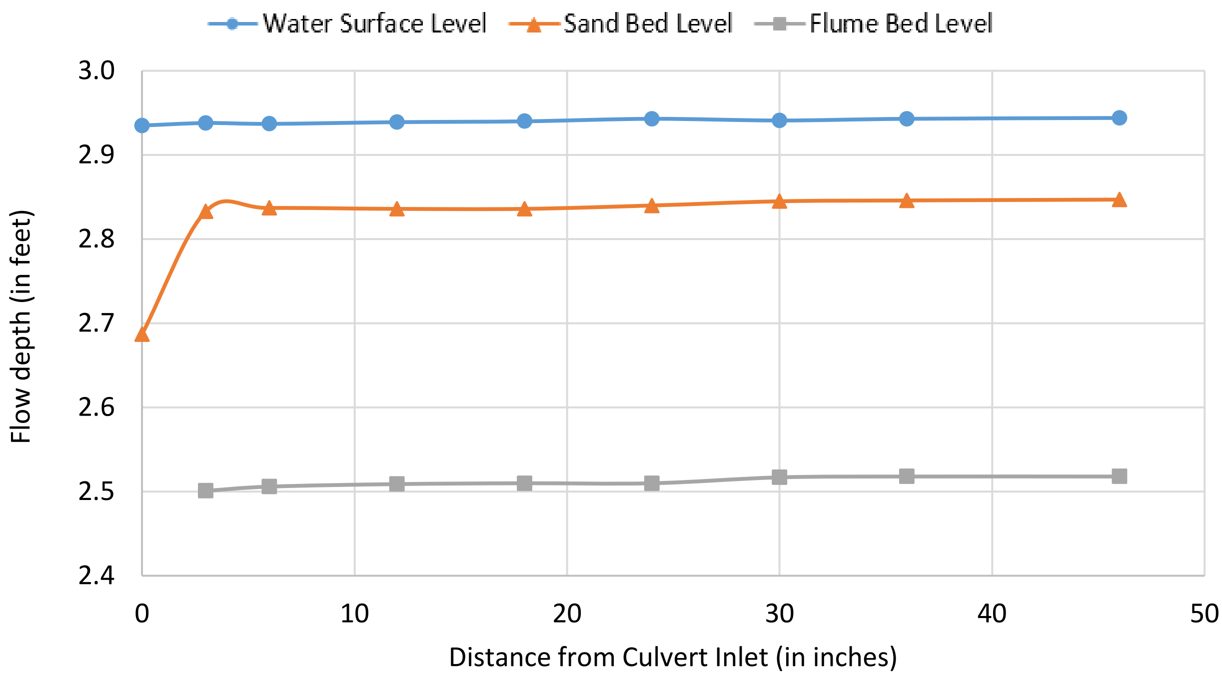


Figure 5.24: Upstream Flow and Bed Profile for the Intermediate Flow of Soil Saver Wall with V-Notch

5.7 Results Discussion

For all seven tests, bed scour can be seen just upstream of the soil saver wall. Although the shape and extent were different for each type of soil saver wall, the unique finding was there was less scour upstream of the middle of the soil saver wall and the extent of scour was greatest almost one-quarter of the distance from the sides of the flume. The maximum distance scour propagated for the square notch was 10 inches, which is equivalent to 20 ft. However the scour depth was very shallow at that distance. The most severe scour occurred upstream of the soil saver wall one-quarter distance from the boundary. At this location the depth of the scour was below the culvert level. Based on these results, a cutoff wall would be necessary to prevent piping erosion beneath the culvert.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

This study contains a summary of the current state of practice with respect to box culverts and aquatic organism passage (AOP), and a discussion of preliminary research to find an efficient and cost effective alternative or improvement to the soil saver wall that better facilitates AOP. Several alternatives were identified or evaluated through the literature review, the state DOT survey, and flume testing at the KU Water Resources Laboratory.

6.1.1 Promoting AOP for Stream Crossings

Stream simulation is widely considered to be the current best practice for AOP at box culverts according to FHWA HEC 26 (Kilgore et al., 2010), as well as several state transportation officials surveyed for this study. Roughened channels are another popular and effective option, and this method is currently used by a number of states. Baffles, or alternating baffles, are used by several states and could be an effective option for promoting AOP. Baffles are also sometimes used in conjunction with roughened channels.

6.1.2 Effectiveness of Drop Inlets

Most state Departments of Transportation prefer soil saver walls for erosion control because they are hydraulically efficient and are effective in reducing upstream scour. KDOT's preference for a soil saver wall in the inlet of the RCB culvert is consistent with DOT practices in the United States. Based on the survey of those states that recommend and use the RCB, a number of states use soil saver wall-type structures to prevent headcutting, although these features have different names. Examples of structures used include vertical concrete walls, gabion walls as an upstream weirs, and stone masonry upstream walls. Some states create a drop inlet with sloping upstream riprap instead of a vertical drop.

Fifteen site visits were carried out to determine the existing condition of soil saver walls in Kansas. All of the soil saver walls were functioning well as they retained the upstream soil and there was either a small amount of local scour or no scour at all. Moreover, the hydraulic efficiency is improved by the soil saver wall as it controls the flow upstream. Therefore, soil saver walls enhance the hydraulic performance of the RCB culverts.

6.1.3 Flume Testing of Soil Saver Wall Modifications for Enhancement of AOP

The authors built models of several prototype culverts and tested them in the flume at the KU Water Resources Laboratory. It was observed that headcutting for the culverts with the uniform depth soil saver wall, soil saver wall with V-notch, and soil saver wall with a square notch were almost equal, however, the pattern of headcutting was different depending on the type of barrier as well as amount of flow. From these tests it was observed that for higher flows, headcutting was more apparent upstream and was deeper near the soil saver wall than for lower flows. Also, the local scour was highest immediately upstream of the wall and approximately one-quarter of the distance from the side boundary to the center of the flume. For the V-notch and square notch flume tests, only local scour was observed due to the notch. The local scour was within the boundary of the headcutting area. While the V-notch resulted in slightly higher local scour for high flows, it also formed a soil ramp on the apron of the culvert during low flow conditions which would appear to be more favorable for AOP.

6.2 Recommendations

This report contains the results of a preliminary study to identify possible alternatives or modifications to the existing soil saver wall that could be implemented to make culverts more conducive to AOP. This report recommends the notched soil saver wall on a preliminary basis as a practical alternative, with the V-notch being the more promising candidate.

Additional flume study to quantitatively evaluate the hydraulic efficiency of the V-notch soil saver wall is recommended. The culvert would be modified to include a lid as well as a simulated roadway. More detailed laboratory experiments are recommended on the selected soil saver wall geometry to develop hydraulic rating curves for this type of culvert. Specifically, this would involve testing the V-notch soil saver walls for a range of geometries, flows, and tailwater elevations. The geometric variables would include notch depth, soil saver wall depth, culvert dimensions (height, width, wing wall configuration), as well as number of barrels. Dimensionless geometric variables would be identified to incorporate all of the geometric parameters. The bottom of the notch would be at the elevation of the bottom of the culvert at the inlet. Froude number similarity would be used to set the range of flows and velocities corresponding to typical prototype Kansas culverts with soil saver walls. Either the 1-ft or the 2.5-ft-wide flume would be used to conduct the tests. Coordination with the appropriate regulatory agencies is also recommended to ensure that the tested designs have the potential to meet regulatory requirements.

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