Design and Testing of an Ecological Invert Culvert

I-SERIES™

Scott D. Aston, PE - Contech
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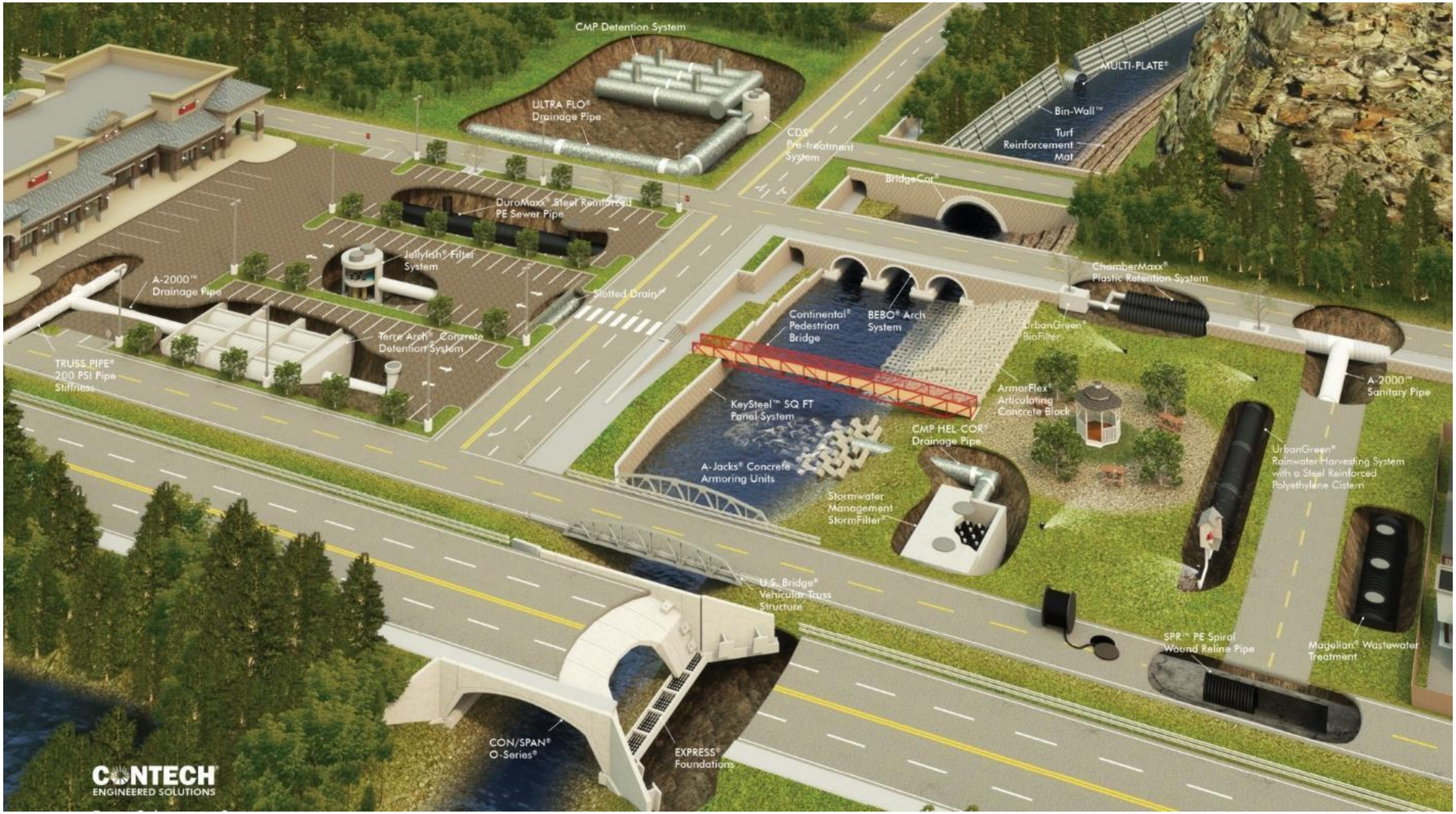
Research and testing performed by:
Miles B. Yaw – Colorado State University

PURDUE ROAD SCHOOL
EST. 1914
TRANSPORTATION CONFERENCE & EXPO

Contech Engineered Site Solutions



Bridges & Structures, Stormwater Management, Pipe, Erosion Control, Retaining Walls, Wastewater Treatment i-SERIES™

BridgeCor®

CON SPAN®
-SERIES®

EXPRESS™ Foundations

CONTECH®
STRUCTURAL PLATE

CON SPAN®
BRIDGE SYSTEMS

BEBO®
Arch Systems

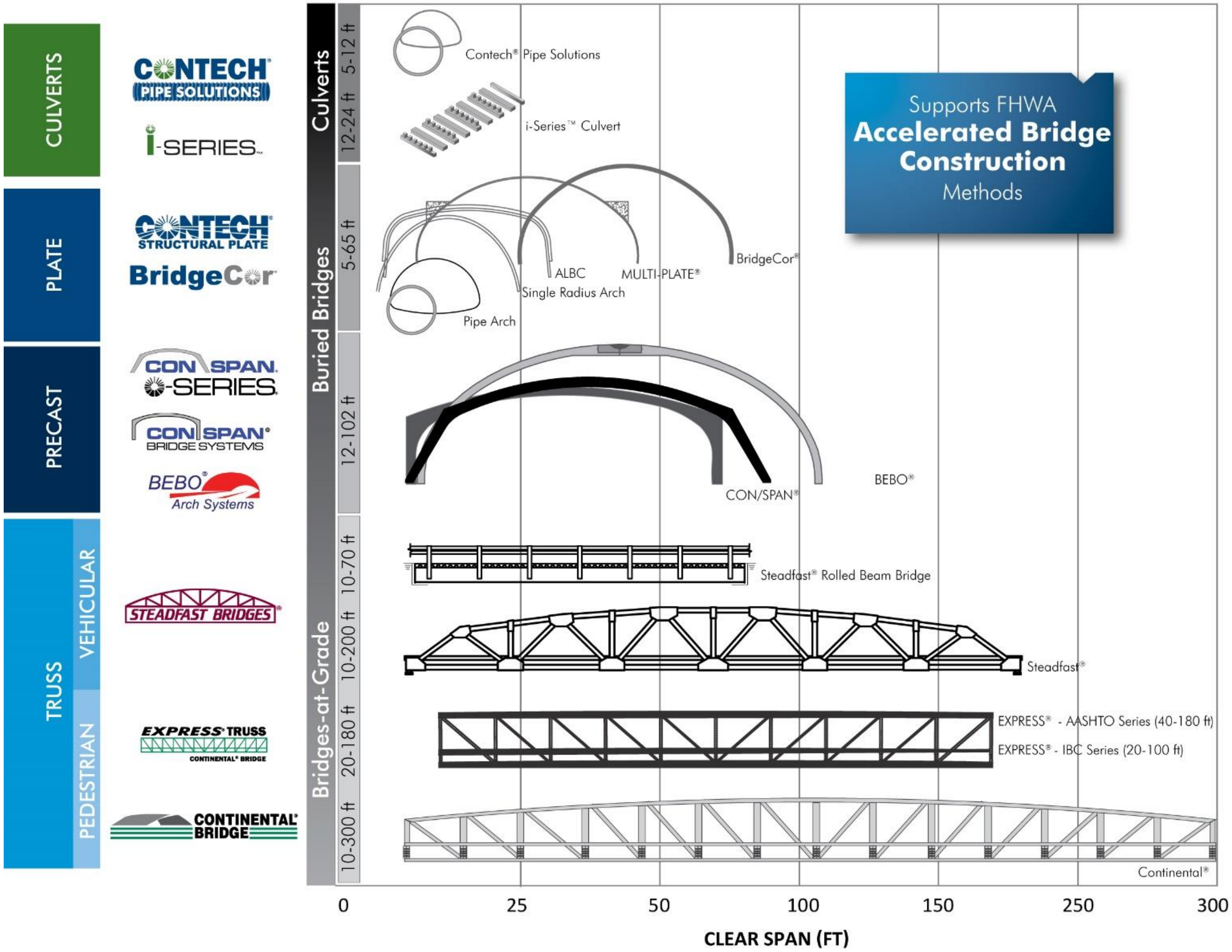
CONTINENTAL®
BRIDGE

EXPRESS™

STEADFAST BRIDGES®

CROSSINGS. CULVERTS. BRIDGES. CONTECH.

CLEAR SPAN BRIDGES

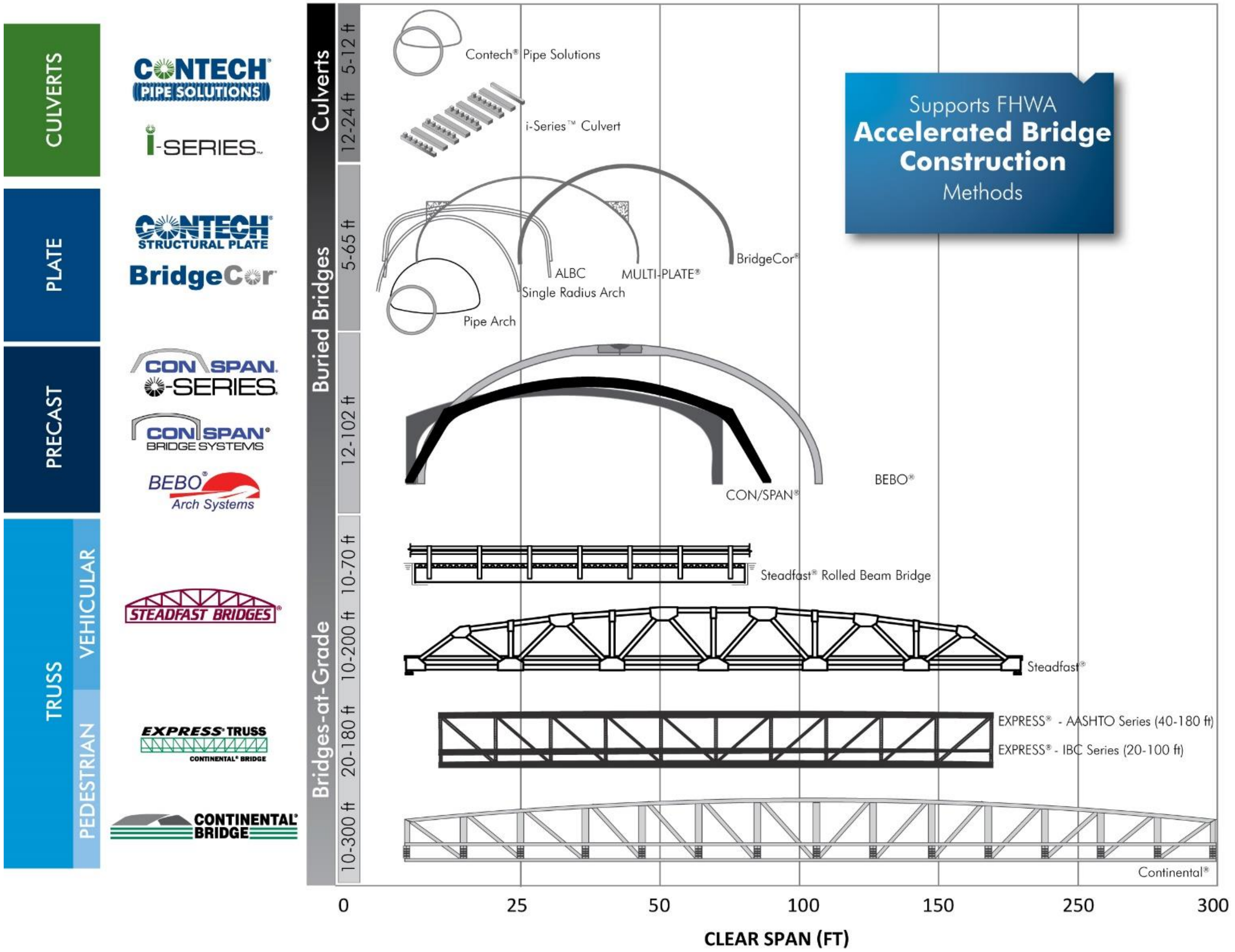


Supports FHWA **Accelerated Bridge Construction** Methods

Porter County Bridge #130

CROSSINGS. CULVERTS. BRIDGES. CONTECH.

CLEAR SPAN BRIDGES



Supports FHWA **Accelerated Bridge Construction** Methods

Accelerated Bridge Program

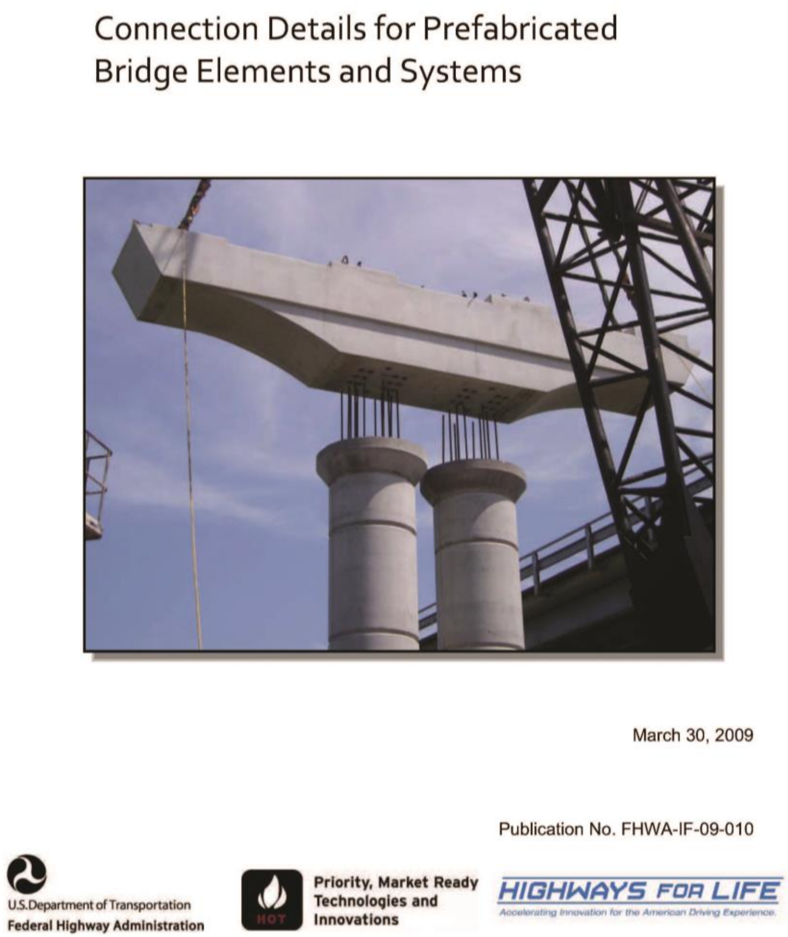
U.S. Department of Transportation
Federal Highway Administration

Accelerated Bridge Construction (ABC):

- ABC is bridge construction that uses innovative planning, design, materials, and construction methods in a safe and cost-effective manner to reduce the onsite construction time that occurs when building new bridges or replacing and rehabilitating existing bridges

Prefabricated Bridge Elements and Systems

- PBES are structural components of a bridge that are built offsite, or near-site of a bridge and include features that reduce the onsite construction time and the mobility impact time that occurs when building new bridges or rehabilitating or replacing existing bridges relative to conventional construction methods.



Connection Details for Prefabricated Bridge Elements and Systems

March 30, 2009

Publication No. FHWA-IF-09-010

U.S. Department of Transportation
Federal Highway Administration

Priority, Market Ready Technologies and Innovations

HIGHWAYS FOR LIFE
Accelerating Innovation for the American Driving Experience.

Figure 2.4.3-1 depicts a proprietary arch system call the Con/Span® Bridge System. This system, including the arch elements, the spandrel walls, the wingwalls and the footings, can be completely made with precast concrete elements. The connections shown in Figure 2.4.3-1 are described in the following sections.

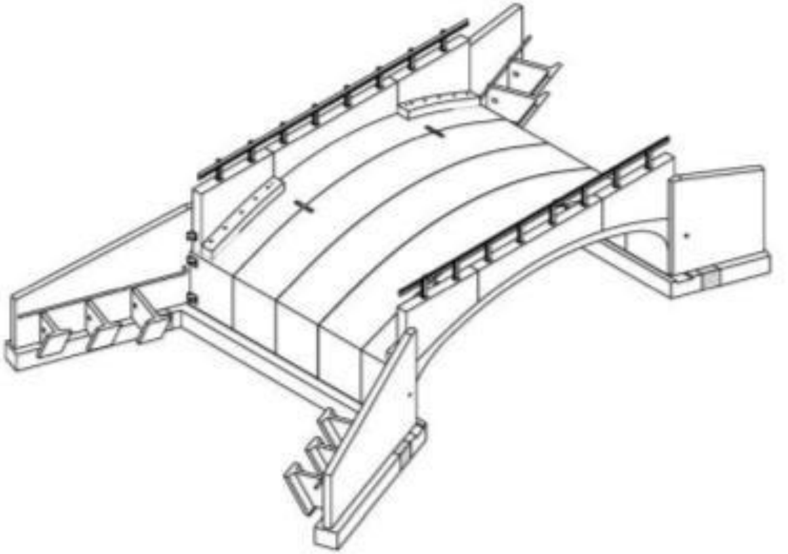


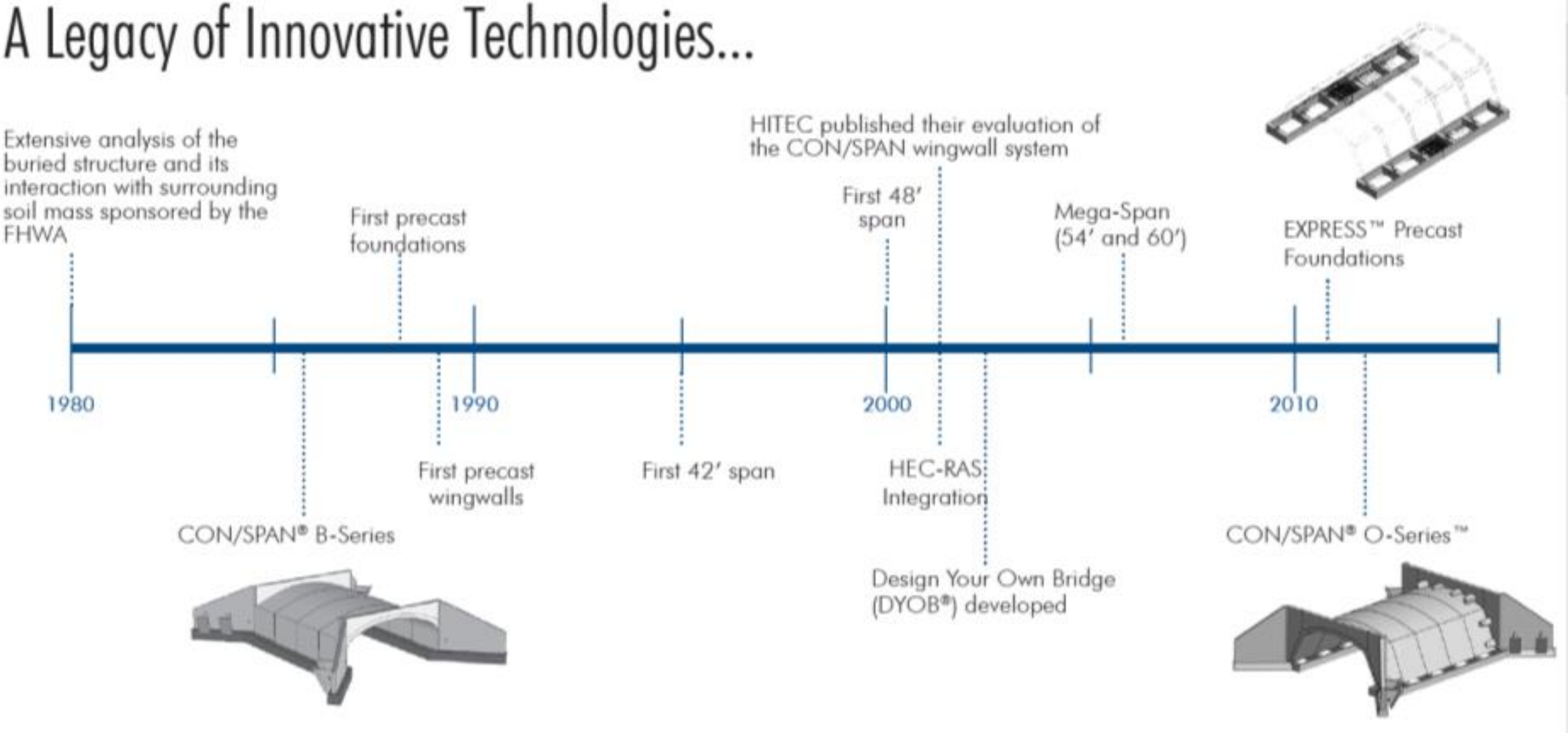
Figure 2.4.3-1 Con/Span® Bridge System

Page 2-181

"Prefabricated elements of a bridge produced off-site can be assembled quickly, and can reduce design time and cost, minimize forming, minimize lane closure time and/or possibly eliminate the need for a temporary bridge."

CON/SPAN® O-SERIES™

A Legacy of Innovative Technologies...



1980

Extensive analysis of the buried structure and its interaction with surrounding soil mass sponsored by the FHWA

CON/SPAN® B-Series

First precast foundations

First precast wingwalls

1990

First 42′ span

First 48′ span

2000

HITEC published their evaluation of the CON/SPAN wingwall system

HEC-RAS Integration

Design Your Own Bridge (DYOB®) developed

Mega-Span (54′ and 60′)

2010

EXPRESS™ Precast Foundations

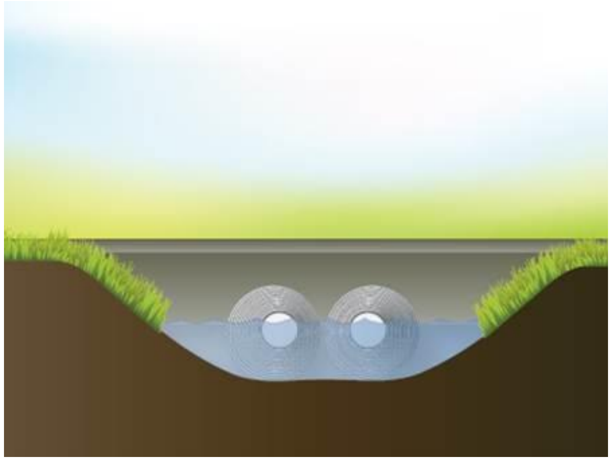
CON/SPAN® O-Series™

S.R. 9 Shelbyville, IN

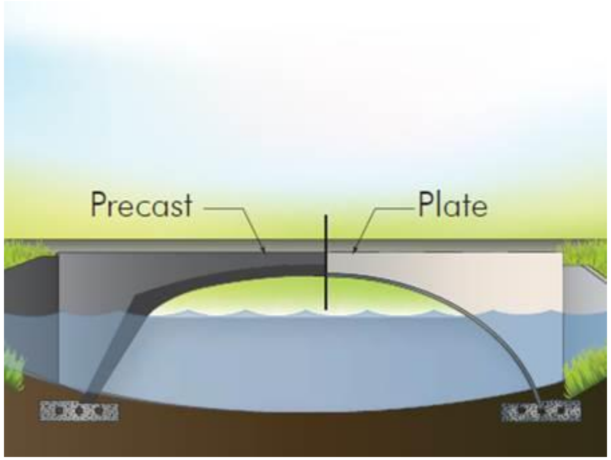
Washington Street Bridge, Vincennes IN

CONSPAN O-1485 Temple, Texas

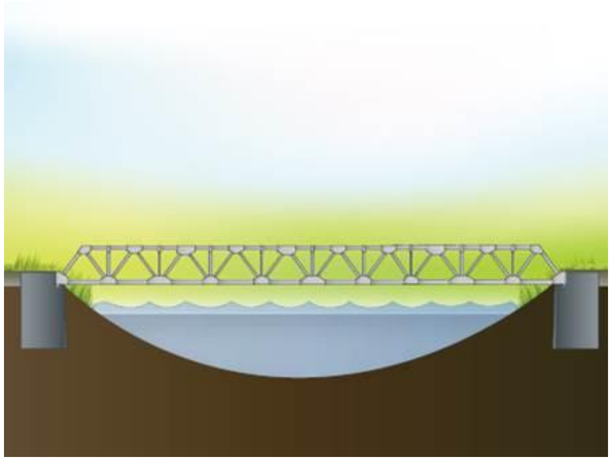
CULVERTS



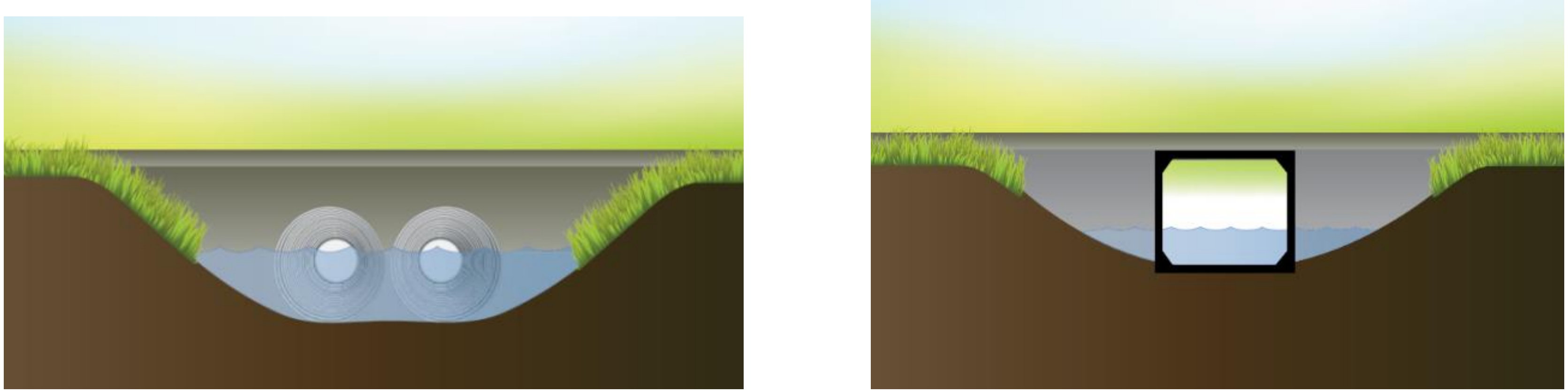
BURIED BRIDGES



BRIDGE AT-GRADE



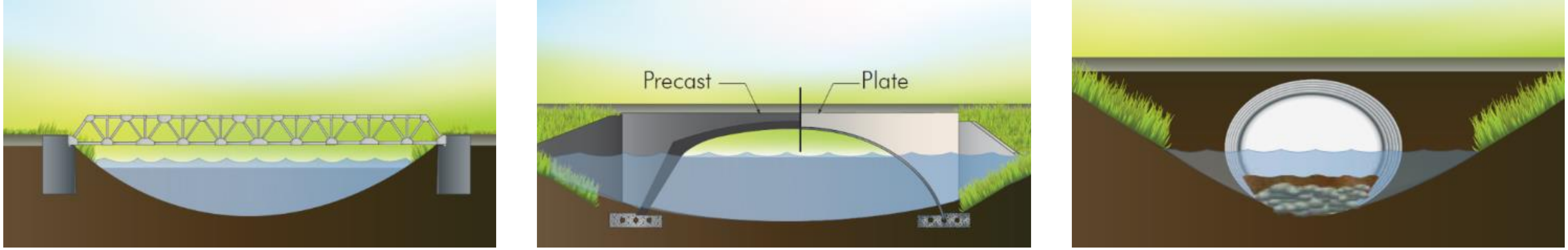
Traditional Culvert



- Traditional culverts are typically designed to pass hydraulic flows without consideration for stream ecology impacts

Hydraulically Designed Traditional Culverts

Stream Ecology Considerations



- Stream ecology
- Stream biology
- Fish passage
- Aquatic organism passage (AOP)

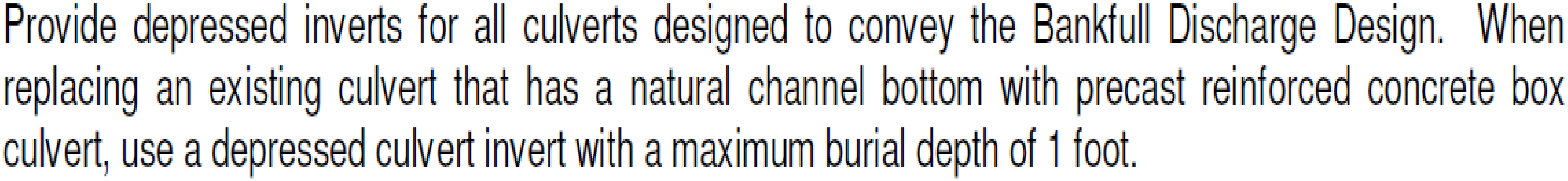
<u>Stream ecology:</u>

- Profile continuity
- Hydraulic diversity
- Sediment transport continuity
- Low flow continuity
- Margin habitat
- Bed Gradation continuity
- Hyporheic zone connectivity

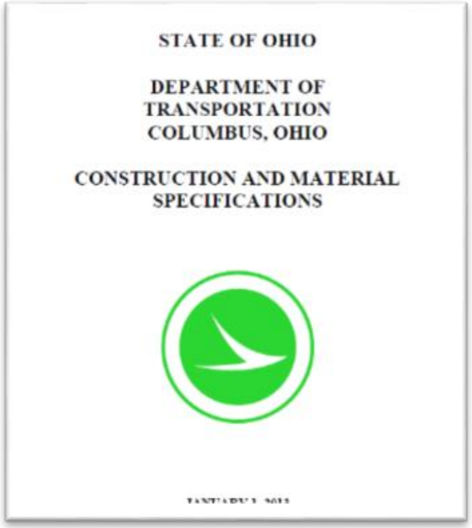
L&D Manual updates made on a quarterly basis.

Letter summarizing updates is distributed to all registered with office of hydraulics.

Changes made in 2015 to section 1105.2.2 removing the following language:



Provide depressed inverts for all culverts designed to convey the Bankfull Discharge Design. When replacing an existing culvert that has a natural channel bottom with precast reinforced concrete box culvert, use a depressed culvert invert with a maximum burial depth of 1 foot.



STATE OF OHIO

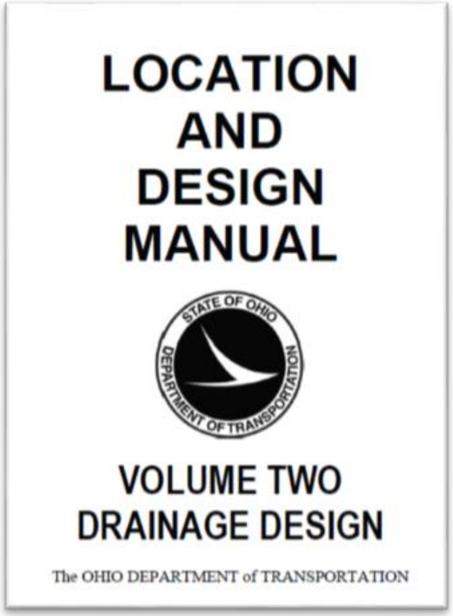
DEPARTMENT OF
TRANSPORTATION
COLUMBUS, OHIO

CONSTRUCTION AND MATERIAL
SPECIFICATIONS

Specifications and Design Procedures

Ohio Department of Transportation (ODOT)

CMS Manual and L&D Manual



LOCATION
AND
DESIGN
MANUAL

VOLUME TWO
DRAINAGE DESIGN

The OHIO DEPARTMENT of TRANSPORTATION

COLORADO STATE UNIVERSITY

Design & Development Challenge:

- Culvert with invert & open bottom
- Elements that promote sedimentation and retain material
- Service condition provides as many successful culvert design outcomes as possible (per Washington State Department of Fish and Wildlife)
    - Profile continuity
    - Hydraulic diversity
    - Sediment transport continuity
    - Low flow continuity
    - Margin Habitat
    - Bed Gradation Continuity
    - Hyporheic zone/connectivity
- Understand design limitations
    - (i.e. gradient, velocities, shear stress)

Foundation of Development

CULVERT
SEDIMENTATION

FISH
PASSAGE

- From HEC-26: “aquatic organisms in the stream are exposed to similar forces and stresses experienced by the streambed material. The design goal is to provide a stream crossing that has an equivalent effect, over a range of stream flows, on the streambed material within the culvert compared with the streambed material upstream and downstream of the culvert.”

Testing Program

Lit. Review

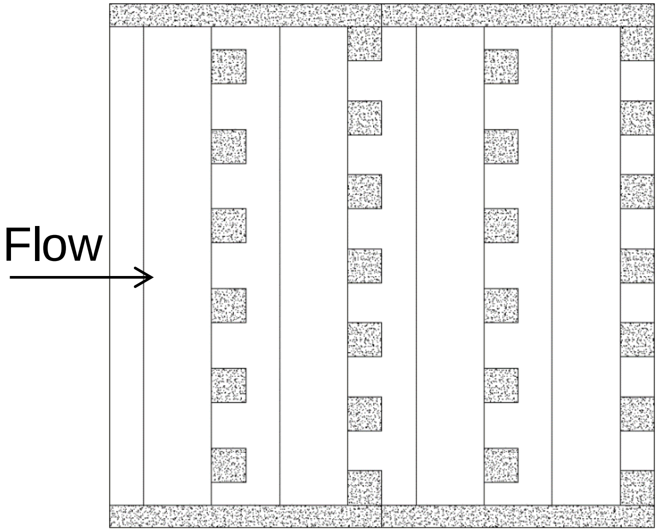
Scaled Testing

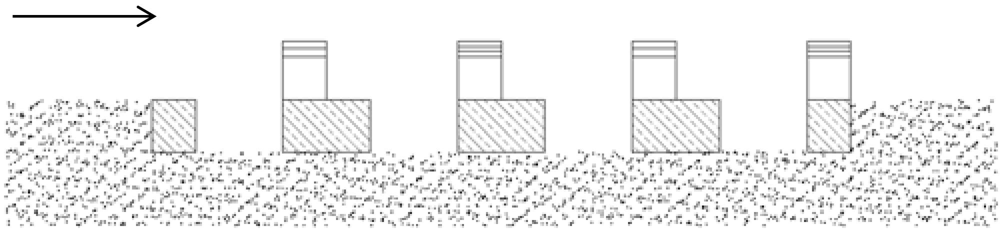
- 1:8 Froude scale
- Proof of concept
- Design refinement

Prototype Testing

- Full scale
- Unit width

Initial Design



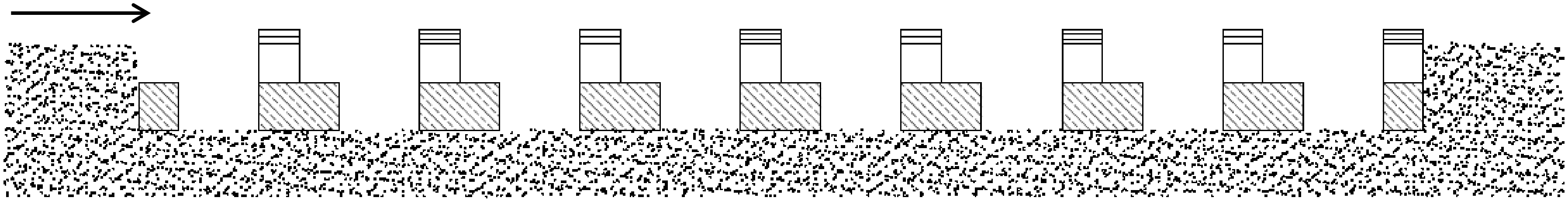


- Contech constraints
  - 50% bottom open area
  - 8-ft layable sections
  - 14” slat height
  - Baffles on leading edge

- Roughness element guidelines
  - Height ~10% of rise
  - Transverse spacing ~10% span
  - Long. spacing ~60-75% of rise

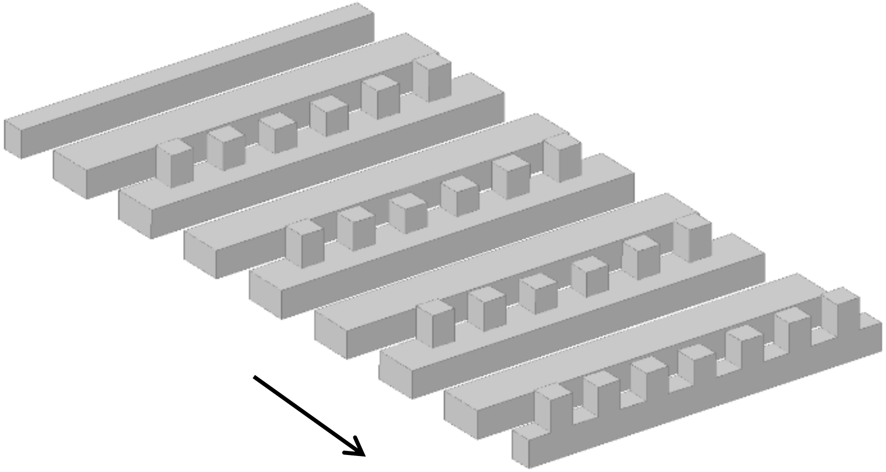
Initial Testing

Design Refinement

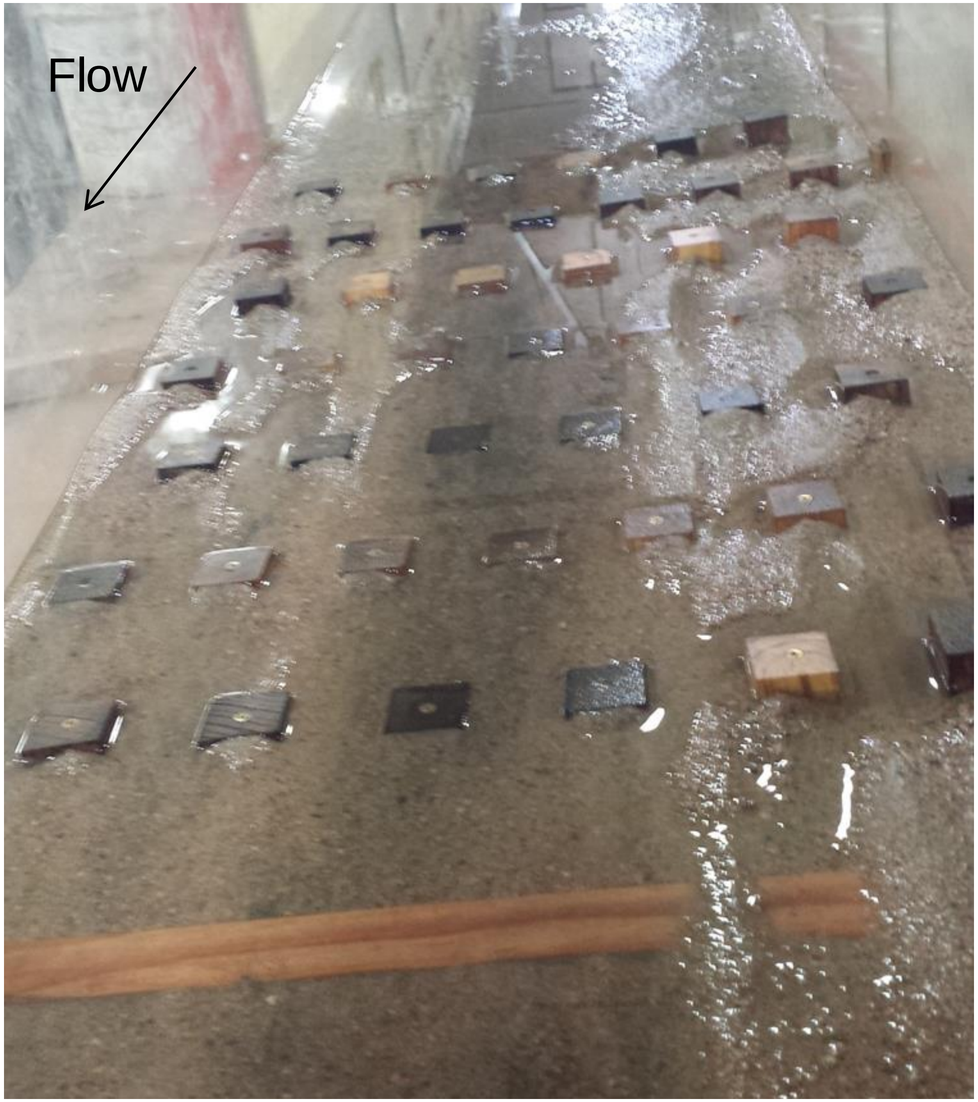


- Lowered invert elevation
- Extended test section
- Q=0.37-2.15 cfs (*66-389 cfs)*

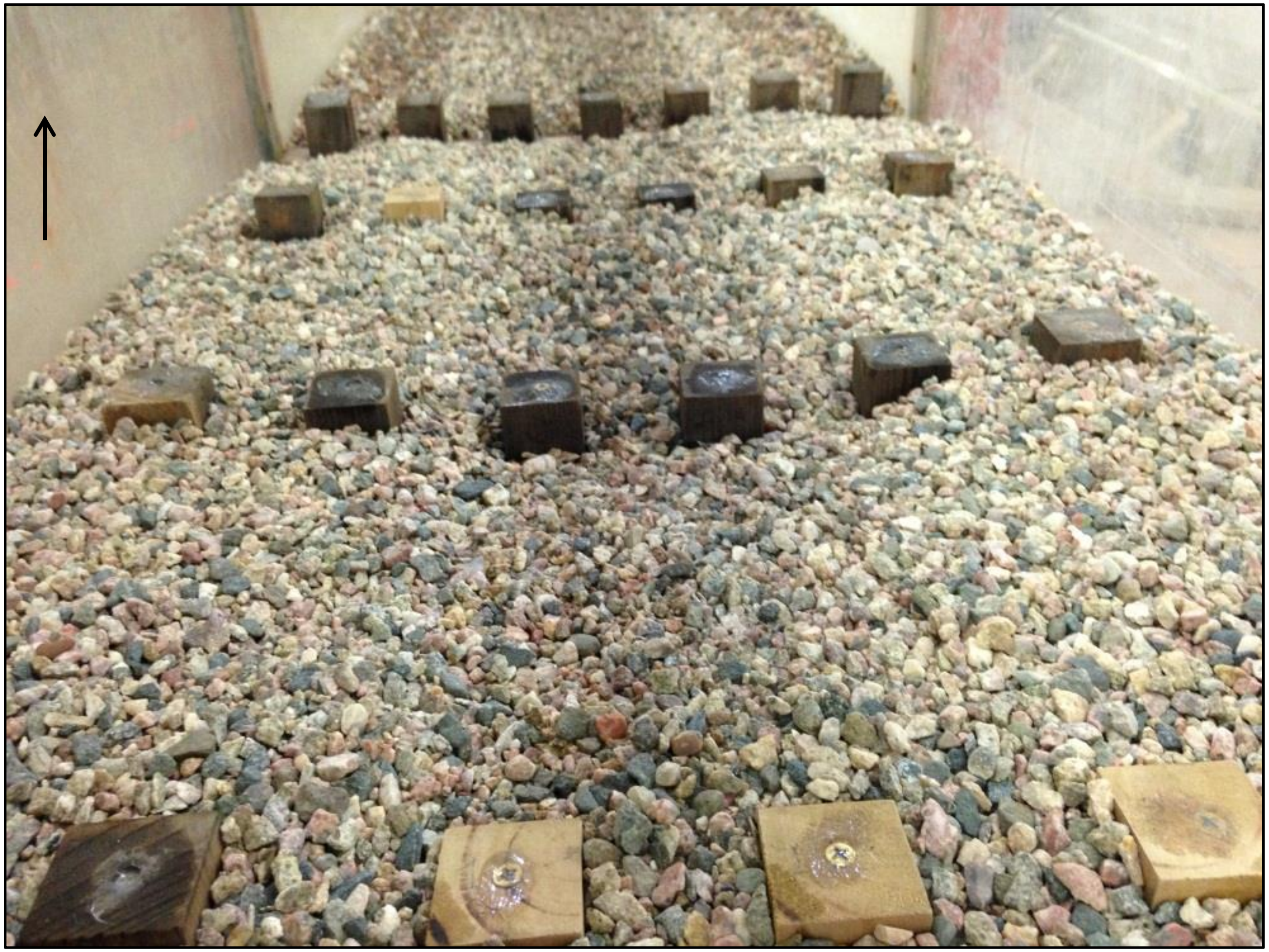
Final Scaled Model



Final Scaled Model

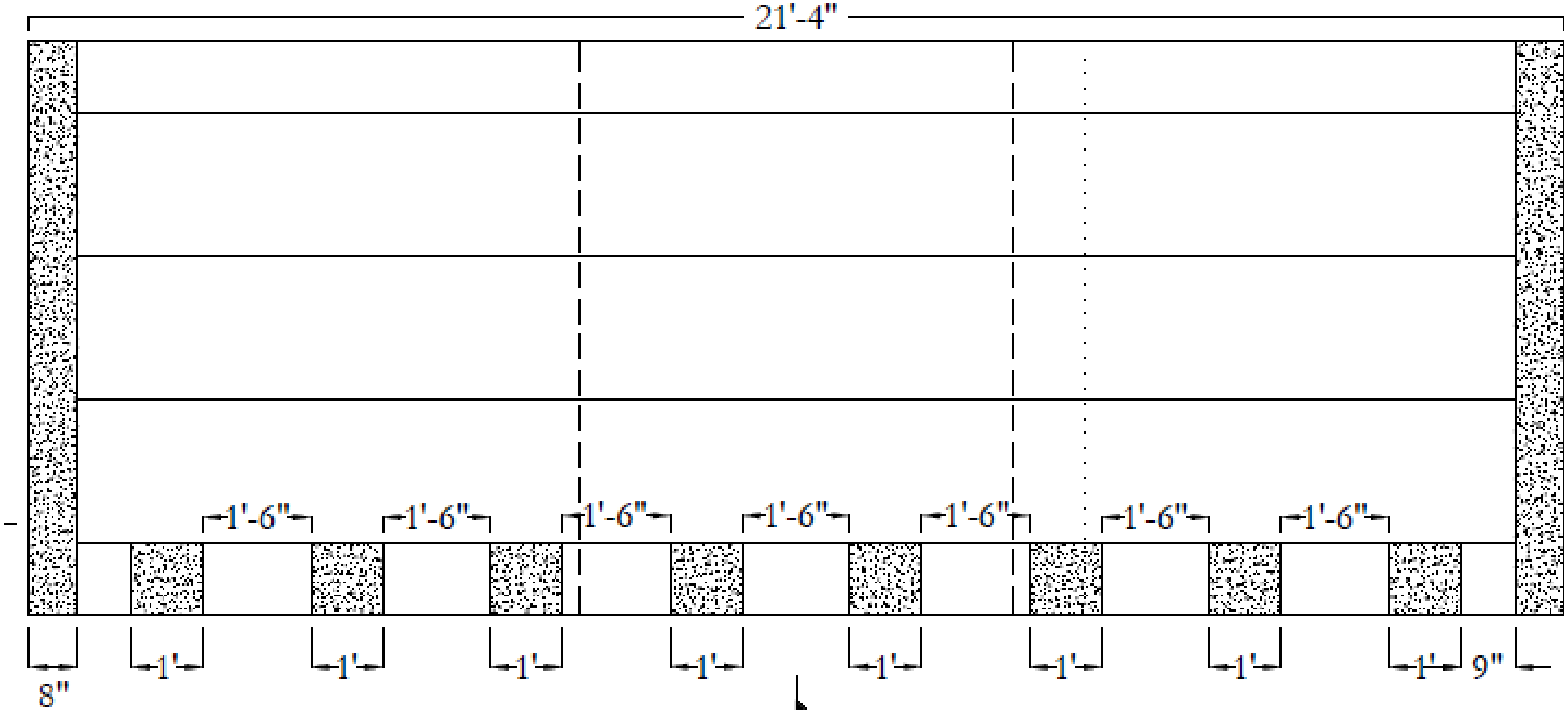


Final Scaled Model



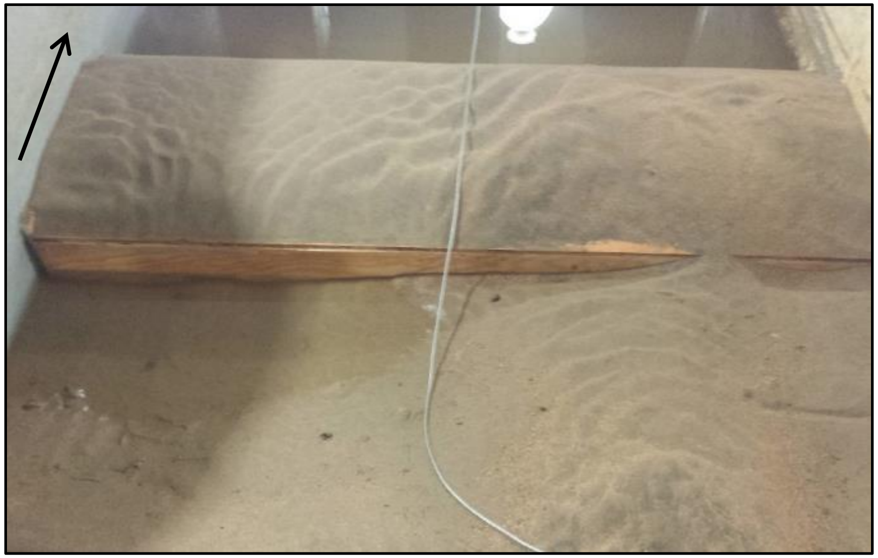
Full Scale Testing Program

- Knowledge gained from scaled testing applied to expected culvert sizes
- 12’, 14’, 16’, 20’ spans were laid out
- 6’ from the edge and middle of each were chosen for possible modeling in 6’ flume



12’ Middle Model

- Testing started with 12’ middle model
- Installed empty, filled with waves of sediment at ~6 cfs

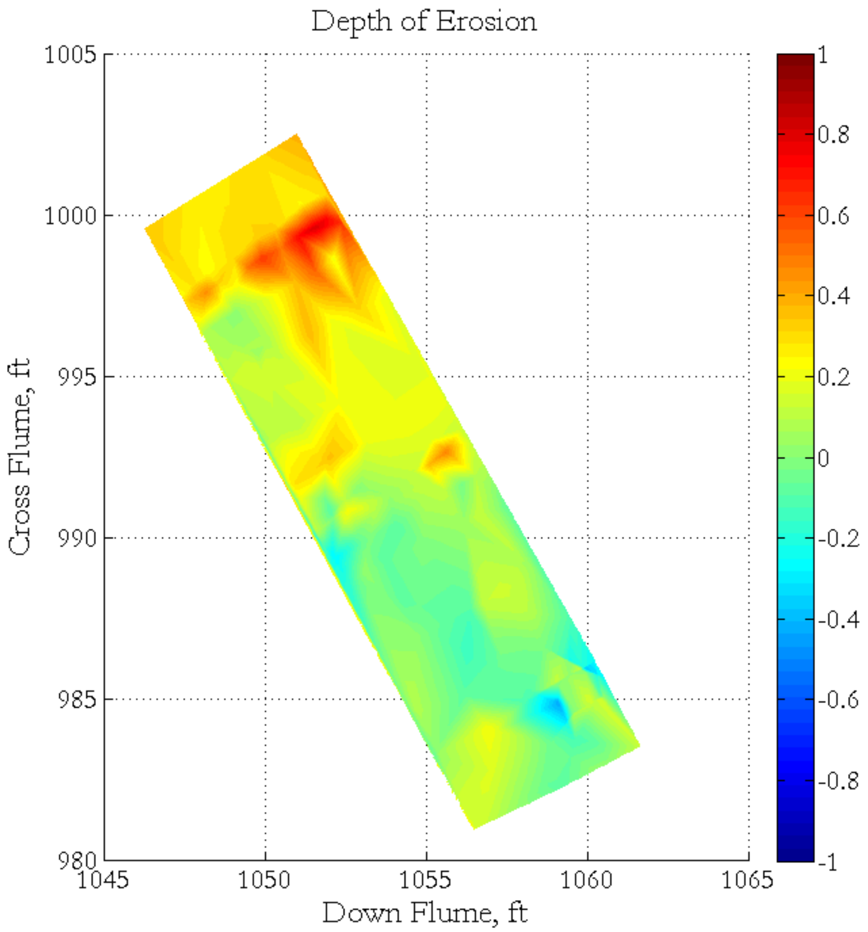


- Negative velocity near bed behind slats
- Zones of zero velocity behind roughness elements
- Velocity ~0.6 fps between roughness elements

12’ Middle Model

12’ Middle Model

- Tested at 5 unique discharges, up to 21.1 cfs at 1% slope
- Max shear stress: 1.86 psf

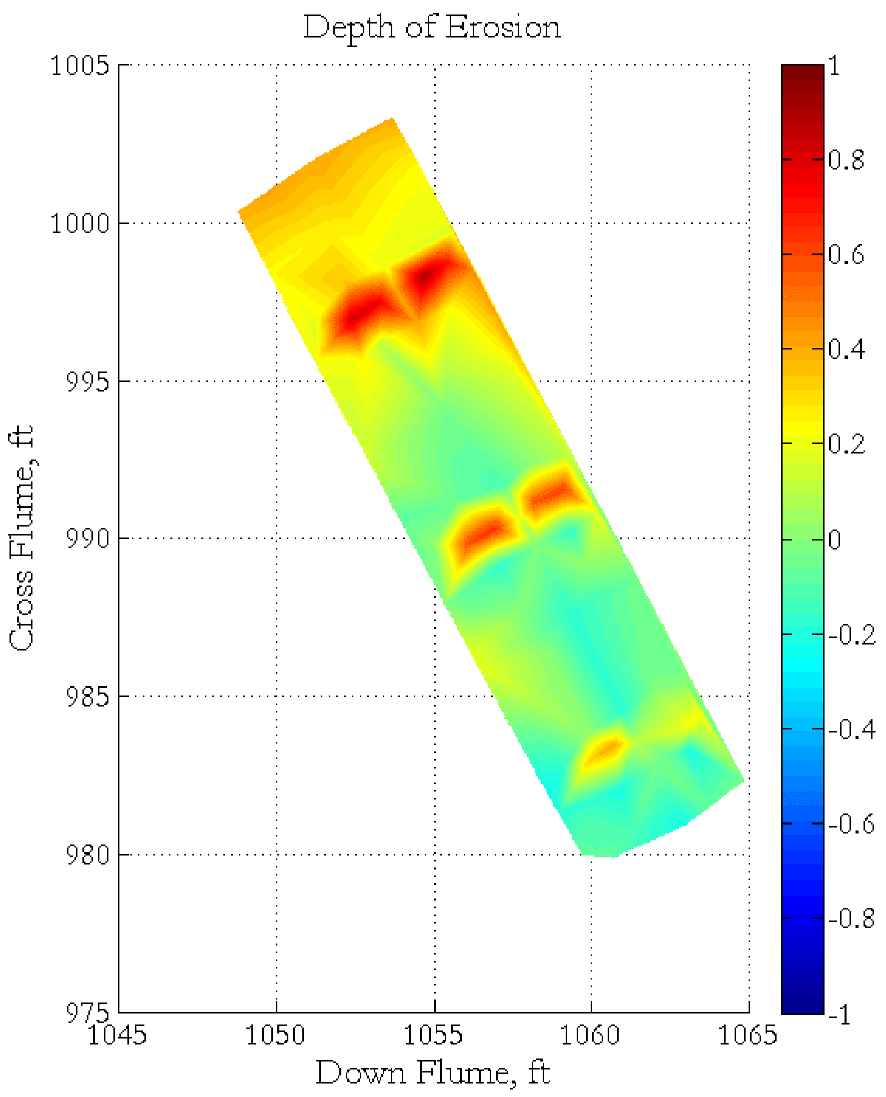


Total depth of erosion, in feet, at max shear stress

20’ Edge Model

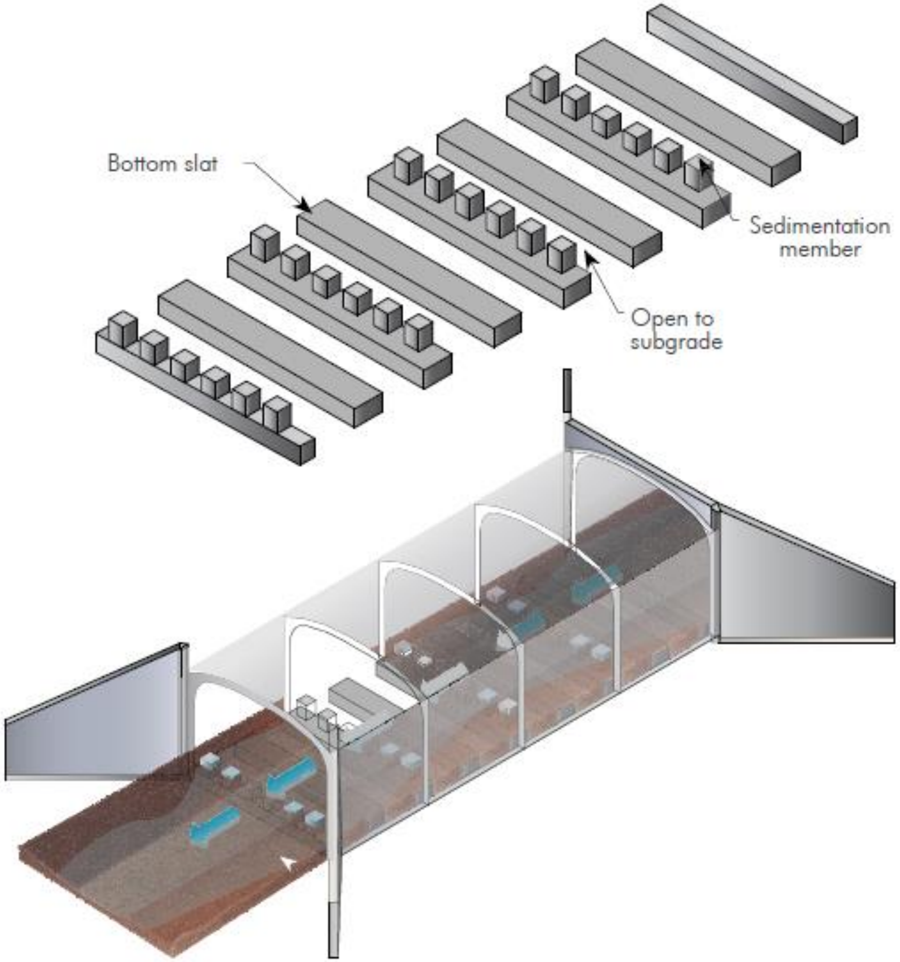
- 20’ edge model was tested next
- Tested under same 5 conditions as 12’ middle model
- Scour in front of roughness elements was deeper, performance was similar

20’ Edge Model



Test	Max Shear (psf)	Avg. Erosion (ft)
12’ Mid	1.86	0.14
Staggered	1.73	0.16
20’ Edge	1.82	0.12

i-Series Invert Technology



Culvert Performance Summary

Successful Culvert Design Outcomes*	FLOOD CONVEYANCE	FISH PASSAGE	PROFILE CONTINUITY	HYDRAULIC DIVERSITY	SEDIMENT TRANSPORT CONTINUITY	LOW FLOW CONTINUITY	MARGIN HABITAT	BED GRADATION CONTINUITY	DEBRIS TRANSPORT	CONNECTIVITY TO SUBGRADE (hyporheic zone)
i-Series™ Culvert	●	●	●	●	●	●	●	●	●	●
Traditional Culvert w/ Invert (may include buried invert)	●								●	

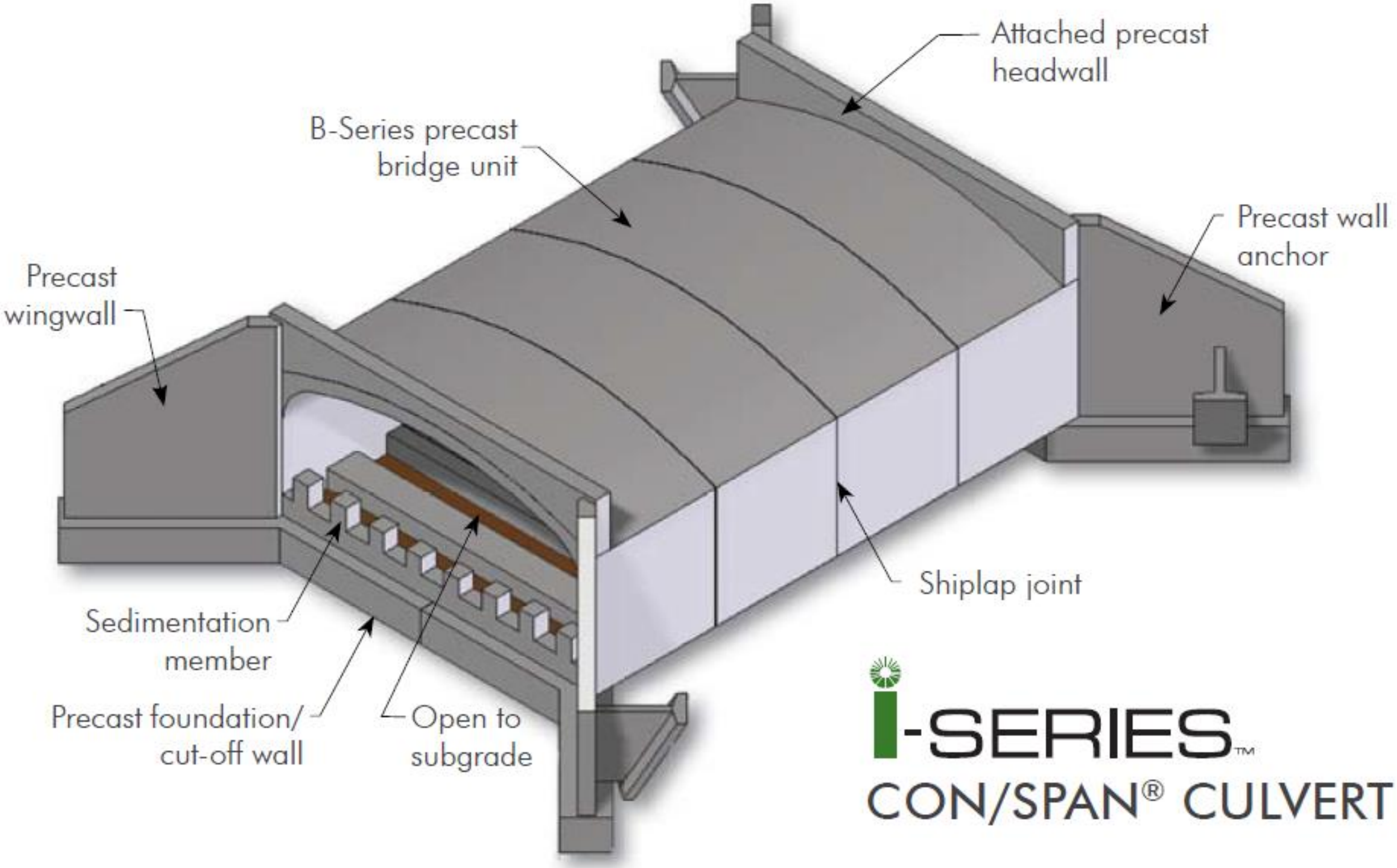
* Per the Washington Department of Fish & Wildlife

- This performance summary is based on extensive testing from Colorado State University.
- Comprehensive testing report available upon request.
- Bed gradation continuity can be achieved by manual filling of the culvert with natural bed sediments during installation.

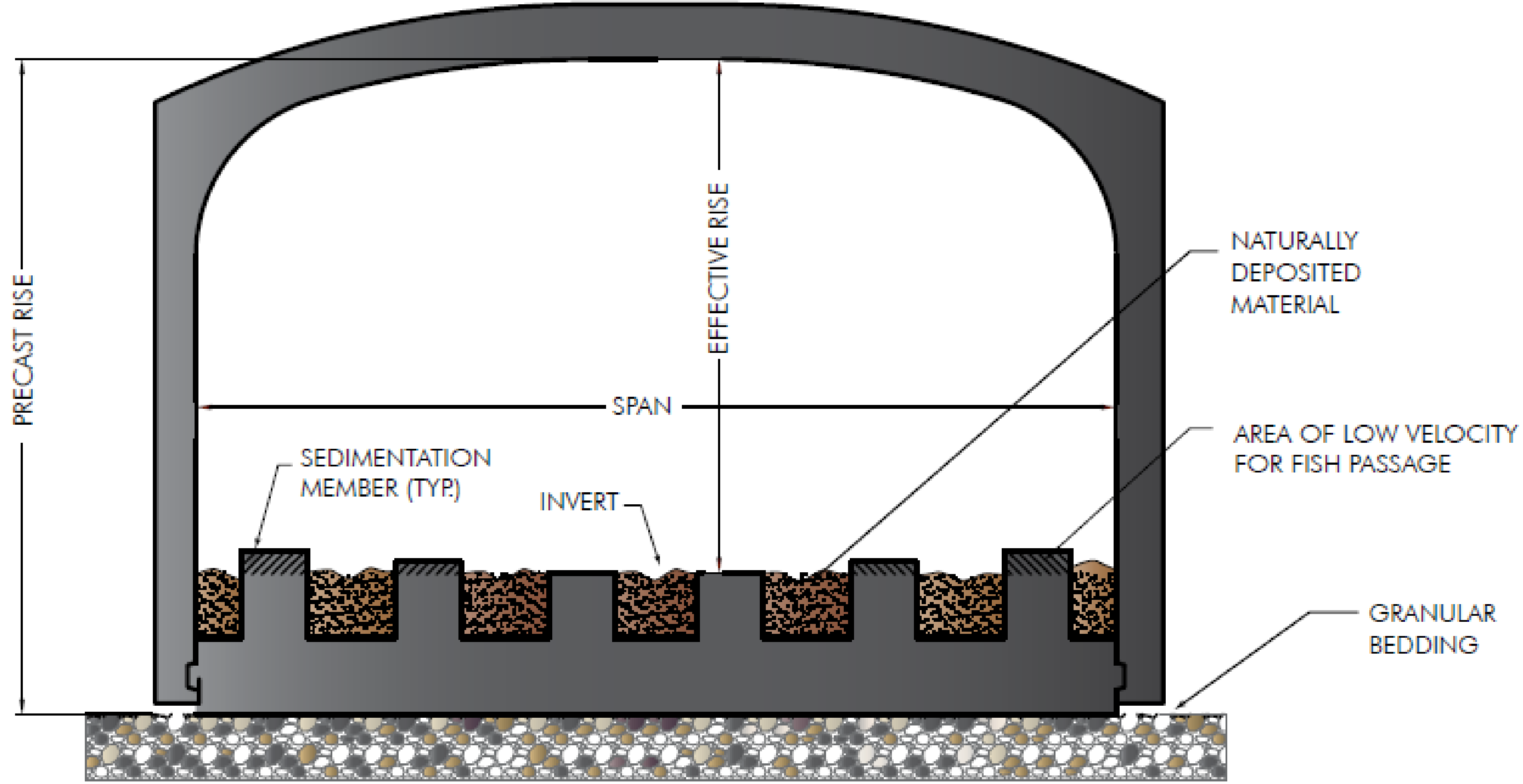
CONTECH® ENGINEERED SOLUTIONS

i-SERIES™ CON/SPAN® CULVERT

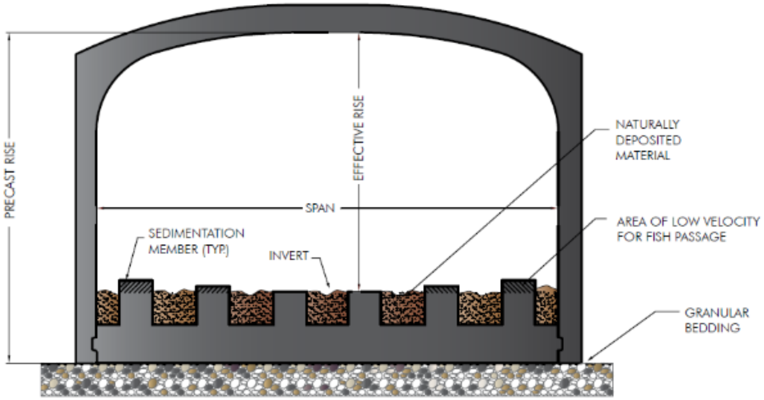
i-Series: Complete System

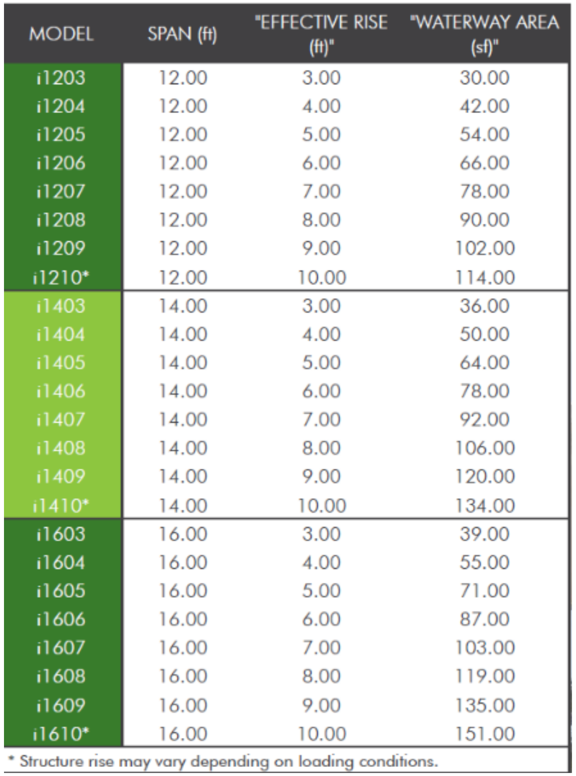


i-Series Functionality



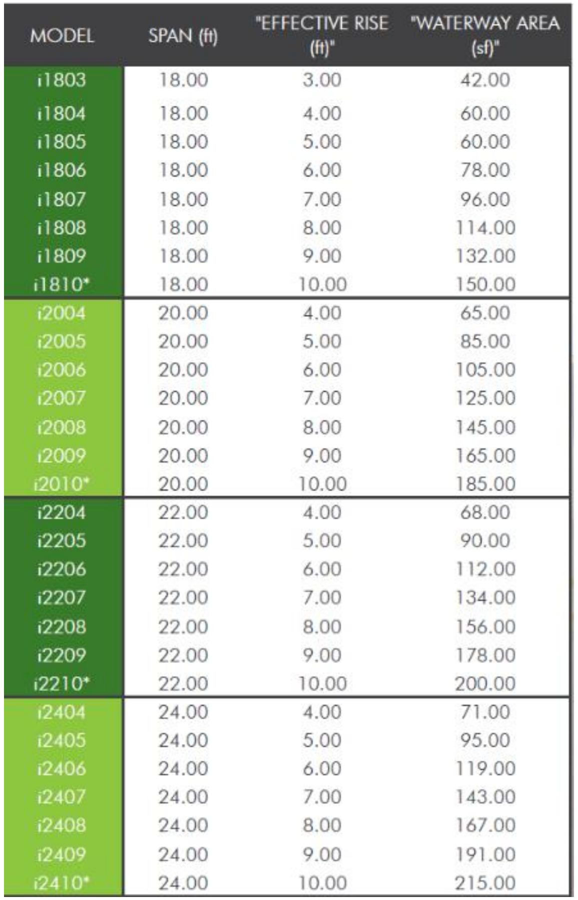
Size Ranges





MODEL	SPAN (ft)	"EFFECTIVE RISE (ft)"	"WATERWAY AREA (sf)"
i1203	12.00	3.00	30.00
i1204	12.00	4.00	42.00
i1205	12.00	5.00	54.00
i1206	12.00	6.00	66.00
i1207	12.00	7.00	78.00
i1208	12.00	8.00	90.00
i1209	12.00	9.00	102.00
i1210*	12.00	10.00	114.00
i1403	14.00	3.00	36.00
i1404	14.00	4.00	50.00
i1405	14.00	5.00	64.00
i1406	14.00	6.00	78.00
i1407	14.00	7.00	92.00
i1408	14.00	8.00	106.00
i1409	14.00	9.00	120.00
i1410*	14.00	10.00	134.00
i1603	16.00	3.00	39.00
i1604	16.00	4.00	55.00
i1605	16.00	5.00	71.00
i1606	16.00	6.00	87.00
i1607	16.00	7.00	103.00
i1608	16.00	8.00	119.00
i1609	16.00	9.00	135.00
i1610*	16.00	10.00	151.00

* Structure rise may vary depending on loading conditions.



MODEL	SPAN (ft)	"EFFECTIVE RISE (ft)"	"WATERWAY AREA (sf)"
i1803	18.00	3.00	42.00
i1804	18.00	4.00	60.00
i1805	18.00	5.00	60.00
i1806	18.00	6.00	78.00
i1807	18.00	7.00	96.00
i1808	18.00	8.00	114.00
i1809	18.00	9.00	132.00
i1810*	18.00	10.00	150.00
i2004	20.00	4.00	65.00
i2005	20.00	5.00	85.00
i2006	20.00	6.00	105.00
i2007	20.00	7.00	125.00
i2008	20.00	8.00	145.00
i2009	20.00	9.00	165.00
i2010*	20.00	10.00	185.00
i2204	22.00	4.00	68.00
i2205	22.00	5.00	90.00
i2206	22.00	6.00	112.00
i2207	22.00	7.00	134.00
i2208	22.00	8.00	156.00
i2209	22.00	9.00	178.00
i2210*	22.00	10.00	200.00
i2404	24.00	4.00	71.00
i2405	24.00	5.00	95.00
i2406	24.00	6.00	119.00
i2407	24.00	7.00	143.00
i2408	24.00	8.00	167.00
i2409	24.00	9.00	191.00
i2410*	24.00	10.00	215.00

Westfield, IN

Westfield, IN

Westfield, IN

I-SERIES

Westfield, IN

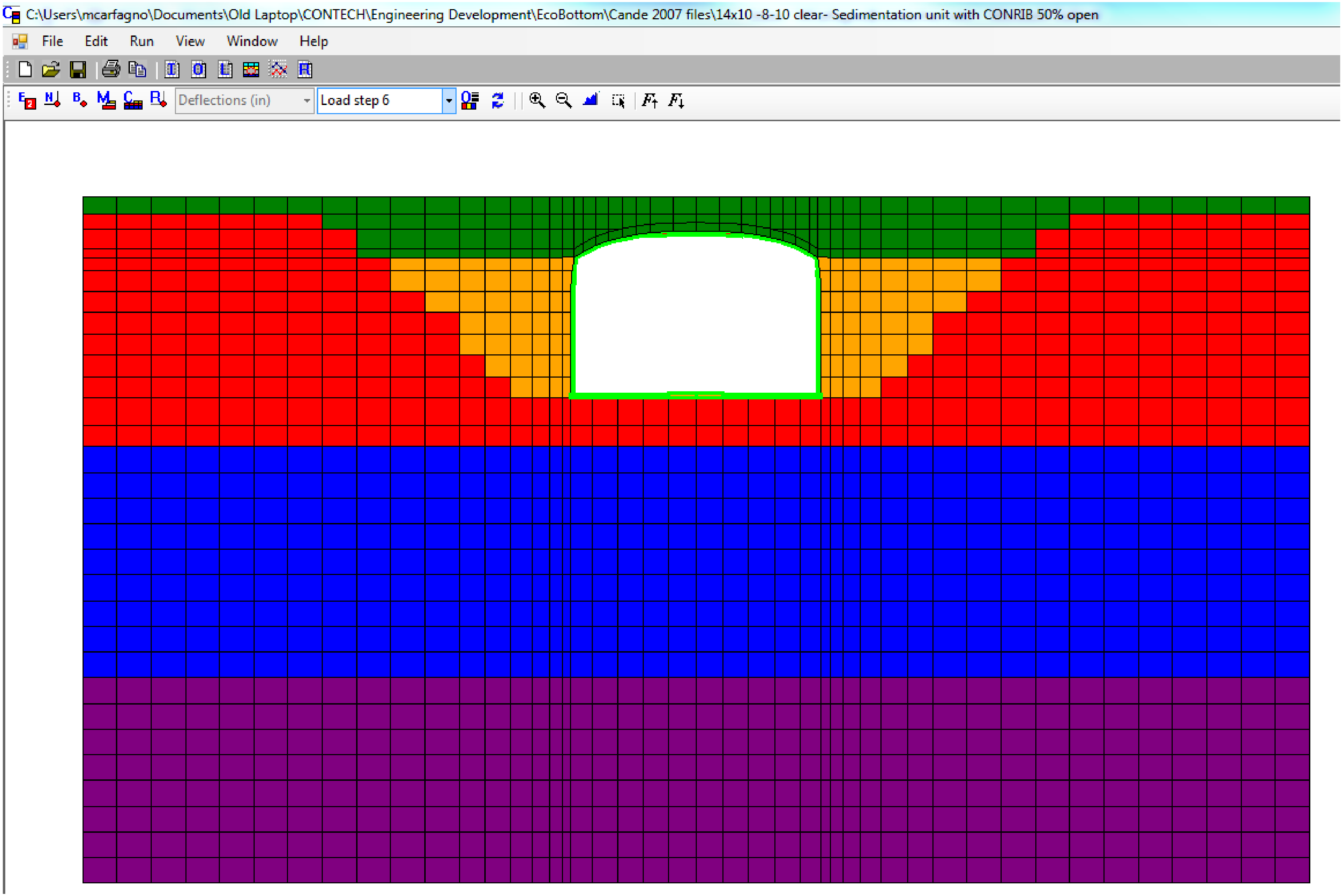
Westfield, IN

i-SERIES™

Westfield, IN

Westfield, IN

i-Series - CANDE 2007 Model

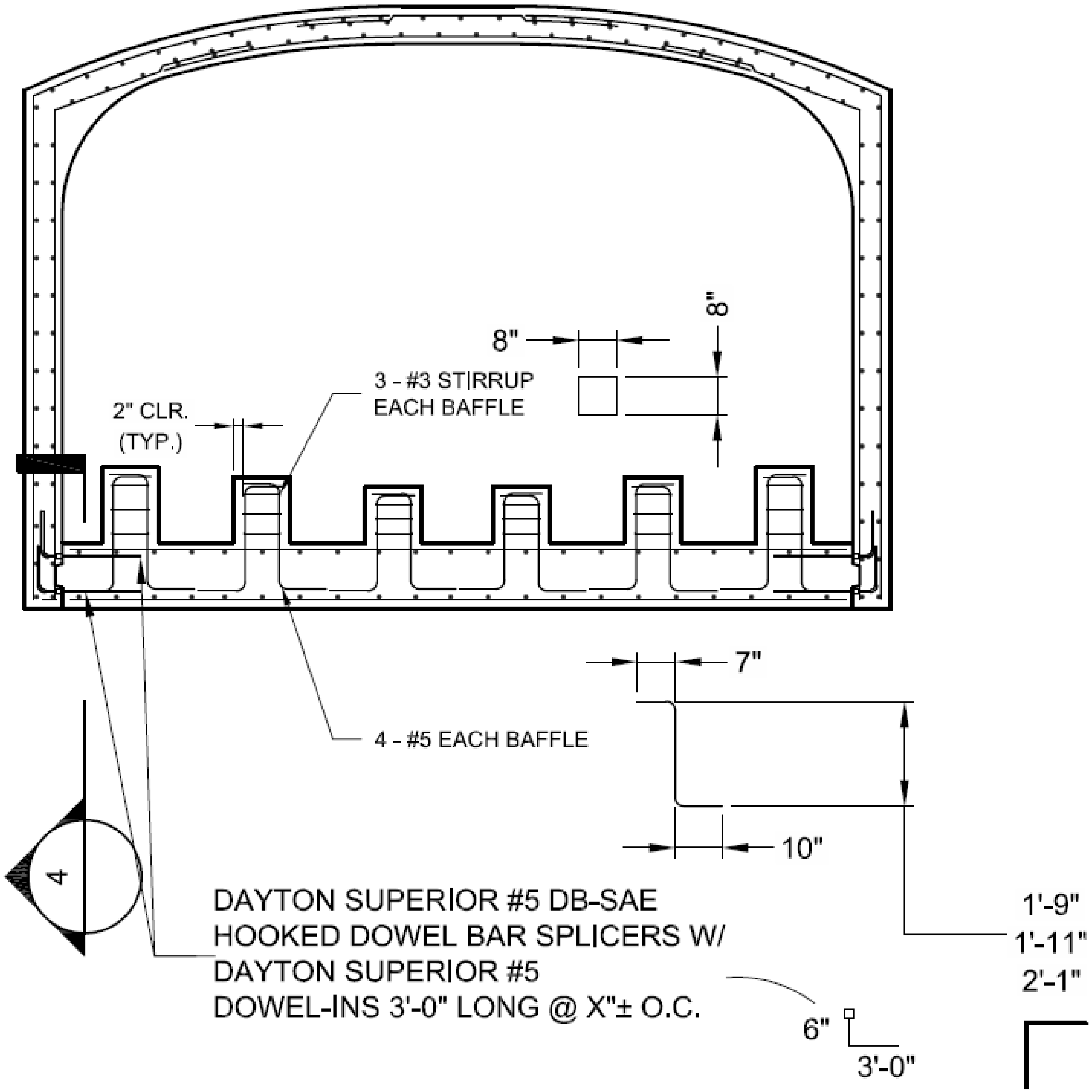


C:\Users\mcarfagno\Documents\Old Laptop\CONTECH\Engineering Development\EcoBottom\Cande 2007 files\14x10 -8-10 clear- Sedimentation unit with CONRIB 50% open

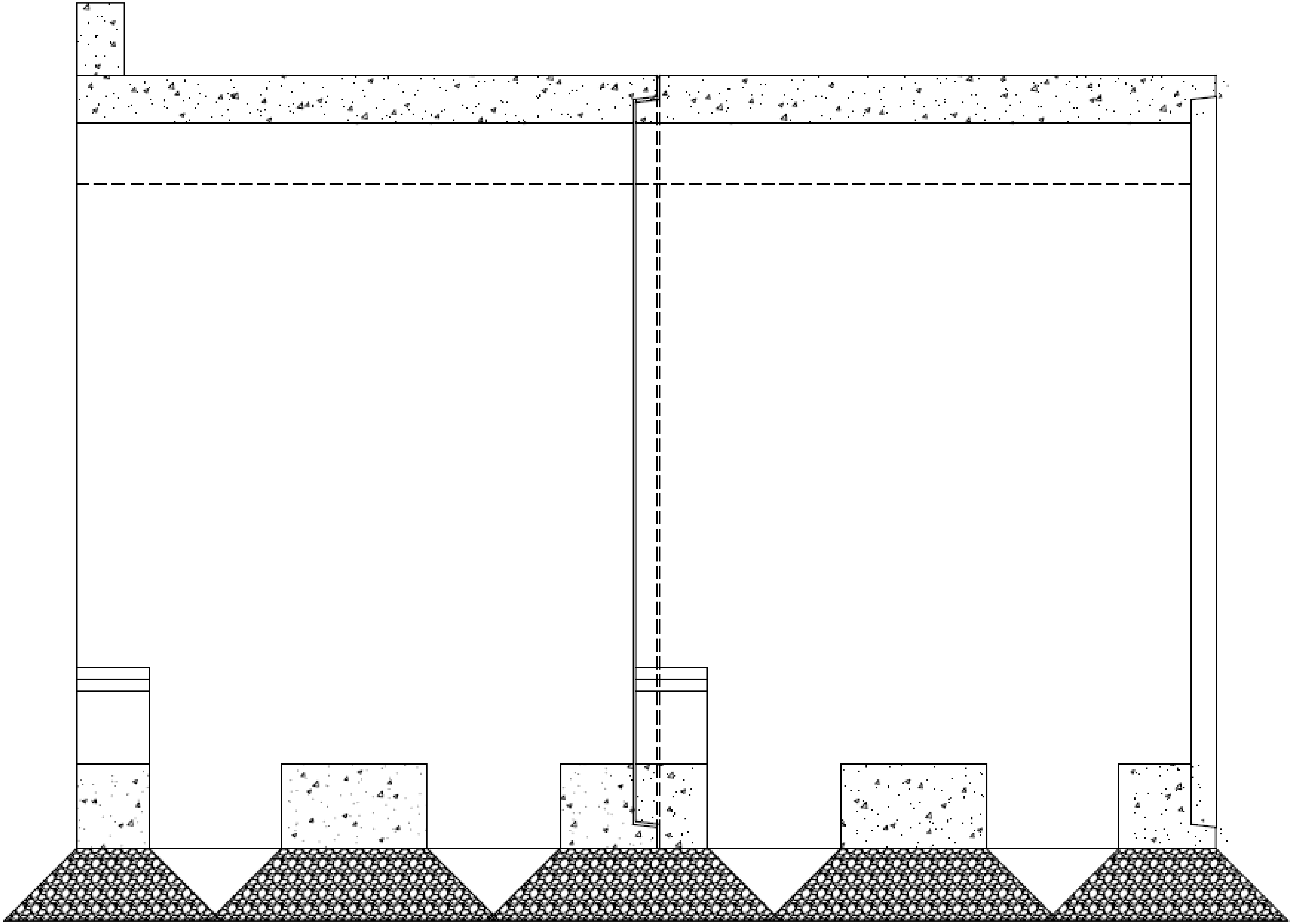
Deflections (in)

Load step 6

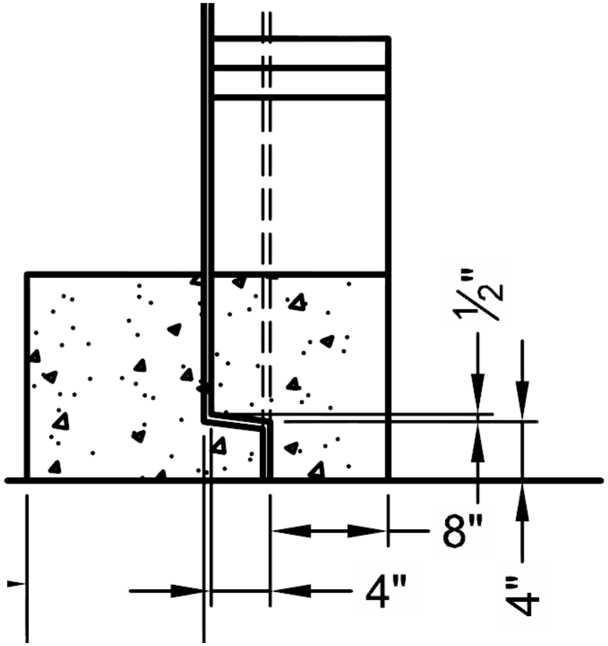
i-Series


8"
8"
3 - #3 STIRRUP
EACH BAFFLE
2" CLR.
(TYP.)
7"
4 - #5 EACH BAFFLE
10"
4
DAYTON SUPERIOR #5 DB-SAE
HOOKED DOWEL BAR SPLICERS W/
DAYTON SUPERIOR #5
DOWEL-INS 3'-0" LONG @ X"± O.C.
1'-9"
1'-11"
2'-1"
6"
3'-0"

i-Series – Foundation Bearing



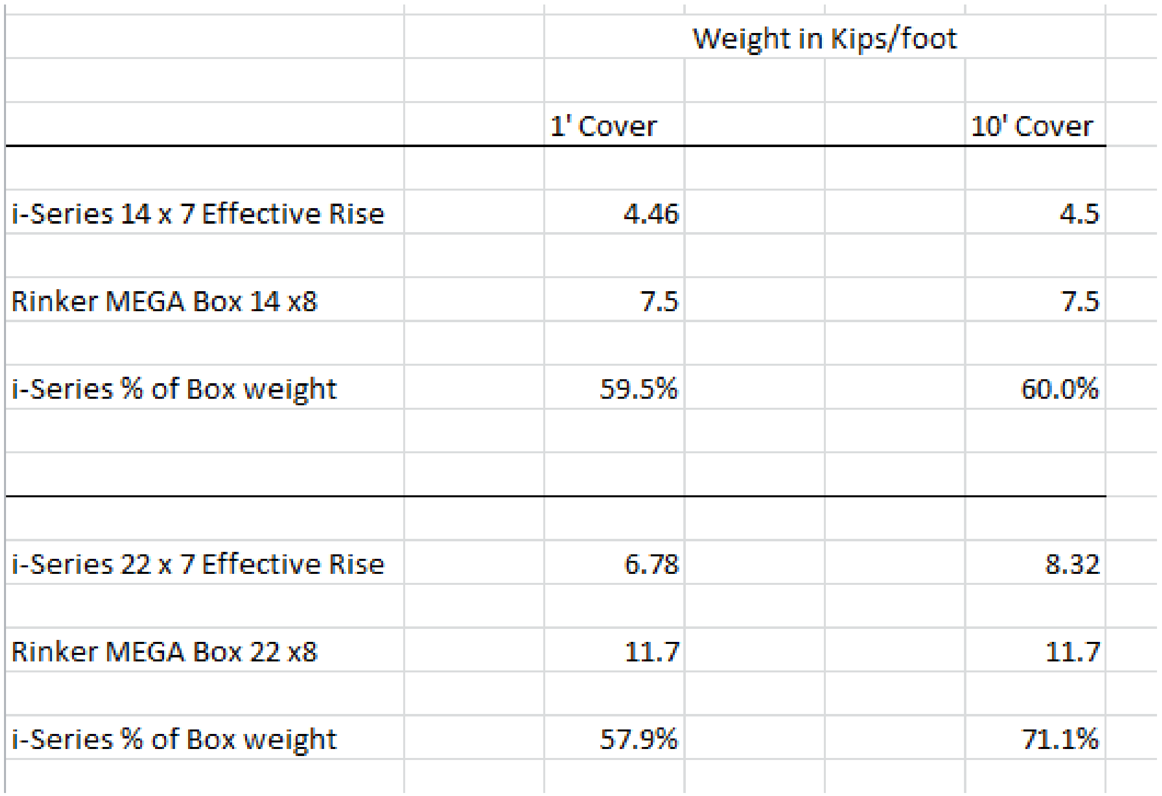
i-Series – Ship Lap Joint



i-Series – Benefits

Key Benefits:

- Ecological advantage
- No ongoing maintenance
- Complete system
- Material efficiency

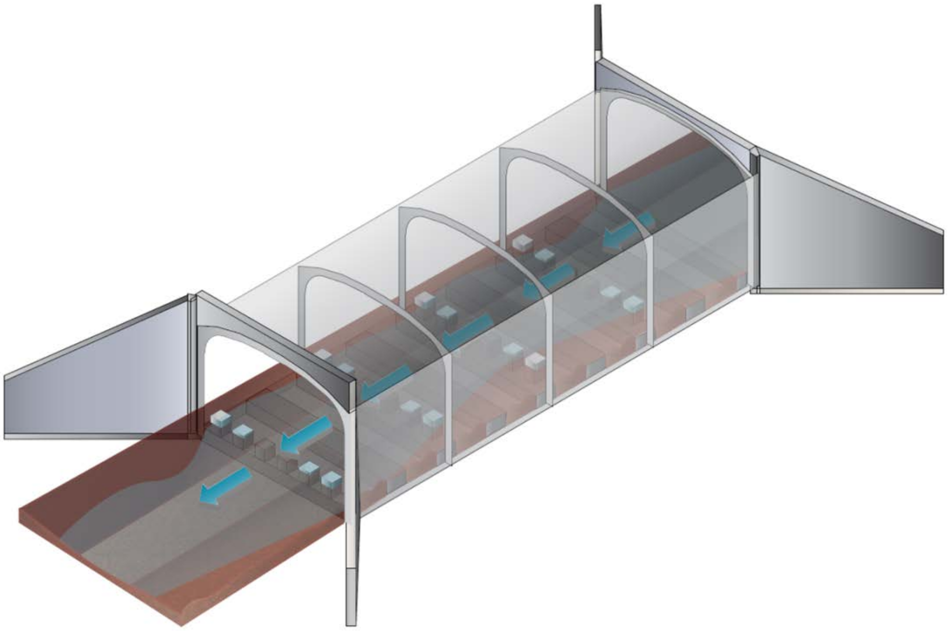


	Weight in Kips/foot	
	1' Cover	10' Cover
i-Series 14 x 7 Effective Rise	4.46	4.5
Rinker MEGA Box 14 x8	7.5	7.5
i-Series % of Box weight	59.5%	60.0%
i-Series 22 x 7 Effective Rise	6.78	8.32
Rinker MEGA Box 22 x8	11.7	11.7
i-Series % of Box weight	57.9%	71.1%

Questions & Discussion

Colorado State University

Design and Testing of an Ecological Bottom Culvert



Mr. Miles Yaw

For:

Contech Engineered Solutions, LLC.

June 2014

I. INTRODUCTION

A. Project Summary

Colorado State University (CSU) has been contracted by Contech Engineered Solutions, LLC (Contech) to develop a bottomless baffled culvert technology. Contech believes that developing a functional ecological bottom culvert can fill a market gap between four-sided concrete box culverts and 3-sided Conspan® arches. The resulting design will be a four-sided "bottomless" culvert, wherein the culvert will be open to the streambed but will have a series of concrete roughness elements, slats, and open gaps to encourage sedimentation in the culvert. Inducing a natural bed through the culvert is analogous to inducing fish passage. A successful design will result in the following outcomes:

- Unimpeded fish passage,
- Profile continuity,
- Hydraulic diversity,
- Sediment transport continuity,
- Low-flow continuity,
- Margin habitat,
- Debris transport capacity, and
- Flood conveyance.

Anecdotal evidence suggests that traditional four-sided box culverts (and other traditional culverts) disrupt ecosystem connectivity by a variety of failure mechanisms, such as creating a velocity barrier, outlet perching, and many others. Historical culvert design has focused primarily on passage of a flood discharge without consideration of the environmental impact of the stream crossing. As detailed in Section II, stream simulation culverts were implemented as an environmentally friendly alternative to traditional box or pipe culverts. Stream simulation culverts require a more intensive design process and are installed at a much higher price than traditional culverts. This project seeks to fulfill the most important outcomes of stream simulation culverts, while being similar in price to more traditional options.

Project completion consisted of four phases. Phase I, completed in July 2013 was a literature review of the state of the art of bottomless and baffled culverts. The literature review details the goals of modern culvert design and the historical development of current design practices from 1956 to present. Focus of the literature review is lent specifically to culvert sedimentation research, baffle design, and modern culvert design practices.

Knowledge acquired during the literature review was applied to Phase II – scaled physical model testing. Phase II began in January 2014 after consultation with Contech on the initial model design. Testing was conducted on a 1:8 geometric Froude scale model of the agreed upon initial design. Modifications were made to the initial design until a satisfactory level of performance was reached.

Phase III began in April 2014 on a unit-width prototype scale model of the successful culvert design. The objective of Phase III was to confirm performance of the ecological bottom culvert under expected installation conditions.

Phase IV consisted of reporting the results of model design and testing. The following report details the process and results of Phases I through III and is presented to Contech under the guidelines and objectives of Phase IV.

All testing was performed at the Hydraulics Laboratory of the Colorado State University Engineering Research Center by the following staff:

- Mr. Cory Arnold and Mr. Eric Boileau, undergraduates, Department of Civil and Environmental Engineering, along with various other undergraduate staff,
- Mr. Miles Yaw, Graduate Research Assistant, Department of Civil and Environmental Engineering;
- Mr. Bryan Scholl, Hydraulics Laboratory Manager, Co-Principal Investigator, Department of Civil and Environmental Engineering;
- Ret. Gen. Steven Abt, Ph.D, PE, Professor Emeritus, Department of Civil and Environmental Engineering; and
- Dr. Christopher Thornton, Ph.D., PE, Hydraulics Laboratory Director, Principal Investigator, Department of Civil and Environmental Engineering.

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- Mr. Scott Aston, PE, Vice President, Bridge Structures,
- Mr. Daniel Wasniak, PE, Area Bridge Director – West, and
- Mr. Michael Carfagno, Vice President, Engineering Development.

II. LITERATURE REVIEW

A. Introduction

Stream crossing structures are a necessary and ubiquitous result of human population growth the world over. In North America alone, hundreds of thousands of culverts have been installed in fish-bearing streams and threaten river connectivity by creating barriers between fish populations and critical habitat (Park 2008, Poplar-Jeffers 2009). Ecological effects of creating artificial stream barriers are well documented, and include: habitat and population fragmentation, reduced genetic diversity, negative water quality, substrate alterations, and decreasing or destruction of fisheries populations (Poplar-Jeffers 2009, Price 2010, Anderson 2012).

Until the late 20th century, very little attention was paid to the watershed-scale, or even reach-scale, effects of culvert installations. Initial attitudes treated culverts as a means for quickly and efficiently redirecting water through or around human developments (MacPherson, *et al.* 2012). Although public awareness of the severity of the problem is increasing, and even as the dire state of the continent's aquatic habitat becomes known to federal and state agencies, there remain untold thousands of culverts which desperately need replacing, retrofitting, or rehabilitating. On federal land in Washington and Oregon alone, there are over 10,000 culverts on fish-bearing streams, at least half of which are barriers to fish passage and in need of rehabilitation. The Washington State Department of Transportation (WSDOT) further reports that 60% of its 3,175 culverts are fish barriers (Price 2010). As state agencies begin to restore riverine habitat through culvert replacement, decisions are rarely made based on biological strategy and watershed-scale benefits, but are instead based on opportunistic reach-scale criteria (Poplar-Jeffers 2009).

Even when the decision is made to replace a culvert there is no guarantee of increased function, despite extensive legislation requiring stream crossings to allow fish passage. A random survey of 77 new and repaired culverts in the Puget Sound Basin of Washington State found that 23 were fish barriers. The alarmingly high failure rate was attributed primarily to poor permitting by biologists, and by noncompliance to the permit during construction. However, this is by all indications an improvement over historical practices in the Puget Sound, where anthropogenic disturbances of salmon habitat have decreased natural salmon abundance by 92% since 1850. It is also encouraging from both a business and an environmental standpoint to note that between 1999 and 2009, more than 3,500 fish passage barriers were repaired on Washington streams, at a cost of over $139 million (Price 2010). Mitigation of the culverts on federal lands in Washington and Oregon is estimated by the Government Accountability Office to cost at least an additional $375 million (Frei 2006).

Several factors are known to present potential barriers to fish passage through culverts:

- Excessive flow velocity,
- Insufficient flow depth,
- Excessive outlet drop,
- Debris accumulation,
- Excessive turbulence,
- Species-specific physical and behavoiral traits and capabilities,
- Outlet plunge pool depth,
- Streambed discontinuity,
- Water temperature, and
- Darkness (Frei 2006, Hays 2009, MacPherson 2012).

Further complicating matters is the fact that a design engineer must harmonize the biological interests of fish with the hydraulic requirements of a culvert installation. For instance, in high-gradient alpine streams, it may be virtually impossible to install a culvert which simultaneously satisfies the demands of both conveyance of a design flow and maximum velocities associated with fish passage. When culverts are installed on streams with grades greater than about 5%, they customarily become fish barriers by either creating high velocities or perched outlets (Poplar-Jeffers, 2009). Moreover, many states' laws require that new culvert installations be passable for every species of fish in a stream, about many of which little or nothing is known (Barnard 2013).

There is also evidence to suggest that the cumulative effects of a series of passable culverts can result in a fish barrier, especially when the culverts are only marginally passable. As stresses on a fish build up with each successive passage, the fish may become too fatigued and unmotivated to continue to upstream habitats (Webb 2009). Culvert remediation should therefore not be a matter of simply picking the most offensive culverts for replacement, but rather a series of criteria need to be evaluated to determine the true benefit of any remediation. These criteria include considering the spatial context of each fish barrier (proximity to other crossings, amount of upstream habitat opened, etc.), maintenance requirements of a new crossing, costs of remediation, public support, target species abundance, severity of the barrier, uncertainty in assessing the barriers, and upstream habitat quality (Coulton 1998, Anderson 2012).

Most research in the area of fish passage is undertaken in the Pacific Northwest, and culvert design practices implemented in British Columbia, Washington, Oregon, California, and Alaska are typically the most progressive (Anderson 2012). While fish passage concerns are most intensely focused on the anadromous salmonid populations of the Pacific Northwest and Alaska, it is certainly not a problem limited to this region. There is overwhelming evidence that other diadromous and potamodromous fish species are equally susceptible to the perils of watershed fragmentation, making the problem of fish passage barriers one without borders (Park 2008, Poplar-Jeffers 2009, Alvarez-Vazquez 2011, MacPherson 2012, David 2012).

It is then imperative that the engineering community find ways to construct new culverts and remediate old culverts to allow for fish to migrate unimpeded throughout watersheds. The following is the state of the art of culvert design for fish passage and sedimentation control, from its development to current design practice. It is presented in the hope that previous research will grant insight for prudently designing an initial set of bottomless baffled culverts that will retain sediment during high flows and facilitate fish passage during low and high flows.

III. CONCLUSIONS

The Washington State Department of Fish and Wildlife (WDFW) published a stream-crossing guideline which enumerates nine expected outcomes of a successful stream-simulation culvert design. A tenth outcome (hyporheic connectivity) differentiates the ecological bottom culvert from traditional culvert options. Of these ten outcomes, seven are expected to be fulfilled by the ecological bottom culvert, as supported by the results of the testing program detailed in Sections III and IV. Table V-1 outlines the expected outcomes of successful stream simulation design and which of them are expected to be fulfilled by an ecological bottom culvert and a traditional box culvert.

Table V-1. Expected Outcomes.

	Stream Simulation			Hydraulic Design		
	Bottomless Culvert	Ecological Bottom Culvert	Traditional Culvert with Invert	Bottomless Culvert	Ecological Bottom Culvert	Traditional Culvert with Invert
Flood Conveyance	●	●	●	●	●	●
Fish Passage	●	●	●	●	●	
Profile Continuity	●	●	●	□	□	
Hydraulic Diversity	●	●	●	□	●	
Sediment Transport Continuity	●	●	●	◙	◙	
Low Flow Continuity	●	●	●	●	●	
Margin Habitat	●	●	●	◊	◊	
Bed Gradation Continuity	●	○	●			
Debris Transport	●	●	●	●	●	●
Hyporheic Connectivity	●	●		●	●	

●- *achieved* □- *achieved pending site-specific characteristics* ◙- *provides incremental benefits over traditional culvert with invert* ◊- *pending development of low-flow channel* ○- *achieved over time, or immediately with manual filling of culvert*

Table V-1 was developed in consort with Contech. There are two distinct design groups: stream simulation culverts, which are oversized to prevent channel constriction[1], and hydraulic design culverts, which are sized simply to pass the design flow. Phase II and III testing focused on the "Stream Simulation Ecological Bottom Culvert." Results for the "Hydraulic Design" options represent expected performance of each type of culvert based on knowledge gained during the testing program, but no claim is made that the results of the "Hydraulic Design" options were tested or proven in this testing program. Fulfillment of the expected outcomes is detailed in the following section.

Flood conveyance is the ability for the culvert to pass the required design flood. As the ecological bottom culvert is a modification of a Conspan® arch, it is expected to perform equally well during flooding. For flood passage design purposes, it is advisable to consider the clear rise as the open space between the top of the tallest roughness elements and the roof of the culvert. However, flood passage design was beyond the scope of this project. As such, no flow rating relationships have been considered or developed.

Fish passage is achieved through the ecological bottom culvert based on the criteria stated in HEC-26: "aquatic organisms in the stream are exposed to similar forces and stresses experienced by the streambed material. The design goal is to provide a stream crossing that has an equivalent effect, over a range of stream flows, on the streambed material within the culvert compared with the streambed material upstream and downstream of the culvert." This study has been founded on the idea that inducing a natural bottom inside the culvert is analogous to allowing fish passage through the culvert. As the testing program has showed that the streambed material through the culvert behaves in a manner similar to that upstream and downstream, this outcome is fulfilled.

Profile continuity is the preservation of the reachwise stream slope through the culvert. Maintaining slope is achieved by maintaining a natural bed through the culvert which reflects changes in the upstream and downstream reaches, and preventing outlet perching and degradation of the bed inside the culvert. The testing program has shown that both of these are fulfilled by the ecological bottom culvert.

Profile continuity can be jeopardized by constriction of a channel due to increased shear stress and bedload movement through the culvert as compared to the upstream reach. Scour inside

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[1] Per the WDFW Water Crossing Design Guidelines (2013), stream simulated culverts should be sized to 1.2 times the bankfull channel width, plus two feet. For greater discussion of sizing guidelines, refer to the literature review in Section II.

the culvert can cause steepening of the stream slope inside the culvert and result in increased barrier velocities for fish. One mechanism by which scour through a constricted culvert can be prevented is by coarsening the grain size of the bed material, such that bedload transportation rates through the culvert match transport rates upstream despite the increased shear stress. Because of this, fulfillment of profile continuity in the hydraulic design options will be achieved pending site specific characteristics. In traditional box or barrel culverts on constricted channels, extensive anecdotal evidence shows the failure to meet profile connectivity.

Hydraulic diversity is the presence of zones of low, zero, or negative (upstream) flow velocities within the culvert along with regions of higher velocities. These zones are thought to provide resting habitat for aquatic organisms inside the culvert. These organisms would then use burst swim speeds to pass through the areas of higher velocity. This has been shown to be achieved in the ecological bottom culvert by increased deposition of sediment in the lee of exposed roughness elements, and confirmed by measurement with a Marsh-McBirney flow meter. Hydraulic diversity exists not only behind the roughness elements, but across the whole cross-section of the culvert as evidenced by decreased flow velocities along the left side of the flume in Test 11.

The slats, gaps, and roughness elements of the ecological bottom culvert will provide hydraulic diversity even in a hydraulically designed option. Significant hydraulic diversity does not exist in traditional box or barrel culverts, but may exist in hydraulically designed bottomless culverts provided that large woody debris or even large (boulder size) sediment becomes trapped inside the culvert.

Sediment transport continuity means that bed material transported through the upstream reach is continuously supplied to the culvert bed and supplied by the culvert to the downstream reach at an equivalent rate, allowing the culvert to reflect the bed structure of the stream reach. This has been achieved by using slats, gaps, and roughness elements to encourage deposition of sediment inside the culvert, which is then maintained by a constant supply of sediment from the upstream reaches. The testing program has shown that by using the ecological bottom culvert, the bed inside the culvert mimics the stream bed in the surrounding reach.

In a constricted channel, sediment transport continuity can be achieved, but not to the extent achieved in stream simulation culverts. The channel constriction will cause greater sediment mobility inside the culvert. It is expected that by using either an ecological bottom culvert or a bottomless culvert (such as a Conspan® arch) in a hydraulic design will reach dynamic equilibrium at a point before failure of the culvert. This is expected because the slats and gaps will provide for sediment retention and the roughness elements will provide roughness for the channel, decreasing flow velocities and reducing sediment mobility. The degree of these incremental benefits will depend on the amount of channel constriction.

Low flow continuity is the maintenance of a channel for fish passage during low-flow events. This was demonstrated in Test 10 by the fact that more sediment was deposited near the culvert walls, with development of a thalweg along the centerline of the channel. Using taller roughness elements on the culvert edges decreases flow velocities (as shown in Phase III testing) by increasing channel roughness. These decreased edge flow velocities facilitate sedimentation on the channel edges and promote development of a thalweg along the culvert centerline. This is corroborated in part by the fact that slightly greater erosion rates were observed in the 12' middle model than in the 20' edge model. While the development of a thalweg through the culvert was shown in Test 10, and the effect of taller roughness elements on flow velocities was shown in Test 11, the effectiveness of the ecological bottom culvert in creating a low-flow channel should be confirmed in a field setting under the influence of a natural annual flow and sediment hydrograph.

Margin habitat is the existence of areas of low velocity and turbulence along and near the banks of a stream where fish, especially juveniles, can use for migration. In the ecological bottom culvert, it is a consequence of developing a low-flow channel in the culvert. If a low-flow channel develops, it will have stream banks which provide margin habitat for aquatic organisms. In stream simulation culverts, low-flow channels and margin habitat must be built during installation of the culvert. It is expected that a low-flow channel and margin habitat will develop naturally in the ecological bottom culvert. This makes it superior to a stream simulation design in that the stream channel is manually constructed in stream simulation culverts, whereas the low flow channel in margin habitat should develop without intervention in the ecological bottom culvert.

Bed gradation continuity is the maintenance of a bed material grain size distribution through the culvert which is equivalent to the grain size distribution of bed material upstream and downstream of the culvert. In the testing program, bed gradation continuity was achieved, as evidenced by the gradation curves in Appendix C. However, the sediments used during the testing program were poorly-graded, which will not be the case in a natural setting. It is likely that the material initially deposited in the slats will be coarser than the natural streambed material. Over time the bed material in the culvert will begin to more accurately reflect the material in the surrounding stream, but any such processes cannot be confirmed by the testing program. This problem could be alleviated by manual filling of the culvert at installation with natural bed sediments.

In hydraulically designed options, bed gradation continuity is not expected to be achieved if profile continuity is desired. It is likely that coarser bed material will be needed to achieve profile continuity.

Debris transport is the ability for the culvert to pass large woody debris or miscellaneous detritus. The presence of exposed roughness elements in any culvert can impede the passage of debris at low flows. If the ecological bottom culvert fills with sediment as anticipated, the exposed roughness elements may be no more than 2-4 inches above the streambed and will not significantly hinder debris passage. At high flows, debris passage is simply a result of proper design and maintaining enough clear space between the design flood water surface and the culvert roof. Proper design will result in the ecological bottom culvert performing equally as well as any stream-simulation culvert.

The hyporheic zone is the region beneath and alongside the streambed where there is interaction between the groundwater and the surface water. The hyporheic zone provides ideal habitat for microbes and invertebrates which are critical to the overall health of the stream. Connectivity of the hyporheic zone is achieved by the ecological bottom culvert by the fact that it is open to the substrate. Culverts with inverts will disrupt the hyporheic zone, as they will not allow for interaction of groundwater with the surface stream.

Thus, the testing program detailed in this report supports the expectations presented in Table V-1. Each of the nine outcomes of a stream simulation culvert are fulfilled by an ecological bottom culvert, compared to just one for a traditional box culvert. The culvert design presented in this report will fill a market gap between stream simulation culverts and traditional box culverts.