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INDIANA DEPARTMENT OF TRANSPORTATION
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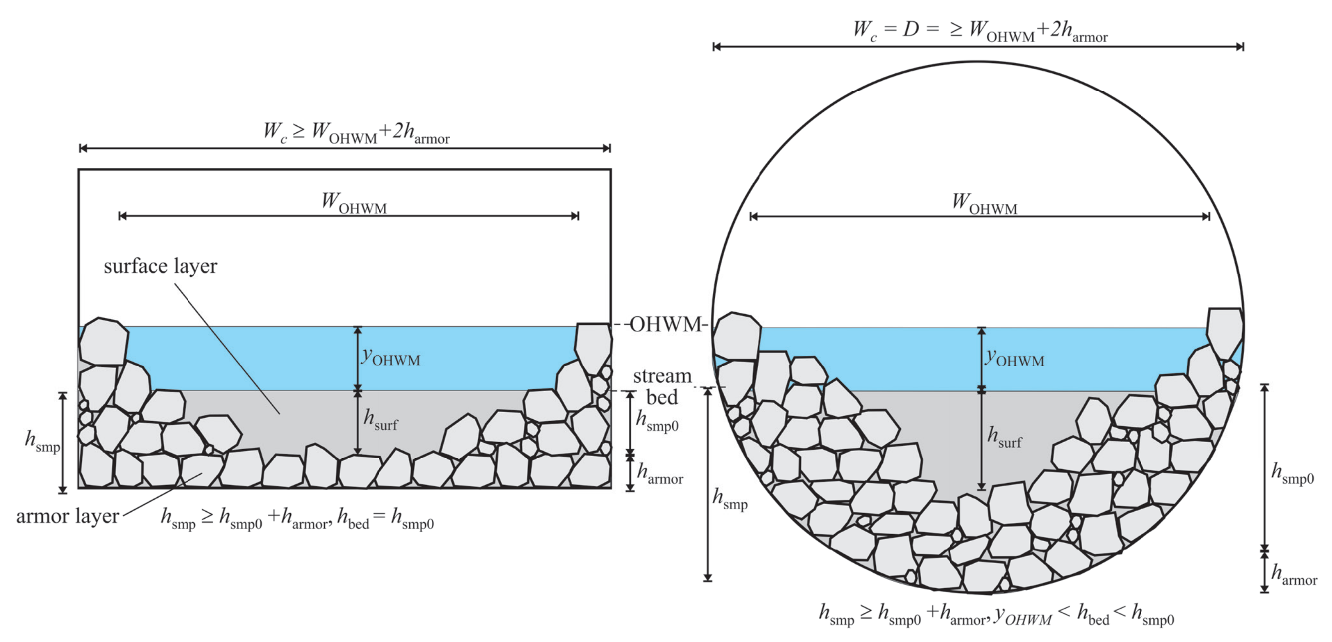
Ecologically Aware Design of Waterway-Encapsulating Structures



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SPR-3814 • Report Number: FHWA/IN/JTRP-2016/21 • DOI: 10.5703/1288284316344

RECOMMENDED CITATION

Lyn, D. A., & Sangwan, N. (2016). *Ecologically aware design of waterway-encapsulating structures* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/21). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316344

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Print ISBN: 978-1-62260-437-1
ePUB ISBN: 978-1-62260-438-8

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/IN/JTRP-2016/21	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Ecologically Aware Design of Waterway-Encapsulating Structures		**5. Report Date** August 2016 **6. Performing Organization Code**
7. Author(s) Dennis A. Lyn, Nikhil Sangwan		**8. Performing Organization Report No.** FHWA/IN/JTRP-2016/21
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051		**10. Work Unit No.** **11. Contract or Grant No.** SPR-3814
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

Aquatic organism passage (AOP) in waterways-encapsulating structures, particularly culverts, is of growing concern to environmental regulatory agencies, and the Indiana Department of Transportation (INDOT) is seeking systematic responses to this concern in the hydraulic design of such structures. This study reviews design approaches to enhance or accommodate aquatic organism passage through culverts, and proposes a simplified design procedure that requires less data input and analysis, and yet results in a structure complying with the current regional general permit (RGP) conditions. It also makes as much use of already existing INDOT standard specifications for riprap and coarse aggregates that would be as backfill material to form a stable bed within the culvert. The simplified procedure is intended for new larger structures for which a culvert bed needs to be installed, and for expected Indiana conditions of low-gradient (<3%) and predominantly sandy or gravelly streams.

Because of their larger size compared to traditional culverts, AOP-designed structures are associated with higher installation and material costs, which may however be compensated partially or wholly by lower costs over their operational lifetime. Previous work on life-cycle cost (including social/ecological costs) analysis of AOP-designed culverts was reviewed, but it is concluded that reliable data and methodologies for an adequate analysis are not yet available. The study then explores the consequences of alternative regulatory schemes formulated on the basis of habitat or biotic integrity indices. These may permit simple yet more flexible schemes with the same or even better ecological outcomes.

17. Key Words culvert, design, aquatic organism passage, stream restoration		**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 54	**22. Price**

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

ECOLOGICALLY AWARE DESIGN OF WATERWAY-ENCAPSULATING STRUCTURES

Introduction

Aquatic organism passage (AOP) in waterways-encapsulating structures, particularly culverts, is of growing concern to environmental regulatory agencies, and the Indiana Department of Transportation (INDOT) is seeking systematic responses to this concern in the hydraulic design of such structures. This study reviews (i) the literature on AOP in culverts, especially as it relates to design, and (ii) the two main AOP design approaches—namely, the "stream simulation" approach developed by the U.S. Forest Service (USFS) and an alternate approach developed for the Federal Highway Administration (FHWA). Both approaches require substantial additional data and analysis, which motivated the development of a simplified design procedure tailored to Indiana-specific conditions, requiring less data input and analysis, but which at the same time results in a structure complying with the current regional general permit (RGP) conditions. It also makes as much use of already existing INDOT standard specifications for riprap and coarse aggregates that would be used as backfill material to form a stable bed within the culvert.

Findings

Drawing on elements of both the USFS and FHWA approaches, the simplified procedure is intended for larger structures for which a culvert bed needs to be installed, and for expected Indiana conditions of low-gradient (<3%) and predominantly sandy or gravelly streams. It determines (i) the culvert span, (ii) the sump depth, and (iii) the design of the bed within the culvert. Similar to the USFS approach but unlike the FHWA approach, it determines the culvert span from observations of the ordinary high water mark (OHWM, or possibly bankfull) widths and also explicitly includes bank-like features. Similar to the FHWA approach but unlike the USFS approach, the proposed procedure for the culvert-bed design explicitly considers two layers—a surface layer and an armor sublayer beneath the surface layer. The armor sublayer substrate would generally consist of riprap-like material, which is intended to be immobile for all flows up to the peak discharge, while material in the surface layer is allowed to be mobile, but only if the natural stream material is also mobile for the same flow.

The proposed procedure differs from both the USFS and FHWA approaches in the choice of material for the armor sublayer and the surface layer, and the thicknesses of the two layers. For the armor sublayer, the simplified procedure makes as much use of the already existing INDOT standard specifications for riprap, and current INDOT practice as regards the permissible velocities for each riprap class, though some modifications are made. The main simplification is obtained through a "conservative" choice of material for the surface layer. Both the USFS and FHWA approaches attempt to replicate the natural channel material characteristics in the culvert bed, and so require a detailed characterization of the natural channel material. The proposed procedure requires only a gross assessment of the predominant channel material (e.g., sand, gravel or other) and then chooses a standardized bed mixture that should remain immobile for all material in a group (or subgroup). In many cases this could result in the culvert-bed substrate being much coarser than that of the natural stream, but it should result in a stable bed. The minimum thickness of the surface layer will usually be taken as equal to the flow depth under OHWM (or possibly bankfull) condition, while the minimum thickness of the armor sublayer would generally be the size of the stone used in the sublayer.

Because of their larger size compared to traditional culverts, AOP-designed structures are associated with higher installation (including material) costs. Depending on the ratio of the spans of the AOP-designed culvert and the traditional culvert, the ratio of the corresponding installation costs range from 1 to 3. It has been argued that the increased installation costs may be compensated partially or wholly by lower costs over their operational lifetime. Previous work on life-cycle cost analysis (including social/ecological costs) of AOP-designed culverts was reviewed, but it is concluded that reliable data and methodologies for an adequate quantitative analysis are not yet available.

The current RGP distinguishes between smaller and larger streams based on the OHWM width, such that larger streams (those with OHWM widths greater than 12 ft) need to comply with additional more specific (and onerous) conditions. While there may be some practical and theoretical justification for this criterion, the study explores alternative regulatory schemes formulated on the basis of habitat or biotic integrity indices, such as the Qualitative Habitat Evaluation Index (QHEI) or the fish-Index of Biotic Integrity (fish-IBI). These indices are intended to measure more directly habitat potential or present quality, and so they may yield more intuitive and flexible schemes with the same or even better ecological outcomes. The implications of different schemes based on QHEI and/or IBI were examined by considering the Indiana Department of Environmental Management (IDEM) database of QHEI and IBI measurements at numerous sites in Indiana as representative of possible culvert sites. For example, if a criterion QHEI <45 (IDEM considers QHEI <51 as poor habitat potential) is used instead of the current OHWM width of 12 ft, then a sizeable fraction (about 15%) of sites with OHWM widths greater than 12 ft might qualify for an exemption from the additional AOP requirements. Conversely, if the minimum OHWM width for the additional AOP requirements were reduced to 8 ft (instead of 12 ft), then a comparable fraction (about 11%) of smaller streams would then be subject to the additional AOP requirements.

Implementation Plans

INDOT's hydraulic design guidelines for culverts are not entirely compliant with the current regional general permit specifications (except for a general catch-all qualification that all appliÙcable environmental regulations should be complied with). The proposed guidelines were designed to comply with RGP specifications, and so it is recommended that INDOT adopt them as one (but perhaps not only) standard acceptable approach. In the proposed approach, the design of a stable bed within the culvert relies on the availability of standard material mixtures. For one class of stream substrates, namely a predominantly sandy-bed stream, an existing standard mixture was designated as adequate, but for other classes, other standard mixtures will need to be defined. An approach for such a definition was suggested, and it is recommended that other standard mixes be developed as part of the implementation. Discussions are being held with the Indiana Department of Environmental Management regarding current and future RGP conditions, and the results of these discussions may influence implementation.

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1. INTRODUCTION, MOTIVATION, AND PROJECT SCOPE

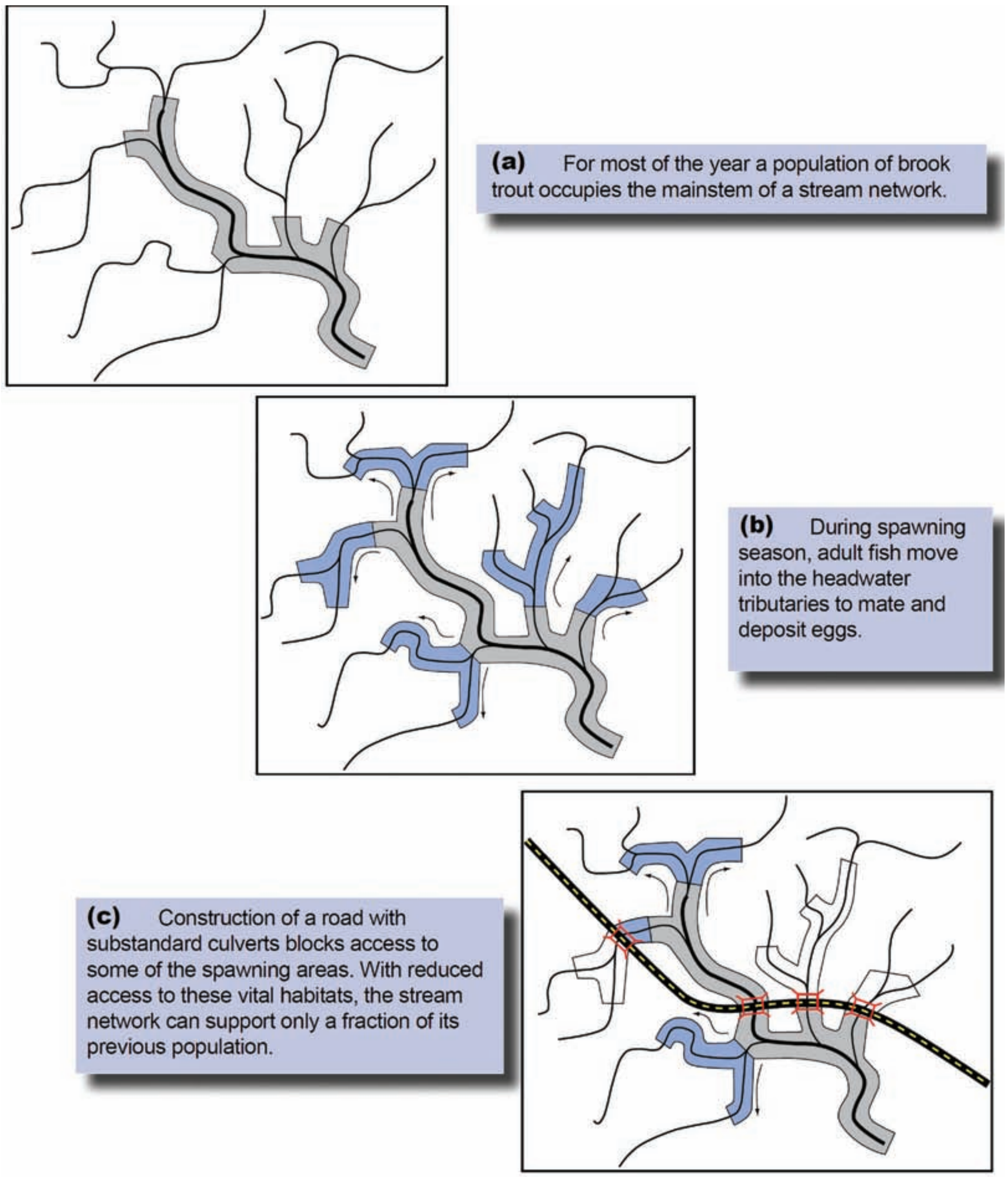
The generic term waterway-encapsulating structure refers to any structure that crosses a natural stream or other waterway, with structural elements interacting strongly with the flow, either in the main channel or in the floodplain. The term includes both bridges and culverts. Until recently, the ecological consequences of waterway-encapsulating structures have received little or no consideration during hydraulic analysis and design. The main concern is that these structures may lessen stream connectivity with negative long-term impacts on the ecology of aquatic organism communities. This is illustrated in Figure 1.1 and Figure 1.2 in which traditionally designed culverts are shown as inhibiting aquatic organism passage (AOP), thereby fragmenting aquatic habitats and reducing the diversity of resources available to aquatic organism communities, possibly leading to significant negative impacts. In general, as depicted in Figure 1.3, the typically more costly bridge option (at the top in Figure 1.3) is viewed as being the least restrictive with regards to connectivity, while the lower-cost traditional culvert (at the bottom in Figure 1.3) is considered the most restrictive. As such, the present study will mainly examine the hydraulic design of culverts since this case will be of most interest to the Indiana Dept. of Transportation (INDOT).

Ecological concerns have led to increased regulatory attention as manifested in the permitting requirements for waterway-encapsulating structures in the U.S. as a whole, and in the Midwest and Indiana in particular. Current specifications by the Indiana Department of Environmental Management (IDEM) for a regional general permit (RGP) explicitly require that "New permanent stream encapsulations … must allow the passage of aquatic organisms in the waterbody" and also include rather detailed design restrictions such as "Either have no bottom … or are embedded (sumped)" or for perennial streams with OHWM (ordinary high water mark) width greater than or equal to 12 feet "[must] have a width equal to or wider than the existing OHWM."

Current INDOT design policy (in the INDOT Design Manual, Chapter 203-2.02, to be referred to as INDOT2013-203-2.02) states generally that "The culvert design should incorporate the environmental requirements of IDNR, IDEM, USACE, and other applicable government agencies." Otherwise, the only other design specification relevant to AOP relates to culvert sumping, referring to the placement of the bottom of a structure (and any scour protection) below the natural stream bed (or in the case of a replacement structure, what can be reasonably presumed to be the level of the natural stream bed). INDOT2013-203-2.02 (INDOT, 2013) states that "Sumping should be provided for each structure over Waters of the United States and Waters of the State" to comply with permitting requirements, and sump depths in line with the current RGP are given. The recommendation that "The sump area of the structure and end section or riprap will not require backfill as part of the contract work, but will be allowed to fill in naturally over time" is however at variance with the current RGP which states "…natural stream substrate must be placed in the encapsulation in accordance with Federal Highway Administration Hydraulic Engineering Circular No. 26: Culvert Design for Aquatic Organism Passage."

Although it may be possible to satisfy current RGP requirements through an ad hoc modification of current design procedures, e.g., through "oversizing" culverts, a more systematic design procedure incorporating ecological concerns may be desirable for INDOT, especially if the regulatory environment becomes more challenging. The present study aims to evaluate the available tools, data resources, and design approaches to deal with the issue of AOP for possible adoption by INDOT in their design practice. While the evaluation intends to take into account the current RGP, it will not necessarily be bound by it, and may explore options that are at variance with it, but could be considered as offering advantages, either from the ecological or the hydraulic perspective.

The present report is organized as follows. Chapter 2 reviews the literature regarding AOP passage in culverts, emphasizing aspects relevant to culvert design and to Indiana-specific conditions. The dominant design approaches are discussed in Chapter 3, where a simplified approach tailored to Indiana-specific conditions is also proposed. Chapter 4 examines the economic or cost aspects of AOP-designed culverts, and within that context explores alternative potentially more effective regulatory approaches. A summary and implementation recommendations are given in Chapter 5.

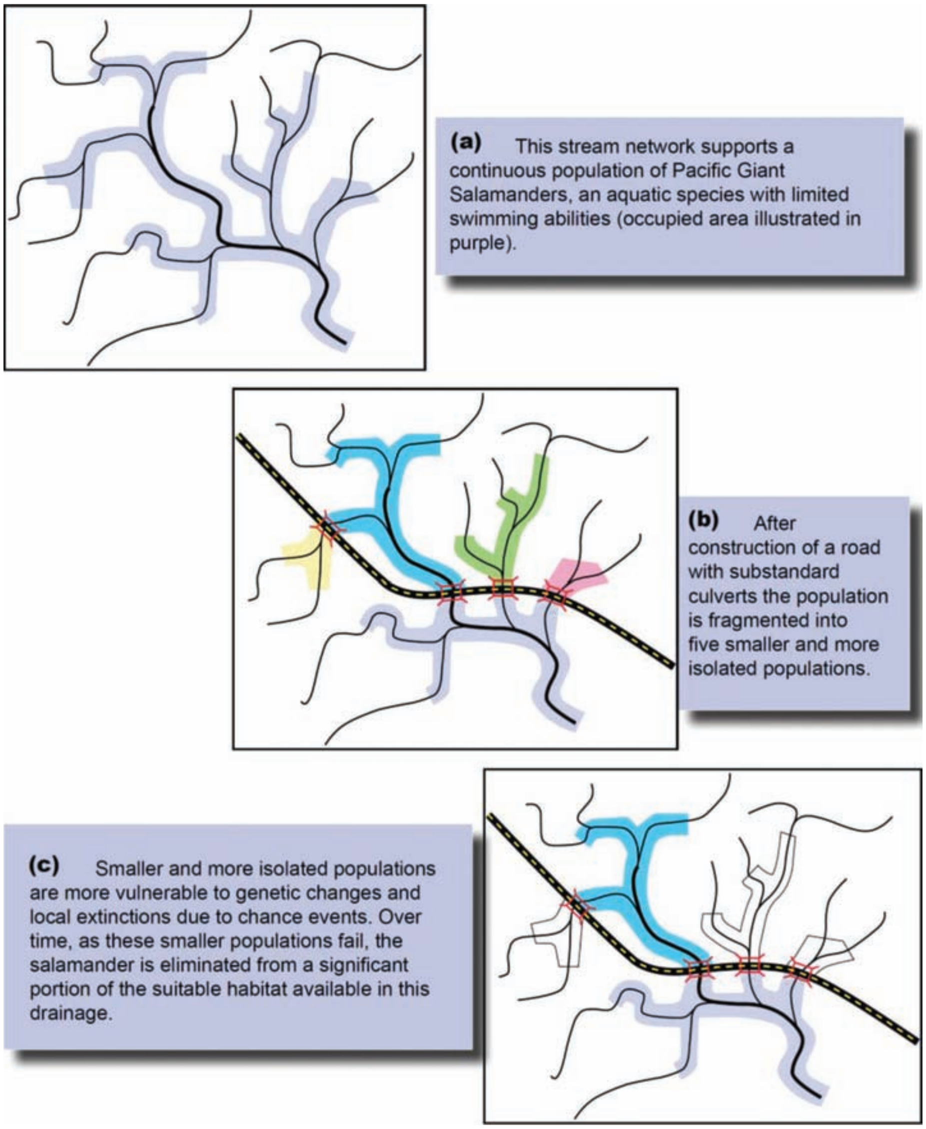


(a) For most of the year a population of brook trout occupies the mainstem of a stream network.

(b) During spawning season, adult fish move into the headwater tributaries to mate and deposit eggs.

(c) Construction of a road with substandard culverts blocks access to some of the spawning areas. With reduced access to these vital habitats, the stream network can support only a fraction of its previous population.

Figure 1.1 Illustrative example of potential adverse long-term ecological effects of unconsidered roadway crossing (culvert) on spawning fish species. (Taken from U.S. Forest Service Stream Simulation Group, 2008, hereafter to be referred to as USFS2008.)



(a) This stream network supports a continuous population of Pacific Giant Salamanders, an aquatic species with limited swimming abilities (occupied area illustrated in purple).

(b) After construction of a road with substandard culverts the population is fragmented into five smaller and more isolated populations.

(c) Smaller and more isolated populations are more vulnerable to genetic changes and local extinctions due to chance events. Over time, as these smaller populations fail, the salamander is eliminated from a significant portion of the suitable habitat available in this drainage.

Figure 1.2 Illustrative example of potential adverse longer-term ecological effects of unconsidered culvert design on aquatic organism (salamanders) due to ecosystem fragmentation. (Taken from USFS, 2008.)

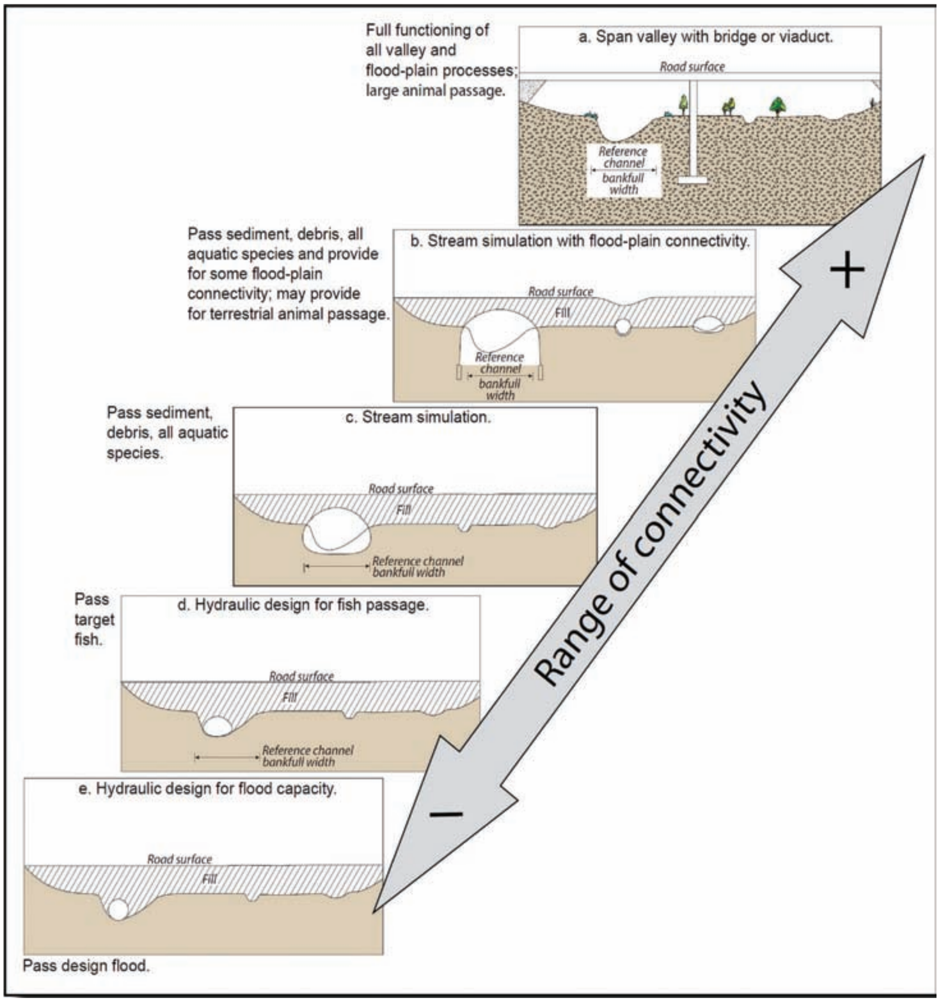


Figure 1.3 Schematic of range of water-encapsulating structure solutions, each with primary ecological objective and degree of stream and floodplain connectivity indicated. (Taken from USFS, 2008.)

2. A REVIEW OF THE LITERATURE

Current literature deals with different aspects related to ecological effects of waterway-encapsulating structures. This review focuses on the literature that might have more direct applications for the design of culverts, especially for the conditions prevalent in Indiana, namely, low-gradient streams with a predominantly sandy or gravelly substrate. Studies of passability and ecological effects are first reviewed, leading to a discussion of passability models, mainly viewed as providing a practical consensus view on the variables that might be of most importance in the design of culverts for AOP. Experience with AOP culvert design in the Midwest is then recounted, followed by an overview of various approaches taken by different state agencies.

2.1 Passability and Ecological Effects of Traditional Culverts

The traditional hydraulic design of culverts did not take account of ecological considerations in the analysis, and minimizing costs often implied minimizing the culvert size (or maximizing its conveyance) to satisfy a constraint on the headwater (essentially the water surface elevation just upstream of the culvert). This led to a number of features in the flow through the culvert that are thought to present a barrier of varying degrees to AOP during periods when species are traveling, including (USFS, 2008):

- perched outlets, which are characterized by a large difference in elevation between the water surfaces at the culvert outlet and in the channel just downstream of the culvert,
- high velocities, and
- lack of a continuous substrate/refugia (refugia refers to places providing refuge to aquatic organisms from predators or adverse environmental conditions).

Culvert design for AOP is aimed at improving the passability of culverts by aquatic organisms in general and fish species in particular, and so studies of passability are relevant. Direct observations of passability require effort and specialized expertise, typically involving electrofishing for fish capture, tagging, re-release in the stream, and then recapture. Interpretation of results can be rendered difficult by low recapture rates, which can often be lower than 20% (e.g., Bouska & Paukert, 2010; Briggs & Galarowicz, 2013), such that the fate of a large majority of tagged fish is unaccounted for. Fish motivation also complicates such studies because the reason for fish not moving through a particular structure during the time of the study may be unrelated to the culvert characteristics (Burford, McMahon, Cahoon, & Blank, 2009; Mahlum, Wiersma, Kehler, & Clarke, 2014). The evidence generally indicates that such structures may reduce passability (Bouska & Paukert, 2010; Briggs & Galarowicz, 2013; Burford et al. 2009; Mahlum et al., 2014). Because these studies were not necessarily aimed at culvert design, but simply whether such structures have a measurable effect, they have not usually examined in detail the effect of individual culvert characteristics. Briggs and Galarowicz (2013) in a study of culverts in small (first- or second-order) central Michigan low-slope (less than 2%) streams is an exception, in investigating the effects of culvert type (box, pipe-arch, bottomless), length, and culvert-width to stream-width ratio. They concluded somewhat surprisingly that box were better than bottomless culverts, while the culvert length was found to be the most important feature (more important than e.g., culvert velocity or culvert width/bankfull stream width, both of which have been the focus of AOP culvert design), at least with regards to the passage of a particular species (Creek Chubb). Whether these conclusions would be generally applicable to Indiana conditions is uncertain.

The software, FishXing, developed by the U.S. Forest Service (Furniss et al., 2006) to predict fish passage for given flow conditions, has been the subject of a number of studies. A study by Baral and Tritico (2013) for the Ohio DOT used FishXing for predicting fish passage through low-slope (less than 2%) culverts in northeastern Ohio, and found that the large majority (almost 90%) posed a complete barrier for a range of flows (up to the 2-year flow). Direct measurements of fish passage have however found FishXing to be very conservative in its predictions. Burford et al. (2009) found that only one of 11 culverts was classified correctly by FishXing as complete barriers, while Mahlum et al. (2014) stated that "We were unable to accurately predict the movement of fish passage through culverts using FishXing."

Another type of related study, also requiring fish capture but not tagging, examines the fish (or other aquatic organism) communities upstream and downstream of a structure (Favaro, Moore, Reynolds, & Beakes, 2014; MacPherson, Sullivan, Lee Foote, & Stevens, 2012; Perkin & Gido, 2012; Wofford, Gresswell, & Banks, 2005). Differences in the characteristics of the upstream and downstream populations, such as the species densities and richness (or diversity), biomass, or composite measures of biotic integrity, e.g., the fish-IBI (see Chapter 4 for a more detailed discussion of fish-IBI), if found, might then be attributed partially or wholly to the presence of the structure. Studies will generally include in their analysis reference sites without any structure for a more convincing argument. Burford et al. (2009) found "little indication that fish distributions in the drainage were restricted from culvert barriers," but suggested that this might be due to a seasonal effect or that isolated populations could be self-sustaining even when separated by a complete barrier. Some overall characteristics may show little or no difference, while others show more marked differences. Favaro et al. (2014) found fish density differences to be species-specific, but found little difference in total fish density, total fish biomass or species richness. In an Alaskan study, Davis and Davis (2011) found differences in juvenile salmon catch per unit trap depending on whether the stream slope was less or greater than 1%, and cautioned that "measures of channel modifications at crossing locations alone are not adequate to evaluate potential migration barriers." The study of Ogren and Huckins (2015) may be of particular interest in that it examined the effect of replacing three culverts in northern Michigan that were believed to be seasonal barriers by a CONSPAN arch bridge, a bankfull box culvert with a natural substrate, and a bottomless arch culvert. Both a macroinvertebrate index (NLFBCI) and a fish-IBI were monitored before and after the replacement. They concluded that "substantial improvements in overall biotic scores … were *not* [my italics] detected within 3–5 years of the improved road-stream crossings," and they remark that "Local restoration efforts will not substantially increase biotic integrity if the biotic communities are driven by larger watershed processes or if degraded conditions are prevalent throughout the watershed."

While the above studies generally find that culverts can cause measurable ecological effects, little detailed quantitative reliable information that might be useful in culvert design was found. For example, if the bankfull stream width is taken as a reference, is the effect of choosing a culvert span that is 0.75 of the bankfull width negligible or catastrophic? This is relevant as a screening tool developed for the Washington Dept. of Fish and Wildlife (Barber, 2009; see the discussion in the next subsection and Figure 2.1) uses this as a passability criterion. Or, if median diameter of the substrate within the culvert is twice that in the natural stream, what is the effect, if any, on passability or the broader stream ecology?

2.2 Passability Modeling

Because of the effort required to measure directly passability, attempts have been made to predict culvert passability from more easily observed physical characteristics of culverts (despite the admonition of Davis and Davis (2011) above). The FishXing software model developed by the U.S. Forest Service is an example of a very detailed model, but as noted already has been found to be very conservative. For the present purposes, the focus is less on the predictive performance, but rather on the choice of culvert variables

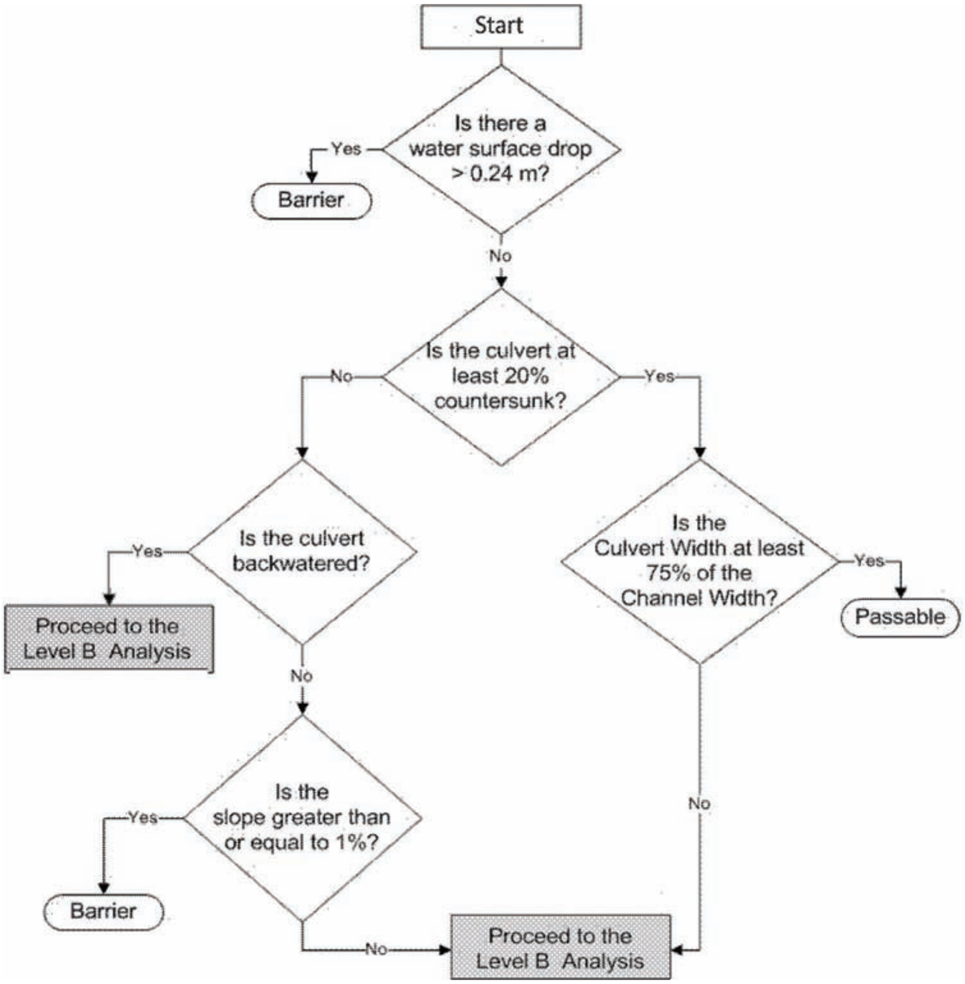


Figure 2.1 Flow chart for a screening tool developed by Barber, Cierebiej, and Collins (2009) for assessing culvert passability.

as these might be considered the consensus view on the most important culvert characteristics in AOP design.

The passability variables most commonly encountered are: (i) a perching parameter, such as drop in the outlet water surface elevation, (ii) velocity within the culvert (or possibly a constriction ratio, such as the culvert-width to bankfull-width ratio), (iii) the presence or absence of a "natural" substrate within the culvert, (iv) the degree of embeddedness or sumping of the culvert, and (v) the water depth in the culvert, where a base flow is usually assumed. Whereas Diebel, Fedora, Cogswell, and O'Hanley (2014) used all five variables to quantify passability, Januchowski-Hartley et al. (2014) chose to use only (i) and (ii), primarily due to the lack of any available reliable data for the other three variables. A flowchart of a screening tool developed for the Washington Dept. of Fish and Wildlife to assess culvert passability is given in Figure 2.1. The water surface or outlet drop (from culvert outlet to stream) measures the degree of perching, while countersinking implies an embedded structure with a "natural" substrate all along its length. Thus, if the outlet drop is less than ≈ 9 in (24 cm), the structure is embedded at least 20% of its rise, and the culvert width is at least 75% of the channel width, then according to Figure 2.1 the culvert is passable. A more in-depth level B analysis involving flow calculations may be needed if these conditions are not fulfilled. The empirical basis of the values chosen (e.g., 0.24 m drop, or 20% embedment, or 75% of the stream width) is not well documented.

A related but different approach was taken by Barnard, Yokers, Naygygyor, and Quinn (2014) in evaluating the "performance" of culverts designed according to the stream simulation philosophy. Stream simulation, which aims to simulate the natural stream *within* the culvert, is described in more detail in USFW2008 and in the next chapter. Passability was not directly determined, but the evaluation quantified how similar the stream within the culvert was to the natural stream, in terms of, e.g., sediment characteristics, velocities, and depths, and this was taken as an indicator of the "performance" of a culvert. Interestingly, it was found that "None of the study culverts shows the effects of culvert span relative to bankfull width on sediment texture, velocity ratio, or thalweg depth.," though the authors speculate that "there were too many factors at play to demonstrate what should be obvious and causal relationships."

2.3 Experience with AOP Designed Culverts in the Midwest and Other Regions

2.3.1 Ohio

Tumeo and Pavlik (2011) reported on a study of sumped bankfull culverts for the Ohio Dept. of Transportation (ODOT). At that time, to comply with regulation, ODOT culvert design policy specified that bankfull culverts, which approximate the stream width-to-depth ratio at bankfull discharge, should be installed and that these should be buried ≈ 10% below stream grade. It appears that, similar to the current INDOT design policy, backfilling is *not* required, under the assumption that a natural substrate will eventually become established due to sediment being transported from the upstream channel and being deposited within the structure. The ODOT (2014) design procedure for bankfull-width culverts differs from the widely known U.S. Forest Service approach (USFS2008) or the Federal Highway Administration (FHWA) approach (described in Kilgore, Bergendahl, & Hotchkiss, 2010; to be referred to hereafter as HEC-26) that will be discussed in detail in the next chapter.

From a sample of 59 structures, Tumeo and Pavlik (2011) found that only 22 of 44 circular, 9 of 12 box, and 3 of 3 elliptical culverts could be classified as embedded, i.e., had a continuous substrate throughout the length of the culvert, with the maximum substrate thickness for the circular culverts varying from 3.5% to 50% of the diameter. Although there may seem to be dependence on culvert geometry, Tumeo and Pavlick (2011) cautioned that the sample size of non-circular culverts was too small for a statistically significant conclusion. They did conclude that, in cases with larger slopes (>1%), a natural substrate throughout the structure was generally absent, leading to their recommendation that sumped "bankfull culverts should not be installed at slopes greater than 1%." In line with this recommendation, the current ODOT (2014) policy exempts culverts with slopes greater than 1% from the sumped bankfull design requirement. It should however be pointed out that slope is strongly correlated with bank-full width (and discharge), and hence with culvert span and even type as well as characteristic substrate size, and it is difficult to isolate the effects of slope from the effects of those other variables. Regional variations are also likely to play a role. Also some of the photographs in their report suggest that the culvert spans may not have been close to bankfull width, which might also have contributed to the absence of sediment within the structure.

While they did not include it in their major recommendations, Tumeo and Pavlik (2011) did suggest, based on their data analysis, that backfilling with sediment or installing features such as baffles within the culvert could be beneficial. It is also interesting that they also conducted assessments of the qualitative habitat evaluation index (QHEI—this index is discussed in greater detail in Chapter 4) at sites where QHEI had been assessed prior to the culvert installation. They assumed that any upstream change in QHEI was due to "natural" causes, while any downstream change was due to the culvert, which seems rather simplistic. Changes in QHEI greater than ±10 were common, which is somewhat surprising since most of the metrics making up the QHEI should be relatively insensitive to the changes that could result from the presence of the structure. Indeed, Tumeo and Pavlik (2011) found no correlation between the net difference between upstream and downstream QHEI changes and the other parameters.

The study of Baral and Tritico (2013), also performed for ODOT, was already mentioned in the preceding subsection with regards to their application of the FishXing software. While FishXing might be overly conservative in predicting passability, its qualitative results regarding the important culvert variables to enhance passability may still be useful. From their FishXing simulations, they found that embedding the culvert with gravel (resulting in a Manning's n roughness coefficient of 0.04, thus reducing velocities and increasing depths for given discharge) and increasing the culvert diameter (again thus reducing the velocities) were the two measures most effective in converting a complete barrier (according to FishXing) to a partial barrier.

2.3.2 Minnesota

In Minnesota, an AOP culvert design approach has been developed, and is generally referred to by the acronym MESBOAC, an abbreviation for:

i. Match culvert width to bankfull stream width
ii. Extend culvert length through to the side slope toe of the road
iii. Set culvert slope the same as the stream slope
iv. Bury the culvert
v. Offset multiple culverts
vi. Align the culvert with the stream channel
vii. Consider headcuts and cut-offs

It is pointed out that several of these items (iii, iv, and vi) are already recommended in the INDOT standard culvert design, and the main difference is item (i). It seems also to be the case that the Minnesota practice, as currently in Ohio and Indiana, does not require backfilling and "embedding" the culvert with a more natural substrate. The study of Hansen, Johnson, Nieber, and Marr (2011) examined 13 culverts in Minnesota designed following the MESBOAC procedure, including burying or recessing the culverts. Unlike the Tumeo and Pavlik (2011) study, most of the culverts in the Hansen et al. (2011) study were relatively large (sumped culvert spans larger than or equal to 8 ft) and indeed most sites had multiple culverts (which complicates interpretation), as well as low-gradients (maximum slope <2.5%) and gravel/cobble substrates. They, similar to Tumeo and Pavlik (2011), classified 6 of the 13 MESBOAC culverts as not functioning as designed if less than 10% of the length of the (main) recessed culvert had a sediment substrate. Two of the three single-barrel sites deemed non-functioning were severely undersized (culvert span to bankfull width ratio <0.55), while the third was also undersized (culvert span to bankfull width ratio of 0.8) but had some sediment and so was not classified as not functioning. It was not clear whether the culvert span was deliberately designed against the MESBOAC guidelines, or the undersizing resulted from an "erroneous" evaluation of bankfull width. In contrast to Tumeo and Pavlik (2011) "non-functioning" culverts were equally divided in slopes greater than and less than 1%, and so it was concluded that there was "no correlation between higher culvert slope and a lack of accumulated sediments in the recessed culvert."

The culvert design guidelines addressing AOP issues in Indiana, Ohio and Minnesota requires sumping the culvert but not backfilling or embedding with a substrate. The laboratory study of Kozarek and Mielke (2015) funded by the Minnesota Dept. of Transportation examined conditions under which a sumped but not backfilled "bankfull-width" box culvert would become "naturally" embedded through sediment transport from the upstream channel. In order to maintain instrument access within the model culvert, the top of the culvert was omitted and so it was not possible to simulate high discharges. As a result, washing out of sediment within the culvert was not observed. For a model recessed culvert in a moderate-slope (1.5%) fine to medium gravel-bed channel, an initially not backfilled culvert was observed to become eventually embedded in both a steady bankfull-discharge flow and in an unsteady hydrograph flow during which bankfull discharge was exceeded, but in the latter case some degradation was noted at upstream and downstream sections. When initially backfilled, the culvert remained embedded under the same flow hydrograph, but under a steady bankfull flow some degradation occurred at upstream sections. For a low-slope (0.2%) channel with a sand substrate, an initially not backfilled culvert was observed to remain unfilled or only partially filled under the different flow conditions, but remained filled with an initially backfilled culvert. For a higher-gradient (3%) fine-to-medium gravel channel, extensive scour occurred and a stable substrate was difficult to achieve under the different flow conditions. Only with the introduction of "structures," by which is meant stable "non-native" elements such as large cobbles placed in a regular form so as to enhance substrate stability, could a substrate over the entire length of the culvert be maintained. These results indicate that, though a sumped non-backfilled culvert may eventually develop a natural bed, it may require detailed analysis to determine the appropriate conditions. At least for low- to moderate-slope conditions, backfilling a sumped bed is more likely to lead to a stable substrate within the culvert. For higher-slope (or possibly higher-transport) conditions, "artificial" stabilizing elements may be necessary. Because of scaling limitations as well as the restriction to moderate discharges, the results should be cautiously interpreted. For example, the artificial "structures" may also be necessary for substrate even for low- and moderate-slope conditions, and what precisely would low- and moderate-slope conditions correspond to in the field can be debated. While Kozarek and Mielke (2015) considered their 3% slope "high-gradient," this is often considered the limit of "low-slope" restriction for "no-slope" or "low-slope" culvert design (discussed further below).

2.3.3 Wisconsin

An ongoing research project is being conducted by the Wisconsin Department of Transportation (WisDOT) with a number of culverts following two different AOP-design approaches, that of USFS2008 and that of HEC-26, being installed. A project report has not yet appeared, though some results have been presented (Kirsch, 2014); more details of two field cases studied will be given in Chapter 3.2 and 3.3, where these two design approaches are discussed.

2.3.4 Other states

Several states, either Depts. of Transportation or other agencies, have published design guidelines addressing AOP issues (Barnard et al., 2013; Bates & Kirn, 2009; Caltrans, 2007; MaineDOT, 2008; MassDOT, 2010). Detailed design aspects are discussed where relevant in the next chapter; here broader considerations are noted. The very strong influence of the general approach developed in Washington is apparent in most of these guidelines (one of the key figures in the development of the Washington approach was a coauthor of the Vermont guidelines). Three main approaches are described: (i) a "stream simulation" approach (that advocated in USFS2008), (ii) a no-slope or low-slope simplified approach, and (iii) a "hydraulic" design approach (see also Figure 1.3). In the present context, the point to emphasize is the different approaches for different conditions. The "no-slope" or "low-slope" might be considered a simplification of the "stream simulation" approach for cases of low-gradient smaller streams (restrictions vary, but in the Washington manual, short culvert of length less than 75 ft, slope less than 3% and bankfull width less than 10 ft are given as rough guidelines). The hydraulic design option targets specific species, and requires explicit information regarding species characteristics such as swimming speeds and jumping abilities. The Washington manual suggests that this option has only "limited application in exceptional circumstances," but the Maine guidelines might be categorized as adopting this approach. Due to its reliance on detailed species characteristics, which for Indiana is not widely available, the present work will not consider the hydraulic design option.

2.4 Summary

The literature on AOP in and passability of culverts, emphasizing work that might be especially relevant to hydraulic design, was reviewed. Direct effects on passability have been observed, but these can be quite species- and season-specific, and interpretation can be further complicated by low recapture rates and questions regarding fish motivation. The complexities also cause difficulties in attributing effects to specific design choices, such as culvert span to channel width or culvert length or culvert bed characteristics. Thus, models such as FishXing aiming to predict passability can be overly conservative and may not be reliable in their assessment of completely impassable barriers.

Unlike some western and northeastern states such as Washington, California, and Massachusetts, that have essentially adopted the USFS2008 stream simulation approach, midwestern states such as Indiana, Ohio and Minnesota have recently started experimenting with various AOP-motivated measures such as bankfull spans and sumping. Backfilling to install a bed within the culvert was generally not required, under the assumption that a sumped culvert would naturally develop a bed. It was however noted that many or even most of these non-backfilled culverts did not develop a continuous bed along its length, raising questions about the design. In view of the latest Indiana regional general permit conditions requiring backfilling for culverts with spans larger than 12 ft, a more systematic study of culvert design for AOP may be warranted.

3. CULVERT DESIGN APPROACHES

3.1 The Traditional and Current INDOT Approaches

A culvert is defined by the FHWA and in INDOT2013-203-2.02 as a structure with a total span less than 20 ft, and the focus of the present study will be on such structures, as they are considered to be more problematic than bridges (with spans greater than 20 ft) as far as habitat connectivity and fragmentation are concerned. The traditional hydraulic design of culverts is described in Normann, Houghtalen, and Johnston (2001), and embodied in the standard software HY-8 (up to version 7.3, which is assumed in the following) and HEC-RAS (up to version 4.1). As specified in INDOT2013-203-2.02, HY-8 and HEC-RAS are the *only* "computer programs allowed for the hydraulic analysis of culverts," though the manual (non-software) "FHWA HDS #5 *Hydraulic Design of Highway Culverts* is also acceptable." The detailed modeling in HY-8 and HEC-RAS differs slightly, and the present study will assume HY-8 as the more common tool for culvert analysis. The discussion is restricted to hydraulic aspects with those considered especially relevant to AOP issues to be highlighted; structural or geotechnical questions will not be addressed, except insofar as they distinguish traditional from non-traditional approaches.

3.1.1 Design Objectives, Constraints, and Guidelines

The primary objective in traditional culvert design is the satisfaction of a constraint on the headwater, i.e., the water surface elevation just upstream of the culvert, for a single design peak discharge, Q_T, typically based on a recurrence interval, T (or exceedance probability), such as a 100-yr event (Q_{100}, corresponding to an exceedance probability of 1%). This may also be expressed in terms of the backwater (as in INDOT2013-203-2.02, Figure 203-2C, which lists the different Q_T for different types of roadways), which is the change in water surface elevation that can be attributed to the presence of the structure relative to the *existing* condition. In the case of a culvert replacement project, the existing condition is already created by an existing culvert (in INDOT2013-203-2.02, existing condition for a replacement structure is more restrictively defined as those constructed prior to 1974) and may not be "natural." In the case of a new culvert, the existing condition would be that associated with the "natural" stream undisturbed by any structure. Current Indiana Dept. of Natural Resources (IDNR) regulations limit the backwater to 0.14 ft (INDOT2013-203-2.02 gives some exceptions), but for replacement projects, INDOT has a more restrictive policy. While the traditional design is based on a single discharge, the standard HY-8 automatically evaluates a series of headwater values for a range of discharges up to a maximum discharge, $Q_{\max}$, with $Q_T \leq Q_{\max}$.

In addition to the basic objective of satisfying the headwater constraint, several other recommended guidelines in INDOT2013-203-2.02 may be highlighted as relevant to the discussion of AOP. These are not directly related to standard culvert hydraulics and so are not treated in HY-8, and include (INDOT, 2013):

i. "The culvert length and slope should be chosen to approximate existing topography and, as practical, the culvert invert should be aligned with the channel bottom and the skew angle of the stream."
ii. "It is not recommended that the plan location of a culvert should result in a "severe or abrupt change in channel alignment upstream or downstream."
iii. "The culvert profile should approximate the natural stream profile."
iv. "The minimum velocity in the culvert barrel should result in a tractive force, $\tau = \gamma dS$, greater than critical τ of the transported streambed material at a low-flow rate. A flow rate of 3 ft/s should be used if the streambed-material size is not known."
v. "Sumping should be provided for each structure over Waters of the United States and Waters of the State. … The sump area of the structure and end section or riprap will not require backfill as part of the contract work, but will be allowed to fill in naturally over time."

Points (i), (ii), and (iii) indicate already a design objective to adapt the culvert to specific site conditions, and an awareness of the potential practical advantages of minimizing disturbances to the natural stream geometry, that is similar to the perspective motivating AOP design considerations. Point (iv) however is intended, like similar guidelines in sewer design, to inhibit deposition of material and hence to keep the culvert clean, thus maintaining its hydraulic conveyance and performance. Viewed more generously, this condition may be interpreted as a preference for a stable bed that neither aggrades (builds up due to excess deposition) nor degrades (scours due to excess erosion). Further if a bed is initially designed to exist in the culvert and its elevation does not undergo any long-term changes due to aggradation or degradation, then its hydraulic performance also should not change from that initially designed. The referred to low-flow rate though is not well defined. The last point (v) reflects an attempt by INDOT to deal with the AOP issue through the use of oversized embedded or sumped culverts. Point (v) may be problematic, and even might be considered inconsistent with point (iv). If the aim of point (iv) is successful and deposition is inhibited, and if the sumped area of the structure is not backfilled, then the natural filling-in process will not occur at all or will occur only very slowly, so that the sumped area may differ from the natural stream profile for a long time.

The above guidelines from INDOT2013-203-2.02 suggest that the current INDOT culvert design standard already takes into account some of the concerns raised by AOP at least to a limited extent. For new culvert installations, the combination of the sumping recommendation and the constraint on backwater may be sufficient to result in a design that complies in most if not necessarily all respects with the newly published AOP-related regulations. A weak point concerns the design of the bed within the culvert, since the current IDEM RGP requirements mandate a backfilled culvert, but this is not covered in INDOT2013-203-2.02. Because regulation of replacement culverts may differ from those of new culverts, the present study is aimed mainly at new structures, but the basic approach should also be applicable to replacement structures.

3.1.2 Data Requirements

The basic data required in HY-8 and of the traditional culvert hydraulic design consist of:

i. design discharge (or range of discharges),
ii. tailwater (the water surface elevation just downstream of the culvert) conditions, which can be characterized by various means, including
    a. a single cross-section just downstream of the culvert, which, together with the corresponding channel slope, is used to determine a normal depth, or
    b. a rating curve, which relates the downstream water surface elevation to any given discharge,
iii. roadway characteristics, such as the elevation and the crest length (these data are used for examining the consequences of roadway overtopping, and are of little relevance for the present purposes),
iv. culvert attributes, such as geometry and roughness, used to determine the headwater for given discharge and given culvert, and
v. site data, such as culvert length and slope, which might also be considered culvert attributes and serve the same purpose.

The above basic data requirements reflect the main concerns of the design procedure. Detailed characterization of the stream is not necessary, indicating little attempt in the analysis to replicate stream conditions within the structure. To what extent the flow and boundary characteristics within the culvert approximate the natural conditions rests therefore primarily on the general recommendations discussed in the preceding subsection.

3.1.3 Scour Issues

Scour is an important issue in the design of culverts though the major motivation for dealing with scour has traditionally been the integrity of the structure rather than any concern for AOP. The often high velocities resulting from the traditional emphasis on minimizing culvert size can lead to conditions at the outlet (and possibly also the inlet) that are especially conducive to local scour unless countermeasures are taken. HY-8 includes a software tool for scour design at culvert outlets, but the standard options, such as drop structures, may not be AOP-friendly. On the other hand, some options such as the riprap basin (or energy dissipator according to INDOT2013-203-2.04) may prevent or mitigate the development of a perched culvert that is usually considered (see Chapter 2) a serious barrier to AOP. It should be noted that INDOT2013-203-2 does not describe in detail a number of scour-countermeasure options available in HY-8, but rather refers to FHWA manuals such as HEC-14. The only two scour countermeasures covered in any detail in INDOT2013-203-2 are riprap aprons and riprap basins, and so are likely the most commonly chosen in Indiana practice. As such, the HY-8 energy dissipator design tool may be relatively little used.

3.1.4 Current INDOT Guidelines and Compliance with the Regional General Permit Conditions

The current standard INDOT (2013) design guidelines as given in INDOT2013-203-2.02 have already been summarized in Section 3.1.1; here, the "gaps" related to the current Regional General Permit (RGP) conditions will be highlighted. The RGP conditions specifically related to AOP may be divided into those that apply to any waterway-encapsulating structures and those that apply only to larger structures that span a channel with an ordinary high water (OHWM) width, $W_{\mathrm{OHWM}} > 12$ ft. The sumping requirements, for example, apply to any structure. Two aspects of the RGP conditions that are not specifically dealt with in the INDOT2013-203-2.02 concern (i) the size of the structure, and (ii) the backfilling within the structure. Although INDOT2013-203-2.02 explicitly includes the RGP sumping requirements, and so implicitly calls for "oversized" structures, explicit guidance on structure size is not given. On the other hand, the RGP specifies not only a minimum area (related to the channel area below the OHWM) for all structures, but also a minimum width, namely the OHWM width, for channels with $W_{\mathrm{OHWM}} > 12$ ft. Also for $W_{\mathrm{OHWM}} > 12$ ft, the RGP also requires that the culvert be backfilled with "natural" material, whereas INDOT2013-203-2.02 specifically states that backfilling is not necessary. INDOT2013-203-2.02 does have a "catch-all" clause stating that all applicable IDEM regulations should be followed, which presumably supersedes all other specific recommendations. Tying design guidelines closely to regulations does have the disadvantage that changing regulations will require changes in the standard design approach, and design guidelines may be more flexibly formulated in terms of more general procedures that might be applied to a wide range of regulations and/or policies. The following focuses on the requirements for larger culverts requiring the design of the culvert bed and the backfill material.

3.2 The U.S. Forest Service Stream Simulation Approach

3.2.1 Design Objectives, Constraints, and Guidelines

As described in USFS2008, the stream simulation approach to AOP design of culverts developed by the Washington Dept. of Fish and Wildlife and the U.S. Forest Service, as the earliest documented comprehensive design procedure for the U.S. focusing on the AOP issue, has been extremely influential. The approach is primarily geomorphic, emphasizing the characterization of the natural stream geomorphology, and aiming at reproducing as much as practical the natural stream characteristics within the encapsulating structure. If this objective were perfectly satisfied, then the AOP issue would be resolved as the conditions encountered by aquatic organisms within the structure would be exactly the same as those in the natural stream. The approach borrows substantially from the Rosgen stream restoration technique in terms of concepts and terminology. Thus, it relies on the identification of a reference reach, the bankfull width plays a prominent role in sizing the structure, and the Rosgen stream classification scheme is often used. The natural variability of streams over time is also recognized and potential channel dynamic response to culvert installation is considered.

Chapter 6 of USFS2008 lists the main steps involved in a (USFS) stream simulation culvert design as:

i. Determine project alignment and profile
ii. Verify reference reach and stream simulation feasibility
iii. Design bed material size and arrangement
iv. Select structure size and elevation
v. Verify stability of simulated streambed inside structure
vi. Document design decisions and assumptions

While the traditional approach focuses and expends the most design effort on step (iv), the USFS procedure takes a broader perspective. With the primary objective of reproducing as closely as practically feasible the natural stream conditions within the culvert, much more attention is paid to alignment and profile considerations. The implications of channel processes, such as incision, for the project alignment/profile are discussed in detail. As in stream restoration, the stable reference reach is selected as a model or template for the project reach, and the two should be similar as far as stream hydraulics, hydrology, and sediment transport are concerned. For a new construction, the reference reach can be the existing reach, while for a replacement project, the reference reach is often chosen as being sufficiently far upstream (or possibly downstream) so as to be effectively undisturbed by the existing culvert, but still similar to the "natural" project reach, particularly in slope.

Culvert span sizing. The hydraulic analysis of culverts aims to determine mainly the appropriate span (width, W_c) and rise (height, R_c) of the structure, and if the culvert is to be embedded, the sump depth, h_{smp}, to satisfy the various design objectives and constraints. The major consideration in the sizing of the culvert span according to USFS2008 is the reference reach bankfull width, W_b, defined as that occurring at bankfull elevation (stage), which is in turn conceptually defined as that when a channel is just filled (see Figure 3.1a). In practice, identification of the bankfull width may be imprecise, and small differences could lead to relatively large changes in bankfull width. In Figure 3.1b and c (taken from USFS, 2008), cross-sectional profiles are shown with bankfull elevations defined, but while that in Figure 3.1b evidently fits the simple conceptual definition, that in Figure 3.1c less obviously fits as there is no clear break in slope to mark the channel top. Guidelines in identifying bankfull elevation are given in USFS2008 (see also Robinson, 2013 for a study of bankfull widths of wadeable Indiana streams). Where the bankfull elevation may not be well defined, e.g., bedrock channels, the ordinary high water mark (OHWM), which is a physical indicator (scarring) on the bank marking the upper boundary of the region of long-term submergence, is to be used. USFS2008 also discusses the identification of the OHWM but this is treated in much greater detail in Olson and Stockdale (2010). Appendix A compares bankfull and OHWM widths for Indiana streams.

The designed culvert span, W_c, is typically larger than W_b, as shown in Figure 3.2, to allow the inclusion of boundary or bank features and some limited stream adjustment. The bank features are designed to be immobile for all flows, and USFS2008 suggests that a bank region with a width as much as 2 d_{95} (here d_a refers to the size such that $a\%$ by weight of the material would be smaller than d_a) on each side might be considered in an initial preliminary design. For a channel consisting of finer material with $d_{95} \leq 3$ in, a minimum class size of 6 inches minus rock, i.e., $d_{100} = 6$ in was recommended, which would add at least another foot to W_b for the culvert span. For streams with much coarser material (large cobbles and boulders), the $2d_{95}$ suggestion may add excessively (more than 3 ft) to the width, and a more detailed stability analysis may yield smaller-sized bank material. A number of states that specify the stream simulation or the related no-slope approach for AOP culvert design have given as a rough rule, $W_c = 1.2W_b$. Barnard et al. (2013) in the Washington state manual is even more expansive, recommending that $W_c = 1.2W_b + 2\text{ft}$, though they admit that "The degree to which the culvert sides must extend beyond

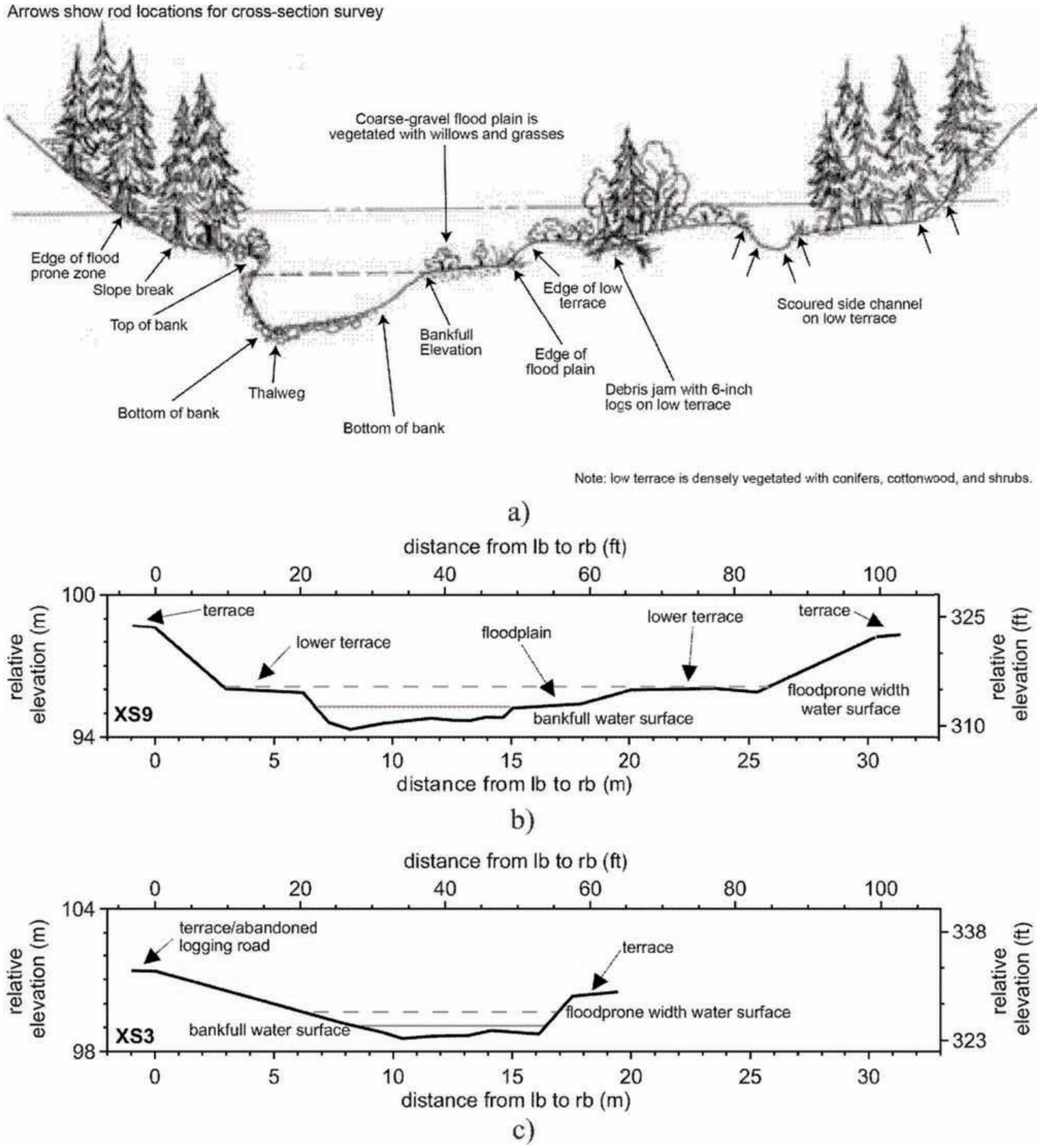


Figure 3.1 (a) Sketch of channel cross-section, indicating bankfull elevation, (b) and (c) sample cross-sectional profiles indicating bankfull water surface. (All taken from USFS, 2008.)

this width [bankfull width] is a matter of debate, …" Also the requirement that the installed bank features should be immobile for all flows implies that large stones (see Figure 3.5 for an example) are used for the banks, which might be considered unnatural.

Culvert sump depth and rise. Streams are typically wider than they are deep, and so a bankfull-width-based guideline for the span might result in a larger than necessary culvert rise if a circular culvert were chosen, and so may make these impractical. For non-circular culverts, culvert sizing may require a specification of the rise or height (R_c) in addition to W_c, and also the related sump depth, h_{smp}. INDOT2013-203-2.02 and the current RGP specify h_{smp} depending on structure size and stream bed material.

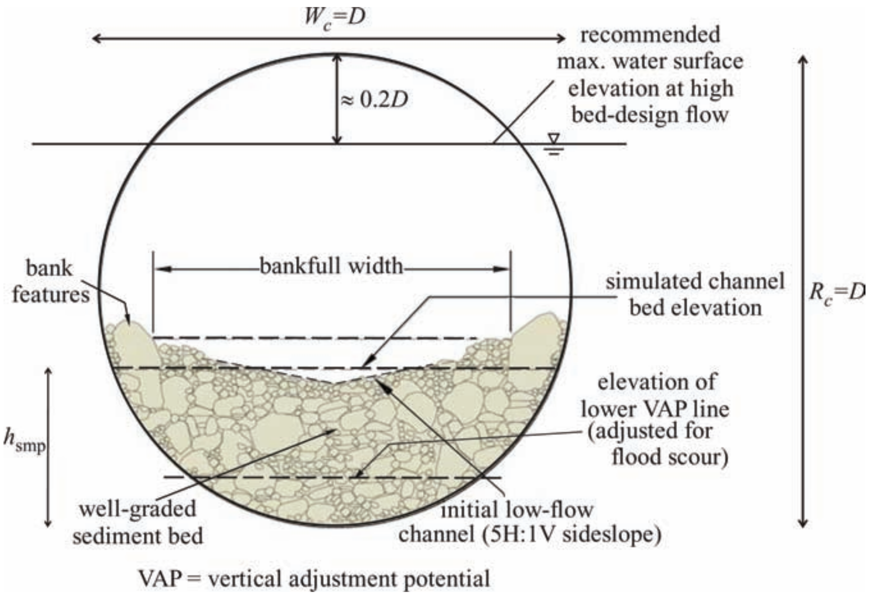
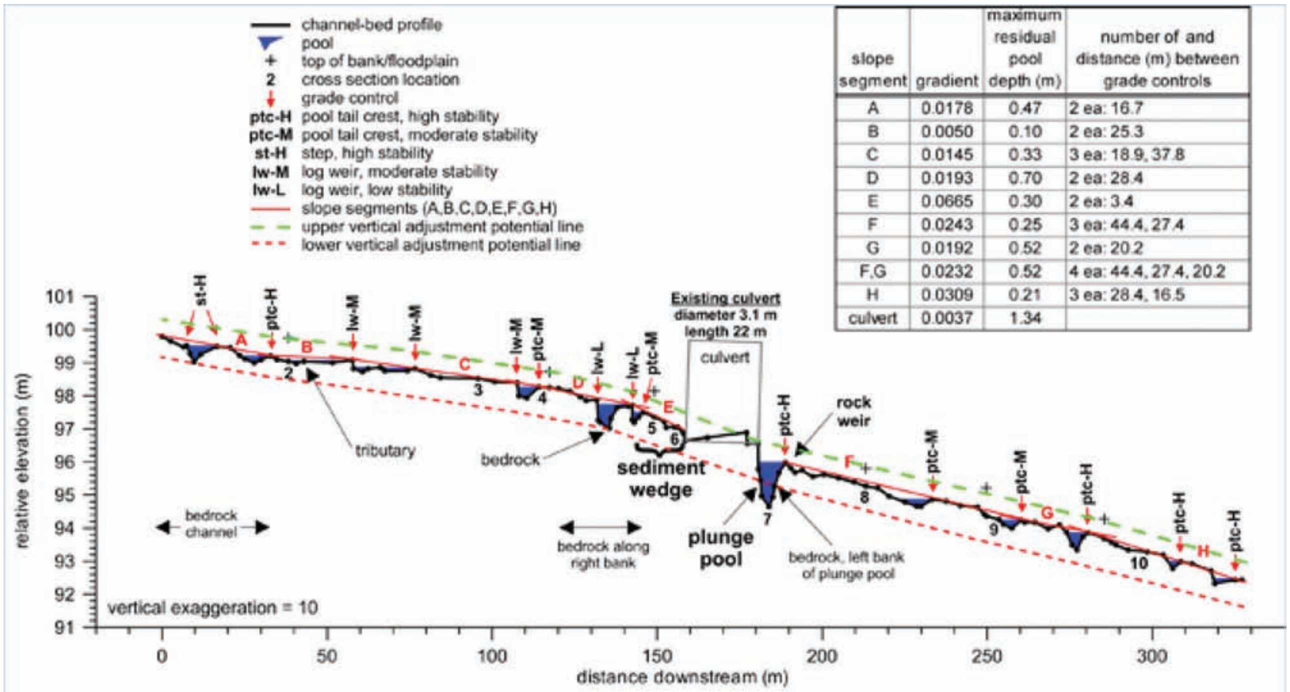


Figure 3.2 Sketch of simulated streambed within a circular embedded (sumped) culvert sized to contain the bankfull width as well as bank features. (Adapted from USFS, 2008.)



slope segment	gradient	maximum residual pool depth (m)	number of and distance (m) between grade controls
A	0.0178	0.47	2 ea: 16.7
B	0.0050	0.10	2 ea: 25.3
C	0.0145	0.33	3 ea: 18.9, 37.8
D	0.0193	0.70	2 ea: 28.4
E	0.0665	0.30	2 ea: 3.4
F	0.0243	0.25	3 ea: 44.4, 27.4
G	0.0192	0.52	2 ea: 20.2
F,G	0.0232	0.52	4 ea: 44.4, 27.4, 20.2
H	0.0309	0.21	3 ea: 28.4, 16.5
culvert	0.0037	1.34	

Figure 3.3 Example of longitudinal stream profile and the definition of upper and lower vertical adjustment potential (VAP) lines. (Taken from USFS, 2008.)

In the USFS2008 approach, culvert rise, R_c, and sump depth, h_{smp}, are discussed in terms of the vertical adjustment potential (VAP) or upper and lower VAP lines. By definition, these lines "represent respectively the highest and lowest likely elevations of any point on the streambed surface in the absence of any crossing structure." In order to avoid a situation where the culvert bottom becomes exposed, the culvert needs to be sumped to a level below the lower VAP line (see Figure 3.2). For a channel in stable equilibrium, i.e., one that is neither degrading nor aggrading, the lower VAP line is typically estimated from the longitudinal streambed (thalweg) profile by identifying the deepest naturally occurring pool. The depth of this pool relative to the mean bed elevation at that section is taken as the depth of the lower VAP line. This is illustrated in Figure 3.3, an example taken from USFS (2008). The deep pool at the existing culvert outlet is not considered as it is thought to be directly caused by a purely local and "non-natural feature," namely the culvert. The underlying assumption is that the reach over which the longitudinal profile, including the section where the deepest pool is located, is entirely representative of conditions at the crossing, and hence that the same processes leading to the development of the deepest pool could potentially also occur within the culvert over the culvert lifetime.

The choice of the extent of the reach in which the longitudinal profile is taken therefore assumes an important role in the USFS2008 approach, as the choice of a shorter overall reach in the example of Figure 3.3 might have resulted in a lower VAP line that was significantly higher in elevation. On the other hand, choosing an overly long reach increases the likelihood that segments are included that might not be representative of the stream crossing region. It might also be argued that it would be more logically consistent to base the determination of the VAP lines solely on the reference reach, which however may be too short to be representative.

In addition, because the measured streambed profile may reflect mainly the state corresponding to the flow conditions at the time when the profile was taken, the potential effect of scour or erosion during a flood event may need to be considered in estimating the lower VAP line for use in culvert design. A recommendation is given in USFS2008 only for the limited case of armored gravel-cobble bed streams, namely that the lower VAP line should be lowered further by $2d_{90}$ to account for possible scour. For more highly mobile material, scour could be considerably more severe, so that the lower VAP line may need to be lowered substantially.

The upper VAP line can also be similarly determined, and the culvert rise should be chosen so as allow the culvert bed elevation to increase to the upper VAP line without any serious blockage. In practice, this is less likely to be of concern, as an upper bound for the upper VAP line is usually the bankline, and if the span is chosen to be equal to or greater than the bankfull width, the bankline will typically be significantly below the culvert crown.

Design discharges. The choice of the culvert rise will also be influenced by the design discharges. In USFS2008, culverts are designed specifically to pass two types of discharges: (i) a high structural-design flow, $Q_{\text{st-d}}$, and (ii) a high bed design flow, $Q_{\text{b-d}}$. Although USFS2008 defines $Q_{\text{st-d}}$ as "A high flow which, when exceeded may cause the crossing structure to fail," it seems to correspond to the traditional design peak flow, which is however not necessarily related to structural integrity. The high bed-design flow, $Q_{\text{b-d}}$, is "A high flow, which when exceeded may mobilize rocks designed to be permanently immobile and possibly cause the simulated streambed to wash out of the culvert" (USFS, 2008). No specific recommendation is given for the choice of $Q_{\text{b-d}}$ (or $Q_{\text{st-d}}$) but in some contexts, the flow that causes a certain sediment size, e.g., d_{85}, to move in the reference reach, is used. In practice, $Q_{\text{b-d}}$ seems to be taken as the traditional peak flow. Cenderelli, Clarkin, Gubernick, and Weinhold (2011) and Gillespie et al. (2014) indicate that in stream simulation designs the headwater to depth ratio is required to be less than 0.8 (see Figure 3.2) for Q_{100} (which is a typical peak discharge for culvert design) and are often found with values as low as 0.6.

A low flow is also mentioned but no guideline is given nor any analysis performed that is specifically aimed at dealing with low-flow conditions, other than an initial low-flow channel (suggested sideslope of 5H:1V) be installed in the simulated stream (see Figure 3.2). This initial low-flow channel is not expected to be stable, but instead a natural low flow channel will emerge as the result of the flow working on the bed within the structure. The assumption is that if the simulated stream is correctly designed based on the reference reach, then any low-flow condition should be automatically accounted for, with no need for any specific low-flow measures.

Culvert bed design. The stable culvert bed/bank is the defining feature in the stream simulation approach, which aims to recreate (simulate) the stream within the culvert as much as is practical. As such, a prime design problem is the specification of the bed material to be used. Ideally the material within the culvert bed should match the material in the stream, particularly in the reference reach. A perfect match is however unlikely to be achieved in practice, due to limitations in the characterization of the channel material. USFS2008 points out the standard pebble count surface sampling procedure typically used for gravel-bed streams will generally under-represent the finer material in the subsurface. Basing the sediment size distribution of the culvert bed on pebble counts will therefore result in a mixture that is coarser overall than the reference reach distribution, but this specification is accepted as including a "safety factor for the simulated bed" as the coarser material is less likely to be scoured. A major concern is however that the coarser material might allow too much infiltration and flow into the bed, which might be especially problematic under low-flow conditions. It should therefore be ensured that there should be sufficient fine material to fill the voids between the coarse material so as to limit subsurface flow. Finally, in a discussion of managing risks during flood events where flood-plain flows are forced to go through the culvert, one recommended option for maintaining a stable bed within the culvert is to "bury a layer of riprap deeply below the simulated streambed." Under the more frequent conditions, the riprap would not be exposed, but in high-flow events the riprap layer would be engaged but would remain immobile and thus act as an armor layer so that the bare culvert surface would not be exposed.

The no-slope design. In states that have officially adopted the stream simulation approach as standard,

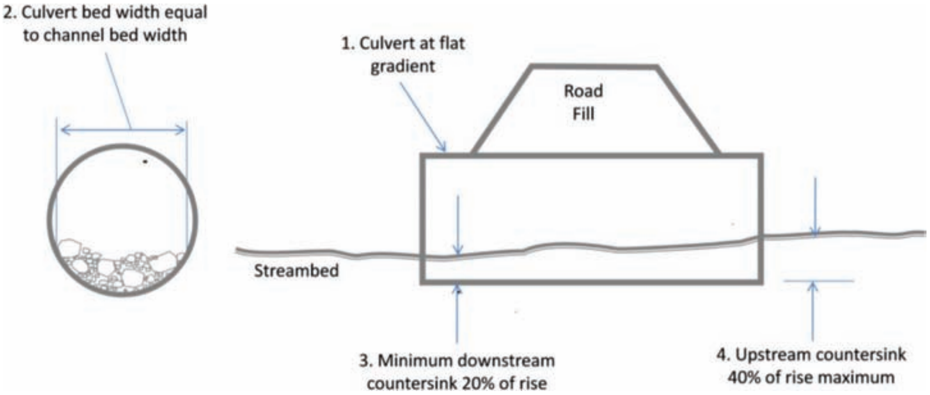


Figure 3.4 Sketch of a no-slope culvert design according to Barnard et al. (2013) for Washington State.

the no-slope approach is usually also accepted under restricted conditions of small streams and low channel gradients (e.g., less than 3%). The no-slope approach might be considered as a simplification of the stream simulation, in that as Barnard et al. (2013) notes, it was intended to require "no special design expertise or survey information." Similar to the stream simulation approach, culvert spans are typically based on the bankfull width, such as $W_c \approx 1.2W_b$ for a circular culvert ($W_c \approx W_b$ for a box culvert). The term "no-slope" describes the zero-slope at which the culvert is installed, which however implies a varying sump depth (Figure 3.4). At the culvert outlet, the sump depth is specified to be at least 20% of the culvert rise, while at the inlet, it is specified to be at most 40%, with the variation due to sloping bed within the culvert. These sump conditions also limit the practical culvert length to less than 75 ft. The characteristics of the backfill material and its placement should attempt to replicate those in the natural channel. In California (Caltrans, 2007), a low-slope version is accepted where the culvert slope is matched to the stream slope, and if the culvert is short enough (less than 50 ft), then backfill is not required.

3.2.2 Data Requirements

USFS2008 does not discuss the detailed hydraulic analysis of culverts (as e.g., discussed in the standard manuals, such as the FHWA HDS-5 (2012), or as performed by HY-8), but their procedure implicitly assumes that such analysis will be done, e.g., to determine whether the culvert to be designed is submerged or not at the inlet for $Q_{\text{b-d}}$. Thus the basic data of the traditional approach listed in Section 3.1.2, necessary for the hydraulic analysis, are also required. In addition, however, because the design approach relies on replicating the geomorphology of the existing "natural" stream within the structure, data must be acquired about the stream geometry and the characteristics of the bed sediment that might interact strongly with the flow. Chapter 5 of USFS2008 lists the data needed for site assessment:

- longitudinal profile: extending between 20 and 30 channel widths in each direction upstream and downstream of the structure, the profile is aimed at evaluating channel slopes and their variability, and identifying existing grade controls and features such as pools and riffles and scour holes
- cross-sectional profiles: a sufficient number should be taken upstream and downstream of the structure to determine the natural stream geometry (and their variability), especially those associated with the bankfull state (width, depth, and area), and the connected floodplain, such as the entrenchment ratio, that might be useful in characterizing the channel type. USFS2008 suggests that for relatively uniform uncomplicated channel reaches, two to three cross-sections upstream and downstream might be sufficient.
- characterization of stream bed and bank materials: The composition and in particular the size distribution of the natural material will determine the "design" or specification of the material to form the stable bed within the structure, and also to assess the mobility of sediment and hence the extent to which the upstream channel will be able to replenish any sediment eroded within the structure. Obtaining sediment data may, depending on the material type, involve pebble counts for predominantly coarse material, or bulk sampling and sieve analysis for material with a wide range of sizes. Sampling methods and strategies are discussed in USFS2008, which also suggests that, for predominantly fine (sand sized) materials that are readily mobilized, detailed analysis may not be necessary as the design of bed with such materials tends to be less critical. Thus, in certain cases, a visual assessment of the bed material may be adequate.

The above makes clear that the data requirements for the USFS2008 stream simulation approach can be substantially greater than those for the traditional culvert design. Special expertise, not necessarily readily available, may also be needed to acquire reliable data, e.g., identifying bankfull elevation or grade controls, or characterizing the bed material. Processing and analyzing the data will also require additional effort. For large projects, where the design and construction of culverts form a relatively small fraction of the overall costs, the extra cost over that of the traditional approach may not be significant. For smaller projects, however, the additional effort may be quite onerous.

3.2.3 Example Case: Wisconsin DOT-U.S. Forest Service Design of STH139 Crossing over the Duck Creek in northern Wisconsin in the Nicolet National Forest Region

Duck Creek in the Nicolet National Forest region of northern Wisconsin is classified as a class 2 trout stream, i.e., it supports some natural trout reproduction but still requires stocking for sport fishery. The channel characteristics are summarized in Table 3.1 (data are courtesy of D. Higgins, U.S. Forest Service, Chequamegon-Nicolet National Forest, who was largely responsible for the AOP design). In the vicinity of the crossing, the drainage area is 3.2 sq. miles, and the creek is relatively steep. The results of a pebble-count analysis indicated a gravel-cobble bed, which, especially in a forest setting, makes the USFS2008 approach appealing. The pre-existing STH 139 crossing of Duck Creek was a 4.5-ft diameter corrugated metal pipe (CMP) structure. Figure 3.5a shows the inlet to this structure, and though some substrate due to transported sediment is seen, the barrel is mostly bare.

In the reference reach (located downstream of the crossing), the bankfull width was estimated as 7.7 ft, and the replacement culvert was chosen as a 10.7 ft × 6.9 ft pipe arch structure, sumped ≈ 2 ft into the stream. Due to the relatively large d_{95} (≈ 1.3 ft), and perhaps the relatively small design discharges (e.g., $Q_{100} \approx 87$cfs), the adjustment to the lower VAP line for flood scour is only about 1 ft rather than $2d_{90}$, and similarly the culvert span includes a bank region on each side of width $\approx d_{95}$ rather than $2d_{95}$. For the bank features designed to be immobile and prominent in Figure 3.5b, stones in the size range 18-in to 24-in, so $\approx d_{100}$, were specified. The bed mix for the culvert was chosen to match closely the size distribution estimated from the pebble count. Due to the choice of the culvert span, the HEC-RAS culvert model predicted a water surface level for Q_{100}, that is substantially below (about 3.6 ft or more than 0.5 D) the culvert crown. The replacement AOP culvert was installed in 2008, and so has been in operation for over 7 years, and so should have experienced a range of flows. The image in Figure 3.5b taken on 1/2016 during relatively low-flow conditions gives evidence that the bank features at least have been stable, and though the bed cannot be seen clearly under the flow the scattered large stones in midstream suggests a stable bed, and hence a stable bed design that has been largely successful thus far. The larger question whether the ultimate goal of a measurable and substantial net ecological benefit can be attributed to the AOP culvert design is much more difficult to answer, and would require much more extensive study.

TABLE 3.1
Summary of channel and culvert characteristics for the STH139 crossing over Duck Creek, northern Wisconsin (data courtesy of D. Higgins).

Channel characteristics			Culvert characteristics	
			Pre-existing	**AOP**
Range in slopes	0.015–0.45	Slope	0.028	0.032
Bankfull width (ft)	7.7	Span (ft)	4.5	10.7
Depth of lower VAP line[†] to bed elev. (ft)	≈ 1	Rise (ft)	4.5	6.9
d_{50}, d_{95}, d_5 (in)	4.8, 16, 0.2	Culvert type	CMP	CM pipe arch
Q_{100}, Q_2 (cfs)	87.1, 31.1	Sump depth (ft)	≈ 0	≈ 2

[†] Unadjusted for flood scour.


(a)
(b)

Figure 3.5 (a) Pre-existing 4.5-ft CMP culvert, (b) culvert designed according to USFS (2008) and installed in 2008 (image taken 1/6/2016, over Duck Creek in northern Wisconsin).

3.3 The FHWA HEC-26 Stream Simulation Approach

3.3.1 Design Objectives, Constraints, and Guidelines

To the extent that it also aims to replicate certain aspects of the natural stream conditions, the HEC-26 approach to the AOP problem also adopts the stream simulation label. One of the lead authors (Robert Gubernick) of the USFS2008 also served on the advisory committee in the development of the HEC-26 manual, and the influence of USFS2008 can be found in subtle aspects. The HEC-26 approach does differ from the USFS2008 approach in avoiding a geomorphic basis for the culvert design. Thus, it does not define a reference reach nor does it rely explicitly on bankfull width for culvert sizing, arguing that these can be difficult to identify or estimate precisely. Rather, in common with the traditional approach and in distinct contrast to the USFS2008 approach, it is discharge-based. Instead of a single peak discharge,Q_p as in the traditional approach, the HEC-26 approach defines two other discharges specifically related to AOP. The high-passage discharge, Q_H, is the largest discharge at which fishes (or more generally aquatic organisms) are thought to move actively along the stream (fish are thought to seek shelter under very high flow conditions and only move when the flow is reduced below some level), while the low-passage discharge, Q_L is the smallest discharge for which AOP is required. The designed culvert must satisfy constraints formulated in terms of these discharges, namely that (i) the bed within the structure should be stable in the long term, (ii) the average velocity within the structure during the high-passage flow should be similar to that in the channel upstream and downstream of the structure, and (iii) the flow depth within the structure should at the low-passage flow remain above a minimum allowable flow depth. In HEC-26 (as in USFS2008), a stable bed is defined conservatively as one wherein the particles are immobile; this avoids the complication of performing detailed sediment transport analysis to support the case that replenishment of sediment by upstream transport will be sufficient to maintain a bed level within the culvert that does not undergo any significant long-term changes.

Design discharges. The main questions then concern the choice of these discharges.Q_p is the traditional peak discharge such as the 50-year or 100-year flow, already defined in the INDOT design manual for the various classes of roadways. HEC-26 lists choices of Q_H and Q_L in various states. One recommended procedure for choosing both Q_H and Q_L is based on flow-duration curves. For a site where stream gage information is available daily, the flow-duration curve (FDC) developed from daily streamflow data gives the fraction of time that a specified flow is equaled or exceeded, and so usually termed the exceedance probability. This should not be confused with the exceedance probability that is the basis of the peak flow definition. The FDC can also be obtained from the analysis of a more restricted time period, e.g., the migration season, and several states use this approach in determining Q_H and Q_L. HEC-26 recommends that, in the absence of any site-specific guidance, Q_H and Q_L be chosen as the discharges corresponding to the 10% and the 90% values of the annual FDC. For ungaged sites, regionalized FDC regression relationships, if available, provide a convenient solution that is however associated with greater uncertainty (regional FDC relationships for Indiana and Illinois have been studied by Over, Riley, Sharpe, & Arvin, 2014). If no FDC information is available, HEC-26 suggests that Q_H be chosen as a fraction, e.g., 0.25, of the two-year discharge, and Q_L be chosen as 1 ft^3/s.

Except for the more specific definition of a low flow, Q_L, the treatment of low flows in the FHWA HEC-26 approach seems to have borrowed from USFS2008 in the suggestion that, if necessary, a low-flow channel (a triangular cross-section with a 5H:1V slope) be provided. Such a channel is expected to be only transitory, with a more natural low-flow geometry developing over time. Both approaches stress the importance of fines in the culvert bed composition in order to avoid the problem of the stream surface flow becoming transformed entirely into interstitial subsurface flow at low discharges.

Culvert bed stability and bed design. The HEC-26 culvert design procedure is diagrammed in Figure 3.6. After the initial step of identifying the relevant discharges, Q_p, Q_H, and Q_L, steps 2 through 5 largely parallels those in either USFS2008 or the traditional approach. Whereas in USFS2008, bankfull width essentially determines culvert size, in HEC-26, the comparable operative constraint (step 10 in Figure 3.6) is that for Q_H the mean velocity within the structure should be similar to velocities upstream and downstream of the structure. If Q_H were comparable to the bankfull discharge, this velocity constraint would be expected to result in a culvert of comparable size to that determined using USFS2008. Similarly, like USFS2008, a major concern of HEC-26 is the stability of the bed within the structure (steps 6 and 8), and much of the analysis/design effort is devoted to satisfying the constraint on culvert bed stability. Especially for the peak discharge, Q_p, HEC-26 recommends a two-layer approach, where a coarse (artificial armoring) sublayer is placed below a surface layer of more natural bed material (Figure 3.7). Kilgore, Hogan, and Bergendahl (2014), in discussing experience with HEC-26, also emphasized the importance of the two-layer design. As noted above, while such an approach may not be preferred in USFS2008, it is also presented there as an option for dealing with the situation where flood-plain constriction poses a problem. Also, unlike the HEC26 procedure, the USFS2008 approach does not aim at an immobile bed at the peak design flow (termed the high structural design flow, $Q_{\text{st-d}}$) only at the high bed-design flow, $Q_{\text{b-d}}$.

A further notable difference in design procedure between the HEC-26 and the USFS2008 approaches concerns the determination of the sump depth, h_{smp}. The USFS2008 approach examines the longitudinal profile and identifies the lower vertical adjustment potential

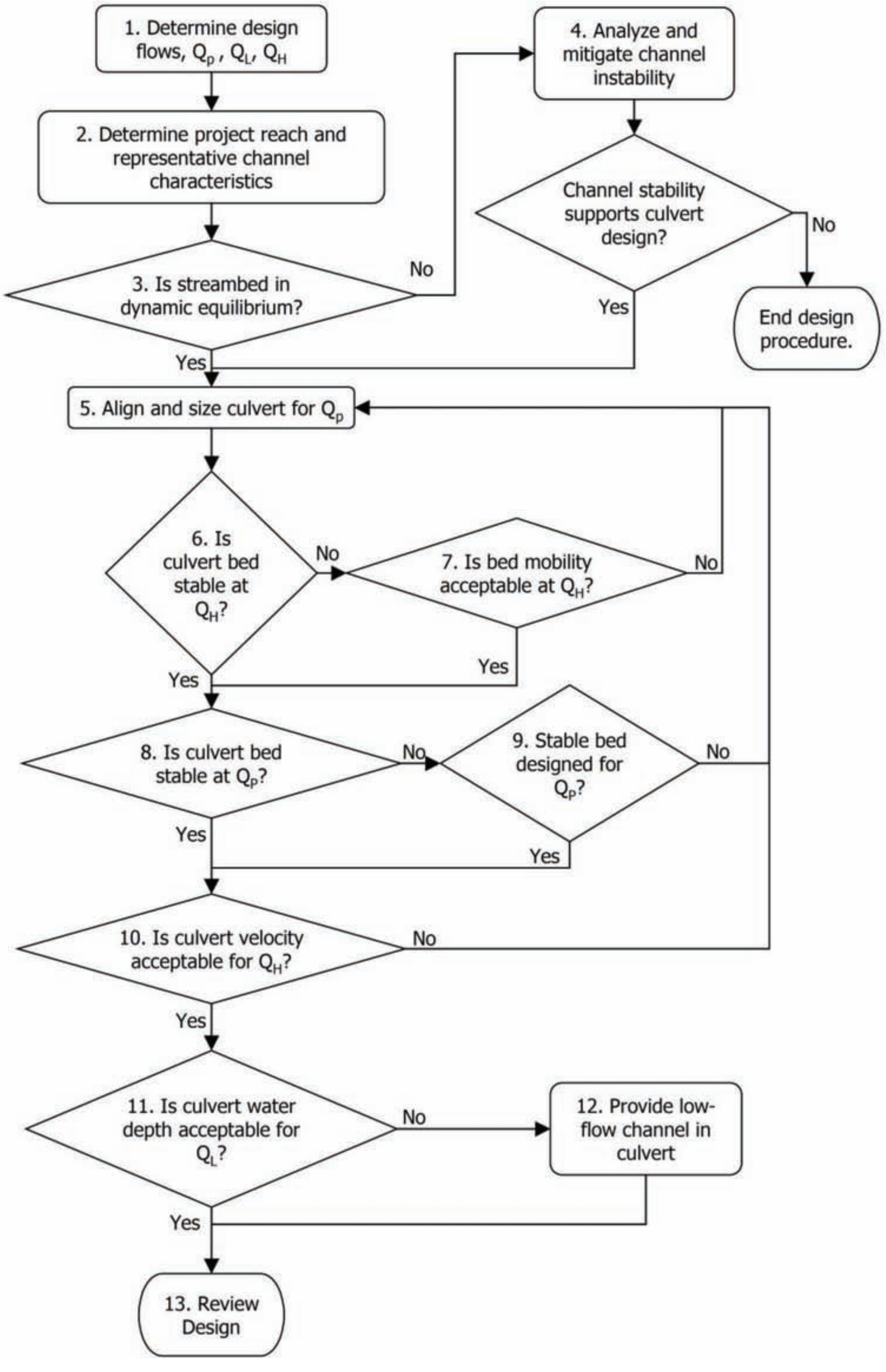


Figure 3.6 Flow chart for FHWA HEC-26 culvert analysis for AOP. (Taken from Kilgore et al., 2010.)

line from which h_{smp} is derived. In contrast, the HEC-26 approach (somewhat similar to the current INDOT 2013-203-2.02 approach and the current RGP) specifies h_{smp} in terms of the culvert rise (R_c), a bed-material characteristic (d_{95}), and a minimum value (e.g., 2 ft). Due to differences in geometry (mainly the bottom curvature), the recommendations for h_{smp} for box and pipe arch culverts differ from those of circular and elliptical culverts. These are given as:

for box and pipe – arch culverts: $h_{smp} = \max(0.2R_c, d_{95}, 2 \text{ ft})$

for circular and elliptical culverts: $h_{smp} = \max(0.3R_c, 2d_{95}, 2 \text{ ft})$

The above are minimum values, and larger more conservative (for bed stability) values may be chosen,

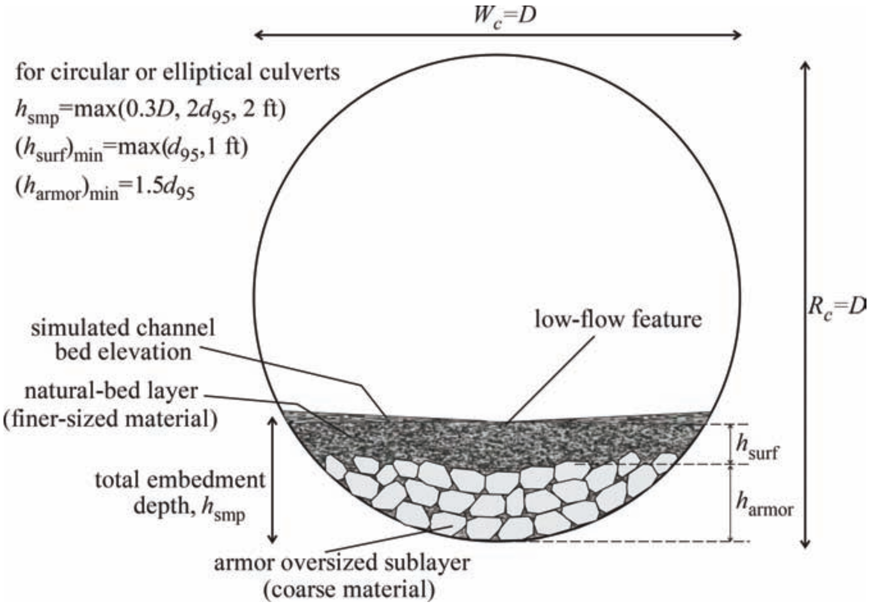


Figure 3.7 Schematic of FHWA HEC-26 recommended bed design within culvert.

though will likely adversely affect the conveyance and the cost.

The HEC-26 and the USFS2008 procedures may be related at least for certain types of culverts and for smaller streams through the following argument. It seems plausible that the depth to the lower VAP line (relative to the streambed), which determines h_{smp} in the USFS2008 approach, should scale with the bankfull depth, y_b, and perhaps with the bankfull width, W_b. The chosen culvert rise, R_c, may therefore be expected to correlate with the bankfull depth, y_b. Hence because both R_c and the depth of the lower VAP line correlate with y_b, the USFS2008 sump depth may be expected to correlate well with R_c. It should not surprise then if both USFS2008 and HEC-26 generally lead to similar h_{smp}, in spite of the difference in methodology, particularly as seen in the example in Section 3.2.3 when other practical considerations influence the choice.

Because HEC-26 emphasizes the two-layer embedment solution to achieve stability at peak discharge, the thickness of the two layers needs also to be specified where such a solution is chosen. The recommended thicknesses of the surface-layer material (h_{surf}) and the armoring sublayer (h_{armor}) are given as:

$$h_{surf} = \max(d_{95},\ 1\text{ ft})\ \text{for all culvert geometries}$$

$$h_{armor} = \begin{cases} d_{95} & \text{for box and pipe-arch culverts} \\ 1.5d_{95} & \text{for circular and elliptical culverts} \end{cases}$$

These are again minimum values, and HEC-26 recommends that the sum of h_{surf} and h_{armor} should at least equal to the recommended minimum value of h_{smp}. The inclusion of d_{95} in the specification of h_{smp} ensures that the embedment is deep enough to contain the largest fractions of the natural channel material, while its inclusion in specifying h_{armor} is motivated by the assumption that sediment sizes that are d_{95} and larger will be immobile except under extreme conditions.

Like USFS2008, the size distribution of the surface layer should replicate that of the natural stream, but must explicitly satisfy a stability criterion, namely that at the high-passage flow the culvert bed material should be mobile only if the natural stream is mobile. This criterion plays a more important role in HEC-26 than in USFS2008 because unlike the geomorphic bankfull-width approach of USFS2008, the culvert size is determined from a discharge. As such, it cannot be ensured that the same material as the natural channel placed in such a culvert would be mobile only when the material in the natural channel was already mobile.

3.3.2 Data Input Requirements

The data requirements for the FHWA HEC-26 approach are similar to the basic data recommended in the USFS2008 approach. The project reach for which a longitudinal profile is taken is specified as a maximum of three (3) culvert lengths or 200 ft upstream and downstream of the planned culvert. The profile is intended to provide information regarding the natural variation in bed elevation as well as other characteristic features of the stream bed, such as pools and riffles. This may be compared with 20 to 30 channel widths in each direction recommended in USFS2008. A minimum of three cross-section profiles upstream and downstream of the structure is specified in FHWA HEC-26, with the cross-section locations chosen based on stream geomorphology. This should be compared with the USFS2008 recommendation of two or three cross-sections upstream and downstream of the crossing for relatively uniform channels, though the number should be based on the variability of the channel characteristics and assessment of the risks at the crossing site. For the bed material composition, one sample upstream and one downstream of the structure are considered as sufficient if the bed is reasonably homogeneous over the entire project reach. Where more variability is found, up to one sample per cross-section may be taken. USFS2008 discusses sampling strategies and methodology in some detail, but stops short of giving specific general recommendations regarding the number of samples to be taken, preferring instead to give guidance for different bed types, such as high-mobility channels, pool-riffle or step-pool reaches.

While the data requirements for both approaches are technically comparable, those of USFS2008 tend to be formulated in a more open ended and more case-specific manner, and those of HEC-26 in a more specific prescriptive manner. For example, while the USFS2008 allows the possibility of a visual estimation of bed material characteristics in certain cases, HEC-26 does not.

3.3.3 Example Case: Wisconsin DOT Design of STH80 Crossing over the Little Platte River Near Livingston, WI in Southwestern Wisconsin

The state highway, STH80, crosses the Little Platte River in a rural agricultural southwestern Wisconsin region near Livingston, WI (approx. 50 miles west-southwest of Madison, WI). The pre-existing culvert was a double barreled structure, each a corrugated metal pipe (CMP) 5-ft in diameter. A perched outlet and a large scour pool had developed at the structure outlet (see Figure 3.8). As the perched outlet might be considered as inhibiting AOP, a new crossing was designed generally following the FHWA HEC-26 approach (Rodney Taylor, Ann-Marie Kirsch, both of Wisconsin DOT, and John Vorhees of AECOM, personal communication). Details of the design have not yet been published but some information was given in a conference presentation (Kirsch, 2014), on which much of the following is based. The engineering plan for the culvert is shown in Figure 3.9. The new culvert is a single barreled corrugated metal structural plate pipe arch structure with a span, W_c=13.25 ft and a total rise, R_c=9.33 ft. The span of the new structure was slightly wider than the estimated bankfull width, $W_b \approx 12$ ft. In contrast to the typical USFS2008 design, the absence of bank features is conspicuous. The structure was sumped to a total depth of 2.67 ft, i.e, $h_{\mathrm{smp}} \approx 0.3D$ (this is somewhat larger than the HEC-26 specification of 0.2 D for a pipe- arch structure). Even with the embedment, the total open area of the new structure was about 70% more than that of the two-barrel pre-existing structure.

Figure 3.8 Perched outlet of pre-existing crossing structure with large scour pool. (Taken from Kirsch, 2014.)

The two-layer feature of the bed within the culvert (shown in detail to the bottom left of Section A-A) is characteristic of the HEC-26 approach. The design discharges (Q_p, Q_H, and Q_L) were not available, but presumably the sizing of the medium riprap in the armor sublayer is based on bed stability at Q_p. Wisconsin DOT medium riprap is similar though not identical to INDOT revetment riprap. The coarse aggregate no. 2 used for the surface layer is a commercially available standard (in Wisconsin) concrete aggregate chosen to match as closely as practical the size distribution of the native streambed material. This coarse aggregate is smaller ($d_{50} \approx 1$ in) than INDOT class 2 coarse graded aggregate ($d_{50} \approx 1.5$ in), but notably does *not* contain material finer than 4.75 mm (0.19 in, $d_5 \approx 0.375$ in). As was emphasized earlier, HEC-26 recommends that d_5 should not be larger than 2 mm, in order to ensure sufficient fines to avoid too much infiltration and hence pure subsurface flow at low discharges. A conversation with Kirsch (2016, personal communication) indicated that such a situation might have developed during the summer months. It is notable that this bed material composition was extended downstream of the culvert to section B-B (see detail in Figure 3.9). Careful examination of the Section A-A detail in Figure 3.9 also shows an initial low-flow channel of triangular cross-section with a sideslope much shallower than the 5:1 suggested in HEC-26.

An image of the culvert interior (taken on 1/6/2016, during relatively low flow) looking downstream is shown in Figure 3.10. In the foreground, near the inlet, the surface layer of relatively coarse aggregate is exposed, as a low-flow channel has developed naturally on the right wall of the culvert. Some of this surface layer material may also have originated from the upstream channel and deposited within the structure. Further downstream, a somewhat deeper and more extensive pool-like feature seems to have also naturally developed, so that the coarse bed material is no longer visible. From wading into the downstream pool, it was inferred that the culvert bed had a much more muddy texture, with the surface layer there apparently consisting of markedly finer material. The origin of the fine material is unclear, and might be from the upstream channel, or alternatively might be a concentration of fines from the coarse aggregate. Because, like the natural streambed, the bed within the structure

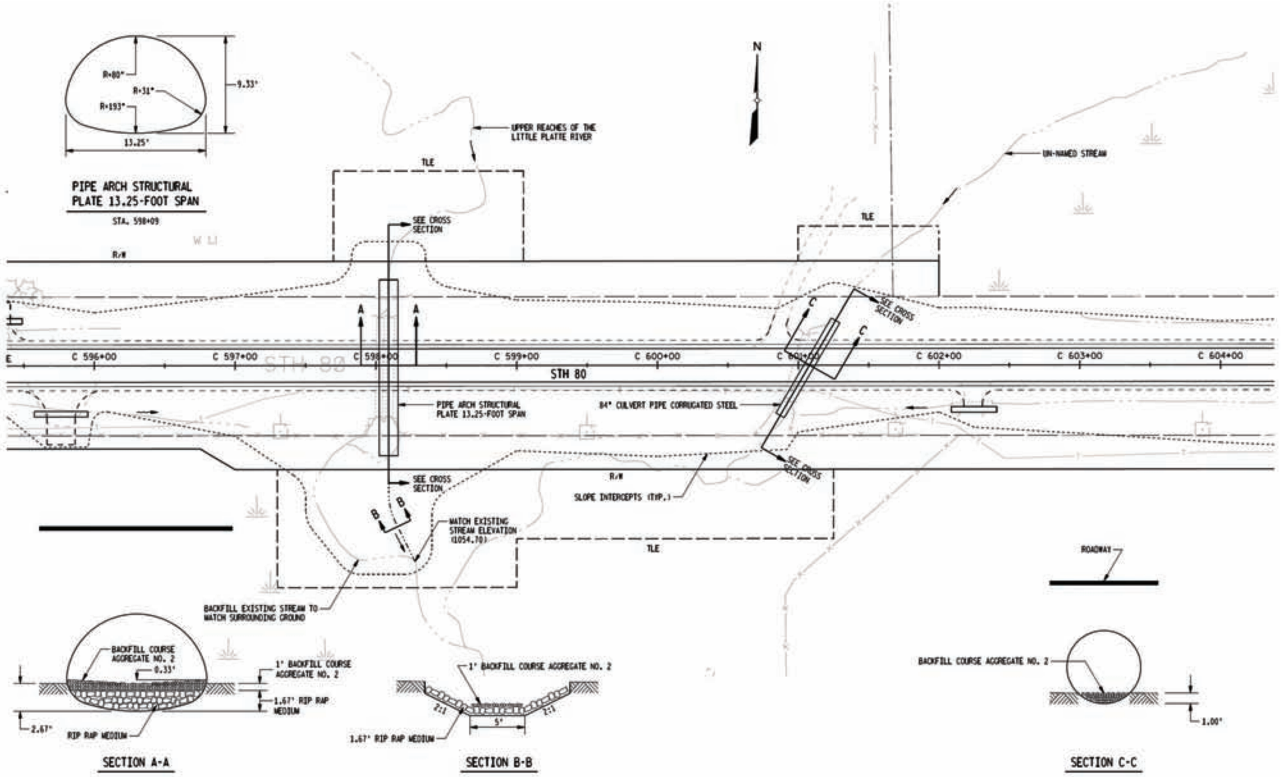


Figure 3.9 Engineering plan for replacement culvert(s) on STH80 over Little Platte River near Livingston, Wisconsin.

Figure 3.10 Image of STH80 CMP pipe-arch culvert over the Little Platte River, taken near the culvert inlet, and looking downstream.

does not remain static but may rather respond dynamically to flow conditions, it is difficult to assess with a single visit whether the designed bed is behaving as designed. The structure is relatively new (installed in 2013) and may not have been subjected to design flow conditions since its installation. Nevertheless the presence of a continuous substrate over the entire length of the structure after some time in operation does indicate some measure of success.

Another new culvert installed at the same time approximately 300 ft to the east of the FHWA HEC-26 culvert provides an interesting comparison. This culvert, an 84-in diameter corrugated metal pipe (CMP), was also sumped according to the design plan (Figure 3.9) though only to a depth of 1 ft and was to have been backfilled with the same surface-layer material (Wisconsin no. 2 concrete coarse aggregate), but with no armor sublayer of riprap material (see detail Section C-C in Figure 3.9). From this information, it is presumed that this culvert was not designed according to HEC-26, but could be considered as satisfying the current IDEM regional general permit condition as far as sump depth and backfilling are concerned. An image of the inlet of the culvert (view downstream) taken at the same time as Figure 3.10 is shown in Figure 3.11. It is not clear that the culvert was installed according to the engineering plan (Figure 3.9), but if it was, then it must be concluded that much of the backfill material has been washed downstream as the culvert barrel bottom is mostly bare, at least near the inlet. Again caution should be exercised in making any conclusion based on a single site visit, but Figure 3.11 does raise some doubt that the backfilled bed is sufficiently stable, especially in comparison to the nearby HEC-26 designed culvert.

Figure 3.11 Image looking downstream of inlet of new embedded backfilled culvert installed about 300 ft to the east of the FHWA HEC-26 culvert.

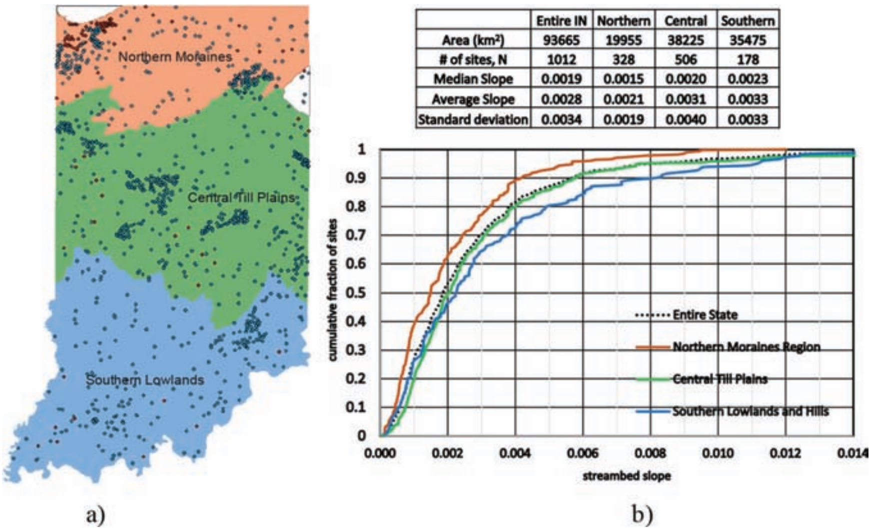
3.4 Software Implementation/Resources

The current version 7.3 of the standard culvert analysis software, HY-8, does not model the stream channel flow and has no capability to examine bed stability within the culvert, and as such is of limited use in any stream-simulation-type and specifically HEC-26 culvert design. Similarly, the standard software for general open-channel flow, HEC-RAS, models both the culvert as well as the stream, but also does not deal with the sediment bed in the culvert, primarily because the culvert module essentially mimics the current HY-8. The HEC-26 procedure, as is the USFS2008 stream simulation approach though to a lesser extent, may involve iteration, as seen in the loops of the flowchart in Figure 3.6. Even a semi-manual procedure involving the use of HEC-RAS for each open-channel flow computation could become tedious and time-consuming. The analyses of both of the case studies discussed in Sections 3.2.3 and 3.3.3 were accomplished using HEC-RAS in a semi-manual procedure.

A beta version of HY-8 (version 7.4.0) has recently (February, 2015) been released with AOP design capabilities following the HEC-26 design procedure. The data requirements are those of HEC-26, except that as in the diagrammed flow chart of Figure 3.6, the longitudinal profile is not explicitly used. In contrast to the single data page needed for the simple traditional culvert analysis, two data pages must be completed for the culvert AOP analysis. On the first page, the three design discharges, and a minimum of three upstream and three downstream cross-sections must be specified (the culvert definition is taken from the traditional crossing analysis, which must be run before the AOP analysis is undertaken). On the second page, the sediment gradation of the channel is given, and the flow resistance models for the channel and for the culvert are chosen. The analyst also needs to certify that the channel is in dynamic equilibrium, i.e., is stable. The traditional crossing analysis must first be carried out, and then the AOP analysis can be performed. The results of the AOP analysis are presented on a third page, in which five checks are made: whether (i) the embedment depth satisfies the HEC-26 recommendation, (ii) the culvert bed is mobile and the channel bed is immobile under the high-passage flow, (iii) the culvert bed is stable under the peak flow, (iv) the velocity in the culvert is smaller than or equal to the velocity in the channel under the high-passage flow, and (v) the flow depth exceeds the minimum acceptable flow depth for AOP under low-flow conditions. If any of the constraints is not satisfied (color-coded as red), then the analyst will need to choose a different culvert (size and/or shape, as well as embedment), and the procedure is repeated. Some automated "optimization" capabilities are built-in, so as to facilitate the iterative design procedure, but these can be rather limited and may not lead to a solution without the intervention of the analyst. In its present beta version state, the AOP module in HY-8 7.4 still seems too problem-prone, e.g., it considers locally adverse stream slopes as being erroneous, and may be too inflexible regarding inputs.

3.5 A Proposed Procedure

The preceding sections have discussed the elements of the two main approaches, those in USFS2008 and HEC-26, to designing culverts in order to enhance aquatic organism passage. Both approaches require similar data inputs and arguably similar design effort. In focusing on discharges with constraints and in not incorporating bank features in the design, the HEC-26 approach resembles more closely the traditional approach and will likely lead to somewhat smaller structures than those following the USFS2008 approach. The (future) availability of a software tool to aid in the analysis increases the attractiveness of the HEC-26 approach, though it may prove too inflexible. In the following, a hybrid approach drawing on elements of both approaches is proposed with the aims of (i) tailoring the solution to Indiana conditions, (ii) making use where feasible of current INDOT standard specifications, (iii) complying with the current (and foreseeable) RGP conditions and filling in the gaps in INDOT's design guidelines, and (iv) simplifying the procedure as much as possible. The proposed approach is not intended as a general approach like the USFS2008 or HEC-26, but is to be applied to straightforward problems with a reasonably stable channel, i.e., with no significant issues regarding lateral migration, degradation or incision, or aggradation. In this respect, it may be considered similar to the no-slope or low-slope design approach (see end of Section 3.2.1). Consistent with the preceding, this section is confined mainly to culvert sizing, embedment, and bed/bank design, and will not address other topics such as alignment and length. Due to the emphasis on simplification of the analysis, the resulting structure may however not necessarily be the smallest or the most economical in terms of material and installation costs. The focus will be on the larger culvert sizes where a culvert bed needs to be designed.



	Entire IN	Northern	Central	Southern
Area (km²)	93665	19955	38225	35475
# of sites, N	1012	328	506	178
Median Slope	0.0019	0.0015	0.0020	0.0023
Average Slope	0.0028	0.0021	0.0031	0.0033
Standard deviation	0.0034	0.0019	0.0040	0.0033

Figure 3.12 (a) Locations of QHEI sites to characterize Indiana conditions, (b) cumulative distribution function for channel slopes at QHEI sites (and statistics).

3.5.1 Indiana-Specific Conditions

Both USFS2008 and HEC-26 aim to be comprehensive and general in scope, and so applicable without any regional bias. Taking Indiana-specific conditions into account may, however, allow for simplifications, at least for "routine" cases. Two main geomorphological characteristics may have implications for AOP design procedures, namely, streambed slope and bed material composition. It is recalled that the Tumeo and Pavlick (2011) study for Ohio DOT found that for channel slope exceeding 1%, an embedded culvert that was not backfilled did not tend to backfill naturally such that a sediment bed did not develop within the culvert at least within a reasonable time interval. Similarly, and possibly related, USFS2008 emphasized that a predominantly sandy substrate may be more forgiving in terms of AOP design in that being more easily mobilized, the culvert bed will be more quickly replenished by sand transported from the upstream channel. Thus, even if during a high-flow event the culvert bed is completely washed away, and the artificial culvert material is exposed, the culvert bed will re-establish within a relatively short time (possibly even during the same event when the flood recedes) due to upstream re-supply. The two characteristics are related in that finer material tends to be associated with lower stream slopes. Also, the simplified no-slope design approach discussed at the end of Section 3.2.1 is typically restricted to low-gradient streams.

To examine the prevalence of slopes and substrate types in smaller Indiana streams, the database of QHEI (Qualitative Habitat Evaluation Index) as compiled by the Indiana Dept. of Environmental Management (IDEM, kindly provided by Sobat, personal communication) was interrogated. Because culverts are suitable only for smaller streams, the analysis was restricted to widths smaller than 10 m (33 ft; here widths are the measured top width at the time of the site visit, and so is most likely less than either the bankfull width or the ordinary-high-water width). Indiana is often divided into three geological or geomorphic regions (see, e.g., Robinson, 2013): the Northern Moraine region, the Central Till Plains region, and the Southern lowlands region. The location of QHEI sites in each of the three regions are shown in Figure 3.12a, and is reasonably broad, though there is a tendency for more sites in the vicinity of the large urban areas or towns.

Streambed slope. The cumulative distribution function of channel slopes (at the QHEI sites with widths less than 10 m $\approx$ 33 ft) shown in Figure 3.12b indicates that streambed slopes are rather small (in all three regions, over 90% of sites had slopes smaller than 0.01), with typical slopes increasing from north to south. It should be emphasized that at any specific crossing the local channel slope in any region may be greater than 0.01, and any detailed analysis and design of a crossing structure should be based on local conditions and not on the statistical results of Figure 3.12b. The characterization of Indiana streambed slopes as generally small can however motivate the development of a design procedure that assumes small slopes and that should still be widely applicable.

Substrate type. The predominant (greater than 75% of the sample streambed area) substrate type (sand, gravel, or other) is also characterized in the QHEI assessment on a per unit streambed area basis. As shown in Figure 3.13, in all three regions, the predominantly sandy substrate constitutes the majority of the sites tested, and only in the Southern Lowlands was less than 50% of sites determined to be sandy.

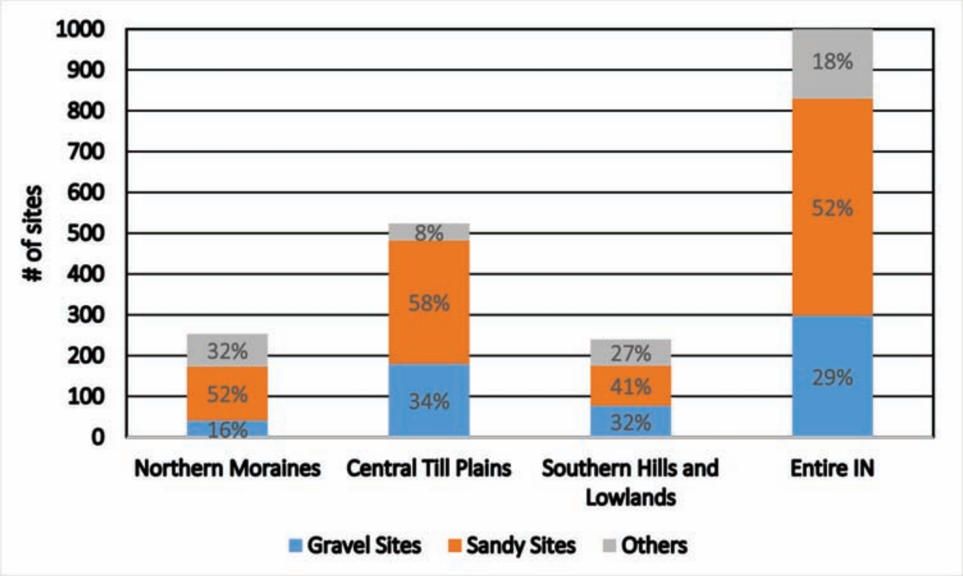


Figure 3.13 Bar diagram of number of sites in each region with predominantly gravel, sand, or other substrate.

3.5.2 INDOT Standard Specifications for Aggregates and Riprap

Where feasible, it would be convenient to make use of already existing INDOT standard specifications. In Appendix B, the standard INDOT (2014) course aggregate size specifications are given for coarse aggregates and riprap. Sand is defined as material with diameters between 0.06 mm and 2 mm (corresponding to standard sieve numbers 10 and 230), with gravel ranging from 2 mm to 64 mm (corresponding to standard sieve number/size 10 and 2½ in). Where appropriate, riprap will be used for an armoring sublayer, similar to that in the HEC-26 approach, while a coarse aggregate will be used in the surface layer. A dense graded class is preferred for this purpose as the dense grading will ensure a low permeability of the surface layer, thus minimizing the likelihood that at low flows the surface flow will become a subsurface flow. Unfortunately, there are only two dense graded classes in the current INDOT standard specifications, and they differ only slightly. Thus, it is unlikely that they will be sufficient to address the wide range of conditions to be encountered in the present context, and so new mixes will likely be necessary.

3.5.3 Recommendations for a Simplified Procedure

Both the dominant approaches to AOP culvert design, the U.S. Forest Service (USFS2008) and the FHWA (HEC-26), described above in Sections 3.2 and 3.3, require significant additional data input, analyses, and hence engineering effort. A simpler approach requiring less effort (though not necessarily resulting in any reduced installation costs) might be sought which would be tailored for stream characteristics typical of Indiana, and would exploit much of current INDOT design practice as well as standard specifications. Simplification of federal guidelines for INDOT purposes is not unusual as INDOT's riprap design procedure considerably simplifies the FHWA HEC-11 procedures. In the current context, simplification will result from a gross characterization of stream geometry and substrate, and a conservative choice of material to be used for the bed within the culvert. The following proposed procedure focuses on larger structures, as constructability issues in installing the culvert bed may limit applicability to such structures. Barnard et al. (2013) indicate that in Washington a stream simulation design may because of culvert-bed constructability be restricted to culverts larger than 7 ft, referring presumably to circular culverts.

Stream characterization and data input. Whereas both USFS2008 and HEC-26 attempt a rather detailed characterization of the stream through longitudinal and cross-sectional profiles as well as substrate sampling, the proposed simplified procedure requires information only about the OHWM (or optionally, the bankfull) width, and a gross assessment as to the predominant type of bed material. In the USFS2008 approach, the longitudinal profile through the evaluation of the vertical adjustment potential is used to determine the sump depth, h_{smp}. Because of its reliance on an armor sublayer, HEC-26 does not explicitly depend on the longitudinal profile, and specifies the sump depth only in terms of structure size and substrate size (and the new AOP-capable HY-8 also does not use longitudinal profile information). The proposed procedure adopts the armor sublayer aspect of HEC-26, and so will similarly not need a longitudinal profile to determine h_{smp}. Cross-sectional profiles play a more integral role in HEC-26 in that velocities within the culvert should not exceed the average velocities outside of the culvert at the high-passage flow and the culvert bed surface layer material should not be mobile if the natural stream bed material is not mobile at the high passage flow. Because of its reliance on bankfull width (in a reference reach), the USFS2008 approach does not directly use the cross-sectional information for structure sizing. The proposed procedure takes an approach similar to the USFS2008 in basing structure size on the OHWM (or bankfull) width, and so will not need detailed cross-sectional data.

Both USFS2008 and HEC-26 require detailed substrate size distribution in aiming to replicate a stable streambed within the culvert (in the case of HEC-26, at least in the surface layer). Rather than a detailed determination of particle size distribution, the proposed procedure is based on a gross assessment of whether the predominant streambed material is sand or smaller, i.e., $d_{50} < 2$ mm, or at most coarse gravel, i.e., $2 \text{ mm} < d_{50} < 32$ mm or other larger material (i.e., $d_{50} > 32$ mm, including possibly bedrock). Such an assessment is already partially done to fulfill current sump requirements which vary depending on whether the substrate type is sand, other soil or unconsolidated till (including cohesive material, gravel, and cobble), or bedrock or consolidated till. The proposed assessment will require more effort and be more precise than that for sumping, but should not require detailed sampling and determination of size distribution. Those familiar with the QHEI (Qualitative Habitat Evaluation Index) frequently used in aquatic habitat evaluation should also be familiar with such a gross substrate assessment. As discussed previously in Section 3.5.1, based on IDEM's QHEI database, a large fraction of Indiana streams is expected to be predominantly sandy or gravelly. This simple substrate characterization will permit a conservative design of a stable bed within the culvert, by choosing a standard aggregate class for each substrate type rather than attempting to replicate exactly the natural particle size distribution of the stream.

Design flows. HEC-26 defines two design flows in addition to the traditional peak flow: the high-passage flow and the low-passage flow. As argued above, the first can be thought of as equivalent to the discharge associated with the OHWM (or the bankfull discharge), and allows HEC-26 to dispense with defining a bankfull width (like the USFS2008 approach). As the proposed approach is based on identifying OHWM characteristics, it does not need to define a high-passage flow (though it may still be useful as a check to do so). Similarly, the proposed approach will by default create an initial low-flow channel feature, and so an explicit definition of a low-passage flow is also not necessary. The only design flow that is needed in the proposed procedure is therefore the traditional peak design flow.

Bed design. Much of the USFS2008 and HEC-26 is concerned with the design of the "simulated" streambed within the culvert, which should be immobile under the appropriate conditions. The proposed guideline adopts the HEC-26 approach of an armor sublayer which should be immobile under the peak design flow but there is no attempt to design the surface layer with a size distribution similar to that in the natural channel. Rather the surface layer design is simplified, with a preference for stable bed, even if this may result in a culvert bed material coarser than that of the stream bed. The effects of a coarser bed on AOP are uncertain, and will be discussed below. The material for both layers will be chosen as much as possible from already existing standard specifications (see Appendix B) for riprap (for the armor sublayer) and coarse aggregate (usually for the surface layer, but possibly for the armor sublayer).

3.5.4 Details of the Simplified Procedure

The three main design parameters to be determined are (i) the structure size (mainly the span, W_c, but possibly also the rise, R_c), (ii) the sump depth, h_{smp}, and (iii) the material for the culvert bed, both for the armor sublayer and the surface layer (if they are different). For some common structure shapes, such as the circular or the pipe arch, W_c, R_c, and h_{smp} may all be closely related for commercially available structures. As in most design problems, some amount of iteration may be necessary for an acceptable solution. The main data inputs other than those already required for a conventional culvert design, such as that required for using the standard HY-8 software, are (i) the OHWM width, W_{OHWM} (because the current RGP is formulated in terms of the OHWM, W_{OHWM} is preferred to the bankfull width), and (ii) a classification as to whether the substrate is sand, gravel, or other (needed to design the substrate within the culvert). The general design procedure consists of the following steps.

1. Choice of initial structure parameters. In this first step, a preliminary sizing of the structure is performed. A span, W_0, is chosen equal to or greater than the OHWM width, W_{OHWM}. An initial traditional culvert analysis is performed, with an assumed initial sump depth, h_{smp0}, that will depend on the OHWM depth, y_{OHWM}, and the culvert geometry. As discussed in Appendix A, a large scatter in y_{OHWM} as reported by INDOT personnel is found, and it is recommended for greater consistency that y_{OHWM} be estimated from a model equation based on bankfull rather than OHWM depths:

$$y_{OHWM} = 0.06\, W_{OHWM} + 0.4 \tag{3.1}$$

where both y_{OHWM} and W_{OHWM} are in feet.

a. For a constant-width shape, such as a box culvert, h_{smp0} is taken equal to y_{OHWM} (see Figure 3.14a). In HEC-26, the sump depth for a box culvert is taken as a fixed fraction (20%) of the structure rise with a minimum of 2 ft. Here it is argued that the sump depth should be more physically based on a flow parameter, such as y_{OHWM}, rather than a somewhat arbitrary structure rise.
b. For a variable-width shape such as a circular or pipe arch geometry, the structure is vertically located so that the OHWM coincides with the location where the culvert is widest (see Figure 3.14b). The initial sump depth is then taken such that the sum of h_{smp0} and y_{OHWM} (estimated

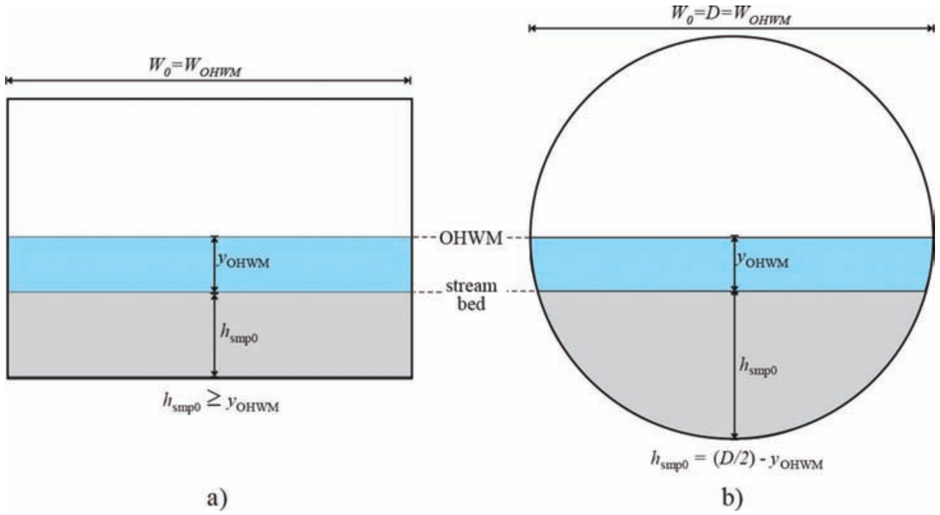


Figure 3.14 Choice of initial sump depth, h_{smp0}, for traditional analysis: (a) for a box culvert, and (b) for a circular culvert.

TABLE 3.2
Permissible cross-sectionally averaged velocities at peak discharge for the armor sublayer.

Armor layer material class	Permissible velocity limit (ft/s)
New dense-graded coarse-aggregate class (defined in Appendix B)	<4
Revetment riprap	<8
Class 1 riprap	<10
Class 2 riprap	<13

using Equation (3.1)) is equal to the distance from the bottom of the structure to the elevation where it is widest. If the latter distance is smaller than 2 y_{OHWM}, then a larger structure should be considered. For the same span, this initial sump depth for the circular culvert may be significantly larger than that for the box culvert (Figure 3.14), but because y_{OHWM} is generally less than $0.2W_{OHWME}$ (see Appendix A), this choice will generally satisfy the condition that $h_{smp0} > 0.3D$, as recommended in HEC-26.

It is emphasized that h_{smp0} is *not* the final design sump depth, h_{smp}, which is obtained in step 4 below, and which will be larger than h_{smp0}. This initial value, h_{smp0}, is needed only for a preliminary hydraulic analysis of the culvert. It is also expected that the proposed final design sump depth will satisfy the current RGP sump depth requirements, which depend on structure type as well as substrate material.

2. Traditional HY-8 culvert analysis. For the structure shape, size, and sump depth chosen in step 1, the standard hydraulic analysis using the standard HY-8 (without any AOP features) is then performed for a range of flows, up to and including the design peak flow, Q_p. Two aspects of the HY-8 analysis will be special interest with regards to AOP design. The first is the outlet velocity at Q_p, as this will determine the sizing of the armor sublayer stone as described in the next step. The other main aspect concerns the difference between the water surface elevation at the culvert outlet and the water surface elevation in the tailwater channel under conditions around the ordinary high water mark, as this will reflect any perching of the culvert. The culvert outlet depth should not exceed the tailwater depth by a specified value, e.g., 0.5 ft, otherwise a wider span should be selected. At this point a preliminary culvert span, W_0, has been determined that satisfies a no-perching condition for the ordinary high water mark flow and also satisfies a preliminary sump height condition. While the present design focuses on AOP issues, any design will still need to consider traditional headwater or cover constraints.

3. Armor sublayer stone sizing. From the HY-8 results of step 2, the outlet velocity is taken as a typical velocity within the culvert, and is used to determine the sizing of the stone in the armor sublayer. Unlike HEC-26, the INDOT stability criterion for riprap design is velocity-based rather than shear-stress-based, and was found to be overly conservative for lower velocities, and may be only marginally conservative at higher velocities. For the proposed procedure, the recommended permissible limit velocities for the various classes are given in Table 3.2. The limits for classes 1 and 2 riprap in Table 3.2 are the same as those in the standard INDOT riprap design, while the limit for revetment riprap has been increased (from 6.5 ft/s to 8 ft/s), and a new coarse aggregate dense-graded class, defined in Appendix B, for the surface layer, may be used for the armor layer for low velocities (less than 4 ft/s).

If the resulting velocity is greater than 13 ft/s, then a structure of larger span should be chosen, and the procedure repeated. For velocities larger than 4 ft/s, at least a single layer of the appropriate riprap is to be placed as an armor sublayer below the surface layer, such that the average thickness of the armor sublayer, h_{armor}, is given by $(d_{50})_{armor}$. The new coarse-aggregate class for low-velocity cases is characterized by $(d_{50})_{armor} = 32$ mm

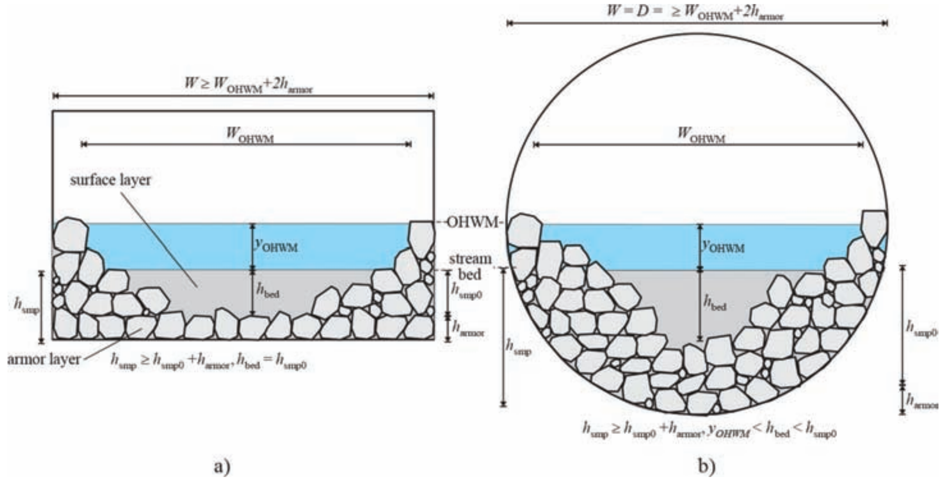


Figure 3.15 Proposed AOP culvert design choices for span and sump depth for (a) box culvert and (b) circular culvert.

(=1.25 in), which is considered too small, and so a minimum value of 0.5 ft is specified for h_{armor}. In summary, the thickness of the armor layer is specified as:

$$h_{\text{armor}} = \max[(d_{50})_{\text{armor}}, 0.5\,\text{ft}] \tag{3.2}$$

4. Culvert span and sump depth. With an appropriate armor layer thickness, h_{armor}, and a preliminary culvert span, $W_0 \geq W_{\text{OHWM}}$, and preliminary sump height, h_{smp0}, determined in the previous steps, a "tentative" final design choice for the culvert span, W_c, and sump depth, h_{smp}, is made, namely:

$$W_c \geq W_0 + 2h_{\text{armor}} \text{ and } h_{\text{smp}} \geq h_{\text{smp0}} + h_{\text{armor}} \tag{3.3}$$

An additional $2h_{\text{armor}}$ is added to W_0 in order to accommodate bank-like features similar to the USFS2008 approach, while an additional h_{armor} is added to the initial sump height in order to accommodate an armor sublayer similar to that in HEC-26. Figure 3.15 illustrates these design choices for box and circular culverts under ordinary high water mark flow conditions. Because of the highly sloping sides of the circular culvert, stability of the armor riprap material used in constructing the bank features may require multiple layers of the riprap. Provided the thickness of the surface layer is larger than y_{OHWM}, then this should be of no concern, but if this condition is not satisfied, a larger structure should be considered.

The initial HY-8 analysis did not account for the bank features. Because the proposed final design structure is actually oversized compared to that in the initial analysis, this should more than compensate in the evaluation of both culvert velocities and headwater.

It is expected that the final-design sump depth, h_{smp}, including the thickness of the surface layer and the armor layer, should satisfy the current IDEM RGP requirements, at least for the larger structures that are the focus of this design approach. As an example, consider a stream with the smallest OHWM width of $W_{\text{OHWM}} = 12\,\text{ft}$ required to comply with the RGP backfill requirement, and assume that revetment riprap (so that $(d_{50})_{\text{armor}} \approx 0.8\,\text{ft}$) was found in step 3 to be suitable for the armor layer. If a box culvert is used, then a culvert span of $W_c = W_{\text{OHWM}} + 2(d_{50})_{\text{armor}} = 13.6\,\text{ft}$ would be chosen, together with a sump depth of $h_{\text{smp}} = y_{\text{OHWM}} + (d_{50})_{\text{armor}} \approx 2\,\text{ft}$, where the OHWM depth has been estimated as $y_{\text{OHWM}} = 0.06W_{\text{OHWM}} + 0.4 \approx 1.2\,\text{ft}$. Thus, a sump height of 2 ft exceeds the largest required sump height in the IDEM RGP, and is even consistent with the recommendation of HEC-26.

5. Surface-layer characteristics. The choice or design of the surface-layer material is based on a gross assessment of stream substrate type, whether sandy, gravel (though not including the largest gravel), or other. The surface layer size is chosen to preclude the culvert bed material from being washed out of the culvert, i.e., the culvert material becomes mobilized only if the channel substrate is also already mobilized and becomes able to resupply the culvert bed with upstream sediment. This requires that the size of the culvert surface layer, $(d_{50})_{\text{surf}}$, must be equal to or larger than the median diameter of the stream channel, $(d_{50})_{\text{chan}}$. If a detailed characterization of the stream substrate is available, as must be obtained for the USFS2008 and HEC-26 approaches, then an attempt to match culvert and stream bed material can be attempted. If only a gross characterization of the stream material in terms of broad types (sandy, gravelly, etc.) is available, as assumed in the present approach, a "conservative" strategy can be adopted in choosing a surface layer material for each group (or most of each group). The above assumes that the range of design flows being considered are such that the culvert bed material will be mobilized.

For a channel assessed to be predominantly sandy, then it is assumed that most of the material is less than 2 mm in size, and so backfill material coarser than this is sought. An already defined standard INDOT coarse aggregate, the dense-graded class #53, satisfies this condition. As discussed in Appendix B, this standard aggregate has a median diameter, $d_{50} \approx 4$ mm, such that, if the stream substrate is mainly sand, then this backfill material will be mobile only when the stream material is already mobile. The dense-graded (or well-graded) characteristic refers to a broad and even size distribution with sufficient fines fraction resulting in low void content, high bulk density and low permeability. In the present context, a dense-graded fill is desirable in order to minimize interstitial flow at low discharges when a stream might "disappear" into a high-permeability substrate. Both USFS2008 and HEC-26 recommend that the d_5 of any backfill mixture should not exceed 2 mm (note that $d_5 = 0.05$ mm for the dense-graded class #53, thus satisfying this condition).

The already defined INDOT standard dense-graded classes are not suitably conservative choices for a predominantly gravel-bed channel, and so a new dense-graded aggregate class was defined for gravel (at least up to coarse gravels)-bed streams. In Appendix B.2, this new additional aggregate class is defined based on the Fuller-Thompson model for dense grading and designed to obtain $d_{50} \approx 32$ mm (1.25 in) which should be stable for all except the largest gravel subgroup (termed very coarse gravel with a size range ranging from 32 mm to 64 mm). If desired, other standard classes of backfill can be similarly "designed" or defined to cover other substrate size ranges. It should be emphasized (USFS2008, HEC-26) that the Fuller-Thompson equation on which the design is based has not been widely used in the culvert-bed context, and might be considered only as a starting point of the bed material design.

The above approach is conservative only in the sense of a stable culvert bed as it chooses a coarser material for the surface layer. USFS2008 recommends that the culvert bed material should be no more than 25% coarser than stream material though the empirical basis for this recommendation is unclear as are the consequences of using a much coarser well-graded material. From a hydraulic point of view, the coarser material is expected to increase the roughness and so decrease velocities under open-channel-flow conditions, which might be considered favorable for AOP. It is also likely that, due to sediment transport from upstream, a layer of natural channel material will become established over the installed culvert surface layer. In essence, the surface layer acts as a secondary armor sublayer on which native material can deposit, and so the HEC-26 logic of an armor sublayer is extended to the surface layer which becomes an intermediate layer beneath a native layer. In comparison to the current INDOT no-backfill guideline, which relies on natural refilling of the entire sump depth, which might occur over a very long time duration and incur other undesirable effects such as headcutting, the proposed backfill approach may be viewed as still relying on natural refilling, but only over a small fraction of the sump depth, over a much shorter time span, and avoiding to a large extent issues such as headcutting.

6. Other comments and issues. There are two other design issues to discuss, namely, the culvert rise and the scour prevention outside of the culvert. For standard variable-width culvert geometries such as the circular or the pipe-arch geometry, the rise is not independent of the span, and so does not need to be separately determined. For a box culvert, the rise can be chosen within reason separately from the span. Other considerations for determining the box culvert rise will include the more traditional constraints of headwater, cover, serviceability and costs. An additional constraint that might be considered is a preference for a flow through the culvert that is entirely open-channel flow, similar to a natural stream. USFS2008 suggested that, for the "high-bed-design flow" (see Chapter 3.2), the culvert inlet should not be submerged. An entirely open-channel flow may not be practical for all flows, but a criterion (similar to that for serviceability) might be formulated in terms of a design flow less than the peak flow.

Appropriate scour prevention measures at the culvert inlet and outlet should be taken. Even if perched conditions do not prevail at culvert installation, scour at the outlet could eventually lead to perched conditions that will degrade or even completely prohibit AOP. The culvert bed, including armor and surface layer, should be extended some distance upstream and downstream of the culvert ends and the stream banks suitably protected (see the example of the HEC-26 design in Figure 3.9). Standard culvert energy dissipator designs may be used as guidelines for the extent of the scour protection.

Detailed checks on the final design, such as the stability of the culvert bed, or the resulting headwater elevation, can be performed if desired using the procedures and equations found in HEC-26 (or USFS2008) with the help of software such as HEC-RAS.

3.5.5 Comparisons of the Simplified Design Procedure and Traditional, USFS2008, and HEC-26 Design Procedures

Compared to the traditional culvert design procedure, the only additional data input required by the simplified design procedure is the OHWM width and a gross characterization of the channel substrate, both of which will likely be already available since they are necessary for compliance with the IDEM RGP conditions. In contrast, the USFS2008 and HEC-26 procedures require cross-sectional and longitudinal profiles as well as detailed substrate characterization. A major difference between the proposed procedure and the USFS2008 and HEC-26 procedures is that, in order to simplify the design of a stable culvert bed, it does not attempt to replicate the natural substrate characteristics within the culvert, with the result that the culvert bed material may be substantially coarser than that in the channel. Whether this will have any significant negative consequences for AOP is unclear, but over time any such negative effects may be mitigated by deposition of natural material (particularly for sandy substrates). Recall that, even in the USFS2008 stream simulation design, the bank material designed to be immobile will often be coarser than that in the channel due to problems in substrate sampling. It is expected that the resulting size of the culvert from the proposed procedure will be intermediate between the USFS2008 and the HEC-26 designs as it is based on the OHWM width rather than bankfull width, but also accommodates bank features. Viewed as a simplified procedure, similar to the no-slope design approach, it is suggested that a prudent limit at this time for the application of the proposed procedure is a maximum channel slope of 3% similar to that typically specified for the no-slope design.

3.6 Other Considerations

The proposed simplified design procedure addressed issues raised in the IDEM RGP conditions for new larger (OHWM widths >12 ft) culverts. The design of smaller culverts should also be re-examined. For example, should sumping be required for all culverts, even those for which a culvert bed cannot be practically installed? If sumping is required for even small culverts, are there measures to promote the natural estabilishment of a bed and avoid any problems with headcutting?

3.7 Summary

The current INDOT design guidelines, together with the two dominant approaches to culvert design for AOP were reviewed. From the AOP regulatory perspective, the main gaps in the current INDOT design guidelines concerned the larger culverts requiring backfill and installation of a continuous substrate over the length of the culvert. The USFS2008 and HEC-26 design approaches both attempt to offer a comprehensive and general solution to AOP culvert design, but both require substantial additional data input and analysis. A simplified design procedure is proposed that is tailored to Indiana conditions where it is expected that stream channels are mostly low-gradient with either sandy or gravelly substrates. It draws elements of both the USFS2008 and HEC-26 approaches but makes design choices taking advantage of already existing INDOT standard specifications with regards to riprap and coarse aggregates and expressing a preference for stable culvert beds (even if the material characteristics will be coarser than that in the natural channel). The resulting culvert should also comply with the current RGP conditions.

4. COSTS/BENEFITS, HABITAT INDICES, AND REGULATORY STRATEGIES

Costs (and benefits, which are negative costs) can provide the basis for either engineering or regulatory decisions if all relevant costs are included. Because of its generally larger size, the initial costs of the AOP-designed culverts are generally larger than those of traditional culverts, and in the context of scarce resources, it may be asked to what extent the additional costs can be justified. This question will be addressed in this chapter in a discussion of life cycle costs of culverts. Design decisions are taken within a regulatory context and other regulatory options might be examined that might lead to better outcomes from an environmental or ecological point of view, or similar outcomes at less costs.

4.1 Costs and Benefits of an AOP-Designed Culvert

The additional constraints on the hydraulic design of culverts for AOP implies a size that is invariably larger than the "traditionally" designed culvert, and hence greater costs in terms of materials and installation, and to a certain extent, engineering effort. For Indiana, this does not necessarily mean that the costs will be substantially larger than that incurred in current INDOT practice. As noted earlier, even prior to the current RGP conditions, the INDOT Design Manual require sumped and hence oversized culverts. The available studies of costs of AOP-designed culverts, such as those discussed below, have typically compared the costs to those of traditional culverts and so care should be taken in applying these to Indiana conditions.

4.1.1 Installation (+ Material) Costs of AOP-Designed Culverts Compared to Traditional Culverts

Two studies were found that focused on the costs (material and installation) of AOP culverts, and compared these costs to those of traditional culverts. In a study for the Minnesota Dept. of Transportation (MnDOT), Hansen, Neiber, and Lenhart (2009) examined the costs of a type of AOP-culvert design, known as MESBOAC, developed by MnDOT and discussed earlier in Chapter 2.3. The cost estimates (for 11 sites) were not detailed engineering estimates, but rather hypothetical in that the costs of actual recently installed conventional culverts were compared with the costs of re-engineered MESBOAC-designed culverts, making gross assumptions, e.g., the same 1-ft sump depth for all 11 sites and restricting any change in culvert width to be less than 2 ft. Interestingly all but one of the "conventional" culverts (all box culverts) were designed with span in excess *of bankfull width, and so it should not be automatically assumed, even in Indiana, that culverts designed without AOP considerations are necessarily substantially undersized.*

Christiansen et al. (2014), in a study for the Wisconsin Dept. of Natural Resources (WDNR), compiled the results of other studies (see Table 4.1), but its main focus was a comparison of life-cycle costs, i.e., it included maintenance and other potential costs, and attempted to quantify not only fiscal benefits but also social and ecological benefits (to be discussed further below). The following relies on their study, but also critically looks at their methodology and conclusions.

Several comments should be considered in interpreting Table 4.1, which summarizes the ratios of installation + material costs for AOP-designed and non-AOP-designed culverts:

- The low values for the Minnesota cases are explained largely by the spans of the non-AOP-designed culverts exceeding the bankfull width for all but one of the sites.

TABLE 4.1
Ratios of installation + material cost of AOP-designed culvert to traditional culvert (values taken from Christiansen et al., 2014).

State/region	Main source	No. of sites	Average ratio of costs	Range of ratio of costs
Minnesota	Hansen et al. (2009)	11	1.1	1–1.3
Maine	Long (2010)	4	10.7	6.8–19
Vermont (Green Mountain Nat'l Forest)	Gillespie et al. (2014)	5	1.5	1.2–1.6
Wisconsin (Green Bay)	Christiansen et al. (2014)	495	1.9	1.1–4.7

As such, the AOP-designed culvert had a span equal to or even smaller than the non-AOP-designed culvert for all but one case. With span being one of the major contributors to culvert costs, the ratios of costs are not surprisingly close to 1. Indeed, the highest ratio of 1.33 was incurred in the only case where the AOP-designed culvert (10 ft span) was larger than the non-AOP-designed culvert (8 ft span). This illustrates that cost ratios without regard to span ratios can be misleading.

- The extraordinarily large ratios for the Maine sites are based on actual project costs, but are likely skewed because of the apparently grossly undersized existing culverts in the projects included. In three of the four projects, existing culverts were less than or equal to 3 ft in diameter, and were replaced by culverts with 12-ft spans. Further, these 12-ft spans necessitated the use of pipe-arch structures rather than the less costly circular structures. Nevertheless, the costs for the conventional structures seem to be much underestimated, compared to the estimates found by the New England Environmental Finance Center (2010) also for the Maine Department of Transportation (see Appendix C).
- The Vermont ratios are "anticipated" estimates, but only three of the five structures were actually constructed, and somewhat surprisingly, the actual costs reported in Gillespie et al. (2014) were actually less than anticipated. The actual ratios for the three constructed projects averaged 1.1 (compared to 1.5 in Table 4.1), and ranged from 1.09 to 1.22. No details of the sizes and types of existing and replacement structures was given, and so these ratios should be interpreted cautiously. Because actual costs of both traditional and AOP culverts exceeded $100,000, it is believed that these were larger structures.
- Like the Minnesota study, the Wisconsin study developed hypothetical cost estimates for the AOP-designed culverts, based on a modified culvert replacement cost estimator used by the WDNR. It includes costs arising from, e.g., the culvert pipe, excavation, bedding, and reconstruction, and assumes that most of the AOP-designed culverts have a width of 1.2 times the bankfull width and require 2 feet deeper excavation than traditional culverts to satisfy embedment requirements. Traditional culverts were assumed to require no sumping and to be the same width as the existing culvert. Information on the ratio of span widths is not given and as emphasized previously this makes interpretation more difficult. While the large sample size (495 sites) might reduce the effect of bias seen in the Minnesota and Vermont study, the aggregation has a problem with real intra-sample variation, i.e., there may be systematic (non-random) variation within the sample. This is illustrated by the graph taken from Christiansen et al. (2014), shown in Figure 4.1, which plots the fiscal benefits (to be defined later) against the bankfull width, and indicates a distinct non-random increase in scatter for increasing bankfull width. This is likely due in part to the fiscal benefits not being normalized so that larger projects (due to larger bankfull widths) will be associated with larger benefits (both negative and positive), but also may point to systematic variations due to variations in bankfull width. For example, it might be speculated that cost ratios for smaller structures or for those projects requiring a smaller span ratio to comply with AOP designs could have substantially different cost ratios than those of larger structures or those requiring large span ratios for AOP compliance. With such qualifications, the results of the Wisconsin study in Table 4.1 may provide a very rough guide to the increased installation costs due to AOP designs.

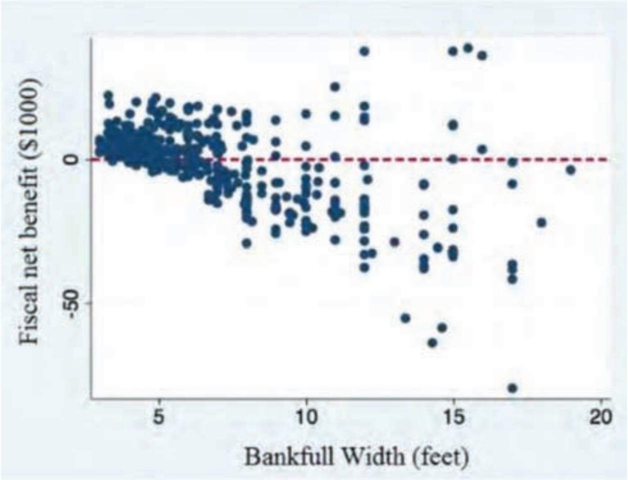


Figure 4.1 Variation of fiscal benefits with bankfull width from Christiansen et al. (2014).

Another useful estimate of installation (+ material) costs was made by the New England Environmental Finance Center (2010), for the Maine Department of Transportation. They provided costs for various culvert options for a hypothetical replacement project (including an in-kind replace-ment, as well as bankfull culverts with span approximately equal to 1.2 times the stream bankfull width with and without a conventional bottom). Selected estimates from that work are given in Appendix C. That study did make the qualification that "the models are representative of very basic culvert replacement projects and may not reflect the tremendous variety and scale of variable [sic] could be present in an actual culvert replacement project." Three-sided

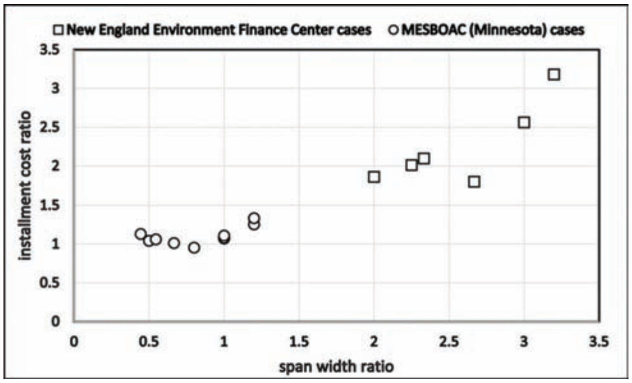


Figure 4.2 Installment cost ratios for hypothetical culvert replacement cases estimated by the New England Environmental Finance Center for MaineDOT as a function of span width ratio; MESBOAC (Minnesota) cases also added.

bottomless structures were found to be even costlier than the more conventional bankfull culvert. The cost ratios for the least cost bankfull culvert compared to the in-kind culvert are plotted as a function of span ratios in Figure 4.2. Also included in Figure 4.2 are the Minnesota MESBOAC data, which largely cluster around a span ratio near to unity. These data would suggest that cost ratios may vary strongly with span ratios, and so lumping these together into a single average cost ratio may be misleading.

4.1.2 Life-Cycle Costing of Culverts

Because of the likely larger size of AOP-designed culverts and hence their likely greater initial costs, advocates of AOP-designed culverts, such as the sources in Table 4.1, have emphasized the importance of life-cycle costing. They argue that overall costs over the lifetime of an AOP-designed structure may be comparable or even less than that of a conventional structure. Life-cycle cost analysis (LCCA) is a standard procedure in private industry, especially manufacturing, but is less widely applied to public infrastructure investment, though has been embraced by the U.S. Department of Transportation (USDOT, 2002). A primary difficulty is the valuation of the (potential) costs (and benefits) of public goods. For example, Perrin and Jhaveri (2004) argued that user delay costs due to damage to the structure, although not immediately borne by the agency paying for the structure, but rather borne by the public, should be included in the life-cycle costs. Even if a standard commonly accepted valuation procedure is agreed on, the data needed to perform a meaningful LCCA are often unavailable. The lifetime of a structure is a key parameter in any LCCA, yet hard historical data on culvert service life are sparse, and so gross assumptions need to be made. In the case of a new design, historical use cost data by definition are not available, and so comparisons become rather speculative.

In their Wisconsin study, Christiansen et al. (2014) included (i) maintenance costs, (ii) costs due to potential catastrophic failure during the structure lifetime, including user delay costs, and (iii) costs related to flood damage. A major assumption is a uniform service lifetime: 35 years for a conventional culvert, and 70 years for an AOP-designed culvert. It is generally thought (hard statistics are rare) that lifetimes will depend on pipe material, with concrete pipes lasting 100 years or more, while corrugated steel pipes may vary in lifetime from 10 years to more than 50 years depending on abrasion and corrosion conditions (Maher, Hebeler, & Fuggle, 2015; Perrin & Jhaveri, 2004; Taylor & Marr, 2012) as well as type of coating such as aluminization and polymerization and thickness (gauge). In the absence of a catastrophic failure, an AOP-designed structure of the same material (+coating) and thickness and differing mainly in span width will be subject to much the same lifetime deteriorating factors as the non-AOP-designed structure, and the gross assumption of double the lifetime may be questioned.

Maintenance costs. The maintenance costs in the Christiansen et al. (2014) study was limited only to clean-out costs to remove any obstruction, with the required clean-out rate being based on a county dataset (1615 culverts) of observed obstructions (so not necessarily actual clean-out frequency). A statistically significant relationship between constriction ratio and observed obstruction (and by assumption a maintenance need) was found. An average reduction of about $1900 per culvert in maintenance costs over the 70-year time horizon was estimated for AOP-sized structures compared to non-AOP-sized structures. On the one hand, this amounts to less than $30 per year per culvert, which might be considered as slight; on the other hand, when a very large number of culverts are involved (INDOT culvert database indicates over 100,000 small culverts and over 8000 large culverts, the dividing line between small and large culverts being a span of 4 ft), the total savings per year could still be substantial.

Catastrophic failure and flood damage costs. From limited evidence in Vermont during Hurricane Irene (Gillespie et al., 2014), estimated costs due to potential catastrophic failure assumed that AOP-designed culverts (specifically the USFS2008 design, since the Vermont cases involved USFS2008 culverts) reduced failure rates by 75% compared to conventional culverts. The costs included replacement cost, though at emergency rates, which are much higher than normal rates, as well as user delay costs as was suggested in Perrin and Jahveri (2004). User delay costs were estimated according to the procedure of Mallela and Sadavisam (2011), a study prepared for the FHWA, and required assumptions regarding the likelihood of overtopping, and the consequent delays due to repair. Overtopping was assumed to occur for a 25-year flow event for non-AOP culverts and for a 50-year flow event for AOP culverts if the culvert cover was less than the stream bankfull width. Current INDOT culvert design

TABLE 4.2
Summary of benefits/costs estimated by Christiansen et al. (2014) of AOP culverts compared to non-AOP culverts (negative values are costs, 3.5% discount rate and 70 years' time horizon assumed).

Type of benefits	Benefit source	Average	Standard deviation
Fiscal benefits/costs	Installation	-16,600	14,600
	Structure lifetime	7,200	4,900
	Maintenance	1,900	700
	Failure rate	1,500	900
	Flood damages	1,700	1,100
Total fiscal benefits/costs		-4,300	
Non-fiscal benefits/costs	Wetlands	5,600	3,600
	Fish passage	3,200	10,000
	Water quality	1,300	2,900
	Road user	2,000	1,300
Net non-fiscal benefits		12,100	
Net benefits		7,800	16,500

policy specifies the design flow for different types of roads, such that, e.g., a roadway with average annual daily traffic (AADT) larger than 1000 should be serviceable for a 25-year design flow, and if AADT >3000, then a 100-year design flow is to be used. Thus, if a non-AOP culvert is installed under these roadways, then it should have been designed to pass safely at least the 25-year flow (and for larger AADT roads the 100-year flow) and so should not be overtopped. Similarly, estimates of costs incurred due to flood damage (but not catastrophic failure) assumed that damage will be caused by 25-year flows. Because such gross assumptions may not be applicable for many culverts in Indiana, the numerical results of Christiansen et al. (2014) regarding cost advantages (Table 4.2) should be considered critically.

While the detailed assumptions made in the above cost estimates may be contested, the included cost items (with the possible exception of user delay costs) and valuation approach are mainly non-controversial. Christiansen et al. (2014) termed these items "fiscal" benefits, and the net fiscal benefits from AOP-designed culverts vs non-AOP-designed culverts that they estimated were already presented in Figure 4.1 as a function of bankfull width. The average net fiscal benefits were estimated by Christiansen et al. (2014) to be negative (-$4500 per culvert). Nevertheless, positive net fiscal benefits were found for 44% of culverts. As emphasized above, the numerical values should be viewed with caution, but these results do suggest the possibility that the AOP-design of some fraction of culverts could be justified based solely on these narrow cost estimates.

4.1.3 Social and Ecological Benefits/Costs

Christiansen et al. (2014) distinguished fiscal benefits from "non-fiscal" social and ecological benefits resulting from AOP-designed structures. Because these benefits do not accrue to INDOT (or conversely their costs are not borne by INDOT), whether they should be included in any life-cycle costs/benefits analysis is a policy question that remains to be resolved. Even if a positive answer to this question is received, questions regarding appropriate valuation procedures still need to be addressed. Christiansen et al. (2014) considered only four sources of socio-ecological benefits of AOP-designed culverts: those associated with

- impacts on wetlands – by changing water levels upstream and downstream from natural levels, the total acreage of wetlands adjacent to undersized culvert locations may be positively (increased) or negatively (reduced) affected, with resulting benefits (costs),
- increased fish passage – this is the main motivation for AOP-designed culverts, though how it can be appropriately valued is debatable,
- improved water quality – the direct effect of AOP-designed culverts on water quality would seem to be linked to its effect on sediment transport and scour, since their effect on chemical or biological species, such as phosphates and nitrates and *e. coli*, is negligible, and
- road user costs – essentially the same as user delay costs already discussed previously.

The detailed methodology for estimating the benefits/costs of each of these sources is fraught with difficulties and uncertainty due to the lack of empirical data and methodological questions.

Wetland impacts. The valuation of wetlands in terms of the costs of wetland restoration (per unit area) may be considered reasonable but the assessment of the total impact of a culvert on an adjacent wetland is rather crude. A probabilistic model related the constriction ratio of a culvert to a wetland factor that is the net wetland acreage gained from replacing a non-AOP to an AOP culvert. This is then multiplied by the fraction of the watershed that consists of wetlands. Although this methodology led to estimates of less than 0.1 acre net wetland gain for most culverts, the average benefit per culvert was rather high due to the assumed high average cost per acre ($128,000) of wetland restoration. It should also be considered whether an average cost of restoration be used rather a marginal (incremental) cost, which might be different.

Fish passage impacts. Although improved fish (or aquatic organism) passage is directly the main aim of AOP culverts, the ultimate aim is an improved aquatic ecosystem. If valuing improvements in fish passage is difficult, valuing ecosystem improvements due solely to changes in culvert design is daunting. Accurately assessing fish passage improvements can be done but requires much effort and specialized expertise as discussed in the literature review (Chapter 2). Such detailed studies are impractical for large-scale regional studies, and Christiansen et al. (2014) instead relied on the highly simplified model and data of Januchowski-Harley, Diebel, Doran, and McIntyre (2014) to predict culvert passability. The Januchowski-Harley et al. model is *not* based on actual passability studies, but rather is based on observations at 2235 culvert sites in the Great Lakes basin of (i) stream velocities when stream flows were less than or equal to base flows, and (ii) whether a culvert had a perched outlet, both of which are taken as surrogate indicators of passability, and on which a change in passability is assigned. If a replacement structure such as an AOP culvert resulted in the removal of a fish passage barrier, then a change in passability rating of 1 would be assigned. Christiansen et al. (2014) based their estimate of benefits/costs of AOP culverts on this rating (for 11 fish species), the species population density in the stream, and the market value of each species. Their estimates of velocities might be inconsistent with the data of Januchowski-Harley et al. (2014), and a more critical issue is that they attribute the entire value of the fish present in the stream to the passability of a single structure, which seems unrealistic.

Water quality impacts. The willingness-to-pay (WTP) approach to the valuation of water quality improvements was adopted by Christiansen et al. (2014) to estimate the benefits/costs of AOP culverts. In particular, they relied on the results of a preceding study of the benefits of runoff water quality improvements of the Green Bay region conducted by Moore, Provencher, and Bishop (2011), in which an average benefit of $122/household per year was estimated for improvements in the water quality of Green Bay. This value was used by Christiansen et al. (2014) for their estimate of the benefits of AOP culverts (in the Green Bay region). A difficulty is that the WTP approach of Moore et al. (2011) was based on a stated preference survey that is rather non-technical. The survey question was "If you were voting in a referendum on steps to reduce nutrients and runoff into Green Bay and the cost to your household in increased state and local taxes would be $_____ per year for the foreseeable future, how would you vote?" with various amounts from $50 to $1000 were given as options. As such, the amount of any improvements due solely to AOP culverts is not specifically addressed. The question as to whether numerical values can be applied generally to culvert applications, e.g., in Indiana, can be raised because these values were obtained for improvements in the water quality of Green Bay, rather than the water quality in the vicinity of the culvert. The value of water quality in a large waterbody such as Green Bay may be quite different, e.g., because of its recreational value, than that of a small stream or drainage ditch over which a culvert might cross. In addition, Christiansen et al. (2014) made the gross assumption that any evidence of upstream ponding or downstream scour implied continuous sediment mobilization and hence degradation in water quality. Sediment mobilization and transport may, depending on the substrate characteristics, occur in the natural stream, and so would still occur even in an AOP culvert. Further, upstream ponding may enhance sediment deposition rather than mobilization, while downstream scour may reach an equilibrium such that after some time, it stops and there is no longer any net growth. Evidence of upstream ponding or downstream scour are likely quite poor indicators of overall water quality.

Road user impacts. Estimates of the costs of road user impacts were made in the same way as previously discussed with regards to catastrophic failure, and seems to have been separated out in the analysis of Christiansen et al. (2014).

4.1.4 Summary of Christiansen et al. (2014) Estimates

The individual benefits/costs as estimated by Christiansen et al. (2014) are summarized in Table 4.2, and is divided into fiscal and non-fiscal benefits. As discussed above, due to the grossly simplified assumptions underlying them, the numerical values should be regarded with great caution, especially with a view to application to Indiana conditions. The large standard deviation for each entry, including the final net benefit estimate, should be noted. Thus, even if the values are accepted, the large associated uncertainty would from a purely statistical point of view imply that the values are not statistically different from zero. While this might be viewed as nullifying the conclusion of a positive net total (fiscal and non-fiscal) benefits of AOP culverts, it could also be conversely viewed as pointing to no significant cost disadvantage to such culverts. As argued above, the large standard deviation may be due in part to the aggregation of structures of all sizes so that a more refined analysis distinguishing between different structure sizes might lead to different results. The relative contributions also give some indications of the importance of the assumptions made in the estimate. Thus, assumptions of structure lifetime or wetland impacts seem to exert a strong influence on estimated benefits.

Despite the questions surrounding the detailed assumptions underlying their benefit estimates, two general recommendations made by Christiansen et al. (2014) merit consideration, namely that the Wisconsin DNR (i) "prioritize the implementation of stream-simulation culverts based on the measurable environmental impacts of existing culvert," and (ii) "collect data on culvert maintenance costs." More specific recommendations that rely on the detailed results would prioritize replacement of undersized culverts that directly impact wetlands, exhibit features indicative of fish barriers, such as a perched outlet or very high velocities, and extensive downstream scour, and culverts on smaller streams.

4.2 Considerations for a Regulatory Scheme

With the costs and benefits of AOP-designed culverts still debatable, an examination of the basis of current regulations may be motivated and other regulatory strategies explored. The current RGP conditions distinguish between smaller and larger culverts, with the latter subject to more specific requirements. Specifically, for OHWM widths larger than 12 ft, minimum culvert spans as well as the installation of a culvert bed are required. An OHWM width of 12 ft as a dividing line may be justified from various perspectives, including the fact that constructability of the culvert bed may require a minimum culvert size, and also that larger streams are generally more capable of sustaining a rich and diverse ecological system (see the results below on habitat and biotic indices). The following explores another option. While being based on previous work, it does not attempt any detailed benefit/cost valuation but rather focuses on biotic and habitat indices, IBI (Index of Biotic Integrity) and QHEI (Qualitative Habitat Evaluation Index), and a general "do no harm" philosophy that aims to not contribute to any further habitat degradation of the local stream system. Constructability of the culvert bed still presents a constraint but an OHWM width of 12 ft may not be the minimum size that will satisfy a constructability constraint.

4.2.1 Indices of Habitat (or Ecological) Quality

Because the main concern in discussions of AOP is the adverse ecological effect of conventional non-AOP culverts, a regulatory strategy based on measures of ecological or habitat quality of a stream may be motivated. Two standard indices widely used in the Midwest are the Index of Biotic Integrity (IBI) and the qualitative habitat evaluation index (QHEI). A useful description of water quality monitoring tests or measures in general and specific indices such as IBI and QHEI is given by Frankenberger and Esman (2012). Both indices, which are based on a composite of a suite of metrics, are being routinely measured by IDEM at representative sites in Indiana.

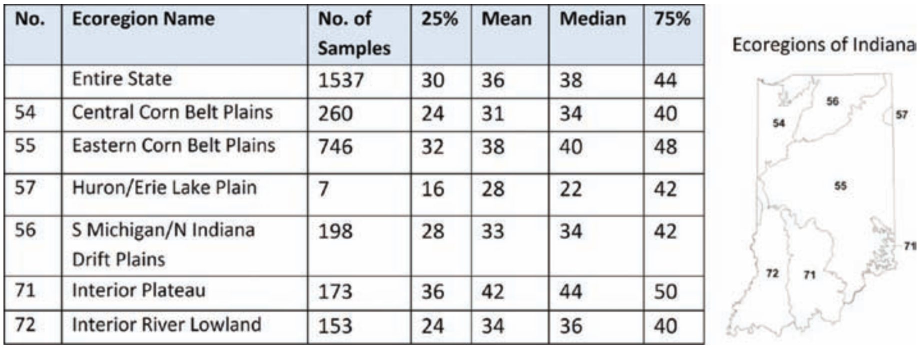
Index of Biotic Integrity (IBI). The (fish)-IBI is derived from actual fish sampling or catch in the stream, which is performed with specialized techniques such as electrofishing. Here the IBI being considered is sometimes termed fish-IBI, as other IBI may also be based on macroinvertebrates. It also requires an in-depth knowledge of fish species and their characteristics. Twelve individual metrics are given scores of 1, 3, and 5, with 5 representing the best quality habitat, for a maximum total score of 60. The metrics can be broadly classified in several groups: species diversity and composition, indicator species (dependent on sensitivity to or tolerance of water quality degradation), trophic (position in the food chain, e.g., carnivores and omnivores) and reproductive (substrate quality) functions, and abundance and condition (e.g., number of diseased fishes with abnormalities, such as lesions and tumors).

According to the Indiana Administrative code (327 IAC 2-1-3), "all waters, except those designated as limited use, will be capable of supporting a well-balanced warm water aquatic community." A stream reach with a total IBI score of less than 35, and thus an integrity class of poor or lower (Table 4.3) has been interpreted by IDEM as not supporting aquatic life use. Even divided into 6 (EPA level 3) ecoregions, streams within each region may be characterized by a broad distribution of total IBI scores (Figure 4.3), suggesting that IBI scores may be quite site-specific, and assigning a single value to a large region will not be useful. Results from a more refined (EPA level 4) ecoregion definition were also obtained, but do not change the broad conclusion. From Figure 4.3, the "current" status of most Indiana streams may be classified as fair or lower, with only the upper quartiles achieving a "good" or better classification.

Qualitative Habitat Evaluation Index. In contrast to the IBI, the Qualitative Habitat Evaluation Index (QHEI) does not require any specialized sampling technique or in-depth knowledge of fish species, though, for consistent and reproducible results, some training is necessary. It is not based on any direct measurement of biotic integrity, but rather indirectly assesses habitat quality by considering the physical characteristics of streams that are believed to be closely associated with habitats "capable of supporting a well-balanced warm water aquatic community." The metrics are usually listed in six categories related to the extent and/or characteristics of the (i) substrate, (ii) instream cover, such as overhanging vegetation, logs, boulders, (iii) channel morphology, such as sinuosity, development of pools and riffles, and evidence of channelization, (iv) riparian zone and bank erosion, including riparian width and evidence of bank erosion, (v) pools and riffles, and the (vi) map gradient or slope, adjusted for width and drainage area. The maximum score for each of the first four categories is 20, while that for the last two categories is 10, with a maximum total score of 100. The IDEM interpretation of the QHEI score given in Figure 4.4, with only three ranges and in which QHEI <51 is taken as indicative of poor habitat, is a simplification of the original Ohio EPA interpretation (Frankenberger & Esman, 2012) with a more refined number of ranges (five rather than only three) and a slight difference in the treatment of headwater streams and

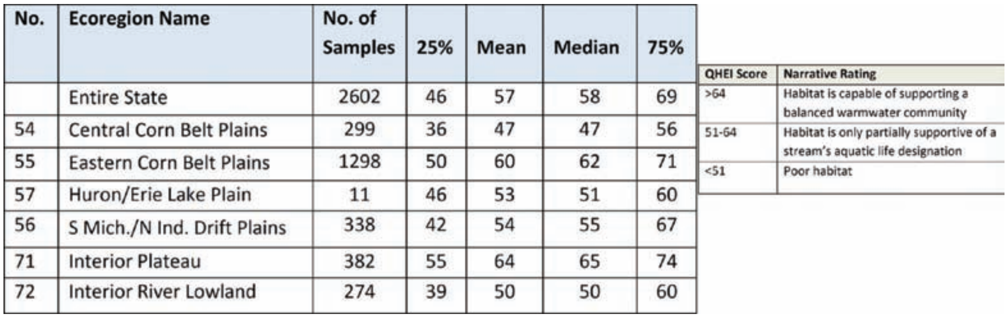
TABLE 4.3
Total IBI scores and the associated IDEM integrity class level.

Total IBI score	Integrity class	Attributes
53–60	Excellent	Comparable to "least impacted" conditions, except assemblage of species
45–52	Good	Decreased species richness (intolerant species in particular), sensitive species present
35–44	Fair	Intolerant and sensitive species absent, skewed trophic structure
23–34	Poor	Top carnivores and many expected species absent or rare, omnivores and tolerant species dominant
12–22	Very poor	Few species and individuals present, tolerant species dominant, diseased fish frequent
<12	No fish	No fish captured during sampling



No.	Ecoregion Name	No. of Samples	25%	Mean	Median	75%
	Entire State	1537	30	36	38	44
54	Central Corn Belt Plains	260	24	31	34	40
55	Eastern Corn Belt Plains	746	32	38	40	48
57	Huron/Erie Lake Plain	7	16	28	22	42
56	S Michigan/N Indiana Drift Plains	198	28	33	34	42
71	Interior Plateau	173	36	42	44	50
72	Interior River Lowland	153	24	34	36	40

Figure 4.3 Fish IBI statistics for Indiana streams for level 3 ecoregions from IDEM data (1996–2010; taken from Frankenberger & Esman, 2012).



No.	Ecoregion Name	No. of Samples	25%	Mean	Median	75%
	Entire State	2602	46	57	58	69
54	Central Corn Belt Plains	299	36	47	47	56
55	Eastern Corn Belt Plains	1298	50	60	62	71
57	Huron/Erie Lake Plain	11	46	53	51	60
56	S Mich./N Ind. Drift Plains	338	42	54	55	67
71	Interior Plateau	382	55	64	65	74
72	Interior River Lowland	274	39	50	50	60

QHEI Score	Narrative Rating
>64	Habitat is capable of supporting a balanced warmwater community
51-64	Habitat is only partially supportive of a stream's aquatic life designation
<51	Poor habitat

Figure 4.4 QHEI statistics for Indiana streams for level 3 ecoregions (same as in Figure 4.3) from IDEM data (1996–2010; taken from Frankenberger & Esman, 2012) and the IDEM interpretation of QHEI scores.

larger streams. As with the IBI, regional differences in QHEI scores are notable, but even within a single level 3 ecoregion, a broad distribution of QHEI scores is found. QHEI scores for the more refined level 4 ecoregions do not give a different picture than is given by Figure 4.4.

Indices, interpretations, and width variation. The QHEI and the IBI strive to provide an overall measure of the quality of the aquatic habitat or ecology. Based on fish sampling, the IBI more directly measures the ecological quality of a stream at the time of sampling, though its composite nature raises questions regarding the weighting and choice of metrics, and sampling issues may complicate interpretation. Habitat quality is a complex and amorphous concept, and it is difficult to evaluate the effectiveness of an index of habitat quality. The QHEI and the IBI are expected to be highly correlated, as the QHEI scoring was designed so that the "Highest scores were assigned to habitat parameters that have been shown to be correlated with streams that have high biological diversity and biological integrity" (Rankin, 1989). Much of the foundational document on QHEI (Rankin, 1989) examines the correlation of QHEI (and its individual metrics) with the IBI. Because it is restricted to physical characteristics and does not consider other chemical, biological, or ecological aspects that are external and often anthropogenic, the QHEI may be viewed as measuring the habitat potential, rather than the actual prevailing conditions as would be measured by the IBI. Thus the strongest correlation between QHEI and IBI would be expected in "minimally impacted" or most "natural" streams. In Figure 4.5 the IBI scores are plotted against the corresponding QHEI scores. The correlation is weak (in fact, the linear regression is not statistically significant), but this may be attributed in part to the streams not being "minimally impacted" as well as regional variation. The correlation for Ohio headwater (drainage area less than 20 sq. miles) streams was stronger (Rankin, 1989).

In the context of culvert design, smaller streams are of particular interest, and the variation of QHEI and IBI with estimated bankfull width is relevant. The box-and-whiskers plot in Figure 4.6 shows that both QHEI and IBI scores tend to increase with increasing width, as larger streams are more likely to be more capable of sustaining a richer more biologically diverse ecosystem. Interestingly, the scores for "fair" levels (QHEI >51 and IBI >35) occur for widths larger than ≈ 12 ft, which is the smallest width specified in the RGP for which additional AOP measures must be carried out. Within each width interval however a wide variation is seen in both IBI and QHEI scores, so that even for larger streams (widths greater than 12 ft) a significant number of sites are found with low IBI and QHEI scores, and conversely, a significant number of smaller streams are found with high IBI and QHEI scores. It should also be noted that the Ohio EPA, which had developed the QHEI, advocates the use of an alternative index, the Headwater Habitat Evaluation Index (HHEI), for streams with a drainage area less than 1 sq. mile *and* a maximum pool depth less than 40 cm as a more appropriate index for classifying stream ecology. The HHEI is not as widely used as the QHEI, e.g., IDEM does not routinely measure the HHEI, and so it will not be considered further.

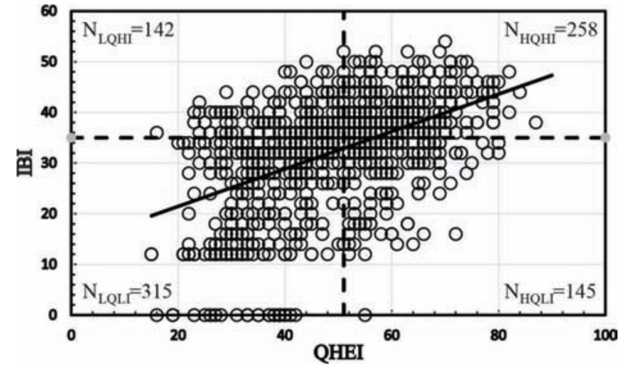


Figure 4.5 Relationship between IBI and QHEI for streams with drainage areas less than 20 sq. miles.

4.2.2 Options for a Regulatory Scheme Based on Habitat Indices

The current RGP conditions that might be considered as specifically addressing AOP issues distinguish between streams with ordinary high water mark (OHWM) widths smaller than 12 ft and those with OHWM widths larger than 12 ft. If the OHWM width is smaller than 12 ft, AOP-specific conditions are that (i) the culvert cross-sectional area be at least 1.2 times the flow area under OHWM conditions, and (ii) sumping requirements. Where the OHWM width is larger than 12 ft, more stringent requirements are imposed, namely: (i) the structure span should be at least the OHWM width, and (ii) a bed should be established within the structure. The present discussion considers other options to the criterion of an OHWM width of 12 ft for the additional AOP design requirements. This criterion is simple, and takes into consideration indirectly constructability issues and habitat quality. As noted in the preceding subsection, a span of 12 ft would also be consistent with a median (or mean) stream (bankfull or OHWM) for fair levels of both IBI and QHEI. On the other

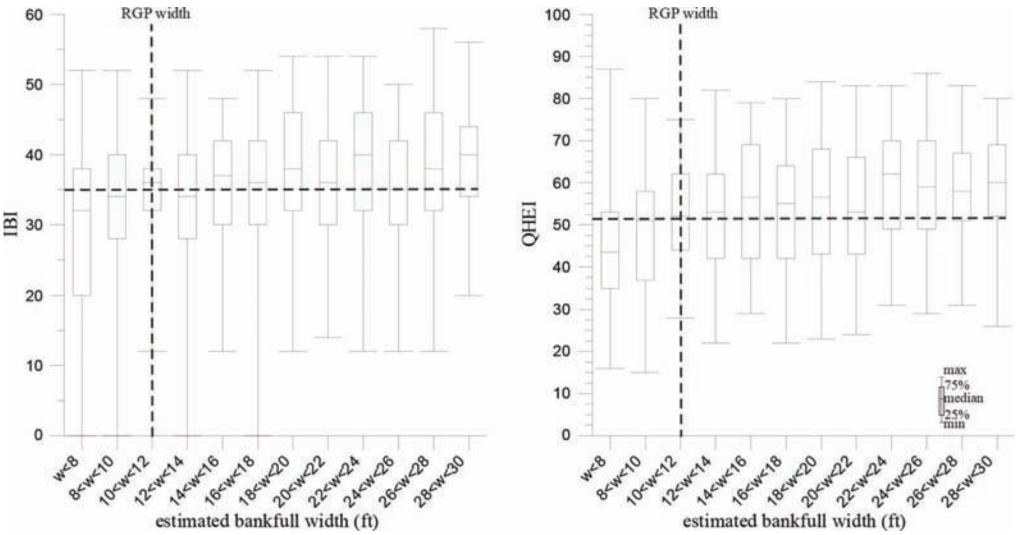


Figure 4.6 Box-and-whisker plot of the variation of IBI and QHEI with estimated bankfull width.

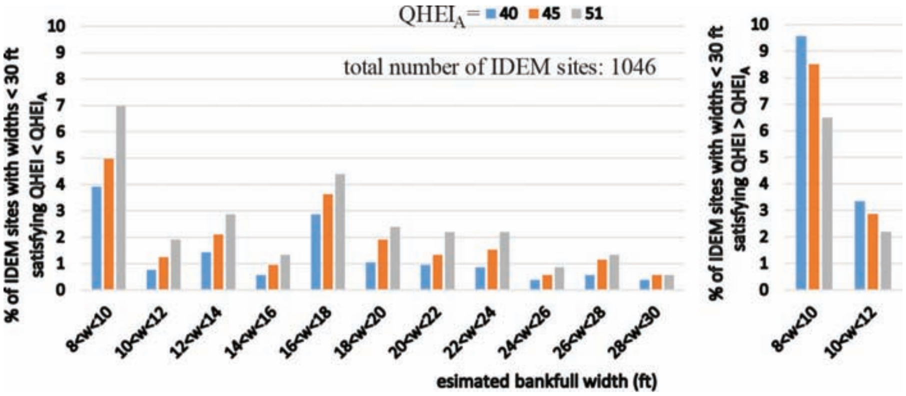


Figure 4.7 Percentage of IDEM sites (with estimated bankfull widths <30 ft) that would be exempted based on QHEI < QHEI_A for different values of QHEI_A as a function of estimated bankfull width.

hand, a uniform choice of 12 ft does not directly consider habitat quality or the present ecological state and the regional variations of both.

Rather than the indirect relation to habitat quality afforded by a width specification, a more direct distinction for the application of the more complete AOP conditions may be motivated. The elements of a regulatory scheme requiring the AOP design as proposed in Chapter 3.5 (or the more general USFS2008 or HEC-26 approaches) but more directly based on standard habitat quality indices might then be formulated as follows. It is assumed that any constructability issue has already been addressed, e.g., in a specification of a culvert rise above which the installation of a bed/substrate presents no problem. The considered scheme assumes a *default*, namely that the AOP design of Chapter 3 be implemented, but that exemptions may be allowed. These exemptions would involve partially or entirely on standard habitat indices such as QHEI or IBI. Thus, it would be incumbent on the agency, such as INDOT, desiring to install the waterway-encapsulating structure, to seek an exemption. For some sites, such as those Indiana waters designated for special protection as listed in the RGP or those with endangered species, no exemptions might be allowed. The exemptions might be defined at different levels, with succeeding levels becoming more onerous or stringent, with however an emphasis on simplicity of formulation.

At the first level, a simple condition might be that QHEI < QHEI_A, where QHEI_A could be taken as a constant value. This value might be chosen to reflect a poor habitat quality, e.g., QHEI_A =45, so that if the habitat potential as represented by the QHEI is poor, then the requirement to satisfy the complete AOP conditions may be viewed as unjustifiable. IDEM considers QHEI <51 as poor habitat potential and so a choice of QHEI_A <45 may be viewed as being conservative with regards to habitat potential. A value of QHEI_A=45 is also consistent with the more refined Ohio EPA classification of poor habitat quality for larger streams (Frankenberger & Esman, 2012; see also Rankin, 1989).

The consequence of such a regulatory scheme, particularly compared to the current RGP condition, is examined in Figure 4.7. It assumes that the IDEM sites where QHEI (and IBI) assessments have been made are representative of culvert sites in Indiana, and so the fraction of these sites satisfying various criteria would be similar to that which would occur for the culvert sites. The percentage of IDEM sites with estimated bankfull widths <30 ft that would have satisfied the exemption requirement of QHEI < QHEI_A (and the inverse condition, QHEI > QHEI_A) provides some information regarding the likelihood of an exemption to the full AOP design conditions. For estimated bankfull widths, $12\,\text{ft} < W_b < 30\,\text{ft}$, a significant percentage (a total of ≈ 19%, 15%, 10% for a choices of QHEI_A = 51, 45, and 40 respectively) of total IDEM sites is found to satisfy QHEI < QHEI_A, and therefore would satisfy the condition for an exemption. On the other hand, if the minimum width for constructability is set at 8 ft (rather than the current 12 ft), this would also mean that more smaller streams (8 ft < W_b < 12 ft), a total of ≈ 9%, 11%, 13% for choices of QHEI_A = 51, 45, and 40 respectively, would be subject to the full AOP design conditions because QHEI > QHEI_A. The smaller values chosen for QHEI_A, the less likely that exemptions would be granted. It should be emphasized that exemption does not imply AOP considerations are entirely overlooked, but rather that only the primary requirements of flow area and sumping (these may need further re-examination) would be imposed.

The QHEI score already takes into account regional variations, but the choice of a uniform value of QHEI_A might be criticized for not similarly considering regional variation. A more refined variation of the original condition might incorporate regional variations in QHEI_A, such that QHEI_A might be chosen based on the probability distribution of QHEI for the level 3 ecoregion, e.g., as obtained from IDEM QHEI statistics, in which the site is located. In order not to allow exemptions in ecoregions with already generally low QHEI scores, a condition might for example be formulated as QHEI_A= min(QHEI_{25},45), where QHEI_{25} is the 25% (quartile) value of QHEI in the ecoregion in which the site is located. Thus from Figure 4.4 QHEI_A would be 39 for ecoregion 72 (Interior River Lowland), but 45 for ecoregion 71 (Interior Plateau).

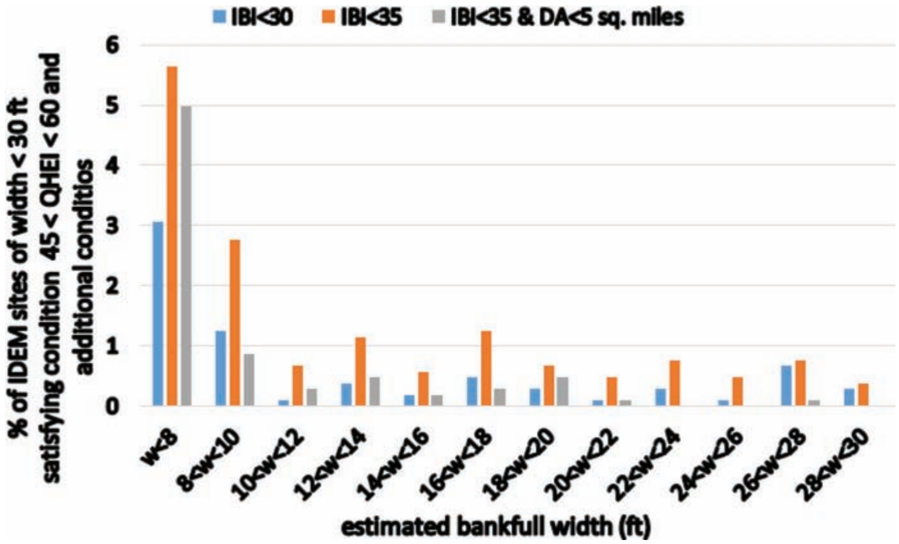


Figure 4.8 Percentage of IDEM sites with estimated bankfull widths <30 ft and 45 ≤ QHEI < 60 satisfying a second-level condition based on IBI or drainage area.

A condition based solely on QHEI would seem appropriate for a first level exemption because QHEI assessments can be carried out relatively inexpensively; more onerous higher-level exemption conditions might also be considered. This might involve a next range of QHEI scores, e.g., $\mathrm{QHEI_A} \leq \mathrm{QHEI} < \mathrm{QHEI_B}$. If the values $\mathrm{QHEI_A} = 45$ and $\mathrm{QHEI_B} = 60$ are chosen for this next level, additional more stringent conditions could be specified as these QHEI values suggest greater habitat potential. An additional condition could be specified in terms of IBI scores. Thus even though the QHEI score is fair, an exemption could be justified if the current ecological state as reflected in the IBI is poor. A structure following only the primary AOP constraints of flow area and sumping is unlikely to contribute in any manner to further ecological deterioration as the current poor ecological state may be due to larger-scale, e.g., watershed, aspects. IBI assessments will generally be more costly than QHEI assessments, so an IBI-condition will be more onerous. In some cases involving higher-cost larger structures, it might still be advantageous for an agency to seek an exemption that would require an IBI assessment. The effect of such a condition is examined in Figure 4.8 which shows the percentage of IDEM sites with (estimated bankfull) widths <30 ft and 45 ≤ QHEI < 60 satisfying a condition based on IBI scores. For estimated bankfull widths, 12 ft $< W_b <$ 30 ft, a small percentage of sites are found that satisfy IBI <30 (2.8%), or IBI <35 (6.5%), and hence would qualify for an exemption based solely on an IBI condition. The condition IBI <35 corresponds to an IDEM poor integrity class.

Another type of condition that might be formulated is based on the potential scale of the impact, measured in terms of the drainage area, DA. Thus, if the extent of the impact of a structure is deemed very localized, i.e., with a small drainage area, then this could justify an exemption. A composite condition, IBI <35 *and* DA <5 sq. miles, when applied to the IDEM dataset, is found to be more stringent than the simple condition, IBI <30, in that a *smaller* percentage (1.6% compared to 2.8%) of IDEM sites with 12 ft $< W_b <$ 30 ft would qualify for an exemption. For the IDEM sites, the bankfull width, W_b, was estimated from DA, and so a DA- condition acts in a manner similar to but more weakly than the current RGP width condition. The choice of 5 sq. miles as a cutoff drainage area is ad hoc, but ≈ 46% of the IDEM sites satisfying 12 ft $< W_b <$ 30 ft have DA <5 sq. miles.

4.3 Summary

The costs/benefits of AOP-designed culverts compared to traditional culverts (not necessarily the same as current INDOT standard-designed culverts) were examined. Installation (including material) cost ratios (the ratio of cost of an AOP-designed to a traditional culvert) will likely depend on the span ratio (i.e., the ratio of span of an AOP-designed to a traditional culvert) and could range from 1 to 2 for span ratios between 1 and 2.5. Life-cycle cost analysis is difficult due to lack of data as well as questions such as service lifetimes. The larger issue of non-fiscal or social costs/benefits also needs to be considered, but involves additional methodological problems.

In view of the uncertainties in life-cycle costs/benefits, an alternative basis for a regulatory scheme is sought in habitat and biotic integrity indices (QHEI and IBI). The default rule would require the design of culverts for AOP according to the procedures discussed in Chapter 3, but exemptions could be sought on the basis of the values of QHEI and/or IBI obtained on-site. The likelihood of exemptions depending on various schemes were evaluated for various alternative habitat-indices-based regulatory schemes.

5. SUMMARY, CONCLUSIONS, AND IMPLEMENTATIONS

5.1 Summary and Conclusions

Two main topics were studied, (i) design approaches to enhance or accommodate aquatic organism passage (AOP) through waterway-encapsulating structures such as culverts, and (ii) (life-cycle) costs/benefits of AOP-designed culverts and alternative regulatory schemes. After a review of the two main design approaches to culvert design for AOP, a simplified design procedure was proposed that requires less data input and analysis, results in a structure complying with the current IDEM RGP condition, and makes use of already existing INDOT standard specifications for riprap and coarse aggregates. The simplified procedure is intended for new larger structures for which a culvert bed needs to be installed, and for expected Indiana conditions of low-gradient (<3%) and predominantly sandy or gravelly streams.

Although a life-cycle cost approach to project evaluation is appealing, in the case of traditional and AOP-designed culverts, it is difficult to apply due not only to lack of reliable and relevant data, but also due to methodological questions regarding the valuation of public goods. The data on installation + material costs are probably the least controversial, and suggest that the ratio of the cost of an AOP-designed culvert to that of a traditional culvert may range from 1 to 2 depending on the ratio of spans of the respective culverts, and also on location and site-specific conditions. It is emphasized however that the current INDOT standard-designed culvert is *not* the traditional culvert, and so the additional costs in Indiana of adopting a more complete AOP-designed culvert may not be as substantial as might be otherwise thought. Because a broad life-cycle costs approach, including social/ecological costs, is unlikely to be available in the foreseeable future, alternative regulatory schemes based on habitat and biotic integrity indices were examined. Specifically, the use of the Qualitative Habitat Evaluation Index (QHEI) and Index of Biotic Integrity (IBI), both of which are already widely used in Indiana, was considered as possible basis for exemption from some AOP requirements.

It is recommended that the U.S. Forest Service stream simulation and the Federal Highway Administration HEC-26 approaches be considered as generally acceptable for INDOT culvert design for AOP, and that the simplified procedure proposed in this work be acceptable for low-gradient (<3%) and predominantly sandy or gravelly streams. It should be noted that the already existing INDOT standard specification for dense-graded aggregate is only recommended for sandy streams, and so other dense-graded mixes will need to be specified for gravels or even coarser material.

5.2 Implementation Plans

Current INDOT culvert design policy as specified in INDOT2013-203-2.02 is at variance with the current IDEM regional general permit conditions for larger culverts in at least two important respects. It does not specify a minimum culvert span, such as the channel ordinary high-water mark width, and while it does specify sumping, it states that backfilling with an appropriate substrate material is *not* necessary. As such, some formal recognition of the changed IDEM conditions is needed in an updated INDOT policy that might incorporate the above recommendaions. There is however a possibility that the IDEM regional general permit conditions could soon be modified along the lines suggested in Chapter 4, such that a criterion for which the additional conditions are imposed may be based on a measure of habitat quality, such as the Quantitative Habitat Evaluation Index (and/or the Index of Biotic Integrity) rather than on a fixed ordinary high-water mark width of 12 ft. It may therefore be worthwhile to wait until more clarity about the IDEM regional general permit conditions is firmly established before any extensive revision of INDOT's culvert design policy. In the interim, the proposed simplified procedure (or the U.S. Forest Service stream simulation approach or the FHWA HEC-26 approach) may be suggested as informal guidelines.

Regardless of the detailed criteria for additional AOP requirements to comply with IDEM's regional general permit conditions, material specifications will be necessary for backfilling of sumped culverts. If the simplified approach described in Chapter 3.5 is adopted, then already existing INDOT specifications (see Appendix B.1) may be used for the armor sublayer and for the surface layer only for the case of a predominantly sandy channel substrate. For channel substrates with predominant material larger than sand sizes, however, new mixture specifications for the surface layer will need to be formulated. In Appendix B.2, a specification appropriate for predominantly gravel (median diameter up to 32 mm) substrates was defined; it is suggested that at least this specification be adopted as standard by INDOT, as, together with the already existing INDOT standard specifications, most of the range of cases expected would be covered. Mixture specifications appropriate for channel substrates with even larger material could be defined as needed.

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APPENDIX A: WIDTHS AND DEPTHS CORRESPONDING TO BANKFULL AND TO ORDINARY HIGH WATER MARK CONDITIONS FOR SMALL INDIANA STREAMS

The USFS2008 approach to sizing waterway-encapsulating structures is based on bankfull widths, while the proposed approach, in part due to current regulations, is based on the ordinary high water mark (OHWM) widths. In this appendix, measurements of the two widths are compared for the three Indiana geologic regions, the Northern Moraine and Lake region, the Central Till Plains region, and the Southern Lowlands region (Figure A.1). The observed bankfull widths are taken from Robinson (2013), while the OHWM widths were obtained by INDOT personnel (as reported in Saksena & Merwade, 2015). Consistent with the focus on culvert applications, the data are restricted to widths less than ≈ 40 ft. Because the OHWM depths are also used in the proposed design approach, bankfull and OHWM depths are also examined from the same datasets and with the same restrictions.

A.1 Bankfull and OHWM Widths

Robinson (2013) found distinct regional variations in the dependence of bankfull widths in Indiana on drainage area (DA), and bankfull and ordinary-high-water-mark (OHWM) widths are compared in Figure A.2. In the Northern Moraine and Lake region, the two widths are comparable in magnitude; the OHWM width is however consistently smaller than the bankfull width, which might be intuitively expected. In the Central Till Plains region, the OHWM width does not appear to be consistently smaller than the bankfull width. In the Southern Lowlands, the differences between the two widths seem to be larger, with the OHWM width rather substantially smaller than the bankfull width. The small sample size of OHWM widths in Figure A.2 and the uncertainties in estimates of both bankfull and OHWM widths suggest caution in drawing any strong conclusions, but, for the present purposes, the data in Figure A.2 lend support to the thesis that, at least for the Northern and Central Indiana regions, culvert spans based on either bankfull

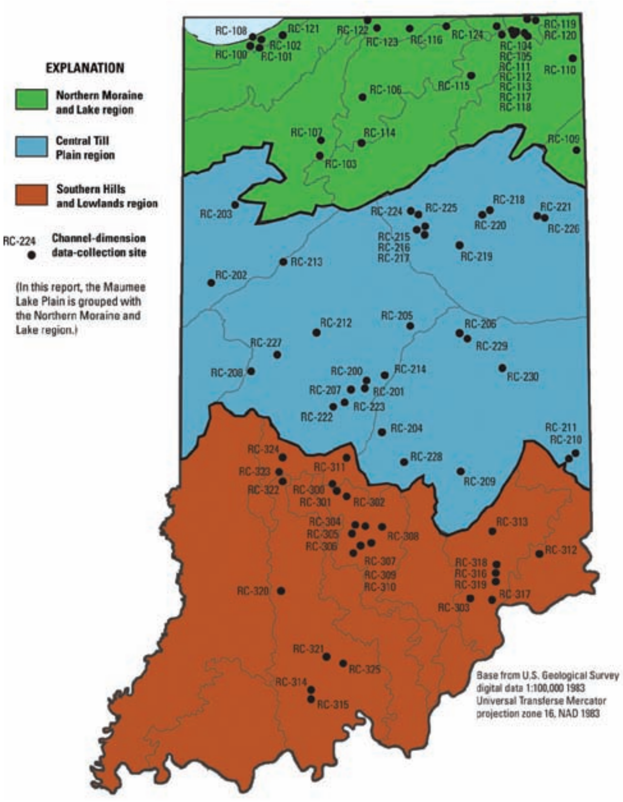


Figure A.1 Geologic regions used in the comparison of bankfull widths and ordinary high water mark widths in Figure A.2 (taken from Robinson, 2013).

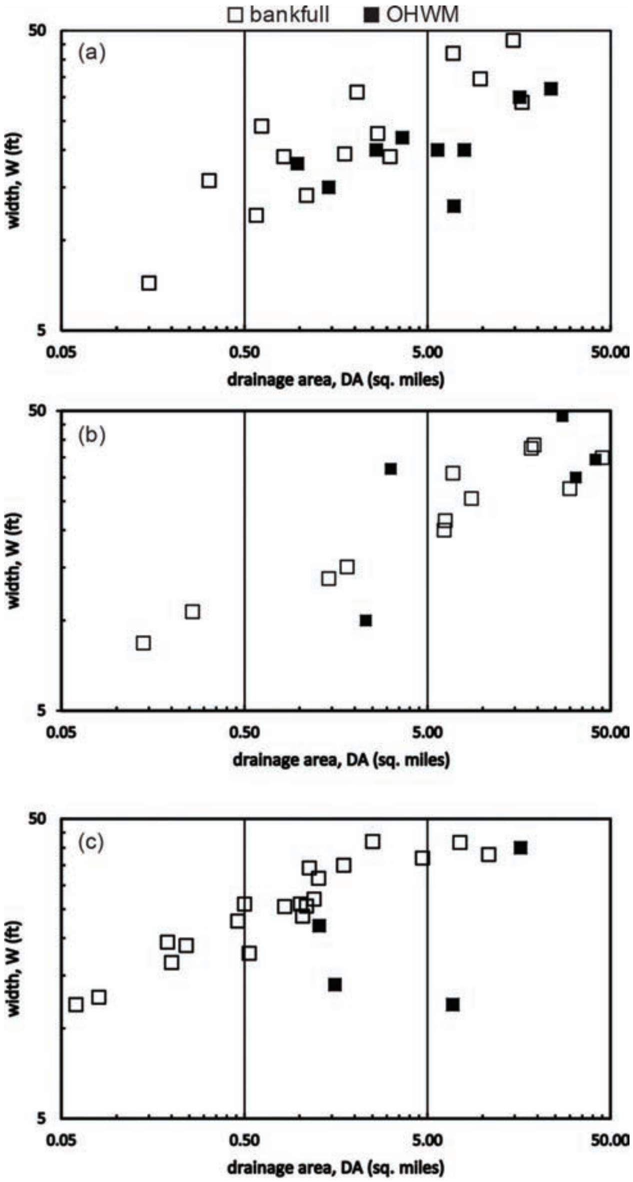


Figure A.2 Comparison of bankfull with ordinary high water mark widths, for (a) the Northern Moraine and Lake region, (b) the Central Till Plains region, and (c) the Southern Lowlands region.

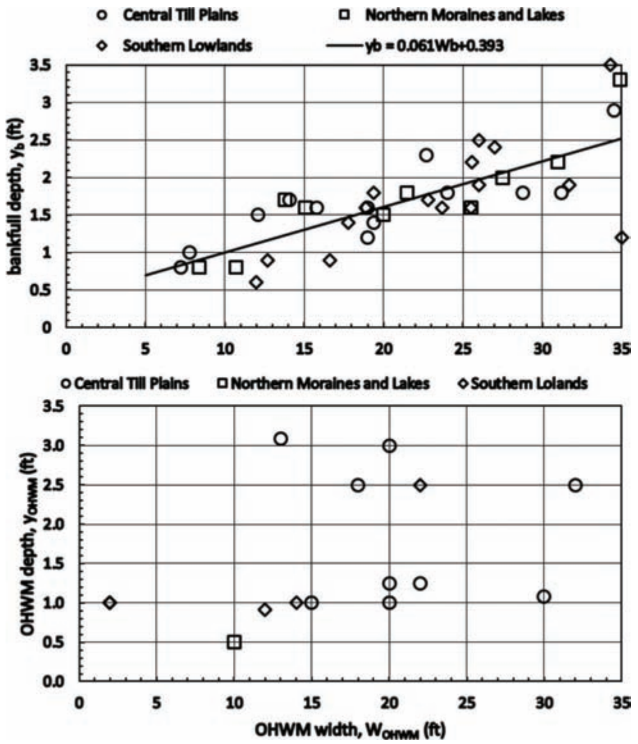


Figure A.3 Variation of (a) bankfull depth with bankfull width (data from Robinson, 2013), and (b) OHWM depth with OHWM width (data compiled by Saksena & Merwade,

or OHWM widths will not differ greatly. In the Southern region, if the observed OHWM width is much smaller than an expected bankfull width, a prudent design might consider increasing a span based solely on the OHWM width, or using the bankfull width instead of the OHWM width.

A.2 Bankfull and OHWM Depths

The variation of bankfull depth, y_b, with bankfull width, W_b, for all three Indiana regions is shown together in Figure A.3a. Unlike the dependence on drainage area, a strong regional dependence is not seen, and a single linear relationship ($R^2 \approx 0.52$) between y_b and W_b may be found:

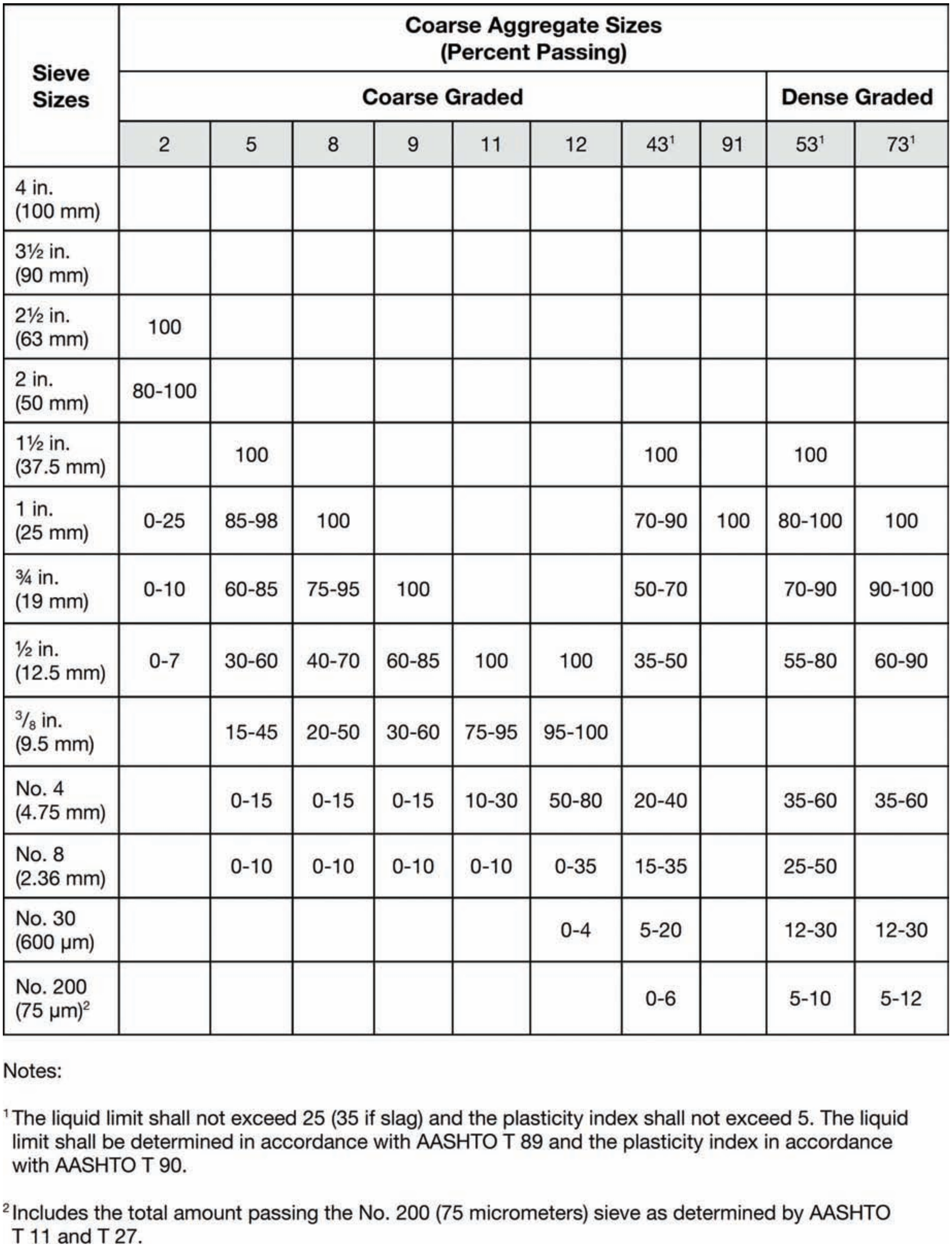
$$y_b = 0.061\,W_b + 0.39 \tag{A.1}$$

with both y_b and W_b measured in feet. The variation of OHWM depth, y_{OHWM}, with OHWM width, W_{OHWM}, is shown in Figure A.3b. In contrast to the bankfull depth data in Figure A.3a, the very scattered OHWM data show little dependence of depth on width. Some of data, e.g., two points in the Central Till Plains data, give OHWM widths that are larger than the scatter in the bankfull depth data. The limited data (only one point is available for the Northern region) also do not inspire confidence. As such, the width-depth relationship based on the bankfull condition is recommended for use in the proposed design approach.

APPENDIX B: SUBSTRATE DESIGN FOR SANDY AND GRAVEL STREAMS IN INDIANA

B.1 INDOT Standard Coarse Aggregate and Riprap Classes

The following specifies INDOT standard coarse aggregate and riprap classes (Indiana Dept. of Environmental Management, 2007; INDOT, 2014), some of which will be used in the design of surface and armor layers of the culvert bed.

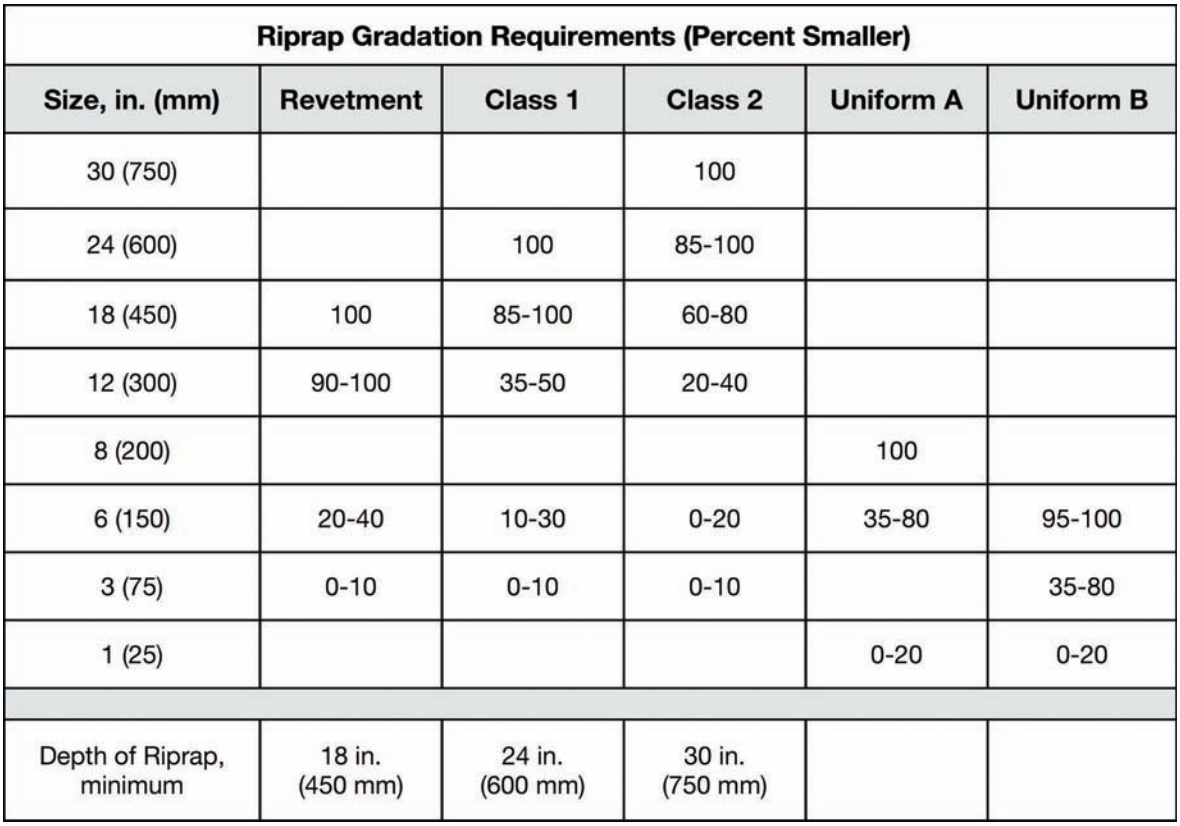


Sieve Sizes	Coarse Aggregate Sizes (Percent Passing)									
	Coarse Graded								Dense Graded	
	2	5	8	9	11	12	43[1]	91	53[1]	73[1]
4 in. (100 mm)										
3½ in. (90 mm)										
2½ in. (63 mm)	100									
2 in. (50 mm)	80-100									
1½ in. (37.5 mm)		100					100		100	
1 in. (25 mm)	0-25	85-98	100				70-90	100	80-100	100
¾ in. (19 mm)	0-10	60-85	75-95	100			50-70		70-90	90-100
½ in. (12.5 mm)	0-7	30-60	40-70	60-85	100	100	35-50		55-80	60-90
⅜ in. (9.5 mm)		15-45	20-50	30-60	75-95	95-100				
No. 4 (4.75 mm)		0-15	0-15	0-15	10-30	50-80	20-40		35-60	35-60
No. 8 (2.36 mm)		0-10	0-10	0-10	0-10	0-35	15-35		25-50	
No. 30 (600 µm)						0-4	5-20		12-30	12-30
No. 200 (75 µm)[2]							0-6		5-10	5-12

Notes:

[1] The liquid limit shall not exceed 25 (35 if slag) and the plasticity index shall not exceed 5. The liquid limit shall be determined in accordance with AASHTO T 89 and the plasticity index in accordance with AASHTO T 90.

[2] Includes the total amount passing the No. 200 (75 micrometers) sieve as determined by AASHTO T 11 and T 27.



Riprap Gradation Requirements (Percent Smaller)					
Size, in. (mm)	Revetment	Class 1	Class 2	Uniform A	Uniform B
30 (750)			100		
24 (600)		100	85-100		
18 (450)	100	85-100	60-80		
12 (300)	90-100	35-50	20-40		
8 (200)				100	
6 (150)	20-40	10-30	0-20	35-80	95-100
3 (75)	0-10	0-10	0-10		35-80
1 (25)				0-20	0-20
Depth of Riprap, minimum	18 in. (450 mm)	24 in. (600 mm)	30 in. (750 mm)		

B.2 Designing Stable Culvert Bed Substrate Size Distributions

A stable substrate continuous throughout the culvert is desired. Sumped culverts that are not backfilled may develop the desired continuous substrate due to sediment transport from the upstream channel, but the conditions under which this would occur within a reasonable time period are not clear and other problematic issues such as headcutting upstream of the structure reduces its appeal. Some evidence (Kozarek & Mielke, 2014) indicates that backfilling with some additional "structural" features provides a more robust solution. This raises the question of the design of the backfill, specifically the size distribution and the "structural" features if these are considered necessary. Both the USFS2008 and the HEC-26 design approaches strive to reproduce as much as practicable the natural substrate in the undisturbed channel. This requires detailed sampling and analysis of the stream substrate. An alternative is proposed that does not require detailed sampling and analysis but does require a gross assessment of the predominant substrate type, whether sand or gravel or other. The proposed approach does not therefore aim at "simulating" in detail the natural substrate, but will emphasize some aspects. In particular, it is designed to be mobile only when the natural substrate is mobile, but due to a conservative emphasis on stability, deliberately chooses a coarser than natural size distribution in most cases. The designed substrate also aims to minimize the possibility that at low flows the stream will infiltrate entirely and so "disappear" into the culvert bed by pursuing a maximum-density-gradation low-permeability design strategy. One practical advantage of this approach is that a small number (initially two) of standardized fill material can be defined, rather than the infinitely varied site-specific fill that would be necessary to reproduce the natural substrate.

Only two standardized classes of backfill material are proposed, one for a predominantly sandy (for which a median diameter less than 2 mm is assumed) natural substrate, and the other for a predominantly gravel (for which a median diameter less than 32 mm is assumed) substrate. To obtain a low-permeability fill, the FHWA-modified Fuller-Thompson equation is used to obtain an appropriate size distribution. This equation was originally intended to characterize mixtures for concrete and for pavement design, and its applicability to the present problem remains open to question, but both USFS2008 and HEC-26 have discussed its use in the present context. The equation is expressed as:

$$p_i = 100\left(\frac{d_i}{d_{\max}}\right)^m \tag{B.1}$$

where p_i is the percent passing the i-th sieve, d_i is the opening of the i-th sieve, $d_{\max}=d_{100}$ is the maximum particle size, and the exponent m is chosen to achieve the appropriate gradation. The standard FHWA choice of $m=0.45$ differs slightly from the original $m=0.5$ of Fuller and Thompson, while both USFS2008 and

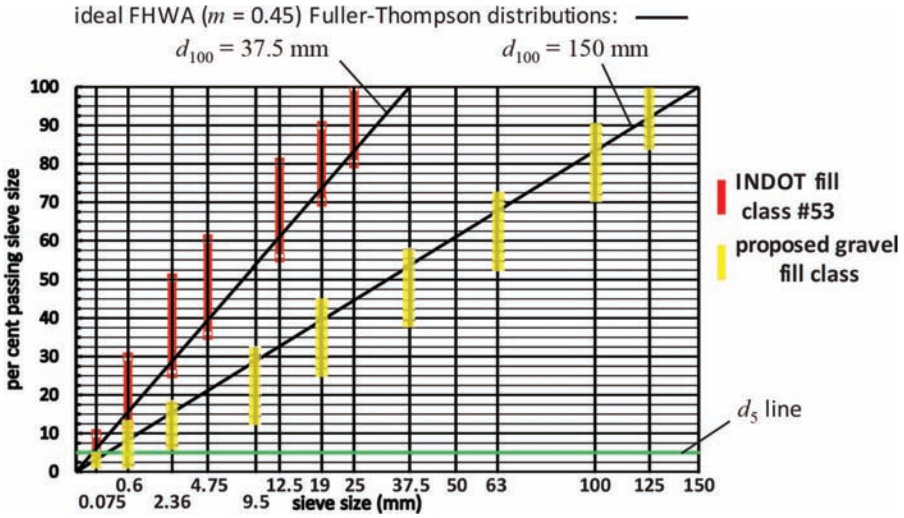


Figure B.1 Specifications for coarse aggregate for use as backfill in AOP-designed culverts; the already defined INDOT class #53 ($d_{100} = 37.5$ mm for use in predominantly sandy streams) and newly proposed class.

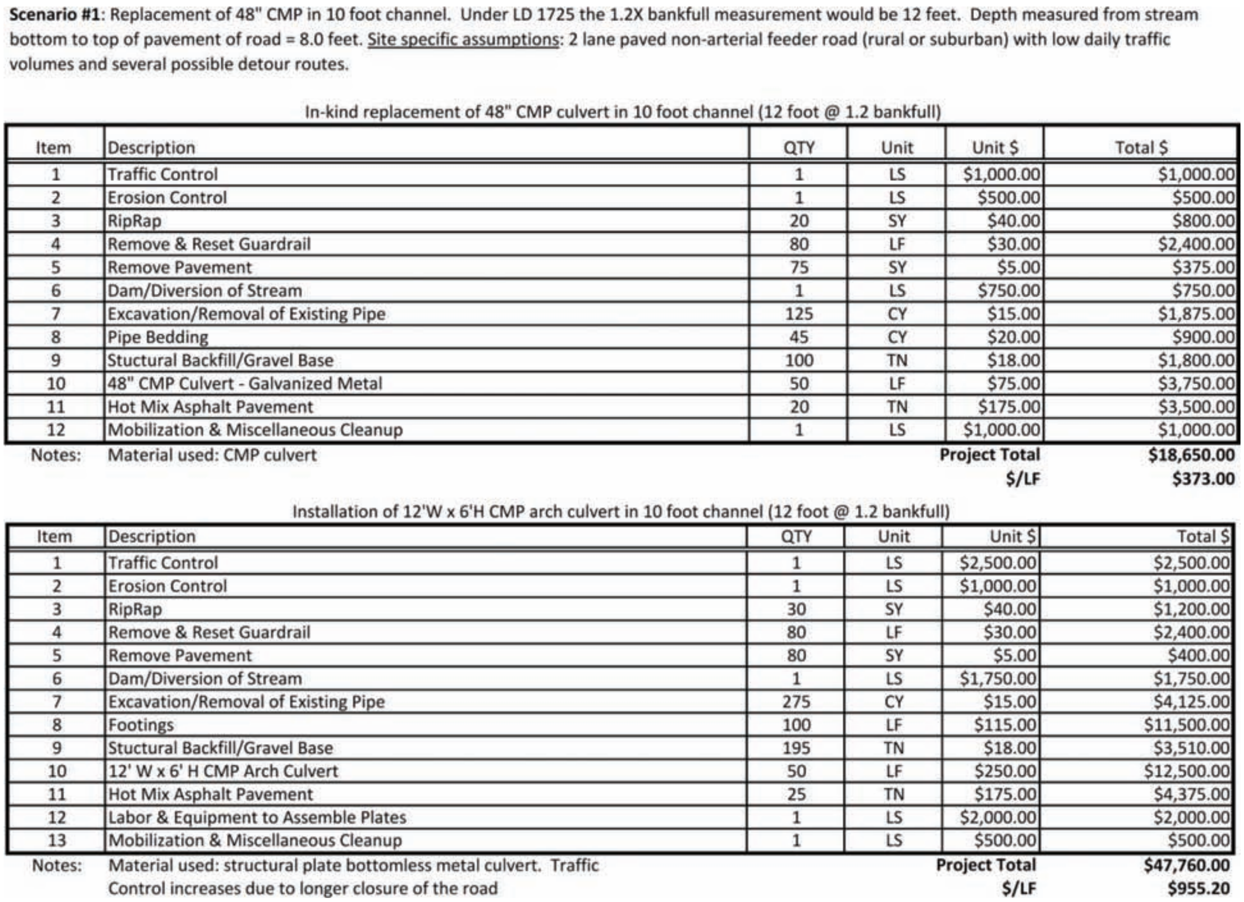
HEC-26 suggest that a range of 0.45 to 0.7 may be applicable. A mixture size distribution approximating the Fuller-Thompson equation with $m=0.45$ (or $m=0.5$) is termed dense-graded, and is characterized by low permeability and high stability. Both USFS2008 and HEC-26 have recommended that the value of d_5, the sediment size for which 5% by weight is finer, should not exceed 2 mm in order to achieve sufficiently low permeability and limit interstitial flow through the substrate. As will be seen, a dense-graded mixture satisfies this requirement.

In its standard specifications for coarse aggregates, INDOT already has defined two dense-graded classes, namely #53 and #73, which differ in d_{100} but are otherwise very similar, and so only #53 for which $d_{100} = 37.5$ mm (= 1.5 in) is examined here. For $m=0.45$, the Fuller-Thompson equation results in a median diameter of $d_{50} \approx 8$ mm. This median diameter is larger than that which is conventionally termed sand (<2 mm), and so if the stream has a predominantly sandy substrate this dense-graded fill class (#53) will become mobile only when flow conditions far exceed those that will mobilize the stream substrate. The other INDOT standard dense-graded class (#73) for which $d_{100} = 25$ mm (= 1 in) results in a median diameter of $d_{50} \approx 5$ mm and so would also be adequate for sandy streams. For fill class #53, $d_5 \approx 0.05$ mm, while for fill class #73, $d_5 \approx 0.04$ mm, easily satisfying the condition that d_5 should not exceed 2 mm. Although an alternate dense-graded class could be defined more specifically for use in sandy streams, say with $d_{100} = 9.5$ mm (= 0.375 in), it is convenient and prudent to take advantage of an already existing standard even if overly conservative specification. The INDOT class #53 specification with d_{100} = 37.5 mm is plotted in Figure B.1 in standard FHWA coordinates in which ideal FHWA (with exponent, $m=0.45$) Fuller-Thompson size distributions plot as a straight line (and so the x-axis is *not* linearly scaled).

While much of Indiana may be characterized by sandy streams (in the IDEM QHEI dataset, over 50% of streams of width less than 10 m were recorded as sandy), and so would be taken care of by the fill class #53, a large fraction has a predominantly gravel substrate (in the same IDEM QHEI dataset, 18% of streams were recorded as having a predominantly gravel substrate) for which neither fill class #53 nor fill class #73 would be suitable. A new standard class is proposed that would satisfy the mobility constraint for a large proportion but perhaps not all gravel-bed streams. The new class is obtained with the choice of $d_{100} = 150$ mm (= 6 in), resulting in $d_{50} \approx 32$ mm and $d_{100} = 37.5$ mm, and hence would be suitable for gravel-bed streams with median diameters up to 32 mm (1.2 in). The ideal Fuller-Thompson size distribution for this new class is also plotted in Figure B.1 in standard FHWA scales, together with suggested sieve fractions chosen with a bias to coarser grades. Conventionally, the term gravel is applied to a sediment size range from 2 mm to 64 mm, so the upper limit of $d_{50} \approx 32$ mm covers most but not all of the gravel range. Thus, if the stream substrate consists primarily of the largest gravels ($d_{50} > 32$ mm) or cobbles, and if the design flows are such that they can mobilize sediment sizes with $d_{50} \approx 32$ mm then this class may not be suitable as backfill as it may be washed out of the structure before the channel material becomes mobilized.

APPENDIX C: INSTALLATION COSTS OF VARIOUS CULVERT OPTIONS ESTIMATED BY THE NEW ENGLAND ENVIRONMENT FINANCE CENTER

The following are example estimates of installation costs (including material costs) for various culvert options including stream simulation designs (spans chosen as 1.2 times bankfull widths) made by the New England Environment Finance Center (2010), for the Maine Department of Transportation.



Scenario #1: Replacement of 48" CMP in 10 foot channel. Under LD 1725 the 1.2X bankfull measurement would be 12 feet. Depth measured from stream bottom to top of pavement of road = 8.0 feet. Site specific assumptions: 2 lane paved non-arterial feeder road (rural or suburban) with low daily traffic volumes and several possible detour routes.

In-kind replacement of 48" CMP culvert in 10 foot channel (12 foot @ 1.2 bankfull)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$1,000.00	$1,000.00
2	Erosion Control	1	LS	$500.00	$500.00
3	RipRap	20	SY	$40.00	$800.00
4	Remove & Reset Guardrail	80	LF	$30.00	$2,400.00
5	Remove Pavement	75	SY	$5.00	$375.00
6	Dam/Diversion of Stream	1	LS	$750.00	$750.00
7	Excavation/Removal of Existing Pipe	125	CY	$15.00	$1,875.00
8	Pipe Bedding	45	CY	$20.00	$900.00
9	Stuctural Backfill/Gravel Base	100	TN	$18.00	$1,800.00
10	48" CMP Culvert - Galvanized Metal	50	LF	$75.00	$3,750.00
11	Hot Mix Asphalt Pavement	20	TN	$175.00	$3,500.00
12	Mobilization & Miscellaneous Cleanup	1	LS	$1,000.00	$1,000.00
Notes:	Material used: CMP culvert			**Project Total**	**$18,650.00**
				$/LF	**$373.00**

Installation of 12'W x 6'H CMP arch culvert in 10 foot channel (12 foot @ 1.2 bankfull)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$2,500.00	$2,500.00
2	Erosion Control	1	LS	$1,000.00	$1,000.00
3	RipRap	30	SY	$40.00	$1,200.00
4	Remove & Reset Guardrail	80	LF	$30.00	$2,400.00
5	Remove Pavement	80	SY	$5.00	$400.00
6	Dam/Diversion of Stream	1	LS	$1,750.00	$1,750.00
7	Excavation/Removal of Existing Pipe	275	CY	$15.00	$4,125.00
8	Footings	100	LF	$115.00	$11,500.00
9	Stuctural Backfill/Gravel Base	195	TN	$18.00	$3,510.00
10	12' W x 6' H CMP Arch Culvert	50	LF	$250.00	$12,500.00
11	Hot Mix Asphalt Pavement	25	TN	$175.00	$4,375.00
12	Labor & Equipment to Assemble Plates	1	LS	$2,000.00	$2,000.00
13	Mobilization & Miscellaneous Cleanup	1	LS	$500.00	$500.00
Notes:	Material used: structural plate bottomless metal culvert. Traffic Control increases due to longer closure of the road			**Project Total**	**$47,760.00**
				$/LF	**$955.20**

Scenario #4: Replacement of 30" CMP in 6.75 foot channel. Under LD 1725 the 1.2X bankfull measurement would be 8 feet. Depth measured from stream bottom to top of pavement of road = 6.0 feet. ***Note: cost evaluation of a 3-side concrete box culvert was not performed for this scenario.*** Site specific assumptions: 2 lane paved non-arterial feeder road (rural or suburban) with low daily traffic volumes and several possible detour routes.

In-kind replacement of 30" CMP culvert in 6.75 foot channel (8 foot @ 1.2 bankfull)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$500.00	$500.00
2	Erosion Control	1	LS	$500.00	$500.00
3	RipRap	20	SY	$40.00	$800.00
4	Remove & Reset Guardrail	100	LF	$30.00	$3,000.00
5	Remove Pavement	45	SY	$5.00	$225.00
6	Dam/Diversion of Stream	1	LS	$500.00	$500.00
7	Excavation/Removal of Existing Pipe	95	CY	$15.00	$1,425.00
8	Pipe Bedding	20	CY	$20.00	$400.00
9	Stuctural Backfill/Gravel Base	70	TN	$18.00	$1,260.00
10	30" CMP Culvert - Galvanized Metal	50	LF	$35.00	$1,750.00
11	Hot Mix Asphalt Pavement	15	TN	$175.00	$2,625.00
12	Mobilization & Miscellaneous Cleanup	1	LS	$500.00	$500.00

Note: Towns would likely not use guardrail in this situation due to shallow fill. MaineDOT may be required to use guardrail so it has been included for comparison.

Project Total **$13,485.00**
$/LF **$269.70**

Installation of 95" x 67" CMP Galvanized Arch Pipe in 6.75 foot channel (8 foot @ 1.2 BF)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$1,250.00	$1,250.00
2	Erosion Control	1	LS	$750.00	$750.00
3	RipRap	30	SY	$40.00	$1,200.00
4	Remove & Reset Guardrail	100	LF	$30.00	$3,000.00
5	Remove Pavement	575	SY	$5.00	$2,875.00
6	Dam/Diversion of Stream	1	LS	$1,750.00	$1,750.00
7	Excavation/Removal of Existing Pipe	135	CY	$15.00	$2,025.00
8	Pipe Bedding	35	CY	$30.00	$1,050.00
9	Stuctural Backfill/Gravel Base	250	TN	$18.00	$4,500.00
10	95" x 67" CMP Galvanized Arch (Elliptical) culvert	60	LF	$120.00	$7,200.00
11	Hot Mix Asphalt Pavement	125	TN	$175.00	$21,875.00
12	Mobilization & Miscellaneous Cleanup	1	LS	$1,000.00	$1,000.00

Notes: Pipe will be imbedded by 20% so actual height will be reduced from 67" to 54" however, the depth of cover will need to be increased thus lengthening pipe and resulting in substantial reconstruction of road including:increasing fill and pavement.

Project Total **$48,475.00**
$/LF **$969.50**

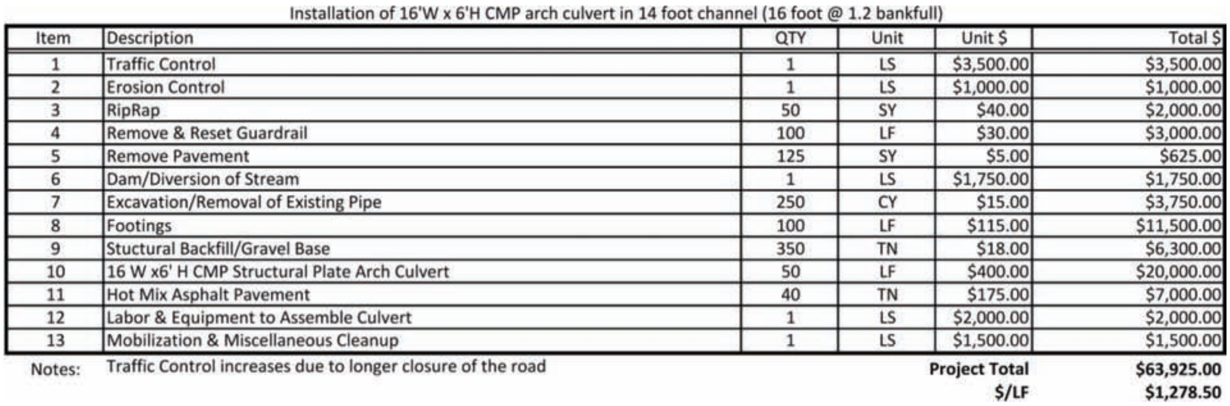
Scenario #5: Replacement of 72" CMP in 14 foot channel. Under LD 1725 the 1.2X bankfull measurement would be 16 feet. Depth measured from stream bottom to top of pavement of road = 10.0 feet. Site specific assumptions: 2 lane paved non-arterial feeder road (rural or suburban) with low daily traffic volumes and several possible detour routes. Replacement construction at this depth may require safety shoring.

In-kind replacement of 72" CMP culvert in 14 foot channel (+/- 16 foot @ 1.2 bankfull)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$2,000.00	$2,000.00
2	Erosion Control	1	LS	$1,000.00	$1,000.00
3	RipRap	25	SY	$40.00	$1,000.00
4	Remove & Reset Guardrail	90	LF	$30.00	$2,700.00
5	Remove Pavement	115	SY	$5.00	$575.00
6	Dam/Diversion of Stream	1	LS	$1,000.00	$1,000.00
7	Excavation/Removal of Existing Pipe	400	CY	$15.00	$6,000.00
8	Pipe Bedding	45	CY	$30.00	$1,350.00
9	Stuctural Backfill/Gravel Base	450	TN	$18.00	$8,100.00
10	72" CMP Culvert - Galvanized Metal	50	LF	$105.00	$5,250.00
11	Hot Mix Asphalt Pavement	35	TN	$175.00	$6,125.00
12	Mobilization & Miscellaneous Cleanup	1	LS	$500.00	$500.00

Note: A 72" culvert will require a minimum 10 foot wide trench to safely construct.

Project Total **$35,600.00**
$/LF **$712.00**



Installation of 16'W x 6'H CMP arch culvert in 14 foot channel (16 foot @ 1.2 bankfull)

Item	Description	QTY	Unit	Unit $	Total $
1	Traffic Control	1	LS	$3,500.00	$3,500.00
2	Erosion Control	1	LS	$1,000.00	$1,000.00
3	RipRap	50	SY	$40.00	$2,000.00
4	Remove & Reset Guardrail	100	LF	$30.00	$3,000.00
5	Remove Pavement	125	SY	$5.00	$625.00
6	Dam/Diversion of Stream	1	LS	$1,750.00	$1,750.00
7	Excavation/Removal of Existing Pipe	250	CY	$15.00	$3,750.00
8	Footings	100	LF	$115.00	$11,500.00
9	Stuctural Backfill/Gravel Base	350	TN	$18.00	$6,300.00
10	16 W x6' H CMP Structural Plate Arch Culvert	50	LF	$400.00	$20,000.00
11	Hot Mix Asphalt Pavement	40	TN	$175.00	$7,000.00
12	Labor & Equipment to Assemble Culvert	1	LS	$2,000.00	$2,000.00
13	Mobilization & Miscellaneous Cleanup	1	LS	$1,500.00	$1,500.00
Notes:	Traffic Control increases due to longer closure of the road			**Project Total**	**$63,925.00**
				$/LF	**$1,278.50**

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at:
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The recommended citation for this publication is:

Lyn, D. A., & Sangwan, N. (2016). *Ecologically aware design of waterway-encapsulating structures* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/21). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316344