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Culvert design for aquatic organism passage: an enviromental approach

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Abstract: The design of culverts at road and watercourse crossings, such as streams or rivers, has traditionally focused on the hydraulic safety requirements for the road. This approach to culvert design has neglected the biological elements of the watercourse, such as fish and other aquatic organisms, which are an essential part of the ecosystem and are disrupted by the physical barrier of the culvert. Furthermore, some physical factors are also altered, such as erosion and the deposition of sediments and debris, which also change the environmental conditions for fish, resulting in barriers that impede the natural development of their life cycle and endanger their reproduction. With an eye toward environmentally friendly design, concepts and guidelines have been developed for the design of culverts at road and watercourse crossings that facilitate the passage of aquatic organisms through the culvert, allowing them to move as they would in the natural watercourse. This paper presents some guidelines for the environmentally friendly design of culverts, which are addressed by Kilgore et al (2010), Schall et al. (2012), Bates and Kirn (2009), Henrik et al (2019), Kozarek and Mielke (2015), Olson et al (2017) and Vermont Department of Fish and Wildlife (2016).

Key words: rivers; culvert; fish passage; environment

1 Introduction

In the traditional practice of culvert design at road and stream or river crossings, hydraulic criteria such as the hydraulic head at the culvert inlet, approach and exit velocities, and the head-to-diameter ratio (HW/D) are used to ensure the passage of the design flow without structurally or functionally affecting the road. These criteria have proven quite practical from an engineering standpoint, resulting in fairly efficient designs. Proper alignment with respect to the flow direction and the types of material in the channel bed and slopes have, of course, been included to prevent erosion, gradation, and unwanted flooding of adjacent properties. However, this approach to culvert design has given little consideration to aquatic organisms that depend on the environment and its preservation to survive without risk of extinction. Thus, culvert construction can sometimes affect the environmental conditions that ensure their mobility, reproduction, and life cycle. When a hydraulic head (HW) is created upstream of a culvert, the current velocity changes both upstream and at the outlet, or a hydraulic drop could occur that would be impossible to overcome if a fish required upstream mobility. Researchers Anderson et al. (2014), in a study conducted in two sub-basins in Tucker and Randolph Counties, West Virginia, USA, determined that 55% of the culvert sites visited formed complete barriers and 34% formed partial barriers to the movement of the River Salamander, and that at least 20% of the total length of the streams in the two studied sub-basins were isolated by at least one partial barrier. The Vermont Department of Fish and Wildlife (VFWD, 2016) conducted a study on the passage of aquatic organisms through 1,501 culverts, noting that "less than 6% were found to provide complete passage for aquatic organisms" (p. 1). This gives us an idea of the level of impact that road crossing culverts could have on river and stream ecosystems. The dissemination of methods developed to allow the passage of aquatic organisms through culverts contributes to environmentally friendly designs as more professionals adopt this approach.

2 Development

In the design of the road and culvert crossing, Anderson, P.T., of the United States Forest Service (2011) mentions that "the passage of aquatic organisms and ecological connectivity is the objective and primary design priority for a stream crossing that provides habitat for aquatic life" (p. 2-2). Other design considerations he mentions are "minimizing the consequences of clogging and overflow, including avoiding stream splitting," "providing sufficient hydraulic capacity so that the hydraulic head for peak flow does not cause pressurized flow," and "maximizing benefits while minimizing the project's lifetime cost."

The Spanish Ministry of Agriculture, Food and Environment (2015) establishes preventive measures and technical specifications to ensure the passage of fish and other aquatic organisms, such as fish structures: "Structures that allow the riverbed to remain intact are applicable, basically adapted viaducts, and in some cases, appropriately conditioned drainage systems" (p. 33). This pursues the same objectives described by the United States Department of Agriculture, Forest Service (USFS) in the previous paragraph.

In a study conducted by Michigan Technological University (Olson et al., 2017), the authors found that replacement culverts installed to provide passage for aquatic organisms, designed using stream simulation methods, better retain coarse particulate organic matter through the culverts, and no differences were observed in ecosystem processes between the upstream and downstream reaches of the replacement culverts. This indicates that the replacement culverts did not significantly affect ecosystem processes in the studied streams, but further studies of this type are needed to deepen this understanding.

The Vermont Department of Fish and Wildlife (VFWD, 2016, p. 6) states that safe and stable water crossings allow for the accommodation of aquatic populations and protect the health of the stream while reducing channel erosion and structural damage. Some considerations they make for effective crossing design are:

Structure type: Open-bottom structures such as arches and bridges are preferred because they maintain the natural riverbed and are less prone to developing crossing problems. In many cases, closed (bottom-lined) water-crossing structures are acceptable if properly designed and constructed.

Structure width: The crossing structure shall not reduce the full-flow water width of the channel, excluding floodplain areas.

Structure length: Longer structures alter the stream's habitat more and often make it more difficult and frequent for it to pass. Using wide structures and headwalls can reduce the structure's length and minimize the impact on the stream.

Alignment with the channel flow: The alignment of the crossing structure with the flow is an essential part of the design. When the culvert is not properly aligned with the upstream and downstream channel, hydraulic capacity is reduced and sediment blockage increases.

Vertical alignment: the bottom profile at the crossing should, as far as possible, match the bottom profile of the natural channel of the stream. This profile should be determined based on the terrain conditions prior to construction.

Embedded culvert and natural riverbed: The streambed substrate should be as similar as possible to the natural substrate found in the channel upstream and downstream of the crossing. The culvert should remain embedded, creating a smooth transition between the natural channel and the crossing structure.

Depth and velocity: The crossing should be essentially "invisible" to fish and wildlife. Crossings should be designed to maintain adequate flow and substrates. For low or high flow rates, water depths and velocities should be the same as those of the natural stream upstream and downstream of the crossing.

To design the Aquatic Organism Passage (AOP), it is necessary to simulate the flow of the natural channel of the river or stream, under natural conditions before the culvert and under conditions with the culvert installed. The USFS defines "stream simulation as a design method for crossing structures (usually culverts), with the objective of creating within the structure a channel as similar as possible to the natural channel. The premise is that the simulated channel would not present any additional obstacles beyond those present in the natural channel" (2008, p. 3-1).

Bates et al. (2009) present three methods for the design of passage for aquatic organisms: low slope option, stream simulation option, and hydraulic option.

The "low slope" method is a simplified design method applicable only to low-risk sites with stable but mobile bottoms, low-slope streams, and short culvert lengths. The culvert length is limited to 15.24 m (50 ft), and the channel slope is limited to less than 1%. The culvert bottom is embedded 20 to 40% of its height (diameter for circular culverts, the equivalent for other shapes) to achieve the expected bottom elevation over the project's service life. Minimum cover should be used at the toe of open-bottom structures to achieve the minimum expected channel bottom level. The culvert width at the elevation where it meets the streambed should be at least 1.25 times the average width of the water surface for the bankfull section of the main channel. The culvert does not excessively restrict the active floodplain. This method is only applicable to new installations and where passage for weak aquatic species is required.

The "river stream simulation" method is applied to new culvert and stream installations with any slope. Stream simulation is a geomorphological approach to designing passageways for fish and aquatic organisms. It extends the dimensions of the natural channel, slope, bed material, and banks across the crossing to connect the channels upstream and downstream. Stream simulation creates the various water depths and velocities, hiding and resting areas, and contoured wet habitat that different species need to move. The simulated channel within the crossing would present no more obstacles to movement than those present in the adjacent natural channel.

The "hydraulic design" method is a design process that combines the hydraulic characteristics of a culvert within a specific flow range with the swimming abilities of a target fish species and age. The culvert's hydraulics can be controlled by its slope, width (or diameter), and roughness. This method targets a specific fish species and therefore does not consider the biological requirements of other species.

The stream simulation method is also presented by the Federal Highway Administration FHWA (Schall et al., 2012) and by the Minnesota Department of Transportation (Hernick, et al., 2019) and is considered the best for AOP design, so we will address it in the following lines.

Aquatic Organism Passage Context AOP)

Aquatic Organism Passage (AOP) design for culverts shall be carried out with full consideration of specific site conditions, which are specified as follows.

New construction versus rehabilitation.

Although all culvert aquatic organism passage facilities share the same core goal of enabling smooth passage through culverts, there are differences in scope and available design options between newly-built culverts and renovated ones. New construction projects, including culvert replacement works, allow great flexibility in adjusting culvert type, size, shape, gradient, alignment and inner bed materials to meet aquatic organism passage requirements. Available solutions include open-bottom culverts and closed-bottom culverts with inverts embedded beneath the natural stream bed.

Barrier Crossing

Culverts designed without taking aquatic organisms into account can form barriers that block creatures from moving upstream and downstream in watercourses. Aquatic species need to move freely to forage, seek shelter, evade predators and reproduce. A culvert becomes a barrier to aquatic organism passage when its internal conditions exceed the physical movement ability of aquatic creatures. The specific obstructive factors vary by species and their growth stage (juvenile or adult). For fish, the main common obstacles hindering aquatic organism passage are as follows:

Excessive water velocity.

Drops at the culvert inlet or outlet (see Figure 1). Physical barriers such as weirs, screens, or debris in the culvert conduit. Excessive turbulence caused by flow concentration or expansion. Low flows that provide insufficient depth for the fish to swim (Figure 1).

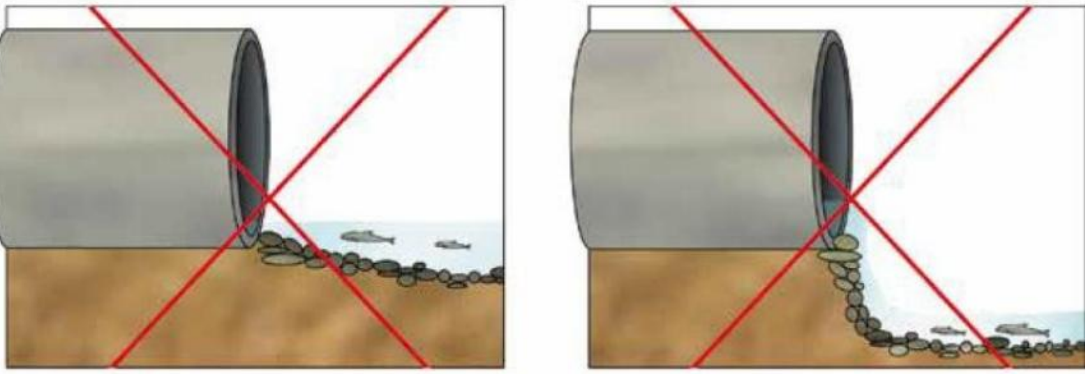

Figure 1. Two alternatives that hinder the ascent of fish due to the low height of the water surface or the significant difference in elevation (taken from the Ministry of Agriculture, Food and Environment of Spain, 2015).

Fish Biology.

A fish's physical capabilities depend on two muscle systems that accommodate different modes of movement: a red (aerobic) muscle system for low-intensity activities and a white (anaerobic) muscle system for short bursts of high-intensity activity. A fish that becomes exhausted during either high-intensity or low-intensity activity will require a period of rest before continuing to move. Extensive use of the white muscle system for high-intensity movements, in particular, causes extreme fatigue, necessitating extended periods of rest.

Fish may fail to pass through a culvert for various reasons. The most common obstacles are those that demand muscular exertion beyond their physical limits. Drop outlets or high-flow sections become barriers when they surpass the fish's surface swimming capacity. Meanwhile, long continuous low-flow sections in culverts force fish to sustain steady swimming speeds for extended periods, which exceeds their inherent swimming capability.

The life stage is also important. A design that meets the needs of a spawning adult salmon, for example, will not necessarily guarantee that a culvert will allow passage for a weaker, juvenile salmon. Furthermore, even if the fish is capable of a specific swimming energy, this does not mean that the fish will choose to expend maximum swimming energy when faced with a particular obstacle. Instead, fish have also been observed seeking out deeper regions with lower velocities within the complex flow dynamics of a culvert to reach the passage.

Hydrology.

Habitat requirements for aquatic organisms differ by species and life stage, and are commonly linked to seasonal changes and flow regimes. For fish, culverts must enable passage across a range of flow rates that match the timing and scope of their movements within stream channels. In natural river reaches, fish seek shelter during high-flow events until channel conditions stabilize. In extreme low-flow conditions, insufficient water depth can render waterways impassable.

Generally, upper and lower limits define the flow conditions under which passage must be provided, and these are referred to as high and low flow rates.

High passage flow QH refers to the upper flow limit where fish can move freely in waterways. Low passage flow QL means the minimum discharge required for fish migration, generally determined by the minimum water depth for fish passage. There is no unified national standard for defining high and low design passage flows. Such discrepancies result from regional variations in hydrology and fish species, as well as inconsistent term definitions.

Geomorphology and Stream Stability.

As a rigid structure in a dynamic environment, all culverts must be designed with the understanding that a channel is in the process of formation. Effective designs consider the channel and watershed within the context of the crossing location. Channels are continually changing, and the potential for channel adjustment must be understood. Without proper consideration, well-intentioned plans could detrimentally affect the stream system and related habitat. For example, if erosion is progressing upstream of the culvert location and is neither identified nor mitigated, that instability will eventually reach the site. Depending on the type of culvert installation, erosion could result in a drop at the culvert outlet, culvert destabilization, or both.

In a study conducted by Kozarek et al. (2015) at the University of Minnesota, which assessed the impacts of backfilling on embedded box culverts during installation in streams with gentle, mild and moderate gradients, the researchers concluded: "In general, backfilling culverts reduces the risk of upstream erosion. Placing in-channel bed material inside culverts during construction also helps retain sediment within culverts under bankfull discharge and simulated storm hydrograph conditions" (p.1). Though not conclusive, this significant finding confirms the vital role of geomorphology in hydraulic simulation for fish passage design.

Design procedure for new facilities

Newly constructed or replacement culvert facilities enable fish passage design to fully take into account all culvert characteristics during design, including culvert type, dimension, gradient, alignment and in-channel bed material. The state-of-the-art method for fish passage design is hydraulic flow simulation (Schall et al., 2012). That is to say, by adopting flow simulation technology, designers can replicate natural flow conditions inside culverts. Thereby aquatic organisms are able to traverse culverts with the same ease as they move freely in natural watercourses, even under the most adverse living conditions for such organisms.

The following section briefly addresses the stream simulation procedure as described in FHWAHEC 26 (Kilgore et al., 2010). This methodology applies to both embedded closed-bottom and open-bottom culverts. In either case, the natural bottom material is provided within the culvert, as illustrated in Figure 2.

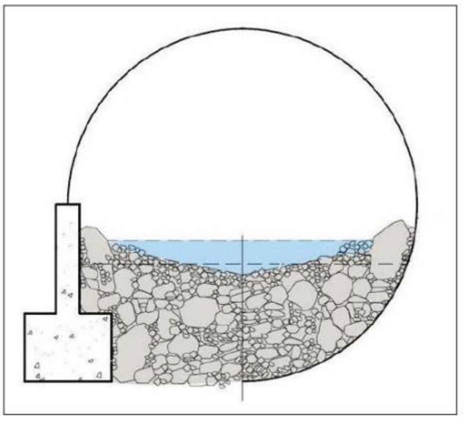

Figure 2. Embedded for open or closed culvert bottom (adapted from USFS, 2008).

Given the wide variety of aquatic organisms that may be relevant to a specific site, stream simulation procedures aim to ensure safe passage without analyzing the behavior of any individual target species. To achieve this, surrogate measures have been established for each stream simulation method to guide designers. The application of stream simulation design methods is best accomplished by an interdisciplinary team consisting of aquatic biologists, geomorphologists and engineers.

Substitute measures.

Given the diverse behavior and capabilities of fish and other aquatic organisms, design procedures necessarily depend on substitute parameters and indicators as measures for successful passage design.

The procedure specified in FHWA HEC-26 (Kilgore et al., 2010) takes sediment characteristics as its surrogate parameter. The underlying assumption is that aquatic organisms in streams are subjected to the same hydraulic forces and stresses acting on bed sediments. Therefore, if culvert design does not alter the near-bed flow forces within the channel, it can be inferred that such design will not change the forces experienced by aquatic organisms. The core design objective is to construct a stream crossing structure that maintains equivalent bed material hydraulic conditions across various flow regimes inside the culvert, consistent with those of the upstream and downstream natural stream reaches.

For both surrogate criteria, if these surrogate standards are met, it is assumed that the hydraulic conditions within the culvert will not pose greater barriers to aquatic organisms than those in the adjacent natural channel. Although there is no mandatory requirement to assess site-specific biological needs, relevant data on particular species can be integrated into the stream simulation design process when available. A fully installed open-bottom culvert in a stream is illustrated in Figure 3.

Figure 3. Fully installed open-bottom culvert (adapted from USFS, 2008)

The flow simulation design procedure specified in FHWA HEC-26 (Kilgore et al., 2010) was developed based on the surrogate measure of bed stability, rather than the bankfull width, to address the limitations in estimating reasonable bankfull widths under numerous field conditions. It was also formulated to establish a reproducible framework in line with best practices, so as to guide design decisions. Conventional design approaches often lead to oversized structures and consequently higher capital costs when constructing aquatic organism passage (AOP) facilities.

The design process focuses on five primary variables that must be determined for each site.

1. Peak design discharge, Qp. This flow rate can be the 25-year, 50-year or 100-year flood discharge required at the site to define flood design flow rates. It is the conventional discharge adopted for culvert design (Qx denotes the discharge corresponding to an X-year return period).

2. High-flow design discharge, QH. This refers to the maximum flow rate used for channel passage design, which can be applicable year-round or for a specific season.

3. Low-flow design discharge, QL. This refers to the minimum flow rate used for channel passage design, which can be applicable year-round or for a specific season.

4. Bed material characteristics. For non-cohesive bed materials, characteristic grain size parameters including D16, D50 and D84 shall be specified.

5. Permissible bed shear stress, τp.

Five fundamental tests are implemented within the design procedure. If any test fails, corresponding design adjustments shall be stipulated. The tests are as follows:

1. Does the culvert meet the requirements of peak design discharge Qp?

2. Under the high-flow design discharge QH, is the bed material inside the culvert stable (i.e., no bed material movement, or incoming sediment volume equals outgoing sediment volume)?

3. Under the peak design discharge Qp, is the bed material inside the culvert stable? (An anchor layer or underlayment beneath the bed material may be needed to pass this test.)

4. Under the high-flow design discharge QH, is the flow velocity inside the culvert consistent with the flow velocity of the upstream and downstream channel reaches?

5. Under the low-flow design discharge QL, is the water depth inside the culvert consistent with the water depth of the upstream and downstream channel reaches?

The first test is the conventional hydraulic suitability verification. All hydraulic adequacy standards and requirements are applicable to POA design, yet they are generally not the dominant limiting factor in the design process.

The second test is the primary assessment of substitute channel bed stability. New and replacement culvert structures designed for POA shall be fitted with natural riverbed material inside the culvert, adopting either open-bottom culverts or embedded closed-bottom culverts. It is ideal that the in-stream bed material remains stable under high-pass design discharge, yet stability cannot be guaranteed for certain bed materials, especially sandy riverbeds. This design procedure provides a framework to judge whether a design complies with this verification requirement.

The third test also checks the stability of the substitute channel bed, but under peak design discharge. This test evaluates the long-term service performance of in-stream bed materials, especially for embedded culverts.Under peak flow conditions, some bed materials may be scoured and washed out of the culvert. Nevertheless, in some cases, such materials can be re-deposited during the recession stage of the flood hydrograph. In most scenarios, it is recommended to adopt an oversized armour layer to prevent exposure of the culvert invert and facilitate sediment re-deposition.

The fourth and fifth tests check the flow velocity under high-flow design discharge QH and the estimated water depth under low-flow design discharge QL inside the culvert as well as in the upstream and downstream channel segments. If both parameters fall within the range observed under natural stream flow conditions, it can be reasonably concluded that aquatic organisms capable of moving through natural watercourses can also pass through the culvert smoothly. This comparison focuses on matching the environmental conditions of the culvert with those of the original stream, rather than targeting the swimming capacity of specific fish species or other aquatic organisms.

If any test fails, this design procedure provides guidance on how to modify the culvert design to meet all five verification criteria. This design method adopts industry best practices to estimate channel bed properties, including permissible shear stress and Manning's roughness coefficient. As technical research and practical understanding of relevant hydraulic processes continue to deepen, the overall analytical framework remains applicable, while updated optimized techniques can be integrated into this design system.

Culvert rehabilitation options

It is sometimes necessary to rehabilitate existing culverts to facilitate aquatic organism passage (AOP), when full replacement is not feasible due to construction constraints or budget limits. In such cases, the culvert size, structural materials as well as its horizontal and vertical alignment are already fixed. The rehabilitation design focus shifts to matching the in-culvert hydraulic conditions (flow velocity and water depth) with the migration capability of target aquatic species, mainly fish.

Screens and large bed boulders are among the measures that can be installed inside existing culverts to reduce flow velocity, raise water depth and create diversified hydraulic conditions.This enables fish at specific life stages and in different seasons to successfully traverse the culvert. Nevertheless, after renovation, the culvert must be checked under maximum flood discharge, to confirm that adding such facilities does not cause an unacceptable drop in its flood carrying capacity.

Designers must recognize that culvert rehabilitation for aquatic organism passage (AOP) purposes involves trade-offs. Efforts need to deliver satisfactory improvements for aquatic organism passage while retaining adequate hydraulic capacity. Just like the design of new and replacement culvert, a multidisciplinary team of biologists and engineers shall collaborate to strike a suitable balance for individual sites.

3 Conclusion

Adopting an eco-oriented engineering design approach to secure ecological connectivity of watercourses involves sizing aquatic-friendly hydraulic crossing structures.

The consensus found in referenced literature is that when designing aquatic organism passages (AOP), culverts must have a cross-section width no less than that of the waterway under full-flow conditions. Their longitudinal slope and flow velocity shall be roughly consistent with those of the original waterway, or similar to those of upstream and downstream reaches. Culverts should adopt an open-bottom or embedded structure, and the bed material shall retain the original grain size characteristics. These design specifications aim to make the hydraulic conditions inside culverts resemble natural river channels. Accordingly, aquatic organisms will encounter no extra obstacles when moving through the passage and its upstream and downstream waters.

As highlighted by Kozarek et al. (2015), another key factor concerning the bed material of aquatic organism passages is that such material shall be sourced from the original riverbed and placed during culvert construction. Otherwise, it will take an extremely long time, even several years, for low-gradient watercourses to naturally replenish native bed sediment. This will fail to meet the design goal of preserving the original environmental conditions within the culvert.

Although multiple design methods are available for aquatic organism passages, scholars including Schall et al. (2012), Olson et al. (2017) and Hernick et al. (2019) regard flow simulation as the optimal approach. It applies to watercourses with varying slopes, considers local geomorphological and hydrological features, and adopts modern numerical simulation techniques to facilitate comparative analysis of different design schemes.

As proposed by Schall et al. (2012), professionals from diverse disciplines are required to define design parameters for this innovative culvert design method, particularly aquatic biologists, geomorphologists, hydrologists and hydraulic engineers. Biological research on various aquatic species in watercourses across different regions of the country is essential for the practical application of this culvert design methodology.

Although culverts designed based on the aquatic organism passage principle have larger dimensions than those designed purely by hydraulic standards and raise road project costs, they boast better capacity and operational performance, and are eco-friendly to aquatic environments.

Advanced hydrological and hydraulic simulation technologies enable the adoption of culvert design methods for aquatic organism passage, helping conserve aquatic biodiversity in watercourses crossing roads. Environmental professionals can achieve the established goals by mastering and applying relevant expertise.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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