DESIGN METHODOLOGY FOR CULVERTS WITH FISH PASSAGE

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ABSTRACT

Introduction

Fish passage requirements for culverts were introduced as part of the Freshwater Fisheries Regulation in 1983 and its enforcement has been a responsibility of DOC. Under the RMA (1991), control of the environmental effects of culverts became the responsibility of Regional Councils. In practice, the impact of the above on culvert design was relatively small. Guidelines for fish passage at culverts continued to focus primarily on the swimming characteristics of fish. Engineering design guidelines for achieving culvert hydraulics that support passage of New Zealand native fish were not well defined and lacked measurable design criteria. The introduction of the New Zealand Fish Passage Guidelines (Franklin et al., 2018) aimed to fill this gap. The guidelines included an approach for obtaining suitable hydraulic parameters for meeting fish passage. However, in practice, the approach did not provide clear quantitative design requirements that can easily be included in a design methodology. As a result, confirming that a culvert design meets fish passage requirements, particularly the new National Environmental Standards for Freshwater 2020 (NES-F), is difficult. To better align the Fish Passage Guidelines with the new policy requirements set out in the NES-F and the information required for quantitative design, NIWA is currently in the process of updating the document. In support of the updated Fish Passage Guidelines, this paper reports on a methodology for detailed design of culverts with fish passage.

Typical Culvert Design Methodology without Fish Passage

Run-off from the catchment upstream of the culvert yields the design flow rate for that culvert for particular design storm events. High level flow rate estimates can be obtained using the rational method or the SCS curve number method. More detailed estimates can be obtained through software EPA SWMM which includes various infiltration methods for taking into account the impact of the soil on the run-off. For the design flow, the culvert hydraulics are modelled in software such as HY-8 or HEC-RAS to determine the culvert size. Input parameters include the downstream stream characteristics obtained from the field and the culvert parameters (size, shape, roughness, gradient and length). The model is iterated until a culvert size is found that meets the head-water requirements for all design events (e.g. head-water to be below soffit during 10yr ARI event and 500 mm freeboard below road verge during 100yr ARI event). The culvert size yields the cross-sectional average velocity at the downstream end of the culvert which informs erosion countermeasures and channel stability measures if required.

Proposed Culvert Design Methodology including Fish Passage

The proposed culvert design methodology adds the requirements related to fish passage to the head-water requirements during the iterative modelling steps to obtain a suitable

culvert size. The fish passage requirements are based on water depth and velocity thresholds that allow fish to pass through the culverts between a minimum and maximum design flow rate for which fish passage should be possible.

For single cell culverts, the maximum flow rate for which fish passage should be possible is set to half of the 2yr ARI flow rate. One half of the 2yr ARI event provides a reasonable approximation of the mean annual flood flow, which in small wadable streams is roughly the bank-full flow. Based on information provided by freshwater biologists, native fish migration is likely to occur predominantly up to the bank-full flow. If a measured dry weather flow is available for the stream, it can be used as the minimum flow rate. Using the base flow and the half of the 2yr ARI flow as the design events for fish passage means that the velocity inside the culvert is suitable whenever fish migration is most likely to be occurring. If the base flow is not known, or the stream is ephemeral, a flow rate less than half of the 2yr ARI flow is used to confirm the range of flow rates for which fish passage is possible.

For multi-cell culverts, the procedure is more complicated, as fish passage may be possible in one of the secondary culverts, but not in the primary culvert or vice versa. If the multi-cell culvert has been designed for fish passage to occur during low flows in the primary and in a secondary culvert during high flows, then it must be confirmed that there is a flow rate for which both the primary and secondary culvert yield suitable fish passage conditions. This guarantees that within the range of flows which require fish passage, there is not a flow rate for which fish passage is not possible.

A typical value for the minimum depth threshold is 150 mm (Franklin et al., 2018). The value for the maximum velocity threshold must be based on the swimming capabilities of the fish expected to be present in the area. Franklin et al. (2018) presents a summary of currently available data on swimming velocities for New Zealand native fish species. The swimming velocities enable a comparison to be made with water velocities in the culvert. The swimming velocities must exceed the culvert water velocities by an amount that when multiplied by the duration that the fish can maintain the given swimming speed, the resulting distance is greater than the length of the culvert.

The typical culvert design yields an estimated cross-sectional average (1D) velocity. This estimate is suitable for design of downstream erosion protection, which is based on 1D equations. However, when assessing fish passage, it is important to account for the reduced velocities around the wetted perimeter of the culvert that fish can take advantage of to migrate. The distribution of the cross-sectional velocity in a culvert depends on its shape, wall/bed roughness, and water depth. Zhai et al. (2014) developed a methodology for determining the velocity distribution within a culvert cross-section based on physical and numerical experiments.

HY-8, the culvert evaluation software by USDoT FHWA (United States Department of Transportation Federal Highway Administration), includes a feature that uses the methodology by Zhai et al. (2014) and the calculated maximum cross-sectional average velocity in the culvert, to calculate depth-averaged velocities within a vertical slice of the culvert as a function of distance from the culvert wall. As input for its evaluation of fish passage, the software requires the minimum and maximum flow rates for which fish passage should be possible, the maximum threshold velocity for the flow within a vertical slice that allows fish to pass, and the minimum threshold depth for the flow within a vertical slice that allows fish to pass.

Results from HY-8 for an example single-cell 1.5 m square box culvert with 375 mm embedment are presented in Figure 1. The high flow results correspond to the 50% of the 2yr ARI flow rate. The base flow was not known and was set to 10% of the 2yr ARI flow rate. The maximum threshold velocity was set to 0.25 m/s for this example and the minimum threshold depth to 150 mm. Figure 1 shows that at the low flow rate, the 0.30 m nearest to the culvert wall would reasonably accommodate fish passage. At the high flow rate, the 0.19 m closest to the culvert wall would reasonably accommodate fish passage. It is assumed that if the distance from the wall, where fish passage is accommodated, is greater than the minimum depth threshold, then the culvert design would be considered passable.

Parameter (units)	Value	Value	Value	Value	Value	Value	Value	Value	Value
Low Flow Results									
Distance from wall (m)	0.00 - 0.04	0.04 - 0.08	0.08 - 0.11	0.11 - 0.15	0.15 - 0.19	0.19 - 0.23	0.23 - 0.26	0.26 - 0.30	0.30 - 0.34
Slice Average Velocity (m/s)	0.02	0.05	0.13	0.18	0.20	0.22	0.24	0.25	0.26
Slice Depth (m)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Threshold	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Too Fast
High Flow Results									
Distance from wall (m)	0.00 - 0.04	0.04 - 0.08	0.08 - 0.11	0.11 - 0.15	0.15 - 0.19	0.19 - 0.23	0.23 - 0.26	0.26 - 0.30	0.30 - 0.34
Slice Average Velocity (m/s)	0.02	0.06	0.15	0.20	0.23	0.25	0.27	0.28	0.30
Slice Depth (m)	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Threshold	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Threshod Met	Too Fast	Too Fast	Too Fast	Too Fast

Figure 1: HY-8 Low Flow analysis results table

Conclusions

The proposed culvert design methodology is based on a detailed analysis of the hydraulic parameters of the flow in the culvert, and compares these with the threshold parameters required for fish passage, to ensure that the culvert design accommodates fish passage for the range of flow rates during which fish migration is expected. The methodology adds the fish passage requirements to the head-water requirements during the culvert design process that yields a suitable culvert size. The next step is to add the requirements related to the continuity of geomorphic processes to the design methodology as well.

References

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KEYWORDS

Culvert, Fish Passage, Design Methodology, HY-8