Economic Culvert Design Using Fish Swimming Energy and Power Capabilities

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Abstract–Utilizing fish swimming power and energy capabilities and the hydraulic properties of culverts in those locations within culverts where fish actually swim, the writers have prepared a detailed manual of culvert design procedures for culverts which must provide safe passage of upstream moving, weak swimming fish (Behlke, Kane, McLean, and Travis, 1991). The design procedures utilize hydraulic formulae for profile drag, non-Archimedean buoyant forces, and virtual mass force to quantify the hydraulic conditions within a culvert that the design fish can sustain without exhaustion for various time durations. Final culvert design may then be selected on economic or other bases from the full range of trial designs that are hydraulically suitable for fish passage. This paper provides an overview of the analytical and biological methods used in the preparation of the design procedures and its associated software.

Introduction

A design species and size of fish must be selected as the basis for culvert design for fish passage. The design fish is the weakest swimming fish which must pass through the culvert being designed. Since fish usually do not move at all times of the year, flow conditions which occur during the time of expected fish passage are those selected for hydraulic considerations for fish passage. If fish passage delays of short periods are acceptable, flood peaks may be reduced for fish passage design purposes.

Following selection of the design fish and the associated maximum stream flows during times of passage, the culvert design process proceeds as follows:

1. Fish swimming capabilities of power and energy are determined.
2. Fish swimming behavior when stressed within the limits of its capabilities by a culvert must be defined.
3. Culvert hydraulics where the fish are expected to swim in the culvert must be determined.
4. A culvert is designed to pass the design flood and for which culvert hydraulics, where the fish swim, do not overstress swimming power and energy capabilities of design fish.

Fish Swimming Hydraulics And Capabilities

A satisfactory culvert for fish passage may have distinctly different types of flow occurring simultaneously at the outlet, inlet, and barrel. Typically, higher velocities of flow and/or water accelerations occur at the inlet and outlet, while smaller velocities of flow occur in the culvert barrel. It may, therefore, be necessary for a fish to utilize white muscle (anaerobic) power at the outlet and/or inlet while relying on red muscle (aerobic) power for passage through the culvert barrel. Thus, it is necessary to determine the design fish's swimming capabilities in each of these modes. Typically, white muscle mode swimming allows the fish to deliver much greater swimming limited. When white muscle energy capabilities are depleted, long time periods, perhaps hours, of rest are required before the capabilities return.

The results of swimming performance tests of fish are usually presented as swimming velocity, with respect to the surrounding water, versus time duration of swimming at the specific velocity. Hunter and Mayor (1986) made an extensive search and statistical analysis of previous fish swimming tests by other researchers of various species and sizes of fish. The most useful of their results, for all of the information available to them, were presented in the following form:

$$V_{fw} = a\, L^{b}\, t^{-c} \qquad (1)$$

where L is fish length, t is time duration which the fish is capable of swimming at V_{fw} velocity relative to the water, a and b are constants which depend on fish species and the system of units, and c is a constant which depends on species. They list these constants for all previous study results which they were able to find. Most of the studies were for red muscle mode, relatively long duration, swimming, but some studies were also found for white muscle mode swimming. Eq. 1, is rather extensively documented for red muscle swimming, but not many species have been tested for white muscle swimming. The writers performed field observations to obtain suitable white muscle swimming capabilities for Arctic grayling.

The results of Eq. 1, represent continuous swimming for time t at a constant velocity with respect to the surrounding water (V_{fw}), with little or no horizontal water pressure gradient, and with no acceleration of the fish or the surrounding water. Utilizing a profile drag equation (Webb, 75), the swimming capabilities of Eq. 1, can be transformed to swimming power and energy delivery capabilities which then can be used for predictive swimming performance in more complicated hydraulic environments. The procedure is described in detail (Behlke, et. al., 91) but will be outlined here. A profile drag equation (Webb, 75) for swimming fish is:

$$F_D = b\, k\, (.0072)\, (\rho/2)\, (\nu)^{0.2} L^{1.8}\, (V_{fw})^{1.8} \qquad X$$

where F_D is the fish's profile drag, b is a ratio of the fish's body surface area to that of a square flat-plate having a dimension equal to the fish's length, k is a constant, between 3 and 5, which relates well documented flat-plate drag to swimming fish profile drag (we have used $k = 4$), ρ and ν are, respectively, the mass density and kinematic viscosity of water for the temperature at which the fish swims, and L is the length of the design fish.

Profile drag of Eq. 2, is multiplied by the swimming velocity of the fish with respect to the water (V_{fw}) in order to obtain net fish swimming power, P, delivered by the fish while swimming in an experimental environment at velocity V_{fw}. So,

$$P = F_D\, (V_{fw}). \qquad (3)$$

Net energy, E, delivered to overcome the profile drag is the product of P and the time duration which the fish swims at velocity V_{fw} (Eq. 1). That is,

$$E = P\, t. \qquad (4)$$

Thus, net power and energy delivery capabilities are determined from experimental fish swimming tests. We assume these capabilities suitably define the upper limits for net power and energy delivery for similar fish swimming in the more complex hydraulic conditions of culvert flow.

Fish Swimming Hydraulics

In the real world of fish passage structures, fish are subjected to additional forces beyond that of profile drag. Individual, additional forces result from non-Archimedean buoyancy effects, acceleration of the fish and/or the surrounding water, turbulence, or surface waves generated by swimming close to the water surface. We have ignored the latter two forces, because our field observations of weak swimming Arctic grayling (Thymallus Arcticus) swimming in and near culverts indicate that these forces are usually of minor consequences there.

Behlke (1987, 1991) has shown that where water surfaces slope an adverse force (additional drag), F_G, acts on upstream-swimming fish. This force results from an imbalance between the fish's weight and its buoyant force. This is:

$$F_G = W (\sin \phi + \cos \phi (\tan (\theta - \phi))) \quad (5)$$

where W is the fish's weight, ϕ is the angle (from horizontal) of a streamline along which fish swim, and θ is the angle (from horizontal) at which the hydraulic gradient (HGL), usually the water surface, slopes. In the culvert barrel $\phi = \theta$, and both angles are small, so:

$$F_G = W S_o \quad (6)$$

where S_o is the culvert slope. This force (the "gradient force") is usually small in the culvert barrel if $S_o \leq 1\%$, but it can be significant in the vicinity of the culvert outlet or inlet or where weir-baffles are necessary. Since W varies as L^3, it is relatively of greater importance for large fish than for small fish.

The final force considered here to retard upstream progress of a fish results from upstream acceleration of the fish or downstream acceleration of the surrounding water (Daily and Harleman, 1965). Fish we have observed in culverts appear to accelerate little while moving through culverts (Behlke, et. al., 1989), so we have considered only water acceleration. This (virtual mass) force, can be expressed (Behlke, 1991) as:

$$F_{vm} = 1.2 (W/g) a_{fw} \quad (7)$$

where a_{fw} is the acceleration of the fish with respect to the surrounding water, here the water acceleration, and g is the acceleration of gravity. In order to evaluate this force it is necessary to calculate the water acceleration from the local hydraulics of where the fish is swimming.

Both profile drag and the virtual mass force are semiempirical and are not exact. Future research may better describe them.

These forces together with the net thrust force (T), generated by the fish, and the fish's weight (W) and buoyancy (B) are shown in Fig. 1. (F_G is the resultant of W and B, so W and B do not act in addition to F_G.) When F_D, F_G, and F_{vm} are known for hydraulic conditions where the design fish swims, the power necessary for it to deliver is:

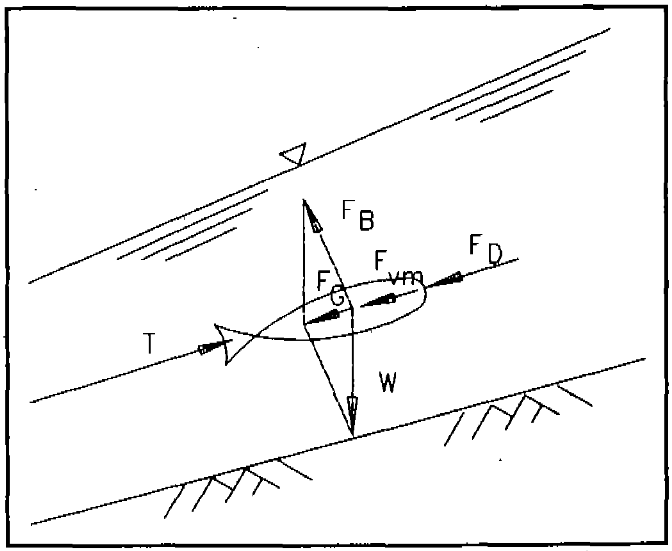

Fig. 1. Drag forces acting on swimming fish and thrust necessary to overcome these forces

$$P = (F_D + F_G + F_{vm}) V_{fw} \quad (8)$$

The energy expended while swimming through any segment of the culvert, where these forces are constant, is the product of P and the time required for the fish to swim through the segment. That is,

$$E = P (\Delta s/V_f) \quad (9)$$

where Δs is the length of the culvert segment being considered, and V_f is the swimming velocity of the fish with respect to the culvert.

Fish Swimming Behavior When Stressed In Culverts

Knowledge of where fish swim within the flow mass of water moving through culverts and how quickly they move with respect to the culvert as they swim upstream is necessary for the proper use of Eqs. 5-9. Our field studies and analysis of Arctic grayling swimming in the culvert environment (Behlke et. al., 1989; Kane et. al., 1989) indicate that fish seek those locations, at any obstacle, where the swimming is least difficult. This is generally at the culvert wall and relatively close to the water surface where the effects of culvert corrugation roughness are most beneficial. They also appear to understand their short term (white muscle) and longer term (red muscle) swimming limitations. They, therefore, appear to attempt to move quickly through those areas where white muscle swimming is required but move much slower through those areas where red muscle effort is required. From our observations, we have selected 0.3 m/s

(1 f/s) for white muscle swimming and 2.5 cm/s (0.1 f/s) for red muscle swimming as average values, both velocities are with respect to the culvert (not the water).

These values must be determined from direct observation of fish swimming in a culvert environment. Other species of design fish would likely move at different speeds than do grayling. We have found the field observations, necessary to provide this information, provide design and resource agency personnel with a much better "feel" for fish behavior and for passage design.

Though past tests of swimming performance indicate that an individual species may have the capabilities to perform certain swimming feats, those fish may not decide to attempt some barriers, though it apparently could successfully do so. This is another area where familiarity with the behaviors of the species is important to designers and regulators.

Culvert Hydraulics

This discussion of culvert hydraulics relates to passage of weak swimming fish. With the exception of flow at very small depths, these fish probably cannot negotiate culverts supporting hydraulically supercritical flow, because water velocities are too great for such fish to negotiate the long barrel segment while swimming in the red muscle mode. Thus, for these fish, the depth of flow with respect to the culvert invert (y) must be greater than the hydraulic critical depth, y_c, and, with few exceptions, the slope of the culvert must be less than critical slope for the design flow for fish passage. These constraints allow only for the existence of hydraulic M-1 and M-2 water surface profiles in the culvert barrel. At the outlet $y \geq y_c$. For a trial culvert, when the Manning n, discharge (Q), S_o and culvert geometry are known, backwater curves can be calculated through the culvert from outlet-pool water surface elevations which support culvert outlet depths equal or greater than y_c.

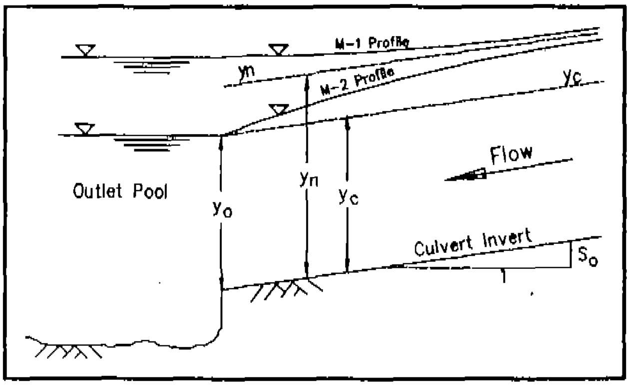

Figure 2. Water surface profiles in the outlet zone. y_n, y_o and y_c are, respectively, hydraulic normal, outlet, and critical depths

Our field measurements (Kane et. al., 1989; Behlke et. al., 1991) show the importance of large scale culvert corrugations. They are central to economic culvert design for passage of weak swimming fish, because they create a zone of relatively slow moving water at the sides of the culvert. This allows the use of greater average velocities (Q/A, where A is the local cross-sectional area of flow) in the culvert than would be allowable if the corrugations are small. Our observations of many culverts indicate that, where fish passage is important, corrugations should be no less than 5 cm (2") in amplitude. We have measured some water velocities, in the fish swimming zone near the culvert wall, which were only 0.1 Q/A. For the present, for circular culverts having 5 cm (2") corrugations, we recommend the use of 0.4 Q/A as a conservative value for water velocities in the barrel near the wall, where the fish actually swim. If an M-2 water surface profile exists in the culvert, water accelerates near the outlet, and velocities near the wall of the culvert more closely approximate Q/A. In the fish swimming zone at the outlet, near the wall, we are using 0.8 Q/A, gradually decreasing to 0.4 Q/A in the barrel upstream from the outlet acceleration zone.

In the barrel, after the fish has passed through any white muscle swimming which may be required by higher velocities near the outlet, the water velocity where fish swim is taken as 0.4 Q/A.

At the culvert inlet, water accelerates as it enters the culvert, resulting in a drop in the water surface. Here the fish must face all three of the forces of Eq. 8. White muscle activity is usually required. For the fish to be able to move upstream out of the culvert inlet, it must have available sufficient white muscle swimming energy. If it has used all of its available white muscle at the culvert outlet zone, it cannot move upstream out of the culvert. Thus, outlet conditions may effect the fish when it arrives at the inlet.

Steep culverts require baffles of some sort. The hydraulics of four weir-baffle arrangements have been experimentally defined by Katopodis and Rajaratnam, 1989. These provide resting cells between successive white muscle exertion points over weirs. Our calculations of power and energy requirements for fish swimming over weir-baffles lead us to believe that streaming flow (Fig. 3) is better than plunging flow for fish passage.

Matching Culvert Hydraulics To Fish Swimming Capabilities

Design of new culverts is a trial-and-error process. For a design fish and a trial culvert design, it is necessary that the designer calculated results of Eq. 8, for each point in the culvert (several points in the outlet, inlet, and barrel, or over a weir-baffle) must not exceed the results observed or given by Eq. 3, for each of white and red muscle mode swimming, recognizing that white muscle mode swimming may be required in some segments of the culvert and red muscle mode swimming is required elsewhere. Similarly the limits observed or given by Eq. 4, for each of these swimming modes, must not be exceeded by the calculated results of Eq. 9. If they do, the trial culvert geometry is not satisfactory, and the calculations must be repeated for a different trial design culvert.

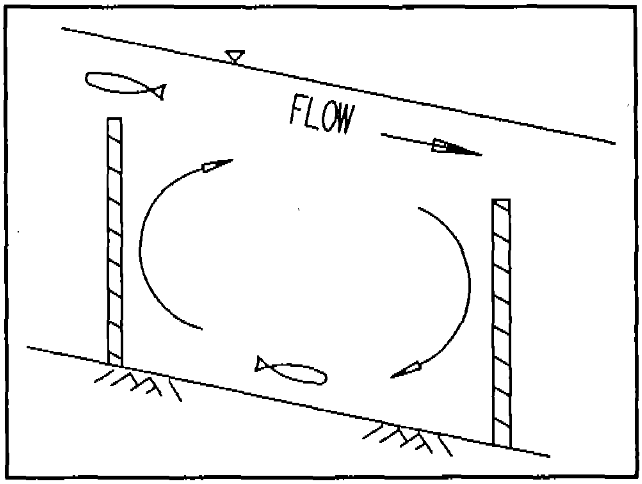

Figure 3. Streaming flow over weir-baffles in culverts. Fish swim in white muscle mode when passing over a baffle

The necessary calculations for each trial configuration are repetitious and lengthy. For this reason we have developed software for design of circular culverts for the passage of weak swimming fish. This software can also be used for design of elliptical culverts where the depth of flow for fish passage is relatively small. This method and software is being utilized by the Alaska Dept. of Transportation and Public Facilities for fish passage culvert design. In 1994 we intend to obtain sufficient in-culvert hydraulic data to prepare the necessary computer programs for design of pipe-arch culverts for fish passage. However, slower flow velocities near the water surface at the wall should be found in all culverts where depths of flow at fish passage times are small enough that the culvert's two walls diverge at the water surface.

Conclusions

Fish swimming power and energy methods provide a very flexible approach to the design of culverts or other passage devices. These methods provide the common denominator between fish swimming performance tests and actual design of culverts for fish passage.

Since power and energy are understood by professional engineers and biologists, this method provides a common ground for fish passage culvert design and regulation. Following the resource agency's determination of the species and length of the design fish, the culvert design suitable for flood flow passage is checked by this almost automatic process to determine suitability for fish passage. If it is not suitable, the determining criterion is fish passage, and appropriate changes are made.

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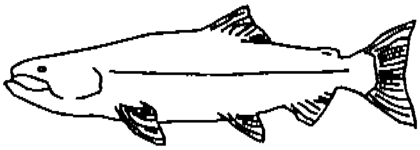

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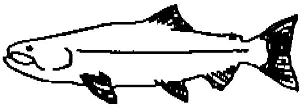

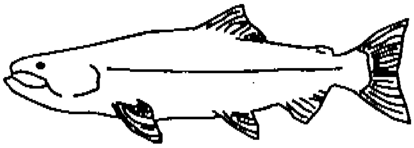

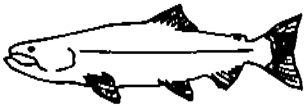

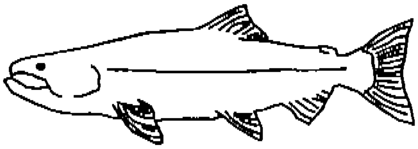

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