

Field Observations of Arctic Grayling Passage Through Highway Culverts

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Potentially important, miscellaneous, qualitative observations of four field studies of spawning migrations of arctic grayling (*Thymallus arcticus*) through highway culverts are discussed. Problems associated with culvert outlets, inlets, and barrels are described together with observed methods that fish use to negotiate culverts. The importance of location where fish actually swim in culverts is discussed. Limited observations of effects of culvert skew on culvert barrel flow patterns indicate such skew can make fish passage less difficult. The necessity of recognizing red muscle and white muscle power and energy capabilities of fish attempting to pass through culverts is indicated. Observations of fish attempting to enter a small fish ladder and a difficult culvert indicate that water-produced noise may attract fish to relatively small passage devices. Fish are observed to resort to leaping to enter difficult passage situations.

The Arctic grayling (*Thymallus arcticus*) was selected by the Alaska Department of Fish and Game as the design species for developing fish passage structure guidelines at highway stream crossings for low swimming performance fish (Group I). Arctic grayling were selected because of their ubiquitous distribution throughout Alaskan waters and their relative importance as a sport fish. Although the literature contains some information on the observed swimming performance of Arctic grayling through drainage structures (1-3), unanswered questions remained regarding (a) the critical water velocities within culvert barrels that grayling could successfully ascend under various conditions, (b) the length of time delay that grayling could withstand at drainage structures without affecting subsequent reproductive success, and (c) other hydraulic forces within culvert drainage structures (in addition to profile drag) that may also affect fish passage. To attempt to answer these questions, four field studies were initiated by the Alaska Interagency Fish Passage Task Force between 1985 and 1988.

These studies were designed to yield quantitative data related to fish energy and power delivered by grayling passing through two different culverts. Two of these studies have been reported (4,5). Reports for the other two are being written. During the course of the studies, several miscellaneous but potentially important phenomena were observed. These observations were made at two culvert sites and at a beaver dam where a small

fish ladder had been introduced to aid fish in moving upstream past the dam. These limited observations are qualitative in nature but are reported here in the hope that others may profit from them and, through their observations and research, may add to the data base.

Fish take the path of least total resistance while swimming in culverts. To minimize the propulsive force necessary to move ahead, they choose paths where water velocities, water surface slopes, and water accelerations are reduced. The forces created by each of these, and the necessary power and energy produced by fish to overcome these effects are reported elsewhere (5-7). However, those involved in design of culverts should be aware that these parameters are deterrents to fish attempting to pass through culverts. We have observed fish attempting to avoid each of these situations. Since these situations usually appear collectively in culvert inlets and outlets, attempts to minimize all of these adverse conditions are encouraged.

Most hydraulic model studies of culverts have been directed toward identifying the effects of culvert inlet shape, slope, cross-section shape, or other geometric variables on discharge through culverts. Since fish swim along paths of least resistance, water velocities, accelerations, and pressure gradients (resulting from sloping water surfaces) in the zone in which the fish actually swim are important and should be analyzed. Mean cross-section water velocities in a culvert may have little meaning except as possible indicators of water velocities where the fish elect to swim within the culvert. However, water velocity is only one of the parameters that affect fish passage.

The distribution of water velocity in culvert barrels is extremely important to fish swimming through this zone of rather uniform flow in a relatively shallow sloping structure. Water velocity measurements by Katopodis et al. (8) and by us (Figure 1) show that water velocities near the boundary of a culvert are smaller than mean cross-sectional velocities at any point in the culvert. Our observations indicate that fish hug the culvert boundaries. Detailed study of the data of Katopodis et al. and Figure 1 reveals that, in culverts that are roughened only by corrugations but not by baffling or other artificial roughness (to reduce local water velocities), the zone of slowest water in a partially full culvert occurs at the intersection of the water surface with either side of the culvert. Recently, from working on a platform in a 9.5-ft-diameter culvert that was flowing approximately 2.5 ft deep, we were able to observe this location within the culvert and document that it was where the fish were swimming upstream.

During times when entrance to the culvert was difficult, fish negotiated the culvert outlet at the edge of the culvert

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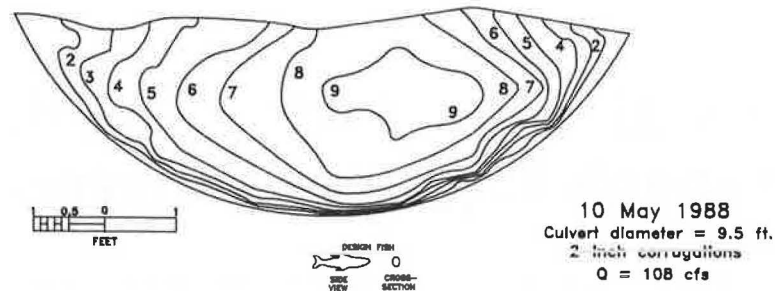


FIGURE 1 Water velocity cross section (ft/second) of Fish Creek Culvert, Denali Highway, Alaska.

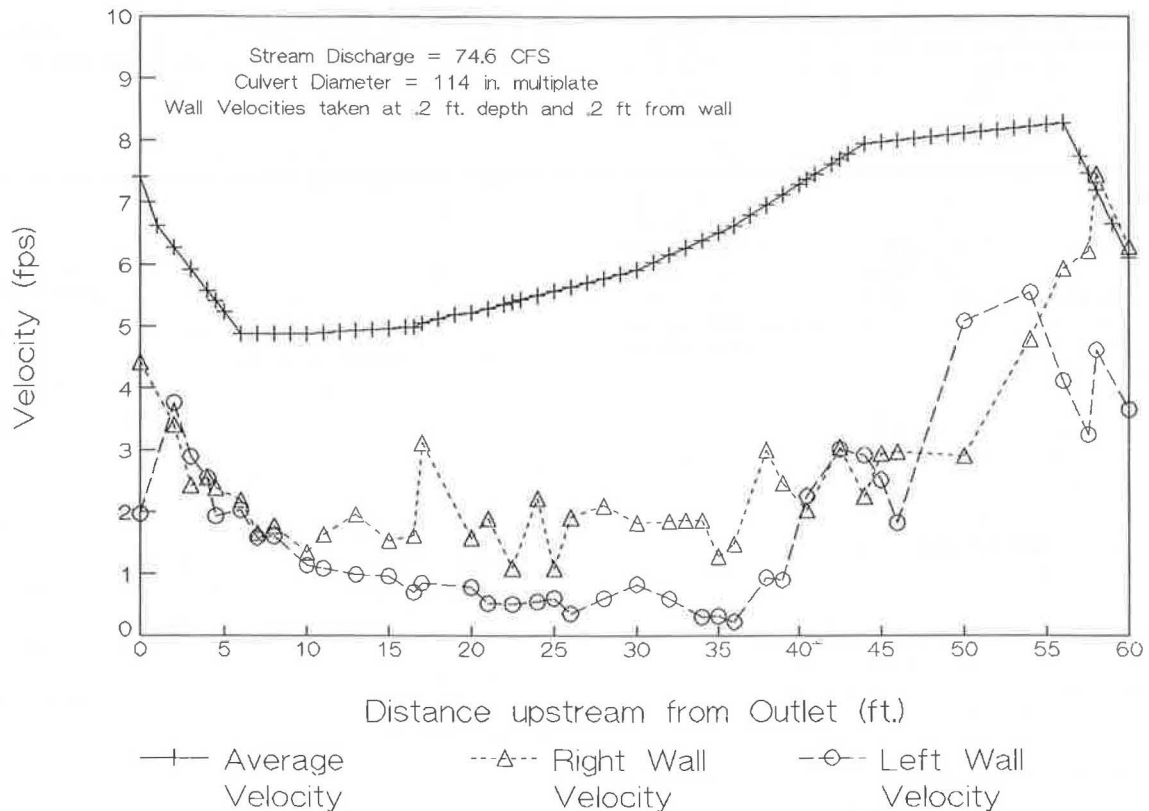


FIGURE 2 Culvert wall velocities of Fish Creek Culvert, May 15-16, 1988.

close to the water surface. Later, when discharges decreased, fish also entered the outlet at the invert and other locations across the bottom of the culvert. During higher discharges, when smaller fish were not able to pass through the culvert, only large fish were able to exit the culvert at the edge of the culvert close to the water surface. All of these occupied zones were areas of least total resistance to the fish.

In most situations, fish swim with their bodies oriented with bellies downward and backs upward. However, most fish swimming at the edge of this culvert and close to the water surface were not oriented vertically but were oriented normal to the sloping culvert wall with their bellies very near the wall.

In other studies by Tilsworth and Travis (4) and by us (5) of another culvert, most grayling were observed to enter the culvert hugging the invert, although many entered the culvert at the sides of the culvert too. This was a situation in which

high-velocity flow, water acceleration, and relatively steep sloping water surfaces existed. Because the culvert diameter was 5 ft, it was not possible to enter the culvert to observe where the fish actually swam in the barrel of the culvert.

The effect of a skewed culvert inlet is important from the perspective of fish passage. Figure 2 indicates water velocity measurements for both edges of the 9.5-ft-diameter culvert mentioned previously. Corrugations were 1-3/8 in. deep and 6 in. apart. Velocity measurements were taken 0.2 ft from the culvert wall at a depth of 0.2 ft, and they are compared with the mean cross-sectional velocity in the culvert at various longitudinal locations. Water approached the inlet of this culvert from an angle of approximately 30° from the axis of the culvert. Clearly, the effect of this entrance skew was felt completely through the 60-ft length of the culvert. Fish clearly preferred the side of the culvert with lesser water velocities.

How much farther downstream this skew would have affected flow if the culvert had been longer is open to conjecture.

This culvert was constructed of bolted corrugated metal plates with the nut end of the bolts projecting inside the culvert. Some fish were observed to swim very close to the line of protruding nuts and bolts. Another culvert, where the axis of the culvert was skewed approximately 45° from the approaching flow, appeared to show a similar effect through a 60-ft culvert, although it was not possible to enter this culvert to obtain actual water velocity measurements. While skew is not desirable from the water passage viewpoint, it appears to show considerable promise for fish passage through large-diameter culverts.

The appropriate parameters for quantifying this effect presently appear to be s/B and Vo/V , where s is longitudinal distance downstream from the culvert inlet, B is the water surface width at location s , Vo is the water velocity at the edge of the culvert close to the water surface where the fish swim, and V is the cross-sectional average water velocity at location s . Water surface widths (B) for the culvert of Figure 2 varied along the culvert but averaged approximately 8 ft, so at the culvert outlet $s/B = 60/8 = 7.5$. The effect of skew was observed to exist throughout the length of this culvert. We are working on better quantifying this effect, since it is apparent from Figure 2 that the effect of skew is more pronounced where water velocities in the culvert were slower, thus suggesting a possible Froude number dependency.

The concept that fish swim with virtually constant velocity with respect to the ground as they move through culverts appears to be incorrect for many fish. Fish were observed to be "treading water" close to the side of the culvert at several locations of low water velocities in the culvert of Figure 2. It can be shown (6,7) that this type of motion leads to more total energy expenditure in passing through the culvert than if the fish swims at constant velocity, but there appears to be a power-energy trade-off that fish choose to make. We observed smaller grayling, burbot, and dolly varden also resting in the fashion outlined above. Interestingly, a single sculpin (approximately 2 in. long) was able to swim in and out of the corrugations and, by remaining very close to the wall, move upstream faster than grayling several times its length. How the sculpin fared in faster water closer to the inlet is unknown.

Fish have two separate muscle systems—red (aerobic) and white (anaerobic) muscles—to propel themselves. Red muscles are used for slow, long-duration swimming, and white muscles are utilized for fast, short-duration swimming. The red muscle system operates in an aerobic mode, and the white muscle system operates in an anaerobic mode. The latter is confined to short periods of output followed by long periods of rest (9). The red muscle and white muscle power and energy capabilities of fish (if known) must be kept in mind for culvert design. We have observed grayling obviously struggling hard in a white muscle mode as they entered culverts. However, when they had passed the difficult culvert outlet conditions, they switched to a larger amplitude and much slower tailbeat frequency, which is typical of the red muscle mode of swimming.

If fish completely deplete their white muscle capability at their entrance through the outlet of a culvert, they can switch to red muscle propulsion to swim through the barrel. But if water conditions at the culvert inlet are too difficult, the fish probably will not have sufficient white muscle capability to

swim out of the culvert. We have seen fish that had difficulty entering a culvert fail the white muscle test in their attempts to leave a difficult culvert. Long rest periods are required to reconstitute white muscle capabilities. But culverts, in which white muscle efforts may be required most, provide little opportunity to rest in the barrel long enough to reconstitute these capabilities.

Our experiences with how water attracts upstream-migrating fish to specific water locations leads us to believe that this relationship should be an area of future research. We recently observed grayling reacting to a high beaver dam that they were unable to negotiate. Many leaped futilely at the water falling over a small spillway section that carried most of the streamflow over the dam. Some also entered a small side channel that carried only 3 percent of the total streamflow. At the upper end of the side channel, this small flow dropped down a 0.6-ft waterfall. Several fish ascended this small waterfall but were unable to get past the dam because of further difficulties.

When a small fish ladder was introduced to carry fish from the upstream end of the waterfall to the pool above the beaver dam, fish quickly utilized the route. After a few hours, they completely ceased leaping at the main channel spillway that was then carrying 94 percent of the total flow. When the same ladder was located so it extended, with no waterfalls, into the main channel scour pool from the pool above the dam, no fish entered it. Fish appeared to have difficulty finding the entrance to the ladder without the presence of a small waterfall to announce the ladder's location.

At another culvert, where fish passage was temporarily blocked by high stream discharges, many fish leaped from the scour pool at a water jet approximately the diameter of a pencil that was emitting from a bullet hole in the side of the full-flowing, 5-ft-diameter culvert. It appears that splashing water such as that from the small waterfall and that created by the bullet hole jet may have a considerable attracting effect for spawning migration fish. This type of attraction may be more important than other attraction methods in which attraction to a passage device is important.

Although leaping can be a very efficient mode for fish to move upstream past difficult vertical obstructions, it is our observation that grayling leap only as a last resort. This observation is a departure from the rule that fish select the easiest way to move from one location to another.

In the 9.5-ft-diameter culvert previously referenced, high-velocity, supercritical flow existed for 20 ft downstream from the inlet because the culvert was relatively steep there. This flow resulted in formation of surface waves that did not attenuate rapidly in the downstream direction. Several small grayling swimming close to the surface at the more favorable side of the culvert were observed to be dislocated rather severely by these waves. Clearly, situations that set up moving waves in culverts are the enemy of small fish, because waves can sweep them away from the low-velocity flow near the boundary, out into higher-velocity flow, which can sweep them out of the culvert.

Any culvert that flows with hydraulically supercritical flow contains water velocities too fast for most small species of fish to negotiate in the culvert barrel. For this reason and because of the attendant transient waves associated with high-velocity flow, culverts should be designed with outlet or downstream pool control.

SUMMARY AND FUTURE WORK

We are incorporating many of the observations from our present study into the preparation of a culvert design manual for the upstream passage of fish. These observations are also being used in the development of retrofit strategies for existing culverts that are incapable of passing upstream-migrant fish. A design manual that incorporates new culvert design recommendations is scheduled for completion late in 1989.

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REFERENCES

1. D. R. Jones, J. W. Kiceniuk, and O. S. Bamford. Evaluation of the Swimming Performance of Several Fish Species From the Mackenzie River. *Journal of Fisheries Research Board of Canada*, Vol. 31, 1974, pp. 1641-1647.
2. C. MacPhee and F. J. Watts. Swimming Performance of Arctic Grayling in Fishway Culverts. Final Report, Fish and Wildlife Service, Anchorage, Alaska, 1976, 41 pp.
3. J. G. Fisher and S. L. Tack. *Performance of Arctic Grayling in a Twenty Foot Section of Model "A" Alaska Steeppass Fish Ladder*. Final Report. U.S. Army Corps of Engineers, Alaska Division, Anchorage, 1977.
4. T. Tilsworth and M. D. Travis. *Fish Passage Through Poplar Grove Creek*. Report FHWA-AK-87-15. Alaska Department of Transportation and Public Facilities, Fairbanks, 1987.
5. C. E. Behlke, D. L. Kane, R. F. McLean, and M. T. Travis. *Spawning Migration of Arctic Grayling Through Poplar Grove Creek Culvert, Glennallen, Alaska, 1986*. Report FHWA-AK-RD-88-03. Research Section, Alaska Department of Transportation and Public Facilities, Fairbanks, 1988.
6. C. E. Behlke. Hydraulic Relationship Between Swimming Fish and Water Flowing in Culverts. *Proc., 2nd International Cold Regions Environmental Engineering Conference*, Edmonton, Alberta, Canada, 1987.
7. C. E. Behlke. Hydraulic Effects on Fish Swimming in Fish Passage Structures. Presented at American Society of Civil Engineers National Hydraulics Specialty Conference, Colorado Springs, Colo., 1988.
8. C. Katopodis, P. R. Robinson, and B. G. Sutherland. *A Study of Model and Prototype Culvert Baffling*. Technical Report 828. Fisheries and Marine Service, Ottawa, Ontario, Canada, 1978.
9. P. W. Webb. Hydrodynamics and Energetics of Fish Propulsion. Bulletin 190. Fisheries Research Board of Canada, Ottawa, Ontario, 1975.

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