

CULVERT HYDRAULICS RELATED TO UPSTREAM JUVENILE SALMON PASSAGE

Patrick D. Powers, P.E.

With assistance from:

Ken Bates, P.E.
Tom Burns, Fisheries Biologist
Bob Gowen, Engineering Aide
Ron Whitney, Scientific Technician



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TABLE OF CONTENTS

	<u>Page</u>
Introduction	3
Biological Considerations	3
Materials and Methods	4
Results	8
Control Tests	8
Velocity	9
Slope	12
Smooth versus roughened pipes	13
Conclusions	15
Example Problem	16
Test Variables	18
References	19

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INTRODUCTION

Culverts designed for fish passage in Washington State are required to meet some average barrel velocity at a given design flow. For upstream passage of adult salmonids this velocity ranges from three to six feet per second, depending on the species and culvert length. Recently the importance for upstream passage of juvenile fish has been documented. Peterson (1982), Cederholm (1988) and King (1995) have documented the importance of this upstream movement. Because of the lower swimming speeds of these smaller fish, culverts sloped greater than 0.2 percent would block upstream passage. A study was performed by the Washington Department of Fish and Wildlife (WDFW) in cooperation with the Washington State Department of Transportation (WSDOT) to determine if certain culvert characteristics allow upstream passage of juvenile coho salmon. The purpose of the study was to investigate the premise that small fish (60 to 90 mm fork lengths) would use the low velocity boundary layer near the wall of a roughened pipe to pass upstream.

The study objectives were to: 1) determine if fish would use the low velocity boundary layer of a roughened pipe to pass upstream and compare this to passage through a smooth pipe, and 2) explore relationships between velocities and turbulence in the boundary layer to passage success. Once the hydraulic conditions which provide optimal passage are defined, these parameters can then be incorporated into new culvert designs and retrofits.

The tests consisted of placing fish in culverts with varying roughness and slope. Fish were counted as they passed, held in the culvert or failed back downstream. To meet the first objective, upstream passage success was compared to the maximum velocity (V_{max}) in the smooth and roughened pipes. For the second objective, four variables (V_{max} , V_{ave} , V_{occ} and slope) were compared to passage success. A simple linear regression model relating V_{max} to percent passage showed that velocities for the 80 percent passage level were 1.3 and 2.0 feet per second (fps) for the coho fry and fingerlings respectively. For the two coho size ranges this equals 6.7 body lengths per second (BL/sec). This value is similar to the 7.0 BL/sec reported by Taylor and McPhail (1985), for a velocity which induced fatigue after 30 minutes of testing.

The major finding of this study was not the documentation of the actual swimming speeds of fish, but the potential for turbulence in the boundary layer actually hindering upstream passage. Comparing a smooth versus a roughened pipe at similar values of V_{max} , it was found that passage success was greater through the smooth pipe (i.e., fish passed at a lower rate when they used the reduced velocity boundary layer).

BIOLOGICAL CONSIDERATIONS

Swimming speeds of fish have generally been classified as "burst speed," "prolonged speed" and "sustained speed" (Bell, 1985, Orsborn and Powers, 1985). Burst speed is a single attempt lasting from one to six seconds, prolonged speed up to 20 minutes and sustained speed for more than an hour (Blake, 1983). When passing through culverts, fish most often use prolonged speed with an occasional burst at the inlet or outlet, or a series of bursts between resting areas.

Griffiths and Alderdice (1972) tested 75 to 95 mm wild coho salmon from British Columbia in a stamina tunnel with varying temperature and found the maximum swimming speed varied from 1.4 to 1.8 fps. Taylor and McPhail (1985), studied the variation in burst and prolonged speeds of 40 to 70 mm wild and hatchery coho salmon in British Columbia. Burst swimming was initiated by electronic stimulus and averaged 2.1 to 2.4 fps with a maximum of 3.4 fps. Prolonged stamina tests were performed in oval tanks with test velocities ranging from 1.1 to 1.2 fps and fatigue times ranging from 28 to 17 minutes. Brett, Hollands and Alderdice (1958) studied the effect of temperature on the sustained speed of sockeye and coho salmon again in British Columbia. Maximum sustained velocities were found at 1.0 fps for underyearlings, and 1.3 fps for yearlings.

MATERIALS AND METHODS

This study was performed in the spring and summer of 1995 at the Skookumchuck Salmon Hatchery near Tenino, Washington. On May 3, 1995, 40,500 zero+ coho salmon, *onchorynchus kisutch*, were transferred into two 8 ft by 80 ft vinyl raceways from the Skykomish Hatchery for the subsequent series of tests. Tested fish were returned to a separate pond and were not used again. Tests covered two size ranges of coho salmon (Figure 1) which correspond to the observed upstream migration cycle: 55-65 mm (fry) and 85-95 mm (fingerlings) (Peterson, 1982 and Cederholm, 1988). Coho fry were tested in the spring (May 1995) and the fingerlings tested in the summer (August 1995). The times were selected based on desired fish length. Water temperature during testing for these two time periods ranged from 48°F to 56°F.

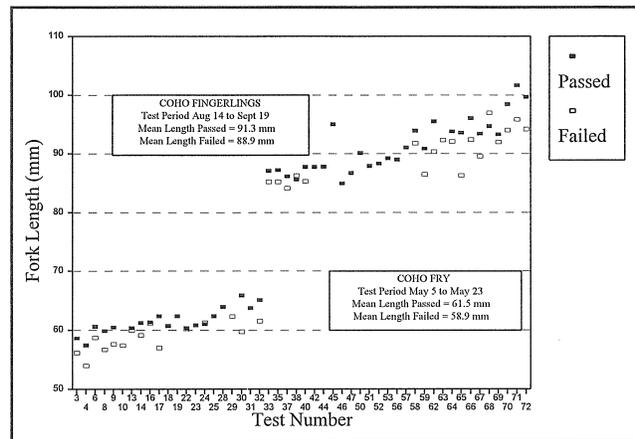


Figure 1 - Fork lengths of fish that passed and failed for the two test periods.

Passage was evaluated through one smooth pipe and three standard corrugated metal pipes with varying corrugation sizes (American Iron and Steel Institute, 1993). The smooth pipe was a 12-inch diameter PVC plastic pipe. The culvert with the ½ inch by 2-⅔ inch corrugations was 18 inches in diameter. The culvert with the 1 inch by 3 inch corrugations was 36 inches in diameter, and the culvert with the 2 inch by 6 inch corrugations was a quarter section of a 60-inch diameter multiplate. Annular and spiral corrugations were tested, except for the multi-plate which only comes in annular corrugations. A smooth plywood wall down the centerline of the multiplate culvert cut the 60-inch culvert in half to reduce the flow requirements. There was a velocity boundary layer effect along this wall, but it was far enough away from the roughened wall not to affect the study results. The different pipes are labeled throughout the report as shown in Table 1.

Culvert Label	Culvert Diameter	Corrugation Size, Type
0	12 inches	smooth PVC
.5S	18 inches	½" x 2-⅔" spiral, cmp
1S	36 inches	1" x 3" spiral, cmp
1A	36 inches	1" x 3" annular, cmp
2A	60 inches	2" x 6" annular, multiplate

Table 1. Description of culverts tested. “S” are spiral corrugations. “A” are annular corrugations.

The testing apparatus consisted of an upper box, culvert and lower box (Photo 1). The upper box contained an inflow pipe with a flow control valve, energy dissipators, a flow measuring weir and screens for holding the fish once each test was complete. In addition, cover structures were installed in the upper box to provide refuge areas so fish would not fall back downstream. All of the culverts were 40 feet long. The slope was adjusted with trailer jacks. Screens were fitted inside the culvert to contain the fish during acclimation and testing. The lower box had, a flow measuring weir, a tailwater control weir and an outlet pipe. Pipes were open at the top, but shaded from the direct sunlight for daytime testing (Photo 2).

The test sample size was 100 fish. Fish were placed in the culvert and acclimated at a velocity of 0.4 fps (2 BL/sec) for 20 minutes before the actual testing. Fish were confined to the lower five feet of culvert by screens. At the end of twenty minutes, the flow was slowly increased and the tailwater decreased over a two minute period to meet desired hydraulic conditions. The tailwater was adjusted to provide uniform depth in the pipe. The inside screen was then pulled and the fish given 20 minutes to pass. During the test, fish passage and behavior were observed. Fish were recorded as either passing, holding in the culvert or failing. If fish were impinged on the outlet screen, for more than 10 seconds they were removed and counted as failing. Fish that passed did so within the first three to five minutes. In all 73 tests, not once were fish noticed passing toward the end of the test, which indicated the test time was adequate.

At the end of the test, the screens were installed and the flow shut off. Fish were then separated and counted. Fork lengths were then measured and recorded. Behavioral observations were also made of fish holding and swimming upstream in relation to the corrugations. Video and photo documentation was made. Velocity mapping was done for each slope tested by taking point velocity measurements with a Nixon Model 403 Low Speed Probe. The Nixon probe is a propeller flow meter designed for measuring velocities as low as 0.1 fps. The probe was attached to a point gage which allowed incremental measurements along the horizontal and vertical planes.

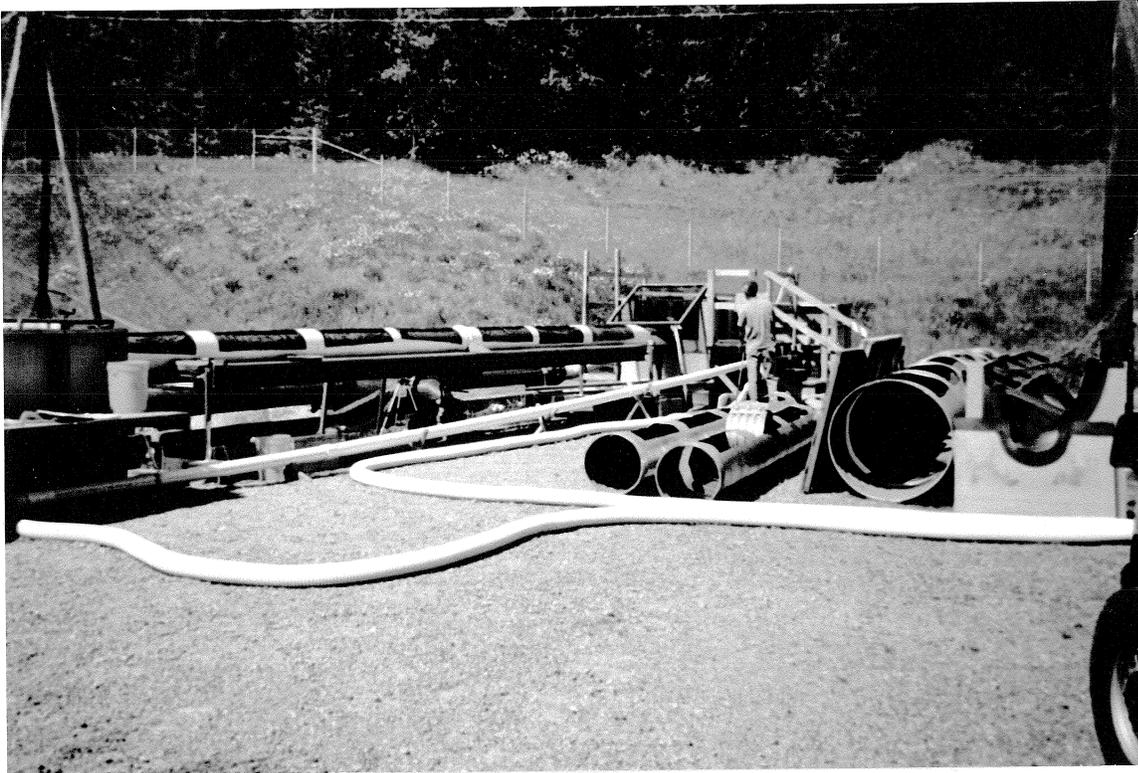


Photo 1. - Testing apparatus setup shown with 40 foot long -12 inch diameter smooth pipe in place. Flow in from right to left. The 18 inch and 36 inch culverts are shown to the right. Observation ports are covered with black vexar screens to reduce shading.



Photo 2. - View looking upstream through 40 foot long 18 inch diameter spiral corrugated culvert. Observation ports are shown on top. Note turbulence along the culvert wall on the left side of the picture.

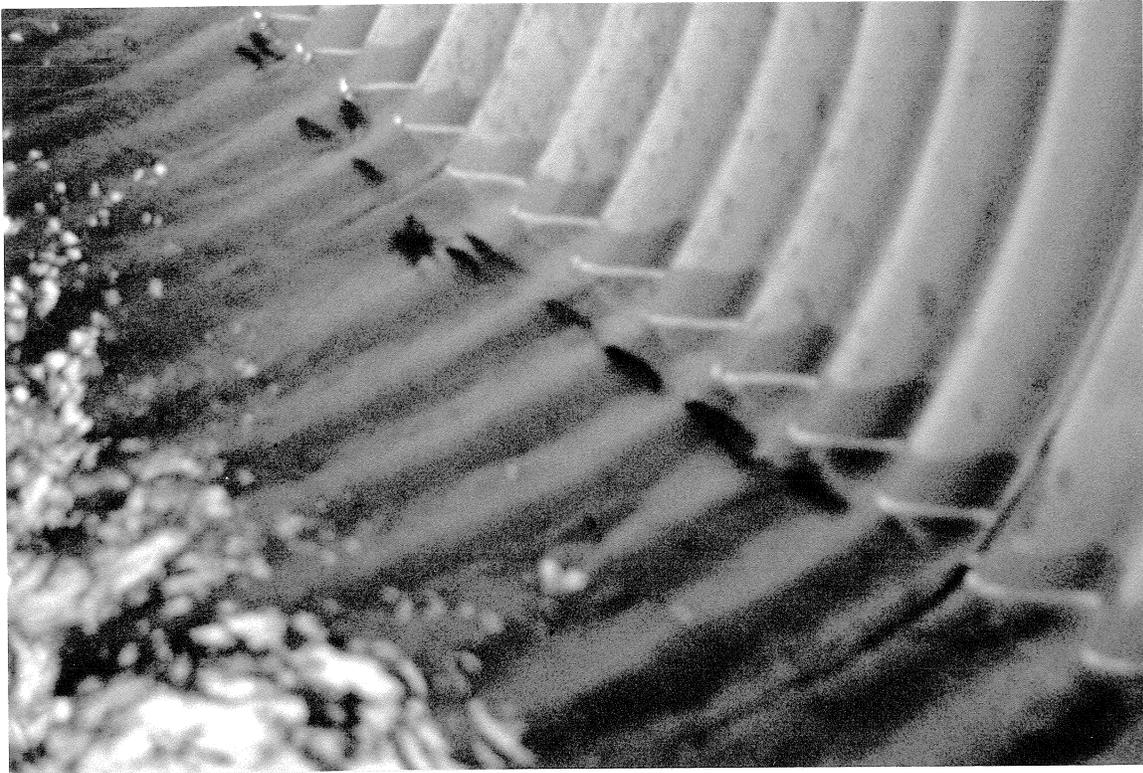


Photo 3. - Coho fry swimming upstream in a reduced velocity boundary layer along the culvert wall.

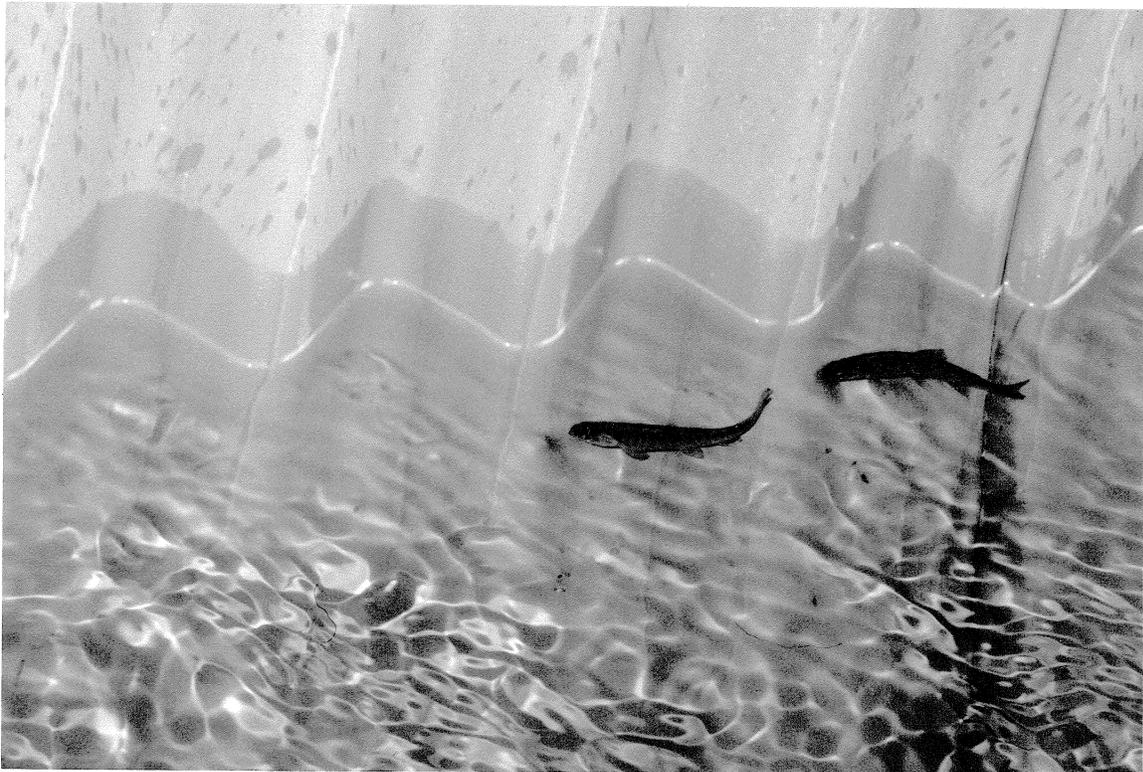


Photo 4. - Coho fry holding in the boundary layer next to the culvert wall. Fish were observed moving upstream in this area and holding.

RESULTS

Control tests were run to identify fish passage success without roughness and velocity as variables. They were also used to document the swimming abilities of the fish through a smooth pipe. Four different test variables (V_{max} , V_{ave} , V_{occ} and slope) were recorded and compared to passage success for the roughened pipes. Of the four variables, V_{max} correlated best to passage success. Passage rates through smooth pipes were compared statistically to passage rates through rough pipes at similar V_{max} values. The fry used the roughened boundary layer more for successful passage because they were swimming at lower velocities than the fingerlings, where the turbulence was not as significant.

Control Tests

The objective of the control tests were to determine: 1) the percentage of fish that were motivated to move through the culvert without a velocity that challenges their swimming ability and 2) the swimming ability of the fish without roughness and turbulence as a variable. To meet the first objective, tests were run each day of testing with the culvert tested that day. The acclimation velocity was set at 0.4 fps. Fish did not use the boundary layer at the 0.4 fps velocity, but moved there as soon as the velocity was increased above 0.4 fps (Photo 3). The number of fish that passed for each control test was averaged and normalized to 100 percent. For the fry, 95 fish passing out of 100 was normalized to 100 percent passage, and for the fingerlings, 85 fish passing out of 100 were normalized to 100.

For the second objective, control tests were also run with a smooth pipe to determine the velocities that fish can pass without roughness and turbulence as a variable. Since any significant slope created a velocity barrier, the flow was adjusted along with the tailwater control to provide the desired test velocities. This created a hydraulic gradient and depths that were not uniform for the full length of the culvert. The maximum velocity (V_{max}) was plotted versus number of fish passed. The V_{max} values shown in Figure 2 are measured at the culvert half way point. For example, in test # 30-0 (Test number 30 with the smooth (0) pipe), V_{max} was reported as 1.6 fps, but it actually varied from 1.5 at the culvert inlet to 1.7 at the outlet. For the coho fry the full range of passage (from 0 to 100 percent) was from 1.0 to 2.0 fps, and for the fingerlings 1.1 to 4.6 fps.

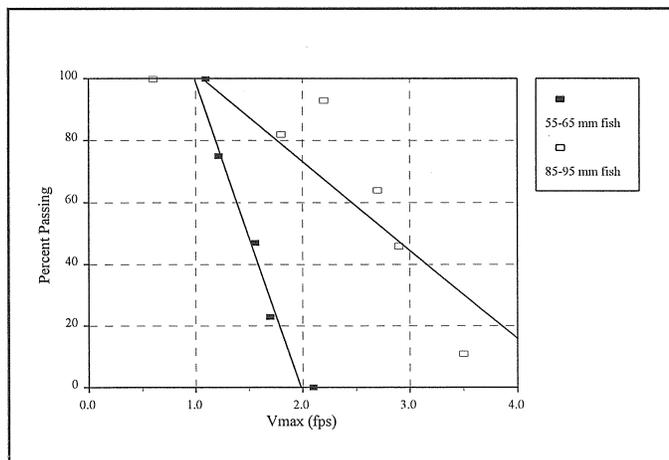


Figure 2 - Percent of juvenile coho salmon passing through a 40 foot long smooth pipe versus V_{max} .

Velocity

Three different velocities were recorded for each test, the maximum velocity (V_{\max}), the average velocity (V_{avg}) and the occupied velocity (V_{occ}). The average velocity was computed as (Q/A) . The relationships between these three variables are shown in Table 2. There was a good correlation for all pipes tested, except for the 1S culvert with the spiral corrugations. Figures 4a through 4e show how the percent passage varies as a function of the three velocity variables. Data points and regression lines are shown. The heavy lines sloping down to the right are percent passage. The heavy line furthest to the left is for the fry, and the line to the right is for the fingerlings, except for Figure 4b, which is only for the fingerlings (fry were not tested). The light type lines sloping up are velocity. The solid line is V_{ave} , and the dashed lines are V_{\max} and V_{occ} .

For example: Figure 4a (pipe with the largest roughness), at a percent passage rate of 80 percent for the fingerlings, $V_{\text{ave}} = 1.2$ fps, $V_{\max} = 1.3$ fps and $V_{\text{occ}} = 0.5$ fps. Moving down to a passage success rate of 20 percent, $V_{\text{ave}} = 2.8$ fps, $V_{\max} = 3.4$ fps and $V_{\text{occ}} = 0.9$ fps. In Figure 4e (smooth pipe) at the same passage percent levels, $V_{\text{ave}} = 1.4$ fps, $V_{\max} = 1.8$ fps and $V_{\text{occ}} = 1.3$ fps. At the 20 percent passage level $V_{\text{ave}} = 3.3$ fps, $V_{\max} = 3.9$ fps and $V_{\text{occ}} = 3.2$ fps. Clearly these figures show that as the average velocity increases, passage success decreases even though V_{occ} values remain within the swimming ability of both size ranges of fish.

The maximum and occupied velocity were determined from velocity contour mapping. V_{\max} values correlated best to passage success. Reported V_{occ} values are average values taken over some time but vary greatly because of turbulence in the boundary layer. Figure 3 shows the variability in V_{occ} measured on one second intervals. The average V_{occ} values (which was the one reported in the test results) was 0.9 fps, but from Figure 3 the values range from 0 to 2.2 fps. These velocity fluctuations may be an indicator of turbulence in the boundary layer for this type of roughness. Barber and Downs (1996) in a companion hydraulic study found also that velocity measurements taken near the corrugations were widely scattered.

Culvert Label	Average Velocity (V_{avg}), fps		R^2	
			V_{max}	V_{occ}
2A	$0.82V_{max}^{1.01}$	$3.67V_{occ}^{2.16}$	.97	.97
1A	$0.72V_{max}^{1.00}$	$1.63V_{occ}^{1.66}$	.99	.99
1S	$0.82V_{max}^{0.96}$	$7.15V_{occ}^{1.43}$	.97	.56
.5S	$0.63V_{max}^{1.20}$	$1.51V_{occ}^{1.42}$	.98	.83
0	$0.75V_{max}^{1.16}$	$1.15V_{occ}^{0.91}$	.98	.98

Table 2. - Equations relating the average velocity to the maximum and occupied velocity and corresponding coefficient of determination.

Since the study did not measure the turbulence and cannot predict the conditions which create undesirable turbulence for fish passage, some velocity further away from the culvert wall which can be estimated will be used. Because fish passage success correlated so well to V_{max} , it was decided to use this variable at some distance from the wall to serve as the indicator of acceptable boundary layer conditions for upstream passage. For example: For the .5S culvert, at the 80% passage success level V_{max} is 1.6 fps for the coho fry. The distance from the culvert wall out to V_{max} was 9 inches. Therefore, for any size .5S culvert (i.e., culvert with $\frac{1}{2} \times 2\text{-}\frac{2}{8}$ corrugations) the velocity 9 inches from the culvert wall would have to be less than or equal to 1.6 fps. Used in this way, the 1.6 fps becomes an empirical design velocity method of providing acceptable passage conditions in the boundary layer.

For the pipes tested with roughness, fish were swimming or holding near the culvert wall (Photo 4) and just below the surface. With the smooth pipe fish were distributed throughout the water column. For the rough pipes this occupied area was defined vertically as $0.8d$, and horizontally 1.5 inches away from the culvert wall. The water velocity in this area was defined as V_{occ} (velocity occupied), and was recorded for each test. There was a fair correlation for some of the culvert/corrugation types, but not as good as the correlations to V_{max} . In general, as roughness increases, V_{occ} values to maintain the same level of passage success had to decrease. This again suggests that turbulence in the boundary layer may hinder passage success.

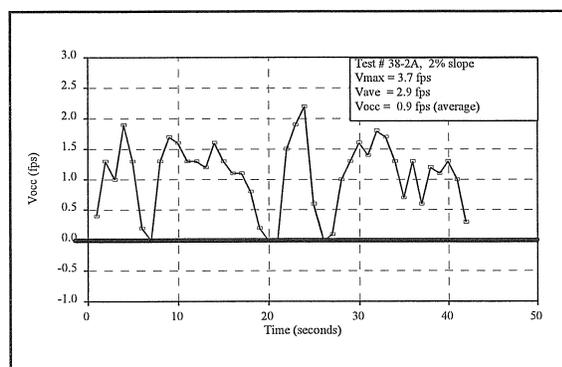


Figure 3 - V_{occ} values for Test 38-2A taken on one second intervals to show fluctuation in values near culvert wall.

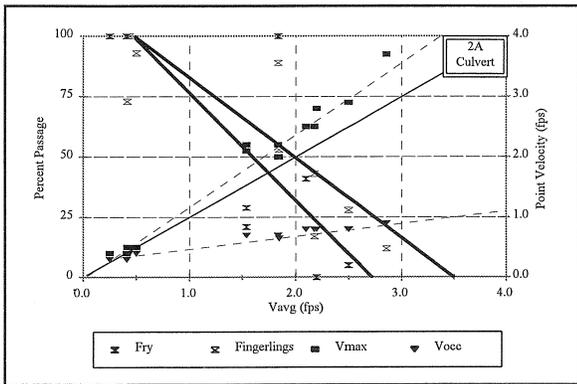


Figure 4a - Data points and regression lines for percent passage and velocity for the 2 inch annular corrugations.

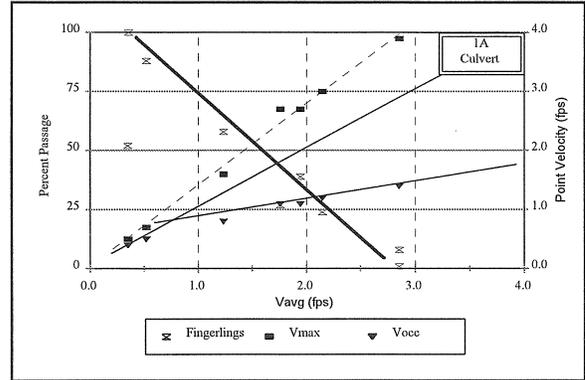


Figure 4b - Data points and regression lines for percent passage and velocity for the 1 inch annular corrugations.

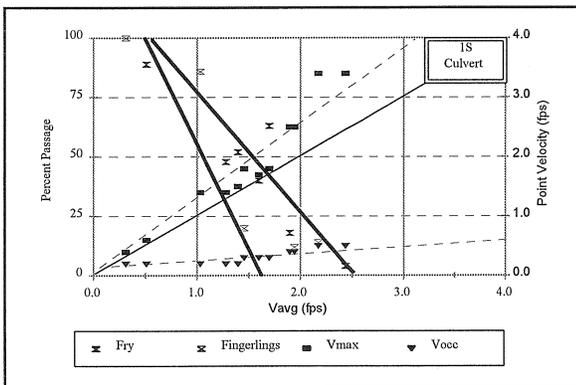


Figure 4c - Data points and regression lines for percent passage and velocity for the 1 inch spiral corrugations.

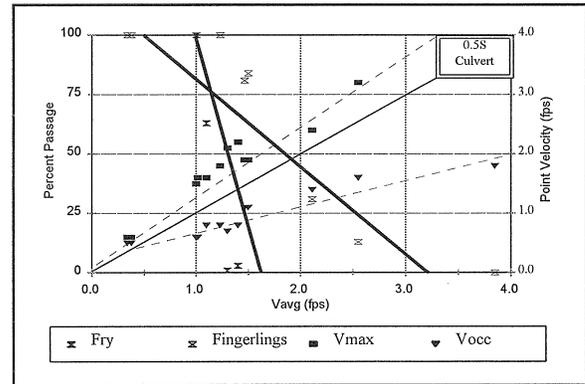


Figure 4d - Data points and regression lines for percent passage and velocity for the 1/2 inch spiral corrugations.

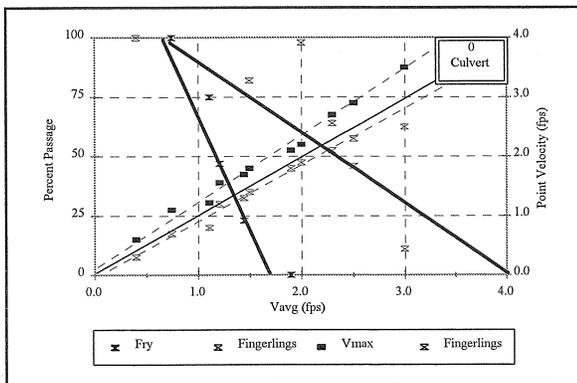


Figure 4e - Data points and regression lines for percent passage and velocity for the smooth pipe.

A companion study was completed at Washington State University. Barber and Downs, 1996 studied in detail velocity profiles for two different annular culvert corrugations (½ inch and 1 inch). One objective of the study was to develop a model to predict the distance from the culvert wall to a desired velocity contour for a given discharge, culvert diameter, corrugation size and slope. This distance was termed effective width. A program called JUFIPP - Juvenile Fish Passage Program was developed to compute this effective width.

Slope

Slope tests (for the full range of passage from 0 to 100 percent) ranged from 0.2 to 1.0 percent for the fry and 0.2 to 2.0 percent for the fingerlings. As the culvert slope increased passage success decreased. For the smooth culvert slopes less than 0.2 percent blocked both size ranges of coho. The culvert slope was set before each test with a survey level and rod. Flow and tailwater elevation were adjusted to maintain a uniform depth in the lower 35 feet of culvert. There was a slight increase in depth at the inlet because of the transition from the head box to the culvert.

A simple linear regression analysis was done with slope versus numbers of fish passed, and the correlation coefficient calculated. Values for R^2 ranged from 0.73 to 0.89 for the fry, and 0.54 to 0.91 for the fingerlings. Table 4 shows the slopes calculated from the regression equation at the 80, and 20 percent passage levels. The (.5S) culvert had the steepest slopes that fish passed at the 80 percent level (0.25 and 0.52%) for the fry and fingerlings respectively. The 2A culvert had the steepest slopes fish could pass at the 20 percent level (0.66 and 1.44%) respectively. Results again indicate that turbulence in the boundary layer likely prohibited upstream movement as velocity increased.

Slope (%)				
Culvert label	fry		fingerlings	
	80% passage	20% passage	80% passage	20% passage
0	.02	.11	.06	.15
.5S	.25	.41	.52	1.14
1S	.10	.77	.25	.75
1A	NT	NT	.25	.71
2A	.14	.66	.10	1.44

Table 4. - Slope in percent for the five different types of pipes. Values shown are for the 80, and 20 percent passage success levels for coho fry and fingerlings. (NT=not tested)

Smooth Versus Rough Pipes

A main objective of this study was to test the premise that juvenile fish will use the low velocity zone in a roughened pipe to pass upstream. With baseline criteria developed for smooth pipes on the swimming ability of juvenile coho, the next step was to test these fish in a pipe with a roughened boundary. The low velocity zone can be shown graphically in Figure 5, which is a plot of horizontal velocity profiles from the culvert wall out 16 inches, for four different roughness types at a common V_{max} of 2.9 fps. During all tests with corrugations, fish were observed swimming very close to the wall (estimated from observation to be within 1.5 inches out from the top of the corrugations (Photos 3 and 4). Figure 5 does show a small boundary layer for the smooth (0) culvert, but fish were not observed using this area.

Figure 5 shows that at a common V_{max} of 2.9 fps, the velocity 1.5 inches from the wall varies from 2.6 fps for the smooth (0) culvert to 0.5 fps for the culvert with the most roughness (2A).

To test the original premise of the study, passage success was compared at common V_{max} values. The maximum velocity was used because this test variable correlated best to passage success. For example: the smooth (0) culvert with a V_{max} of 1.8 fps was compared to the (2A) culvert with a V_{max} of 1.8 fps, etc. A hypothesis test was performed assuming that more fish would pass through the rough pipes when compared to the smooth pipe because of the low velocities in the boundary layer. A 90 percent confidence interval was selected and the number of standard deviations away from the mean (Z) calculated. Table 1 is a summary of results.

YES indicates passage success was higher through the rough pipes when compared to the smooth pipes for the given V_{max} , and NO indicates passage success was not significantly better through the rough pipes. The V_{max} values of 1.2, 1.5 and 1.8 fps represent 80, 50 and 20 percent passage levels respectively for the fry and the V_{max} values of 2.1, 2.8 and 3.5 fps represent 80, 50 and 20 percent passage levels respectively for the fingerlings.

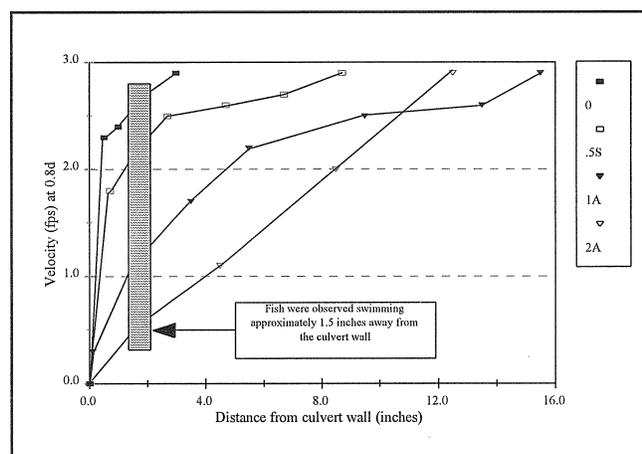


Figure 5 - Velocity profiles at 0.8 x depth for four different roughness types with a common V_{max} of 2.9 fps.

Culvert Label	Vmax (fps)					
	1.2	1.5	1.8	2.1	2.8	3.5
.5S	YES	YES	YES	NO	NO	NO
1S	NO	NO	YES	NO	NO	NO
1A	NT	NT	NT	NO	NO	NO
2A	NO	YES	YES	NO	NO	NO

Table 5 - Comparison of passage success to a smooth pipe at common V_{max} values. YES indicates passage success was higher for the corrugated culverts at the given V_{max} , and NO indicates passage success was higher for the smooth pipe. Bold type indicates fry, and standard type fingerlings. (NT = not tested)

Fish did use the boundary layer when passing through the roughened culverts, but the results in Table 1 indicate passage success was better for the smooth pipes in most cases, especially for the larger fish and high velocities. Clearly, the larger fish (which had a much higher swimming ability from Figure 2) did not use the corrugations for passage as well as the fry. This again points to a possibility of turbulence hindering upstream movement (see discussion).

CONCLUSIONS

This study has shown that juvenile coho salmon will use the low velocity boundary layer to pass upstream, but only when V_{max} values are less than or equal to about 2.0-fps. At higher values of V_{max} , conditions in the boundary layer for the rough pipes seems to hinder passage when compared to the smooth pipes. For the smooth pipes V_{max} at the 80 percent passage level was 1.2 and 1.8-fps for the fry and fingerlings respectively. As can be seen from Table 5, the only culvert with roughness that allowed V_{max} to increase because fish were using the boundary layer was the (.5S) culvert. V_{max} for this corrugation type can be increased from 1.2-fps for the smooth pipe to 1.6-fps for the (.5S) culvert (for the same 80 percent passage level).

The occupied velocity (V_{occ}) values are also shown in Table 5. As noted earlier these variables are difficult to measure and correlate to passage success because of turbulence, and it is recommended that further study be done to define the turbulence component and the effect on passage success.

Culvert Label (b)	V_{max} (fps)		V_{avg} (fps)		V_{occ} (fps)	
	Fry	Fingerlings	Fry	Fingerlings	Fry	Fingerlings
0 (NA)	1.3/1.8	2.0/3.6	1.0/1.5	1.7/3.3	NA	NA
.5S (9 inches)	1.6/2.1	1.8/3.4	1.1/1.5	1.3/2.7	0.6/0.8	1.0/1.6
1S (27 inches)	0.7/2.6	1.1/2.7	0.6/2.1	0.9/2.1	0.2/0.4	0.3/0.4
1A (15 inches)	NT	0.8/3.2	NT	0.6/2.3	NT	0.7/1.3
2A (15 inches)	1.1/2.7	1.1/3.4	0.9/2.2	0.9/2.8	0.4/0.8	0.5/0.9

Table 5. - Velocities for the 80 and 20 percent passage success levels for five culverts with varying roughness. Fry size is (55-65 mm) and fingerlings (85-95 mm). Bold value is for the 80 percent passage level, and standard type is for 20 percent passage level. The value (b) is the minimum distance away from the culvert wall that V_{max} can occur to maintain passable conditions in the boundary layer.

The recommended method to design a culvert for upstream passage of juvenile coho salmon, considering the use of the boundary layer is to use the V_{max} values from Table 5. If the culvert size is within the ranges tested for this study (less than or equal to 4 feet in diameter), V_{max} values should

be used directly from Table 5. Relationships between V_{\max} and V_{avg} have been developed in Table 2, and can be used for design purposes. Barber and Downs (1996) also present information relating V_{\max} and V_{avg} based on corrugation height and pipe diameter. For culverts larger than 4 feet in diameter it is recommended that a surrogate of V_{\max} be used. V_{\max} must occur no closer than the value (b) shown in Table 5.

To make this calculation, the computer program (JUFIPP) developed by Barber and Downs (1996) is required. The design velocity entered into the program would be the V_{\max} values from Table 5. The horizontal dimension (b) would have to be greater than or equal to the values shown in Table 5.

The Barber and Downs study only used the (.5A) and (1A) corrugation types (annular). Observation from the biological study which used the (.5S) and (1S) culverts (spiral corrugations) showed that the spiral culverts created different boundary layer conditions compared to the annular corrugations. This flow difference has been documented by Silberman (1959). Flow followed a path perpendicular to the direction of the corrugations, which resulted in the maximum velocity being located along one wall. Also, since V_{\max} was further from the opposite wall, the velocities in the boundary layer were lower when compared to the annular corrugations.

The difference was most significant for the (1S) culvert with the larger corrugations (1 inch compared to 0.5 inches). Further study is needed to identify the ranges where this phenomenon occurs, and how it affects fish passage. Even though the (.5S) culvert had some spiraling of flow the boundary layers were fairly even, especially at the test velocities where passage success was high.

Example Problem

Given: Culvert diameter 6 feet
 $\frac{1}{2} \times 2\text{-}2/3$ corrugations, $n = 0.024$
 Slope 1 percent
 Flow 50 cubic feet per second (cfs)
 Design velocity = 1.2 fps for coho fry
 $b = 9$ inches

Solution: $V_{\text{ave}} = 5.5$ fps
 depth = 1.9 feet
 Using the computer program (JUFIPP), $b = 2.6$ inches
 (2.6 is less than 9 inches, so design conditions are exceeded, that is V_{\max} occurs too close to the culvert wall).

At what flow does $b = 9$ inches?

Answer: 3.5 cfs ($V_{\text{avg}} = 2.9$ fps, $V_{\max} = 3.6$ fps)

Because the culvert length tested was only 40 feet, there was an initial concern this would not be adequate for comparison to longer culverts. In all 73 tests, fish passed in the first three to five minutes of the 20 minute test period. After this time fish either held in the corrugations or failed downstream. Fish were swimming in prolonged speed mode (which can be maintained for approximately 20 minutes). It is reasonable to assume that these results could be extrapolated up to culvert lengths of 200 feet. Most road culverts are between 50 and 300 feet long, and the length of the culvert may not be relevant to the ability of the fish to pass. It is only relevant to the probability of passage in that a fish may get caught by the high velocity flow away from the low velocity boundary layer and be swept back downstream. Behavioral observations indicated fish will not move out of the boundary layer to attempt passage upstream, but remain and either hold or fall back.

The V_{occ} values for the culverts with corrugations may be misleading. Average values are reported, but there was a high variability in taking the reading. The general trend was that as roughness increased, to maintain the same passage success level, V_{occ} had to decrease.

The suggestion that turbulence in the boundary layer of corrugated culverts effects upstream passage success, may not be applicable to larger fish. The two to three inch fish sizes used in this study is smaller than the corrugation size used in the direction of flow (three to six inches). Fish used the areas in between the corrugations to hold. Larger fish could not use these areas for holding. There is likely a scale effect, where larger fish are not affected by the turbulence, and may pass upstream through higher velocities in the boundary layer. For the size of fish used in this study there was no obvious benefit for using standard corrugated culverts over smooth pipes. To ensure adequate upstream passage for juvenile fish through culverts, the design must be based on velocity without roughness as a variable. Further tests with different types of roughness inside culverts may yield different results. Culverts lined or filled with river cobble may provide roughness similar to a natural channel.

TEST VARIABLES

Culvert Labels

- 0** Smooth plastic, PVC, 12 inch diameter
- .5S** ½" X 2-2/3" spiral corrugations, CMP, 18 inch diameter
- 1S** 1" X 3" spiral corrugations, CMP, 36" diameter
- 1A** 1" X 3" annular corrugations, CMP, 36" diameter
- 2A** 2" X 6" annular corrugations, CMP, 1/4 Section of 60" diameter

Test Nomenclature

- 1-2A Test number one, with **2A** test pipe
- 15-1S Test number 15, with **1S** test pipe
- 24-.5S Test number 24, with **.5S** test pipe
- 29-0 Test number 29, with **0** test pipe

- V_{max} Maximum velocity measured in a cross section 30 feet downstream from the culvert water inlet (cm/sec, ft/sec).
- V_{ave} Discharge divided by flow area (cm/sec, ft/sec).
- V_{occ} The velocity the location the fish were swimming, determined from velocity mapping of cross sections measured 30 feet downstream of culvert inlet. Velocity selected at coordinates $0.8*d$ and a distance of 1.5 inches from the wall (top of corrugation),(cm/sec, ft/sec).
- Q Discharge (m^3/sec , ft^3/sec)
- D Diameter of test pipe (cm, in)
- d maximum depth of flow measured at the centerline (or wall for 1/4 section) from top of corrugation to water surface (cm, in).
- b Horizontal distance from the culvert wall to the point where V_{max} is measured (cm, in).
- Y Vertical dimension from bottom of culvert (top of corrugation) to point of interest in cross section (cm, in)
- X Horizontal dimension measured from centerline or vertical wall of culvert to point of interest in cross section (cm, in).
- S Culvert slope measured with survey level and rod (%).

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