INVESTIGATION OF CULVERT HYDRAULICS RELATED TO JUVENILE FISH PASSAGE

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16. ABSTRACT

Culverts often create barriers to the upstream migration of juvenile fish. Fish will not travel upstream under high water velocity conditions. It is hypothesized that low velocity regions exist near culvert boundaries. Therefore, the objective of this study was to determine hydraulic characteristics of culverts with different flow conditions. Methods of predicting flow profiles were developed by both Chiu and Mountjoy. Two equations were compared to experimental results. The Mountjoy equation proved to yield better results for velocity profile predictions. An area of flow corresponding to a predetermined allowable velocity can be calculated using the Mountjoy equation. This can then be used in the design of culverts as fish passage guidelines. The following report contains a summary of background information, experimental methodology, the results of experimental tests, and an analysis of both the Chiu and Mountjoy equations.

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Fish Passage Culvert Design

INVESTIGATION OF CULVERT HYDRAULICS RELATED TO JUVENILE FISH PASSAGE

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EXECUTIVE SUMMARY

Cross-sectional velocity distributions were measured by performing laboratory tests on four metal culverts, with inside diameters ranging from 30.5 cm (12 in) to 73.7 cm (29 in), with the objective of developing a method of predicting the percentage amount of cross-sectional area of a large diameter culvert with velocities sufficiently low enough to pass juvenile fish. Using this area, estimates are made for the width of the velocity zone. Fifty-one experimental runs were conducted under varying flow, slope, relative depth, and downstream control conditions. Because measured velocity distributions were often non-symmetrical about the centerlines of the culverts, it was not possible to predict exact two-dimensional velocity distributions. Instead, the areas between adjacent velocity contour lines were converted to symmetrical ring-shaped bands which were then used to create an "effective" two-dimensional velocity distribution. This effective velocity distribution represents average band widths of a given velocity range that could be expected in the culvert. The band widths allow the amount of cross-sectional area with acceptable velocities to be determined, which is an important design parameter in the design of culverts to provide juvenile fish passage.

Two existing equations were used to predict the centerline velocity distribution for the conditions that were tested. The first equation was taken from Chiu (1993), and the second equation was taken from Mountjoy (1986). The curves resulting from the two equations were compared to an "effective" symmetrical velocity distribution obtained from the experimental data. Based on a statistical analysis, the Mountjoy equation was the more accurate method of predicting the "effective" velocity distribution for the highway culverts. It was concluded that the Mountjoy equation provides a means of predicting "effective" cross-sectional velocity distributions in large diameter highway culverts.

Chapter 1
INTRODUCTION

1.1 Problem Statement

Barriers to upstream migration of juvenile fish have been recognized for their negative impact on the long-term preservation of fish populations. For many species of fish, this migration is essential for survival (Baker and Votapka, 1990). Juvenile salmonids as well as many resident fish species migrate both upstream and downstream. Upstream migration of juvenile anadromous fish has been documented by several authors, including Skeesick (1970) and Cederholm and Scarlett (1981). Juvenile sockeye salmon are particularly vulnerable to upstream blockages in stream systems that require upstream migration to reach suitable habitat (Dane, 1978). According to the Washington Department of Fish and Wildlife (WDFW), juvenile fish may migrate upstream in response to water conditions, predation, or population pressures (WDFW, 1990). Some studies, however, have not clearly shown there to be an upstream migration of juvenile salmon. Therefore, it is not certain that upstream juvenile fish migration will always occur, only that it can and does occur on some occasions (Baker and Votapka, 1990).

Barriers to juvenile fish passage exist in many forms. There are natural barriers such as waterfalls, debris jams, and temperature barriers. There are also artificial barriers such as log jams, dams, roadway crossings, and pollution (Evans and Johnston, 1980). There is a potential for an artificial barrier to occur when corrugated metal culverts are used at roadway crossings. Excessive velocities within the culvert barrel however, can pose a barrier to juvenile, as well as adult fish migration (Bates, 1992).

There are currently culvert fish passage design standards which dictate the maximum average flow velocity through the culvert barrel. The WDFW currently uses this approach for juvenile fish passage through culverts. These standards assume open channel flow, as dictated by Manning's equation, and are often based on the swimming capabilities of adult migrating fish. Juvenile fish have lower swimming capabilities than do adult fish (Gebhards and Fisher, 1972).

Consequently, a culvert that may be passable by adult fish may pose a barrier to juvenile fish. This would seem to suggest using a lower average velocity criteria for culverts where it is necessary to provide passage for juvenile fish. On the other hand, it has also been observed that juvenile fish will use the low velocity regions of the culvert's boundary layer for passage. Thus, a culvert designed to meet the maximum average flow velocity criteria for juvenile fish passage may be overly conservative.

In response to endangered species legislation, as well as the growing concern for the survival of salmon and other resident fish species, the Washington State Department of Transportation (WSDOT) has began studying the issue of providing acceptable passage to juvenile salmon at culvert roadway crossings. The WSDOT has proposed that if an adequate low velocity region is provided through the culvert, juvenile fish will use this layer for passage. This would eliminate the need for an overly conservative average flow velocity criteria in culverts for juvenile fish passage.

Research into the hydraulic conditions of culverts, with particular interest in the low velocity region near the wall, has been conducted. The results of this research will be used to develop a method of predicting relative velocity distributions in highway culverts. Research is also being performed by the WDFW to determine how large of a low velocity region is necessary, and what are the limiting velocity and slope to allow upstream passage of juvenile salmon and trout. By combining the two studies, researchers will be able to examine if upstream migrating juvenile salmon and trout use the low velocity region near the wall of a culvert for passage.

Chapter 2

LITERATURE REVIEW / BACKGROUND INFORMATION

2.1 General Background

A culvert is any conduit or waterway used to allow passage of flow underneath a roadway or embankment. Culverts are available in a variety of shapes and materials. Circular corrugated metal is more widely used for roadway crossings because it is more cost effective than other options. Therefore, as requested by WSDOT, circular corregated metal culverts with annular corrugations ranging from smooth to 7.6 x 2.5 cm (3 x 1 inch) were selected for this research.

To provide a comprehensive background on the subject of juvenile fish passage in culverts, three areas of previous works were emphasized in this search. These areas were:

1. Fish Passage in Culverts: Problems and requirements.
2. Open Channel Flow: Application to culverts flowing partially full.
3. Velocity Profiles: Attempts at 1-D and 2-D modeling of velocity distributions.

A brief summary of the findings is presented in this report. A full discussion is included in the technical report (Barber and Downs, 1995).

2.1.1 Fish Passage in Culverts: Problems and Requirements.

Numerous studies have been published on fish passage through culverts (i.e. Baker and Votapka, 1990; Behlke et al. 1989; Kane and Wellen, 1985). In the State of Washington, per RCW 75.20.060 and 77.16.210, juvenile salmonid passage must be provided in reaches of streams where migration to seasonal rearing habitat occurs (WDFW, 1990). The design of a roadway culvert must consider the magnitude of the hydrologic design flow as well as provide for adequate fish passage at a fish passage desgin flow. To accomplish these tasks, culvert designs must specifically look at the biological criteria of the species of fish, the hydraulics of the culvert design storm, and the hydraulics of the fish passage design flow.

Biological Criteria. - Fish use two separate muscle systems to propel themselves through the water. Red muscles (aerobic) are used by fish for long periods of steady swimming, and white muscles (anaerobic) are used for short periods of sprint swimming (Behlke et al. 1989). The swimming capabilities of fish can be broken down into three categories: (1) sustained (cruising) speed; (2) prolonged speed; and (3) burst speed. Sustained speed is a speed fish can maintain for an extended period of time without fatigue. Prolonged speed is a speed fish can maintain for a considerable length of time (between 10 and 500 minutes) but ultimately will result in fatigue. And finally, fish can maintain burst speed for only a very short period of time (nominally 7 seconds although sometimes considered to be between 5 and 60 seconds).

Bell (1973) provides a listing of the cruising speed, sustained speed, and burst speed of several adult fish species. Bell suggests that migrating fish normally swim at cruising speed and use sustained speed to pass through difficult areas such as culverts. This conclusion is substantiated by a report prepared for the State of Alaska by Kane and Wellen (1985). The report, based on studies performed by Jones et al. (1974) and MacPhee and Watts (1976), also suggests that sustained speed be used for culvert design.

In the State of Washington, a maximum average velocity of 4 ft/s (122 cm/s) is given by the WDFD for adult salmonids. This is based on an assumption that the culvert being passed is less than 60 feet (18.3 meters) in length. This criterion is assumed to satisfy juvenile passage needs in that the roughness of the corrugations provides a low velocity region near the wall of the culvert and the juvenile passage disgn flow is something less than the adult passage design flow.

Several authors have developed relationships between fork length, which is the length of the fish, and swimming capability for various fish species. The U.S. Department of Transportation (USDOT) (Baker and Votapka, 1990) provided a graph of fork length versus water velocity for several types of adult fish (taken from Jones et. al., 1974) . The graph shows that as the fork length of a fish increases so does its ability to pass through higher velocities of flow. To relate adult fish behavior to juvenile fish behavior, the USDOT provided an additional plot taken from work done by MacPhee and Watts (1976). As shown in Figure 2.1, this plot relates the relative length of a juvenile fish to a relative swimming velocity by a non-linear curve. The USDOT report also included a similar plot of the swimming capability of migrating salmon. Water velocity is plotted versus the maximum allowable distance between resting pools in this figure. This upper curve on the plot was taken from Ziemer (1965) of the Alaska Department of Fish and Game and the lower curve was prepared by Evans and Johnston (1980).

In 1978, the U.S. Department of Agriculture (USDA) Forest Service in Alaska took a similar approach to determining the swimming capability of juvenile salmon. A graph is provided in the USDA report (see Figure 2.2) which shows sustained speed versus fork length. This plot indicates a linear relationship between the sustained speed capability of a juvenile fish and its fork length. In this plot, it is assumed that the jumping capability of juvenile fish is non-existent (USDA Forest Service, 1978).

A 1972 report to the Idaho Fish and Game Department (IFGD) provided fish passage guidelines currently still used in Idaho (Gebhards and Fischer, 1972). The authors note that the swimming ability of a fish is a function of its size. In general, large fish have greater swimming capabilities than small fish. The report states that the sustained speed capability for juvenile salmonids is approximately four body lengths per second depending on water temperature. This estimate is based on a study performed in Rome, Italy by Blaxter (1969).

Considerably more biological information regarding the fish response is available. For example, studies documenting swimming ability as a function of water temperature or the consequences of the timing of juvenile fish migration or the response to the first fall freshet are available (WDFW, 1995). Because this report focuses on the hydraulic factors involved with fish migration, only an overview of the biological criteria has been provided.

Culvert Hydraulic Considerations.- The installation of a highway culvert creates changes in the hydraulic characteristics of the stream. Often these changes are detrimental to the passage of both adult and juvenile fish. Historically, the most important design consideration has been the culverts' ability to pass the design flow. However, for fish passage consideration, the velocity distribution through the culvert barrel and the cross-sectional area with velocities less than or equal to those acceptable for passage are important.

2.1.2 Modeling Flow in Culverts

Relevant Governing Equations.- To estimate average cross-sectional flow velocity, Manning's equation is the most widely used formula in the world (Chow, 1959; Henderson, 1966). Despite the typically non-uniform cross-sectional distribution of flow through culverts, the Manning equation is often used for hydraulic design because the equation can be used easily and provides acceptable results when average velocity or total discharge values are needed. The Manning equation for velocity is as follows:

$$V = \frac{1}{n} R^{2/3} S_f^{1/2} \quad \text{(SI Units)} \qquad (2.1)$$

where **V** is the average flow velocity **[m/s]**; **n** is the Manning roughness coefficient; **R** is the hydraulic radius **[m]**, and **S_f** is the friction slope. The constant, 1, becomes 1.486 for English units thus allowing n to appear dimensionless.

Manning's equation can also be solved for the discharge (**Q**) by multiplying both sides of Equation 2.1 by the cross-sectional area of flow (**A**). This yields:

$$Q = VA = \frac{1}{n} A R^{2/3} S_f^{1/2} \quad \text{(SI Units)} \qquad (2.2)$$

The Manning roughness coefficients (n) have been determined experimentally for a large number of channel surfaces. The Federal Highway Administration (FHWA) (Normann, 1980) produced a series of plots showing Manning roughness coefficients versus pipe diameter for a number of corrugated metal pipes. The American Iron and Steel Institute (1980) also published a table which gives Manning n values for a wide variety of culverts.

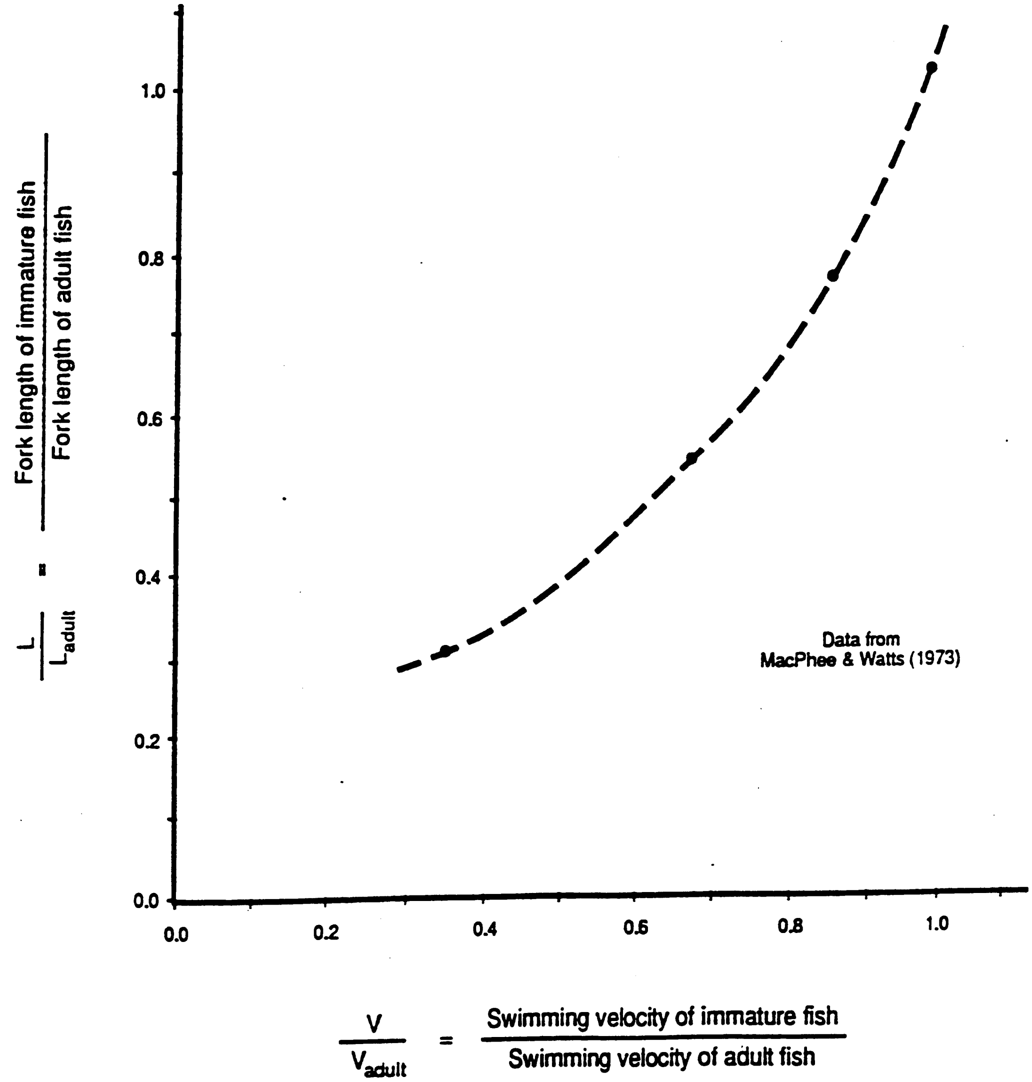


Figure 2.1. Relative length versus relative swimming velocity for fish based on grayling data (from MacPhee and Watts, 1976).

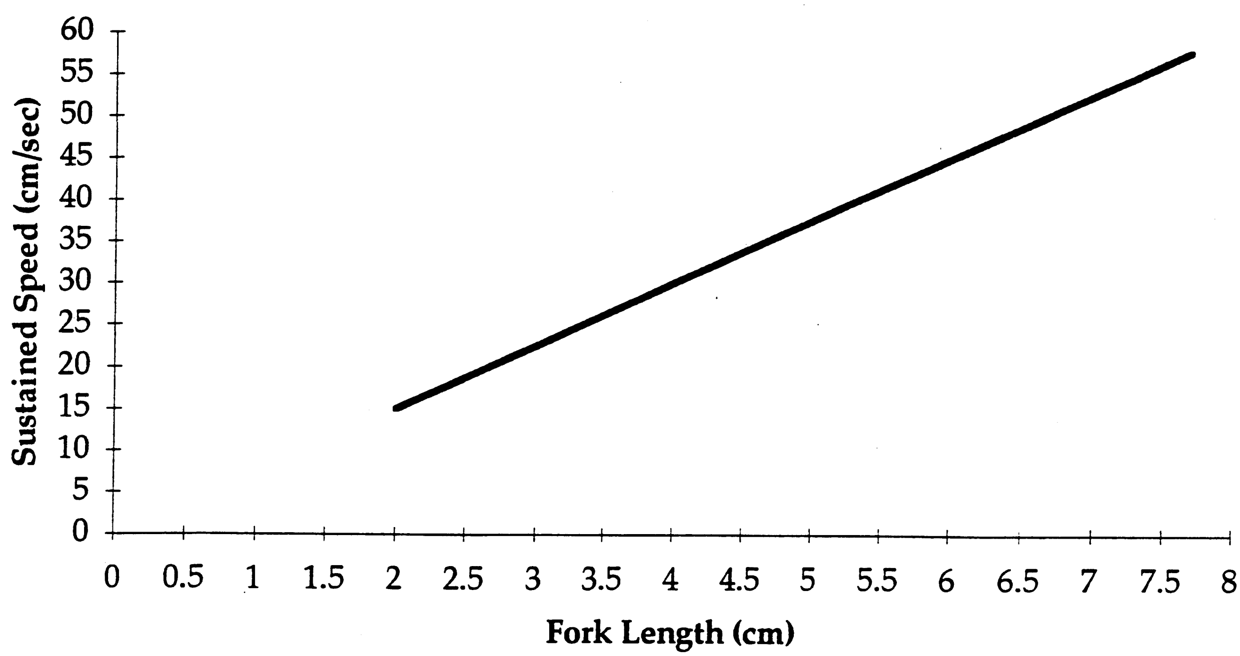


Figure 2.2. ,Sustained speed versus fork length for juvenile salmon (Modified from USDA Forest Service, 1978).

Boundary Layer and Shear Stress.- The boundary layer is the region of fluid near the wall of the conduit. The flow velocity in the boundary layer is reduced because of the shear stress at the wall boundary (Roberson and Crowe, 1990). It has been proposed that juvenile fish will use the lower velocity of the boundary layer to pass through a highway culvert. Existing methods of predicting velocity distributions in open channel flows are discussed in Section 2.1.3.

Energy and Momentum Coefficients.- Two coefficients, the energy coefficient, α, and the momentum coefficient, β, are necessary in the analysis of velocity distributions in open channel flow through a culvert. The energy coefficient, α, is necessary because the flow velocity varies from one point to another in the cross-section. The energy coefficient is given by the following equation:

$$\alpha = \frac{\int V^3 dA}{V_m^3 \int dA} = \frac{\left(\sum_{i=1}^{N} V_i^3 A_i\right) \cdot \left(\sum_{i=1}^{N} A_i\right)^2}{\left(\sum_{i=1}^{N} V_i A_i\right)^3} \tag{2.3}$$

where $\mathbf{V_i}$ is the velocity in subarea $\mathbf{A_i}$ **[m/s]**; and $\mathbf{V_m}$ is the mean cross-sectional velocity **[m/s]**.

The second velocity distribution coefficient necessary was the momentum coefficient, **β,** which accounts for non-uniform distribution of velocities in open channel flow in the computation of momentum. The momentum coefficient is found from:

$$\beta = \frac{\int V^2 dA}{V_m^2 \int dA} = \frac{\left(\sum_{i=1}^{N} V_i^2 A_i\right) \cdot \left(\sum_{i=1}^{N} A_i\right)}{\left(\sum_{i=1}^{N} V_i A_i\right)^2} \tag{2.4}$$

where $\mathbf{V_i}$, $\mathbf{A_i}$, and $\mathbf{V_m}$ have been previously defined.

2.1.3 Velocity Profiles

There have been numerous attempts to mathematically model velocity distributions for open channel flow (i.e. Prandtl-von Kármán Universal Law, 1979; Morsel et al. 1981; Chiu et al. 1988). These attempts can be divided into two types: (1) one-dimensional models which predict velocity as a function of depth; and (2) two-dimensional models which predict velocity throughout the cross-section.

One Dimensional Velocity Profiles.- The one-dimensional models for velocity distribution examined make use of a logarithmic relationship to predict the velocity. Roberson and Crowe (1990) detail the following two methods of determining the one-dimensional velocity distribution in the turbulent boundary layer: (1) The logarithmic velocity distribution; and (2) the Power-Law formula for velocity distribution.

The logarithmic velocity distribution of the turbulent boundary layer is given by:

$$\frac{u}{u^*} = 5.75 log\left(\frac{yu^*}{\nu}\right) + 5.56 \qquad (2.5)$$

where **u** is the velocity **[m/s]; u*** is the shear velocity (γRS_f) **[m/s]; g** is the specific weight of the fluid **[N/m³]; R** is the hydraulic radius **[m]; S_f** is the friction slope; **y** is the depth **[m]**, and ν is the kinematic viscosity **[m²/s]**.

According to Roberson and Crowe (1990), the Power-Law formula has been shown to reasonably approximate the velocity distribution in the turbulent boundary layer for Reynolds numbers ranging from $10^5 < R_e < 10^7$. Moreover, the Power-Law formula has been shown to compare reasonably with experimental results for the range of 0.1 < **y/d** < 1. (Roberson and Crowe, 1990). The Power-Law Formula is:

$$\frac{u}{u_o} = \left(\frac{y}{\delta}\right)^{1/7} \qquad (2.6)$$

where **u** is the velocity **[m/s]; u_o** is the mean velocity **[m/s]; y** is the depth **[m]**; and **d** is the thickness of the boundary layer **[m]**. Both of these methods are limited to the boundary layer thickness and require knowledge of the boundary layer thickness in order for them to be applied.

Chiu (1993) presents the Prandtl-von Kármán Universal Law interpreted for axial symmetric pipe flow taken from Schlichting (1979). For axis symmetric turbulent flow in a pipe, the Prandtl-von Kármán Universal Law is as follows:

$$\frac{u_{max} - u}{u_*} = -\frac{1}{k} ln\left(1 - \frac{r}{D}\right) \qquad (2.7)$$

where **u** is the flow velocity **[m/s]; u_{max}** is the maximum velocity that occurs at the center of the pipe **[m/s]; u_*** is the shear velocity **[m/s]; k** is the von Kármán constant; **r** is the radial distance from the center of the pipe cross-section **[m]**; and **D** is the diameter of the pipe **[m]**.

Chiu (1993) discusses the following limitations of the Prandtl-von Kármán Universal Law. The Universal Law does not satisfy the boundary condition that u=0 at r=R. Therefore the model is inaccurate at the pipe wall. The Universal law also goes to infinity at r=R, so it is also inaccurate at the center of the pipe.

Kane and Wellen (1985) make use of an equation from Chow (1964) to predict the one-dimensional velocity distribution in highway culverts. The equation depends on average flow velocity, relative depth, and a roughness coefficient. Chow (1964) specifies that the equation is applicable to turbulent flow in a wide channel and that the equation does not apply near the bed or near the water surface. The equation is as follows:

$$\frac{(v-V)C}{V\sqrt{8g}} = 2\,log\left(\frac{y}{y_0}\right) + 0.88 \qquad (2.8)$$

where **v** is the velocity at a point **[m/s]; V** is the mean velocity; **C** is the Chezy roughness coefficient; and $\frac{y}{y_0}$ is the relative depth.

The Chezy roughness coefficient (**C**) can be related to the Manning roughness coefficient (**n**) which was used previously. This relationship is given as:

$$C = \frac{R^{1/6}}{n} \qquad (2.9)$$

where **R** is the hydraulic radius which was previously defined.

This relationship is substituted into Equation 2.8 and rearranged yielding the following expression for **v**:

$$v = \frac{(32g)^{1/2}(V_{avg})n}{R^{1/6}} log_{10}\left(\frac{y}{y_0}\right) + \frac{0.88(8g)^{1/2}(V_{avg})n}{R^{1/6}} + V_{avg} \qquad (2.10)$$

Mountjoy (1986) rewrites the above equation as:

$$v = A\,log_{10}\left(\frac{y}{y_0}\right) + B \tag{2.11}$$

where $A = \frac{(32g)^{1/2}(V_{avg})n}{R^{1/6}}$, and $B = \frac{0.88(8g)^{1/2}(V_{avg})n}{R^{1/6}} + V_{avg}$. Mountjoy then develops a method of predicting the coefficients **A** and **B** during the design phase of the culvert. The method of prediction involves using the correlation between the velocity at $\frac{y}{D_0}$ = 0.6 and the coefficient **B**. The correlation between the coefficient **B** and the coefficient **A** is then used to predict **A**. Based on a study of 49 sites throughout Alaska, Mountjoy developed prediction equations for the coefficients **A** and **B**.

Two-Dimensional Velocity Distributions.- Morsel et al. (1981) proposed the concept of an occupied zone to address fish passage through culverts. Based on observations that fish use the low velocity region near the wall of the culvert for passage, the authors developed equations to predict $\mathbf{V_{occupied}}$, which is the velocity in this occupied zone. The equations Morsel et al. (1981) developed are as follows:

$$V_{occupied} = V_{skin} + 0.25(V_{avg} - V_{skin}) \tag{2.12}$$

where $\mathbf{V_{skin}}$ is the water velocity adjacent to the culvert wall **[m/s];** and $\mathbf{V_{avg}}$ is the average water velocity in the culvert barrel **[m/s].**

Kane and Wellen (1985) make mention of the approach proposed by Morsel et al. (1981) and make some algebraic substitutions to present the following relationships which allow $\mathbf{V_{occupied}}$ to by determined directly from $\mathbf{V_{avg}}$:

$$V_{occupied} = 1.25\ V_{skin} = 0.625\ V_{avg} = 0.5\ V_{max} \tag{2.13}$$

where $\mathbf{V_{occupied}}$, $\mathbf{V_{skin}}$, $\mathbf{V_{avg}}$, and $\mathbf{V_{max}}$ have been previously defined. Manning's equation is often used to calculated V_{avg} and $V_{occupied}$ can be approximated using Equation 2.13. Kane and Wellen (1985) state reservations about the form of the equations presented by Morsel et al. (1981). They suggest that first the size of the occupied zone be defined by the size and species of fish and then established equations be used to determine the velocity in the occupied zone.

Chiu (1988) has developed a state-of-the-art approach for predicting two-dimensional velocity distributions in open channel cross-sections based on probability and entropy. Chiu (1993) further developed this approach and applied it to pipe flow studies. Chiu recommends the use of the following velocity distribution equation for pipe flow as an alternative to existing one-dimensional equations:

$$\frac{u}{u_{max}} = \frac{1}{M} ln\left[1 + \left(e^{M} - 1\right)\frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right] \tag{2.14}$$

where **u** is the velocity at a point **[m/s]**; $\mathbf{u_{max}}$ is the maximum velocity **[m/s]**; **M** is the dimensionless entropy parameter; and ξ is a dimensionless, independent variable used for the coordinate system. According to Chiu (1988), the entropy parameter, M, is a measure of the uniformity of the probability and velocity distributions. A value of M equal to zero represents a uniform distribution and corresponds to the (theoretical) maximum value of entropy. A value of M approaching infinity represents an invariant velocity distribution and corresponds to the minimum entropy situation.

For the case of open channel culvert flow with axial symmetry, at the centerline the variable ξ is given by:

$$\xi = \frac{y}{d-h} exp\left(1 - \frac{y}{d-h}\right) \tag{2.15}$$

where **y** is the vertical distance from the bottom of the culvert **[m]**; **d** is the depth of flow **[m]**; and **h** is the depth below the water surface where V_{max} occurs **[m]**.

Chiu (1988) derives an equation which relates the entropy parameter, M, to the ratio of $\frac{u_{avg}}{u_{max}}$. The equation is as follows:

$$\frac{u_{avg}}{u_{max}} = e^{M}\left(e^{M}-1\right)^{-1} - \frac{1}{M} \tag{2.16}$$

where u_{avg} is the average velocity of the flow cross-section.

2.1.4 Field Observations and Experimental Data

While there has not been extensive research into the velocity distribution of culverts, several papers were found to contain relevant information. Chow (1959) states laboratory investigations have revealed that flow in a straight prismatic channel is three-dimensional, exhibiting a spiral motion. According to Shukry (1950), a small disturbance at the entrance is usually unavoidable and can result in the shift of the zone of highest water level to one side and cause single spiral motion to occur. Two plots of the velocity distribution components in a straight rectangular channel are also given by Shukry and used by Chow. The first plot shows the shift of the velocity component normal to the cross-section to one side of the channel (see Figure 2.3a). The second plot shows the direction lines and the magnitude of the lateral velocity components and illustrates the spiral motion that is occurring in the channel (see Figure 2.3b).

Replogle and Chow (1966) examined circular pipes flowing partially full to determine the tractive-force distribution. Velocity distribution data was taken for three depths of flow in the pipes, at approximately one-third, one-half, and two-thirds of the diameter of the culvert, D_o. The authors mention that no attempt was made to examine a range of velocities because Kennedy and Fulton (1961) reported that the magnitude of the velocity had an insignificant effect on the velocity distribution for the range of velocities normally encountered. Two cross-sectional velocity distributions for the steel pipe are shown (see Figure 2.4 and Figure 2.5). The channel geometry is theorized to play a major role in triggering and establishing secondary currents which are believed to impact the location of maximum velocity in the pipe cross-section.

The most pertinent study was performed by Katopodis et al. (1978). A report was written on a study of model and prototype culvert baffles. To determine the effects of the baffles, a culvert was tested without baffles at various discharges and relative depths. Cross-section velocity distributions were taken at two stations within the culvert. The velocity distributions were plotted from the perspective of looking upstream with the flow coming out of the paper. This differs from the other velocity plots shown in this paper which are referenced as looking downstream with the flow going into the paper. The velocity profiles for two different discharges are shown in Figures 2.6 and 2.7.

Behlke et al. (1989) made field observations of fish passage through a culvert in Fish Creek which is located in Alaska. The culvert tested in the study was a 2.9 meter (9.5 feet) diameter culvert with 15.2 x 3.5 cm (6 x 1.4 inch) annular corrugations and a discharge of 3.06 m^3/s (108 cfs). The velocity distribution that was generated is shown in Figure 2.8. The skew in the velocity distribution is attributed to the culvert not being installed parallel to the stream flow. In other words, no attempt has been made to provide a smooth upstream transition so water enters the pipe at an angle due to bends in the natural stream channel. Also, Behlke took his measurements at a distance of 9.14 meters (30 feet) from the inlet. It should be noted that observations of other researchers, as well as from this research, do not support the assumption of Behlke et al. (1989) that the flow was fully developed at the sampling point.

2.2 Discussion of Existing Knowledge

2.2.1 Limitations of Existing Knowledge

The objective of this research is to improve design parameters for passage of juvenile fish through highway culverts. One step that would go a long way in reaching this objective is being able to accurately predict the two-dimensional velocity distribution in a highway culvert. The problem with even the state of the art two-dimensional model proposed by Chiu (1993) is that it will predict a velocity distribution that is symmetrical about the centerline. However, culverts are not smooth-walled pipes, and the corrugations create turbulent and chaotic flow in the

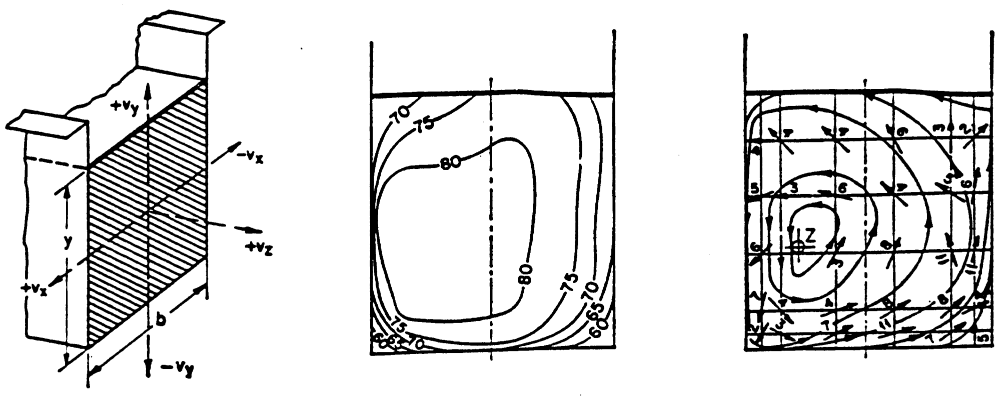


Figure 2.3. Distribution of normal and lateral velocity components in a straight rectangular channel (Modified from Chow, 1959). Velocity magnitudes shown are in cm/s.

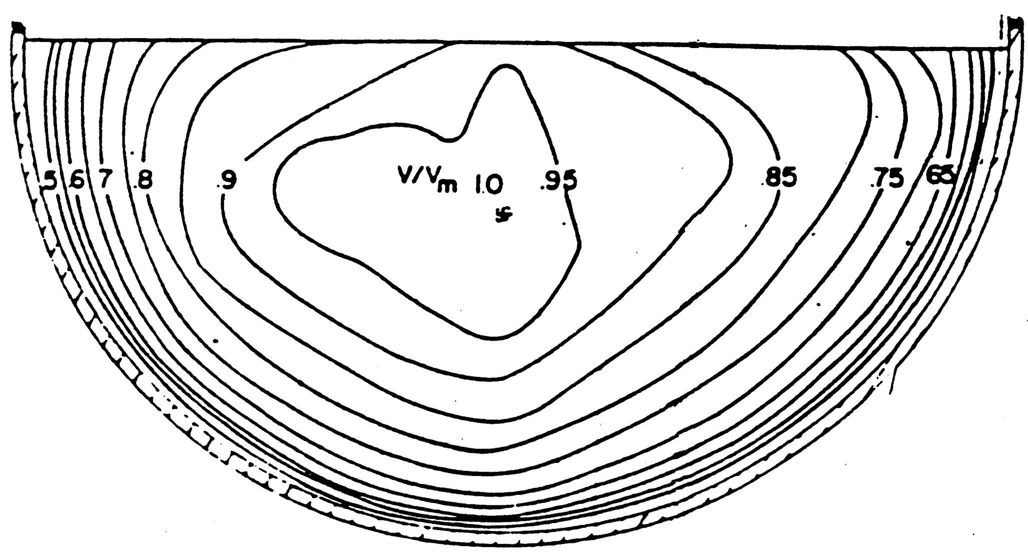


Figure 2.4. Relative velocity distribution for 13.3 cm (5.2 inch) diameter steel pipe with a flow rate of 0.0034 m^3/s (0.12 cfs), slope of 0.2%, and relative depth of $0.50*D_O$.

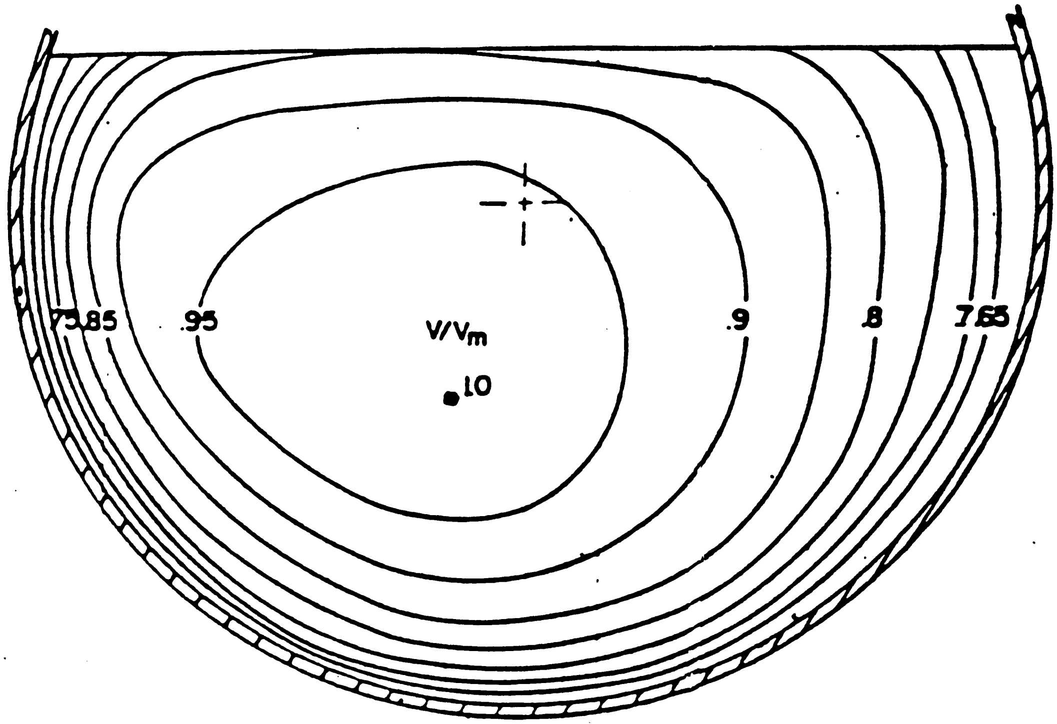
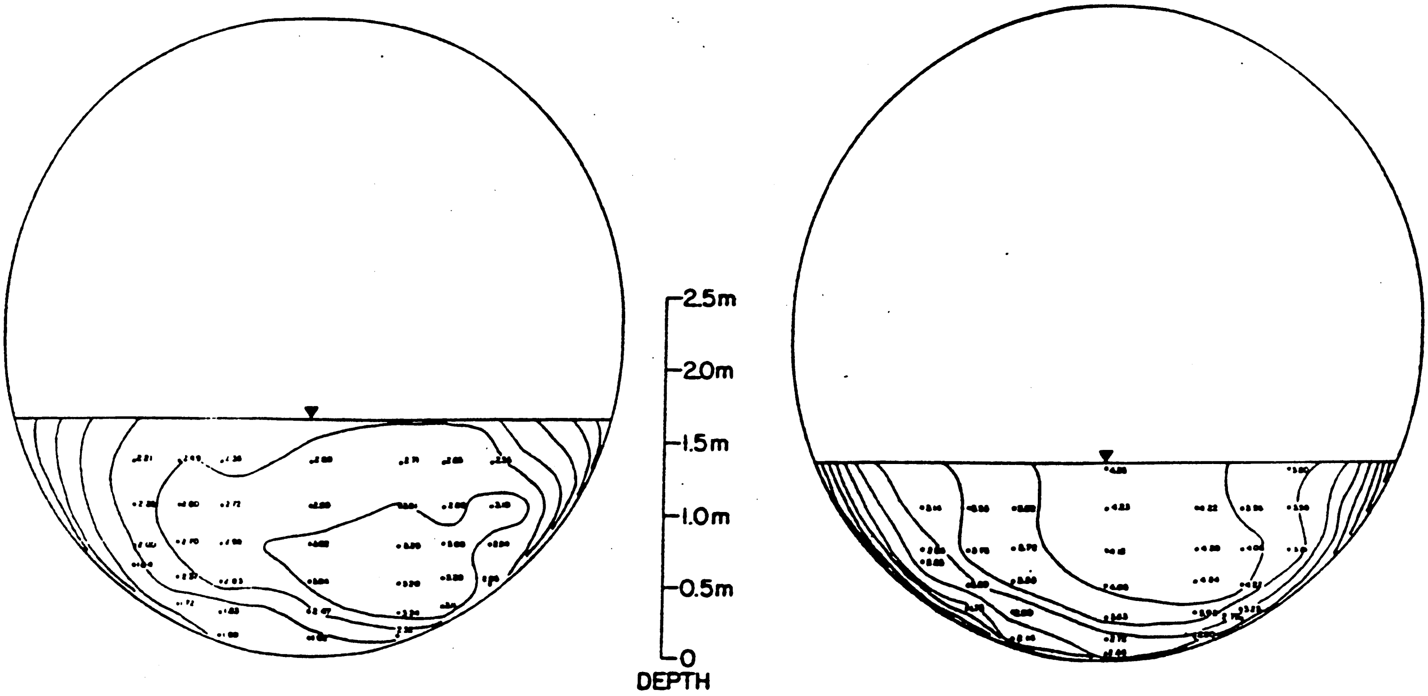
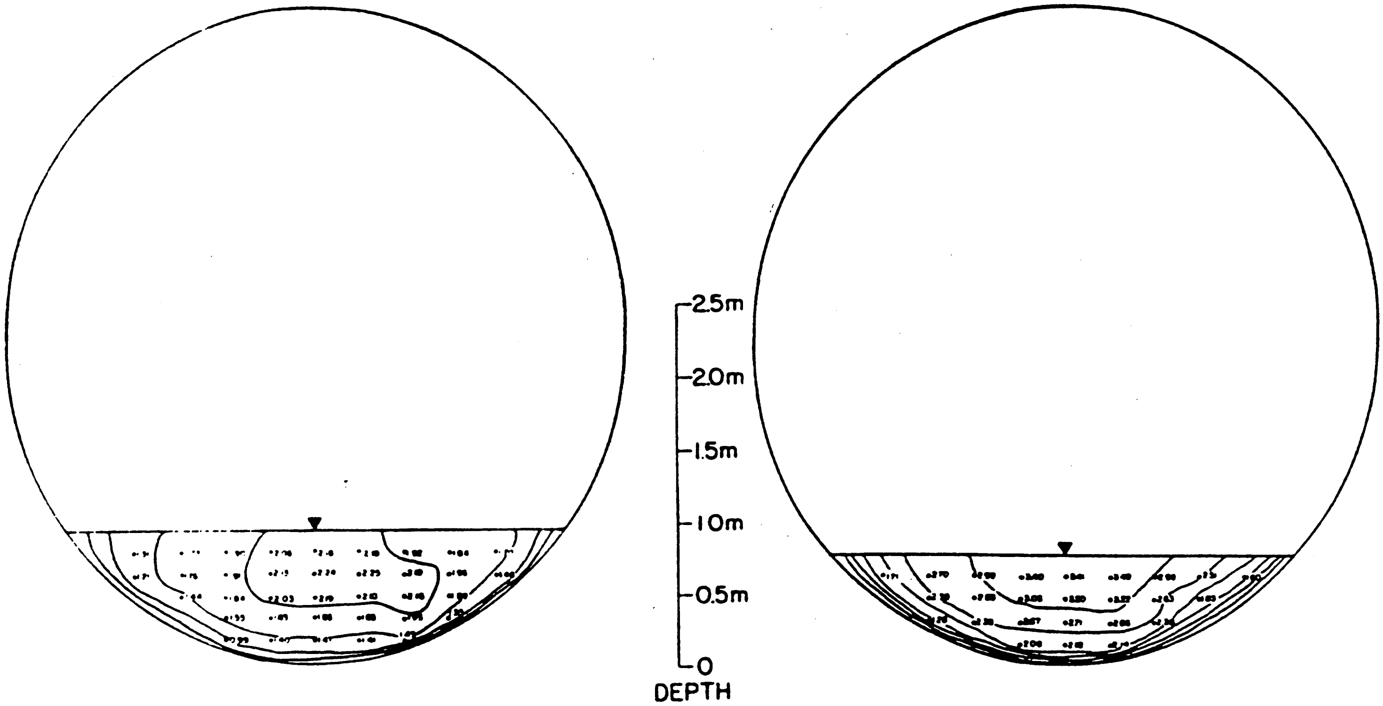


Figure 2.5. Relative velocity distribution for 13.3 cm (5.2 inch) diameter steel pipe with a flow rate of 0.0106 m^3/s (0.374 cfs), slope of 0.8%, and relative depth of $0.65*D_O$.



(a) Upstream station (b) Downstream Station

Figure 2.6 Velocity distributions at upstream and downstream stations with a flow rate of 12.2 m^3/s (430 cfs). (Modified from Katopodis et al. 1978).



(a) Upstream station (b) Downstream Station

Figure 2.7 Velocity distributions at upstream and downstream stations with a flow rate of 3.8 m^3/s (134 cfs). (Modified from Katopodis et al. 1978).

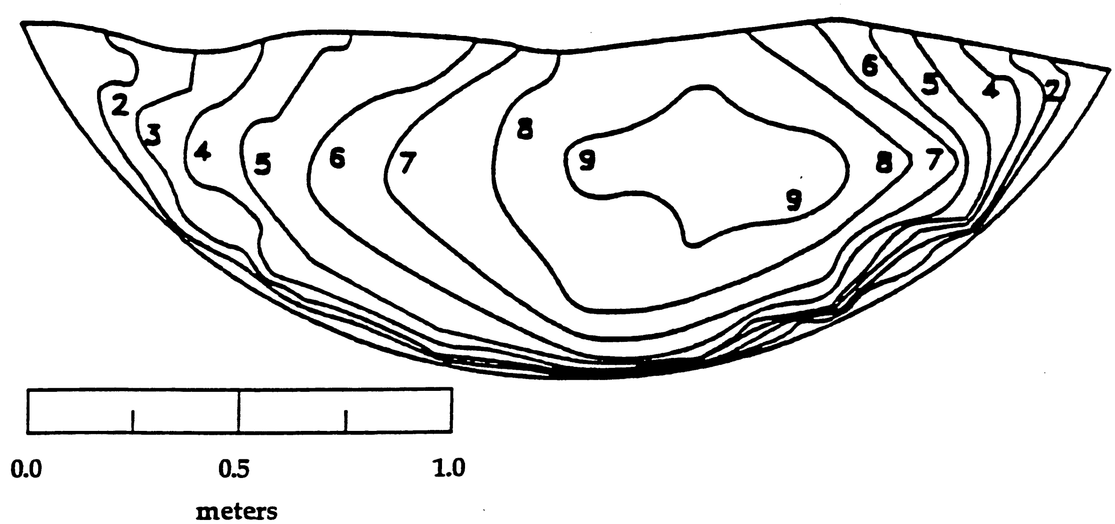


Figure 2.8 Velocity cross-section from 2.9 m (9.5 feet) diameter culvert, with 15.2 x 3.5 cm annular corrugations, in Fish Creek Denali Highway, Alaska. Flow rate was 3.06 m^3/s (108 cfs). (Modified from Behlke et al. 1989).

boundary layer. As has been illustrated by field observations of culverts and experimental data on smooth pipes, there is currently no accurate method of predicting the velocity distribution in corrugated culverts. Entrance conditions, depth of flow, and irregularities of the culvert or its corrugations can all cause the cross-sectional velocity distribution to become non-symmetrical. The problems encountered in obtaining symmetrical velocity distributions even under laboratory conditions are further complicated by current road construction practices. It is likely that culverts installed in the field will not be placed perfectly parallel to the natural stream flow and that little notice will be given to whether or not the culvert is truly round with no irregular corrugations or dents. Although problems with culvert alignment, irregularities, etc. become less noticable at lower velocities likely to be associated with juvenile fish passage, persistent skewness was seen in the velocity profiles. Another limitation is that none of the existing work has proposed an adequate method of predicting velocity distributions in corrugated highway culverts. The shape of the $\mathbf{V_{occupied}}$ zone changes with flow and roughness which is also not accounted for in existing models. Furthermore, regardless of average velocity, the period and magnitude of turbulence may also be a barrier to fish migration.

2.2.2 Extension of Existing Knowledge

Based on preliminary results obtained from experiments on the first test culvert and results from other researchers, this research focused on determining a method of predicting the size of the low velocity zone and the low velocity in this zone. This research proposes to extend the existing knowledge through the development of a method of predicting the velocity distribution. The ability to characterize the velocity distribution will provide the hydraulic engineer with a valuable tool that will help to insure juvenile fish passage. The intention of this research is not to attempt to account for every molecule of water flowing through a culvert, but rather to provide an empirical approach that will predict the amount of cross-sectional area in a culvert and corresponding top-widths that has velocities which are sufficiently low to provide passage for juvenile fish. The data generated from this research may also be used to extend the knowledge of the hydraulic characteristics of flow through corrugated highway culverts. It must be noted that this research dealt exclusively with circular culverts with annular corrugations. It also must be noted that only hydraulic characteristics of flow were considered related to juvenile fish passage. The prediction of the velocity distributions must be combined with considerations of other factors that may impact juvenile fish passage, such as high sediment load, temperature and fish passage design flow.

Chapter 3
METHODOLOGY

As previously stated, the primary objectives of this research were to measure the velocity distributions in small-diameter highway culverts and to develop a means of extrapolating these results to other size highway culverts. To help reach these objectives, both an experimental setup and an experimental procedure were developed. The following chapter briefly describes these methodologies and the rational behind them. A thorough discussion of the methodology can be found in the technical report (Barber and Downs, 1995).

3.1 Experimental Setup

The research for this project was conducted at the R.L. Albrook Hydraulic Laboratory operated by the Department of Civil and Environmental Engineering at Washington State University in Pullman, Washington. Whenever possible, existing laboratory facilities were used in the research.

Individually, each experimental culvert was placed in an existing tilting flume. The flume head box was supplied by a maximum of four pumps. The flume allowed for culverts up to 76.2 cm (30 inches) in diameter to be tested with flow rates up to 0.14 m^3/s (4.9 cfs). The flume also has a tailgate that allows for downstream control. To provide straight flow that was normal to the cross-section of the flume, two honeycomb flow aligners were placed immediately after the head box. And finally, to reduce the effect of the contraction created by the culvert entrance, a transitional entrance structure was built out of plywood and a lightweight concrete compound.

The velocity measurements were taken by a Nixon Model 403 Low Speed Probe. The Nixon probe generates an analog signal which is read by a battery powered Streamflow Model 422 Digital Indicator and is read in units of Hertz. The units of Hertz are then converted to a velocity in cm/s via a calibration chart supplied by the manufacturer. The Nixon probe was attached to a point gage which in turn was mounted on a horizontal slide bar (see Figure 3.1).

The slide bar was attached to a suspended platform which was able to be moved along the length of the flume. The point gage allowed for the vertical movement of the probe to be measured and the horizontal slide bar allowed for the horizontal movement of the probe to be measured. To take velocity measurements near the sides of the pipe, the Nixon probe was attached to the point gage via a rotation joint. The joint allowed for the probe to be angled at 45 degrees to reach the sides of the culvert.

Collection of the probes output signal was done via an Apple Macintosh Quadra 650 equipped with a Lab-NB I/O board. The software LabVIEW was installed on the computer and allowed for the voltage being read in by the I/O board to be calibrated to the frequency reading generated by the Nixon Probe. The Quadra was used as a data logger and allowed an average velocity to be taken from a large number of readings.

3.2 Calibration and Verification of Experimental Setup

The slope of the flume was verified through the use of a surveyors level. The screw jacks were calibrated to a ruler that was mounted on the support of the jack. The magnetic flow meters were calibrated by using a trapezoidal (Cipolleti) weir with end inclinations of 4V:1H (Grant, 1979). The flow rate over a range of discharges was measured manually using the weir. The flow rate was then plotted versus the flow gage reading for each gage. A linear regression was performed using KaleidaGraph software and the equations for flow gages #1 and #2 are as follows:

$$Q = 0.0020 + 0.0007 * G \qquad R^2=0.99 \qquad \text{(Gage \#1)} \tag{3.1}$$

$$Q = -0.0019 + 0.0012 * G \qquad R^2=0.98 \qquad \text{(Gage \#2)} \tag{3.2}$$

where **Q** is the flow rate **[m^3/sec]**; and **G** is the magnetic flow gage reading.

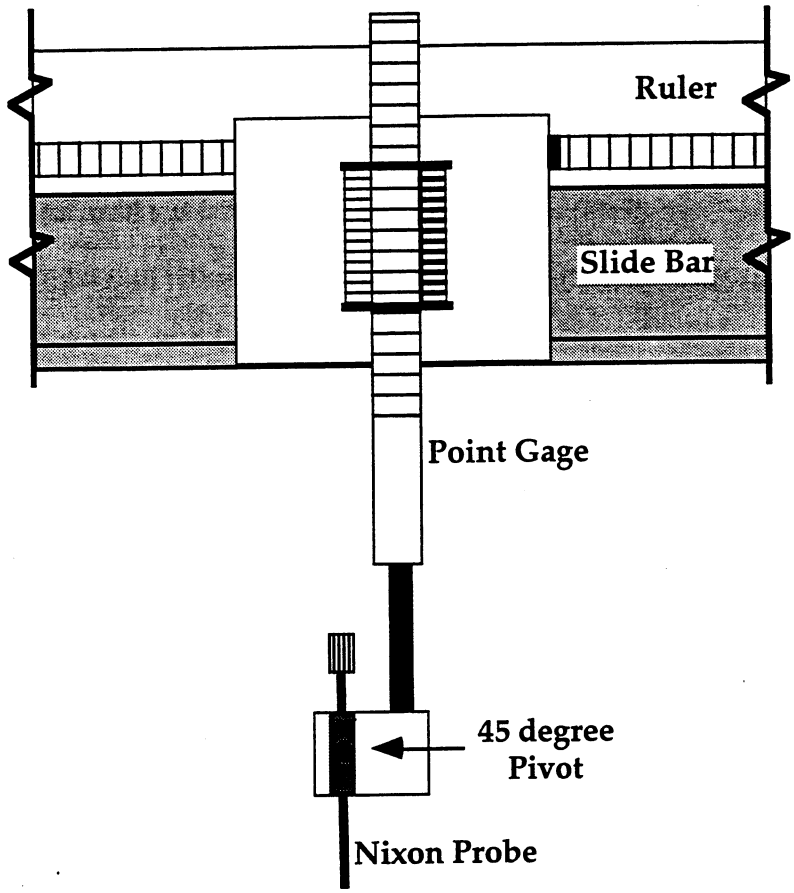


Figure 3.1 Diagram of Nixon probe mounting.

3.3 Experimental Procedure

The first task that had to be undertaken was to select the culverts that would be tested. The second and more difficult task was to develop a procedure for testing the culverts.

3.3.1 Culvert Selection

One of the primary goals of this research is to provide a means of extrapolating results from small-diameter experimental culverts to any size diameter culverts used for fish passage. Ideally, the results of one of the small-diameter culverts would be compared directly to results from a large-diameter fish passage culvert, with both of the culverts tested in the laboratory under controlled conditions.

Based on logistic constraints, it was decided to test three corrugated culverts and one smooth steel pipe. Since large-diameter culverts used for fish passage have annular corrugations, all of the corrugated culverts tested had annular corrugations. Spiral culvert tend to create larger flow disruptions and may not be as suitable for fish passage due to this increased turbulence. Culverts were selected based on discussion with WSDOT. Table 3.1 provides the diameter, length, and corrugation properties for each of the three culverts that was selected. Diagrams of the 6.8 x 1.3 cm (2.67 x 0.5 inch) and the 7.6 x 2.5 cm (3 x 1 inch) annular corrugations are shown in Figure 3.2 and provide a comparison between the two corrugations. No 5.1 x 15.2 cm (2 x 6 inch) corregation pipe was available in diameters which would fit into the existing flume.

Each of the three highway culverts were constructed of several sections of 16-gage steel plate that were overlapped and plug welded together to form the culverts. Each of the shorter pipe sections was plug welded along its longitudinal axis to form a cylindrical section. When the shorter pipe sections were assembled and welded together, the welds that ran along the longitudinal axis of each pipe section were not lined up. The non-corrugated steel pipe (Culvert #4) was also constructed of 16-gage steel in four welded pipe sections which were then welded together. As was the case for the corrugated culverts, the welds that ran along the axis of each pipe section were not lined up when the four sections were welded together.

Table 3.1 Experimental Culverts

Culvert #	Inside Diameter	Length	Corrugation
1	30.5 cm	6.10 m	6.8 x 1.3 cm
2	61.0 cm	12.20 m	6.8 x 1.3 cm
3	73.7 cm	9.74 m	7.6 x 2.5 cm
4	61.0 cm	6.10 m	none

For Culvert #2 and Culvert #3 a corrugated coupling band with a band angle connector was used to joint together the two lengths of culvert. The coupling band was made from the same corrugated steel as each of the culverts and was tightened by bolts passing through the band angle connector. The coupling bands for each culvert were sealed with silicone caulking to prevent water from leaking out of the joints.

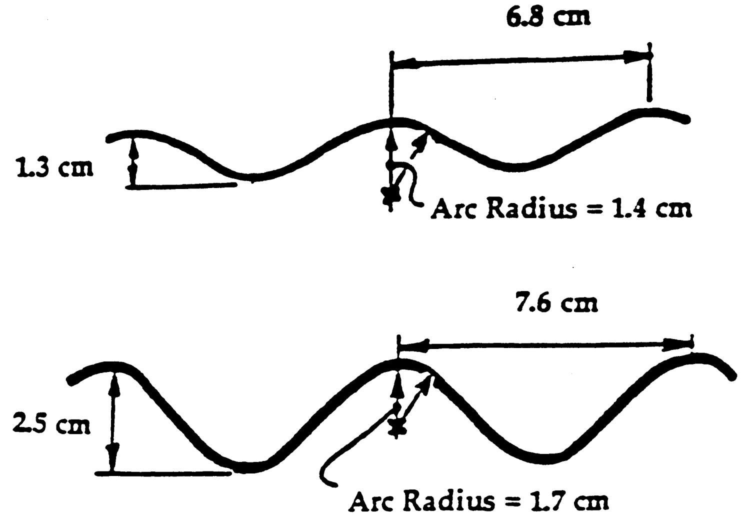


Figure 3.2 Shapes of Annular Corrugations for 6.8 x 1.3 cm (2.7 x 0.5 inch) and 7.6 x 2.5 cm (3 x 1 inch) corrugations

3.3.2 Testing Procedure

The first culvert was placed in the flume and secured by semi-circular templates that supported and held the culvert in the center of the flume. The entrance of the culvert was fitted with a flat plate made of plywood. Extensive testing was performed on this culvert in order to develop a testing procedure for the remaining culverts.

Small access holes were cut along the top centerline of the culvert at intervals of one diameter. At three different flow rates and two different slopes the centerline velocity distributions were taken at several stations along the culvert in an attempt to find the point where flow in the culvert became uniform and "typical". The centerline velocity plot for a flow rate of 0.113 m^3/s (4 cfs) at one-half percent slope with a relative depth of $0.5*D_o$ is shown in Figure

3.3. This plot shows the centerline velocity distribution continuing to change at stations along the culvert. This plot is typical of the centerline distributions that were taken and demonstrates the inability to find a "typical" cross-section for the selected culverts. Because the location of a typical cross-section was not determined, it was decided to take cross-sectional velocity distributions at two stations in the culvert. This allowed for a two-dimensional investigation of how the velocity distribution of the flow developed as it traveled down the culvert.

The velocity measurements were taken at data points in a grid that covered the cross-section of the flow. Depending on the relative depth and the culvert diameter, the number of data points varied between fifty and one hundred and twenty. Because of the interest in the region near the wall for this research, more data points were taken near the boundary of the culvert than in the center of the flow.

At the eight diameter station (L/D=8), a large access slot was cut in the top of the culvert to allow for the Nixon probe to take velocity measurements at points throughout the cross-section. A flow rate of 0.127 m^3/s (4.5 cfs) was used with a slope of one-half percent with no downstream control. The velocity readings from the Nixon probe were consistently higher on the left side of the culvert (looking downstream) and the velocity distribution was not symmetrical about the centerline. A standing wave was also observed throughout the length of the culvert that appeared to originate at the culvert entrance. The wave seemed to be caused by the sudden contraction caused by the flat plate at the entrance. At this point it was decided to build the entrance region to provide a gradual transition from the rectangular flume to the circular culvert. This reduced, but did not totally eliminate the standing wave.

The decision was also made to use the tailgate on the flume as a downstream control device to control the depth of flow in the culvert. The tailgate and lower flow rates were used, in addition to the entrance region, in an attempt to provide more symmetrical velocity distributions. Velocity distributions were taken at the 8 diameter station and the 14 diameter station under the new conditions. However, because the tailgate caused a backwater effect, the depth at the 8 diameter station was different than the depth at the 14 diameter station.

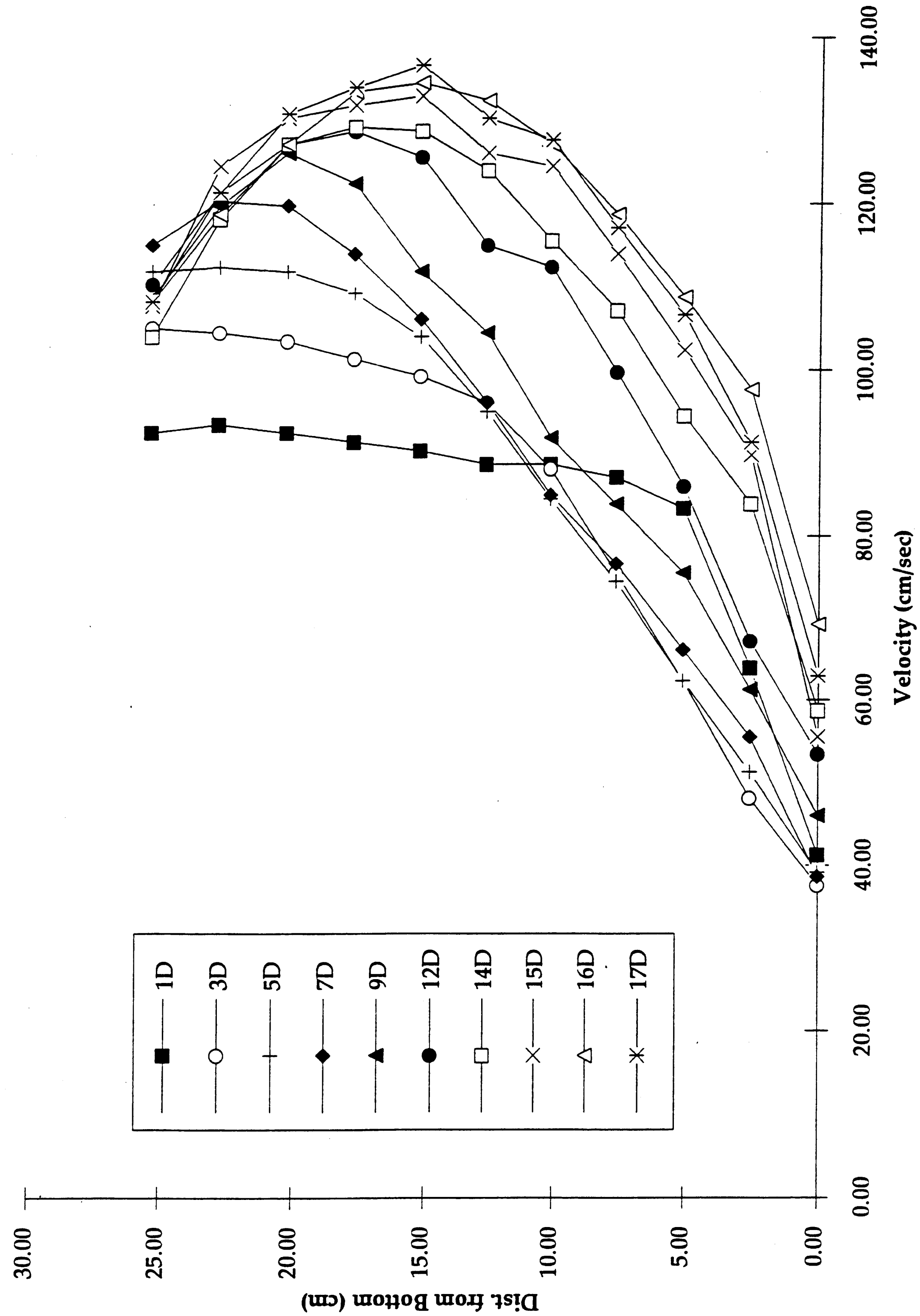


Figure 3.3 Centerline velocity distributions for culvert # 1 at 0.113 m^3/sec (4 cfs), slope = 1/2%, relative depth = $0.5*D_o$, with no downstream control.

To preserve continuity at both stations for each testing condition, the relative depth of flow at the entrance was set to be $0.5*D_O$. This resulted in relative depths that ranged from $0.52*D_O$ to $0.56*D_O$ for the station at L/D=8, and from $0.54*D_O$ to $0.62*D_O$ for the station at L/D=14, depending on flow rate and slope. The velocity distributions still showed a skew to the left side of the culvert despite the honeycomb aligners, entrance region, and lower flow rates.

Two more slots were cut in the culvert to measure the velocity distributions at distances of 1 diameter and 12 diameters from the entrance. On the basis of the results obtained from the velocity distributions taken at various stations through the culvert, the decision was made to test each of the culverts at a distance approximately 70% of the length of the culvert from the entrance to minimize the impact of the entrance and the exit of the culverts.

WDFW requested that experimental runs be performed at relative depths other than $0.5*D_O$. It was also of interest to investigate the effect of the backwater caused by the tailgate. A relative depth of $0.25*D_O$ provided the opportunity to test the flow through the culvert with and without the tailgate. The decision was made to scale the flow rate down from the flow rate used for the relative depth of $0.5*D_O$. From Manning's equation (Equation 2.2) it was assumed that the roughness coefficient, **n**, and the friction slope, S_f, were constant for the culvert and that $AR^{2/3}$ was the term that varied. Based on this assumption it was decided to scale the flow rate by the ratio $\frac{AR^{2/3}_{0.25D_0}}{AR^{2/3}_{0.5D_0}}$. The culvert was first run with a relative depth at the entrance of $0.25*D_O$, with the tailgate and a scaled flow rate. The culvert was run again at a relative depth of $0.25*D_O$ but with no tailgate and at the flow rate required to make the relative depth $0.25*D_O$ at the entrance.

The selection of the 30.5 cm (12 inch) diameter culvert provided the opportunity to test a culvert under conditions that were not possible for the other two culverts. The culvert was tested at relative depths greater than $0.5*D_O$ without the tailgate. WDFW requested that experimental runs be made with slopes up to five percent, so the culvert was installed at a slope of three percent relative to the floor of the flume for a number of runs. This allowed for the culvert to be tested at slopes of three and five percent.

Based on the test results and the previous work discussed in Section 2.1.4, it was concluded that it would not be possible to predict the exact shapes of the velocity cross-sections because of the skew that was experienced in the velocity cross-sections. The decision was made to experimentally determine the percentage of area of the cross-section with various relative velocities. The contours of the velocity distribution plots were at relative velocities of $0.2*V_{max}$, $0.4*V_{max}$, $0.5*V_{max}$, $0.6*V_{max}$, $0.8*V_{max}$, $0.9*V_{max}$, and $0.95*V_{max}$. The percentage of area in the cross-section that was within the boundary of each contour line was determined for each of the velocity distribution plots that was taken. A total of fifty-one cross-sections were taken in the four culverts. The station, flow rate, slope, relative depth, and downstream control testing conditions were recorded for each run. These testing conditions were selected based on requests from the WSDOT and the WDFW, and to allow for an investigation of the impact on the velocity distribution of change in diameter, use of corrugation, change in corrugation, change in slope, change in flow rate, and use of downstream control. The results from these fifty-one runs were then used to develop an empirical method of predicting the percentage of area in the cross-section with velocities acceptable for juvenile fish passage.

Chapter 4
RESULTS

A considerable amount of data was recorded throughout this research project due to the need to examine variations in flow, location, culvert diameter, slope, corrugation size, and other variables. In addition to solving for relevant parameters, this information was used to develop a method of predicting velocity distributions. Discrete velocity measurements were recorded with their respective X-Y coordinates. The software Spyglass Transform was used to translate the inputted data into a X-Y matrix with magnitudes of velocity. Velocity values at the inputted points were preserved and the software interpolated between these known points by using a Kriging fill method.

The resulting contour plots were digitized and the areas between adjacent contour isovel lines were determined. For each of the experimental runs, a comparison was made between the discharge measured by the magnetic flow meters and the discharge calculated from the cross-sectional contour plots to verify that continuity was preserved.

In addition, these areas were used to determine the velocity distribution coefficients α and β. These areas were also used to calculate "effective" cross-sectional areas, which are discussed in Section 4.2. Prediction of these "effective" cross-sectional areas and subsequent development of a method of predicting velocity distributions through the use of the Chiu equation (Equation 2.14) and the Mountjoy equation (Equation 2.11) are discussed in Section 4.3. Qualitative observations and discussion of the flow through each of the four test culverts are presented in Section 4.4. Finally, sensitivity analysis and discussion for both the Chiu and the Mountjoy equations are included in Section 4.5.

4.1 Tabulation of Results

Velocity measurements were made on three corrugated and one non-corrugated steel culverts. Several parameters were measured or calculated for each of the fifty-one experimental runs. These parameters include the discharge, slope, existence of downstream control, depth, relative depth, maximum velocity, average velocity, hydraulic radius, α, β, Reynolds number, and shear velocity. The methods used to determine the calculated parameters are discussed briefly in Chapter 2. A tabulation of these parameters for each experimental run is given in Table 4.1.

4.2 Effective Cross-Sections

Cross-sectional contour plots of the relative velocity (V/V_{max}) were generated for each of the fifty-one experimental runs. The contours were based on the discrete velocity measurements made at various points in the cross-section. The contour plots are shown looking downstream. Because of space requirements, the contour plots are not shown here. Readers are referred to the technical report for a complete appendix of the plots (Barber and Downs, 1995).

Often the contour plots were irregularly shaped with respect to the theoretical, symmetrical shape about the centerline. A typical non-symmetrical velocity distribution is shown in Figure 4.1. In terms of fish passage, evidence suggests the non-symmetric nature of the velocity distribution is not significant since the fish appear capable of finding low velocity passage zones. Consequently, when considerations are being made for juvenile fish passage, it is important to be able to predict the thickness of the region of the velocity distribution with acceptable velocities. For this reason, the areas between isovel lines in the contour plots were converted to "effective" areas. That is to say, a given digitized area was converted to an equivalent, symmetrical ring-shaped band having the same area. This concept is illustrated in Figure 4.2. The thickness of each additional band represents an average thickness that could be expected with relative velocities below a certain level. This means given a desired relative velocity, the average thickness of the boundary layer with velocities below this desired level can be predicted.

Table 4.1. Parameters for Experimental Runs.

Run #	Culvert	Discharge (cms)	Slope (%)	Downstream Control	Depth (cm)	Relative Depth	Vmax (cm/sec)	Vavg (cm/sec)	Hyd. Radius (cm)	α	β	Reynold's No.** Re	Shear Velocity (v^*) (cm/sec)
1	1	0.0052	5.0%	N	5.1	0.17	101.9	65.0	3.1	1.39	1.13	2.26E+04	12.4
2	1	0.0064	3.0%	N	7.0	0.23	82.0	55.3	4.2	1.32	1.11	2.35E+04	11.1
3	1	0.0082	1.0%	N	10.4	0.34	61.2	41.2	5.8	1.36	1.13	2.41E+04	7.5
4	1	0.0094	0.5%	N	10.4	0.34	59.9	38.0	5.8	1.40	1.15	2.77E+04	5.3
5	1	0.0124	0.5%	Y	20.7	0.68	34.5	23.9	8.9	1.37	1.14	2.35E+04	6.6
6	1	0.0124	1.0%	Y	23.1	0.76	33.2	22.5	9.2	1.41	1.15	2.16E+04	9.5
7	1	0.0142	5.0%	Y	15.0	0.49	63.1	38.6	7.5	1.41	1.15	3.35E+04	19.2
8	1	0.0213	0.5%	Y	17.0	0.56	85.1	56.2	8.1	1.38	1.14	4.64E+04	6.3
9	1	0.0278	3.0%	N	13.2	0.43	125.9	84.9	6.9	1.32	1.12	7.10E+04	14.3
10	1	0.0284	1.0%	N	16.0	0.52	92.7	70.2	7.9	1.22	1.08	6.43E+04	8.8
11	1	0.0290	5.0%	N	12.0	0.39	169.3	106.8	6.4	1.51	1.19	7.85E+04	17.8
12	1	0.0438	5.0%	N	14.0	0.46	178.0	129.9	7.2	1.18	1.07	1.08E+05	18.8
13	1	0.0456	0.5%	N	22.0	0.72	108.5	74.6	9.1	1.44	1.17	8.25E+04	6.7
14	1	0.0527	3.0%	N	19.0	0.62	159.6	103.6	8.6	1.43	1.16	1.06E+05	15.9
15	1	0.0539	1.0%	N	24.0	0.79	124.4	83.2	9.3	1.34	1.13	9.07E+04	9.5
16	2	0.0153	0.5%	Y	23.3	0.38	26.4	16.0	12.6	1.34	1.12	2.11E+04	7.9
17	2	0.0153	0.5%	Y	20.4	0.33	29.2	18.5	11.4	1.33	1.12	2.28E+04	7.5
18	2	0.0153	1.0%	Y	24.0	0.39	25.2	15.5	12.9	1.38	1.14	2.07E+04	11.2
19	2	0.0283	0.5%	Y	35.2	0.58	22.8	16.2	16.6	1.29	1.11	3.01E+04	9.0
20	2	0.0283	0.5%	Y	34.4	0.56	26.6	17.4	16.4	1.34	1.13	3.06E+04	9.0
21	2	0.0396	0.5%	N	15.7	0.26	90.1	60.8	9.2	1.31	1.11	6.83E+04	6.7
22	2	0.0396	0.5%	N	15.9	0.26	84.9	60.7	9.3	1.44	1.16	6.78E+04	6.7
23	2	0.0515	1.0%	N	15.7	0.26	108.0	80.3	9.2	1.28	1.10	8.88E+04	9.5
24	2	0.0566	0.5%	Y	30.9	0.51	51.3	39.6	15.4	1.14	1.05	6.56E+04	8.7
25	2	0.0566	0.5%	Y	33.5	0.55	46.3	33.9	16.1	1.21	1.08	6.22E+04	8.9
26	2	0.0566	0.5%	Y	34.5	0.57	41.8	30.7	16.4	1.18	1.07	6.10E+04	9.0
27	2	0.0566	0.5%	Y	34.3	0.56	44.9	31.7	16.4	1.20	1.07	6.12E+04	9.0
28	2	0.0566	1.0%	Y	38.1	0.62	37.6	26.5	17.3	1.27	1.10	5.70E+04	13.0
29	2	0.0850	0.5%	Y	33.1	0.54	69.1	47.4	16.0	1.24	1.09	9.42E+04	8.9
30	2	0.0850	0.5%	Y	33.2	0.54	64.2	49.1	16.0	1.15	1.05	9.40E+04	8.9
31	2	0.0850	0.5%	Y	32.9	0.54	69.8	49.9	16.0	1.15	1.06	9.46E+04	8.8
32	2	0.0850	1.0%	Y	30.9	0.51	71.5	56.6	15.4	1.16	1.06	9.85E+04	12.3
33	2	0.0850	0.5%	Y	38.5	0.63	58.2	41.2	17.3	1.24	1.09	8.49E+04	9.2
34	2	0.1274	0.5%	N	30.7	0.50	118.4	81.3	15.3	1.15	1.05	1.48E+05	8.7
35	3	0.0153	0.5%	Y	23.0	0.31	22.2	14.6	13.0	1.38	1.14	1.96E+04	8.0
36	3	0.0153	1.0%	Y	45.4	0.62	9.9	7.3	20.7	1.19	1.07	1.29E+04	14.3
37	3	0.0153	1.0%	Y	24.5	0.33	20.5	12.5	13.7	1.47	1.16	1.89E+04	11.6
38	3	0.0566	0.5%	Y	42.3	0.57	31.2	22.5	20.0	1.30	1.11	5.00E+04	9.9
39	3	0.0566	1.0%	Y	43.0	0.58	33.9	23.6	20.2	1.30	1.11	4.94E+04	14.1
40	3	0.0575	0.5%	N	17.5	0.24	120.8	76.7	10.3	1.52	1.19	8.57E+04	7.1
41	3	0.0664	1.0%	N	18.2	0.25	135.1	87.9	10.7	1.50	1.18	9.69E+04	10.2
42	3	0.0850	0.5%	Y	42.0	0.57	46.6	32.2	19.9	1.39	1.14	7.54E+04	9.9
43	3	0.0850	1.0%	Y	43.2	0.59	44.2	30.4	20.2	1.36	1.13	7.40E+04	14.1
44	4	0.0153	0.5%	Y	17.3	0.28	27.4	21.4	9.9	1.16	1.06	2.50E+04	7.0
45	4	0.0153	1.0%	Y	20.4	0.33	23.1	18.2	11.4	1.16	1.06	2.28E+04	10.6
46	4	0.0527	0.5%	N	14.0	0.23	127.2	104.5	8.3	1.14	1.05	9.68E+04	6.4
47	4	0.0563	1.0%	N	13.4	0.22	140.2	117.6	8.0	1.15	1.06	1.06E+05	8.9
48	4	0.0566	0.5%	Y	35.0	0.57	38.9	34.0	16.5	1.08	1.03	6.04E+04	9.0
49	4	0.0566	1.0%	Y	36.0	0.59	36.8	31.4	16.8	1.09	1.03	5.93E+04	12.8
50	4	0.0850	0.5%	Y	34.3	0.56	59.7	50.9	16.4	1.09	1.03	9.20E+04	9.0
51	4	0.0850	1.0%	Y	35.2	0.58	54.2	47.0	16.6	1.08	1.03	9.04E+04	12.8

**** Hydraulic radius (R) used as characteristic length for Reynold's number (Re).**

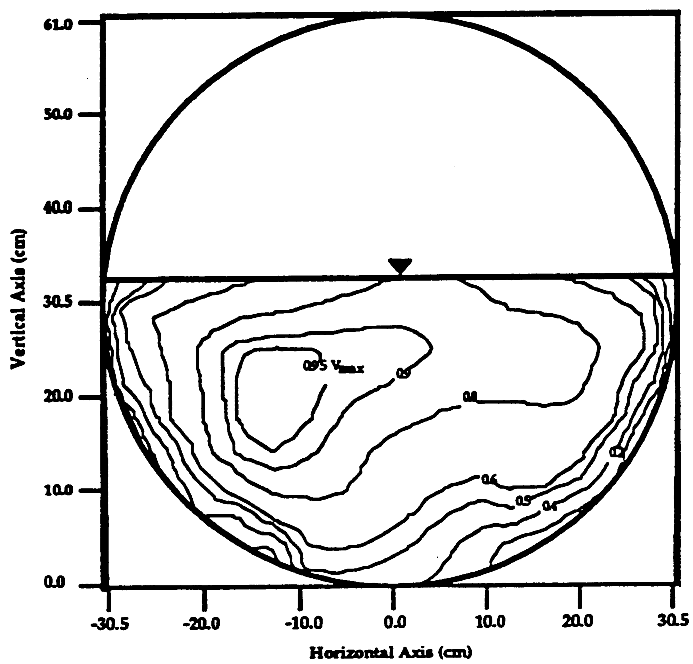


Figure 4.1. Example of non-symmetrical relative velocity contour plot for Culvert #2, looking downstream. Discharge = 0.0850 m^3/s (3.0 cfs), Slope = 1/2%, Vmax = 69.1 cm/s (27.2 in/s), taken at L/D = 12.

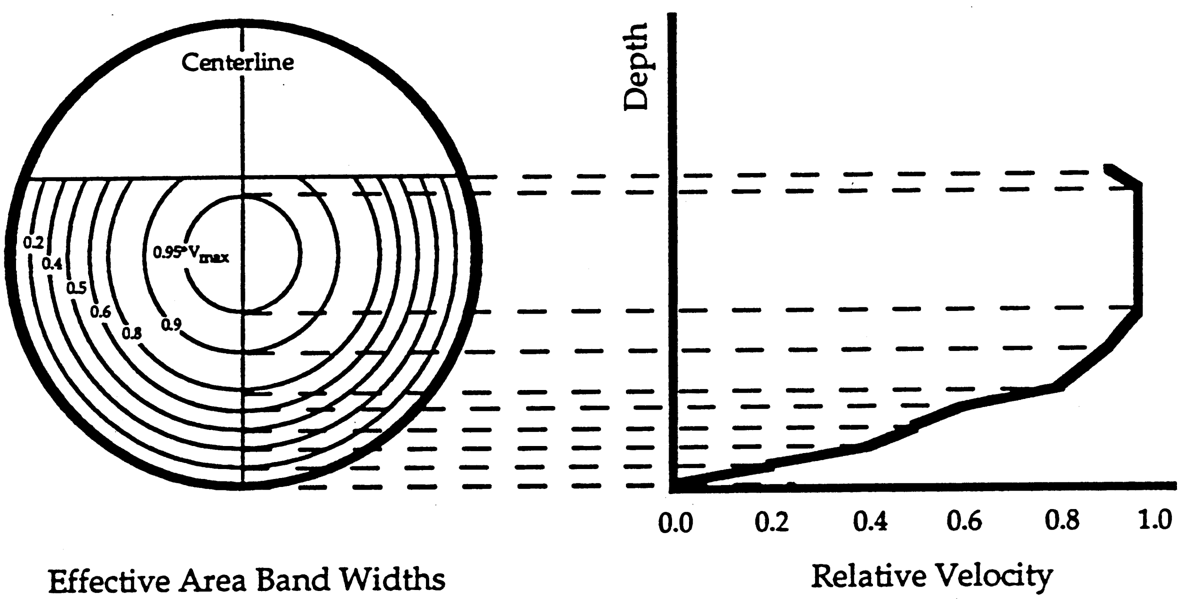


Figure 4.2 Illustration of effective area concept.

The effective band widths for each of the experimental runs were calculated for relative velocities of $0.2*V_{max}$, $0.4*V_{max}$, $0.5*V_{max}$, $0.6*V_{max}$, $0.8*V_{max}$, $0.9*V_{max}$, and $0.95*V_{max}$. These effective band widths are tabulated in Table 4.2.

4.3 Prediction of Velocity Distributions in Culverts

One of the primary objectives of this research was to develop a means of predicting cross-sectional velocity distributions in any diameter circular corrugated culvert. A centerline plot of the relative velocities taken from the effective cross-section was used as the experimental data to be fitted to an appropriate velocity distribution equation. The equation that adequately predicts the centerline velocity distribution can be used to scale up to larger diameter culverts and predict the effective band widths, and thus the effective cross-section, for the culvert.

Two equations were examined for use in predicting the one-dimensional centerline velocity distribution of the effective cross-sections. The first equation was the Chiu (1995) equation (Equation 2.14) and the second equation used was the Mountjoy (1986) equation (Equation 2.11). Each of these equations are discussed in Section 2.1.3. The Chiu equation was used only to predict the one-dimensional velocity distribution along the centerline.

4.3.1 Application of Chiu Equation

The Chiu equation (Equation 2.14) was used to predict the centerline velocity distribution. Based on experimental data from the four culverts and previous studies on three additional culverts, a linear relationship between $\frac{V_{avg}}{V_{max}}$ and $\frac{CorrugationHeight}{PipeDiameter}$ was found. This relationship is illustrated in Figure 4.3.

Table 4.2 Band Widths for Effective Cross-Section

Run #	Band Width 0.0*Vmax (cm)	Band Width 0.2*Vmax (cm)	Band Width 0.4*Vmax (cm)	Band Width 0.5*Vmax (cm)	Band Width 0.6*Vmax (cm)	Band Width 0.8*Vmax (cm)	Band Width 0.9*Vmax (cm)	Band Width 0.95*Vmax (cm)
1	0.0	0.1	0.6	1.0	1.6	2.5	3.5	4.2
2	0.0	0.1	0.3	1.2	2.0	3.0	4.2	5.0
3	0.0	0.4	0.8	1.4	2.4	4.0	6.0	8.2
4	0.0	0.4	1.1	1.8	2.6	4.8	7.2	8.7
5	0.0	0.6	1.5	2.1	2.9	5.6	8.4	10.3
6	0.0	0.7	1.8	2.4	3.3	5.6	8.4	11.0
7	0.0	0.6	1.3	2.3	3.9	7.6	9.7	12.1
8	0.0	0.7	1.5	2.0	3.0	5.7	10.0	13.8
9	0.0	0.3	0.9	1.7	2.5	5.4	7.6	9.7
10	0.0	0.1	0.7	1.2	1.8	3.7	6.8	8.8
11	0.0	0.7	1.6	2.2	2.8	4.8	7.6	9.2
12	0.0	0.2	0.4	0.8	1.6	4.9	8.0	9.9
13	0.0	0.9	1.9	2.4	3.1	5.1	7.8	10.1
14	0.0	0.8	1.7	2.5	3.4	6.2	10.1	12.3
15	0.0	0.6	1.3	2.1	3.2	6.6	9.5	12.5
16	0.0	0.6	1.9	3.4	6.4	11.5	18.0	21.3
17	0.0	0.5	1.6	2.8	4.9	9.9	13.0	16.9
18	0.0	0.8	2.3	3.7	6.3	13.4	16.4	20.2
19	0.0	0.7	2.2	3.2	4.9	10.1	16.4	23.8
20	0.0	0.9	2.4	3.5	5.5	10.5	15.3	19.9
21	0.0	0.4	1.1	2.1	3.6	7.0	9.9	12.3
22	0.0	0.6	1.8	2.8	4.2	7.2	9.3	10.9
23	0.0	0.4	0.7	1.7	3.6	7.0	9.9	12.3
24	0.0	0.3	0.6	1.5	2.3	4.9	8.2	16.9
25	0.0	0.4	0.9	2.4	4.3	9.9	15.7	21.0
26	0.0	0.2	0.8	2.2	4.3	10.9	16.9	24.2
27	0.0	0.3	1.0	2.7	4.8	12.5	21.7	27.4
28	0.0	0.7	1.4	3.5	5.5	11.4	18.1	22.3
29	0.0	0.3	1.5	3.2	5.4	12.3	20.5	24.9
30	0.0	0.1	0.6	1.3	2.8	9.3	15.0	19.2
31	0.0	0.2	0.9	1.8	3.5	11.5	22.7	28.9
32	0.0	0.2	0.8	1.5	2.9	6.0	10.9	17.7
33	0.0	0.7	1.8	2.6	4.8	11.3	19.3	25.4
34	0.0	0.2	0.7	2.1	4.3	13.9	25.2	27.7
35	0.0	0.7	2.0	3.6	5.6	10.2	14.2	16.8
36	0.0	0.3	1.4	2.4	5.0	13.4	19.3	25.7
37	0.0	0.9	3.2	4.8	7.5	12.3	16.9	19.8
38	0.0	1.0	2.6	4.0	5.7	11.7	16.4	24.8
39	0.0	0.7	2.5	4.3	7.0	13.6	20.3	27.5
40	0.0	1.2	2.3	2.9	4.7	7.8	10.6	13.1
41	0.0	1.0	2.4	3.5	4.5	7.5	10.4	12.5
42	0.0	1.2	3.5	5.0	7.0	12.7	18.1	23.6
43	0.0	1.3	3.1	4.5	7.0	13.6	19.7	25.0
44	0.0	0.0	0.4	1.0	2.3	4.3	7.6	11.1
45	0.0	0.2	0.5	1.1	1.9	5.1	8.6	12.2
46	0.0	0.1	0.1	0.8	1.4	2.8	4.3	6.9
47	0.0	0.1	0.4	0.8	1.2	2.0	3.3	5.9
48	0.0	0.0	0.2	0.6	1.2	3.5	6.5	10.9
49	0.0	0.2	0.4	0.6	1.2	4.3	8.5	14.9
50	0.0	0.1	0.3	0.9	1.7	3.6	7.4	16.3
51	0.0	0.1	0.3	0.7	1.3	3.5	7.0	12.7

The entropy parameter M was calculated for each of the four test culverts using $\frac{V_{avg}}{V_{max}}$ and Equation 2.16. The entropy parameters that were calculated are given in Table 4.3. The Chiu equation was used to predict the centerline velocity distribution for each of the experimental runs assuming that V_{max} occurred 0.10*Depth below the surface of the flow. The predicted centerline velocity distribution was compared to the centerline velocity distribution taken from the effective cross-sections. Plots of the predicted centerline velocity distribution curves for each of the conditions examined in the experimental runs are included in Appendix C of the technical report (Barber and Downs, 1995).

Because the Chiu equation tended to over predict the relative centerline velocity distribution using the calculated entropy parameters, a best fit entropy parameter was calculated for each experimental run. The best fit entropy parameter varied from 0.49 to 4.33. An attempt was made to correlate the variation in the best fit entropy parameter to a property of the flow. Correlation attempts were made for several parameters of the flow including Reynolds number, hydraulic radius, wetted perimeter, shear velocity, friction factor, and relative depth. No significant relationship could be found between the best fit entropy parameter and these variables. Linear correlations were found between the best fit entropy parameter and the velocity head coefficient, α, and between the best fit entropy parameter and the momentum coefficient, β. A sensitivity analysis of the entropy parameter for each of the culverts is included in Section 4.5.

For use in fish passage design, it was determined that the entropy parameter could be calculated from $\frac{V_{avg}}{V_{max}}$, which could be calculated from $\frac{CorrugationHeight}{PipeDiameter}$ for a given culvert. This would provide a constant M for each culvert. Because no correlation could be found between the best fit entropy parameter and a flow property that would be known during culvert design, it was determined the constant calculated entropy parameter must be used for Chiu's equation.

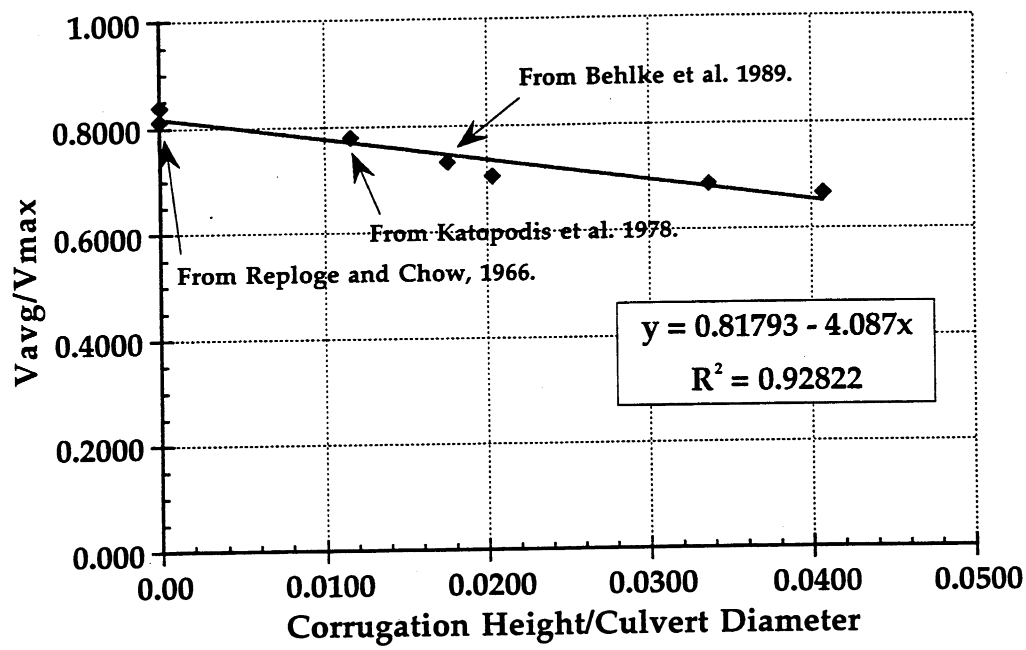


Figure 4.3 Plot of $\frac{V_{avg}}{V_{max}}$ versus $\frac{CorrugationHeight}{PipeDiameter}$ with linear regression line and equation.

Table 4.3 Calculated Entropy Parameters.

Culvert	Entropy Parameter
1	2.14
2	2.76
3	2.43
4	6.13

A statistical analysis of the experimental data fit to Chiu's equation was performed. The three statistical parameters used were the Bias, the Mean Absolute Error (MAE), and the Root Mean Squared Error (RMSE). These parameters provide a means of comparing different curve fits to experimental data. The bias indicates the tendency of the equation to over or under predict. A positive bias indicates a trend of over prediction, a negative bias indicates a trend of under prediction, and a Bias of zero indicates that the equation shows no tendency to over or under predict. The MAE and RMSE are always positive, and lower values of MAE and RMSE indicate less error in the fit. The magnitudes of MAE and RMSE are a function of the input values, so they are only useful as a comparison between different fits. The Bias, MAE, and RMSE for the Chiu equation are shown in Table 4.4.

To apply the Chiu equation to fish passage culvert design, the $\frac{CorrugationHeight}{PipeDiameter}$ ratio would predict a value of $\frac{V_{avg}}{V_{max}}$ for the culvert. This could then be used to determine the entropy parameter for the culvert. Given discharge and the flow depth, V_{avg} can be determined by $V_{avg} = Q/A$, and V_{max} could be determined from the value for $\frac{V_{avg}}{V_{max}}$ that had been predicted earlier. The allowable velocity for the design juvenile fish would then be expressed as V_{allow}/V_{max}. The Chiu equation could then be used to solve for the thickness of the boundary layer with relative velocities (V/V_{max}) sufficient for fish passage.

4.3.2 Application of Mountjoy Equation

The Mountjoy (1986) equation (Equation 2.11) was the second equation used to predict the one-dimensional centerline velocity distribution. The Mountjoy equation requires knowledge of the average velocity (V_{avg}), hydraulic radius (R), Manning's coefficient (n), and the depth of the flow (y_o). These values can be determined given the diameter and corrugation of the culvert, the discharge (Q), and the depth of flow in the culvert.

The Mountjoy equation was examined as a comparison to the one-dimensional application of the Chiu equation which was discussed in Section 4.3.1. The Manning n values were taken from the American Iron and Steel Institute (1980). Plots of the centerline velocity distribution curves predicted by the Mountjoy equation for each of the experimental runs are included in Appendix C of the technical report (Barber and Downs, 1995). A sensitivity analysis of the selection of a Manning n value is included in Section 4.5 for a typical run from each of the culverts.

A statistical analysis of the bias and the error of the experimental data fit to the Mountjoy equation was again performed. The three statistical parameters used were the Bias, the Mean Absolute Error (MAE), and the Root Mean Squared Error (RMSE). These parameters provide a means of comparing different curve fits to experimental data. The Bias, MAE, and RMSE for the Mountjoy equation are also shown in Table 4.4.

To apply the Mountjoy equation to fish passage, the discharge (Q), properties of the culvert (corrugation and diameter), and the depth of flow (y_o) would be used to determine V_{avg}, hydraulic radius (R), and Manning's coefficient (n). These values would be used in the Mountjoy equation along with the relative depth (y/y_o) to predict a velocity. The allowable velocity for the design juvenile fish would then be used as the target velocity and the relative depth at which this velocity occurs could be determined from the Mountjoy equation.

4.4 Observations and Discussion

From the analysis of the results obtained from the experimental runs on the four culverts, several important, qualitative observations were made. These are discussed in the following subsection.

Table 4.4. Statistical Parameters for Chiu and Mountjoy Equations.

	Chiu			Mountjoy		
RUN #	Bias	MAE	RMSE	Bias	MAE	RMSE
1	0.097	0.108	0.052	0.001	0.047	0.018
2	0.060	0.086	0.035	-0.038	0.074	0.032
3	0.068	0.068	0.019	-0.010	0.029	0.003
4	0.097	0.097	0.038	0.024	0.025	0.003
5	0.023	0.025	0.005	-0.036	0.065	0.018
6	0.037	0.051	0.018	-0.019	0.073	0.032
7	0.091	0.091	0.034	0.026	0.028	0.004
8	0.063	0.063	0.015	0.007	0.031	0.006
9	0.050	0.054	0.013	-0.031	0.042	0.016
10	-0.032	0.046	0.011	-0.101	0.112	0.047
11	0.110	0.110	0.050	0.035	0.047	0.010
12	-0.021	0.069	0.021	-0.093	0.104	0.054
13	0.027	0.047	0.010	-0.031	0.070	0.024
14	0.065	0.065	0.017	0.006	0.040	0.008
15	0.026	0.039	0.016	-0.033	0.082	0.031
16	0.107	0.107	0.050	0.038	0.046	0.009
17	0.097	0.097	0.040	0.018	0.031	0.005
18	0.119	0.119	0.058	0.048	0.048	0.010
19	0.044	0.044	0.007	-0.026	0.037	0.006
20	0.058	0.058	0.013	-0.015	0.031	0.006
21	0.089	0.089	0.034	0.000	0.030	0.005
22	0.122	0.122	0.065	0.031	0.045	0.009
23	0.075	0.078	0.028	-0.012	0.038	0.009
24	-0.063	0.077	0.026	-0.139	0.150	0.088
25	0.007	0.042	0.008	-0.068	0.079	0.028
26	-0.007	0.060	0.016	-0.074	0.085	0.037
27	0.030	0.063	0.016	-0.033	0.062	0.027
28	0.030	0.041	0.007	-0.040	0.051	0.011
29	0.041	0.060	0.015	-0.031	0.042	0.017
30	-0.046	0.078	0.031	-0.113	0.124	0.069
31	0.008	0.067	0.019	-0.047	0.084	0.038
32	-0.042	0.057	0.016	-0.112	0.123	0.059
33	0.030	0.036	0.007	-0.018	0.048	0.009
34	0.012	0.078	0.026	-0.046	0.082	0.039
35	0.094	0.094	0.037	0.008	0.027	0.004
36	-0.032	0.058	0.018	-0.100	0.112	0.051
37	0.126	0.126	0.069	0.045	0.047	0.013
38	0.021	0.022	0.002	-0.052	0.063	0.015
39	0.031	0.037	0.006	-0.044	0.055	0.013
40	0.131	0.131	0.075	0.038	0.050	0.012
41	0.122	0.122	0.065	0.027	0.050	0.010
42	0.053	0.053	0.012	-0.022	0.041	0.008
43	0.047	0.047	0.008	-0.025	0.036	0.007
44	0.086	0.102	0.047	0.055	0.065	0.025
45	0.115	0.115	0.059	0.034	0.081	0.035
46	0.090	0.090	0.041	0.053	0.071	0.027
47	0.100	0.100	0.053	0.057	0.092	0.037
48	0.000	0.022	0.002	0.003	0.052	0.010
49	0.031	0.031	0.007	0.031	0.063	0.021
50	0.029	0.033	0.006	0.028	0.062	0.016
51	0.019	0.026	0.003	0.020	0.064	0.017

4.4.1 Qualitative Observations

CULVERT 1 (30.5 cm (12 in) diam, 6.8 x 1.3 cm (2.7 x 0.5 in) corrugation, 6.1 m (20 ft) long)

Cross-sectional velocity distributions were taken at this culvert for relative depths ranging from $0.16*D_O$ to $0.78*D_O$, and slopes from 0.5% to 5%. The velocity distributions were, for the most part, nearly symmetrical about the centerline. There were a few exceptions, however, as a few of the contour plots showed a slight shift of the velocity contours to the left side of the culvert, and a couple of plots showed a slight shift to the right side of the culvert.

CULVERT 2 (61.0 cm (24 in) diam, 6.8 x 1.3 cm (2.7 x 0.5 in) corrugation, 12.2 m (40 ft) long)

Cross-sectional velocity distributions for Culvert #2 were taken at several stations along the culvert. These stations were at L/D = 0, 1, 8, 12, and 14. The velocity distributions were taken on this culvert for a range of relative depths from $0.25*D_O$ to $0.62*D_O$, and slopes from 0.5% to 1%. Many of the velocity distribution plots taken at stations along the barrel of the culvert showed a distinct shift toward the left side of the culvert. This shift was less pronounced for relative depths below $0.40*D_O$, although it still existed.

CULVERT 3 (73.7 cm (29 in) diam, 7.6 x 2.5 cm (3 x 1 in) corrugation, 9.74 m (32 ft) long)

Culvert 3 was the largest diameter culvert to be tested and it also had the largest corrugations. This culvert was tested for a range of relative depths from $0.25*D_O$ to $0.62*D_O$, and slopes from 0.5% to 1%. Similar to Culvert #1, the velocity distribution plots for Culvert #3 were mostly symmetrical about the centerline with some velocity plots showing a slight skew to either the left or the right side of the culvert.

CULVERT 4 (61.0 cm (24 in) diam, non-corrugated, 6.1 m (20 ft) long)

Culvert 4 was the smooth walled pipe and this culvert was tested for a range of relative depths from $0.20*D_O$ to $0.57*D_O$, and slopes from 0.5% to 1%. The velocity distribution plots produced for this culvert were mostly symmetrical about the centerline. The velocity distribution in Culvert 4 was not nearly as varied as the distributions seen in the corrugated culverts. Most of the flow area in Culvert #4 had relative velocities above $0.8*V_{max}$.

4.4.2 Gradually Varied Flow

For the experimental runs with no downstream control, the flow through the culvert was gradually varied. The gradually varied flow in the culverts approached normal depth and uniform flow. However, because of the lengths of the culverts tested, the flow was not able to fully develop into uniform flow before the outlet of the culvert. The flow profile through the culvert can be determined through the use of the Direct Step Method (Chow, 1959). For subcritical flow, the assumption of uniform depth would provide a conservative estimate of flow velocities since the uniform flow depth would be less than the actual depth.

4.4.3 Discussion

Based on the ability of the two equations to predict "effective" cross-sectional areas for various combinations of flow, slope, relative depth, downstream control, culvert corrugation, and culvert diameter, it was observed that the parameters important for fish design consideration were discharge, slope, culvert diameter, corrugations, and depth of flow. The two equations predicted the effective cross-section equally well regardless of the use of downstream control.

A comparison of the statistical parameters calculated for each of the two equations shows that the Mountjoy equation provided a better fit to the experimental data for more of the runs. All three of the statistical parameters were found to favor the Mountjoy equation in twenty-six of the runs. The Chiu equation was favored by all three of the statistical parameters for eighteen of the runs. For seven of the runs the statistical parameters did not favor one equation over the other. Although the Chiu equation was favored for eighteen of the runs, on only four of the runs were the magnitudes of all three of the statistical parameters for the Mountjoy equation greater than double the corresponding parameters for the Chiu equation. Therefore for many of the runs that the Chiu equation predicted better, the Mountjoy prediction was not significantly worse.

For the Mountjoy equation, the "effective" cross-sections predicted were compared to the actual "effective" cross-sections obtained experimentally. The region with velocities below $0.5*V_{max}$ were considered, because according to preliminary results from the WDFW (Powers, 1995) it was assumed that juvenile fish swimming capabilities were below this level The Mountjoy equation prediction produced the greatest error for Run #24, which was the cross-section taken at the entrance on Culvert #2. The areas calculated between the band widths had an average of 49% error up to the contour line at $0.5*V_{max}$. The Mountjoy equation provided several very good fits such as the fit on Run #35 which was a velocity distribution taken for Culvert #3. The areas that were calculated between the band widths for this run had an average error of only 13% up to the contour line at $0.5*V_{max}$. These percentages may be slightly different depending on the cross-sectional area of the low velocity region being examined.

The results of the Chiu fit were improved when a best fit entropy parameter was found for each run. However, because no correlation could be found that would enable the best fit entropy parameter to be determined, and also because Chiu states that the entropy parameter is constant for a channel section, the best fit entropy parameter was not used.

4.5 Sensitivity Analysis of Equation Fits

A sensitivity analysis was performed for each of the two equations used for predicting the effective velocity cross-section. For the Chiu equation the impact of the entropy parameter selection was examined, and for the Mountjoy equation the impact of the Manning n selection was examined.

4.5.1 Chiu Equation Sensitivity Analysis

A constant calculated entropy parameter (M) was calculated for each culvert. These values were given in Table 4.3. Best fit entropy parameters were calculated for each of the runs. For Culvert #1 the best fit entropy parameters ranged from 0.11 to 3.15. For Culvert #2 the best fit entropy parameters ranged from 0.48 to 4.33. For Culvert #3 the best fit entropy parameters ranged from 0.06 to 3.40. And for Culvert #4 the best fit parameters ranged from 3.30 to 6.24.

Given a depth, the Chiu equation predicts a relative velocity for that depth. The percentage of error in the relative velocity prediction was calculated for the difference between the each of the extreme values of the best fit M and the constant M which was calculated for the culvert. A plot was made for each of the four culverts showing the percent error in the relative velocity versus the relative depth for each of the extreme best fit entropy parameter values. These plots show how much the relative velocity values predicted by the Chiu equation, using best fit values for M, differed from the relative velocity values predicted using the constant value for M. The values vary exponentially with relative errors of 10-20 % at relative depths of 0.1. Details may be found in the technical report (Barber and Downs, 1995).

4.5.2 Mountjoy Equation Sensitivity Analysis

The values for Manning's n used in the Mountjoy equation to predict effective velocity cross-sections were taken from the American Iron and Steel Institute (1980). However, as was discussed in Section 2.1.2, the Manning n can vary for a given cross-section. For Culvert #1 and Culvert #2 the Manning's n was assumed to be 0.024, for Culvert #3 the Manning's n was assumed to be 0.027, and for Culvert #4 the Manning's n was assumed to be 0.012.

Given a relative depth the Mountjoy equation predicts a velocity at that depth. For a typical experimental run from each of the four culverts, the impact of varying the Manning's n ± 0.002 was examined. Three curves were produced for each analysis, one for each of the three Manning's n values used. The percentage differences between the relative velocities predicted using the assumed value of n and the varied values of n were calculated. A plot was made for each of the four culverts showing the percentage error in the calculated velocity versus the relative depth. The values vary exponentially with relative errors of 5-10 % at relative depths of 0.1. Details may be found in the technical report (Barber and Downs, 1995)

4.6 Example Problem

Given the following information, determine the band width and the area of flow with a velocity below the design criteria for juvenile salmon.

Design information:

Design velocity for juvenile fish = 0.5 m/s;
Discharge (Q) = 1.2 m^3/s;
Pipe slope = 0.25%;
Culvert diameter (D) = 1.5 m with 7.62 cm x 2.5 cm annular corrugations;
Manning roughness coefficient (n) = 0.027.

Using an iterative approach with Equation 2.2, the total area of flow and the hydraulic radius can be determined. Recall Equation 2.2:

$$Q = VA = \frac{1}{n} A R^{2/3} S_f^{1/2} \quad \text{(SI Units)}$$

For partial pipe flow as shown below in Figure 4.4;

the flow area (A) = $\frac{1}{8}(\theta - \sin\theta)D_o^{\;2}$ and the hydraulic radius (R) = $\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)D_o$

Choose theta (θ) and iterate until desired discharge of 1.2 m^3/s is obtained.

Table 4.5. Calculation of flow parameters

Theta radians	n	Slope	Flow Area (m^2)	Hyd. Radius	Calc (Q) (m^3/s)	Vavg (m/s)	
3.40	0.027	0.0025	1.028	0.4031847	1.04	1.01	
3.50	0.027	0.0025	1.083	0.4125839	1.11	1.03	
3.62	0.027	0.0025	1.148	0.4226898	**1.20**	1.04	<== OK
3.70	0.027	0.0025	1.190	0.4286996	1.25	1.05	

Determine the depth of flow (y_o)

Depth of flow (y_o) = $\frac{D_O}{2} + \frac{D_O}{2}\left(\sin\left(\frac{\theta - 3.1416}{2}\right)\right)$; $y_o = 0.93$ m

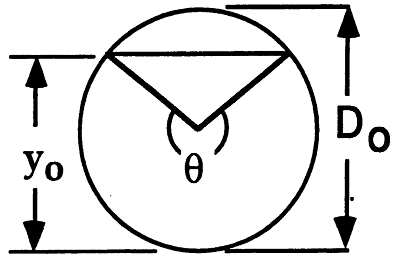


Figure 4.4. Partially Full Culvert Cross Section

Using the Mountjoy equation, the bandwidth can be calculated

Recall Equation 2.11: $v = A\,log_{10}\left(\frac{y}{y_0}\right) + B$

where v is the velocity at depth y, $A = \frac{(32g)^{1/2}(V_{avg})n}{R^{1/6}}$ and $B = \frac{0.88(8g)^{1/2}(V_{avg})n}{R^{1/6}} + V_{avg}$

Next, calculate A and B using data in Table 4.5 (all parameters should have consistent units.):

$g = 9.81$ m/s^2; $V_{avg} = 1.04$ m/s; $n = .027$; $R = .4227$; $y_o = 0.93$ m

Therefore A = 0.574 and B = 1.293

v = the design velocity for fish passage (0.5 m/s)

Rearranging equation 2.11: $log_{10}\left(\frac{y}{y_0}\right) = \frac{v - B}{A}$

or $y = y_0\, 10^{\left(\frac{v-B}{A}\right)}$

Evaluating this equation yields y = 0.039 m or **4 cm**.

Thus a band width of 4 cm will have flow velocities lower than 0.5 m/s. The corresponding area of flow with a velocity less than 0.5 m/s is 0.103 m^2. This is approximately 10% of the total flow cross-sectional area.

Effective Width Calculation:

In their hatchery experiments, WDFW observed juvenile fish swimming in the low velocity boundary layers in the upper corners of the pipe. Moreover, the juvenile fish traveled near the surface within 0.3 times the depth of flow. These migration zones are shown as shaded regions in Figure 4.5. This observation is consistent with other researchers. As a result of these observations, attempts were made to determine the horizontal velocity profile at 0.8*d with the ultimate goal of determining the width of the migration area. Since neither the Mountjoy or Chiu equations adequately predicted the velocity along the horizontal profile, an empirical method was examined which computed the effective width from the effective area calculation proposed in this research. The effective area is converted to an equivalent area on each side of the pipe. A trial and error iteration procedure is used to determine the width required to produce that area. The program converts the area determined by the previous method into assumed symmetric areas. Through the use of a Downs Correction Factor (DCF), the widths are scaled down to match those measured in the hydraulic testing program. A range of DCF values from 1 to 4 is plotted Figure 4.6 although the designer is free to choose any positive value depending on the level of safety factor required and the certainty of the design requirements. For example, selecting a value of 3 for a situation with no tail water control produces width estimates which are reasonable or conservative for nearly 67 percent of the cases with an assumed maximum permissible velocity of 38 cm/sec (1.25 feet/second). For the current example problem, this calculation results in a width of approximately 3.0 cm. It will be up to the biological constraints as to whether or not this width is acceptable.

A DCF of 1.0 for tail water conditions provides conservative estimates of widths for nearly all the flow cases tested. As would be expected, measurements of these values were dependent upon the downstream tail water depth, and therefore, varied significantly. However, in most every case (2 exceptions) the correction factor was less than one.

An interesting point must be made concerning the concept of tail water or backwater control. In most instances, no attempt was made to insure backwater conditions existed throughout the pipe. Situations where the outfall is partially submerged but the culvert resumes near uniform flow conditions at an upstream location within the pipe may produce more severe conditions with respect to fish passage. Consequently, in designs where backwater conditions are expected to dominate the outlet, the designer should make sure that such controls exist throughout the culvert.

A program called JUFIPP - JUvenile FIsh Passage Program was developed to compute the effective widths. The user provides information concerning the discharge, slope, diameter, roughness, DCF, and error tolerance (typically 0.001 meters), and the program computes the width.

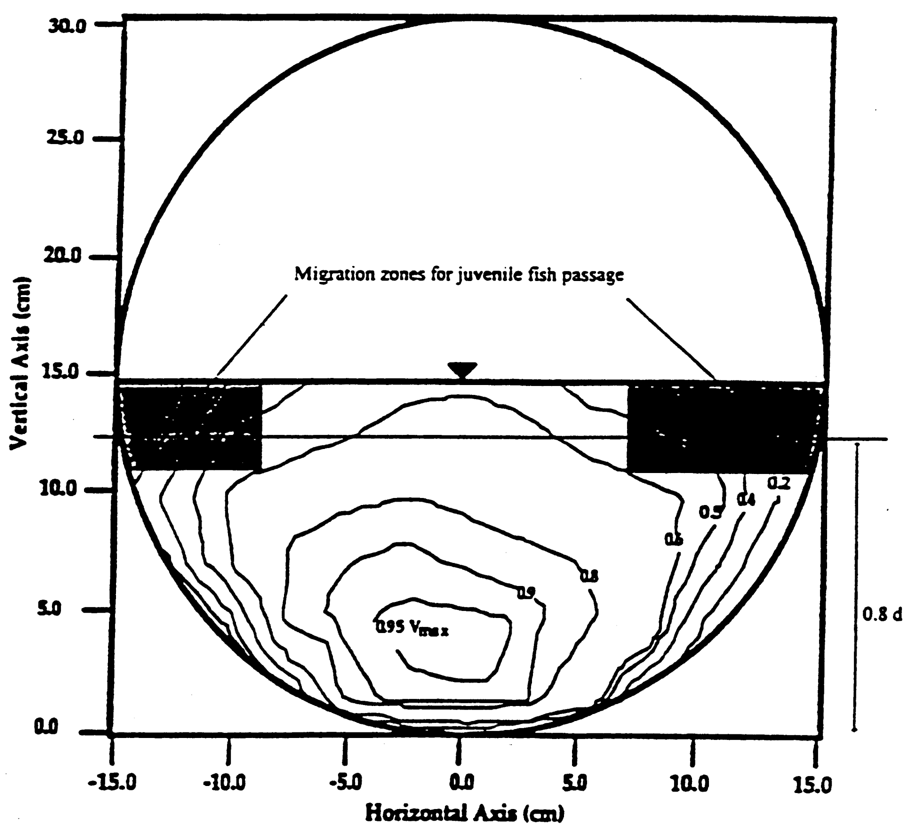


Figure 4.5 Migration zones for juvenile fish passage

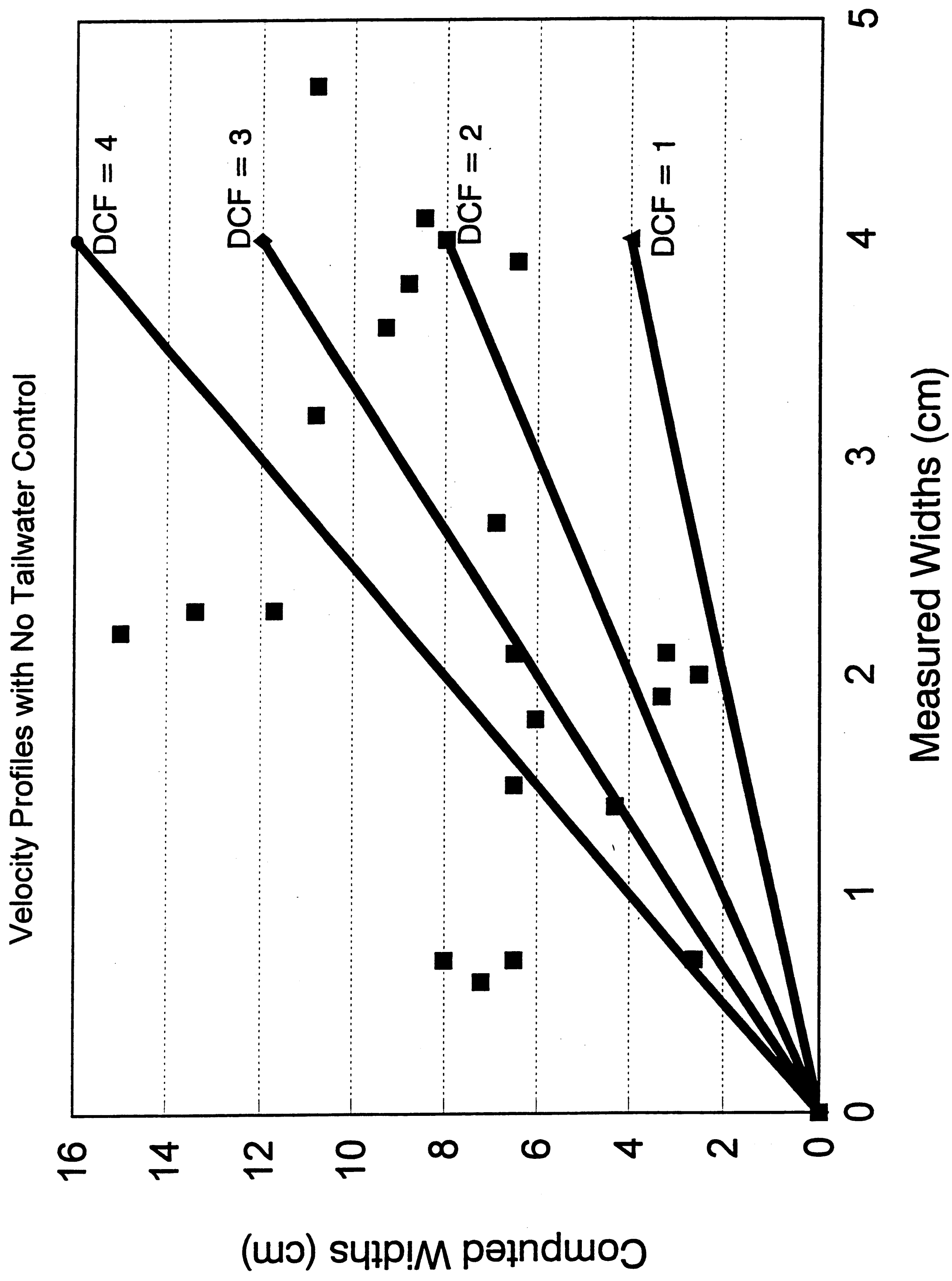


Figure 4.6 Downs Correction Factor for width adjustment

Chapter 5
SUMMARY AND CONCLUSIONS

5.1 Summary

The primary objectives of this research were to: (1) measure the cross-sectional velocity distributions in four metal culverts of different diameters and corrugations; and (2) to develop an empirical method of predicting velocity distributions in larger diameter culverts. The velocity distributions measured for the experimental culverts were often non-symmetrical about the centerline, it was not possible to predict the exact two-dimensional velocity distributions. Because of this asymmetry, the areas between the velocity contour lines were converted to symmetrical ring-shaped bands which were then used to create an "effective" two-dimensional velocity distribution. This effective velocity distribution represents average band widths of a given velocity range that could be expected in the culvert, which may be the important design parameter in juvenile fish passage.

Two equations were used to predict the thicknesses of the bands in the effective cross-section based on the centerline velocity distribution. The first equation was the Chiu equation (Equation 2.14) and the second equation was the Mountjoy equation (Equation 2.11). Since the effective band widths were symmetrical, effective velocity distribution cross-sections can be predicted. The equation which provides the best fit allows for the effective velocity distribution in any annular corrugated, circular culvert to be predicted.

5.2 Conclusions

The Mountjoy equation was the more accurate method of predicting effective band widths. The Mountjoy equation provided a better fit to the experimental data than did the Chiu equation for most of the experimental runs. Furthermore, in the runs where the Chiu equation was more accurate, the fit provided by the Mountjoy equation was not significantly worse.

The fit provided by the Chiu equation was improved with the selection of a best fit entropy parameter (M). However, according to Chiu (1995) the value of M is constant for a channel section regardless of discharge and flow depth. Since no relationship was found which would enable the prediction of the best fit M, the constant value of M was used.

The fits provided by each equation did not appear to be affected by the downstream control. The experimental runs covered a wide range of discharge (0.0052 to 0.1274 m^3/s (0.1836 to 4.499 cfs)), relative depth ($0.17*D_o$ to $0.79*D_o$), and slope (0.5% to 5.0%) combinations for each of the test culverts. Both the Mountjoy equation and the Chiu equation provided reasonable fits to the experimental data regardless of the experimental condition experienced.

5.2.1 Limitations of Conclusions

The results obtained in this study and the conclusions drawn from these results are valid only for circular, metal culverts with annular corrugations. This research also concentrated solely on the hydraulic conditions in the culvert. Juvenile fish passage may be impacted by other factors, such as high sediment load and temperature, which were not included in this study.

5.3 Recommendations for Further Studies

The WDFW is currently conducting research related to the swimming capabilities of juvenile fish in highway culverts. Preliminary results indicate juvenile salmon, approximately 63 mm (2.5 inch) long, will not pass in velocities greater than 36.6-39.6 cm/s (14.4-15.6 in/s) or slopes greater than 1% (Powers, 1995). The final results should be combined with this study to provide better design criteria. It is also recommended that research be performed into ways of providing acceptable velocities for juvenile fish in existing culverts. Finally, field studies could be conducted in cooperation with the WDFW to examine the juvenile fish in their natural habitat. The hydraulic effects of approach velocities, downstream conditions, and unsteady flow could be examined.

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