REVIEW OF LABORATORY EXPERIMENTS AND COMPUTER MODELS FOR BROKEN-BOX CULVERTS

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by

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15. Abstract

The Oklahoma Department of Transportation plans to replace more than 120 box culverts located on Interstate Systems, National Highway Systems, and State Transportation Systems. Severe scour and erosion problems are observed around and downstream of box culverts. This report presents two simultaneous efforts of laboratory analyses and analytical tools using softwares applicable to box culverts.

A review of literature indicates that a research program was made in both laboratory analysis and software development over the last twenty years. However, the laboratory data collection and analysis did not focus on analyzing the box culvert problems. It pertained to individual pieces of hydraulics of drop structures and hydraulic jump. The effort on software development is more recent, in less than past ten years. This report includes a review of detailed data analysis and three softwares developed by the Federal Highway Administration, the Nebraska Department of Roads, and the Iowa Department of Transportation.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yds
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.00155	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectacres	ha	ha	hectacres	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallon	3.785	liters	L	L	liters	0.2642	gallon	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Fahrenheit	9/5(°C)+32	degrees Celsius	°F
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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I. Introduction

The state of Oklahoma has been facing the problem of water scour in and around culverts. To date, the Oklahoma Department of Transportation (ODOT) has identified 121 scour-critical culverts throughout the state. These culverts are located on interstate, national, and state highways. This paper has chosen two of these scour-critical culverts to evaluate. The evaluation process consists of using the in situ parameters, i.e. discharge, culvert dimensions, etc., in various formats to determine the effectiveness of the current culverts to dissipate water energy and to determine what changes may be needed to improve water scour conditions. These formats include design examples derived by Emily Larson, a graduate student from Washington State University, and computer programs developed by such entities as the Nebraska Department of Roads, the Federal Highway Administration, and the Iowa Department of Transportation.

Larson (2004) proposes forcing hydraulic jumps in the outlet section of the culvert to reduce the water's energy and thus reducing the energy available for water scour. This idea of forcing a jump pertains to the addition of an exit weir. An exit weir aids in the formation of a hydraulic jump by eliminating the need for tailwater, which is crucial for the hydraulic jump. Her designs look at two types of culvert layouts that force this jump to form. The first of which is a flat apron the lies at the end of the sloped inlet section and the second has a vertical drop located just after the sloped inlet section of the culvert. Both designs were tested with and without exit weirs to determine the weir's effectiveness in reducing the water's ability to cause scour. From these experiments, she was able to derive a set of equations that are used to aid designers.

Computer programs have been found to be a means by which a designer can determine a close approximation of what culvert design is viable in a given situation. These programs also have the ability to determine the effectiveness of existing culverts and predict whether or not changes can be made to dissipate the water's energy, which reduces the potential for water scour at the outlet of the culvert. These programs include the Broken-back Culvert Analysis Program version 40 (BCAP 40) (1998), HY 8 Energy Model (2000), and IOWA Culvert Hydraulics version 2.0 (2005). Each of these programs have inherent pros and cons associated with them. This means that it is the responsibility of the user to determine if the derived culvert designs meet city, state and federal requirements and regulations.

II. Literature Review

The area of water scour in and around culverts has been gaining interest among state departments of transportation (DOT) over the last two decades. This interest is focused mainly in the area of prevention. The prevention is directly related to the reduction of the water's energy. Since this is relatively a new topic of concern, little work has been done to research the different approaches in solving the current issue. Reviews of the documents that have done or completed work in the area of water scour are summarized in the following section.

Hotchkiss (2001) suggests the use of Broken-back culverts. A Broken-back culvert has one or more breaks in its profile slope and is most often used in areas of high relief and steep topography (Hotchkiss, 2001). These "broken" profiles aid in the reduction of the water energy. A typical profile consists of a beginning flat slope followed by a relatively steep slope, which connects to another flat slope. This layout can force a hydraulic jump to form, which in return decreases the water velocity, thus decreasing the energy present for scour. The methods Dr. Hotchkiss uses to derive the correct profile include the Broken-back Culvert Analysis Program (BCAP) in conjunction with Federal Highway Administration's (FHWA) HY 8 computer software.

The *Simple Methods for Energy Dissipation at Culvert Outlets* (2005) by Hotchkiss and Larson researches the possibility of reducing water scour around a culvert by controlling the water at the outlet. This project examined the effectiveness of a simple weir near the culvert outlet against a culvert having a weir with a drop upstream in the culvert barrel. The area of focus for these examinations deal entirely with the hydraulic jump that was or was not formed. Properties of the jump that were looked at include the geometry and effectiveness in energy reduction. The two designs are intended to reduce the flow energy at the outlet by inducing a hydraulic jump within the culvert barrel, without the aid of tailwater (Hotchkiss and Larson, 2005). These reductions are looked at in terms of the associated Froude numbers. For this work, the range of Froude numbers was from 2.6 to 6.0. It was determined that both forms of outlet control were able to reduce the water velocity, thus reducing energy and momentum.

Transition from Supercritical to Subcritical Flow at an Abrupt Drop (1991) investigates the pressure on the face of the vertical drop in the case of maximum wave due to the presence of a hydraulic jump. In addition to pressure conditions, the hydraulics of the jump is examined. Using the results from their experiments, the authors developed a graphical means to determine the channels ability to produce a worthwhile hydraulic jump.

When considering the effectiveness of a vertical drop structure within a culvert, the flow characteristics at the drop must be addressed. *Flow Characteristics at Drops* (Beirami and Chamani, 2002), developed an empirical equation to examine the flow characteristics at the vertical drop. This equation uses the Froude number to estimate the relative energy loss for supercritical flow. The derived equation is not limited to a range of Froude numbers; therefore, it can estimate the flow characteristics of subcritical flow as well. This equation was compared to experimental data gathered by the authors and it was determined that the equation was very close to the actual lab data. The main difference has been attributed to the air entrainment and bed shear in the downstream section.

Gill (1979) developed a system for determining the flow characteristics at drops by looking at the relationships between channel depths and drop heights. This means of examining the characteristics is critical in determining the proper stilling basin design, which is needed for adequate energy dissipation. The author developed a set of equations that enable a designer to correctly design a vertical drop for a given set of conditions. A trial and error solution is required to use the preceding equations.

Larson (2004) suggests forcing hydraulic jumps to reduce the outlet. Her thesis has two design examples for consideration. The first design example involves a rectangular weir place on a flat apron and the second design has a vertical drop along with a rectangular weir. The two designs are intended to create a hydraulic jump within the culvert barrel, without the aid of tailwater, to reduce the energy of the flow at the outlet. From repeated testing procedures, Larson was able to develop a system of equations that aid in the design of energy reducing culverts. Larson found both designs are effective in reducing outlet velocity, momentum, and energy, all of which will decrease the need for downstream scour mitigation. These two designs also allow for easy access to the culverts, so that they can be maintained.

The Federal Highway Administration (FHWA) produced a manual called *Hydraulic Design of Energy Dissipators for Culverts and Channels* (1983). This manual uses the aid of drop structures and stilling basins to reduce the flow's energy as it leaves the culvert. Drop structures control the slope of the channel in such a way that the high, erosive velocities never develop (FHWA, 1983). The use of stilling basins aids in energy dissipation through the impact of the falling water on the floor, redirection of the flow, and turbulence. This manual has with it a design example that illustrates the step-by-step process involved in determining the correct design of the straight drop structure and the appropriate stilling basin.

When designing any culvert, there are certain considerations that must be addressed. The *Hydraulic Design of Highway Culverts* (2001), from the FHWA, has a listing of these special considerations. These considerations include, but are not limited to the following: erosion, sedimentation and debris control, fish passage, and flow control and measurement. Erosion is discussed as water scour at inlets and outlets and is a very important area when determining the efficiency of a culvert. Another area of concern relates to the economics of the culvert. The economics of the structure depends on its service life, comparisons between culvert and bridges, comparisons between materials and shapes, and risk analysis. This manual illustrates the need for the culvert to be feasible and be able to serve as a means of protection from water scour.

The Texas Department of Transportation (TxDOT) addresses velocity protection and control devices for culverts in the state's *Hydraulic Design Manual* (2004). This manual illustrates the need to choose the culvert based on the criteria: construction and maintenance costs; risk of failure; risk of property damage; traffic safety; environmental and aesthetic considerations; and construction expedience.

In the culvert section of the manual, there is a design procedure listed that enables the design engineer to follow a set lists of guidelines for proper culvert design and construction. This procedure involves the use of broken-back culvert to fulfill the state's requirements. Within this design, there is special attention given to the creation of a hydraulic jump, which aids in the reduction of the water's exit velocity. This reduction in velocity is directly related to a reduction in the water scour damage around the culvert outlet.

III. Culvert Hydraulics

For this project, there were two types of culverts investigated. These are broken-back and drop-box culverts. Both types of culverts are capable of dissipating energy, thus lower the effects of water scour. This research work is to determine which type of culvert is the most efficient at reducing water scour. The process of evaluation looks at different parameters that are thought to be related to the damaging effects of scour on culverts. These parameters include but are not limited to Froude number, hydraulic jump, and the water energy.

A. Broken-Back Culverts

Broken-back culverts can be classified either as single or double broken-back. A single broken-back culvert consists only of a steeply sloped section and an outlet section, where as a double broken-back culvert is comprised of an inlet section, a steeply sloped section and an outlet section (Hotchkiss and Shafer, 1998). Broken-back culverts can also have add-on aprons. These aprons add to the broken-back culverts ability to reduce the energy of the water after the flow has left the culvert. The drop-box culvert with or without energy dissipaters, i.e. weir or friction blocks, forces the formation of a hydraulic jump thus reducing the water's energy and reducing the potential for water scour. The elevation view of the each culvert is found in Figure 1. The layout of either type of broken-back culvert is important due to the nature of how the water behaves. This layout can force a hydraulic jump to form, which in return decreases the water velocity thus decreasing the amount of energy present that is available for water scour. The focus in these different layouts is concerned with control sections. A control section is defined as a point that limits the culvert's ability to pass flow and is used to calculate the headwater depth at the inlet (Hotchkiss and Shafer, 1998). For broken-back culverts, there are two distinct control sections present, one being at the inlet and the other located at the upper break. These sections are present in the double broken-back culverts where as single broken-back culverts can only be inlet controlled. A culvert that is inlet controlled is said to have greater barrel capacity to convey than the inlet, inversely is true if the section is upper break controlled, then the inlet will have greater capacity than the barrel can convey (Hotchkiss and Shafer, 1998). Once the type of control section has been established, then the water surface profile can be calculated. Either assigning critical depth at the inlet, for inlet control, or at the upper break, for upper break control, makes the calculations for finding the water surface profile possible. The FHWA has provided four different equations that aid in calculating the water depth for inlet control sections. Equations 1, 2, and 3 are for inlet control sections that are unsubmerged and Equation 4 is for those sections that are submerged.

$$\frac{HW}{D} = \frac{Hc}{D} + K\left[\frac{Q}{A * D^{0.5}}\right]^{M} - 0.5S^{2} \tag{1}$$

$$\frac{HW}{D} = K\left[\frac{Q}{A * D^{0.5}}\right]^{M} \tag{2}$$

$$Hc = Dc + \frac{Vc^{2}}{2g} \tag{3}$$

$$\frac{HW}{D} = c\left[\frac{Q}{A * D^{0.5}}\right]^{2} + Y - 0.5S^{2} \tag{4}$$

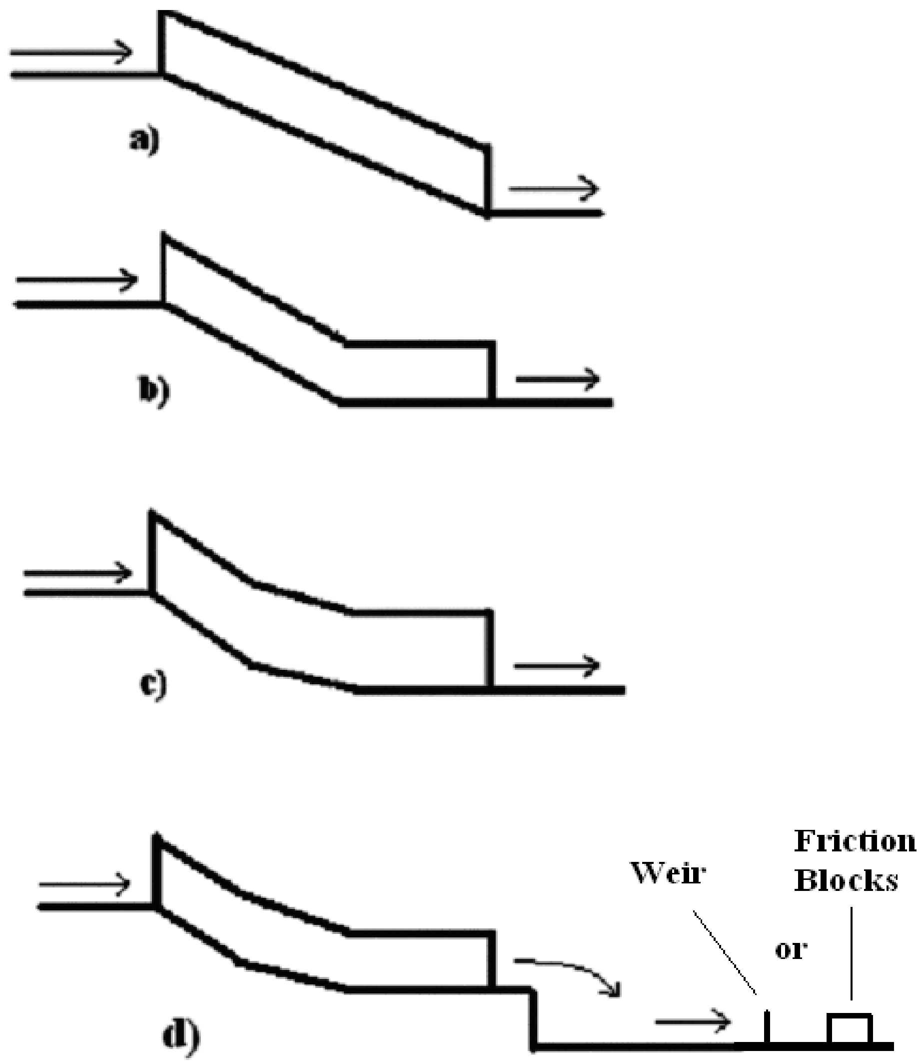


Figure 1: Types of Culverts: a) Straight Culvert, b) Single Broken Back Culvert, c) Double Broken Back Culvert, and d) Double Broken Back Culvert with drop box and weir or friction blocks.

Where:

HW = headwater depth above inlet invert, ft

D = culvert height or diameter, ft

H = specific head, ft

Dc = critical depth, ft

Vc = critical velocity, ft/sec

g = acceleration of gravity, ft/sec^2

Q = discharge, cfs

A = cross sectional area of culvert, ft^2

K, **M**, **c**, **Y** = constants

Upper break control sections also have a set of equations that are utilized to determine what the water depth is in the culvert. As with the inlet controlled broken-back culverts, the FHWA has provided two equations for calculating the water depth in upper break control sections. Equations 5 and 6 are what the FHWA has suggested for this determination process.

$$\mathbf{BCELEV = Dc + HL + UBELEV} \qquad (5)$$

$$\mathbf{HL = \left(1 + KE + \frac{29n^2 * L}{R^{\left(\frac{4}{3}\right)}}\right) * \frac{V^2}{2g}} \qquad (6)$$

Where:

BCELEV = break control elevation, ft

Dc = critical depth, ft

UBELEV = culvert upper break elevation, ft

HL = head loss, ft

KE = entrance loss coefficient

n = Manning roughness coefficient

L = inlet section length, ft

R = hydraulic radius, ft

V = full flow velocity, ft/sec

g = acceleration of gravity, ft/sec^2

Now that the water surface profile has been calculated, it is possible to determine if there will be a hydraulic jump present. The hydraulic jump shows the evidence of the reduction in the water's velocity and ability to cause scour. The presence of a hydraulic jump is evident when there is a transition from supercritical flow to subcritical flow in the runout section of the culvert. This flow transition can be attributed to a long outlet section or when there is sufficient tailwater depth (Hotchkiss and Shafer, 1998).

B. Drop-Box Culverts

A drop-box structure is a culvert that has a vertical drop located within it. Vertical drops are the most common hydraulic structure used in irrigation, water distribution, and wastewater collection networks and in recent years in stepped spillways (Chamani and Beirami, 2002). The reasoning behind a drop-box is that is will force a hydraulic jump to form downstream of the drop. This formation is due to the flow over the drop hitting the pool of water and thus changing the flow from supercritical to subcritical flow, which is required for a hydraulic jump. The hydraulic jump allows for the reduction in the water's energy, which reduces the amount of water scour at the outlet of the culvert.

When there is a lack of sufficient runout length, i.e. no jump will form, these types of culverts can be utilized to force hydraulic jumps in the barrel of the culvert. This is achieved by placing an exit weir down stream of the vertical drop. Reasoning for forcing the jump involves the stabilizing of its location without the assistance of tailwater, or subcritical flow downstream (Larson, 2004). The location of the exit weir is the controlling factor on the location and type of hydraulic jump formation.

The supercritical flow conditions over the drop can be found using equations derived by Gill (1979). These equations use the Froude number as well water depths before and after the vertical drop. Figure 2 shows the positions from which the components of the equations are observed. It should be noted that these equations do not address the hydraulic jump that forms within the culvert barrel, they pertain to the sections of the barrel before the jump occurs, but are necessary in finding the parameters associated with the hydraulic jump. The momentum and continuity principles for a control volume of flow between sections 1 and 2 (Fig. 2) yield the following relation (Chamani and Beirami, 2002):

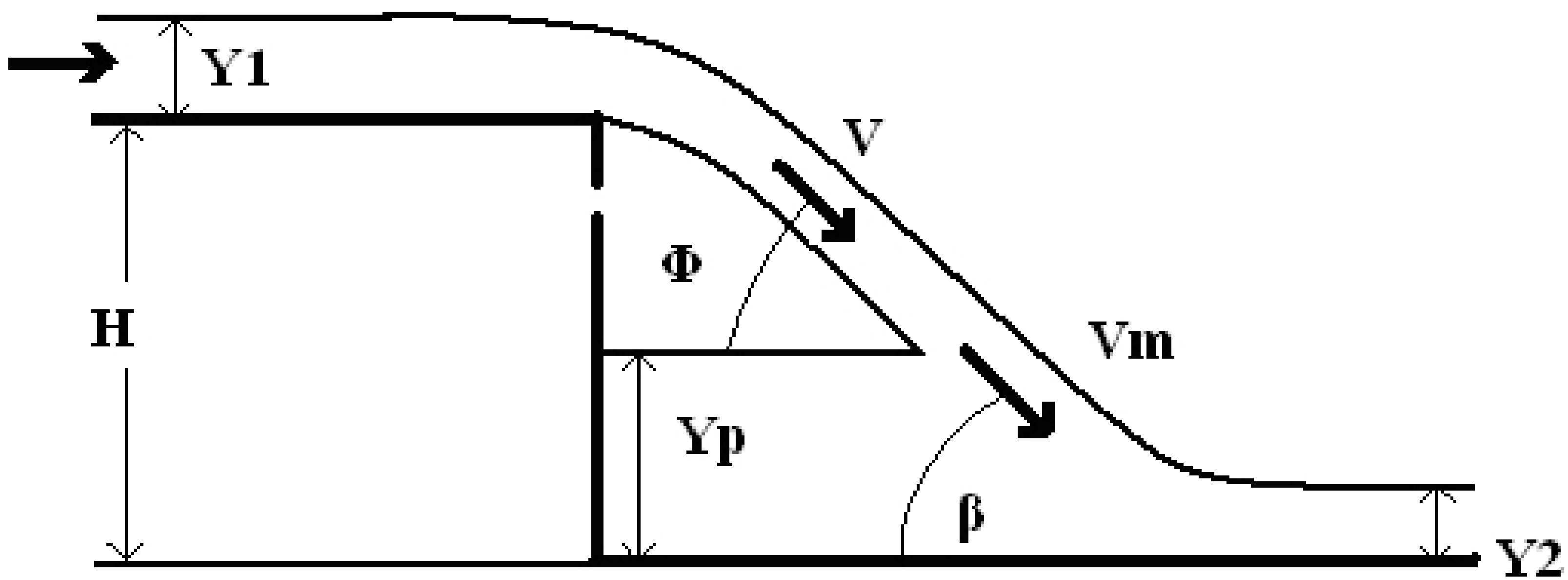
$$\frac{\mathbf{Yp}}{\mathbf{Y_1}} = \sqrt{\left(\frac{\mathbf{Y_2}}{\mathbf{Y_1}}\right)^2 + 2\mathbf{F_1^2}\left(\frac{\mathbf{Y_1}}{\mathbf{Y_2}}\right) - \left(2\mathbf{F_1^2} + 1\right)} \tag{7}$$

Where:

Y= flow depth at sections 1,2 and p

$$\mathbf{F_1} = \frac{\mathbf{V_1}}{\sqrt{\mathbf{gY_1}}}$$

V= average flow velocity at section 1



Y= flow depth at sections 1, 2 and p; **V**= average flow velocity at section 1; **β** = angle of jet at the drop base; **ϕ** = **β** = angle of jet where it hits the pool; **H**= height from drop floor to floor before the drop; $\mathbf{V_m}$ = horizontal component of the jet velocity above the pool

Figure 2: Definition sketch of flow over drop (Chamani and Beirami, 2001)

Gill argued that the jet velocity above the pool, *V*, changes to *Vm* in the thin layer below the pool (Fig. 2). Using the momentum equation in Chamani and Beirami, (2002) Gill found:

$$\mathbf{Vm} = \frac{\mathbf{V}}{\mathbf{2}}(\mathbf{1} + \mathbf{cos}\,\boldsymbol{\beta}) \tag{8}$$

Where:

β = angle of jet at the drop base

Gill further assumed that *Vm* is equal to the horizontal component of the jet velocity above the pool (Chamani and Beirami, 2002):

$$\mathbf{Vx} = \mathbf{Vm}\,\mathbf{cos}\,\boldsymbol{\phi} \tag{9}$$

Where:

ϕ = β = angle of jet where it hits the pool

To determine a relationship between *V* and the pool depth *Yp*, the energy equation is used and combined with Equation 8 to yield the following equation (Chamani and Beirami, 2002):

$$\mathbf{Vm} = \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1} + \mathbf{cos}\,\boldsymbol{\beta})\sqrt{\mathbf{2g}\left[\mathbf{Y_1}\left(\mathbf{1} + \mathbf{0.5F_1^2}\right) + \mathbf{H} - \mathbf{Yp}\right]} \tag{10}$$

Where:

H = height from drop floor to floor before the drop (Fig. 2)

The next step is to evaluate the angle Φ (or β). Rouse (1943) used the momentum equation and derived the following equation (Chamani and Beirami, 2002):

$$\frac{\mathbf{V_1}}{\mathbf{Vm}} = \frac{\mathbf{2F_1^2}}{\mathbf{1 + 2F_1^2}} \tag{11}$$

Combining Equations 9, 10, and 11 yields the following relation (Chamani and Beirami, 2002):

$$\cos\beta = \frac{\left(-1 + \sqrt{1 + \frac{8A}{\sqrt{2B}}}\right)}{2} \tag{12}$$

$$A = \frac{2F_1^2}{\left(1 + 2F_1^2\right)}$$

$$B = \sqrt{\left(1 + 0.5F_1^2 + \frac{H}{Y_1} - \frac{Y_P}{Y_1}\right)}$$

Where:

H = height from the bottom of the drop to the top (Fig. 2)

Finally, the energy equation of Gill's method (1979) yields (Chamani and Beirami, 2002):

$$Y_2^3 - \frac{1}{2g}\left(V_m^2 + 2gY_P\right)Y_2^2 + \frac{q^2}{2g} \tag{13}$$

The above-mentioned equations are used in the iteration process of finding the depth of the pool of water that forms below the vertical drop. The process of iteration is continued until the estimated value of the pool depth matches the calculations. To find the flow depth above the drop at section 1 the following equation is utilized:

$$\mathbf{Y_1 = \left(\frac{q^2}{gF_1^2}\right)^{\frac{1}{3}}}$$

In this equation, the Froude number and the amount of flow are the known values needed to find the water depth before the vertical drop. The results from the energy equation iteration process are utilized in the determination of the location of the exit weir. The steps involved in finding the location of the exit weir are examined in the Laboratory Methodology section of this report.

IV. Laboratory Methodology

This section refers to the culvert design methods as well as the computer programs involved in the evaluation process. Emily Larson (2004) has an iterative process for the designing of two different types of culverts that force a hydraulic jump. They are referred to as Design I and II. Both designs use the addition of an exit weir to force the formation of a hydraulic jump, which allows for a reduction in the water energy available for water scour. Exit weirs are not the only option for energy dissipation, the addition of friction blocks has been proven to aid in the culverts ability to dissipate energy. These friction blocks are examined by the HY 8 program, which is discussed in this section. Design I has a flat layout where as Design II incorporates a vertical drop structure. Once a culvert design has been established, the process of evaluating the effectiveness of the culvert's ability to reduce water scour can be preformed. Computer modeling does this process. The suggested models for this evaluation include the Broken-back Culvert Analysis Program version 40 (BCAP 40) (1998), HY 8 Energy Model (2000), and IOWA Culvert Hydraulics version 2.0 (2005).

Larson Design Examples

The design processes in this section were devised by Emily Larson (2004) for her Master's dissertation at the University of Washington. She designed and set up experiments that were used to evaluate both of the design's ability to reduce the water's energy through the culverts. She then developed a series of iterative equations that allow an individual to design a culvert that is pertinent to the given hydraulic conditions. The purpose of her design examples is to provide a more viable and cost effective means of reducing water scour in and around culverts.

Design I

Design I consists of a flat, rectangular culvert that has an exit weir. Figure 3 illustrates a profile view of the proposed design example. The weir height and location are the variables tested in the experimental process. These two parameters are important due to the nature of the hydraulic jump that forms. For this set up, submerged, complete and standing wave hydraulic jumps were evaluated. This process of evaluation compares the approach momentum with the outlet momentum. The specific momentum function was used to find the approach and outlet momentum (Larson, 2004):

$$\mathbf{M} = \frac{\mathbf{q}^2}{\mathbf{g} * \mathbf{y}} + \frac{\mathbf{y}^2}{\mathbf{2}} \tag{14}$$

M = specific momentum, ft^2

y = flow depth, ft

g = acceleration of gravity, ft/sec^2

q = rate of flow, cfs

Larson (2004) found that for equal approach momenta jumps forced by a weir had a lower outlet momenta than an apron with no appurtenances. Along with the momentum comparison, Larson (2004) also examined the values of dimensionless energy at the same two locations. The results were the same as with the momenta, there had been a dissipation of the energy due to the addition of the exit weir. Dimensionless energy was calculated by Equations 15 and 16, as given below:

$$\mathbf{y'} = \frac{\mathbf{y}}{\mathbf{y_C}} \tag{15}$$

$$\mathbf{E'} = \mathbf{y'} + \frac{\mathbf{1}}{\mathbf{2} * (\mathbf{y'})^2} \tag{16}$$

Where:

$\mathbf{y}$ = water depth at the section, ft

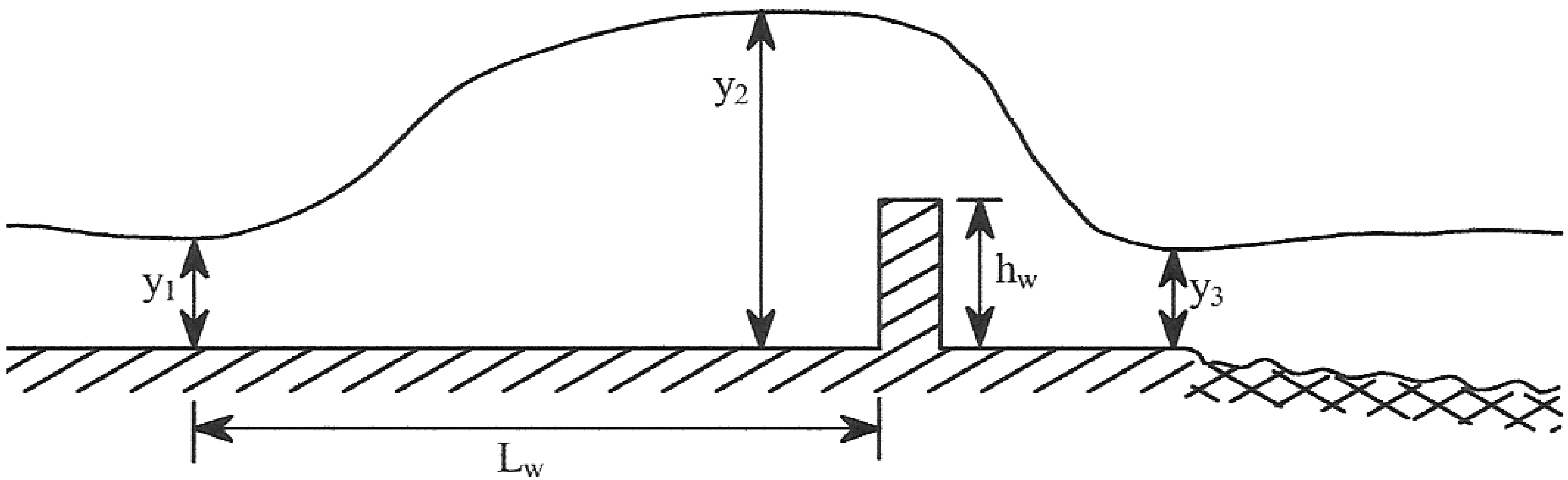
$\mathbf{y_c}$ = critical depth, ft

$\mathbf{y'}$ = dimensionless water depth

$\mathbf{E'}$ = dimensionless energy

Design I Example Problem

Larson (2004) devised a set of equations that use an iterative process to arrive at a final, acceptable Design I layout. This example problem utilizes known in situ parameters such as discharge, Froude number, culvert width, and the acceleration due to gravity to develop the appropriate culvert layout. This designed layout determines the needed weir height as well as where it is located. Since the apron is considered horizontal, the location of the weir has a calculated distance from where the change in slope of the culvert becomes flat. The following set of equations are used to calculate these unknowns and is taken from directly from the Larson paper:



y_1 = approach depth

y_2 = flow depth just upstream from weir

y_3 = downstream flow depth

L_w= distance from jump toe to weir

h_w= weir height

Figure 3: Design I Layout (Larson, 2004)

Given:

$$\mathbf{Q = 500\frac{ft^3}{sec}}$$ Design Discharge

$$\mathbf{Fr_1 = 4.5}$$ Froude Number at the Break

$$\mathbf{B = 14\ ft}$$ Culvert Width

$$\mathbf{g = 32.174\frac{ft}{sec^2}}$$ Acceleration of Gravity

Procedure:

1. Use known design parameters to calculate approach and critical depth:

$$\mathbf{y_1 = \sqrt[3]{\frac{\left(\frac{Q}{B}\right)^2}{Fr_1^2 * g}}} \quad \mathbf{y_1}=1.25\text{ft}$$ Depth of Flow at break

$$\mathbf{y_c = \sqrt[3]{\frac{\left(\frac{Q}{B}\right)^2}{g}}} \quad \mathbf{y_c}=3.41\text{ft}$$ Critical Depth

2. Use approach Froude number and approach depth to find sequent depth:

$$\mathbf{y_2 = \frac{y_1}{2} * \left(-1 + \sqrt{1 + 8Fr_1^2}\right)} \quad \mathbf{y_2}=7.36\text{ft}$$ Sequent Depth

3. Use the following equation to determine weir height:

$$\mathbf{h_w = y_1\left(0.0331 * Fr_1^2 + 0.4385Fr_1 - 0.6534\right)}$$

$\mathbf{h_w}$=2.49ft Weir Height

4. Use the following equation to determine distance between change in slope and weir:

$$\mathbf{L_w = 5 * y_2} \quad \mathbf{L_w}=36.801\text{ft}$$ Distance between break in slope and weir

5. Solve the following equation to determine outlet depth: (It should be noted that there will be three answers to the following, but the correct answer will be between zero and the critical depth.)

$$\mathbf{h_w + y_c + \frac{V_c^2}{2g} = y_3 + \frac{\left(\frac{Q}{2y_3}\right)^2}{2g}} \quad \mathbf{y_3}=1.856\text{ft} \qquad \text{The predicted outlet depth}$$

6. Adjust the predicted outlet depth with the following:

$$\mathbf{y_{3Adjusted} = 1.23 * y_3 + 0.05ft} \quad \mathbf{y_{3Adjusted}}=2.333\text{ft} \qquad \text{Adjusted outlet depth}$$

7. Use adjusted outlet depth, culvert width, and design discharge to determine the outlet conditions:

$$\mathbf{V_3 = \frac{Q}{B * y_{3Adjusted}}} \quad \mathbf{V_3}=15.309\text{fps} \qquad \text{Outlet Velocity}$$

$$\mathbf{Fr_3 = \frac{V_3}{\sqrt{g * y_{3Adjusted}}}} \quad \mathbf{Fr_3}=1.767 \qquad \text{Outlet Froude \#}$$

$$\mathbf{E_3 = y_{3Adjusted} + \frac{V_3^2}{2g}} \quad \mathbf{E_3}=5.975\text{ft} \qquad \text{Outlet Energy}$$

1. Design II

This culvert type consists of a horizontal approach layout that has within it a vertical drop structure with an exit weir located a distance downstream from the drop. Figure 4 is an illustration of the horizontal channel layout. The focus of this structure pertains to the vertical drop as well as the exit weir. These two parameters are vital in reducing the water's energy thus reducing the damage due to water scour. As with the Design I culvert, the process of evaluating the effectiveness of the culvert is done by calculating the approach, outlet energy and momenta then making a comparison based on the results. Equations 14 and 16 are utilized for this process. Larson's (2004) research concluded that the Design II structure dissipated momentum, energy, and velocity more effectively than an apron with no appurtenances.

Design II Example Problem

Using the results from experimentation, Larson (2004) was able to derive a set of equations that can be utilized to determine a culvert layout that is effective in reducing water scour. This process utilizes the same know parameters as the Design process, but this iterative process is far more involved due to the nature of the unknowns. This step-by-step determination is utilized to calculate the height of the vertical drop, the height and location of the exit weir and the outlet conditions of depth, velocity and energy. The following ten step iterative procedure was taken from Larson's (2004) research paper:

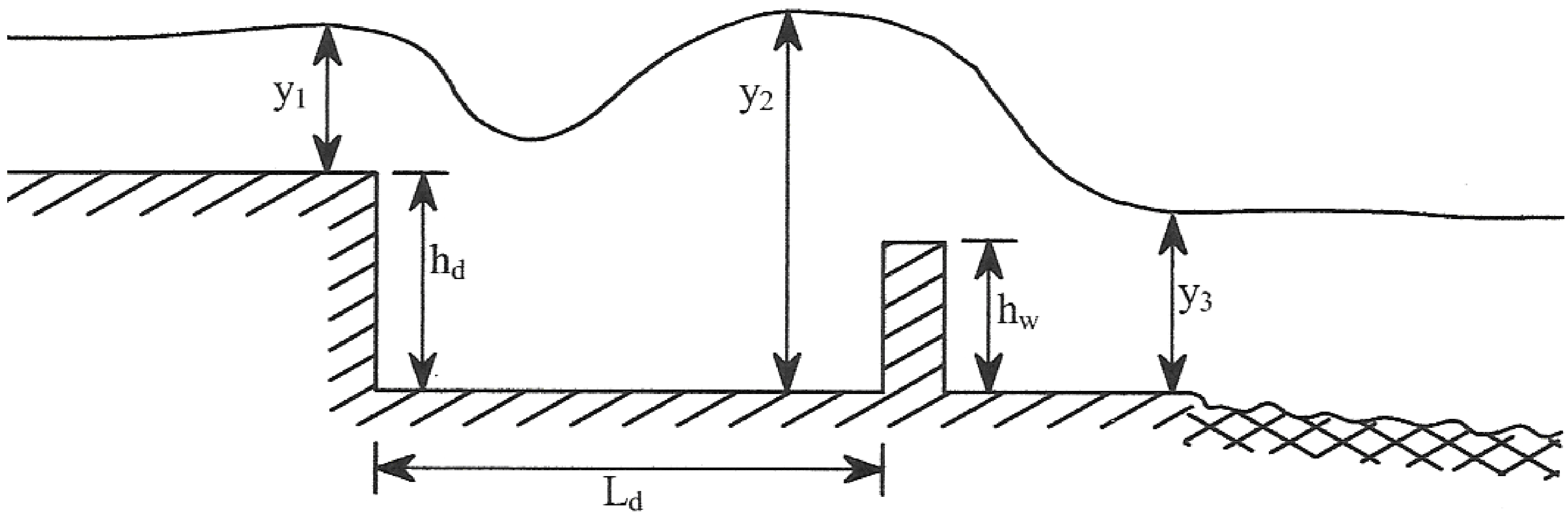
Given:

$\mathbf{Q = 500 \frac{ft^3}{sec}}$ Design Discharge

$\mathbf{Fr_1 = 4.5}$ Froude Number at the Break

$\mathbf{B = 14\ ft}$ Culvert Width

$\mathbf{g = 32.174 \frac{ft}{sec^2}}$ Acceleration of Gravity



$\mathbf{y_1}$ = approach depth

$\mathbf{y_2}$ = flow depth just upstream from weir

$\mathbf{y_3}$ = downstream flow depth

$\mathbf{h_w}$ = weir height

$\mathbf{h_d}$ = height of drop

,$\mathbf{L_d}$ = distance from drop to weir

Figure 4: Design II Layout (Larson 2004)

Procedure:

1. Use known design parameters to calculate approach and critical depth:

$$\mathbf{y_1} = \sqrt[3]{\frac{\left(\frac{\mathbf{Q}}{\mathbf{B}}\right)^2}{\mathbf{Fr_1^2 * g}}}$$ $\mathbf{y_1}$=1.25ft Depth of Flow at break

$$\mathbf{y_c} = \sqrt[3]{\frac{\left(\frac{\mathbf{Q}}{\mathbf{B}}\right)^2}{\mathbf{g}}}$$ $\mathbf{y_c}$=3.41ft Critical Depth

2. Use approach Froude number and approach depth to find sequent depth:

$$\mathbf{y_2} = \frac{\mathbf{y_1}}{\mathbf{2}} * \left(-\mathbf{1} + \sqrt{\mathbf{1} + \mathbf{8Fr_1^2}}\right)$$ $\mathbf{y_2}$=7.36ft Sequent Depth

3. Select a desired outlet Froude number (Figure 5), and use this with design discharge and culvert width to find outlet flow depth:

   $\mathbf{Fr_3}$=1.677

   Selected outlet Froude # is 5.

$$\mathbf{y_3} = \sqrt[3]{\frac{\left(\frac{\mathbf{Q}}{\mathbf{B}}\right)^2}{\mathbf{Fr_3^2 * g}}}$$ $\mathbf{y_3}$=2.416ft Selected Outlet Depth

4. Use selected outlet Froude number and depth to estimate weir height:

$$\mathbf{h_w} = \frac{\mathbf{y_3}}{-\mathbf{1.23} * \mathbf{Fr_3} + \mathbf{2.91}}$$ $\mathbf{h_w}$=2.851ft Weir Height

5. Use the following equation to determine distance between the drop and weir:

$$\mathbf{L_d} = \mathbf{6}(\mathbf{y_c} + \mathbf{h_w})$$ $\mathbf{L_d}$=37.565ft Distance between drop and weir

6. Use Figure 6 to determine drop height:

$$\mathbf{h_d = \frac{h_w^2}{y_1 * \left(0.9326Fr_1^2 - 6.8218Fr_1 + 14.859\right)}}$$

$\mathbf{h_d}$=2.133ft Predicted Drop Height

7. Solve energy equation for outlet depth: (It should be noted that there will be three answers to the following, but the correct answer will be between zero and the critical depth.)

$$\mathbf{h_w + y_c + \frac{\left(\frac{Q}{By_c}\right)^2}{2g} = y_3 + \frac{\left(\frac{Q}{2y_3}\right)^2}{2g}}$$ $\mathbf{y_3}$=1.923ft Predicted Outlet

Depth, no energy loss

8. Adjust predicted outlet depth for energy loss:

$\mathbf{y_{3Adjusted} = 1.23 * y_3 + 0.05ft}$ $\mathbf{y_{3Adjusted}}$=2.415ft Adjusted Outlet Depth

9. Use adjusted outlet depth, culvert width, and design discharge to determine outlet conditions:

$$\mathbf{V_3 = \frac{Q}{B * y_{3Adjusted}}}$$ $\mathbf{V_3}$=14.787fps Outlet Velocity

$$\mathbf{Fr_3a = \frac{V_3}{\sqrt{g * y_{3Adjusted}}}}$$ $\mathbf{Fr_3a}$ =1.677 Outlet Froude #

$$\mathbf{E_3 = y_{3Adjusted} + \frac{V_3^2}{2g}}$$ $\mathbf{E_3}$=5.813ft Outlet Energy

10. Iterate until Froude number in step 9 matches outlet Froude # in step 3.

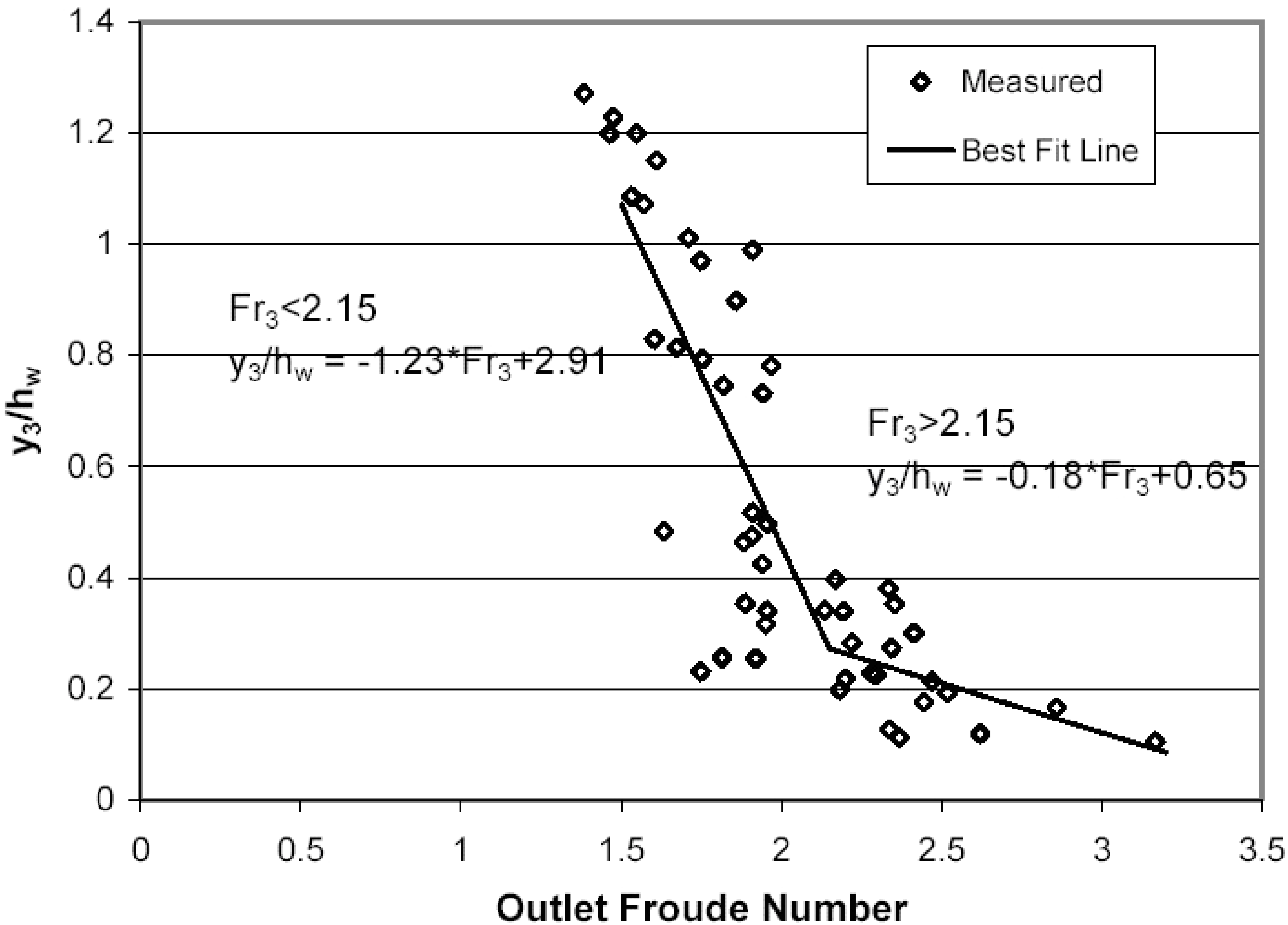


Figure 5: Outlet Froude number determination (Larson, 2004)

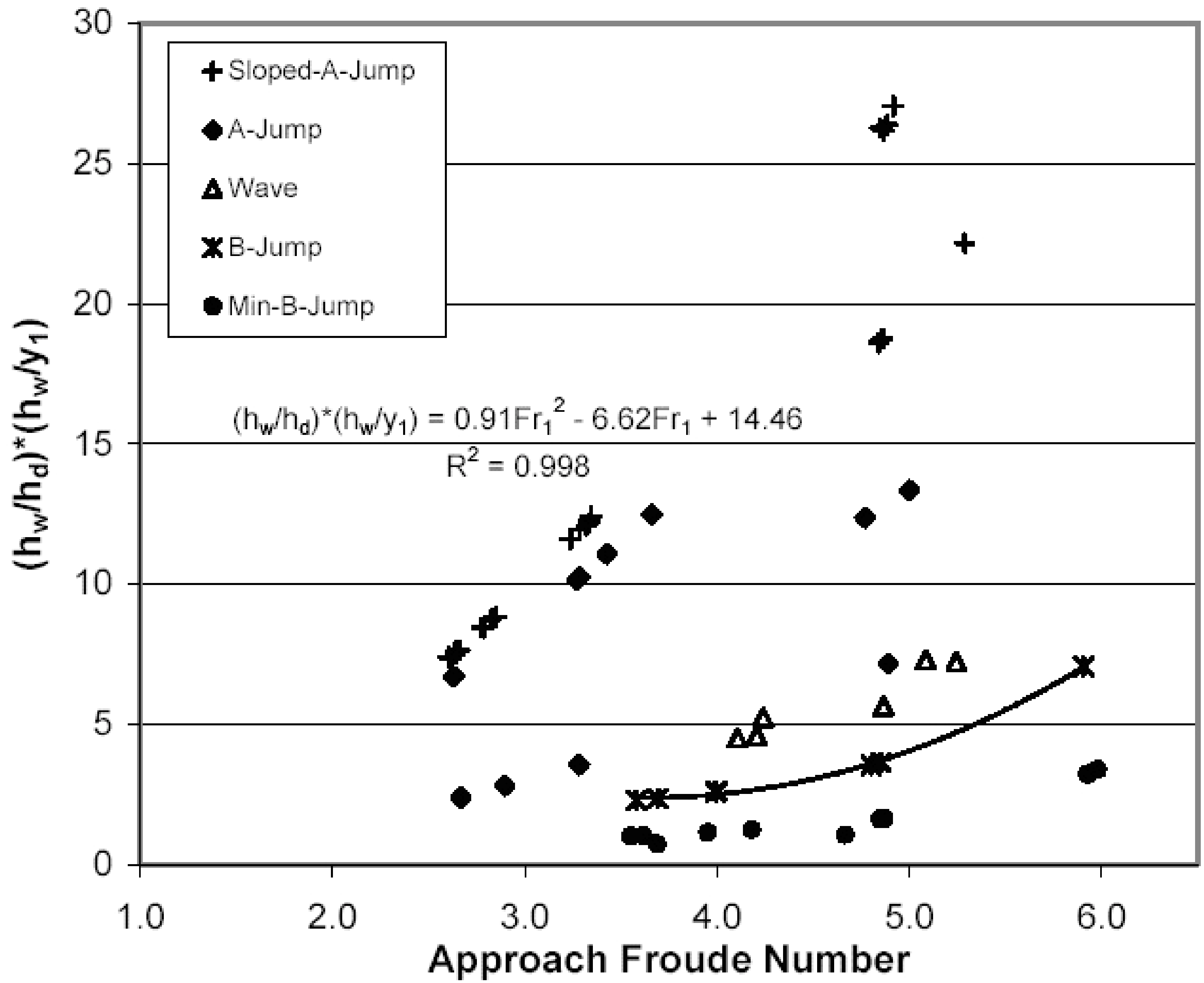


Figure 6: Hydraulic Jump Geometry. The fitted polynomial is for design. (Larson, 2004)

Design I and II experimental conclusions

Larson (2004) determined from her work, that both the Design I and II configurations dissipated energy and momentum, thus reducing the water's exit velocity, which in return reduced the amount of water scour around the culvert outlet. Design I dissipates more energy than Sloped A-jumps and A-jumps, and less than B-jumps and Minimum B-jumps observed in Design II tests (Larson, 2004). Her work also concluded that both the Design I and II with appurtenances dissipated far more effectively than both designs without exit weirs present.

V. Computer Modeling Softwares

There have been many computer programs developed over the years, which aid engineers in the designing and evaluation of certain types of culverts. This section looks at three such programs. These programs can be utilized to evaluate in situ culvert conditions or to determine if a proposed design is viable. Computer modeling has been found to reduce the time needed in the design and evaluation process of engineering work. But it is at the user's discretion to decide which software is appropriate to any given condition. This section of the report evaluates the software and gives the reader a since of what may or may not be a viable solution to the problem of water scour in and around culverts.

A. Broken Back Culvert Analysis Program v. 40 (1998)

The first program examined was the Broken-back Culvert Analysis Program (BCAP 40), which was developed by Hotchkiss and Shafer in 1998. Hotchkiss and Shafer verified the results from the BCAP software by running a series of experiments that simulated the BCAP input parameters. These experiments involved the use of a four-inch Plexiglas, double broken-back culvert that was set at different channel slopes and had different values of flow passing over the structure to simulate a scale model of the inputs into the BCAP program. This program has only one input screen that enables the user to enter the project name, discharge, culvert, culvert profile, and tailwater data. BCAP uses this information, through a series of equations to develop an output screen that lists the following: headwater depth; inlet control elevation break control elevation; critical depth; tailwater depth; occurrence of a hydraulic jump; hydraulic jump location (if occurred); hydraulic jump length (if occurred); outlet depth; outlet velocity; and outlet Froude number

Once the outputs were generated, the collected data was then compared to the actual culvert condition. The flow and tailwater depth along with the headwater and outlet depths were recorded and then compared to the BCAP results. These results show that BCAP is capable of predicting the headwater depth and outlet depth for a range of flows in the prototype.

The BCAP program is not without its limitations. In some cases, the headwater was less than the predicted value. They felt this problem could be due to the formation of a vortex at the inlet. The vortex easily formed when two inches of water covered the inlet, but would not likely form with two feet of water. This program is also designed for culverts that are to be placed in high relief areas. It was when the slopes of the double broken-back culverts were to small, that the program could not correctly generate the required outputs. BCAP was also only designed for box or circular culverts, which leaves the designer with limitations in the number of choices for the geometry of the culvert. Another design limitation was only being able to design culverts less than 55 degrees.

B. HY8 Energy Model (2000)

The second program is the Hydraulic Design 8 Energy Model (HY 8), which was created, in 2000, by the Federal Highway Administration (FHWA). This program is utilized to develop the appropriate means of energy dissipation through different types of culverts. The program is capable of examining circular and rectangular culverts. The inputs for this program include: shape, flow, velocity, diameter, channel slope, peak duration, and drop height, if one exists. Once this information has been entered, HY 8 will produce an output screen that has various parameters that can be presented. The program has a choice of options that include determining the size of the scour hole that will be produced and how to internally or externally reduce the water's energy before it leaves the culvert. Choosing the *Scour* option will provide details on the length, width, volume and depth of water present. The *Internal* and *External* option provide the user with a series of energy dissipation methods on how to reduce the formation of a scour hole. These methods include drop inlets, straight drops, friction blocks, riprap basins, contra costa basins and hook basins. It is at the user's discretion on which type of energy dissipators is appropriate to an individual situation.

There are a few concerns that need to be addressed concerning the HY 8 program. This program does not have an option to choose what the surface roughness of the culvert in question. If the evaluation process is looking at an already constructed culvert, then this becomes a problem. HY 8 will consider the culvert surface roughness to be the same as a new one, which in cases of extreme culvert erosion, will under estimate the amount of energy that culvert is able to dissipate. This program does not produce an exit Froude number. This can be an issue when trying to determine if the presence and type of hydraulic jump is taking place in the outlet section of the culvert. Hydraulic jumps are another area of concern. HY 8 is not capable of determining if the dissipator selected can produce a hydraulic jump. One last area of concern deals with determining if a given dissipator is feasible or not. The program labels each dissipator type as questionable or feasible. HY 8 does not specify to what extent an energy dissipator is questionable or feasible. It is for these reasons that it up to the user to make the final decision on whether or not what type of energy dissipator is viable.

C. IOWA Culvert Hydraulics v. 2.0 (2005)

The IOWA Culvert Hydraulic Software v. 2.0 was the last computer modeling program examined. This program was developed to assist consultants, and city, county, and state engineers with the hydraulic design of culverts in Iowa (Iowa, 2001). IOWA v. 2.0 utilizes the Iowa Runoff chart, USGS Flood Frequency, Lara (1987) and USGS Flood Frequency, Eash (2001) to determine the appropriate design for given hydraulic conditions. This appropriate design is in reference to a culvert that is able to hold the capacity of water desired and at the same time provide for outlet water velocity to be a minimum. The program first calculates the design flow of the culvert by using the drainage area, land use and slope of the land. Once the flows have been calculated, the program then uses this information with the type of culvert in question to determine the depth of the tailwater. IOWA allows the user to choose from a standard Iowa Department of Transportation (IDOT) culvert, tapered inlet culvert, drop inlet culvert or a general design culvert. Once the appropriate culvert has been selected, the user must then enter all the hydraulic and geometry parameters that pertain to that particular culvert. The program then evaluates the design and the user is left with the options that IOWA has chosen. Again, it is up the party in question to determine which design will meet local standards.

IOWA computer software was developed and intended for use with the hydraulic and hydrogeologic conditions and standards in the state of Iowa. It is for this reason that the program should be used with caution. The state has different values for rainfall events and therefore will not correctly calculate the design flows for any other state. Secondly, the program is limited to small drainage areas that range from 1 to 1280 acres (2 square miles). The program is capable of evaluating areas that are bigger than two square miles, but it takes a tremendous amount of effort for the user to delineate the entire drainage area down into sections that are smaller than two square miles.

VI. Results

The following results are drawn based on review of laboratory experiments and computer models for broken-back culverts:

1. Over the past ten years the Federal Highway Administration (FHWA) and various departments of transportation (DOT) developed the broken-back culverts to dissipate energy within the box culverts and reduce degradation downstream leading to lowering of flowlines in tributaries.
2. Software "BCAP" was developed in 1998 by Washington State University that concluded that broken-back culverts do dissipate energy within the box.
3. An experimental study was conducted in 2004 at Washington State University. A culvert that uses exit weir forces a hydraulic jump without the aid of tailwater.
4. Three softwares were developed over the last decade. These include Broken-back Culverts and Analysis v. 40 (1998), HY 8 Energy Model (2000), and IOWA Culvert Hydraulic, v. 2 (2005). IOWA software contains basic hydrology and hydraulics computation for the state of Iowa DOT. The hydrologic equations are different for each state and hydraulic computations also vary for each state.
5. No experimental work has been studied in the laboratory to enhance energy dissipation using friction blocks.
6. No softwares exist that can be universal in hydrology and hydraulics.

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