NDOR Research Project Number
SPR-PL-1(33) P498

PB98-144884

Hydraulic Analysis of Broken-Back Culverts

FINAL REPORT

Jeffrey Shafer and Rollin H. Hotchkiss

Department of Civil Engineering
College of Engineering and Technology

W348 Nebraska Hall
Lincoln, Nebraska 68588-0531
Telephone (402) 472-2371
FAX (402) 472-8934

Sponsored by the
Nebraska Department of Roads
1500 Nebraska Highway 2
Lincoln, Nebraska 68509-4759
Telephone (402) 479-4337
FAX (402) 479-3884
and
Federal Highway Administration
U.S. Department of Transportation

January 1998

University of
Nebraska
Lincoln

REPRODUCED BY: NTIS
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA-NE-98-P498	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Hydraulic Analysis of Broken-Back Culverts		5. Report Date: January 1998
		6. Performing Organization Code
7. Author(s): Jeffrey Shafer and Rollin Hotchkiss		8. Performing Organization Report No. SPR-PL-1(33) P498
9. Performing Organization Name and Address: Civil Engineering Department, University of Nebraska - Lincoln, W348 Nebraska Hall, Lincoln, NE 68588-0531		10. Work Unit No.
		11. Contract or Grant No. SPR-PL-1(33) P498
12. Sponsoring Agency Name and Address: Nebraska Department of Roads, Roadway Design Division, P.O. Box 94759, Lincoln, NE 68509-4759		13. Type of Report and Period Covered: Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes: Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

A broken-back culvert is defined as a culvert in which one or more breaks occur in the culvert profile. An analysis model called Broken-Back Culvert Analysis Program (BCAP) was developed to evaluate the hydraulic performance of such culverts. BCAP uses design inputs of discharge, culvert shape, size, material, and inlet type, culvert profile and tailwater conditions to predict the headwater depth, water surface profile and outlet velocity of a broken-back culvert. Using this information, the user can determine if the culvert is operating satisfactorily or if it needs to be modified by either altering the culvert design or adding an energy dissipator to the culvert. An important feature of BCAP is the ability to predict the occurrence, location, and length of hydraulic jumps inside broken-back culverts. Model results compared favorably to those from tests completed in the Hydraulics Laboratory at the University of Nebraska-Lincoln and to compatible tests from the Federal Highway Administration computer program HY8.

17. Keyword: Culverts, hydraulic design		18. Distribution Statement: No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classification (of this report): Unclassified	Security Classification (of this page): Unclassified	21. No. of Pages: 82	22. Price

Form DOT F 1700.7 (8-72)

EXECUTIVE SUMMARY

A broken-back culvert has one or more changes in slope in the culvert profile. A computer program called Broken-Back Culvert Analysis Program (BCAP) was developed to evaluate the hydraulic performance of such culverts. BCAP uses design inputs of discharge, culvert shape, size, material, and inlet type, elevation profile, and tailwater conditions to predict the headwater depth, water surface profile, and outlet velocity of a broken-back culvert. BCAP also predicts the occurrence, location, and length of a hydraulic jump inside the culvert. With BCAP, designers can determine if the culvert is operating satisfactorily or if it needs to be modified by either altering the design or by adding an energy dissipator. BCAP was developed for circular pipes and box culverts, the two shapes likely to be used in broken-back culvert design. The program has been linked to the Federal Highway Administration's HY8 computer program so that energy dissipation may be evaluated without leaving BCAP. BCAP model results compare favorably to those from tests completed in the Hydraulics Laboratory at the University of Nebraska-Lincoln and to compatible tests from the Federal Highway Administration computer program HY8.

ACKNOWLEDGMENTS

This is the final report of Project No. SPR-PL-1(33) P498, Hydraulic Analysis of Broken-Back Culverts. The research was performed for the Nebraska Department of Roads by the Department of Civil Engineering at the University of Nebraska.

The project monitor was Kevin Donahoo, Hydraulics Engineer, Roadway Design Division, Nebraska Department of Roads. He coordinated the involvement of the Department of Roads in this research. His initiative, interest, and follow through is greatly appreciated. The contributions of the Department of Roads' Hydraulic Committee is also gratefully acknowledged.

DISCLAIMER

The contents of this report reflect the views of the authors who are solely responsible for the findings and conclusions of the research. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Roads, the Federal Highway Administration, or the University of Nebraska - Lincoln. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i

ACKNOWLEDGMENTS ii

DISCLAIMER iii

TABLE OF CONTENTS iv

LIST OF FIGURES vi

LIST OF TABLES vii

NOTATION viii

INTRODUCTION 1

OBJECTIVE OF THE RESEARCH 3

BROKEN-BACK CULVERT HYDRAULICS 3

BROKEN-BACK CULVERT MODELING 5

- Need for Model 5
- Broken-Back Design Procedures and Models 7
- Design Considerations 10

BROKEN-BACK DESIGN PROCESS AND MODEL 14

- Evaluation Process 14
- Computer Model 19

MODEL RESULTS 26

CONCLUSIONS 27

RECOMMENDATIONS 28

- Implementation Plan 28

REFERENCES 29

APPENDIX A - LITERATURE REVIEW 31

Broken-Back Culvert Design 31

Energy Dissipation 32

Computer Models 33

APPENDIX B - CULVERT HYDRAULICS 34

Control Points 34

Flow Profile 36

APPENDIX C - PROGRAM CODE 39

General Calculations 39

Headwater Calculations 48

Profile Calculations 49

Convert.Bat Code 65

Convert.For Code 66

APPENDIX D - PROGRAM VALIDATION 69

APPENDIX E - BROKEN-BACK DESIGN PROGRAM MANUAL 73

Installation Instructions 73

Operating Instructions 73

Output Interpretation 77

Sample Input Files 79

APPENDIX F - DIRECT STEP PROFILE CALCULATION RESULTS 80

LIST OF FIGURES

Figure 1a. Elevation view of double broken-back culvert 2

1b. Elevation view of single broken-back culvert 2

Figure 2. Length to reach critical depth in a rectangular channel 6

Figure 3. Specific momentum curve and sequent depths D1 and D2 8

Figure 4. Length to reach normal depth in a rectangular channel 9

Figure 5a. Outlet depth when hydraulic jump occurs 17

5b. Outlet depth when no hydraulic jump occurs 17

Figure 6. Single and double broken-back culvert analysis flowchart 18

Figure 7. Elevation view of broken-back culvert testing equipment 27

Figure B.1. S2 profile curve 37

Figure B.2. A3, H3, and M3 profile curves 37

LIST OF TABLES

Table 1. Minimum culvert sizes 10

Table 2. Concrete pipe and corrugated metal pipe comparison 11

Table 3. Length and slope comparisons for 150 ft long, 4 ft x 4 ft box culvert ... 13

Table 4. Outlet depth for broken-back culvert analysis 24

Table D.1. Double broken-back validation, 45 deg. bend 70

Table D.2. Double broken-back validation, 22.5 deg. bend, run 1 71

Table D.3. Double broken-back validation, 22.5 deg. bend, run 2 72

Table F.1. Length to reach critical depth, rectangular channel, Slope = 2% 80

Table F.2. Length to reach critical depth, rectangular channel, Slope = 5% 80

Table F.3. Length to reach critical depth, rectangular channel, Slope = 10% 81

Table F.4. Length to reach critical depth, rectangular channel, Slope = 20% 81

Table F.5. Length to reach normal depth, rectangular channel, Q = 100 cfs 81

Table F.6. Length to reach normal depth, rectangular channel, Q = 150 cfs 82

Table F.7. Length to reach normal depth, rectangular channel, Q = 200 cfs 82

NOTATION

A	=	area, $[L^2]$
A	=	polynomial equation coefficient, [1]
BCELEV	=	break control headwater elevation, [L]
BS	=	polynomial equation coefficient, [1]
C	=	polynomial equation coefficient, [1]
D	=	depth, [L]
D_C	=	critical depth, [L]
D_e	=	equivalent depth, [L]
DIP	=	polynomial equation coefficient, [1]
D_S	=	sequent depth, [L]
D_S	=	sequent depth, [L]
E	=	polynomial equation coefficient, [1]
F	=	polynomial equation coefficient, [1]
FR	=	Froude number [1]
FR^2_M	=	mean Froude number squared, [1]
g	=	acceleration of gravity, $[LT^{-1}]$
HL	=	head loss, [L]
ICELEV	=	inlet control headwater elevation, [L]
IE	=	culvert inlet elevation, [L]
KE	=	entrance loss coefficient, [1]
L	=	inlet section length, [L]
n	=	Manning roughness coefficient [1]
P	=	wetted perimeter, [L]
Q	=	discharge, $[L^3T^{-1}]$
q	=	unit flow, $[L^3T^{-1}/L]$
R	=	hydraulic radius, [L]
RISE	=	culvert height or diameter, [L]
S	=	channel slope, [L/L]

SF	=	friction slope, [L/L]
SF_M	=	mean friction slope, [L/L]
SO	=	inlet section slope, [L/L]
SPAN	=	culvert width or diameter, [L]
SR	=	polynomial equation coefficient, [1]
THETA	=	channel angle, radians
UBELEV	=	culvert upper break elevation, [L]
V	=	average velocity, $[LT^{-1}]$
ΔE	=	change in energy, [L]
Δx	=	change in distance, [L]
Δy	=	change in depth, [L]
Φ	=	units coefficient, [1]

INTRODUCTION

A culvert is a hydraulic structure designed to convey water under a roadway. When one or more changes of grade occur within the culvert profile, it is called a broken-back culvert. Broken-back culverts are usually placed in areas where laying a straight culvert would require large excavations or where other site conditions dictate a break should occur. Broken-back culverts may also be intended to reduce outlet velocities when normal outlet velocities are greater than desired.

A double broken-back culvert is characterized by three sections, an inlet section, a steeply sloped section, and the outlet section (Figure 1a). A single broken-back culvert consists only of a steeply sloped section and an outlet section (Figure 1b). As water flows through the steeply sloped section, it becomes supercritical or rapid. Supercritical flow occurs when inertial forces dominate the gravitational forces. If the supercritical flow continues through the outlet section, there will likely be problems with scour at the outlet and erosion in the downstream channel. Therefore, the goal of broken-back culvert design is to produce subcritical or tranquil flow within the outlet section. Subcritical flow occurs when the gravitational forces dominate the inertial forces. If a hydraulic jump occurs or is forced to occur inside the culvert barrel, then the flow at the outlet will be subcritical. It is important for the designer to know the water surface profile throughout the broken-back culvert and to be able to predict the occurrence of a hydraulic jump.

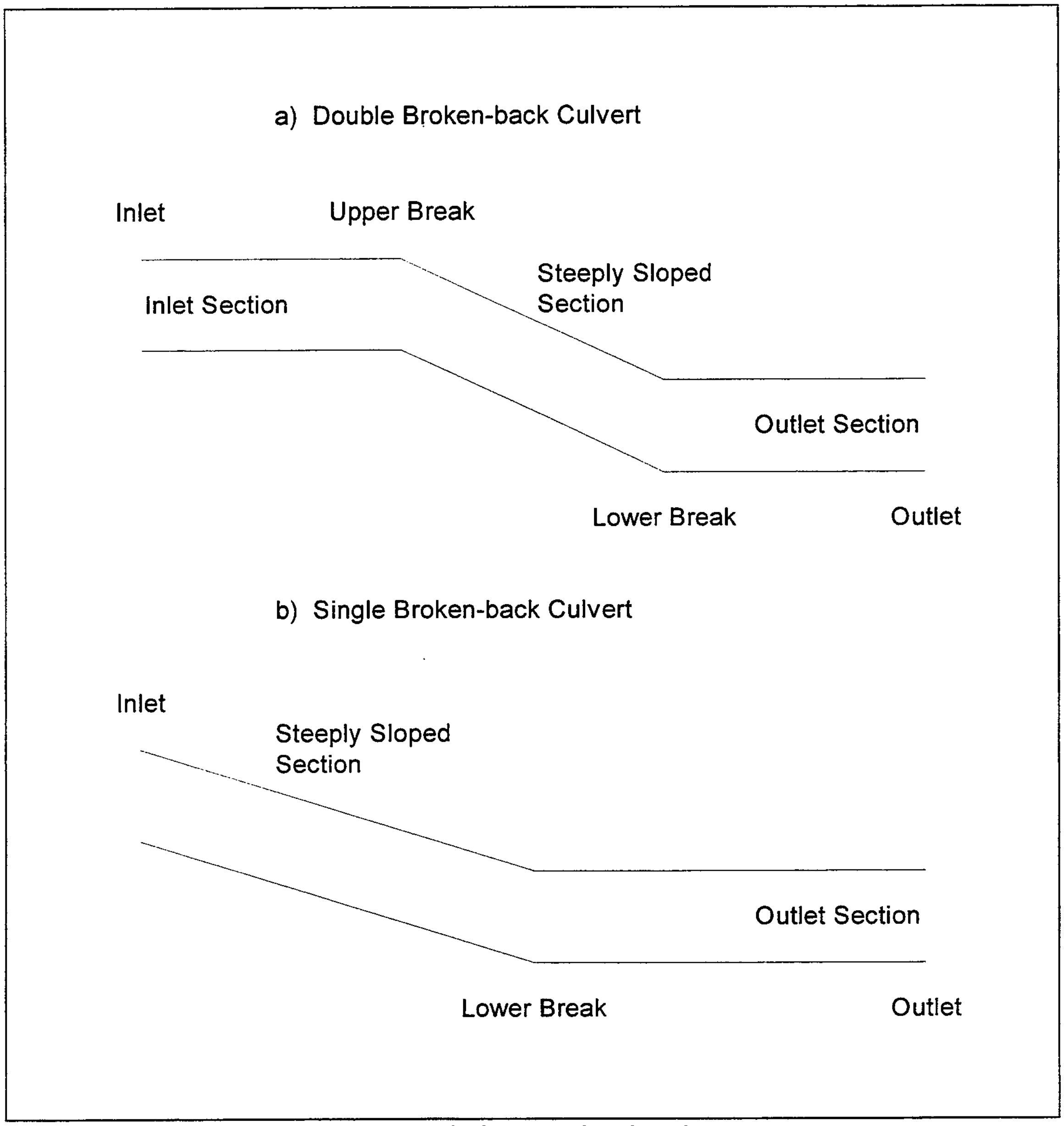


Figure 1a. Elevation view of double broken-back culvert
1b. Elevation view of single broken-back culvert

OBJECTIVE OF THE RESEARCH

The objective of this project was to provide the Nebraska Department of Roads a method for the hydraulic analysis of broken-back culverts and an accompanying computer analysis program. This report fulfills the project objective. The report is separated into a main body and appendices. The main body first presents a short background on broken-back hydraulics. Included in this section are broken-back control sections, flow profile considerations, and energy dissipation. Broken-back culvert modeling is then presented, including a review of existing models and design considerations. Next, the design process and computer program are presented, including laboratory test results. Finally, the conclusions and future directions are presented.

More detailed descriptions of the research may be found in Appendices A and B. The computer code and description are in Appendices C and D, respectively, while a user's manual is found in Appendix E. Hydraulic calculations supporting statements in the report are in Appendix F.

BROKEN-BACK CULVERT HYDRAULICS

The hydraulic properties of a broken-back culvert are similar to a straight culvert in many ways. However, there are a few differences that are important and must be considered when evaluating culvert performance. The properties include the control sections and the water surface profile calculations.

A control section is defined as a point that limits the culvert's ability to pass a flow and is used to calculate the headwater depth at the inlet. In a double broken-back culvert there are two possible control sections: the inlet and the upper break. If the inlet is the control section, the barrel has a greater capacity to convey than the inlet. If the upper break is the control, the inlet can allow more water into the culvert than the barrel will convey. The inlet control headwater depth is affected by submergence, culvert size and shape, and inlet type. The break control headwater depth is affected by the barrel size and shape, material, and inlet type.

When calculating the flow profile through the culvert, there are two possible scenarios that may occur. If the culvert is operating in inlet control, the water surface profile is calculated by assigning critical depth to the inlet and moving down the culvert. If the culvert is operating with the control at the upper break, critical depth is assigned to the break and the water surface profile is calculated from this starting point.

If the culvert is a single broken-back, there is no inlet section; therefore, the culvert will operate in inlet control, and the water surface profile can be calculated by assigning critical depth to the inlet. A complete section on culvert hydraulics can be found in Appendix B.

BROKEN-BACK CULVERT MODELING

Need for Model

The Nebraska Department of Roads (NDOR) does not have an analysis model to evaluate the hydraulic performance of broken-back culverts. Limited guidelines (NDOR Design Manual, 1996) recommend using the longest of three possible outlet section lengths:

- 10 feet
- 1.5 times the vertical drop from the inlet to the outlet
- 4 times the barrel height or diameter

The outlet section is to be set on a near zero grade. Flow profile calculations with these criteria show that these guidelines do not insure that a hydraulic jump will occur in the outlet section. Figure 2 shows the outlet section lengths needed to reach critical depth (assuring a hydraulic jump) for four-, six-, eight-, and ten-ft bottom width runout sections on a zero slope in a box culvert. The starting depth was normal depth for a steeply sloped section with a slope of ten percent . The lengths were calculated using the direct step method (French, 1985). Tables for other initial slopes can be found in Appendix F.

NDOR designers may choose to further evaluate the performance of a broken-back culvert by using direct step drawdown and backwater calculations to calculate the water surface profile. Currently, these must be done by hand, a long and tedious process. There is often insufficient time to complete the calculations, especially when there are many different possible profiles and configurations to evaluate.

NDOR designers also do not perform break control headwater depth calculations for double broken-back culverts because there is no defined procedure for doing so. This may lead to underpredicting the headwater depth and increasing the chance that the water will overtop the road.

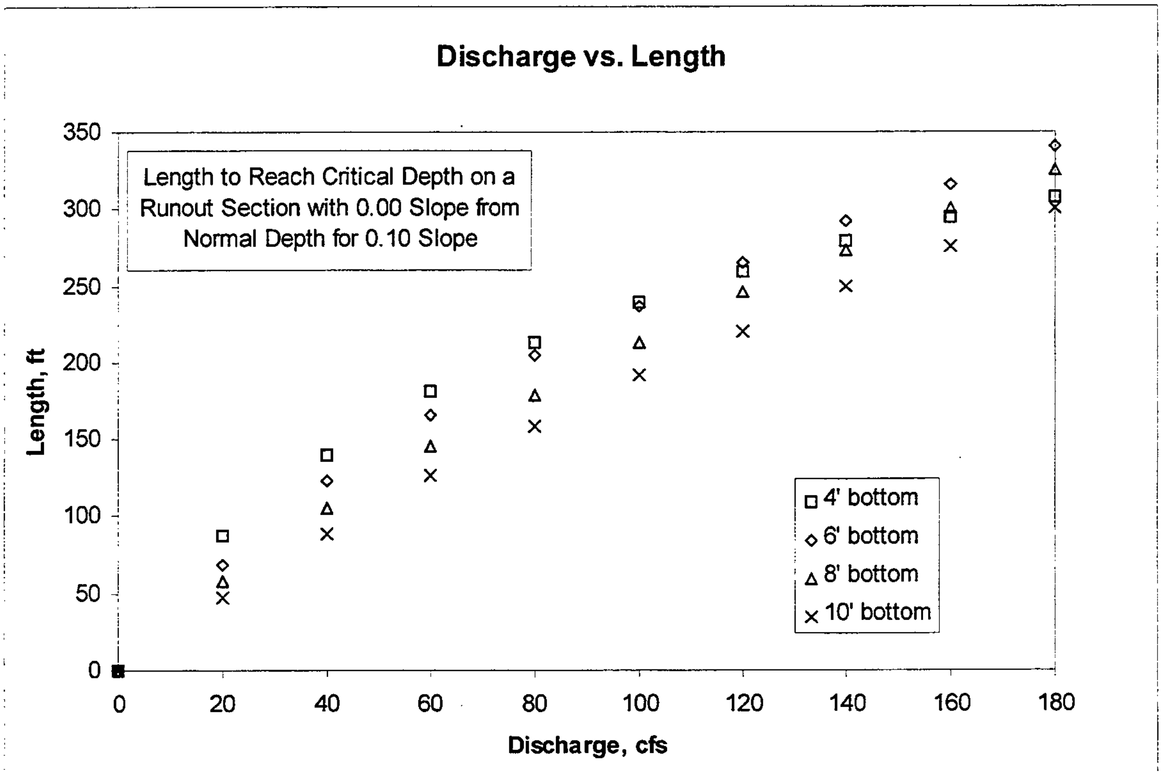


Figure 2. Length to reach critical depth in a rectangular channel

The current NDOR policy and design manual for broken-back culvert design does not provide designers with all the information needed for a complete analysis. A model is needed that will calculate the headwater at the inlet, the water surface profile through the culvert, and the outlet depth and velocity. The following models were examined but were found to be incomplete. Also, none of the models allow the designer to evaluate energy dissipation.

Broken-Back Design Procedures and Models

Texas Dissertation

Price (1967) predicted the occurrence of a hydraulic jump in both rectangular and circular broken-back culverts. The computer program compared the specific momentum of the supercritical flow and subcritical flow regimes in the outlet. The flow depth with the larger specific momentum value was assigned as the model depth. A hydraulic jump was predicted when the larger value changed from the supercritical flow to the subcritical flow. Price also suggested possible situations that could produce greater tailwater depths to produce a hydraulic jump. They included adding a sill at the outlet or placing the outlet section on an adverse slope. No provisions were made for calculating the headwater depth or flow profile in the upper sections.

HDS-5

Hydraulic Design Series No. 5 (HDS-5), Hydraulic Design of Highway Culverts (FHWA, 1985) includes discussion on control sections and calculating the headwater depths for broken-back culverts. HDS-5 states that the control can be at the inlet, outlet or the upper break. For inlet control, the headwater is calculated the same way as for a straight culvert. For outlet control, the bend losses are added to the other losses (inlet and barrel friction). For upper break control, the outlet control calculations are applied to the inlet section, assuming critical depth at the break. HDS-5 also states that broken-back culverts can be analyzed in detail using standard backwater and drawdown calculation methods.

<u>The State of Texas</u>

The Texas State Department of Highways and Public Transportation Bridge Division Hydraulic Manual (1985) provides a method for determining if a hydraulic jump occurs in both box culverts and circular pipes. The flow into the outlet section is assumed to be the normal depth of the preceding steeply sloped section. The outlet section water surface profile is then calculated and the sequent depths are compared to the tailwater depth. For a given flow there are two possible depths for each value of specific momentum (Figure 3). The depths are known as sequent depths. If the tailwater depth is greater than the sequent depth, a hydraulic jump will occur. Also, the water surface profile depth is compared to the critical depth. If the profile reaches critical depth, the outlet depth is set equal to the critical depth. If no hydraulic jump has occurred and the profile depth is less than critical at the outlet, the manual recommends a change in the culvert profile or the addition of a split sill at the outlet for energy dissipation.

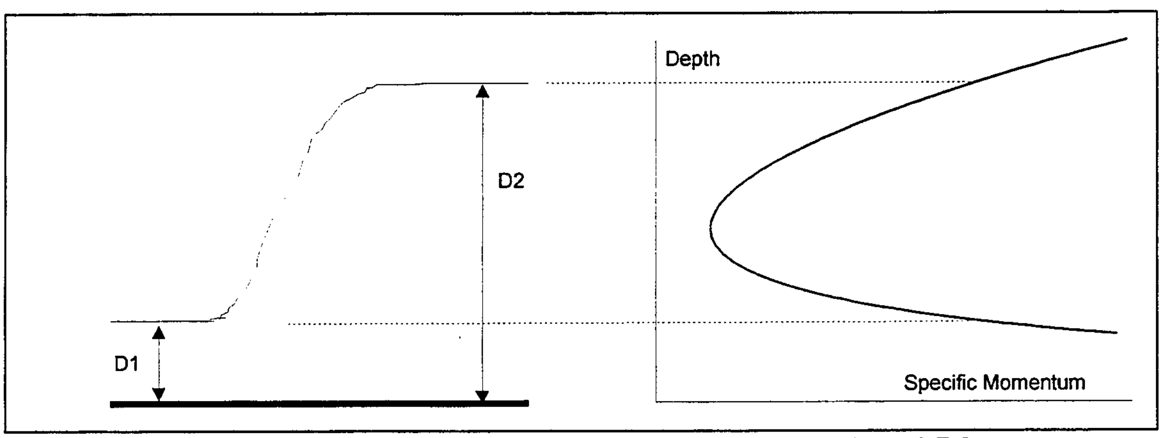


Figure 3. Specific momentum curve and sequent depths D1 and D2

The manual only deals with the water surface profile through the outlet section. The assumption that the depth at the beginning of the runout section is equal to the normal depth from the preceding steeply sloped section is not realistic. This will cause the outlet velocity to be overpredicted. Figure 4 shows the lengths of the steeply sloped section required to reach normal depth from critical depth in four-, six-, eight-, and ten-ft bottom width rectangular box culverts. The discharge is 200 cfs. Tables of lengths for other discharges can be found in Appendix F. Most steeply sloped culvert sections are shorter.

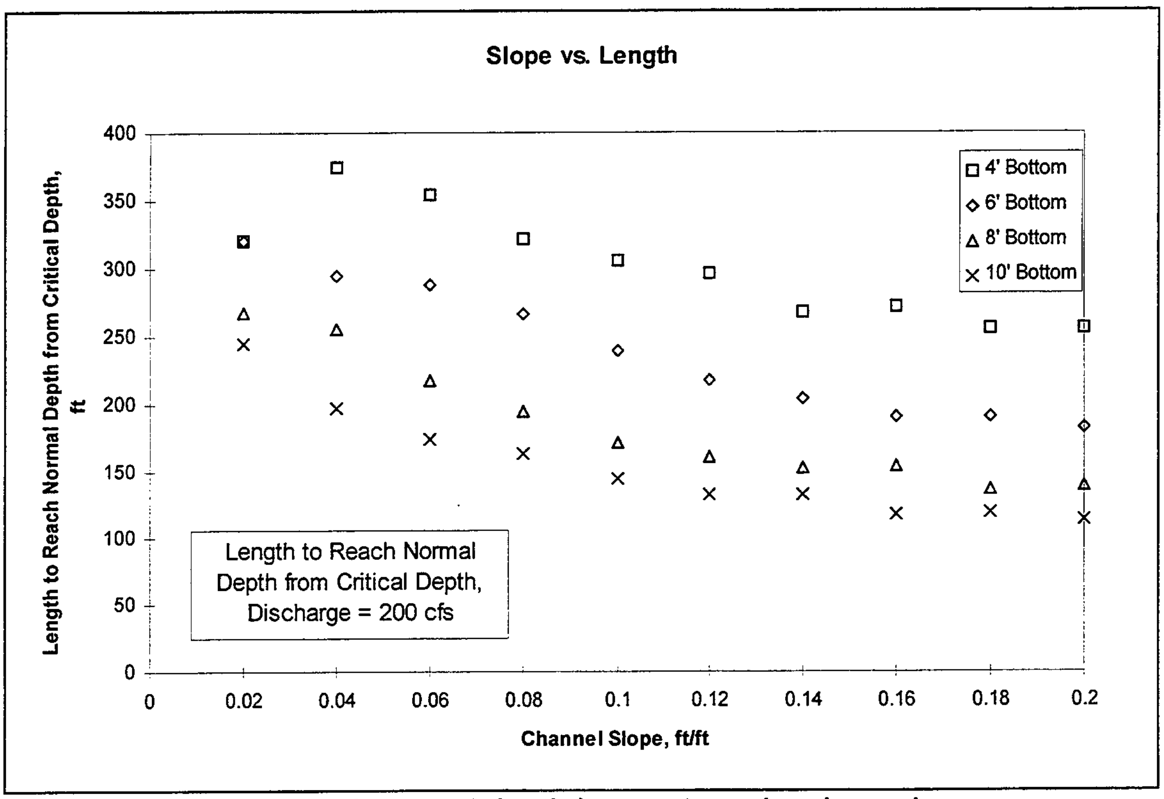


Figure 4. Length to reach normal depth in a rectangular channel

Design Considerations

When designing a broken-back culvert, there are many factors that the designer must consider: culvert size, shape, and material; the inlet type; the culvert profile; evaluation of the tailwater conditions; and whether or not an energy dissipator needs to be installed. The following sections discuss each of the factors and their influence on the hydraulic performance.

Culvert Size

The culvert size will affect the headwater depth and the water surface profile. The smaller the culvert size, the more headwater will be needed to force the flow through the culvert. The size also affects critical depth, which is the starting point of the water surface profile calculations. The larger the culvert, the smaller critical depth becomes. The minimum culvert sizes allowed by NDOR are indicated in Table 1 (NDOR, 1996).

Table 1. Minimum culvert sizes

Type of Structure	Minimum Size
Cross drain pipe	24"
Median drain pipe	18"
Flume pipe	15"
Drive pipe	18"
Box culvert	4' x 4'
Storm sewer - transverse	15"
Storm sewer - longitudinal	18"

Culvert Shape

The designer should choose a shape based on the discharge. For low flows, a circular pipe will be more cost-effective than a box culvert; since, the minimum box size allowed by NDOR is 4 ft x 4 ft. Also, for high discharges, there may not be a circular pipe available large enough to pass the flow.

Culvert Material

The culvert material will affect the break control headwater depth and the water surface profile through the culvert. The material roughness coefficient is used to calculate energy losses due to friction; the higher the coefficient, the more energy loss there will be. This will result in a larger headwater depth (if operating under break control) and outlet depth and will increase the chances of a hydraulic jump forming in the outlet section. Table 2 compares concrete pipe (roughness coefficient = 0.013) and corrugated metal (0.024) headwater depths and water surface profiles in a circular culvert with diameter = 4 ft, slope = 0.01, length = 100 ft, a square edge inlet with headwall, and discharge = 150 cfs. The greater roughness increased the headwater depth by 1.51 ft, and decreased outlet velocity by 1 ft/s.

Table 2. Concrete pipe and corrugated metal pipe comparison

	Concrete Pipe	Corrugated Metal Pipe
Headwater Depth - Inlet Control	8.29'	8.16'
Headwater Depth - Outlet Control	7.04'	9.80'
Normal Depth	3.16'	3.59'
Outlet Depth	3.27'	3.59'
Outlet Velocity	13.65 ft/s	12.61 ft/s

Culvert material for reactive soils should be selected with guidance from design manuals (Nebraska Department of Roads, 1996).

Inlet Type

The inlet affects the headwater depth and determines the starting known depth for the profile calculations. A measure of the inlet efficiency is used in both inlet control and break control calculations. An efficient inlet will not cause sharp bends in the flowlines and will have less loss. If the inlet section is the control section, the starting point is the inlet and the depth is critical depth. If the control is break control, the starting depth is at the upper break station and the known depth is critical depth.

Culvert Profile

The length and slope of each broken-back culvert section are important for calculating the water surface profile and headwater depth. The length and slope of the inlet section are used in the break control headwater equations for calculating energy losses. Energy loss is proportional to length and slope. To maximize the outlet depth, the outlet section length should be increased or the slope of the upstream section should be decreased. However, these options are mutually exclusive. If the slope is decreased for the steep section, the outlet length will decrease and if the outlet section length is increased, the steeply sloped section slope will be increased. Eliminating the inlet section of a broken-back culvert, producing a single broken-back culvert, will allow the designer to either increase the outlet length or decrease the slope in the steep section. The designer may want to evaluate a range of slopes and outlet lengths so that the maximum outlet depth can be found. The slope of the steeply sloped section should not be greater than 55 degrees. Slopes greater than 55 degrees entrain air, and hydrostatic pressure distribution requirements are not met (Pugh, 1997).

A sample problem would be a 150 ft long, 4 ft x 4 ft box culvert with an inlet elevation of 100 ft and outlet elevation of 85 ft, and discharge = 150 cfs. Using critical depth as the starting point, a range of outlet depths was calculated for both double (runs 1-7) and single broken-back culverts (runs 8-9). Also computed were the results from a straight culvert (run 10). The results can be found in Table 3. The optimum run was run 9 with the greatest depth and lowest velocity.

Table 3. Length and slope comparisons for 150 ft long, 4 ft x 4 ft box culvert

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Inlet Station, ft	0	0	0	0	0	0	0	0	0	0
Inlet Elevation, ft	100	100	100	100	100	100	100	100	100	100
Upper Break Station, ft	100	50	50	50	25	25	25			
Upper Break Elevation, ft	99	99	100	99	100	100	100			
Lower Break Station, ft	125	100	100	100	100	75	50	50	25	
Lower Break Elevation, ft	86	86	85	85	85	85	85	85	85	
Outlet Station, ft	150	150	150	150	150	150	150	150	150	150
Outlet Elevation, ft	85	85	85	85	85	85	85	85	85	85
Outlet Depth, ft	1.25	1.40	1.40	1.42	1.46	1.53	1.58	1.65	1.71	1.23
Outlet Velocity, ft/s	30.0	26.8	26.8	26.4	25.7	24.5	23.7	22.7	21.9	30.5

Tailwater Conditions

The tailwater conditions will affect the outlet depth and the water surface profile in the outlet section. The designer can predict the tailwater depth by applying the Manning equation to the downstream channel. The designer should be careful when approximating the downstream channel shape and size so that the depth is not over estimated. The greater the tailwater depth, the greater the possibility that the outlet velocity will be reduced or that a hydraulic jump will occur in the outlet section. Also, if the tailwater depth is greater than the interior height, the culvert will likely flow full through the outlet section, reducing the outlet velocity.

Energy Dissipation

An energy dissipator may be needed when the outlet velocity is greater than acceptable. Energy dissipation can be achieved either inside the barrel or outside the culvert. Energy dissipation in the barrel can be accomplished by changing the barrel material to increase the roughness in the outlet section. Energy dissipators placed outside the culvert reduce the energy by absorbing energy at impacts or slowing the flow with pools and steps. Types of external dissipators include drop structures, stilling basins, and at-streambed-level structures. Hydraulic Engineering Circular No. 14 (HEC-14) (FHWA, 1983) describes many different internal and external dissipators for culverts.

BROKEN-BACK DESIGN PROCESS AND MODEL

The objective of this research project was to provide the NDOR with an analysis model to evaluate the hydraulic performance of broken-back culverts. To complete this task an evaluation method was first developed, then implemented into a user friendly computer program named Broken-back Culvert Analysis Program (BCAP).

Evaluation Process

The evaluation process starts with the preliminary culvert design, including culvert shape, size and material; inlet type; profile; and tailwater conditions. Separate evaluation processes were developed for double broken-back and single broken-back culverts. Each process calculates headwater depth, water surface profile through the culvert, and outlet velocity.

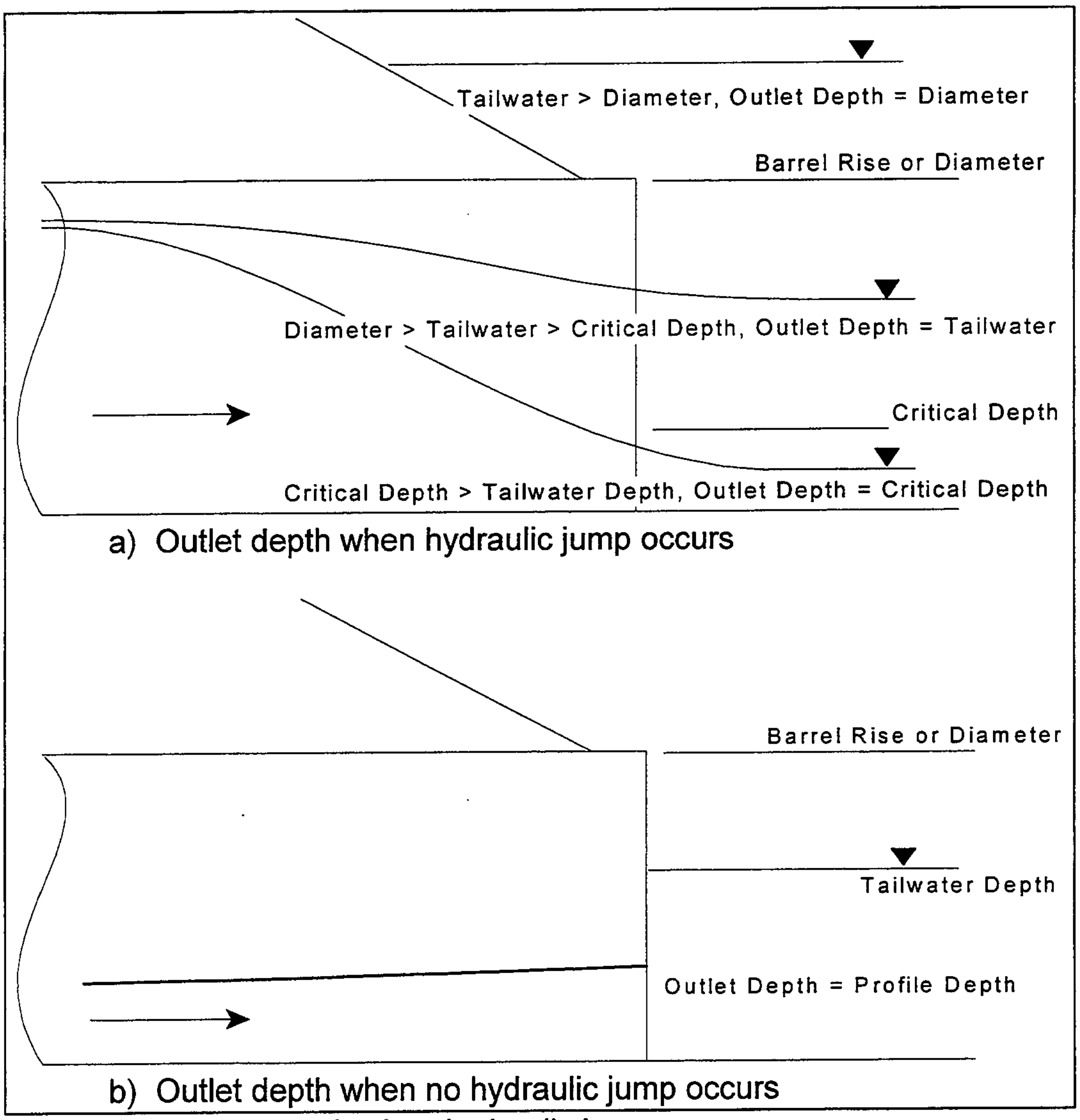
Double Broken-back

The designer needs to calculate headwater elevation for inlet control and break control. Equations can be found in Appendix B or the HY8 computer software. The more conservative (higher) elevation of the two is used as the headwater elevation. The headwater depth is equal to the difference between the headwater elevation and the inlet elevation. If the headwater depth is acceptable, the hydraulic evaluation can continue. If not, the culvert should be reshaped or made larger and the headwater elevation recalculated.

The water surface profile is then calculated using the direct step method (French, 1985). The direct step method calculates length between two incremental depths by comparing the energy lost. A known starting elevation is required for the first calculation. The starting elevation corresponds to the control section, and is critical depth at the inlet or upper break. Each additional calculation will use an increment of 0.01 feet. The equations for the direct step method are found in Appendix B.

As stated before, the starting point for inlet control is the inlet. Depths and locations of the water surface profile are then calculated for the inlet section. If the inlet section slope is steeper than critical, 0.01 feet is subtracted from each preceding depth. If the slope is less than critical, 0.01 feet is added. When the total distance is greater than the inlet section length, the depth is recorded and used for the starting depth in the steeply sloped section. If the depth is greater than critical, the starting depth for the steeply sloped section should be set to critical because the flow will plunge through critical depth at the break. The direct step method is then restarted by subtracting 0.01 feet from the new depth. The depths and lengths are recorded. When the distance is greater than the steeply sloped section length, the final depth is recorded as the outlet section starting depth. The profile computations are then started for the outlet section. The sequent depth is first calculated for the starting depth. If the tailwater depth is greater than the sequent depth, a hydraulic jump will occur. The jump length is calculated and the sequent depth is used for the starting depth for the direct step method for the rest of the outlet section. If the tailwater depth is less than the sequent depth, 0.01 feet is added to the previous depth and the corresponding downstream location is calculated. The process is then repeated. If the Froude number is less than 1.7 an undular, or weak, jump will occur (Chow, 1959).

The outlet depth is determined by whether or not a hydraulic jump occurred. If a hydraulic jump occurs, critical depth is compared to the barrel interior height and tailwater depth (Figure 5a). If the tailwater depth is greater than the barrel interior height, then the depth is considered to be equal to the interior height. If the tailwater depth is greater than critical depth but less than the barrel interior height, the tailwater depth is used as the outlet depth. If the tailwater depth is less than the critical depth, then outlet depth is assumed to be equal to critical depth. If no hydraulic jump occurs, the profile depth is used for the outlet depth (Figure 5b). This can be shown by looking at the specific momentum curve (Figure 3). Any depth less than the sequent depth has a lower specific momentum value and will be forced outside the culvert by the supercritical depth. The outlet velocity is calculated using the continuity equation (Equation 18). If the outlet velocity is acceptable, less than 10 feet per second for NDOR, the design is complete. If not, the designer must either redesign the culvert profile or add an energy dissipator



a) Outlet depth when hydraulic jump occurs

b) Outlet depth when no hydraulic jump occurs

Figure 5a. Outlet depth when hydraulic jump occurs
5b. Outlet depth when no hydraulic jump occurs

Single Broken-back

The hydraulic evaluation of a single broken-back culvert is similar to that of a double broken-back culvert. The culvert will only operate in inlet control, and the water surface profile is calculated with a known depth equal to the critical depth at the inlet. A flowchart for the analysis process of either single or double broken-back culverts is found in Figure 6.

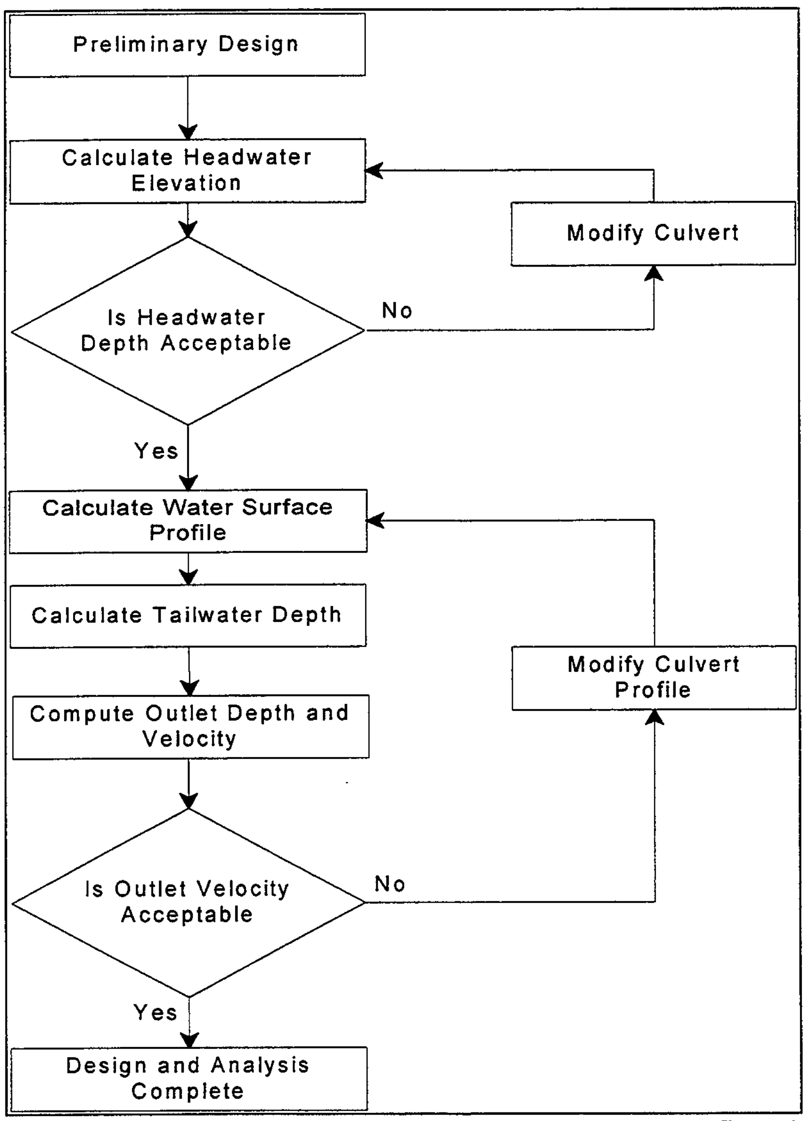


Figure 6. Single and double broken-back culvert analysis flowchart

Computer Model

The computer model (BCAP) completes all of the processes for evaluating either single or double broken-back culverts. BCAP was written in Microsoft Visual Basic 4.0 Professional Edition. The code is listed in Appendix C, and a complete user's manual is included in Appendix E. The user inputs all preliminary design data into the fields on the input form or by opening an existing file. The input fields include the minimum, design, and maximum discharge; number of barrels; the culvert shape, size, material, and inlet type; the culvert profile; and the tailwater conditions. Only box and circular shapes can be used in BCAP. Other shapes are most often used when there is limited fill, which is usually not the case with broken-back culverts. The slope of the steeply sloped section should not be greater than 55 degrees. The slope in the outlet section can be set to zero or have a negative slope.

When all input fields are entered, the designer has the option of evaluating the design discharge or a range of discharges. The following computations are made for the evaluation: critical depth, tailwater depth, inlet control elevation, break control elevation, the water surface profile, the occurrence of a hydraulic jump, and the outlet depth and velocity.

Critical depth is calculated for a box culvert using Equation 1 (French, 1985):

$$D_C = \left(\frac{q^2}{g}\right)^{1/3} \qquad \text{(Equation 1)}$$

where: D_C = critical depth, ft
q = unit flow, $ft^3/s/ft$
g = acceleration of gravity, ft/s^2

The critical depth for a circular channel is calculated by an iterative process in which the Froude number is calculated until it converges to 1. The Froude number is calculated using Equation 2, where hydraulic depth is normally defined as the flow area divided by the top width of the flow. In circular channels, as the flow nears the top, the top width approaches zero and the hydraulic depth approaches infinity. To overcome this mathematical problem, the equivalent depth, obtained from Equation 3 below, is used instead of the hydraulic depth. The area is approximated by a rectangle 2 D_e wide and D_e high.

$$FR = \frac{V}{\sqrt{gD_e}} \qquad \text{(Equation 2)}$$

where: FR = Froude number
V = average velocity, ft/s
D_e = equivalent depth, ft

$$D_e = \left(\frac{A}{2}\right)^{1/2} \qquad \text{(Equation 3)}$$

where: A = area, ft^2
D_e = equivalent depth, ft

The tailwater depth for a downstream channel is calculated using an iterative process with the Manning Equation. Options for the channel shape include trapezoidal, rectangular, triangular, and circular.

$$Q = \frac{\Phi}{n} A^{5/3} P^{-2/3} S^{1/2} \qquad \text{(Equation 4)}$$

where: Φ = units coefficient
Q = discharge, ft^3/s
n = Manning roughness coefficient
A = area, ft^2
P = wetted perimeter, ft
S = channel slope, ft/ft

The inlet control losses for both circular and box culverts are calculated using the following polynomial equations (FHWA, 1996):

$$HL = (A + (BS + (C + (DIP + (EE + F * X) * X) * X) * X) * X - SR * SO) * RISE \quad \text{(Equation 5)}$$

where: $X = Q / (SPAN \times \sqrt{RISE^3})$
HL = head loss, ft
Q = discharge, ft^3/s
SPAN = culvert width or diameter, ft
RISE = culvert height or diameter, ft
A, BS, C, DIP, EE, F, SR= polynomial equation coefficients
SO = inlet section slope, ft/ft

If the head loss exceeds three times the culvert interior height or is less than one-half the same height, the losses need to be recalculated using a weir (Equation 6) or orifice equation (Equation 7).

$$Q = C_d \times L \times HL^{3/2} \quad \text{(Equation 6)}$$

where: Q = discharge, ft^3/s
L = length of weir, ft
C_d = weir coefficient
HL = head loss, ft

$$Q = k \times A \times HL^{1/2} \quad \text{(Equation 7)}$$

where: Q = discharge, ft^3/s
k = orifice coefficient
A = orifice area, ft^2
HL = head loss, ft

Equations 5, 6, and 7 replace the three equations for unsubmerged and submerged inlet control (FHWA, 1985) found in Appendix B. The head loss from Equation 5 is then added to the inlet elevation to find the inlet control headwater elevation:

$$ICELEV = IE + HL \quad \text{(Equation 8)}$$

where: ICELEV = inlet control headwater elevation, ft
IE = culvert inlet elevation, ft
HL = head loss (Equation 5, 6, or 7), ft

The break control losses are calculated using the following equation:

$$HL = (1 + KE + 29n^2L / R^{4/3}) * \frac{V^2}{2g} \qquad \text{(Equation 9)}$$

where: HL = head loss, ft
KE = entrance loss coefficient
n = Manning roughness coefficient
L = inlet section length, ft
R = hydraulic radius, ft
V = average velocity, ft/s
g = acceleration of gravity, ft/s^2

The losses are added to the break elevation and the critical water depth at the break to find the break control headwater elevation.

$$BCELEV = D_c + HL + UBELEV \qquad \text{(Equation 10)}$$

where: BCELEV = break control headwater elevation, ft
D_C = critical depth, ft
HL = head loss (Equation 9), ft
UBELEV = culvert upper break elevation, ft

The water surface profile is calculated using the direct step method. The direct step method determines the distance from one depth in the water surface profile to another depth. Equations 11, 12, and 13 are used for the direct step method (French, 1985):

$$SF = \frac{n^2V^2}{FR^2R^{4/3}} \qquad \text{(Equation 11)}$$

$$\Delta E = \Delta y(1 - FR^2{}_m) \qquad \text{(Equation 12)}$$

$$\Delta x = \frac{DE}{S - SF_M} \qquad \text{(Equation 13)}$$

where: SF = friction slope, ft/ft
n = Manning roughness coefficient
V= average velocity, ft/s
FR = Froude number
FR^2_M = mean Froude number squared
ΔE = change in energy, ft

Δy = change in depth, ft
Δx = change in distance, ft
S = channel slope, ft/ft
SF_M = mean friction slope, ft/ft

For a box culvert the sequent depth is calculated using the following equation developed by Chow (1959).

$$D_S = \frac{D}{2}\left(\sqrt{1+8FR^2}-1\right) \quad \text{(Equation 14)}$$

where: D_S = sequent depth, ft
D = depth, ft
FR = Froude number

The length of the hydraulic jump in a rectangular channel is determined using Equation 15 (Hager, 1992).

$$L = D \times 220 \times \tanh\left(\frac{FR-1}{22}\right) \quad \text{(Equation 15)}$$

where: L = hydraulic jump length, ft
D = depth, ft
FR = Froude number

The sequent depth for a circular culvert is calculated using Equations 16 and 17 Straub (1978) regressed. The equations are as follows:

For a Froude number less than 1.7

$$D_S = \frac{{D_C}^2}{D} \quad \text{(Equation 16)}$$

For a Froude number greater than 1.7

$$D_S = \frac{{D_C}^{1.8}}{D^{.73}} \quad \text{(Equation 17)}$$

where: D_S = sequent depth, ft
D_C = critical depth, ft
D = depth, ft

The length of a hydraulic jump in a circular channel is equal to six times the sequent depth (Hager, 1992).

The outlet depth is determined by comparing the tailwater depth, the barrel critical depth, and the water surface profile depth at the outlet. If a hydraulic jump occurs, critical depth is compared to the barrel interior height and tailwater depth. If the tailwater depth is greater than the barrel interior height, the depth is considered to equal the interior height. If the tailwater depth is greater than critical depth but less than the barrel interior height, the tailwater depth is used for the outlet depth. If the tailwater depth is less than critical depth, the outlet depth is assumed to be critical. If no hydraulic jump occurs, the profile depth is used for the outlet depth. Table 4 summarizes the complete process.

Table 4. Outlet depth for broken-back culvert analysis

Condition	Outlet Depth
Hydraulic Jump Does Not Occur	Profile Depth
Hydraulic Jump Occurs	
Tailwater > Diameter	Diameter
Diameter > Tailwater > Critical Depth	Tailwater Depth
Critical Depth > Tailwater	Critical Depth

The outlet velocity is calculated by applying the continuity equation:

$$V = \frac{Q}{A} \quad \text{(Equation 18)}$$

where: V = average velocity, ft/s
Q = discharge, ft^3/s
A = area, ft^2

The design discharge output form lists the headwater, critical, tailwater, and outlet depths; control elevations; and outlet Froude number. It also indicates whether a hydraulic jump occurred, and if so, its location and length. The culvert data include the discharge; culvert shape, size, and material; and inlet type. The water surface profile data include the water surface profile depths and velocities at critical points in the culvert and the tailwater depth and velocity. From this form the user can return to the input form, view the culvert and water surface profiles, or enter HY8 for energy dissipation analysis.

The discharge range table form provides the following data for discharges ranging from the minimum to the maximum flows: headwater depth, inlet control elevation, break control elevation, critical depth, outlet depth, outlet velocity, outlet Froude number, tailwater depth, and tailwater velocity. From this form the user may return to the input form, access rating curves for the headwater depth, outlet depth, and outlet velocity, or get a more detailed evaluation for each discharge. The detailed evaluation is the same as when the design discharge option is selected on the input form.

The plot option shows the culvert and computed water surface profiles to scale and the culvert data.

When the HY8 energy dissipation option is selected, BCAP creates input and output files that are recognized by the HY8 energy dissipation module. HY8 is then started, and the user can select the pertinent units and continue to the dissipator option. The user should not use any other HY8 options using the files created by BCAP. From the energy dissipation module of HY8, the user can calculate scour hole geometry and add either internal or external dissipators to the culvert. Internal dissipators include tumbling flow and increased roughness. External dissipators include drop structures, stilling basins, and at-streambed level structures.

The user can save the input information on the input form and can print any form in the file menu. BCAP also contains a help form that can be accessed from the help menu.

MODEL RESULTS

BCAP predictions were compared to results using a four-inch Plexiglas broken-back culvert tested in the hydraulics laboratory of the University of Nebraska-Lincoln (Figure 7). The tailwater was controlled with a gate downstream from the culvert. The flows ranged from 0.07 cfs to 0.30 cfs and the tailwater depth ranged from zero to 0.50 feet. The flow and tailwater depth along with the headwater and outlet depths were recorded and compared to results from BCAP using an appropriate friction factor for Plexiglas. Complete tables of results can be found in Appendix D. These results show that BCAP is capable of predicting the headwater depth and outlet depth for a range of flows in the prototype. In some cases the headwater was less than the predicted value. This could be due to scale effects and 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 2 feet of water.

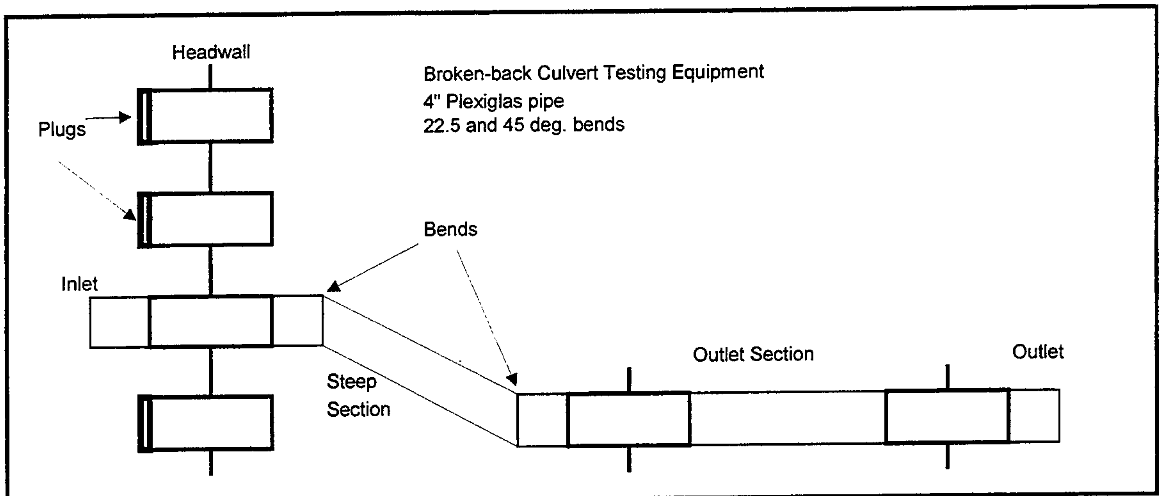


Figure 7. Elevation view of broken-back culvert testing equipment

CONCLUSIONS

The BCAP computer program meets the project objective of providing the NDOR with a method to analyze the hydraulic properties of either single or double broken-back culverts. BCAP allows the user to input the properties of a broken-back culvert and returns output that the user can use to evaluate the resulting hydraulic performance. BCAP was shown to replicate scaled laboratory experiments successfully and was able to reproduce appropriate results from the Federal Highway Administration HY8 computer program. BCAP will allow the NDOR to consistently and efficiently design broken-back culverts that will operate trouble-free.

RECOMMENDATIONS

This project successfully completed the objective of making broken-back culvert analysis easier for NDOR. The model testing involved in the validation process showed that there are two areas that need additional research effort:

1. Air entrainment effects for slopes exceeding 55 degrees; and
2. Hydraulic jump lengths and sequent depths in non-rectangular conduits.

Although BCAP is easy to use, it was not designed to replace the FHWA HY8 computer program. Additional modifications to BCAP would allow for the analysis of constant-slope culverts and therefore serve as a front-end program for HY8.

Implementation Plan

The computer software (BCAP) developed in this project must be integrated into the existing design systems of Departments of Transportation (DOT). It must be demonstrated to designers who have responsibility for the design of culverts. This could be accomplished through seminars, workshops, and a training session. Also, close coordination with a DOT's computer system's office must take place to ensure a smooth transition and adequate systems support.

REFERENCES

Basco, D.R. and Adams, J.R. (1971). Drag Forces on Baffle Blocks in Hydraulic Jumps. Journal of the Hydraulics Division, ASCE. Vol. 97, No. 12.

Chanson, H., and Montes, J.S. (1995). Characteristics of Undular Hydraulic Jumps: Experimental Apparatus and Flow Patterns. Journal of Hydraulic Engineering, ASCE. Vol 121, No. 2.

Chaudhry, M.H. (1993). Open Channel Flow. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Chow, V.T. (1959). Open Channel Hydraulics. McGraw-Hill Book Company, New York.

Federal Highway Administration. (1983). Hydraulic Design of Dissipators for Culverts and Channels, Hydraulic Engineering Circular No. 14. September 1983.

Federal Highway Administration. (1985). Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5. September 1985.

Federal Highway Administration. (1996). FHWA Culvert Analysis Version 6.0, HY8.

French, R.H. (1985). Open Channel Hydraulics. McGraw-Hill Inc., New York.

Gunal, M., and Narayanan, R. (1996). Hydraulic Jump in Sloping Channels. Journal of Hydraulic Engineering. Vol. 122, No. 8.

Hager, W.H. (1992). Energy Dissipators and Hydraulic Jump. Kluwer Academic Publishers, Netherlands.

Husain, D., Alhamid, A., Negm, A. (1994). Length and Depth of Hydraulic Jump in Sloping Channels. Journal of Hydraulic Research. Vol. 32, No. 6.

Nebraska Department of Roads. (1996). Roadway Design Manual.

Negm, A.M. (1996). Hydraulic Jumps of Positive and Negative Steps on Sloping Floors. Journal of Hydraulic Research. Vol. 34, No. 3.

Ohtsu, I., Yasuda, Y., (1991). Hydraulic Jumps in Sloping Channels. Journal of Hydraulic Engineering. Vol. 117, No. 7.

Ohtsu, I., Yasuda, Y., and Gotoh, H. (1997). Characteristics of Undular Hydraulic Jumps: Experimental Apparatus and Flow Patterns (Discussion). Journal of Hydraulic Engineering. Vol. 123, No. 2.

Ohtsu, I., Yasuda, Y., and Hashiba, H. (1996). Incipient Jump Conditions for Flows Over a Vertical Sill. Journal of Hydraulic Engineering. Vol. 122, No. 8.

Price, B.E. (1967). Performance of Circular Culverts on Steep Grades. University of Texas at Austin.

Pugh, Clifford, Bureau of Reclamation, Personal Conversation, 3-17-97.

Straub, W.O. (1978). A Quick and Easy Way to Calculate Critical and Conjugate Depths in Circular Open Channels. Civil Engineering, December 1978.

Texas State Department of Highways and Public Transportation. (1985). Bridge Division Hydraulic Manual.

Vischer, D.L., and Hager, W.H. (1995). Energy Dissipators. A.A. Balkema, Rotterdam.

APPENDIX A - LITERATURE REVIEW

Broken-Back Culvert Design

The 1996 Nebraska Department of Roads design manual contains criteria for the outlet section of a broken-back culvert. The outlet section must be the maximum of the following three lengths: 10 feet, not less than 1.5 times the vertical drop from the inlet to the outlet, or 4 times the barrel interior height or diameter.

HDS-5 (1985) provides some suggestions and criteria for broken-back culvert design regarding erosion, sedimentation, debris control, and minimizing bend losses. Also provided are methods for calculating headwater, bend losses, and control points. Control points may exist at the inlet, the outlet, and either the upper or lower break (in a double broken-back culvert). In inlet control, the headwater is calculated the same way as for a regular culvert. In outlet control, the bend losses are added to other losses. With the upper break, outlet control calculations are applied, assuming critical depth at the break. Control at the lower break is not likely and can be ignored.

Price (1967) determined outlet velocity by predicting the occurrence of a hydraulic jump in circular culverts. This was accomplished by comparing the pressure plus momentum curves for the supercritical flow within the culvert to that of the tailwater. The profile with the larger value is used as the predicted depth. If there was no tailwater present, artificial tailwater was produced by adding a sill or making the outlet section an adverse slope.

The State of Texas (1985) provides a method for determining the occurrence of a hydraulic jump in box and circular culverts by comparing the flows' sequent depth to the available tailwater. The flow into the culvert outlet section is assumed to be the normal depth of the steeply sloped section. This incorrectly infers that flow in the steeply sloped section has reached normal depth by the time it enters the outlet section.

Energy Dissipation

Hydraulic Engineering Circular 14 (HEC 14, 1983), "Hydraulic Design of Energy Dissipators for Culverts and Channels," provides the best information for energy dissipation in culverts. Many different types of energy dissipators, both internal and external, are included in the manual. The energy dissipators are described as: forced hydraulic jump and increased roughness, impact basins, drop structures, stilling wells, and riprap. Equations are included for calculating the efficiency of each structure and the resulting downstream depth.

Hager (1992) provides equations describing energy dissipation of sills and baffle blocks in open channels. Also included are equations for the optimum design of sills and baffle-blocks.

Most work with hydraulic jumps has focused on horizontal rectangular channels. The length of a hydraulic jump in this situation is approximately equal to six times the sequent depth (Hager, 1992). Husain et al. (1994) developed a set of parameters and equations for use in sloping rectangular channels. The equations can also be used for a horizontal channel.

Hydraulic jumps in circular channels are not very well understood. Most research has failed to draw any conclusions. Hager (1992) determined that the hydraulic jump length in a circular channel is approximately six times the sequent depth with a possible variation of one sequent depth.

Computer Models

The computer program HY8, version 6.0, incorporates the FHWA documents HEC-14 and HDS-5 to assist in the design of single or multiple culverts. HY8 output includes inlet and outlet control headwater depths for a range of discharges, calculated water surface profiles for each discharge, and the dimensions of energy dissipation facilities if requested. Calculations are performed in English or SI units. The program has no provisions for adding a break to the culvert slope and therefore cannot be used to analyze broken-back culverts.

Price (1967) included a program to calculate the water profile in the outlet section of the culvert. The program calculates and compares the pressure plus momentum curves for both supercritical and subcritical flows and chooses the greater value as the profile value.

French (1985) included a program to calculate normal depth in rectangular, triangular, trapezoidal, circular, and natural channels. The program is iteratives to normal depth and is helpful in calculating normal depth in circular channels.

APPENDIX B - CULVERT HYDRAULICS

Control Points

The headwater at a culvert inlet rises until there is sufficient energy (depth) to pass incoming discharge downstream. For a straight culvert, the required headwater depth is controlled by either the inlet, called inlet control, or the barrel, called outlet control. In a broken-back culvert there are possible control points at each break in the culvert profile. In broken-back culverts, the headwater depth is calculated at each possible break point, and the greatest value is used as the design headwater depth.

Inlet Control

Inlet control occurs when water rises at the culvert inlet in order to overcome flow restrictions and the culvert is able to pass more water than is able to enter. HDS-5 (FHWA, 1985) provides equations and nomographs for calculating inlet control water depth. The depth is a function of discharge, inlet area, shape and edge treatment, and to a small extent, culvert slope. The equations for calculating inlet control depth are:

Unsubmerged

form 1
$$\frac{HW}{D} = \frac{H_C}{D} + K\left[\frac{Q}{AD^{.5}}\right]^M - .5S^2 \qquad \text{(Equation B.1)}$$

form 2
$$\frac{HW}{D} = K\left[\frac{Q}{AD^{.5}}\right]^M \qquad \text{(Equation B.2)}$$

$$H_C = D_C + \frac{V_C^{\,2}}{2g} \qquad \text{(Equation B.3)}$$

Submerged

$$\frac{HW}{D} = c\left[\frac{Q}{AD^{.5}}\right]^2 + Y - .5S^2 \qquad \text{(Equation B.4)}$$

where: HW = headwater depth above inlet invert, ft
D = culvert height or diameter, ft
H = specific head, ft
D_C = critical depth, ft
V_C = critical velocity, ft/s
g = acceleration of gravity, ft/s^2
Q = discharge, cfs
A = cross sectional area of culvert, ft^2
K, M, c, Y = constants

Outlet Control

Outlet control occurs when the barrel is not capable of conveying as much water as the inlet will allow into the culvert. In the case of a broken-back culvert, outlet control will not occur if the flow depth passes through critical depth at some point in the culvert barrel. Since slope in broken-back culverts is sufficiently steep to produce critical and supercritical depth, outlet control will not occur, and is not considered further.

Break Control

There may be either one or two slope breaks in a broken-back culvert, designated as the upper and lower breaks. The lower break will not produce outlet control and is not important. The upper break is important because it produces critical depth. The headwater depth for this control can be calculated by considering the upper section as a straight culvert operating under outlet control (HDS-5, 1985). Headwater depth is calculated by adding friction losses in the inlet section barrel to critical depth and the break elevation:

$$BCELEV = D_c + HL + UBELEV \quad \text{(Equation B.5)}$$

$$HL = (1 + KE + 29n^2L / R^{4/3}) * \frac{V^2}{2g} \quad \text{(Equation B.6)}$$

where: BCELEV = break control elevation, ft
D_C = 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/s
g = acceleration of gravity, ft/s^2

Flow Profile

In calculating the water surface profile through the culvert, a point of known depth must first be selected before calculations can proceed. For a broken-back culvert, the known depth is at the upper break where the flow passes through critical depth. Calculations then proceed down the culvert. On the steeply sloped section, the profile follows a S2 curve (Figure B.1). This assumes that the slope of that section is greater than the critical slope. The water then flows into the outlet section. The starting depth for the outlet section is the steeply sloped section's ending depth. The water surface profile through the outlet section falls on either an A3, H3, or M3 curve (Figure B.2), depending on the outlet section slope. These curves can be calculated using the direct step method. In using the direct step method, the assumption of hydrostatic pressure distribution throughout the culvert is made (Pugh, 1997).

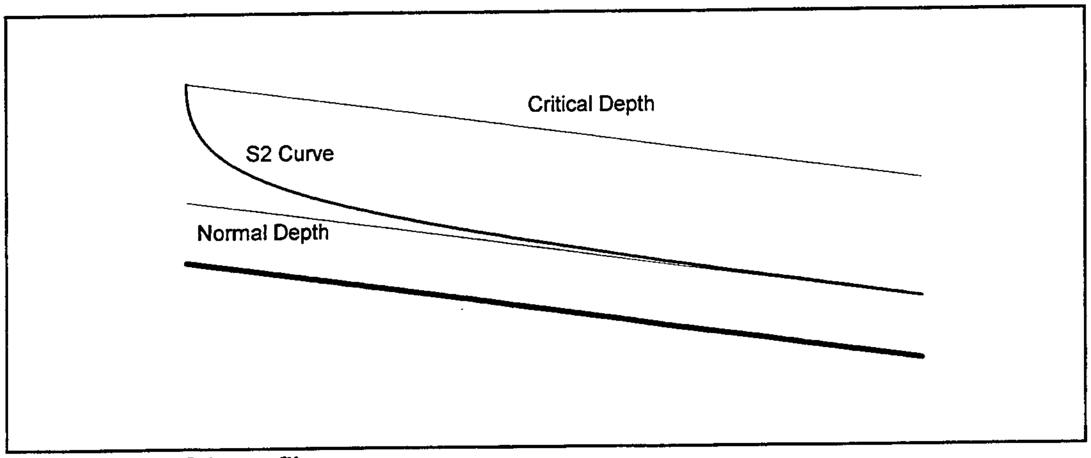


Figure B.1. S2 profile curve

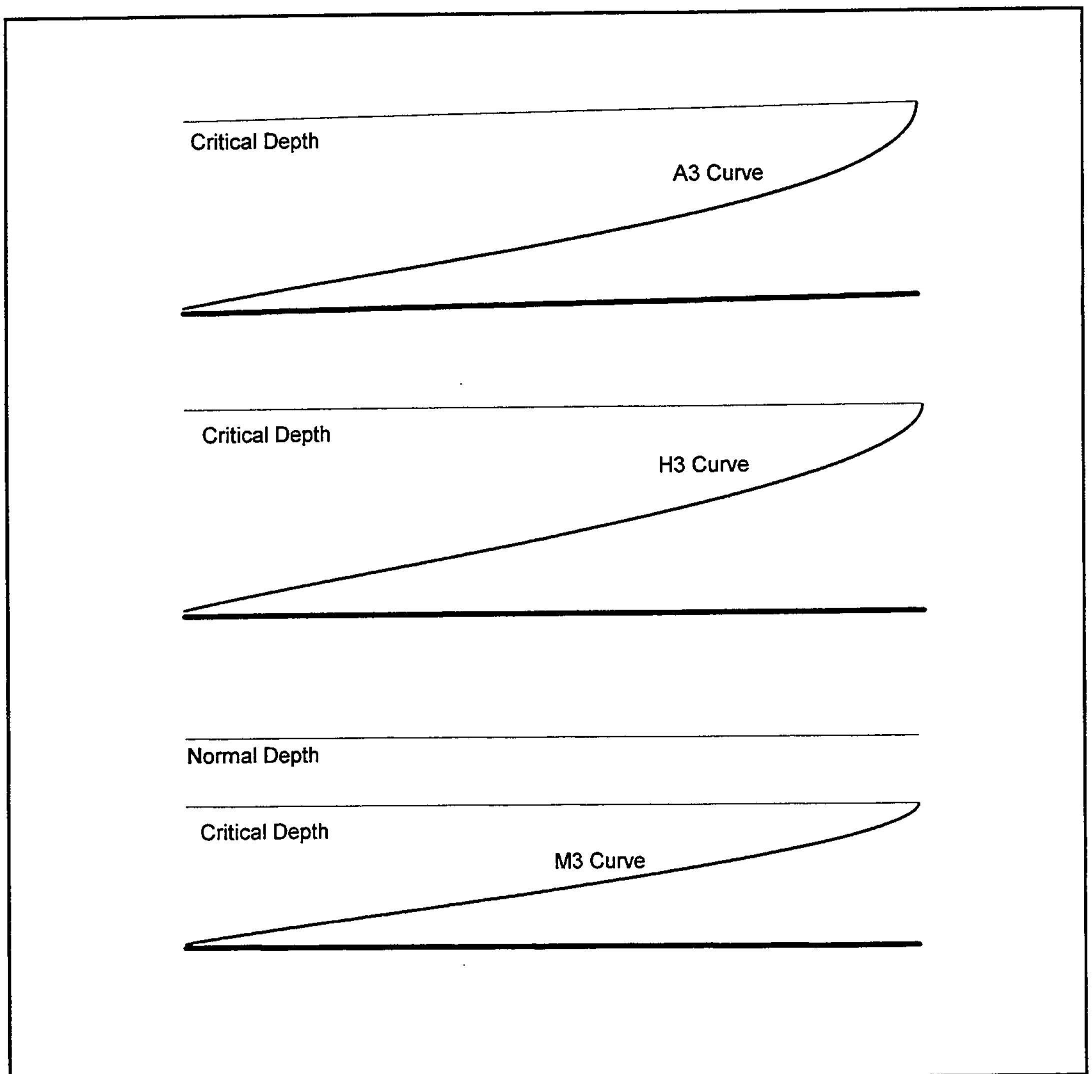


Figure B.2. A3, H3, and M3 profile curves

Hydraulic Jump

A hydraulic jump will occur in the runout section if the sequent depth to the supercritical depth is achieved. Sequent depth is the subcritical depth that produces the same momentum force as the upstream supercritical depth. There is a unique sequent depth associated with each supercritical depth. This sequent depth, and therefore a hydraulic jump, may be produced in two ways. The first case is if the outlet section is very long. As water flows down the culvert, it will lose energy due to friction with the sides and bottom. When enough energy has been lost, an undular, or weak, jump will occur. This is not likely to occur in most culverts because outlet sections are too short to dissipate sufficient energy to produce a jump. The second case is when sufficient tailwater depth exists to match the sequent depth. The tailwater depth can be calculated by applying the Manning equation to the downstream channel.

Outlet Velocity

HDS-5 (1985) provides methods for determining the outlet velocity for straight culverts. The velocity depends on tailwater depth and whether the culvert is operating in inlet or outlet control. In a broken-back culvert, the outlet section operates similarly to the inlet control case in a straight culvert. The outlet velocity is therefore calculated using the continuity equation and the outlet depth calculated from the flow profile.

APPENDIX C - PROGRAM CODE

All code in BCAP was written in Microsoft Visual Basic 4.0 Professional Edition. The code includes the main body, the headwater depth calculations, profile calculations for both box and circular culverts, and convert.bat and convert.for files for HY8 compatibility.

General Calculations

```
Private Sub Image2_Click()
Static LENGTH, YDEPTH(500), XLENGTH(500)
Screen.MousePointer = 11
On Error GoTo Errhandler
If UNIT = 1 Then
  design = txtDesDischarge
  maximum = txtMaxDischarge
  minimum = txtMinDischarge
  NUM = txtBarrels.Text
  Project = txtProject.Text
  Location = txtStation.Text
  When = txtDate.Text
If optSingle.Value = True Then
  STAB1 = txtInletsta.Text
  ELEVB1 = txtInletelev.Text
Else
  STAB1 = txtUppersta.Text
  ELEVB1 = txtUpperelev.Text
End If
  STAI = txtInletsta.Text
  STAB2 = txtLowersta.Text
  STAO = txtOutletsta.Text
  ELEVI = txtInletelev.Text
  ELEVB2 = txtLowerelev.Text
  ELEVO = txtOutletelev.Text
  If optCircle.Value = True Then
    SHAPE = 1
    DIAM = txtDiameter.Text
    RI = DIAM
    SP = DIAM
  Else
    SHAPE = 2
    W = txtSpan.Text
    H = txtRise.Text
    N = txtBoxrough.Text
    RI = H
    SP = W
  End If
  N = txtBoxrough.Text
  NOUT = txtNOut
  If optTWconstant.Value = True Then
    TWSHAPE = 1
```

```
    ELEVTW = txtTWelev.Text
    VTW = 0
  Else
    TWSHAPE = 2
    If TWSH = 2 Then
      B = txtTWbottom.Text
      LZ = txtTWleftside.Text
      RZ = txtTWrightside.Text
    ElseIf TWSH = 1 Then
      B = txtTWbottom.Text
    ElseIf TWSH = 6 Then
      TWDIAM = txtTWdiameter.Text
    ElseIf TWSH = 3 Then
      LZ = txtTWleftside.Text
      RZ = txtTWrightside.Text
    End If
      SLOTW = txtTWslope.Text
      NTW = txtTWrough.Text
  End If
Else
  design = txtDesDischarge * 35.31
  maximum = txtMaxDischarge * 35.31
  minimum = txtMinDischarge * 35.31
  NUM = txtBarrels.Text
  Project = txtProject.Text
  Location = txtStation.Text
  When = txtDate.Text
If optSingle.Value = True Then
  STAB1 = txtInletsta.Text * 3.28
  ELEVB1 = txtInletelev.Text * 3.28
Else
  STAB1 = txtUppersta.Text * 3.28
  ELEVB1 = txtUpperelev.Text * 3.28
End If
  STAI = txtInletsta.Text * 3.28
  STAB2 = txtLowersta.Text * 3.28
  STAO = txtOutletsta.Text * 3.28
  ELEVI = txtInletelev.Text * 3.28
  ELEVB2 = txtLowerelev.Text * 3.28
  ELEVO = txtOutletelev.Text * 3.28
  If optCircle.Value = True Then
    SHAPE = 1
    DIAM = txtDiameter.Text * 3.28
    RI = DIAM
    SP = DIAM
    N = txtBoxrough.Text
  Else
    SHAPE = 2
    W = txtSpan.Text * 3.28
    H = txtRise.Text * 3.28
    N = txtBoxrough.Text
    RI = H
    SP = W
  End If
  NOUT = txtNOut
  If optTWconstant.Value = True Then
    TWSHAPE = 1
    ELEVTW = txtTWelev.Text * 3.28
    VTW = 0
```

```
  Else
    TWSHAPE = 2
    If TWSH = 2 Then
      B = txtTWbottom.Text * 3.28
      LZ = txtTWleftside.Text
      RZ = txtTWrightside.Text
    ElseIf TWSH = 1 Then
      B = txtTWbottom.Text * 3.28
    ElseIf TWSH = 6 Then
      TWDIAM = txtTWdiameter.Text * 3.28
    ElseIf TWSH = 3 Then
      LZ = txtTWleftside.Text
      RZ = txtTWrightside.Text
    End If
      SLOTW = txtTWslope.Text
      NTW = txtTWrough.Text
  End If
  End If
  If minimum > design Then
  MsgBox "Program Error:  Design discharge must be greater than minimum
discharge"
  txtDesDischarge.SetFocus
  Screen.MousePointer = 0
  Exit Sub
End If
If design > maximum Then
  MsgBox "Program Error:  Maximum discharge must be greater than design
discharge"
  txtMaxDischarge.SetFocus
  Screen.MousePointer = 0
  Exit Sub
End If
If OPT3 = 1 Then
    If STAI > STAB2 Then
         MsgBox "Program Error:  Inlet station must be less than lower
break station"""
        txtLowersta.SetFocus
        Screen.MousePointer = 0
        Exit Sub
    End If
Else
    If STAI > STAB1 Then
         MsgBox "Program Error:  Inlet station must be less than upper
break station"""
        txtUppersta.SetFocus
        Screen.MousePointer = 0
        Exit Sub
    End If
    If STAB1 > STAB2 Then
         MsgBox "Program Error:  Upper break station must be less than
lower break station"""
        txtLowersta.SetFocus
        Screen.MousePointer = 0
        Exit Sub
    End If
End If
If STAB2 > STAO Then
         MsgBox "Program Error:  Lower break station must be less than
outlet station"""
```

```
        txtOutletsta.SetFocus
        Screen.MousePointer = 0
        Exit Sub
End If
  'MAIN COMPUTER PROGRAM CODE
'NEED ALL OF THE DATA ENTERED IN THE INPUT SCREEN
'FIRST CALCULATE THE SLOPES AND LENGTHS OF THE SECTIONS
If STAI = STAB1 Then
  LENI = 0
  SLOI = 0
  LENS = STAB2 - STAB1
  LENO = STAO - STAB2
  SLOS = (ELEVB1 - ELEVB2) / LENS
  SLOO = (ELEVB2 - ELEVO) / LENO
Else
  LENI = STAB1 - STAI
  LENS = STAB2 - STAB1
  LENO = STAO - STAB2
  SLOI = (ELEVI - ELEVB1) / LENI
  SLOS = (ELEVB1 - ELEVB2) / LENS
  SLOO = (ELEVB2 - ELEVO) / LENO
End If
If SLOS > 1.42 Then GoTo SLOPEMESSAGE:
Discharge = design
'DO THE TAILWATER CALCULATIONS
Select Case TWSHAPE
'CONSTANT TAILWATER DEPTH
  Case 1
    DTW = ELEVTW - ELEVO

'DOWNSTREAM CHANNEL
  Case 2
'ITERATIVE PROCESS FOR CALCULATING DEPTH
    'MAKE FIRST GUESS EQUAL TO 15 feet
    DTW = 15
    AA = 0
    If TWSH = 2 Then
      'CALCULATE FLOW WITH FIRST GUESS
      area = (B + (RZ * DTW / 2) + (LZ * DTW / 2)) * DTW
      P = B + DTW * Sqr(1 + RZ ^ 2) + DTW * Sqr(1 + LZ ^ 2)
      ITER = 1.49 / NTW * area ^ 1.667 * P ^ -0.667 * SLOTW ^ 0.5
      'SEE HOW CLOSE YOU ARE TO THE ACTUAL
      CHECK = Abs(Discharge - ITER)
      'IF CHECK <> .01 RE   ITERATE
      While CHECK > 0.01
        'MAKE NEW GUESS
        If Discharge > ITER Then DTW = DTW + 0.01 Else DTW = DTW - 0.01
        area = (B + (RZ * DTW / 2) + (LZ * DTW / 2)) * DTW
        P = B + DTW * Sqr(1 + RZ ^ 2) + DTW * Sqr(1 + LZ ^ 2)
        ITER = 1.49 / NTW * area ^ 1.667 * P ^ -0.667 * SLOTW ^ 0.5
        CHECK = Abs(Discharge - ITER)
        'THIS WILL COUNT TO 1500, IF IT IS STILL GOING, IT WILL QUIT
        AA = AA + 1
        If AA > 1500 Then CHECK = 0
      Wend
    ElseIf TWSH = 1 Then
      'CALCULATE FLOW WITH FIRST GUESS
       ITER = 1.49 / NTW * (B * DTW) ^ 1.667 * (B + 2 * DTW) ^ -0.667 *
SLOTW ^ 0.5
```

```
      'SEE HOW CLOSE YOU ARE TO THE ACTUAL
      CHECK = Abs(Discharge - ITER)
      'IF CHECK <> .01 REITERATE
      While CHECK > 0.01
        'MAKE NEW GUESS
        If Discharge > ITER Then DTW = DTW + 0.01 Else DTW = DTW - 0.01
        ITER = 1.49 / NTW * (B * DTW) ^ 1.667 * (B + 2 * DTW) ^ -0.667 *
SLOTW ^ 0.5
        CHECK = Abs(Discharge - ITER)
        'THIS WILL COUNT TO 1500, IF IT IS STILL GOING, IT WILL QUIT
        AA = AA + 1
        If AA > 1500 Then CHECK = 0
      Wend
      area = (B * DTW)
    ' Circle Calculations
    ElseIf TWSH = 6 Then
      DTW = (TWDIAM - 0.0001) / 2
      WW = 2 * DTW / TWDIAM - 1
      ASIN = Atn(WW / Sqr(-WW * WW + 1))
      theta = 2 * ASIN + 3.14159
      area = 0.125 * (theta - Sin(theta)) * TWDIAM ^ 2
      RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * TWDIAM
      ITER = 1.49 / NTW * (area) * (RADIUS) ^ 0.667 * SLOTW ^ 0.5
'SEE HOW CLOSE YOU ARE TO THE ACTUAL
      CHECK = Abs(Discharge - ITER)
'IF CHECK <> .01 REITERATE
      While CHECK > 0.01
'MAKE NEW GUESS
        If Discharge > ITER Then DTW = DTW + 0.01 Else DTW = DTW - 0.01
        WW = 2 * DTW / TWDIAM - 1
        ASIN = Atn(WW / Sqr(-WW * WW + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * TWDIAM ^ 2
        RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * TWDIAM
        ITER = 1.49 / N * (area) * (RADIUS) ^ 0.667 * SLOTW ^ 0.5
        CHECK = Abs(Discharge - ITER)
'THIS WILL COUNT TO 350, IF IT IS STILL GOING, IT WILL QUIT
        AA = AA + 1
        If AA > 350 Then CHECK = 0
      Wend
      If DTW > TWDIAM Then DTW = TWDIAM
      WW = 2 * DTW / TWDIAM - 1
      ASIN = Atn(WW / Sqr(-WW * WW + 1))
      theta = 2 * ASIN + 3.14159
      area = 0.125 * (theta - Sin(theta)) * TWDIAM ^ 2
    Else
     'CALCULATE FLOW WITH FIRST GUESS
     area = RZ * DTW ^ 2 / 2 + LZ * DTW ^ 2 / 2
     P = DTW * Sqr(1 + RZ ^ 2) + DTW * Sqr(1 + LZ ^ 2)
     ITER = 1.49 / NTW * area ^ 1.667 * P ^ -0.667 * SLOTW ^ 0.5
      'SEE HOW CLOSE YOU ARE TO THE ACTUAL
      CHECK = Abs(Discharge - ITER)
      'IF CHECK <> .01 REITERATE
      While CHECK > 0.01
        'MAKE NEW GUESS
        If Discharge > ITER Then DTW = DTW + 0.01 Else DTW = DTW - 0.01
        area = RZ * DTW ^ 2 / 2 + LZ * DTW ^ 2 / 2
        P = DTW * Sqr(1 + RZ ^ 2) + DTW * Sqr(1 + LZ ^ 2)
        ITER = 1.49 / NTW * area ^ 1.667 * P ^ -0.667 * SLOTW ^ 0.5
```

```
        CHECK = Abs(Discharge - ITER)
        'THIS WILL COUNT TO 1500, IF IT IS STILL GOING, IT WILL QUIT
        AA = AA + 1
        If AA > 1500 Then CHECK = 0
      Wend
    End If
    VTW = Discharge / area
End Select

'NEXT CHECK THE SHAPE OF THE CULVERT AND START THE CALCULATIONS
Select Case SHAPE
  Case 2    'BOX CALCULATIONS
'THE NEXT TWO LINES SET THE FLOW PER BARREL AND UNIT FLOWS
    Q = Discharge / NUM
    UNITQ = Q / W
'THIS LINE CALCULATES THE CRITICAL DEPTH
    DCRIT = (UNITQ ^ 2 / 32.2) ^ 0.3333
    If DCRIT > H Then DCRIT = H
'Calculate the normal depths in each of the sections
'inlet section
If SLOI = 0 Then
  DNINLET = H
Else
  DNINLET = H / 2
  AA = 1
  ITER = 1.49 / N * (W * DNINLET) ^ 1.667 * (W + 2 * DNINLET) ^ -0.667 *
SLOI ^ 0.5
'SEE HOW CLOSE YOU ARE TO THE ACTUAL
  CHECK = Abs(Q - ITER)
'IF CHECK <> .01 REITERATE
  While CHECK > 0.01
'MAKE NEW GUESS
     If Q > ITER Then DNINLET = DNINLET + 0.01 Else DNINLET = DNINLET -
0.01
    ITER = 1.49 / N * (W * DNINLET) ^ 1.667 * (W + 2 * DNINLET) ^ -0.667
* SLOI ^ 0.5
    CHECK = Abs(Q - ITER)
'THIS WILL COUNT TO 500, IF IT IS STILL GOING, IT WILL QUIT
    AA = AA + 1
    If AA > 500 Then CHECK = 0
  Wend
End If
If DNINLET > H Then DNINLET = H
'STEEP SECTION NORMAL DEPTH
DNSTEEP = H / 2
 AA = 1
'CALCULATE FLOW WITH FIRST GUESS
 ITER = 1.49 / NOUT * (W * DNSTEEP) ^ 1.667 * (W + 2 * DNSTEEP) ^ -0.667
* SLOS ^ 0.5
 'SEE HOW CLOSE YOU ARE TO THE ACTUAL
 CHECK = Abs(Q - ITER)
 'IF CHECK <> .01 REITERATE
 While CHECK > 0.01
 'MAKE NEW GUESS
   If Q > ITER Then DNSTEEP = DNSTEEP + 0.01 Else DNSTEEP = DNSTEEP -
0.01
   ITER = 1.49 / NOUT * (W * DNSTEEP) ^ 1.667 * (W + 2 * DNSTEEP) ^ -
0.667 * SLOS ^ 0.5
   CHECK = Abs(Q - ITER)
```

```
   'THIS WILL COUNT TO 600, IF IT IS STILL GOING, IT WILL QUIT
    AA = AA + 1
    If AA > 600 Then CHECK = 0
 Wend
 If DNSTEEP > H Then DNSTEEP = H
'OUTLET section
If SLOO <= 0 Then
  DNOUTLET = H
Else
 DNOUTLET = H / 2
 AA = 1
'CALCULATE FLOW WITH FIRST GUESS
 ITER = 1.49 / NOUT * (W * DNOUTLET) ^ 1.667 * (W + 2 * DNOUTLET) ^ -
0.667 * SLOO ^ 0.5
 'SEE HOW CLOSE YOU ARE TO THE ACTUAL
 CHECK = Abs(Q - ITER)
 'IF CHECK <> .01 REITERATE
 While CHECK > 0.01
 'MAKE NEW GUESS
   If Q > ITER Then DNOUTLET = DNOUTLET + 0.01 Else DNOUTLET = DNOUTLET
- 0.01
   ITER = 1.49 / NOUT * (W * DNOUTLET) ^ 1.667 * (W + 2 * DNOUTLET) ^ -
0.667 * SLOO ^ 0.5
   CHECK = Abs(Q - ITER)
   'THIS WILL COUNT TO 600, IF IT IS STILL GOING, IT WILL QUIT
    AA = AA + 1
    If AA > 600 Then CHECK = 0
 Wend
End If
If DNOUTLET > H Then DNOUTLET = H
'THE NEXT LINES START THE HEADWATER CALCULATIONS
    Call BOXCONTROL

'THIS LINE SETS THE CONTROL AS INLET OR BREAK
    If ELEVIC > ELEVBC Then
    Control = 1
    ELEVHW = ELEVIC
    ElseIf ELEVBC > ELEVIC Then
    Control = 2
    ELEVHW = ELEVBC
    End If
    DHW = ELEVHW - ELEVI
'THESE CALCULATE THE PROFILE CALCULATIONS
      Select Case Control
        Case 1
          Call BOXINLET
        Case 2
          Call BOXBREAK
      End Select
  Case 1  'CIRCULAR PIPE CULVERT
'THE NEXT LINE SET THE FLOW PER BARREL
    Q = Discharge / NUM
'THIS LINE STARTS THE CRITICAL DEPTH COMPUTATIONS
    DCRIT = 0.1
    AA = 1
    If DCRIT > DIAM Then
      DCRIT = DIAM
    Else
    W = 2 * DCRIT / DIAM - 1
```

```
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = UBAR / Sqr(GRAV * D)
    CHECK = Abs(1 - FROUDE)
    While CHECK > 0.005
    If FROUDE > 1 Then DCRIT = DCRIT + 0.002 Else DCRIT = DCRIT - 0.002
    AA = AA + 1
    If DCRIT > DIAM Then
      DCRIT = DIAM
      FROUDE = 1
    Else
    W = 2 * DCRIT / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = UBAR / Sqr(GRAV * D)
    End If
    CHECK = Abs(1 - FROUDE)
    If AA > 5000 Then CHECK = 0
    Wend
    If DCRIT > DIAM Then DCRIT = DIAM
    End If
'Calculate the normal depths in each of the sections
'inlet section
If SLOI = 0 Then
  DNINLET = DIAM
Else
  DNINLET = DIAM / 2
  AA = 1
  W = 2 * DNINLET / DIAM - 1
  ASIN = Atn(W / Sqr(-W * W + 1))
  theta = 2 * ASIN + 3.14159
  area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
  RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
  ITER = 1.49 / N * (area) * (RADIUS) ^ 0.667 * SLOI ^ 0.5
'SEE HOW CLOSE YOU ARE TO THE ACTUAL
  CHECK = Abs(Q - ITER)
'IF CHECK <> .01 REITERATE
  While CHECK > 0.01
'MAKE NEW GUESS
    If Q > ITER Then DNINLET = DNINLET + 0.01 Else DNINLET = DNINLET -
0.01
    W = 2 * DNINLET / DIAM - 1
    If W >= 1 Then
    W = 0.9999
    AA = 350
    End If
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    ITER = 1.49 / N * (area) * (RADIUS) ^ 0.667 * SLOI ^ 0.5
    CHECK = Abs(Q - ITER)
'THIS WILL COUNT TO 350, IF IT IS STILL GOING, IT WILL QUIT
```

```
    AA = AA + 1
    If AA > 350 Then CHECK = 0
  Wend
End If
If DNINLET > DIAM Then DNINLET = DIAM
'steep section normal depth
  DNSTEEP = DIAM / 2
  AA = 1
  W = 2 * DNSTEEP / DIAM - 1
  ASIN = Atn(W / Sqr(-W * W + 1))
  theta = 2 * ASIN + 3.14159
  area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
  RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
  ITER = 1.49 / N * (area) * (RADIUS) ^ 0.667 * SLOS ^ 0.5
'SEE HOW CLOSE YOU ARE TO THE ACTUAL
  CHECK = Abs(Q - ITER)
'IF CHECK <> .01 REITERATE
  While CHECK > 0.01
'MAKE NEW GUESS
    If Q > ITER Then DNSTEEP = DNSTEEP + 0.01 Else DNSTEEP = DNSTEEP -
0.01
    W = 2 * DNSTEEP / DIAM - 1
    If W >= 1 Then
    W = 0.9999
    AA = 350
    End If
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    ITER = 1.49 / N * (area) * (RADIUS) ^ 0.667 * SLOS ^ 0.5
    CHECK = Abs(Q - ITER)
'THIS WILL COUNT TO 350, IF IT IS STILL GOING, IT WILL QUIT
    AA = AA + 1
    If AA > 350 Then CHECK = 0
  Wend
If DNSTEEP > DIAM Then DNSTEEP = DIAM
'OUTLET SECTION
If SLOO >= 0 Then
  DNOUTLET = DIAM
Else
  AA = 1
  DNOUTLET = DIAM / 2
  W = 2 * DNOUTLET / DIAM - 1
  ASIN = Atn(W / Sqr(-W * W + 1))
  theta = 2 * ASIN + 3.14159
  area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
  RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
  ITER = 1.49 / NOUT * (area) * (RADIUS) ^ 0.667 * SLOO ^ 0.5
'SEE HOW CLOSE YOU ARE TO THE ACTUAL
  CHECK = Abs(Q - ITER)
'IF CHECK <> .01 REITERATE
  While CHECK > 0.01
'MAKE NEW GUESS
    If Q > ITER Then DNOUTLET = DNOUTLET + 0.01 Else DNOUTLET = DNOUTLET
- 0.01
    W = 2 * DNOUTLET / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
```

```
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    ITER = 1.49 / NOUT * (area) * (RADIUS) ^ 0.667 * SLOO ^ 0.5
    CHECK = Abs(Q - ITER)
'THIS WILL COUNT TO 350, IF IT IS STILL GOING, IT WILL QUIT
    AA = AA + 1
    If AA > 350 Then CHECK = 0
  Wend
End If
If DNOUTLET > DIAM Then DNOUTLET = DIAM

'THE NEXT LINES START THE HEADWATER CALCULATIONS
    Call CIRCLECONTROL
'THIS LINE SETS THE CONTROL AS INLET OR BREAK
    If ELEVIC > ELEVBC Then
    Control = 1
    ELEVHW = ELEVIC
    ElseIf ELEVBC > ELEVIC Then
    Control = 2
    ELEVHW = ELEVBC
    End If
    DHW = ELEVHW - ELEVI
'THESE CALCULATE THE PROFILE CALCULATIONS
      Select Case Control
        Case 1
          Call CIRCLEINLET
        Case 2
          Call CIRCLEBREAK
      End Select
End Select
Screen.MousePointer = 0
frmDesign.Show
Exit Sub

Errhandler:
   MsgBox "BCAP IS UNABLE TO PERFORM TASK, AN ERROR OCCURED DURING
PROCESSING", 48, "BCAP Moniter"
Screen.MousePointer = 0
Exit Sub

SLOPEMESSAGE:
MsgBox "Slope greater than allowable.", 48, "BCAP"
Screen.MousePointer = 0
End Sub
```

Headwater Calculations

Box Culverts

```
DefSng A-Z
Public CONUM As Integer, Base As Integer, I As Integer
```

Circular Culverts

```
'PROGRAM TO CALCULATE BACK WATER CURVE THROUGH THE INLET
Sub BOXBREAK()
```

```
Dim TEMPY(500), TEMPX(500)
'SET THE STARTING DEPTH TO CRITICAL DEPTH AT THE INLET
'CALCULATE THE PROFILE THROUGH THE INLET SECTION AND
```

Profile Calculations

<u>Inlet Control - Box Culvert</u>

```
Sub BOXINLET()
'SET THE STARTING DEPTH TO CRITICAL DEPTH AT THE INLET
'CALCULATE THE PROFILE THROUGH THE INLET SECTION AND
'RECORD THE COORDINATES
'COORDINATE IS SET AS (# OF COORDINATE, LENGTH, WATER SURFACE ELEVATION)
'INITIAL LENGTH, DEPTH, AND COORDINATE NUMBER
          LENGTH = 0
          CONUM = 1
          DEPTH = DCRIT
          YDEPTH(CONUM) = DEPTH
          XLENGTH(CONUM) = LENGTH
          DINLET = YDEPTH(CONUM)
'THESE CALCULATE THE PROFILE CALCULATIONS
'STEP CALCULATIONS FROM INLET TO BREAK1
      SLOPE = SLOI
      If DNINLET < DCRIT Then STEP = -0.01 Else STEP = 0.01
  While LENGTH < LENI
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH + STEP
    If DEPTH >= H Then LENGTH = 100000
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = -0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
    If DISTANCE < 0 Then DISTANCE = 100000
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = LENI
    XLENGTH(CONUM) = LENGTH
    If DEPTH > DCRIT Then DEPTH = DCRIT
    YDEPTH(CONUM) = DEPTH
    DUPPER = YDEPTH(CONUM)
    B1 = CONUM
'STEEP SECTION CALCULATIONS
    SLOPE = SLOS
  While LENGTH < (LENI + LENS)
    If DTW >= H Then
```

```
    If DEPTH + (LENI + LENS - LENGTH) * SLOS < DTW Then
      DEPTH = H
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = (LENI + LENS - (DTW - DEPTH) / SLOS)
      LENGTH = 10000
      JUMP = "NO"
      LENJUMP = 0
      STAJUMP = 0
    End If
    End If
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH - 0.01
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(-0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    If DEPTH < DNSTEEP Then DISTANCE = 100000
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = (LENI + LENS)
    XLENGTH(CONUM) = LENGTH
    SLOPE = SLOO
    DLOWER = YDEPTH(CONUM)
    B2 = CONUM
'OUTLET SECTION CALCS
  If DNOUTLET > DEPTH Then
  If ELEVB2 = ELEVO Then
   theta = 0
  Else
   theta = Atn((ELEVB2 - ELEVO) / LENO)
  End If
    If DTW >= H Then
    DEPTH = H
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
    LENGTH = 200000
    End If
  While LENGTH < (LENI + LENS + LENO)
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
'CALCULATE THE SEQUENT DEPTH
    If FROUDE < 2.89 Then
      SEQUENT = DEPTH / 2 * ((1 + 8 * FROUDE) ^ 0.5 - 1)
```

```
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      X = (FROUDE ^ 0.5 - 1) / 22
      Tanh = (Exp(X) - Exp(-X)) / (Exp(X) + Exp(-X))
      LENJUMP = DEPTH * 220 * Tanh
      DEPTH = SEQUENT
      If DEPTH > H Then DEPTH = H
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH
      LL = LENGTH
      LENGTH = 100000
    Else
    SEQUENT = DEPTH / 2 * ((1 + 8 * FROUDE) ^ 0.5 - 1)
    If SEQUENT < (DTW - (LENI + LENS + LENO - LENGTH)) Then
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      X = (FROUDE ^ 0.5 - 1) / 22
      Tanh = (Exp(X) - Exp(-X)) / (Exp(X) + Exp(-X))
      LENJUMP = DEPTH * 220 * Tanh
      DEPTH = SEQUENT
      If DEPTH > H Then DEPTH = H
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH
      LL = LENGTH
      LENGTH = 100000
    Else
      DEPTH = DEPTH + 0.01
      If DEPTH > H Then DEPTH = H
      area2 = W * DEPTH
      RADIUS2 = area2 / (W + 2 * DEPTH)
      UBAR2 = Q / area2
      FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
      FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
      FROUDEM = (FROUDE + FROUDE2) / 2
      FSLOPEM = (FSLOPE + FSLOPE2) / 2
      DISTANCE = 0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
      LENGTH = LENGTH + DISTANCE
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
    End If
    End If
  Wend
   If LENGTH = 100000 Then
     LENGTH = LL
     If DEPTH = H Then
       CONUM = CONUM + 1
       YDEPTH(CONUM) = H
       XLENGTH(CONUM) = LENI + LENS + LENO
     Else
     While LENGTH < (LENI + LENS + LENO)
       area = W * DEPTH
       RADIUS = area / (W + 2 * DEPTH)
       UBAR = Q / area
       FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
```

```
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH + 0.01
    If DEPTH >= H Then LENGTH = 100000
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    XLENGTH(CONUM) = LENI + LENS + LENO
  End If
Else
  JUMP = "NO"
  LENJUMP = 0
  STAJUMP = 0
  LENGTH = LENI + LENS + LENO
  XLENGTH(CONUM) = LENGTH
End If
Else
  JUMP = "NO"
  LENJUMP = 0
  STAJUMP = 0
  While LENGTH < (LENI + LENS + LENO)
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH - 0.01
    If DEPTH >= H Then LENGTH = 100000
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = -0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    XLENGTH(CONUM) = LENI + LENS + LENO
End If
     If JUMP = "NO" Then
      DOUT = DEPTH
     Else
     If DEPTH > DCRIT Then
      DOUT = DEPTH
     Else
      If DTW >= H Then DOUT = H
```

```
        If H > DTW And DTW > DCRIT Then DOUT = DTW
        If DCRIT >= DTW Then DOUT = DCRIT
       End If
       End If
         VINLET = Q / (W * DINLET)
         VUPPER = Q / (W * DUPPER)
         VLOWER = Q / (W * DLOWER)
         VOUT = Q / (W * DOUT)
         VOUTLET = Q / (W * DEPTH)
         OUTFROUDE = (VOUT / Sqr(GRAV * DEPTH))
End Sub
```

Break Control - Box Culvert

```
'Option Explicit
'PROGRAM TO CALCULATE BACK WATER CURVE THROUGH THE INLET
Sub BOXBREAK()
Dim TEMPY(500), TEMPX(500)
'SET THE STARTING DEPTH TO CRITICAL DEPTH AT THE INLET
'CALCULATE THE PROFILE THROUGH THE INLET SECTION AND
'RECORD THE COORDINATES
'INITIAL LENGTH, DEPTH, AND COORDINATE NUMBER
          LENGTH = 0
          CONUM = 1
          DEPTH = H
          YDEPTH(CONUM) = DEPTH
          XLENGTH(CONUM) = 0
'THESE CALCULATE THE PROFILE CALCULATIONS
'STEP CALCULATIONS FROM INLET TO BREAK1
'SET INITIAL VALUES
  CONUM = CONUM + 1
  YDEPTH(CONUM) = H
  XLENGTH(CONUM) = LENI
   LENGTH = LENI
   DINLET = DCRIT
   DUPPER = H
   DEPTH = DCRIT
   B1 = CONUM
'STEEP SECTION CALCULATIONS
    SLOPE = SLOS
  While LENGTH < (LENI + LENS)
   If DTW >= H Then
   If DEPTH + (LENI + LENS - LENGTH) * SLOS < DTW Then
      DEPTH = H
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = (LENI + LENS - (DTW - DEPTH) / SLOS)
      LENGTH = 100000
      JUMP = "NO"
      LENJUMP = 0
      STAJUMP = 0
    End If
    End If
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
```

```
    DEPTH = DEPTH - 0.01
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(-0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    If DEPTH < DNSTEEP Then DISTANCE = 100000
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = (LENI + LENS)
    XLENGTH(CONUM) = LENGTH
    DLOWER = YDEPTH(CONUM)
    SLOPE = SLOO
    B2 = CONUM
'OUTLET SECTION CALCS
  If ELEVB2 = ELEVO Then
   theta = 0
  Else
   theta = Atn((ELEVB2 - ELEVO) / LENO)
  End If
  If DTW >= H Then
    DEPTH = H
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
    LENGTH = 100000
  End If
  While LENGTH < (LENI + LENS + LENO)
    area = W * DEPTH
    RADIUS = area / (W + 2 * DEPTH)
    UBAR = Q / area
    FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
'CALCULATE THE SEQUENT DEPTH
    If FROUDE < 2.89 Then
      SEQUENT = DEPTH / 2 * ((1 + 8 * FROUDE) ^ 0.5 - 1)
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      X = (FROUDE ^ 0.5 - 1) / 22
      Tanh = (Exp(X) - Exp(-X)) / (Exp(X) + Exp(-X))
      LENJUMP = DEPTH * 220 * Tanh
      DEPTH = SEQUENT
      If DEPTH > H Then DEPTH = H
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH
      LL = LENGTH
      LENGTH = 100000
    Else
    SEQUENT = DEPTH / 2 * ((1 + 8 * FROUDE) ^ 0.5 - 1)
    If SEQUENT < (DTW - (LENI + LENS + LENO - LENGTH)) Then
      JUMP = "YES"
```

```
    CONUM = CONUM + 1
    STAJUMP = LENGTH
    X = (FROUDE ^ 0.5 - 1) / 22
    Tanh = (Exp(X) - Exp(-X)) / (Exp(X) + Exp(-X))
    LENJUMP = DEPTH * 220 * Tanh
    DEPTH = SEQUENT
    If DEPTH > H Then DEPTH = H
    YDEPTH(CONUM) = DEPTH
    LENGTH = LENGTH + LENJUMP
    XLENGTH(CONUM) = LENGTH
    LL = LENGTH
    LENGTH = 100000
  Else
    DEPTH = DEPTH + 0.01
    If DEPTH > H Then DEPTH = H
    area2 = W * DEPTH
    RADIUS2 = area2 / (W + 2 * DEPTH)
    UBAR2 = Q / area2
    FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
    FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = 0.01 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  End If
  End If
Wend
 If LENGTH = 100000 Then
   LENGTH = LL
   If DEPTH = H Then
     CONUM = CONUM + 1
     YDEPTH(CONUM) = H
     XLENGTH(CONUM) = LENI + LENS + LENO
   Else
   While LENGTH < (LENI + LENS + LENO)
     area = W * DEPTH
     RADIUS = area / (W + 2 * DEPTH)
     UBAR = Q / area
     FROUDE = (UBAR / Sqr(GRAV * DEPTH)) ^ 2
     FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
     DEPTH = DEPTH + 0.005
     If DEPTH >= H Then LENGTH = 100000
     area2 = W * DEPTH
     RADIUS2 = area2 / (W + 2 * DEPTH)
     UBAR2 = Q / area2
     FROUDE2 = (UBAR2 / Sqr(GRAV * DEPTH)) ^ 2
     FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
     FROUDEM = (FROUDE + FROUDE2) / 2
     FSLOPEM = (FSLOPE + FSLOPE2) / 2
     DISTANCE = Abs(0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
     LENGTH = LENGTH + DISTANCE
     CONUM = CONUM + 1
     YDEPTH(CONUM) = DEPTH
     XLENGTH(CONUM) = LENGTH
   Wend
     XLENGTH(CONUM) = LENI + LENS + LENO
```

```
      End If
    Else
      JUMP = "NO"
      LENJUMP = 0
      STAJUMP = 0
      LENGTH = LENI + LENS + LENO
      XLENGTH(CONUM) = LENGTH
    End If
         If JUMP = "NO" Then
          DOUT = DEPTH
         Else
         If DEPTH > DCRIT Then
          DOUT = DEPTH
         Else
          If DTW >= H Then DOUT = H
          If H > DTW And DTW > DCRIT Then DOUT = DTW
          If DCRIT >= DTW Then DOUT = DCRIT
         End If
         End If
           VINLET = Q / (W * DINLET)
           VUPPER = Q / (W * DUPPER)
           VLOWER = Q / (W * DLOWER)
           VOUT = Q / (W * DOUT)
           VOUTLET = Q / (W * DEPTH)
           OUTFROUDE = (VOUT / Sqr(GRAV * DEPTH))
End Sub
```

Inlet Control - Circular Culvert

```
Sub CIRCLEINLET()
'SET THE STARTING DEPTH TO CRITICAL DEPTH AT THE INLET
'CALCULATE THE PROFILE THROUGH THE INLET SECTION AND
'RECORD THE COORDINATES
'INITIAL LENGTH, DEPTH, AND COORDINATE NUMBER
      LENGTH = 0
          CONUM = 1
          DEPTH = DCRIT
          If DEPTH = DIAM Then DEPTH = DIAM - 0.001
          YDEPTH(CONUM) = DEPTH
          XLENGTH(CONUM) = LENGTH
          DINLET = YDEPTH(CONUM)
'THESE CALCULATE THE PROFILE CALCULATIONS
'STEP CALCULATIONS FROM INLET TO BREAK1
      SLOPE = SLOI
      If DNINLET < DCRIT Then STEP = -0.005 Else STEP = 0.005
  While LENGTH < LENI
    W = 2 * DEPTH / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    UBAR = Q / area
    'D = 0.125 * DIAM * ((theta - Sin(theta)) / (Sin(theta * 0.5)))
    D = (area / 2) ^ 0.5
    FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH + STEP
    If DEPTH >= DIAM Then
```

```
      LENGTH = 100000
    Else
    W2 = 2 * DEPTH / DIAM - 1
    ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
    theta2 = 2 * ASIN2 + 3.14159
    area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
    RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
    UBAR2 = Q / area2
    D2 = (area2 / 2) ^ 0.5
    FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = -0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
    If DISTANCE < 0 Then DISTANCE = 100000
    End If
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = LENI
    XLENGTH(CONUM) = LENGTH
    If DEPTH > DCRIT Then DEPTH = DCRIT - 0.0001
    YDEPTH(CONUM) = DEPTH
    DUPPER = YDEPTH(CONUM)
    B1 = CONUM
'STEEP SECTION CALCULATIONS
    SLOPE = SLOS
  While LENGTH < (LENI + LENS)
    If DTW >= DIAM Then
    If DEPTH + (LENI + LENS - LENGTH) * SLOS < DTW Then
      DEPTH = DIAM - 0.0001
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = (LENI + LENS - (DTW - DEPTH) / SLOS)
      LENGTH = 100000
      JUMP = "NO"
      LENJUMP = 0
      STAJUMP = 0
    End If
    End If
    W = 2 * DEPTH / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH - 0.005
    W2 = 2 * DEPTH / DIAM - 1
    ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
    theta2 = 2 * ASIN2 + 3.14159
    area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
    RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
    UBAR2 = Q / area2
    D2 = (area2 / 2) ^ 0.5
```

```
    FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(-0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    If DEPTH < DNSTEEP Then DISTANCE = 100000
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = (LENI + LENS)
    XLENGTH(CONUM) = LENGTH
    DLOWER = YDEPTH(CONUM)
    SLOPE = SLOO
    B2 = CONUM
'OUTLET SECTION CALCS
    If DNOUTLET > DEPTH Then
    If DTW >= DIAM Then
    DEPTH = DIAM
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
    LENGTH = 100000
    End If
  While LENGTH < (LENI + LENS + LENO)
    W = 2 * DEPTH / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
'CALCULATE THE SEQUENT DEPTH
    SEQUENT = DCRIT ^ 2 / DEPTH
    If FROUDE < 2.89 Then
      SEQUENT = DCRIT ^ 1.8 / DEPTH ^ 0.73
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      DEPTH = SEQUENT
      If DEPTH > DIAM Then DEPTH = DIAM
      LENJUMP = 6 * DEPTH
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH
      LL = LENGTH
      LENGTH = 100000
    Else
    If SEQUENT < (DTW - (LENI + LENS + LENO - LENGTH)) Then
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      DEPTH = SEQUENT
      If DEPTH > DIAM Then DEPTH = DIAM
      LENJUMP = 6 * DEPTH
      YDEPTH(CONUM) = DEPTH
```

```
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH + LENJUMP
      LL = LENGTH
      LENGTH = 100000
    Else
      DEPTH = DEPTH + 0.005
      If DEPTH > DIAM Then
      CONUM = CONUM + 1
      LENGTH = 300000
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
      Else
      W2 = 2 * DEPTH / DIAM - 1
      ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
      theta2 = 2 * ASIN2 + 3.14159
      area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
      RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
      UBAR2 = Q / area2
      D2 = (area2 / 2) ^ 0.5
      FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
      FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
      FROUDEM = (FROUDE + FROUDE2) / 2
      FSLOPEM = (FSLOPE + FSLOPE2) / 2
      DISTANCE = Abs(0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
      LENGTH = LENGTH + DISTANCE
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
      End If
    End If
    End If
  Wend
   If LENGTH = 100000 Then
     LENGTH = LL
     If DEPTH = DIAM Then
       CONUM = CONUM + 1
       YDEPTH(CONUM) = DEPTH
       XLENGTH(CONUM) = LENI + LENS + LENO
     Else
     While LENGTH < (LENI + LENS + LENO)
       W = 2 * DEPTH / DIAM - 1
       ASIN = Atn(W / Sqr(-W * W + 1))
       theta = 2 * ASIN + 3.14159
       area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
       RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
       UBAR = Q / area
       D = (area / 2) ^ 0.5
       FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
       FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
       DEPTH = DEPTH + 0.005
       If DEPTH >= DIAM Then LENGTH = 100000
       W2 = 2 * DEPTH / DIAM - 1
       If W2 >= 1 Then W2 = 0.9999
       ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
       theta2 = 2 * ASIN2 + 3.14159
       area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
       RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
       UBAR2 = Q / area2
       D2 = (area2 / 2) ^ 0.5
```

```
      FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
      FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
      FROUDEM = (FROUDE + FROUDE2) / 2
      FSLOPEM = (FSLOPE + FSLOPE2) / 2
      DISTANCE = Abs(0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
      LENGTH = LENGTH + DISTANCE
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
    Wend
    XLENGTH(CONUM) = LENI + LENS + LENO
    End If
  Else
    JUMP = "NO"
    LENJUMP = 0
    STAJUMP = 0
    LENGTH = LENI + LENS + LENO
    XLENGTH(CONUM) = LENGTH
  End If
  Else
    JUMP = "NO"
    LENJUMP = 0
    STAJUMP = 0
    While LENGTH < (LENI + LENS + LENO)
      W = 2 * DEPTH / DIAM - 1
      ASIN = Atn(W / Sqr(-W * W + 1))
      theta = 2 * ASIN + 3.14159
      area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
      RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
      UBAR = Q / area
      D = 0.125 * DIAM * ((theta - Sin(theta)) / (Sin(theta * 0.5)))
      FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
      FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
      DEPTH = DEPTH - 0.005
      If DEPTH >= DIAM Then LENGTH = 100000
      W2 = 2 * DEPTH / DIAM - 1
      ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
      theta2 = 2 * ASIN2 + 3.14159
      area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
      RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
      UBAR2 = Q / area2
        D2 = 0.125 * DIAM * ((theta2 - Sin(theta2)) / (Sin(theta2 *
0.5)))
      FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
      FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
      FROUDEM = (FROUDE + FROUDE2) / 2
      FSLOPEM = (FSLOPE + FSLOPE2) / 2
      DISTANCE = -0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM)
      LENGTH = LENGTH + DISTANCE
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
    Wend
    XLENGTH(CONUM) = LENI + LENS + LENO
  End If

       If JUMP = "NO" Then
       DOUT = DEPTH
       Else
```

```
        If DEPTH < DCRIT Then
         DOUT = DEPTH
        Else
         If DTW >= H Then DOUT = H
         If H > DTW And DTW > DCRIT Then DOUT = DTW
         If DCRIT >= DTW Then DOUT = DCRIT
        End If
        End If
      If DOUT >= DIAM Then
        DOUT = DIAM
        area = 3.14159 * DIAM ^ 2 / 4
        D = (area / 2) ^ 0.5
      Else
        W = 2 * DEPTH / DIAM - 1
        If W >= 1 Then W = 0.99999
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        D = (area / 2) ^ 0.5
      End If
      VOUT = Q / area
      OUTFROUDE = (VOUT / Sqr(GRAV * D))
      If DEPTH >= DIAM Then DEPTH = DIAM - 0.0001
      W = 2 * DEPTH / DIAM - 1
      ASIN = Atn(W / Sqr(-W * W + 1))
      theta = 2 * ASIN + 3.14159
      area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
      VOUTLET = Q / area
'INLET VELOCITY
        W = 2 * DINLET / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VINLET = Q / area
'UPPER BREAK VELOCITY
        W = 2 * DUPPER / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VUPPER = Q / area
'LOWER BREAK VELOCITY
        W = 2 * DLOWER / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VLOWER = Q / area
End Sub
```

Break Control - Circular Culvert

```
Sub CIRCLEBREAK()
'SET THE STARTING DEPTH TO CRITICAL DEPTH AT THE INLET
'CALCULATE THE PROFILE THROUGH THE INLET SECTION AND
'RECORD THE COORDINATES
'INITIAL LENGTH, DEPTH, AND COORDINATE NUMBER
Dim TEMPX(500), TEMPY(500)
          LENGTH = 0
          CONUM = 1
```

```
          DEPTH = DIAM
          YDEPTH(CONUM) = DEPTH
          XLENGTH(CONUM) = 0
'THESE CALCULATE THE PROFILE CALCULATIONS
'STEP CALCULATIONS FROM INLET TO BREAK1
'SET INITIAL VALUES
  CONUM = CONUM + 1
  YDEPTH(CONUM) = DIAM
  XLENGTH(CONUM) = LENI
   LENGTH = LENI
   DINLET = DCRIT
   DUPPER = DIAM
   DEPTH = DCRIT
   B1 = CONUM
'STEEP SECTION CALCULATIONS
    SLOPE = SLOS
  While LENGTH < (LENI + LENS)
    If DTW >= DIAM Then
    If DEPTH + (LENI + LENS - LENGTH) * SLOS < DTW Then
      DEPTH = DIAM - 0.0001
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = (LENI + LENS - (DTW - DEPTH) / SLOS)
      LENGTH = 100000
      JUMP = "NO"
      LENJUMP = 0
      STAJUMP = 0
    End If
    End If
    If DEPTH >= DIAM Then DEPTH = DIAM - 0.001
    W = 2 * DEPTH / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
    FSLOPE = (N * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
    DEPTH = DEPTH - 0.005
    W2 = 2 * DEPTH / DIAM - 1
    ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
    theta2 = 2 * ASIN2 + 3.14159
    area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
    RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
    UBAR2 = Q / area2
    D2 = (area2 / 2) ^ 0.5
    FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
    FSLOPE2 = (N * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(-0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    If DEPTH < DNSTEEP Then DISTANCE = 100000
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  Wend
    LENGTH = (LENI + LENS)
```

```
    XLENGTH(CONUM) = LENGTH
    DLOWER = YDEPTH(CONUM)
    SLOPE = SLOO
    B2 = CONUM
'OUTLET SECTION CALCS
    If DTW >= DIAM Then
      DEPTH = DIAM
      CONUM = CONUM + 1
      YDEPTH(CONUM) = DEPTH
      XLENGTH(CONUM) = LENGTH
      LENGTH = 100000
    End If
  While LENGTH < (LENI + LENS + LENO)
    W = 2 * DEPTH / DIAM - 1
    ASIN = Atn(W / Sqr(-W * W + 1))
    theta = 2 * ASIN + 3.14159
    area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
    RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
    UBAR = Q / area
    D = (area / 2) ^ 0.5
    FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
    FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
'CALCULATE THE SEQUENT DEPTH
      SEQUENT = DCRIT ^ 2 / DEPTH
    If FROUDE < 2.89 Then
      SEQUENT = DCRIT ^ 1.8 / DEPTH ^ 0.73
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      DEPTH = SEQUENT
      If DEPTH > DIAM Then DEPTH = DIAM
      LENJUMP = 6 * DEPTH
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH
      LL = LENGTH
      LENGTH = 100000
    Else
    If SEQUENT < (DTW - (LENI + LENS + LENO - LENGTH)) Then
      JUMP = "YES"
      CONUM = CONUM + 1
      STAJUMP = LENGTH
      DEPTH = SEQUENT
      If DEPTH > DIAM Then DEPTH = DIAM
      LENJUMP = 6 * DEPTH
      YDEPTH(CONUM) = DEPTH
      LENGTH = LENGTH + LENJUMP
      XLENGTH(CONUM) = LENGTH + LENJUMP
      LL = LENGTH
      LENGTH = 100000
    Else
      DEPTH = DEPTH + 0.005
      If DEPTH >= DIAM Then DEPTH = DIAM - 0.001
      W2 = 2 * DEPTH / DIAM - 1
      ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
      theta2 = 2 * ASIN2 + 3.14159
      area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
      RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
      UBAR2 = Q / area2
```

```
    D2 = (area2 / 2) ^ 0.5
    FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
    FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
    FROUDEM = (FROUDE + FROUDE2) / 2
    FSLOPEM = (FSLOPE + FSLOPE2) / 2
    DISTANCE = Abs(0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
    LENGTH = LENGTH + DISTANCE
    CONUM = CONUM + 1
    YDEPTH(CONUM) = DEPTH
    XLENGTH(CONUM) = LENGTH
  End If
  End If
Wend
 If LENGTH = 100000 Then
   LENGTH = LL
   If DEPTH = DIAM Then
     CONUM = CONUM + 1
     YDEPTH(CONUM) = DEPTH
     XLENGTH(CONUM) = LENI + LENS + LENO
   Else
   While LENGTH < (LENI + LENS + LENO)
     W = 2 * DEPTH / DIAM - 1
     ASIN = Atn(W / Sqr(-W * W + 1))
     theta = 2 * ASIN + 3.14159
     area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
     RADIUS = 0.25 * (1 - (Sin(theta) / theta)) * DIAM
     UBAR = Q / area
     D = (area / 2) ^ 0.5
     FROUDE = (UBAR / Sqr(GRAV * D)) ^ 2
     FSLOPE = (NOUT * UBAR / (PHI * (RADIUS ^ 0.667))) ^ 2
     DEPTH = DEPTH - 0.005
     If DEPTH >= DIAM Then LENGTH = 100000:
     W2 = 2 * DEPTH / DIAM - 1
     ASIN2 = Atn(W2 / Sqr(-W2 * W2 + 1))
     theta2 = 2 * ASIN2 + 3.14159
     area2 = 0.125 * (theta2 - Sin(theta2)) * DIAM ^ 2
     RADIUS2 = 0.25 * (1 - (Sin(theta2) / theta2)) * DIAM
     UBAR2 = Q / area2
     D2 = (area2 / 2) ^ 0.5
     FROUDE2 = (UBAR2 / Sqr(GRAV * D2)) ^ 2
     FSLOPE2 = (NOUT * UBAR2 / (PHI * (RADIUS2 ^ 0.667))) ^ 2
     FROUDEM = (FROUDE + FROUDE2) / 2
     FSLOPEM = (FSLOPE + FSLOPE2) / 2
     DISTANCE = Abs(0.005 * (1 - FROUDEM) / (SLOPE - FSLOPEM))
     LENGTH = LENGTH + DISTANCE
     CONUM = CONUM + 1
     YDEPTH(CONUM) = DEPTH
     XLENGTH(CONUM) = LENGTH
   Wend
   XLENGTH(CONUM) = LENI + LENS + LENO
   End If
 Else
   JUMP = "NO"
   LENJUMP = 0
   STAJUMP = 0
   LENGTH = LENI + LENS + LENO
   XLENGTH(CONUM) = LENGTH
 End If
      If JUMP = "NO" Then
```

```
        DOUT = DEPTH
        Else
        If DEPTH < DCRIT Then
         DOUT = DEPTH
        Else
         If DTW >= H Then DOUT = H
         If H > DTW And DTW > DCRIT Then DOUT = DTW
         If DCRIT >= DTW Then DOUT = DCRIT
        End If
        End If
      If DOUT >= DIAM Then
        DOUT = DIAM
        area = 3.14159 * DIAM ^ 2 / 4
        D = (area / 2) ^ 0.5
      Else
        W = 2 * DOUT / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        D = (area / 2) ^ 0.5
      End If
      VOUT = Q / area
      OUTFROUDE = (VOUT / Sqr(GRAV * D))
      If DEPTH >= DIAM Then DEPTH = DIAM - 0.0001
      W = 2 * DEPTH / DIAM - 1
      ASIN = Atn(W / Sqr(-W * W + 1))
      theta = 2 * ASIN + 3.14159
      area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
      VOUTLET = Q / area
'INLET VELOCITY
        If DINLET >= DIAM Then DINLET = DIAM - 0.0001
        W = 2 * DINLET / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VINLET = Q / area
'UPPER BREAK VELOCITY
        If DUPPER >= DIAM Then DUPPER = DIAM - 0.0001
        W = 2 * DUPPER / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VUPPER = Q / area
'LOWER BREAK VELOCITY
        If DLOWER >= DIAM Then DLOWER = DIAM - 0.0001
        W = 2 * DLOWER / DIAM - 1
        ASIN = Atn(W / Sqr(-W * W + 1))
        theta = 2 * ASIN + 3.14159
        area = 0.125 * (theta - Sin(theta)) * DIAM ^ 2
        VLOWER = Q / area
End Sub
```

Convert.Bat Code

```
:run_Convert
echo off
c:\hy8\ convert.exe
cls
```

```
echo HY8 input and output files have been created.
pause
echo HY8 Should be used only for Energy Dissipation at this time.
echo Any other option will create errors and the Dissipator option
echo will not operate properly.

echo Choose the units you are designing in by pressing "U".
echo Then enter the energy option by pressing "J"
echo The file name to use is "BCAP"
pause
c:\hy8\hy8.exe
:end_menu
```

Convert.For Code

```
C PROGRAM TO CONVERT THE OUTPUT INTO A FORM THAT HY8 CAN USE IN THE
DISSIPATOR
C PAGE,  WRITTEN IN FORTRAN77
C2356789
      REAL Q,SHAPE,STAB2,ELEV2,STAO,ELEVO,LENO,SLOO
      REAL SP,RI,N,B,Z,SLOTW,NTW,DISCHARGE,DTW,VTW
      REAL ZERO,DHW,DIC,DBC,DN,DCRIT,VOUT,DOUT
      REAL DLO,DOUTL,NUM,TWO
      INTEGER ONE,TWSH
      ZERO = 0.
      ONE = 1
      TWO = 1.
C  OPEN OUTPUT FILE FROM VISUAL BASIC
      OPEN(6,FILE='C:\HY8\BCAP.IN',STATUS='OLD')
      OPEN(7,FILE='C:\HY8\BCAP.OUT',STATUS='OLD')
      OPEN(16,FILE='C:\HY8\BCAP.INP',STATUS='NEW')
      OPEN(17,FILE='C:\HY8\BCAP.PC',STATUS='NEW')
C  READ INPUT VARIABLES FOR .INP FILE
      READ(6,*)Q
      READ(6,*)SHAPE,NUM
      READ(6,*)STAB2,ELEVB2,STAO,ELEVO
      READ(6,*)LENO,SLOO
      READ(6,*)SP,RI,N
      READ(6,*)TWSH
      READ(6,*)B,Z,SLOTW,NTW
      READ(6,*)DISCHARGE,DTW,VTW
      IF(SLOO.EQ.0.) THEN
      SLOO = .0001
      ENDIF
C  WRITE VARIABLES TO .INP FILE
 1600 FORMAT(4F11.3)
 1601 FORMAT(2F6.0)
 1602 FORMAT(6F11.4)
 1603 FORMAT(8F6.0)
 1604 FORMAT(9F10.4)
 1605 FORMAT(3F11.4)
 1606 FORMAT(5F11.4)
 1607 FORMAT(3F19.8)
 1608 FORMAT(5F19.8)
 1609 FORMAT(5F13.3)
 1610 FORMAT(3F10.0)
 1611 FORMAT(F10.6)
 1612 FORMAT(2F13.5)
```

```
 1613 FORMAT(I2)
 1614 FORMAT('BCAP')
 1615 FORMAT('VERSION 6.0')
 1616 FORMAT('01-01-1999')
 1617 FORMAT('N')
 1618 FORMAT(4F11.4)
      WRITE(16,1614)
      WRITE(16,1615)
      WRITE(16,1616)
      WRITE(16,1600)ZERO,Q,Q,TWO
      WRITE(16,1601)SHAPE,NUM
      WRITE(16,1602)ZERO,ZERO,ZERO,ZERO,ZERO,ZERO
      WRITE(16,1618)STAB2,ELEVB2,STAO,ELEVO
      WRITE(16,1618)ELEVB2,ELEVO,LENO,SLOO
      WRITE(16,1602)ZERO,ZERO,ZERO,ZERO,ZERO,ZERO
      WRITE(16,1603)SHAPE,NUM,ZERO,TWO,TWO,ZERO,ZERO,ZERO
      WRITE(16,1604)SP,RI,N,ZERO,ZERO,ZERO,ZERO,ZERO,ZERO
      WRITE(16,1605)ZERO,ZERO,ZERO
      WRITE(16,1606)ZERO,ZERO,ZERO,ZERO,ZERO
      WRITE(16,1617)
      WRITE(16,1617)
      DO 100 I = 1,20
      WRITE(16,1607)ZERO,ZERO,ZERO
  100 CONTINUE
      WRITE(16,1613)TWSH
      WRITE(16,*)
      WRITE(16,1608)B,Z,SLOTW,NTW,ELEVO
      ELEVTW = ELEVO + DTW
      DO 101 I = 1,11
      WRITE(16,1609)Q,ELEVTW,VTW,SHEAR,FTW
  101 CONTINUE
      WRITE(16,1610)ZERO,ZERO,ZERO
      WRITE(16,1611)ZERO
      WRITE(16,1617)
      DO 102 I = 1,15
      WRITE(16,1612)ZERO,ZERO
  102 CONTINUE
C  READ OUTPUT VARIABLES FOR .PC FILE
      READ(7,*)DHW,Q
      READ(7,*)DIC,DBC,DN,DCRIT,VOUT,DOUT,VTW,DTW
      READ(7,*)DLO,DOUTL
      INTQ = Q
      INTZERO = 0
C  WRITE VARIABLES TO .PC FILE
 1700 FORMAT(1X,F8.4,I9)
 1701 FORMAT(F8.2,F9.2,2F7.2,I2,' "2Sn"',F6.2,2F7.2,F6.2,F7.2,F6.2)
 1702 FORMAT(I2,F21.6)
 1703 FORMAT(4F8.2,I2,' "2Sn" ',3I6,1X,F6.5,2F5.1)
      WRITE(17,1614)
      WRITE(17,1616)
      DO 103 I= 1,11
      WRITE(17,1700)DHW,INTQ
  103 CONTINUE
      WRITE(17,1617)
      WRITE(17,*)'1'
      DO 104 I = 1,11
      WRITE(17,1701)Q,DHW,DIC,DBC,ONE,DN,DCRIT,VOUT,DOUT,VTW,DTW
  104 CONTINUE
      WRITE(17,1702)ONE,TWO
```

```
      DO 105 I = 1,11
WRITE(17,1703)Q,ZERO,ZERO,ZERO,ONE,INTZERO,INTZERO,INTZERO,SLOO,DLO,DOUT
L
  105 CONTINUE
      STOP
      END
```

APPENDIX D - PROGRAM VALIDATION

Included in this Appendix are the test results from the broken-back culvert prototype constructed in the hydraulics laboratory. The prototype broken-back culvert was a circular, 4-in. Plexiglas tube. The culvert profile was a double broken-back with either 22.5 degree or 45 degree bends. Flows ranged from 0.07 cfs to 0.30 cfs. The headwater depth, outlet depth, and flow were recorded for each run. The results were then compared to the results from BCAP.

The comparisons show that BCAP is capable of producing results near to what could be expected from a prototype. The prototype culvert was large enough to overcome any effects due to scaling, such as surface tension, and therefore represents a "real world" culvert in all aspects.

Table D.1. Double broken-back validation, 45 deg. bend

Inlet Station (ft)	0.00
Inlet Elevation (ft)	11.50
Upper Break Station (ft)	1.64
Upper Break Elevation (ft)	11.50
Lower Break Station (ft)	3.02
Lower Break Elevation (ft)	10.17
Outlet Station (ft)	9.15
Outlet Elevation (ft)	10.17
Pipe Shape	Circular
Pipe Size (ft)	0.33
Pipe Material	Plexiglas
Material Roughness	0.010
Inlet Type	Thin Edge

Tailwater Depth (ft)		0.00		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.093	0.27	0.09	0.27	0.08
0.164	0.41	0.11	0.36	0.11
0.224	0.57	0.13	0.57	0.11
0.297	0.84	0.15	0.68	0.12

Tailwater Depth (ft)		0.17		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.093	0.27	0.09	0.27	0.08
0.164	0.41	0.11	0.36	0.11
0.224	0.57	0.13	0.57	0.11
0.297	0.84	0.15	0.68	0.12

Tailwater Depth (ft)		0.50		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.093	0.27	0.33	0.27	0.33
0.164	0.41	0.33	0.36	0.33
0.224	0.57	0.33	0.57	0.33
0.297	0.84	0.33	0.68	0.33

Table D.2. Double broken-back validation, 22.5 deg. bend, run 1

Inlet Station (ft)		0.00		
Inlet Elevation (ft)		10.85		
Upper Break Station (ft)		1.61		
Upper Break Elevation (ft)		10.85		
Lower Break Station (ft)		3.12		
Lower Break Elevation (ft)		10.17		
Outlet Station (ft)		9.19		
Outlet Elevation (ft)		10.17		
Pipe Shape		Circular		
Pipe Size (ft)		0.33		
Pipe Material		Plexiglas		
Material Roughness		0.010		
Inlet Type		Thin Edge		
Tailwater Depth (ft)		0.00		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.071	0.23	0.09	0.24	0.07
0.157	0.39	0.13	0.37	0.11
0.227	0.58	0.16	0.57	0.14
0.292	0.82	0.18	0.77	0.16
Tailwater Depth (ft)		0.17		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.071	0.23	0.09	0.24	0.07
0.157	0.39	0.13	0.37	0.11
0.227	0.58	0.16	0.57	0.14
0.292	0.82	0.18	0.77	0.16
Tailwater Depth (ft)		0.50		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.071	0.23	0.33	0.24	0.33
0.157	0.39	0.33	0.37	0.33
0.227	0.58	0.33	0.57	0.33
0.292	0.82	0.33	0.77	0.33

Table D.3. Double broken-back validation, 22.5 deg. bend, run 2

Inlet Station (ft)		0.00		
Inlet Elevation (ft)		12.20		
Upper Break Station (ft)		1.67		
Upper Break Elevation (ft)		12.20		
Lower Break Station (ft)		7.09		
Lower Break Elevation (ft)		10.17		
Outlet Station (ft)		13.58		
Outlet Elevation (ft)		10.17		
Pipe Shape		Circular		
Pipe Size (ft)		0.33		
Pipe Material		Plexiglas		
Material Roughness		0.010		
Inlet Type		Thin Edge		
Tailwater Depth (ft)		0.00		
	BCAP Results		Prototype Results	
Flow (cfs)	Headwater (ft)	Outlet Depth(ft)	Headwater (ft)	Outlet Depth(ft)
0.072	0.23	0.09	0.22	0.07
0.108	0.30	0.11	0.30	0.09
0.184	0.46	0.13	0.46	0.11

APPENDIX E - BROKEN-BACK DESIGN PROGRAM MANUAL

Broken-back Culvert Analysis Program (BCAP) is the result of a project completed at the University of Nebraska - Lincoln Civil Engineering Department and funded by the Nebraska Department of Roads and the Federal Highway Administration to analyze the hydraulic performance of culverts with one or two changes of slope. This manual shows how to properly install and successfully operate BCAP. The following information is contained in the manual:

- Installation Instructions
- Operating Instructions
- Sample Input Files

INSTALLATION INSTRUCTIONS

There are two installation disks for BCAP. Insert disk 1 into the drive, run the setup.exe file, and follow the instructions. The program should be installed into the \hy8\ directory. If the program is not installed into the \hy8\ subdirectory the energy dissipation module will not operate.

OPERATING INSTRUCTIONS

The operating instructions are divided into the input form and output interpretation. Input data include information on entering culvert data into the program and navigating through the program. Output interpretation includes information on evaluating the analysis results.

Input Form

The first form encountered when executing BCAP is the only place where culvert data are entered. The data are separated into the following categories: project, discharge, culvert, culvert profile, and tailwater. Menu options include

File, Unit, and Help options. A rating table for the design flow analysis can be accessed by pressing buttons in the lower right corner of the form.

Culvert Data

The project data are used as a reference and for documentation and are not necessary for the program to operate. The project data include:

- project name
- the station or location
- the date (automatically set)

The discharge data fields include:

- minimum discharge
- design discharge
- maximum discharge
- number of barrels

The design discharge must be greater than the minimum discharge and the maximum discharge must be greater than the design discharge. This is necessary for creating the performance tables and rating curves. The culvert data fields include:

- culvert shape
- size
- inlet
- material
- roughness coefficients

The available shapes are box and circular pipe. The material for the box is reinforced concrete with a roughness coefficient of 0.013. The available circular pipe materials and roughness coefficients are: concrete (0.013), corrugated metal pipe (0.024), and corrugated aluminum pipe (0.031). The inlet types available for the box culvert include:

headwalls:

- square edge (90-45 degrees)
- 1.5:1 bevel (90 degrees)
- 1:1 bevel

wingwall:

- square edge (30-75 degree flare)
- square edge (90 and 15 degree flare)
- square edge (0 degree flare)
- 1.5:1 bevel (18-34 degree flare) **(default)**
- 1:1 bevel (45 degree flare)

The inlet types for concrete circular pipe include:

- square edge with headwall
- groove end projecting
- groove end in headwall
- beveled edge (1.5:1)
- beveled edge (1:1)
- flared end section **(default)**

For the corrugated metal aluminum pipe the available inlets include:

- thin edge projecting
- mitered to conform to slope
- square edge with headwall
- beveled edge (1.5:1)
- beveled edge (1:1)
- flared end section **(default)**

The roughness coefficients listed are the defaults and can be adjusted when operating BCAP. The roughness coefficient for the outlet section can also be adjusted separately.

The culvert profile data include the option of either a single or double broken-back culvert. The single broken-back culvert data fields include the inlet station and elevation, lower break station and elevation, and the outlet station and elevation. The double broken-back data fields include all of the single broken-back fields and the upper break station and elevation. Stations must increase from the inlet to the outlet. The slope of the steep section cannot be exceed 55 degrees. An adverse slope is allowed between the lower break and the outlet.

The tailwater data include the option of entering a constant elevation or using the normal depth in a downstream channel. The data fields include the tailwater elevation for the constant option, and channel shape, size, slope, and roughness coefficient for the downstream channel option. The available shapes include trapezoidal, rectangular, circular, and triangular.

Menus

The file menu has the options of new, open, save, save as, print, and exit. The new option reinitializes the input fields. The open option allows a created file to be displayed. The save and save as options save the input data to a file recognized by BCAP. The print option sends the form to the printer. The exit options shuts BCAP down.

The units menu gives a choice of unit system: English or Metric. The unit system in use is designated with a check. The default unit system is English.

Output Buttons

The rating table and design discharge analysis options call forms that provide results of the hydraulic analysis. More information on them can be found in the Output Interpretation section.

OUTPUT INTERPRETATION

The output interpretation is separated into the design discharge analysis form and the rating table form. The design discharge analysis form has the options of plotting the profile or entering the energy dissipation module. The rating table form has options of rating curves and more detailed analysis for each discharge.

Design Discharge Analysis

The design discharge analysis form contains information that was created during the analysis process. The data are divided into: project, output, water surface profile, and culvert summary. There are also buttons in the lower right corner to plot the profile, enter energy dissipation, and return to the input form.

Analysis Data

The project data are the same as for the input form and are repeated on the page for reference and documentation. The output data fields include:

- 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
- outlet Froude number

The water surface profile data include the depth and velocity at the inlet, upper break, lower break, outlet, and in the downstream channel. These depths are from the calculated water surface profile and do not take into account the tailwater influence in the outlet section.

The culvert summary data include the discharge, shape, number of barrels, size, inlet type, and material. This information is for reference.

Option Buttons

The profile plot button creates a form with the culvert and water surface profiles plotted to scale. The project data are located at the top of the page. The elevation is plotted on the vertical axis and the station is plotted on the horizontal axis. The button at the bottom of the form returns the design discharge analysis form.

The energy dissipation button will operate correctly only if the program is installed properly and the computer has the HY8 program. BCAP creates input and output files that are recognizable by HY8 for energy dissipation only. The files will produce errors and incorrect information if used in other HY8 modules.

When HY8 is started, the desired units can be selected by pressing the "U" key. The energy dissipation module can then be accessed by pressing the "J" key. The name of the file will be "BCAP". The design discharge analysis form is returned when leaving HY8.

Rating Table

The rating table form includes the project data, a rating table, detailed analysis buttons, and rating curve option buttons.

The rating table lists a range of discharges between the minimum and maximum discharges including the design discharge and the following data:

- headwater depth
- inlet control elevation
- break control elevation

- critical depth
- outlet depth
- outlet velocity
- outlet Froude number
- tailwater depth
- tailwater velocity

A detailed analysis for each non zero-discharge can be accessed by pressing the numbered button to the left of each row. The form for the detailed analysis is the same as for the design discharge analysis and has the same information and options.

The rating curves include discharge vs. headwater depth, outlet depth, and outlet velocity. The curves are plotted to scale and include the project data. The button at the bottom of the form returns the rating table form.

SAMPLE INPUT FILES

Included on the installation disks are two sample input files, sample1.bcp and sample2.bcp. They are examples of data input that can be used to operate BCAP.

APPENDIX F - DIRECT STEP PROFILE CALCULATION RESULTS

This section compares the lengths required to reach critical depth from the normal depth for a given slope and the length required to reach normal depth from critical depth for a given flow.

Table F.1. Length to reach critical depth, rectangular channel, Slope = 2%

Length to Reach Critical Depth From Normal Depth, Slope = 2%				
Flow	4' Bottom	6' Bottom	8' Bottom	10' Bottom
0	0	0	0	0
20	42	35	28	24
40	65	63	55	47
60	79	85	77	68
80	88	102	96	88
100	94	119	115	107
120	97	130	132	123
140	99	140	147	136
160	102	150	160	153
180	101	159	170	168

Table F.2. Length to reach critical depth, rectangular channel, Slope = 5%

Length to Reach Critical Depth From Normal Depth, Slope = 5%				
Flow	4' Bottom	6' Bottom	8' Bottom	10' Bottom
0	0	0	0	0
20	71	56	47	38
40	113	101	86	73
60	142	136	120	105
80	165	165	150	132
100	183	192	178	160
120	196	215	202	183
140	207	237	225	209
160	218	255	246	229
180	225	271	268	250

Table F.3. Length to reach critical depth, rectangular channel, Slope = 10%

Length to Reach Critical Depth From Normal Depth, Slope = 10%				
Flow	4' Bottom	6' Bottom	8' Bottom	10' Bottom
0	0	0	0	0
20	88	69	58	47
40	140	123	105	89
60	181	166	145	126
80	213	204	179	159
100	239	237	213	191
120	259	265	246	220
140	279	292	273	249
160	294	316	300	276
180	307	340	325	300

Table F.4. Length to reach critical depth, rectangular channel, Slope = 20%

Length to Reach Critical Depth From Normal Depth, Slope = 20%				
Flow	4' Bottom	6' Bottom	8' Bottom	10' Bottom
0	0	0	0	0
20	101	80	67	55
40	166	139	119	101
60	214	191	163	143
80	253	235	206	180
100	283	274	243	215
120	312	308	279	250
140	334	338	312	280
160	358	368	343	310
180	376	394	371	339

Table F.5. Length to reach normal depth, rectangular channel, Q = 100 cfs

Length (feet) to Reach Normal Depth from Critical Depth, Q = 100 cfs				
Slope	4' Bottom	6' Bottom	8' Bottom	10' Bottom
2%	198	179	129	108
4%	210	149	121	90
6%	192	141	107	83
8%	169	126	90	77
10%	165	115	83	67
12%	147	109	84	65
14%	145	101	75	60
16%	142	100	71	59
18%	135	94	69	53
20%	122	91	63	49

Table F.6. Length to reach normal depth, rectangular channel, Q = 150 cfs

Length (feet) to Reach Normal Depth from Critical Depth, Q = 150 cfs				
Slope	4' Bottom	6' Bottom	8' Bottom	10' Bottom
2%	278	242	206	206
4%	293	239	173	173
6%	282	208	155	155
8%	250	180	148	148
10%	250	170	132	135
12%	223	156	122	122
14%	210	159	113	113
16%	200	146	110	110
18%	189	140	102	102
20%	187	129	98	98

Table F.7. Length to reach normal depth, rectangular channel, Q = 200 cfs

Length (feet) to Reach Normal Depth from Critical Depth, Q = 200 cfs				
Slope	4' Bottom	6' Bottom	8' Bottom	10' Bottom
2%	320	320	267	245
4%	375	294	255	197
6%	354	288	217	174
8%	321	266	194	163
10%	305	239	172	144
12%	296	217	161	133
14%	268	204	153	133
16%	271	191	154	117
18%	255	190	137	119
20%	255	182	139	114