HYDRAIN--Integrated Drainage Design Computer System

Volume VI,
HY8--Culvert Analysis

U.S. Department of Transportation
Federal Highway Administration
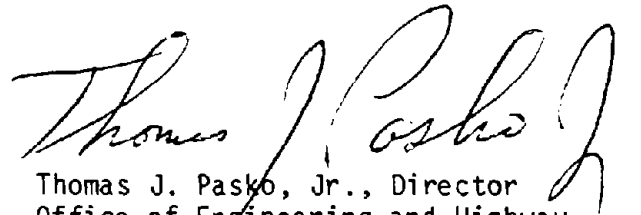
FOREWORD

This report (Volume VI) is a technical reference, and guide for HY-8, the FHWA interactive culvert hydraulic program, as incorporated into the HYDRAIN integrated drainage design computer system. The HYDRAIN system which was developed under a pooled-fund study, includes a system shell and five engineering microcomputer programs for drainage design. The HYDRAIN documentation was published in 6 volumes so that there would be a separate volume for each of the engineering programs. This report will be of interest to hydraulic engineers for State highway agencies, consultants, and other Government agencies who deal with drainage design.

The HYDRAIN microcomputer programs, including HY-8, which is the subject of this volume, have been distributed to the 25 States that participated in the pooled-fund study. Those States will evaluate the programs for a 6 to 12 month trial period after which the programs will be available through McTrans at the University of Florida, located in Gainesville, Florida and the PC-TRANS at the University of Kansas.

Sufficient copies of this report are being distributed by an FHWA transmittal memorandum to provide a minimum of one copy to each regional office, division office, and State highway agency. At least 10 copies are being distributed to those State highway agencies that participated in the study. Direct distribution is being made to the division offices. Additional copies may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

Thomas J. Pasko, Jr., Director
Office of Engineering and Highway
Operations Research and Development

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16. Abstract

This project report, in six volumes, documents a system of computer programs for the design of drainage components: culverts, storm drains, and open channels. The system includes an input generator to estimate design rain, hyetographs, design flow, and hydrographs. Programs are facilitated with semi-expert system shells that generate input data for engineering programs. The system is expandable and designed for personal computers that operate within an MS-DOS environment.

Volume VI is a technical reference guide for HY8 which is an interactive culvert analysis program that utilizes the Federal Highway Administration (FHWA) analysis methods and information published by pipe manufacturers. An important feature of HY8 is that it follows the logic of HDS-5, "Hydraulic Design of Highway Culverts." HY8 allows user defined culverts to be analyzed by selecting appropriate parameters from menus. The program will compute culvert hydraulics for circular, rectangular, elliptical, arch, and user defined geometry.

This volume is one of a series. The entire series is:

FHWA No.	Vol. No.	Short Title	FHWA No.	Vol. No.	Short Title
RD-88-120	I	HYDRAIN	RD-88-123	IV	CDS
RD-88-121	II	HYDRO	RD-88-124	V	WSPRO
RD-88-122	III	PFP-HYDRA	RD-88-125	VI	HY8

To operate all the software, the user needs all six (6) volumes. To individually operate HY8, the user needs Volume I and Volume VI.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
AREA				
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
AREA				
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectares (10 000 m²)	2.53	acres	ac
MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

```
      °F                          °F
      °F    32        98.6        212
     -40    0   40   80   120  160  200
      -40  -20   0   20   40   60   80  100
      °C                  37              °C
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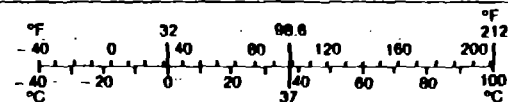
These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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Preface

This report presents documentation for the Hydrain system. HYDRO, PFP-HYDRA, CDS, WSPRO and HY8 are five nonproprietary engineering programs incorporated in the Hydrain system. The Hydrain personal computer oriented system operates the first three of these engineering programs with an interactive program shell written in the C language. The last program, HY8, also has an interactive program interspersed with the analysis code. It is written in BASIC and FORTRAN. Each program is in turn controlled by a common system shell, also in C. The system and program shells are designed with an open architecture for expansion. Hydrain is sponsored as a Pooled Fund Project (PFP) of 23 State highway departments and is managed by the Federal Highway Administration (FHWA). The latest State to join is Texas. The system and its support are expanding.

Within the Hydrain program shell concept, the HYDRO, PFP-HYDRA and CDS program shells allow the user to easily input, edit and run input data files and to scroll through output files. With these three applications, "short" (one-line) and "long" (multiple line) help is provided within the program logic.

The other two applications are incorporated into Hydrain without the high level of help and without program shells. WSPRO has the same type of batch operations as the first three but the input file has to be created with an input file generator (word processor or line editor). Hydrain system shell allows entry to this file generator, and reentry to Hydrain, but the user must rely on hard-copy documentation for help. HY8 is a stand-alone interactive BASIC program that accepts inputs during processing and produces screen outputs that the user can capture with the print screen command. All engineering programs but HY8 are batch oriented, and three steps are built into the process of using them: input file generation, programs execution, and output file screen review or listing. HY8 accepts inputs and generates outputs as the engineering program logic is executing.

HYDRO Program

FORTRAN code for HYDRO was developed to combine existing approaches for rainfall and runoff analyses into one computerized program. Within the Hydrain system, it can be used independently or to generate input data for other engineering programs within the system.

HYDRO offers many hydrologic analysis options to the engineer. Each is site specific based on user-defined coordinates.

- Design Rain Using Digitized NWS Information - Calculates the rainfall intensity for a specific return period, duration, and site.

- Design Hyetograph using Yen and Chow's method - Calculates the rain versus time plot for a return period, duration and site.

- Intensity-Duration-Frequency Curve - Analyzes a specific site and creates two graphs: a plot of points for durations up to 24 hours, and a detail graph of the first 2 hours.

- Design Flow by Rational Method - Uses a specific return period, duration and intensity to determine the peak flow for the site.

- Design Flow by USGS Regression Method - Uses USGS three or seven parameter regression equations or user supplied equations to determine design flow.

- Design Flow by log Pearson type III - Calculates the peak flow for given data.

- Design Hydrograph by Rational Method and Snyder's Unit Graph - The rainfall intensity for a return period is used to calculate the peak flow. A hydrograph is created using Constant's modification of Snyder's method.

- Design Hydrograph by USGS Regression and Snyder's Unit Graph - Develops a hydrograph for a site based on peak flow and a unit hydrograph.

- Design Hydrograph by log Pearson type III and Snyder's Unit Graph - Develops a hydrograph for a site based on peak flow and a unit hydrograph.

- Hydrograph - Develops a hydrograph for a site based on its unit graph for a given flow.

PFP-HYDRA Program

FORTRAN code for PFP-HYDRA previously existed and the Pooled Fund work effort included substantial improvements. PFP-HYDRA is a storm and sanitary sewer system analysis and design program. It is used either to model an existing sewer system or to design a new system.

PFP-HYDRA generates storm flows by using either the Rational Method technique, hydrologic simulation techniques, or accepting a hydrograph generated by a HYDRO analysis. It can be used to design or analyze storm, sanitary or combined collection systems. PFP-HYDRA can handle up to 1,000 contributing drainage areas and 2,000 pipes. Additionally, PFP-HYDRA can be used for cost estimating. The Rational Method approximates the peak rate of runoff from a basin resulting from storms of a given return period. PFP-HYDRA's hydrologic simulation models the natural rainfall-runoff process. In the simulation, runoff hydrographs are generated, merged together and routed through the collection system. Inlet limitations can be analyzed: inlet overflow can be passed down a gutter system, while inlets in sumps can store water in ponds.

In the PFP-HYDRA design process, the program will select the pipe size, slope and invert elevations given certain design criteria. Additionally, PFP-HYDRA will perform analyses on an existing system of pipes (and/or ditches). When an existing system of pipes is overloaded, PFP-HYDRA will show suggested flow removal quantities as well as an increased pipe diameter size as an alternative remedy.

PFP-HYDRA requires the forming of an input file of commands to describe the sewer system. The program shell facilitates this activity. The commands are placed in a logical sequence usually from upper to lower elevation. It is possible that several command sequences can produce the same result. An input file is established for a particular collection system by the engineer and then the PFP-HYDRA program is executed. To change the characteristics of the collection system, the input file can be edited using the program shell. The input file, in itself, is a line by line command language that identifies the computation and provides the required data. Each line of data is preceded with a three-letter command. A typical command is **PDA**, indicating the line contains the design parameters for pipe analysis (PIPE DATA). PFP-HYDRA reads the command line one line (command) at a time and executes each command individually. However, PFP-HYDRA maintains a memory of information, including prior command information and results. Error checking is performed on each command.

The PFP-HYDRA program requires design criteria for the pipes: friction factor (Manning's "n"), minimum diameter, ideal depth, minimum ground cover, minimum velocity (full flow), minimum slope, and maximum diameter. The friction factor is necessary for both analysis and design, while the remaining values are needed only for design. For design, the program selects invert elevations and slope as well as the physical sizing of each link given certain design criteria. In the analysis mode, pipe alignment and sizing are predetermined and the impact of proposed flows are analyzed. Design criteria can be changed for each pipe if so desired. PFP-HYDRA is not an optimization program, thus individual case studies need to be run and analyzed by the engineer.

CDS Program

The Culvert Design System provides the user with two broad options for investigating culvert characteristics. CDS can either (1) hydraulically design a culvert or (2) analyze an existing or proposed culvert. CDS has capabilities for investigating a variety of hydrograph relationships, culvert shapes, materials, and inlet types. With CDS, the engineer can request any of six culvert types: round concrete, round metal, arch concrete, arch metal, oval concrete, and concrete box. CDS routes hydrographs and considers ponding.

The Design option selects a culvert size and number of barrels that are compatible with engineering data, environmental constraints, and site geometry. In this option, hydraulic performance data are calculated for each new culvert system design. The Review option provides hydraulic performance data for any preselected combination of culvert type and size, inlet type, slope, and number of barrels. The initial design and analysis options may be followed by up to five additional culvert types or flow frequencies so a full spectrum of risk scenarios or economic considerations can be simulated at the same time.

Two possible flow scenario methods can be selected: (1) constant flow through the culvert (steady state or irrigation), or (2) time variable drainage flow conditions (dynamic). The dynamic option can route a hydrograph through the culvert system using three hydrograph alternatives: a user input hydrograph for a given discharge, a hydrograph produced by the HYDRO program, or the use of an internally produced default hydrograph (simulating semi-arid, high plains conditions). Additionally, the dynamic flow scenario can accommodate upstream pond storage.

CDS will determine culvert size based on the design headwater, headwater/diameter ratio, inundation, outlet velocity, cover limitations, or any combination of these parameters. The program will automatically increase the number of barrels when the maximum culvert size is exceeded. There is a limit of six barrels for commercial size culverts and five for concrete box culverts. The program can also be used to assess flood hazards, environmental assessments of upstream pond coverage, downstream flooding, channel impact, inlet type and beveled inlet evaluations, and reservoir facilities which use a culvert type structure for the spillway. Based on these data the program will proceed to identify the flow type and the outlet conditions for velocity, Froude number, and brink depth.

WSPRO Program

The Water Surface Profile Computation Model Microcomputer Program has been designed to provide a water-surface profile for six major types of open channel flow situations:

- Unconstricted flow.

- Single opening bridge.

- Bridge opening(s) with spur dikes.

- Single opening embankment overflow.

- Multiple alternatives for a single job.

- Multiple openings.

The United States Geologic Survey (USGS) originally developed WSPRO for the Federal Highway Administration. The model was a batch mode mainframe program, written in FORTRAN. The members of the Pooled Fund Project decided to use WSPRO as the bridge waterways analysis element of the Integrated Computerized Drainage Design System. WSPRO was downloaded to the microcomputer by the USGS and FHWA. The microcomputer version of WSPRO, is dated August 1987. As yet, WSPRO does not have a user friendly, interactive shell to aid in data input and manipulation, although this is planned as a future Hydrain enhancement. The result is that the user must create or edit an input file on a line editor or word processor.

The input file forms a logical description of the physical characteristics of a waterway. Once the user is comfortable with this method of data setup, the program will provide a simple method for determining water surface profiles. The scheme is similar to the Corps of Engineers HEC-2 program. Both WSPRO and HEC-2 are acceptable to the Federal Emergency Management Agency. WSPRO has the advantage that it uses more recent approximation techniques for the backwater effects associated with bridge constrictions.

HY8 Program

HY8 is an interactive culvert analysis program that uses the FHWA analysis methods and information published by pipe manufacturers. The program includes modules to allow the user to interactively enter, save, and edit data. HY8 will compute the culvert hydraulics for circular, rectangular, elliptical, arch and user defined geometry. Additionally, improved inlets can be specified and the user can: analyze inlet and outlet control for full and partially full culverts, analyze the tailwater in trapezoidal and coordinate defined downstream channels, analyze flow over the roadway embankment, and balance flows through multiple parallel culverts.

The initial logic involves calculating the inlet control and outlet control headwater elevations for the given flow. These elevations are compared and the larger of the two is used as the controlling headwater elevation. Tailwater effects are taken into consideration when calculating these elevations. If the controlling headwater elevation overtops the roadway embankment, an overtopping analysis is done in which flow is balanced between the culvert discharge and the surcharge over the roadway. A balancing technique is also used for multiple barrels. If the culvert is less than full for all or part of its length, open channel computations are performed.

A series of data menus, data screens, summary screens, and output screens guides the user through the program. Each menu contains several options to match the desired culvert configuration, while the data screens prompt the user for specific dimensions and coordinates. Summary screens allow the user to edit entered data or change menu selections. Output screens display the output as calculations proceed; hard copy is only obtained using the "print screen" key.

There are three main groups of data to be entered into the program: initial culvert data, downstream channel data, and roadway data. Within the program, the user is sequentially led from one group to the next. From these sets of data, the program develops culvert performance data with or without overtopping. A performance curve can be plotted on a computer with graphics capabilities by typing a V for view. In addition to developing performance curves, the program generates rating curves for uniform flow, velocity, and maximum shear for the downstream channel. Culvert outlet velocities, inlet control head, and outlet control head are also calculated.

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Operation

To allow the software to be used by a wide audience, Hydrain operates on an IBM XT/PC or equivalent microcomputer with 640 K RAM, a hard disk, and a monochrome monitor. A math coprocessor is recommended. Engineering programs are in FORTRAN 77. Shells are in C. The HYDRO, HYDRA, and CDS programs are equipped with a "semi-expert" system that includes extensive input shells and "short" and "long" help files. The other programs available to the experienced to expert Hydrain user, WSPRO and HY8, have received a minimum level of development under the Hydrain system.

Report Contents

The remaining section of this volume provides technical reference and user instructions for the HY8 program. There are a total of 6 such volumes for Hydrain.

Disclaimer

FHWA, the pooled fund States and their agents have, within the limits of their resources, tested and debugged the Hydrain shells. The engineering programs derive from several varied sources and were adapted to Hydrain and also underwent testing and debugging. However, this is a very large and somewhat complicated system of logic and computer code. Errors and omissions may remain in the software. Therefore, use at your own risk. Please document problems and errors and report to FHWA. User support and technical assistance will be provided to pooled fund States. Agents of these States using the system should channel their requests for support or assistance through their sponsor State.

1. Introduction

HY8 is an interactive culvert analysis program that utilizes the Federal Highway Administration (FHWA) analysis methods and information published by pipe manufacturers.[1] An important feature of HY8 is that it follows the logic of HDS-5, "Hydraulic Design of Highway Culverts".[2] HY8 allows user defined culvert to be analyzed by selecting appropriate parameters from menus. The program will compute culvert hydraulics for circular, rectangular, elliptical, arch, and user defined geometry. Improved inlets can also be specified. The user will have the options of inputting either a regular or an irregular cross-section for calculating tailwater, or a fixed tailwater may be specified. HY8 will accept a constant design discharge. The output will be in the form of a performance curve.[3]

The initial logic involves calculating the inlet control and outlet control headwater elevations for the given flow. These elevations are compared and the larger of the two is used as the controlling headwater elevation. Tailwater effects are taken into consideration when calculating these elevations. If the controlling headwater elevation overtops the roadway embankment, an overtopping analysis is done in which flow is balanced between the culvert discharge and the surcharge over the roadway. A balancing technique is also used in the case of multiple barrels. If the culvert is less than full for all or part of its length, open channel computations are performed.

A series of data menus, data screens, summary screens, and output screens guide the user through the program. Each menu contains several options to match the desired culvert configuration, while the data screens prompt the user for specific dimensions and coordinates. Summary screens allow the user to edit entered data or change menu selections. Output screens display the output as calculations proceed; hard copy is only obtained using the "print screen" key.

The program runs on an IBM PC/XT and compatible microcomputers. It is designed to run on the MS-DOS 3.1 and is a combination of executable files linked by a batch program. The source code is written in BASIC and standard FORTRAN, but currently is unavailable to Hydrain users.

There are three main groups of data to be entered into the program; initial culvert data, downstream channel data, and roadway data. Within the program, the user is sequentially led from one group to the next. From these sets of data, the program develops culvert performance data with or without overtopping. Three examples of the program's use are illustrated in the HY8 Culvert Analysis Microcomputer Program Applications Guide.[4] In addition to developing performance curves, the program generates rating curves for uniform flow, velocity, and maximum shear for the downstream channel. Culvert outlet velocities, inlet control head, and outlet control head are also calculated.

2. Overview

The Federal Highway Administration has developed analytical and empirical
techniques to aid in the hydraulic analysis and design of culverts. The design
engineer can utilize the FHWA publications to analyze culverts for a single
design discharge and, with some additional effort, develop a culvert
performance curve. However, evaluating different culverts for several flows
requires considerable effort.

In HY8, a culvert analysis program was developed that is interactive and
utilizes the FHWA analysis methods and the information published by pipe
manufacturers. The program includes modules to allow the user to interactively
enter, save, and edit data, to analyze inlet and outlet control for full and
partially full culverts, to analyze the tailwater in trapezoidal and coordinate
defined downstream channels, to analyze flow over the roadway embankment, and
to balance flows through multiple parallel culverts. HY8 contains data for
different culvert dimensions, materials, and inlets that are not found in any
single publication.

To optimize the size of the culvert, the structure must be analyzed for a
range of discharges from low flow to a flow that overtops the roadway. The
engineer must develop a rating or performance curve that shows the relation
between flow conveyed through the culvert and the height of the water at the
culvert inlet. Once this relation is known, the performance of the culvert can
be evaluated and the benefits of installing a different culvert can be
assessed. In a similar manner, replacing, adding, or improving an existing
culvert requires developing performance curves to compare alternatives.

A series of data menus, data screens, summary screens, and output screens
guides the user through the program. Each menu contains several options to
match the desired culvert configuration, while the data screens prompt the user
for specific dimensions and coordinates. Summary screens allow the user to
edit entered data or change menu selections. Output screens display the output
as calculations proceed.

The main function of the program is to develop performance curves using
the techniques, with some exceptions, published by the FHWA. A series of up to
six parallel culverts with different inlets, inlet elevations, outlets, outlet
elevations, and lengths can be analyzed in combination with overtopping of the
roadway. A parallel pipe solution technique is used to balance flows through
multiple culverts and over the roadway. The direct step method is used to
calculate water surface profiles when open channel flow occurs in the culvert.
Both the multiple culvert balancing technique and direct step method are
exceptions to the procedures in the FHWA publications. That is, when a portion
or all of the culvert is flowing less than full, water surface profile
calculations are used to compute the friction losses in the open channel flow
section. If the length of the full flow section is equal to the full length of
the culvert, then pressure flow exists throughout the culvert. The pressure
flow analysis is the same for steep and mild sloped culverts; however, the open
channel flow analysis differs for steep and mild slopes.

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In addition to developing performance curves, the program generates rating curves for uniform flow, velocity, and maximum shear for the downstream channel. Culvert outlet velocities, inlet control head, and outlet control head are also calculated.

3. **Technical / Operational Methods**

This section investigates some of the technical and operational methods used by HY8 to analyze culverts. First, the analysis involves calculating the inlet control and outlet control headwater elevations for the given flow. These elevations are compared and the larger of the two is used as the controlling headwater elevation. Tailwater effects are taken into consideration when calculating these elevations. If the controlling headwater elevation overtops the roadway embankment, an overtopping analysis is done in which flow is balanced between the culvert discharge and the surcharge over the roadway. A balancing technique is also used in the case of multiple barrels. A more detailed discussion of these calculations follows.

Inlet Control

By regression analysis, FHWA has produced fifth degree polynomial equations to model the inlet control headwater for a given flow. The regression equations have been developed for the range of inlet heads from one half to four times the diameter of the culvert. Analytical equations, based on minimum energy principles, are matched to the regression equations to model flows that create inlet control heads outside of the regression data range.

For culvert discharges within the range of the regression analysis, the FHWA equation gives a direct solution for inlet head. The regression equations are of the form:

$$H_{wi} = (A + B \cdot X + C \cdot X^2 + D \cdot X^3 + E \cdot X^4 + F \cdot X^5) \cdot D \tag{10}$$

where:

H_{wi} = the inlet control headwater, in feet,

D = the height of the culvert barrel, in feet,

A to F = regression coefficients for each type of culvert, and

X = a function of the average outflow discharge being routed through a culvert, culvert barrel height and for box and pipe arch culverts, the width of the barrel.

For discharges that create inlet control heads above the regression equation limits, an orifice equation is used to model flows. The potential head for the orifice equation is given by the difference of the water surface elevation and the elevation of the center of the circular pipe. For non-circular culverts the potential head is determined to be from the center of the culvert, which is approximated by the sum of the invert elevation and one half

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the rise of the culvert. The orifice equation used in the program is of the form:

$$Q = k \cdot A \cdot h^{0.5} \qquad (2)$$

where:

Q = the orifice equation discharge, in ft^3/s,

A = the cross sectional area of culvert, in ft^2,

k = the coefficient based on the headwater, outlet head and the coefficient of contraction, and

h = inlet control headwater, in feet.

The coefficient is determined by setting the orifice equation equal to the regression equation at the upper limit of the regression equation. The orifice equation is then used to determine inlet headwater for all flows exceeding the upper limit.

For discharges that create inlet control heads less than half the diameter of the culvert, an open channel flow minimum energy equation is used with the addition of a velocity head loss coefficient. Critical depth for the minimum energy equation is determined from the following condition:

$$F_r^2 = \frac{Q^2 \cdot T}{g \cdot A^3} = 1 \qquad (3)$$

where:

F_r = the Froude number (equal to one in this case),

Q = the culvert flow rate, in ft^3/s,

A = the culvert's cross sectional flow area, in ft^2,

T = the culvert's cross section top width, in feet, and

g = the gravitational acceleration (32.2 ft/sec^2).

The coefficient is needed to match the minimum energy equation with the regression equation at one half the diameter of the culvert. The minimum energy equation is

$$H_w = d_c + (1 + k_e) \frac{v^2}{2g} \qquad (4)$$

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where:

d_c = the critical depth at culvert entrance for given discharge, in feet, determined for the minimum energy condition above,

k_e = the entrance loss coefficient,

V = the velocity at critical depth, in ft/s, and

g = the gravitational acceleration (32.2 ft/sec^2).

The entrance coefficient is determined by setting the minimum energy equation equal to the regression equation at one half the rise, which is the lower limit of the regression equation.

The minimum energy equation with the additional velocity head loss would seem to describe the low flow portion of the inlet control headwater curve; however, numerical error in the calculation of flow are for very small depths tends to increase the velocity head as the flow approaches zero. This presents little or no problem in most practical cases since the flows that cause this are relatively small. In many of the calculations required for the solution of multiple culverts the inlet control curve must decrease continuously to zero for the iterative calculations to converge. Therefore modifications to this equation have been made to force the velocity head to continually decrease to zero as the flow approaches zero.

As the flow becomes very shallow in the culvert, the rate of width to depth of flow ratio increases greatly. As the flow approaches zero the culvert can be assumed to be very wide and the wide channel approximation of minimum energy is used.

$$E = 1.5 \cdot d_c \qquad \qquad (5)$$

where:

E = the approximation of the minimum energy, and

d_c = the critical depth, in feet.

The critical depth is continuously decreasing and approaches zero as the flow approaches zero.

The inlet head calculation between flow at zero and half the depth must be a combination of the minimum energy calculation with the velocity head loss equation and the wide channel approximation minimum energy equation. This can be accomplished by a linear weighing of the equations in the low flow range.

In the range of flows between 15 percent of the flow that causes an inlet head elevation of one half the culvert diameter (denoted as $Q_{0.5} \cdot D$), to zero

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flow, the velocity head is gradually converted to one half the critical depth by using the following equations:

First, the fractional contribution of a given flow, Q, in relation with the 15 percent flow is calculated;

$$Q_{frac} = \frac{0.15 \cdot (Q_{0.5} \cdot D) + Q}{0.15 \cdot (Q_{0.5} \cdot D)} \tag{6}$$

where:

Q_{frac} = the fractional contribution of a given flow,

$Q_{0.5} \cdot D$ = the discharge that creates inlet control head of one half the diameter of the culvert, and

Q = a given discharge, between 0 and 15 percent flow, in ft^3/s.

Next, a velocity head coefficient, based on the fractional contribution and the velocity head is computed;

$$C_{vh} = \frac{1 - Q_{frac}}{1 + V_h \cdot Q_{frac}} \tag{7}$$

where:

C_{vh} = the velocity head coefficient,

Q_{frac} = the fractional contribution of a given flow, defined above, and

V_h = the velocity head calculated from average velocity, in feet.

Finally, the corrected velocity head can be calculated;

$$V_{hcorr} = Q_{frac} \cdot 0.5 \cdot d_c + V_h \cdot C_{vh} \tag{8}$$

where:

V_{hcorr} = the corrected velocity head, in feet,

$Qfrac$ = the fractional contribution of a given flow, defined above,

d_c = the critical depth for given flow, in feet,

V_h = the velocity head calculated from average velocity, in feet, and

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$$C_{vh} = \text{the velocity head coefficient, defined above.}$$

As the discharge, Q, approaches zero, Q_{frac} approaches unity and C_{vh} vanishes. Inversely, as Q approaches $Q_{0.5} \cdot D$, Q_{frac} vanishes and C_{vh} approaches unity.

From equation 8, it can be said that for very low flows, the inlet control equation becomes:

$$H_{wi} = d_c + (1 + C_{vh}) \cdot V_{hcorr} \tag{9}$$

where:

H_{wi} = the inlet control headwater, in feet,

d_c = the critical depth, in feet, for a given flow Q,

C_{vh} = the velocity head coefficient, and

V_{hcorr} = the corrected velocity head, in feet.

Outlet Control

Outlet control water surface elevation is determined by adding the friction losses in the pipe barrel and the entrance and exist losses to the tailwater elevation. For the losses to affect the headwater, the flow through the culvert must be subcritical. The program initially determines whether the culvert slope is mild or steep and then whether the culvert outlet crown is submerged or unsubmerged (whether the downstream water surface is above or below the outlet crown). The procedure for determining friction losses is decided from these two pieces of information.

If the culvert exit is submerged then at least part of the barrel is flowing full and pressure flow computations are performed to determine the length of the full flow section. When only a portion of the culvert is flowing full water surface profile calculations are used to compute the friction losses in the open channel flow section. If the length of the full flow section is equal to the full length of the culvert, then pressure flow exists throughout the culvert. The pressure flow analysis is the same for steep and mild sloped culverts; however, the open channel flow analysis differs for steep and mild slopes.

On steep culverts, a hydraulic jump may form in the culvert if the flow depth is less than critical. If the jump is detected in the culvert then the culvert is controlled at the inlet. Howver, under this circumstance, the energy elevation at the jump is output for the outlet control elevation. If

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the tailwater is high enough, the jump may submerge the inlet causing the headwater elevation to be controlled by the outlet.

On mild slopes, a backwater routine is used to calculate friction losses through the culvert for low flows. If flow intersects the crown of the culvert, pressure flow is calculated for the remaining length of the culvert.

If the slope of the culvert is steep then a check is made to determine if the inlet is submerged by the tailwater. In most cases where the slope is supercritical the culvert is in inlet control. The program will proceed with head loss calculations from the outlet toward the inlet until either the entrance is reached or critical depth is reached suggesting that a hydraulic jump has formed in the culvert. If the entrance is reached before critical depth, then the inlet control point has been submerged by the tailwater and friction effects force outlet control. When critical depth is calculated in the culvert the flow is controlled at the inlet. The outlet control elevation output by the computer is the sum of minimum energy and an inlet loss at the location where the critical depth has been calculated. The program can display negative outlet control heads which mean that the outlet control effects only reach an elevation that is below the inlet invert.

Friction losses in the barrel are determined by algebraically manipulating Manning's formula to solve for friction slope:

$$S_f = \left[\frac{Q \cdot n}{1.486 \cdot A \cdot R_h^{0.67}} \right]^2 \tag{10}$$

where:

S_f = the friction slope, in ft/ft,

Q = the culvert barrel discharge, in ft^3/s,

n = Manning's roughness coefficient,

A = the cross section flow area, in ft^2, and

R_h = the hydraulic radius of the culvert, in feet.

If the barrel is flowing full, the friction slope is constant over the length of the full flow section and frictional head loss can be computed by the following:

$$H_f = S_f \cdot L \tag{11}$$

where:

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H_f = the head loss due to friction in the culvert barrel, in feet,

S_f = the friction slope, in ft/ft,

L = the length, in feet, of culvert containing full flow.

If open channel flow is occurring in the culvert, the hydraulic parameters are changing with flow depth along the length of the culvert. The friction losses are determined by summing the incremental changes in head loss using the direct step method. The incremental head loss is calculated by:

$$\delta H_f = S_f / \delta L \qquad (12)$$

where:

δH_f = the incremental head loss,

S_f = the friction slope, in ft/ft, at δL, and

δL = the incremental change in length.

The open channel barrel loss calculations proceed as follows:

1. An increment of head loss is determined.

2. The friction slope is calculated at the outlet.

3. The length of culvert is calculated from the friction slope and the specified head loss.

4. A new friction slope is calculated at the distance computed in step three.

5. From the specified head loss and the friction slope determined in step four, an incremental length is calculated and added to the length calculated previously.

6. The incidental head losses are summed and steps four and five are repeated until the summed length from the outlet is greater than the length of the culvert or until the head losses in the culvert cause the water surface to intersect the crown of the culvert (beginning of pressure flow section).

The sum of the incremental head losses computed is the frictional head loss through the open channel flow section of the culvert barrel. If a portion of the barrel is flowing full then the full flow head loss is computed and added to the open channel head loss for the total barrel friction loss.

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Losses at the culvert entrance and exit are computed by the product of a loss coefficient and the velocity at the entrance and exit. The entrance loss equation used in the program is:

$$H_e = k_e \cdot \frac{V^2}{2g} \tag{13}$$

where:

H_e = the entrance head loss, in feet,

k_e = the entrance loss coefficient,

V = the flow velocity just inside culvert barrel, in ft/s, and

g = the gravitational acceleration (32.2 ft/sec^2).

Similarly, the exit loss equation is:

$$H_o = 1.0 \cdot \frac{V^2}{2g} \tag{14}$$

where:

H_o = the exit head loss, in feet,

V = the flow velocity just inside culvert barrel, in ft/s, and

g = the gravitational acceleration (32.2 ft/sec^2).

Downstream Channel

The water surface elevation in the downstream channel may influence the culvert discharge, therefore, it is important to have a reasonable estimate of the water surface elevation and the velocity in the downstream channel. The downstream water surface elevation is important in determining the effects of tailwater on culvert performance. Velocity, shear stress, and Froude number in the channel are important in determining channel stability. The program will calculate uniform flow elevation, velocity, shear, and Froude number values; however, calculations for the culvert performance curve use only the elevation of the water surface.

The uniform flow calculations are performed using Manning's equation:

$$Q = \frac{1.486}{n} A \cdot R_h^{0.67} \cdot S_f^{0.5}$$
(15)

where:

Q = the uniform discharge, in ft^3/s, occurring within a waterway channel's cross sectional area,

A = the channel's waterway cross sectional area, in ft^2,

R_h = the hydraulic radius of a waterway (waterway area divided by wetted parameter), in feet,

S_f = the friction slope, in ft/ft, assumed to be equal to the downstream channel slope, and

n = Manning's friction value for a waterway.

Area and hydraulic radius are functions of water surface elevation and channel geometry. Since the determination of water surface elevation given flow is a direct solution in Manning's formula for only the simplest cases, an iterative technique is used to determine water surface elevation. For channels of simple cross-sectional geometry (trapezoidal, rectangular, and triangular) the area and hydraulic radius calculations are calculated by a single routine. The determination of the water surface elevation for an irregular shaped channel is more involved. A separate module was developed to perform uniform flow calculations in irregular shaped channels.

Under many flow conditions in natural channels, the flow is conveyed in subchannels and overbank regions that have significantly different hydraulic capacities than the main channel. The irregular channel module can calculate uniform flow water surface elevations with three separate subchannels using geometric principles to balance the conveyances in the subchannels.

Velocity calculations for the simple cross-sectional geometries are average velocities. Velocity calculations for the irregular shaped channels are average velocities for the main channel. Shear is calculated by the following equation:

$$Tau = \gamma \cdot S_f \cdot T_w$$
(16)

where:

Tau = the maximum shear, in psf,

γ = the specific weight of water, 62.4 lbs/ft^3,

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S_f = the friction slope (equal to channel slope for uniform flow), in ft/ft, and

T_w = the tailwater depth, or the maximum depth of flow occurring in the natural channel just beyond the culvert outlet, in feet.

Froude number is determined from the following equation:

$$F_r{}^2 = \left[\frac{Q^2 \cdot T}{g \cdot A^3} \right] \qquad (17)$$

where:

F_r = the Froude number,

Q = the discharge in the channel, in ft^3/s,

T = the channel cross section's top width, in feet,

A = the channel's waterway cross sectional area, in ft^2, and

g = the gravitational acceleration (32.2 ft/sec^2).

Roadway Overtopping

The flow that overtops an embankment is similar to that of a broad crested weir. The following weir equation is used by the program to determine flow over embankments:

$$Q_o = C_d \cdot L \cdot H_{wr}{}^{1.5} \qquad (18)$$

where:

Q_o = the discharge over embankment, in ft^3/s,

C_d = the discharge coefficient (weir coefficient),

L = the length of weir crest, in feet, and

H_{wr} = the upstream head above embankment crest, in feet.

The program has two options for selection of the discharge coefficient. The user can specify the surface type and allow the program to determine the coefficient from internal tables or the user can input a discharge coefficient.

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Coefficients determined by the program are interpolated from data points taken from the FHWA discharge coefficient curves for paved and gravel roadway surfaces. The tables are based on the headwater elevation and the roadway width. The coefficients are modified for tailwater submergence by multiplying the coefficients by a submergence factor which is interpolated from data taken from the submergence factor curves for paved and gravel roadways. The coefficients entered by the user are also multiplied by a submergence factor that is interpolated from the data for the gravel roadway surfaces.

For convenience in computations an assumption of a constant roadway surface elevation for the crest of the weir is common, although the section of the roadway that becomes overtopped is usually the low portion of a vertical curve. With little additional computational effort, the calculation of flow can be integrated over the roadway profile described by several coordinates that more accurately define the roadway surface. If given a set of roadway profile coordinates and other data to describe headwater elevation and the coefficient of discharge, the program will integrate the weir equation to determine flow between each of the coordinates and sum the flows to give a total flow over the entire roadway profile.

A four point Gaussian quadrature routine is used to integrate between any two coordinate points. If the information for the roadway surface and tailwater is given, the weir coefficient and submergence reduction is computed at each integration point.

Multiple Barrel Analysis

In some cases an engineer may need to analyze flow through two or more barrels and/or over the roadway. If the tailwater effects are negligible, the determination of headwater elevation and flow conveyed through each of the conduits and over the roadway may be computed by adding performance curves. If each of the barrels is considered identical, the symmetry of the system can be used by dividing the flow by the number of barrels and proceeding with calculations as for a single barrel. However, if there is an effect on the conveyance by the tailwater and the culverts are different, then the simple addition of performance curves may be in considerable error. For a given flow the tailwater elevation can be approximated from normal depth or backwater calculations. Flows in each of the culverts must be such that the total head loss in each culvert is identical (the difference between headwater elevation and tailwater elevation) and the total flow conveyed must be equal to the sum of the flows through each of the culverts and over the roadway. The problem is similar to a parallel pipe problem.

The tailwater and headwater potential are identical for each of the culverts. Given the assumption of no interference of one culvert with another at the inlet or outlet, the head loss dissipated by each of the culverts must be the same. The total flow must be the sum of the flows through each culvert. Streeter and Wylie give an iterative procedure for solving the head loss and

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flow in similar parallel pipe systems.[5] With slight modification to the parallel pipe procedure, the following is the basis for the multiple barrel iterative solution technique.

1. Assume a flow through the control barrel, which is the barrel with the lowest invert.

2. Determine the head loss through the control barrel and the headwater elevation caused by that head loss.

3. Determine flow in the other barrel(s) based on the headwater elevation calculated from the control barrel.

4. Distribute flows by the following equation:

$$Q_i = \frac{Q_{ic}}{\Sigma Q_{ic}}$$ (19)

where:

Q_i = the adjusted flow through barrel i, in ft^3/s,

Q_{ic} = the calculated flow through barrel i, in ft^3/s, and

ΣQ_{ic} = the sum of the calculated flows, in ft^3/s.

5. Use the adjusted flow through the control barrel as the assumed flow in the control barrel and repeat the procedure until the difference in sum of the calculated flows and the given flow and the difference in the headwater elevations from successive iterations are within acceptable limits.

This technique converges rapidly and is stable if the rate of head loss change to discharge change is smaller for the controlling barrel than for the other barrels. In most cases, this translates to the controlling barrel diameter being larger than the diameter of the other barrels. When the controlling barrel diameter becomes much less than that of another barrel, the solution may oscillate. In most practical applications the barrel with the lowest invert is the largest or approximately the same size as the other barrels. However, it is desired that the same iterative procedure be used to balance flows if the roadway is overtopped. In most cases, because the conveyance of the roadway surface is so much larger than that of any culvert, the solution is unstable. Therefore some modifications must be made when the headwater elevation exceeds the roadway elevation.

If the flow that is conveyed over the roadway is treated as flow through another barrel, the above procedure can be used. To prevent oscillations, the overtopping flow must be the controlling flow.

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Initial convergence limits, set on both headwater elevation and percent of total discharge, are well within the accuracy of the Manning's friction coefficient, n. The convergence limits are relaxed for the total number of barrels and for the number of iterations. In some flow situations, a slight change in flow will cause jumps in headwater elevation for a single barrel. This, in turn, will cause the oscillation of the multiple barrel solution.

A limit of 50 iterations is set to abort the process and go on to other calculations. A summary of iterative solution errors will show the error limits for the solution.

The greater the number of barrels in the solution the less stringent the convergence criteria must be for convergence. The criteria for terminating the successive headwater calculations is the iteration where the difference of the prior headwater and the newly computed headwater is less than the empirical value of 0.01 times the number of barrels.

Similarly, the criteria for convergence on percent total flow is when the ratio of total calculated flow to total flow is less than 1 percent times the number of barrels. A maximum of 50 iterations are run at which time the process is aborted.

After the tabulation of the performance curve for multiple culverts, a table of errors due to the iterative technique is given. This table includes error of percent total flow and headwater elevation error.

4. User Documentation

To access the HY8 program, the user types in **HYDRAIN** and presses <CR>. A
credit screen will appear and any key may be pressed to continue. The next
screen appearing is a statement dealing with the responsibilities of the user
and FHWA. Again, any key can be pressed to continue. As illustrated in figure
1, the primary menu screen is the next screen to be shown. Move the cursor to
the HY8 option using the arrow keys and strike <CR> or simply strike the **Y** key.
The HY8 program is now ready to use.

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Figure 1. Hydrain primary menu.

The HY8 culvert analysis program was designed to be as self contained as
possible, lessening the need for a users manual. Data entry is accomplished
through the use of menus and prompts generated by the program. The program has
some error and range checking capabilities for ensuring that only realistic
values are entered by the user. Data is easily edited and summary tables of
input data and output results are generated periodically throughout the data
entry process.

There are three main groups of data to be entered into the program; initial culvert data, downstream channel data, and roadway data. Within the program, the user is sequentially led from one group to the next. The user is provided with an understanding of the necessary procedures used in the analysis of a culvert.

The first type of information to be entered is the initial culvert data. When creating a new culvert file, the user is asked to enter a performance curve discharge range which consists of minimum, maximum, and design flows. The maximum discharge allows the user to enter a discharge consistent with the maximum probable storm event. Next, data concerning the culvert site is entered. There are two possible options for entering this data, the culvert invert option and the embankment-toe option. With the culvert invert option, the stations and elevations of the inlet and outlet are entered. The other option is to enter embankment and toe data which is used by the program to generate invert data for the inlet and outlet. Also, the number of barrels to be used is entered at this point. Following this, the culvert shape and dimensions are chosen along with the inlet type and culvert material. The program has a wide variety of shapes that can be used including, circular, box, elliptical, pipe arch, and irregular. Inlets can be conventional or improved with side tapering or slope tapering. Included in the inlet data is information on headwall and wingwall geometry. The culvert material data is used to determine a Manning's 'n' value. The concrete material option yields an 'n' value consistent with the culvert material chosen.

Downstream channel information is the next group of data to be entered. This information is used to generate a tailwater rating curve. First, a channel shape is chosen from one of the following possibilities; rectangular, trapezoidal, triangular, or irregular. The irregular channel can be described using a maximum of 15 coordinates. There are also options to enter the users own rating curve or a constant tailwater elevation. Two other pieces of information that are needed are the slope and Manning's 'n' value for the channel. Using all of this data, a tailwater rating curve is developed which is in table form and can be plotted if graphics capabilities are available.

After returning to the culvert portion of the program with the rating curve, the user will be prompted for roadway data to be used in the overtopping analysis. A constant roadway elevation can be entered or an irregular profile can be described using 3 to 15 coordinates. A weir coefficient and the embankment width are also needed to do the overtopping analysis. The analysis is similar to that of a broad crested weir and similar data is needed. With regard to weir coefficients, the user has the option to use the two preset coefficients for either paved or gravel roadway surfaces, or enter a user defined value between 2.5 and 3.095.

From these sets of data, the program develops culvert performance data with or without overtopping. A performance curve can be plotted on a computer with graphics capabilities by typing a **V** for view (note: this capability requires the presence of a Color Graphics Adaptor card or the equivalent in the host microcomputer). Three examples of the program's use are illustrated in the "HY8 Culvert Analysis Microcomputer Program Applications Guide."[4]

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