U.S. Department
of Transportation

**Federal Highway
Administration**

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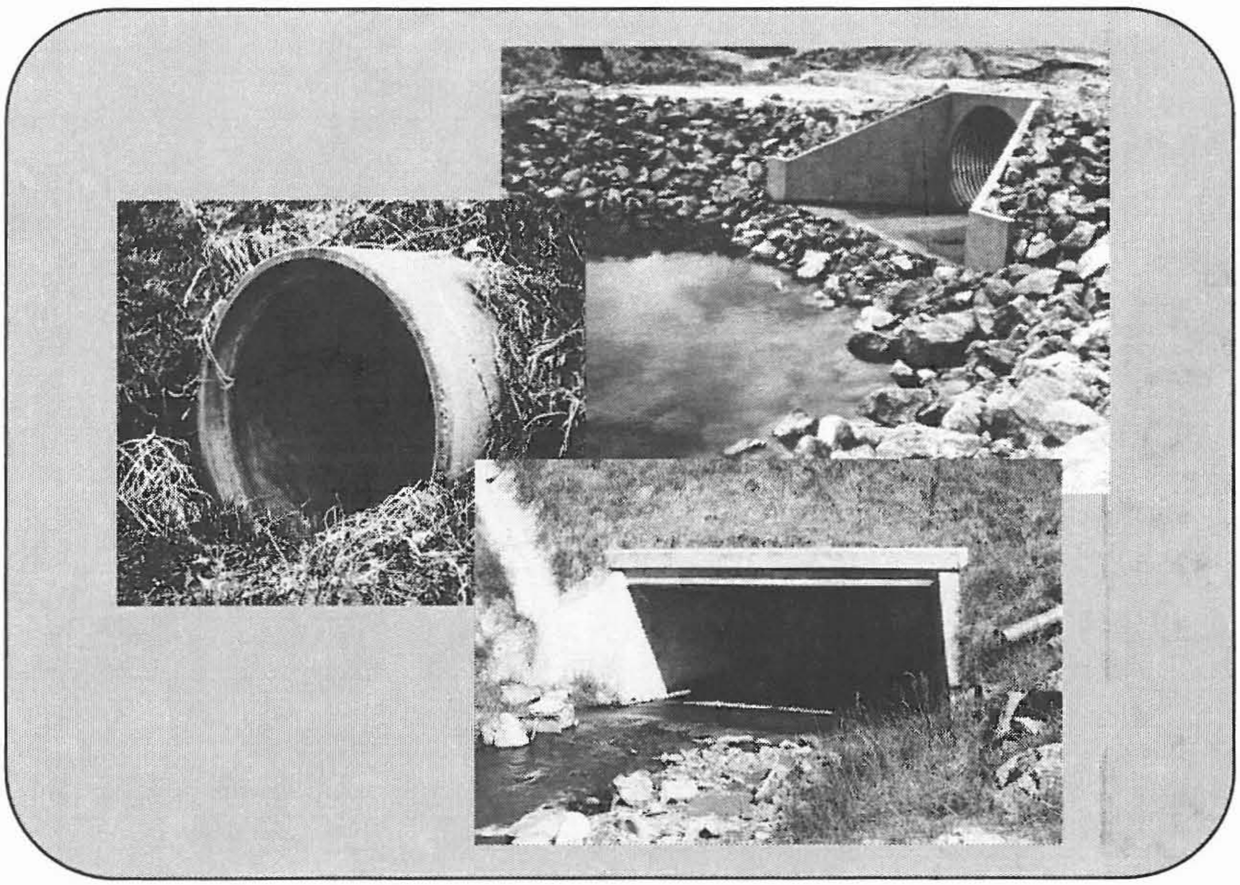
January 1998

NHI Course 13056

CULVERT DESIGN

A Training Course Based on Hydraulic Design Series No. 5

Participant's Workbook



NHI *National Highway Institute*

NHI Course 13056

CULVERT DESIGN

A Training Course Based on Hydraulic Design Series No. 5

LESSON SCHEDULE

LESSON 1 INTRODUCTION

LESSON 2 DESIGN CRITERIA

LESSON 3 BASIC HYDRAULICS

LESSON 4 CONVENTIONAL CULVERT DESIGN

LESSON 5 IMPROVED INLET DESIGN

LESSON 6 CULVERT DESIGN APPLICATIONS

LESSON 7 ENERGY DISSIPATORS

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Fort Collins, Colorado
and
Reagan Engineering Associates
Brownwood, Texas

LESSON 1

INTRODUCTION

OVERVIEW:

Method of Instruction:	Lecture
Lesson Length:	30 minutes
Resources:	Student Workbook Graphics

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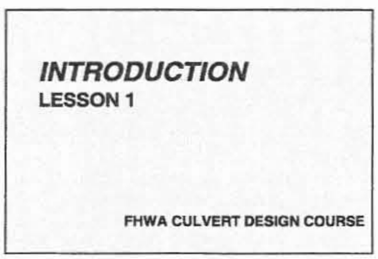

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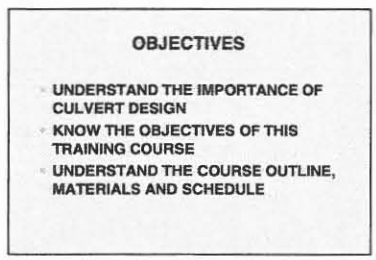

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OBJECTIVES: At the conclusion of this lesson, the participant shall be able to:

1. Understand the importance of culvert design.
2. Know the objectives of this training course.
3. Understand the course outline, materials and schedule.

LESSON OUTLINE

1. INTRODUCTION
   - 1.1. HOST WELCOME
   - 1.2. INTRODUCTIONS
   - 1.3. SIGNIFICANCE OF CULVERT DESIGN
   - 1.4. COURSE OBJECTIVE
   - 1.5. COURSE OUTLINE
   - 1.6. ADMINISTRATIVE NOTES

1.1. HOST WELCOME

1.2. INTRODUCTIONS

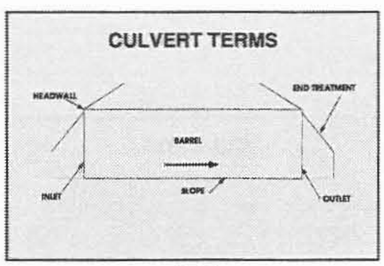
A. Instructors

B. Participants

As participants in this course, you are the center of attention. Your self-introduction defines who you are and what your interests are with respect to culvert design. This information is useful to the instructors and can be helpful to the other course participants.

1.3. SIGNIFICANCE OF CULVERT DESIGN

A. Culvert Definition



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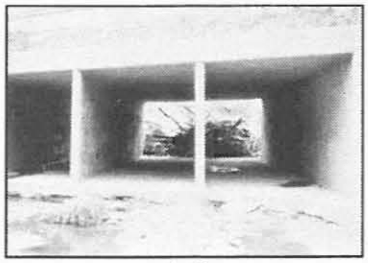
B. Culvert Usage



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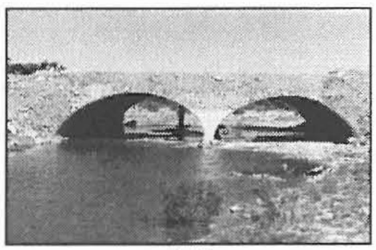

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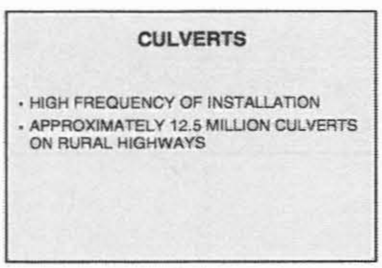
A culvert is used primarily in a roadway system to move water flow (runoff) from one side of the roadway to the other. Culverts can have multiple uses as well.

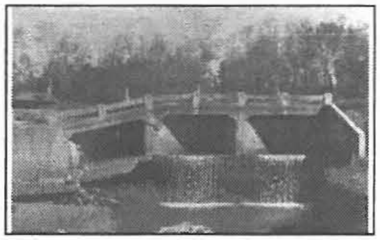


1.6

- Culverts are used on the average of approximately once every 1/4 mile on typical rural highway projects in the United States.

- Since there are 3.1 million miles of rural highways, there are approximately 12.5 million culverts in the United States.

C. Culvert Failure



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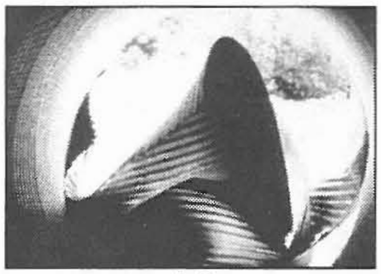

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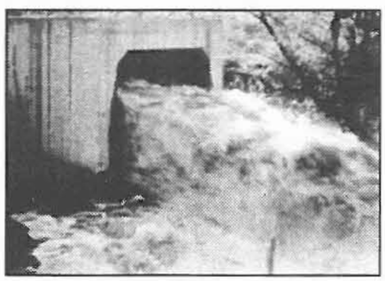
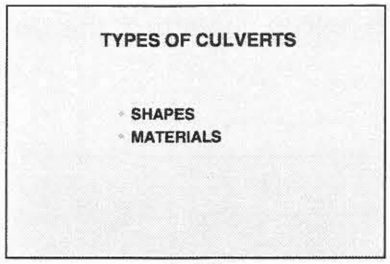


1.9

When culverts fail, the results usually are not catastrophic but, because of their large numbers on highway systems and therefore, high frequency of potential loss, failures are costly and cause considerable interference with normal traffic flow.

D. Types of Culverts



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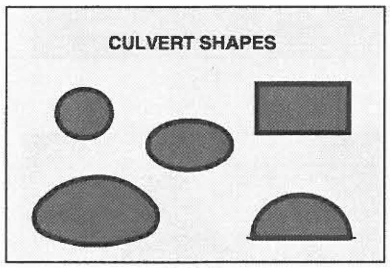
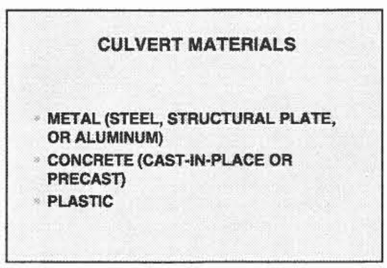


1.11

- Circular
- Oval (elliptical)
- Pipe arch and high and low profile arch

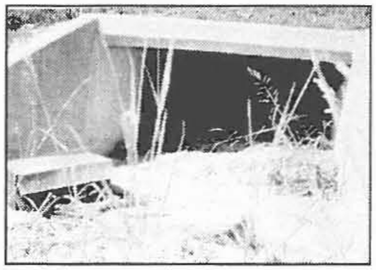


1.12

- Concrete box culverts are either cast-in-place or precast
- Metal box culverts are viable alternatives in some cases
- Pipe culverts of metal, concrete or plastics are either fabricated in a plant or assembled in the field from various components

E. General Culvert Illustrations

Concrete box culvert with wingwalls:



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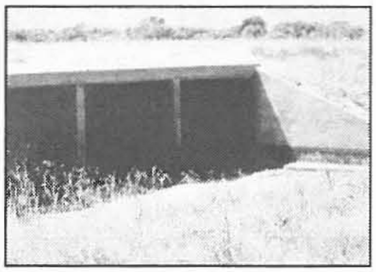
Triple box culvert with wingwalls:



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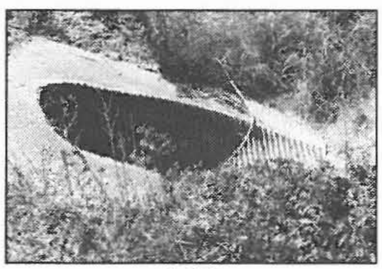
Corrugated metal pipe culvert with a mitered concrete headwall:



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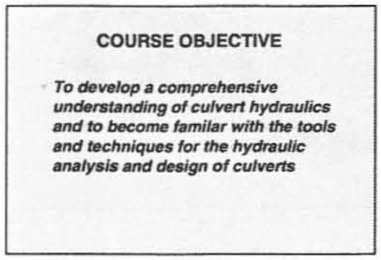
1.4. COURSE OBJECTIVE

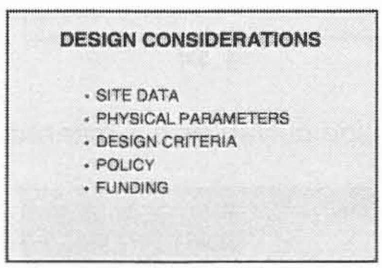
The course objective is to *develop a comprehensive understanding of culvert hydraulics and to become familar with the tools and techniques for the hydraulic analysis and design of culverts.*



1.16

This will be accomplished through lecture presentations, workshop problems and flume demonstrations. The design of a culvert involves many different considerations and decisions:

A. Design Considerations

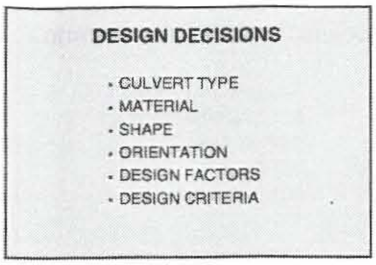


1.17

Identify the design considerations leading to proper culvert designs.

- Site data
- Physical parameters
- Design criteria
- Policy
- Funding

B. Significant Design Decisions

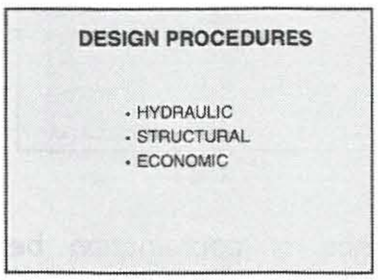


1.18

- culvert types,
- materials,
- shapes,
- orientations,
- design parameters and factors,
- and design criteria.

Understand the significance of early decisions regarding culvert types, materials, shapes, orientations, design parameters and factors, and design criteria.

C. Design Procedures

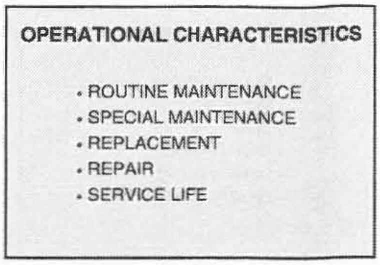


1.19

Understand culvert design principles and procedures regarding hydraulic and structural aspects.

- Hydraulic
- Structural
- Economic

D. Operational Characteristics

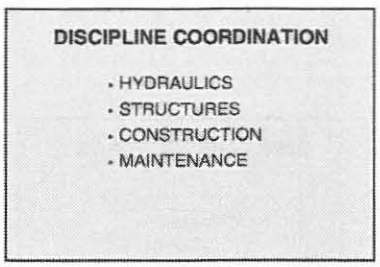


1.20

Recognize the importance of consideration of operational characteristics of culverts.

- Routine maintenance
- Special maintenance
- Replacement
- Repair
- Service life

E. Discipline Coordination



1.21

Realize the importance of coordination between disciplines: hydraulic, structures, construction, and maintenance.

- Hydraulics
- Structures
- Construction
- Maintenance

1.5. COURSE OUTLINE

COURSE LESSONS

1. INTRODUCTION
2. DESIGN CRITERIA
3. BASIC HYDRAULICS
4. CONVENTIONAL CULVERT DESIGN
5. IMPROVED INLET DESIGN
6. CULVERT DESIGN APPLICATIONS
7. ENERGY DISSIPATOR DESIGN

1.22

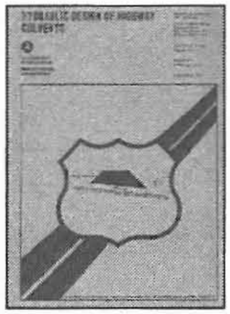
A. Course Schedule

A detailed course outline and schedule is indicated on the pages which follow. The scheduled time, estimated length, topic, and method of instruction are indicated for each lesson. General and specific references regarding the lesson material also are shown.

Course Segment	Topic	Resources	Reference	Session Length (minutes)	Time	Day
Lesson 1	**Introduction**	Graphics	Workbook	30	8:00 - 8:30	1
Lesson 2	**Design Criteria**	Graphics	Workbook	90	8:30 - 10:00	1
	BREAK			15	10:00 - 10:15	1
Lesson 3	**Basic Hydraulics**	Graphics	Workbook	75	10:15 - 11:30	1
	LUNCH			60	11:30 - 12:30	1
	Workshop Problems Culvert 2 Demonstration Flume Demonstration	Flume	(Lesson 2)	135	12:30 - 2:45	1
	BREAK			15	2:45 - 3:00	1
Lesson 4	**Conventional Culvert Design**	Graphics	Workbook	90	3:00 - 4:30	1
	Quiz			30	4:30 - 5:00	1
	Quiz Discussion			30	8:00 - 8:30	2
	Culvert Workshop			60	8:30 - 9:30	2
	BREAK			15	9:30 - 9:45	
Lesson 5	**Improved Inlet Design**	Graphics	Workbook	60	9:45 - 10:45	2
	BREAK			15	10:45 - 11:00	2
	Improved Inlet Workshop			90	11:00 - 12:30	2
	LUNCH			60	12:30 - 1:30	2
Lesson 6	**Culvert Design Applications** Computer Demonstrations Flume Demonstration	Flume		135	1:30 - 3:45	2
	Design Workshop			75	3:45 - 5:00	2
	Design Workshop			135	8:00 - 10:30	3
	BREAK			15	10:30 -10:45	3
Lesson 7	**Energy Dissipator Design**	Graphics	Workbook	75	10:45-12:00	3
	LUNCH			60	12:00- 1:00	3
	Energy Dissipator Video Flume Demonstration	Flume		90	1:00 - 2:30	3
	BREAK			15	2:30- 2:45	3
	Workshop Problem			75	2:45 - 4:00	3

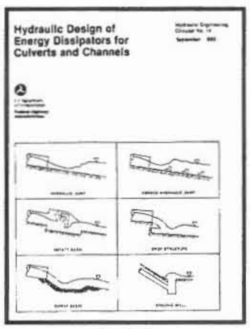
B. Material Sources

The primary references for this course are:



1.23

- Culvert Hydraulics - FHWA Hydraulic Design Series No. 5 (HDS#5), "Hydraulic Design of Highway Culverts", September, 1985. This publication serves as the primary reference for the hydraulic aspects of this course. It is distributed as a course handout. The CD-ROM version of this document will also be distributed.

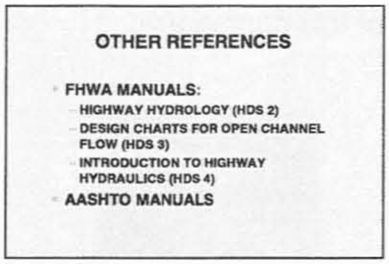


1.24

- Energy Dissipators - FHWA Hydraulic Engineering Circular No. 14 (HEC#14), "Hydraulic Design of Energy Dissipators for Culverts and Channels", September, 1983. This publication is distributed as a course handout.

- Student Workbook - Specific to this course, the Student Workbook comprises notes and information pertinent to the lessons and workshops in the course. This publication is distributed as a course handout.

Other useful documents that are referenced, but not distributed include:



1.25

- Hydrology - FHWA Hydraulic Design Series No. 2 (HDS#2), "Highway Hydrology", 1996.
- Channels - FHWA Hydraulic Design Series No. 3 (HDS#3), "Design Charts for Open-Channel Flow", 1961.
- Channel Design - FHWA Hydraulic Design Series No. 4 (HDS#4), "Introduction to Highway Hydraulics", 1997.

Useful AASHTO references include (available from AASHTO, 444 North Capital Street, N.W., Suite 249, Washington, D.C. 20001):

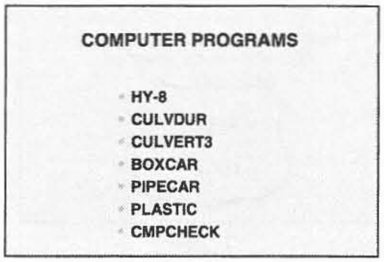
- 1991 AASHTO Model Drainage Manual

1.26

- AASHTO Guidelines, Volume 4

1.27

C. Computer Programs



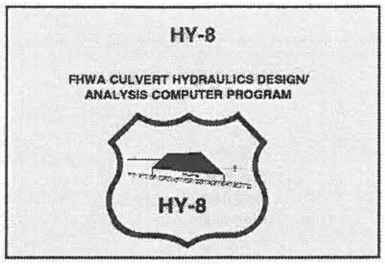
1.28

Numerous computer programs styled for micro-computer application are available to culvert designers. While these are useful design tools, they cannot replace basic design understanding and decision requirements by the designer. Generally, microcomputer software which is useful for culvert design is available through McTRANS or PCTRANS.

McTRANS
512 Weil Hall
University of Florida
Gainesville, FL 32611-2083
(352) 392-0378
e-mail: Mctrans@ce.ufl.edu
web site: www-uftrc.ce.ufl.edu/info-cen/info-cen.htm

PCTRANS
2011 Learned Hall
Lawrence Kansas 66045
(785) 864-5655
e-mail: pctrans@Kuhub.cc.ukans.edu
web site: Kuhub.cc.ukans.edu/~pctrans/index.html

1. HY8



1.29

The FHWA Culvert Hydraulic Analysis Program is distributed to each participant of this course. Documentation for this program is found in "Culvert Analysis Microcomputer Program Applications Guide", May, 1987. Further documentation also may be found in Volume 6 of HYDRAIN.

2. CULVDUR

This FHWA program determines culvert durability for a variety of culvert materials.

3. CULVERT3

The California Department of Transportation's CULVERT2 program is another materials durability program.

4. Other Programs

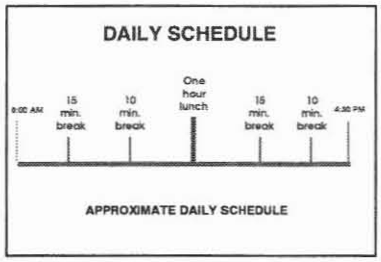
Other culvert programs such as BOXCAR, PIPECAR, PLASTIC, and CMPCHECK facilitate structural analysis. They will not be demonstated during this course.

D. Other References

There are other references throughout the course which will be delineated as appropriate.

1.6. ADMINISTRATIVE NOTES

A. Housekeeping



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Announcements will be made regarding facilities, breaks and lunch, and other activities. Please observe the time limits for breaks and lunches since the complete presentation requires that a time schedule be met.

B. Course Activities

The course activities will comprise a series of lectures, workshops, example problems, flume demonstrations, computer demonstrations, and a quiz.

C. Course Roster and Evaluation

The roster serves as a record of attendance and the basis for certificates. The evaluation is the National Highway Institute's method for obtaining feedback.

NOTES:

LESSON 2

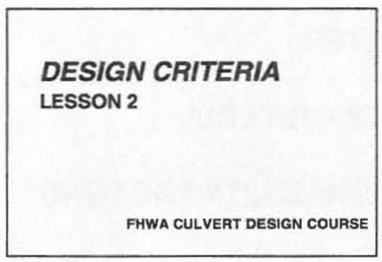
DESIGN CRITERIA

OVERVIEW:

Method of Instruction: Lecture

Lesson Length: 90 minutes

Resources: Student Workbook
Graphics



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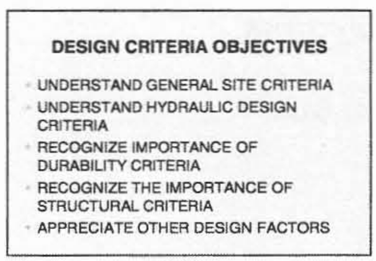


2.0b

OBJECTIVES:

At the conclusion of this lesson, the participant shall be able to:

1. Understand general site criteria, including whether to use a culvert or a bridge, and location and orientation criteria.
2. Understand hydraulic criteria is necessary for the successful design of a culvert.
3. Recognize the importance of environmental and durability considerations.
4. Recognize the importance of adequate structural design.
5. Appreciate other design factors (availability/cost, economy, documentation).

LESSON OUTLINE

2. DESIGN CRITERIA

   2.1. INTRODUCTION

   2.2. GENERAL SITE CRITERIA

   2.3. HYDRAULIC DESIGN CRITERIA

   2.4. DESIGN FREQUENCY CONSIDERATIONS

   2.5. DESIGN HEADWATER

   2.6. OUTLET VELOCITY CRITERIA

   2.7. ENVIRONMENT/DURABILITY FACTORS

   2.8. SAFETY CONSIDERATIONS

   2.9. FISH PASSAGE CRITERIA

   2.10. AVAILABILITY AND COST

   2.11. ECONOMY

   2.12. DOCUMENTATION

   2.13. WORKSHOP - CULVERT2 DEMONSTATION

2.1 INTRODUCTION

INTRODUCTION

- CULVERT DESIGN INVOLVES CONSIDERATION OF:
  - GENERAL SITE CONDITIONS
  - HYDRAULIC FACTORS
  - DURABILITY FACTORS
  - STRUCTURAL FACTORS

2.1

A. Culvert design involves consideration of general site conditions, hydraulic factors, durability factors and structural factors.

B. The design criteria related to each of these considerations will be introduced in this lesson.

2.2. GENERAL SITE CRITERIA

GENERAL SITE CRITERIA

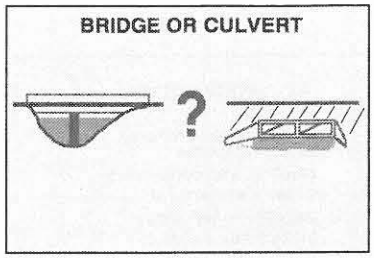
- BRIDGE OR CULVERT ?
- SITE LOCATION AND ORIENTATION
- EVALUATION OF RUNOFF CONTENT

2.2

A. General site criteria includes:

- whether to use a bridge or a culvert (or to consider both),
- specific site location and facility orientation,
- and evaluation of runoff content (ice, debris, etc.).

B. Bridge/Culvert



2.3

1. Use of Bridges

USE OF BRIDGES

- CULVERTS NOT FEASIBLE
- IF MORE ECONOMICAL
- LAND USE REQUIREMENTS
- ENVIRONMENTAL CONSTRAINTS
- AVOID ENCROACHMENTS
- ICE AND LARGE DEBRIS
- CHANNEL DEGRADATION

2.4

Bridges are used where:

- Culverts cannot be used.
- A bridge configuration is more economical.
- Special or unusual land use requirements must be satisfied.
- Environmental harm caused by a culvert must be mitigated.
- Floodway or irrigation canal encroachments must be avoided.
- Ice or large debris must be accommodated.
- Significant vertical degradation in the channel is expected.

2. Use of Culverts

USE OF CULVERTS

- BRIDGES NOT REQUIRED HYDRAULICALLY
- DEBRIS AND ICE CONTENT TOLERABLE
- CULVERTS MORE ECONOMICAL
- ALTERNATE DESIGNS

2.5

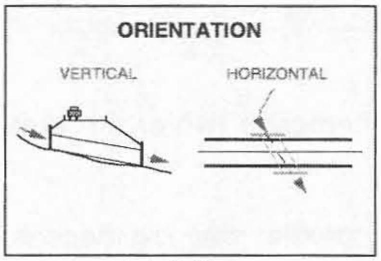
Culverts are used where:

- Bridges are not required hydraulically.
- Debris and ice content are tolerable.
- Culverts are more economical than bridges.

- Some situations justify a design analysis of both types of facilities and may even be shown as alternate designs.

C. Location and Orientation Criteria

In general, the culvert will be located at the point where the main channel of the associated stream crosses the highway location. In some instances, it may be justified to locate the culvert at a different place.



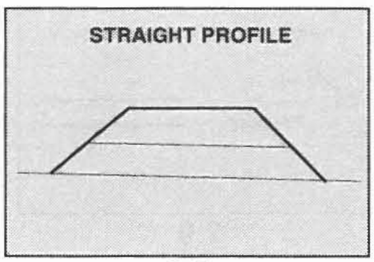
2.6

1. Vertical Orientation

Vertical orientation usually is tied to the stream elevations in the vicinity of the ends of the culvert. Culvert profiles usually match the associated stream bed profile

.

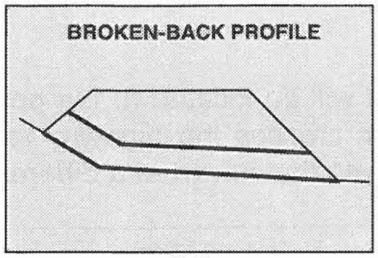
Straight Profile



2.7

The most common profile is simply a straight line between the upstream and downstream flow line elevations of the culvert.

Broken-back Profile

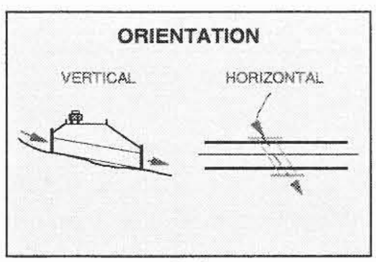


2.8

Broken-back culverts comprise two or more straight profiles within the same culvert.

- A broken-back profile may be necessary to accommodate a large differential of flow line elevation.
- A broken-back profile may be the result of one or more extensions to an original straight profile culvert.
- For certain circumstances, broken-back culverts may be used to control excessive outlet velocities if coupled with an appropriate energy dissipator.

2. Horizontal Orientation

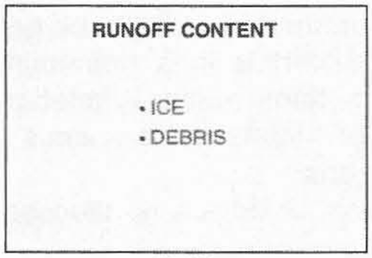


2.9

Horizontal orientation is fixed closely to two items.

- Horizontal orientation of the stream with respect to the roadway centerline.
- Standard plan details available to the designer such as reinforced concrete boxes. The standards may vary from state to state.

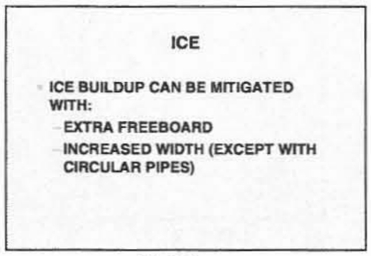
D. Other General Site Criteria (runoff content)



2.10

Aside from the rate of runoff itself, two types of runoff content should be considered by the designer. These are ice and/or debris.

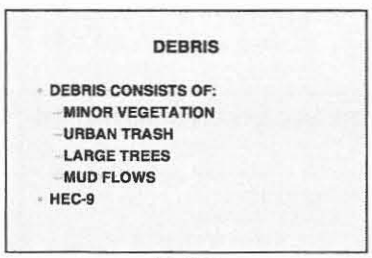
1. Ice



2.11

- Any ice buildup may be mitigated by allowing some freeboard (such as one foot) to the culvert height or diameter.
- For culvert shapes other than circular, further mitigation would be to increase the culvert width to encompass the channel's static ice width. Such mitigation may not be particularly cost effective,

2. Debris



2.12

- Debris in storm runoff can occur in one or more of several different types.
  - Minor dead vegetation.
  - Urban trash.
  - Large trees.
  - Debris flows of rock, vegetation, mud, and trash.

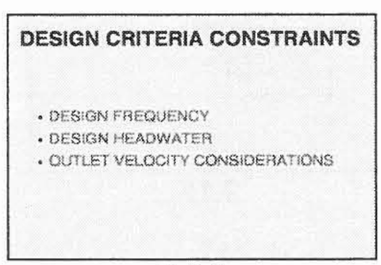
- The designer should be acquainted with the history of the watershed and the type of debris which might be generated by storm events.
  - Where the culvert is in a mountainous or steep region and the watershed contains much vegetation, or if the culvert is under a high fill and/or maintenance access is limited, the designer should beware of debris.
  - If a debris control device is necessary, provide access to clean it out.
- Refer to the FHWA publication "Debris Control Structures", HEC#9 for discussions of debris and suggestions for debris control structures.

2.13

- Normal debris may consist of minor to major vegetation, soil, rocks, trash, and other detritus.
- Debris Flows

2.3. HYDRAULIC DESIGN CRITERIA

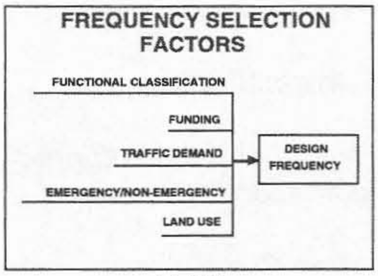
A. The three primary hydraulic design criteria are frequency, headwater and outlet velocity.



2.14

B. The following sections consider each one in detail.

2.4. DESIGN FREQUENCY CONSIDERATIONS

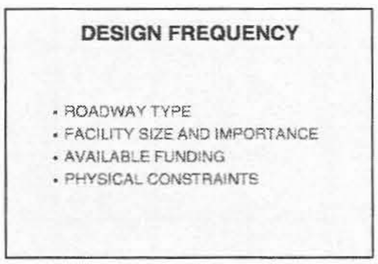


2.15

Culvert design is typically based on selection of a single design frequency; however, culvert performance over a range of flood conditions should also be considered. Generally, there are two approaches to establishing design frequency.

- Design policy
- Risk analysis.

A. Design Policy



2.16

The selection of a specific design frequency based on a policy approach is a function of:

- the type of roadway,
- the importance and size of the facility,
- the available funding,
- certain physical constraints.

1. Type of Roadway

Design frequency should be consistent with the type, level, and importance of the associated roadway.

a. Operational Characteristics

Determine the operational characteristics for a wide range of discharge applications.

b. Roadway/Culvert Combination

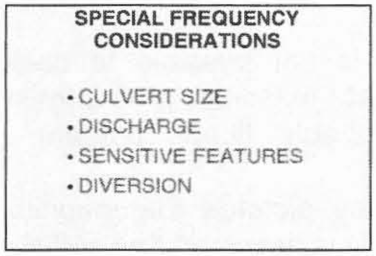
The general geometrics of the associated roadway in combination with the culvert configuration is a design alternative.

c. Example

Design frequency often is dictated by policy. The following table is an example of design frequency assignments relative to the facility type.

Functional Classification and Structure Type	100	50	25	10	5	2
Freeways (Main Lanes)						
Culverts		X				
Bridges		X				
Principal Arterials						
Culverts			X			
Small Bridges			X			
Major River Crossings		X				
Minor Arterials and Collectors (Including Frontage Roads)						
Culverts			X	X		
Small Bridges			X			
Major River Crossings		X				
Local Roads and Streets (Off-System Projects)						
Culverts				X	X	X
Small Bridges				X	X	X

2. Importance and Size of Facility



2.17

A further consideration by the designer in the matter of design frequency criteria is the specific importance and/or size of the culvert.

a. Culvert size.

b. Discharge.

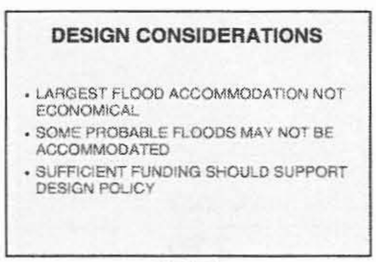
c. Sensitive Features

Proximity of the culvert to sensitive features (both inside and outside the roadway right-of-way).

d. Diversion

Consideration of watershed diversion levels or special roadway profiles.

3. Available Funding

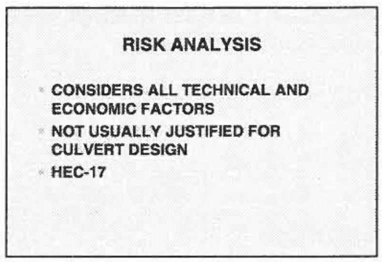


2.18

In most instances, a practical limit of the flood accommodation by the culvert is governed by budgetary constraints for the roadway project.

- Usually, it is not possible to design a culvert economically to accommodate reasonably the largest possible flood.
- Certain probable floods present a risk of not being passed reasonably.
- Where policy dictates the magnitude of the design flood (and frequency), it is assumed that sufficient funding is available.

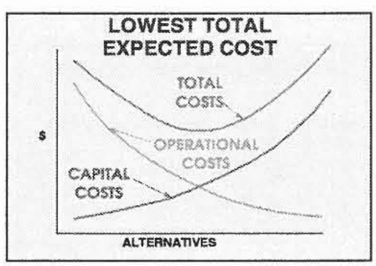
B. Design by Risk Analysis



2.19

Ideally, the actual design frequency can be established systematically by means of a "design by risk analysis (or evaluation)". Design by risk analysis involves the consideration of a wide range of probable floods and not any one design frequency alone.

- Not usually justified for culvert design.
- Refer to HEC #17.



2.20

1. Systematic Process

   This systematic process also involves the consideration of costs of installation and potential losses due to flooding for several possible physical alternatives.

2. Total Cost

   The sum of capital cost and operational cost for an alternative represents the total cost for the alternative. A description of these total costs in relation to the various alternatives is the total expected cost curve.

3. Lowest Total Expected Cost

   The lowest total expected cost is the minimum on that curve. Unless there are other overriding considerations, the designer should select the alternative causing the lowest total expected cost.

4. HEC#17, "Design by Risk Analysis"

   Reference is made to HEC #17 for more comprehensive discussions on the subject of design by risk analysis.

2.5. DESIGN HEADWATER

2.21

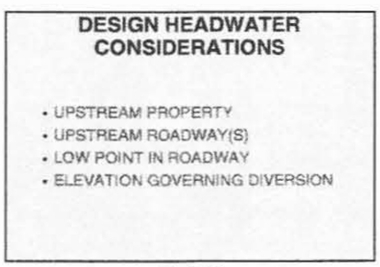
One of the most important design criteria which must be established by the culvert hydraulic designer is the design headwater.

A. Design Criteria

This criteria is used as the basic measure of the adequacy or inadequacy of the culvert configuration.

B. Site Specific

The design headwater at a culvert site is specific to that site and is a function of several considerations.



2.22

1. Design Headwater

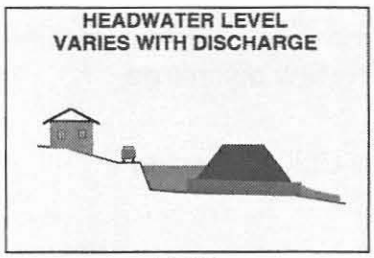
The design headwater is the depth of water that can be ponded at the upstream end of the culvert which will be:

- a cause for no serious damage to upstream property,
- at some arbitrary level with respect to the roadway profile or roadway appurtenances,
- no greater than a critical elevation of an upstream roadway,
- no greater than the low point in the roadway grade,
- no greater than the elevation where flow diverts from the culvert to some other outlet.

2. Consideration of Upstream Features

The designer must establish a design headwater which will preclude the possibility of damage to upstream property by the headwater caused by the culvert as it accommodates the design flow.

C. Several possible "design headwater" levels must be considered.



2.23

1. Basic Design Headwater Elevation

The designer should establish an elevation above which the headwater level caused by the culvert operation will not rise. This basic design headwater elevation governs for a specific frequency of discharge.

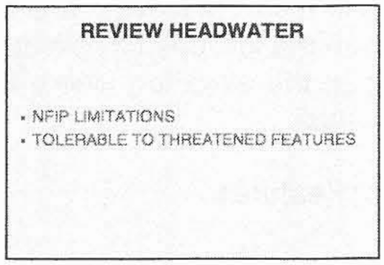
2. Other Headwater Elevations

A wide range of design headwaters is applicable where the culvert is designed and then analyzed for hydraulic performance over a range of discharges.

3. Efficient Accommodation of Low Flows

In some cases, the designer may configure the culvert for efficient accommodation of low to medium flows. Then, allow a higher design headwater for a "design discharge".

D. Review Headwater

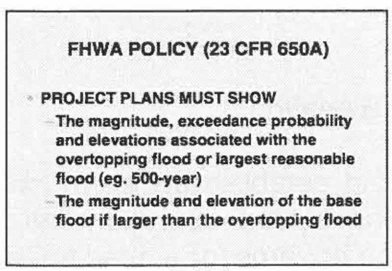


2.24

The review headwater is a flood depth which:

- does not exceed some specified maximum increase over the existing 100-year flood elevation in the National Flood Insurance Program mapped floodplains or in the vicinity of insurable buildings.
- has a level of inundation which is tolerable to upstream property and roadway(s) for the review discharge.

E. Federal Highway Policy on Culvert Design



2.25

Section 650.117 of 23 CFR 650A states that project plans for encroachment locations shall show:

(1) The magnitude, approximate probability of exceedance and ...the water surface elevations associated with the overtopping flood or the flood of Sec. 650.115(a)(1) *(which is the largest flood that may be reasonably estimated such as the 500-year flood)*

(2) The magnitude and water surface elevation of the base flood, if larger than the overtopping flood. *(The base flood is the 100-year flood).*

2.6. OUTLET VELOCITY

OUTLET VELOCITY CONSIDERATIONS

- NATURAL STREAM VELOCITY
- SOIL TYPE
- CHANNEL PHYSICAL CHARACTERISTICS
- PROXIMITY OF THREATENED FEATURES
- SCOURING POTENTIAL
- POTENTIAL DAMAGE DUE TO IMPACT
- PAST CULVERT PERFORMANCE

2.26

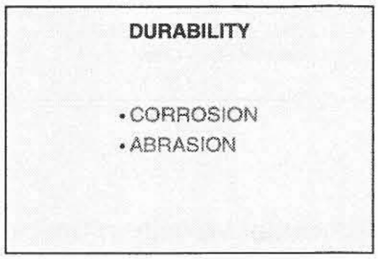
An acceptable culvert outlet velocity must be judged on the basis of:

- natural stream velocity,
- soil type,
- channel physical characteristics,
- proximity of threatened property or facilities,
- scouring potential of soil and/or appurtenances,
- potential of damage due to impact (momentum),
- past culvert performance in the specific locale.

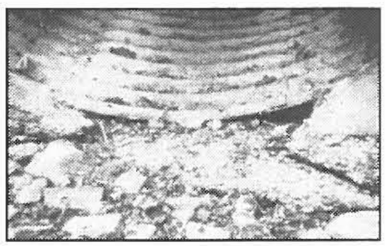
An excessive outlet velocity usually is addressed more economically by specific appurtenances which ordinarily do not affect the upstream headwater.

2.7. ENVIRONMENT/DURABILITY FACTORS

The durability of a culvert depends upon several environmental factors. Statistically, it has been found that the vast majority of culverts do not fail hydraulically or structurally, but rather they wear out from the effects of corrosion and/or abrasion.

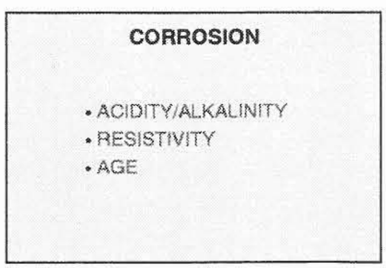


2.27



2.28

A. Corrosion



2.29

Corrosion of a culvert material is a chemical or electro-chemical (also termed galvanic) reaction between associated soil and/or water and the culvert material. The important factors include the acidity/alkalinity and the resistivity of the host soil, the culvert backfill material, the ground water, and the runoff water.

1. pH Factor

Acidity or alkalinity is depicted by the pH factor. The pH factor is the negative logarithm of a measure of hydrogen ion activity.

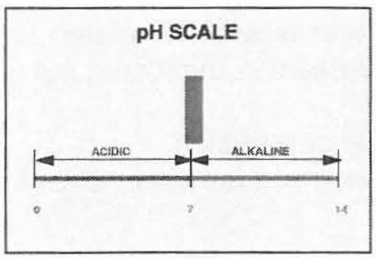
2. Resistivity

Resistivity is the opposite of conductivity and represents the current carrying capacity of a material. A high current carrying capacity is conducive to the electro-chemical reaction represented by corrosion.

3. Character of Ground and Runoff Waters

a. Acidity/Alkalinity

The corrosive potential of water is measured by acidity or alkalinity and the current carrying capacity (resistivity).



2.30

b. Corrosive pH Values

Extreme values of pH include those substances having a pH value of 5.5 or less (strongly acid) and 8.5 or more (strongly alkaline).

- Acid water stems from two sources, mineral and organic.
- A general guide for compatibility between various culvert materials and pH values is shown in the following table. Since conditions vary widely with respect to geographic location, the designer should adapt the table to local experience and conditions.

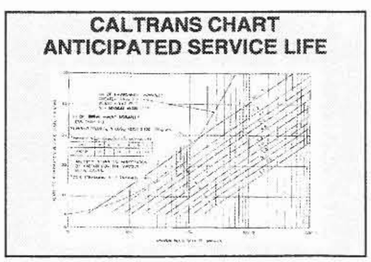
Culvert Material	Recommended pH value range
Galvanized Steel	5.5 - 9.0
Aluminum	4.0 - 8.0
Reinforced Concrete	5.0 - 10.0
Plastic	4.0 - 8.0
Polymer Coated	4.0 - 8.0

c. Resistivity

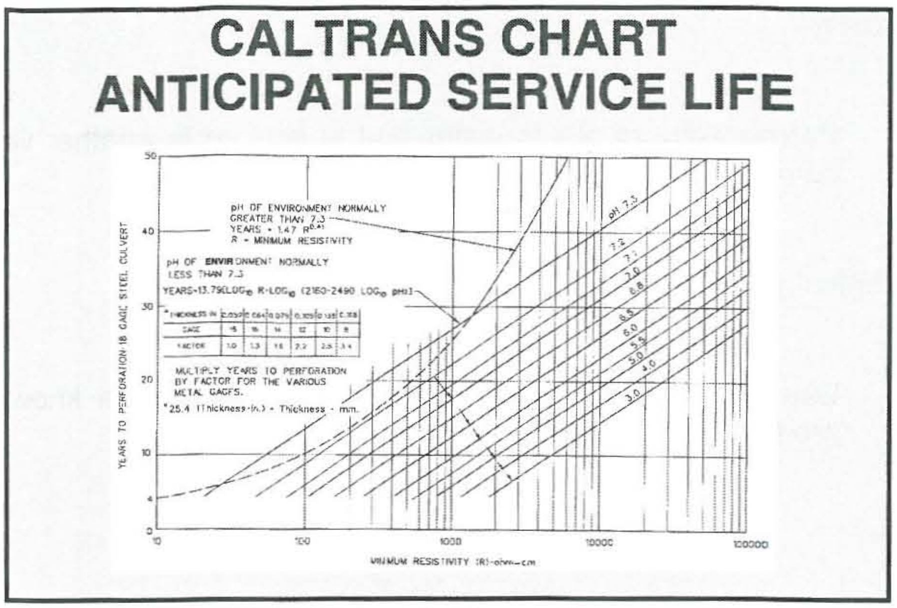
Resistivity in water is usually related to the type and amount of salts which may be present in the water, such as:

- Sea water or intrusion.
- Significant farm fertilizer content.

d. Age



2.31

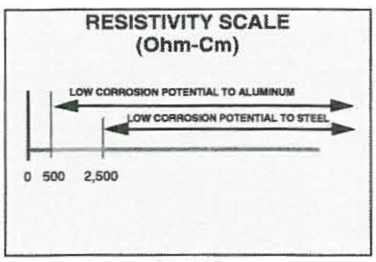


Deterioration due to corrosion and/or resistivity (as well as abrasion) is dependent upon age as well as pH, resistivity, and abrasive content of flow. Typically, the designer will desire a minimum service life for the structure.

4. Soil and Backfill Material

a. General Character

The chemical and physical characteristics of the soil which will come into contact should be known. The following figure is general and should be adapted to local experience and conditions.



2.32

b. Resistivity

Resistivity in the soil is one of the most significant geotechnical factors affecting durability.

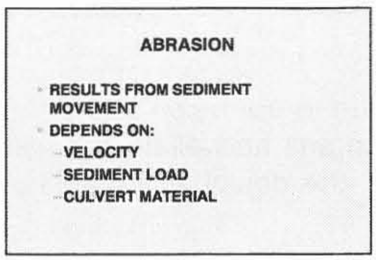
c. Permeability

Permeability of soil to water and to oxygen is another variable in the corrosion process.

d. Geotechnical Data Source

Usually, details of these geotechnical factors are known only on a project-wide basis.

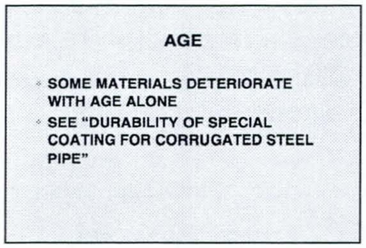
B. Abrasion



2.33

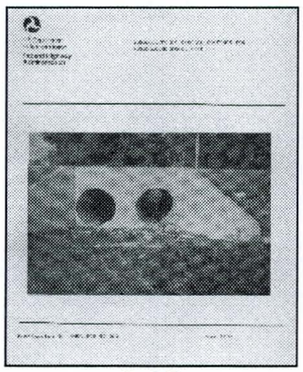
Abrasion is defined as the wearing of the culvert invert by the bed load carried by the water. The mechanism is a function of the velocity of flow and the bed load content of the water. Abrasion potential also depends upon the culvert material.

C. Age



2.34

Age of the culvert material has a direct bearing on the durability of the material. Some materials deteriorate with age alone. The corrosive and/or abrasive threats are exacerbated by greater age in the material.

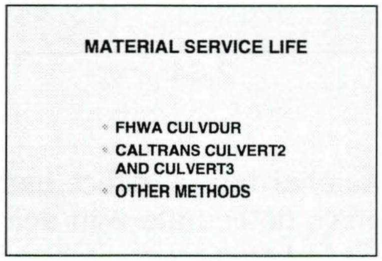


2.35

Refer to FHWA Publication FHWA-FL-91-006, "Durability of Special Coatings for Corrugated Steel Pipe", June, 1991 for a comprehensive compilation of data and discussions regarding durability of various culvert conduit materials, or FHWA-RD-97-xxxx, "Durability Analysis of Aluminum Type II Corrugated Metal Pipe."

D. Service Life

There are several systematic procedures which address the anticipated durability and service life of various culvert materials. The designer should give consideration to experience with respect to durability of materials in association with the geo-technical factors of the culvert site. All procedures are being updated constantly with the accumulation of more experience and data.



2.36

1. CULVDUR and CULVERT2/CULVERT3

- The FHWA Aluminum type II research project included development of the computer program CULVDUR, which evaluates culvert material durability based on several different procedures.
- The CULVERT2/CULVERT3 program is from the California Department of Transportation (CULVERT3 is a newer metric version).
    - Primarily addresses metal pipe.
    - Simple and convenient to use.

2. Other Procedures

Other useful procedures, both computerized and otherwise, are available for use in various states. Typically, these procedures reflect the experience within the specific locality.

2.8. SAFETY CONSIDERATIONS

A. Major safety issues relate to structural and hydraulic adequacy. Assuming that these issues are addressed, supplementary safety issures relate to traffic safety (vehicles leaving the roadway) and child safety.

SAFETY CONSIDERATIONS

- MAJOR SAFETY ISSUES RELATE TO STRUCTURAL AND HYDRAULIC ADEQUACY
- SUPPLEMENTARY SAFETY ISSUES INCLUDE:
  - TRAFFIC SAFETY
  - CHILD SAFETY

2.37

VEHICLES LEAVING ROADWAY

- INLET AND OUTLET LOCATION
- SAFETY BARRIERS AND GRATES

2.38

B. Guidance for safety in culvert design is found in the AASHTO Model Drainage Manual, Chapter 9.

AASHTO SAFETY GUIDANCE

- SMALL CULVERTS
- LARGE CULVERTS
- INSPECTION
- HEAD LOSS ESTIMATION

2.39

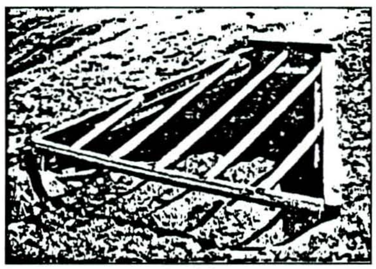
1. Small Culverts

Small culverts (30" in diameter or less) - use an end section or a sloped headwall.

2. Larger Culverts

Culverts greater than 30" in diameter - use one of the following treatments.

- The culvert should be extended to the appropriate "clear zone" distance per AASHTO Roadside Design Guide. A clear zone distance varies with the type of roadway and is usually considered 30 feet beyond the traveled way.
- The culvert should be safety-treated with a grate if the consequences of clogging and causing a potential flooding hazard are less than the hazard of vehicles impacting an unprotected end. If a grate is used, an open area should be provided between the bars of 1.5 to 3.0 times the area of the culvert entrance.
- The culvert should be shielded with a traffic barrier if the culvert is very large, cannot be extended, has a channel which cannot be safely traversed by a vehicle, or has a significant flooding hazard with a grate.



2.40

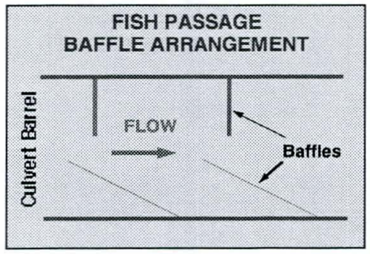
3. Inspection

Periodically inspect each site to determine if safety problems exist for traffic or for the structural safety of the culvert and embankment.

4. Head Loss Estimates

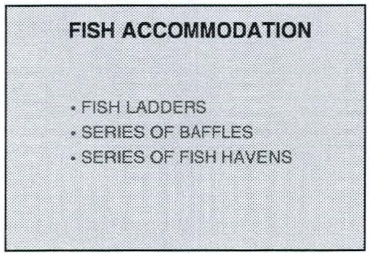
Estimation of head losses due to the application of safety grates is accomplished by procedures and equations found on page 130 of HDS#5.

2.9 FISH PASSAGE CRITERIA



2.41

A. Migrating Fish



2.42

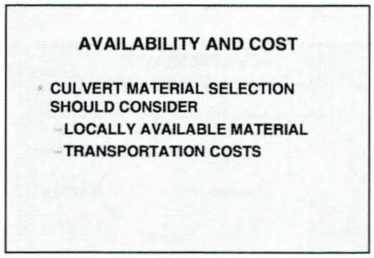
These culvert configurations are provided and used where migrating fish must be accommodated by the stream. There are different types of configurations, including:

- Fish ladders.
- A series of baffles.
- A series of fish havens within the culvert barrel.

B. Hydraulic Capacity Reduction

Any type of fish passage appurtenance characteristically will decrease the hydraulic capacity of the culvert.

2.10. AVAILABILITY AND COST



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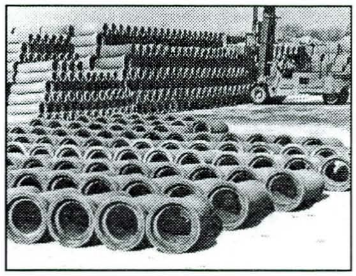


2.44

It is important to consider the material and facility availability in the region of the subject highway project.

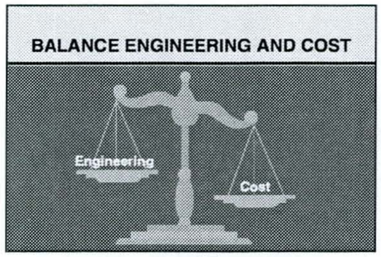
1. Limited Availability

   In most locations, only a few types of culvert materials and facilities are readily available.

2. Cost Considerations

   Any material or facility selection can be furnished; but at a cost which may be unacceptable. Delivery costs may be excessive for remote sites.

2.11. ECONOMY



2.45

The designer is responsible for satisfying the technical demands while minimizing the cost.

1. Alternative Designs

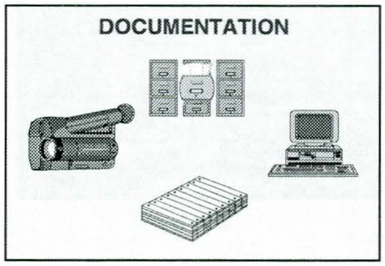
   The designer should consider more than one alternative design for any culvert location in order to:

   - better meet technical demands,
   - minimize costs.

2. Consistency of Alternatives

   The extent of consideration of other alternatives should be consistent with the importance of the structure.

2.12. DOCUMENTATION



2.46

The importance of documentation of the culvert design criteria cannot be over-emphasized. Included in comprehensive documentation should be:

A. Design Criteria Bases

B. Data Evaluation/Reduction

C. Applications

D. Design Qualifications

E. Judgment Clarification

2.13 WORKSHOP - CULVERT2 DEMONSTATION

DISCUSSION

A. Observed Data

B. Design Charts

C. Computer Programs

CULVERT2

This program calculates maintenance-free service design estimates using California test method numbers 417, 422, 532, and 643 as well as the considerations delineated in California DOT Highway Design Manual, Index 850, Physical Standards.

The program is formatted for use on an MS-DOS based microcomputer system and is invoked by the command 'CULVERT2'.

A. Input Considerations

1. Identification

2. Runoff Water

- pH - measure of acidity or alkalinity (negative logarithm of a measure of the hydrogen ion activity in the substance).
- Resistivity - measure of reciprocal of current carrying capacity (ohm-cm).
- Velocity - velocity of flow in the culvert conduit (fps)
- Abrasive material content.
- Other damaging material content.

3. Ground Water

- pH
- Resistivity
- Abrasive material content

4. Local Soil

- pH
- Resistivity
- Salts
- Abrasive characteristics

5. Embankment Soil

- pH
- Resistivity
- Salts
- Abrasive characteristics

6. Backfill Soil

- pH
- Resistivity
- Salts
- Abrasive characteristics

7. Conduit Bedding Soil

- pH
- Resistivity
- Salts
- Abrasive characteristics

8. Conduit protection

- Galvanizing
- Epoxy
- Polymer
- Bituminous
  - Internal
  - External
  - Both
  - Heavy coating
  - Partial coating

B. Output

1. Standard screen

- Controlling factors

- Table of life expectancy
- Footnotes
- Concrete pipe considerations

2. Other screens

C. Discussion

- What to expect.
- Type of installation.
- Alternatives.

D. Example Problem

1. Identification

```
CO.-RTE.-P.M....TUL-99-6.2/6.5
EXP. AUTH.......06-256501
LOCATION........STA. 75+00 40.0 LT
TEST NO.        85-265
OPERATOR ID.....DMC
DATE TESTED.....09-01-93
```

2. Runoff Water

- pH - measure of acidity or alkalinity (negative logarithm of a measure of the hydrogen ion activity in the substance).
- Resistivity - measure of reciprocal of current carrying capacity (ohm-cm).
- Velocity - velocity of flow in the culvert conduit (fps)
- Abrasive material content.
- Other damaging material content.

```
PH = 5.0
RESISTIVITY = 650 OHM-CM
```

3. Ground Water

- pH.
- Resistivity.
- Abrasive material content.

Not applicable for this example.

4. Local Soil

- pH.
- Resistivity.
- Salts.

- Abrasive characteristics.

Non-abrasive.

5. Embankment Soil

- pH.
- Resistivity.
- Salts.
- Abrasive characteristics.

Not applicable for this example.

6. Backfill Soil

- pH.
- Resistivity.
- Salts.
- Abrasive characteristics.

```
PH = 5.2
RESISTIVITY = 550 OHM-CM
CHLORIDES = 700 PPM
SULFATES = 3500 PPM
```

7. Conduit Bedding Soil

- pH.
- Resistivity.
- Salts.
- Abrasive characteristics.

Not applicable for this example.

8. Conduit protection

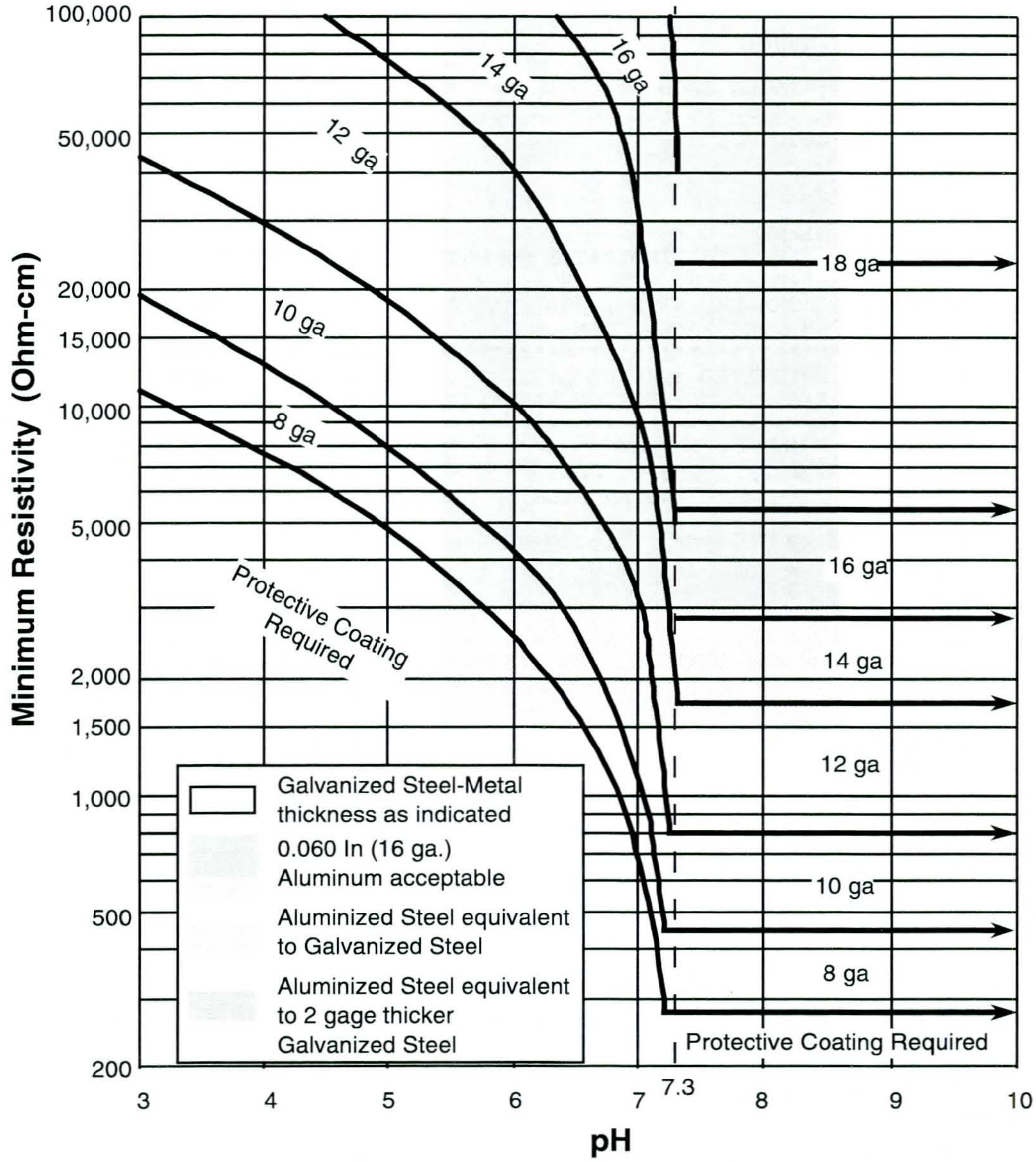
- Galvanizing
- Epoxy
- Polymer
- Bituminous
  - Internal
  - External
  - Both
  - Heavy coating
  - Partial coating

Consider all conduit protections for this example.

E. Program Demonstration

```
MAINTENANCE-FREE SERVICE DESIGN ESTIMATES USING PROGRAM:
'CULVERT2.EXE' (11/11/92 WITH CALIFORNIA CULVERT CRITERIA
----------------------------------------------------------

CO.-RTE.-P.M....TUL-99-6.2/6.5

EXP. AUTH.......06-256501

LOCATION........STA. 75+00 40.0 LT

TEST NO.        85-265

OPERATOR ID.....DMC

DATE TESTED.....09-01-93
******* THE VALUE OF ZERO (0) INDICATES NO DATA INPUT ********
SITE PH = 5.2, WATER PH = 5.0, SOIL PH = 5.2
MINIMUM RESISTIVITY, OHM-CM: SITE = 550, WATER = 650, SOIL = 550
CHLORIDES, PPM... 700,  SULFATES, PPM... 3500
***********************************************************************
                    ESTIMATED SERVICE LIFE OF CSP CULVERTS, YEARS
                    SEE HIGHWAY DESIGN MANUAL FIG. 854.3A & 854.3B
---------------  |------------------------------------------
CSP              |    GALV.     GALV.PLUS      GALV.PLUS      GALV.PLUS
GAGE THICKNESS   |    2 OZ.    BIT. COAT.     BIT.COAT.&     BIT.COAT.
          INCHES |            (WATER SIDE)    PAVED IN.     (SOIL SIDE)
                 |                           (ABRASION)
18      0.052    |    2           10             17              27
16      0.064    |    2           10             17              27
14      0.079    |    3           11             18              28
12      0.109    |    4           12             19              29
 8      0.168    |    7           15             22              32
FLOW VEL. <5 FPS WITH NON-ABRASIVE CONDITIONS, (DEFAULT VALUES)
16 GAGE CAP AND 18 GAGE CSP/CASP MAY BE USED WITH THESE FLOW VELOCITIES

STANDARD REINFORCED CONCRETE PIPE DESIGN MAY BE ADVERSELY
AFFECTED BY CHLORIDES.  REVISED DESIGN IS:

FOR CHLORIDE RESISTANT RCP, ESTIMATED SERVICE LIFE, YEARS = 52
   USING CEMENT CONTENT, SK/CY, C = 7
   USING CONCRETE COVER, INCHES, S = 2
   USING TOTAL MIX WATER, % BY VOL., W = 15

FOR SULFATE RESISTANT RCP
   TYPE V CEMENT OR 7 SK/CY TYPE II MOD. CEMENT

DUE TO ACIDIC CONDITIONS, REINFORCED CONCRETE PIPE
REQUIRES EXTRA COVER OR A PROTECTIVE COATING

AN ALUMINUM CULVERT, CAP, SHOULD NOT BE USED
DUE TO CORROSIVE CONDITIONS
SEE HIGHWAY DESIGN MANUAL FIGURE 854.3B

AN ALUMINIZED STEEL CULVERT, CASP, SHOULD NOT BE USED
DUE TO CORROSIVE CONDITIONS
SEE HIGHWAY DESIGN MANUAL FIGURE 854.3B
```

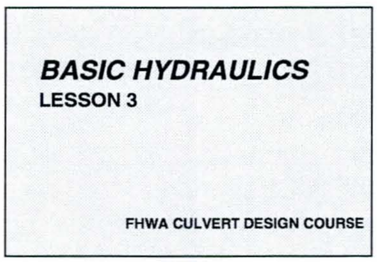
Figure 854.3B
Minimum Thickness of Metal Pipe for 50 Year Maintenance Free Service Life



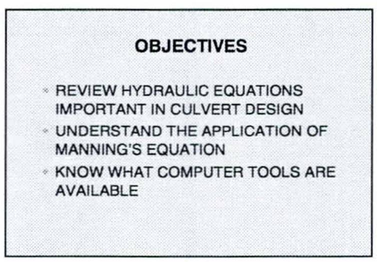
LESSON 3

BASIC HYDRAULICS

OVERVIEW:	Method of Instruction:	Lecture
	Lesson Length:	75 minutes
	Resources:	Student Workbook Graphics



3.0a



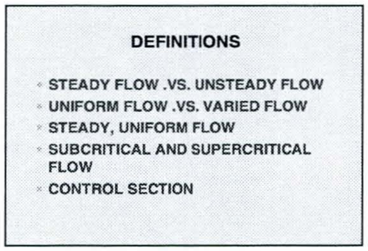
3.0b

OBJECTIVES: At the conclusion of this lesson, the participant shall be able to:

1. Review and understand basic hydraulic equations and theory important in culvert design.
2. Understand the application of Manning's Equation to evaluate tailwater conditions downstream of a culvert.
3. Appreciate the range of computer programs available to assist with open channel flow analysis and their potential application in culvert design.

LESSON OUTLINE

3.1 BASIC DEFINITIONS



3.1

A. Steady flow. Depth of flow at a given cross section does not change or it can be assumed to be constant during the time interval under consideration.

B. Unsteady flow. Depth of flow at a given cross section changes with time.

C. Uniform flow. Depth of flow is the same at every section along the length of the channel.

D. Varied flow. Depth of flow changes along the length of the channel. Varied flow may be either gradually varied or rapidily varied.

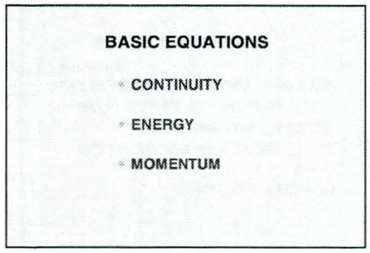
E. Steady, uniform flow. An idealized concept of open-channel flow which seldom occurs in natural channels. However, for many practical applications, the flow is steady and changes in width, depth or direction are sufficiently small that the flow can be assumed as uniform flow.

F. Subcritical flow. A flow condition that can be generally described as relatively deep with low velocity on a mild slope.

G. Supercritical flow. A flow condition that can be generally described as relatively shallow with high velocity on a steep slope.

H. Control Section. Any cross section for which the depth of flow can be uniquely predicted for a given discharge.

3.2. BASIC EQUATIONS

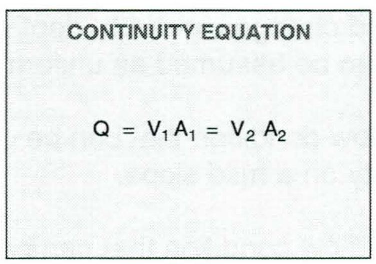


3.2

The three basic equations that govern flow behavior are the continuity, energy and momentum equations. These equations also form the basis for derivation, using mathematics, laboratory experiments and field studies, of other useful hydraulic equations.

A brief review of the continuity, energy and momentum equations is provided below. For more detailed discussion of all three fundamental equations, see "Introduction to Highway Hydraulics" (FHWA HDS-4, 1997) or any standard hydraulics textbook.

A. Continuity Equation



3.3

The continuity equation assumes that discharge remains constant from one cross-section to the next and is represented generally as:

$$Q = V_1 A_1 = V_2 A_2 = \ldots V_n A_n \qquad \text{3-1}$$

where: Q = total discharge (cfs),
V_n = average velocity at section n (fps),
A_n = cross-sectional area of flow at section n (ft^2).

B. Energy Equation

ENERGY EQUATION

$$z_1 + y_1 + \frac{V_1^2}{2g} = z_2 + y_2 + \frac{V_2^2}{2g} + h_L$$

3.4

$$z_1 + y_1 + \frac{V_1^2}{2g} = z_2 + y_2 + \frac{V_2^2}{2g} + h_L \qquad \text{.................................... 3-2a}$$

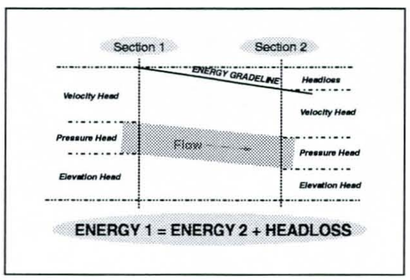
where: z_1 and z_2 = elevations of the streambed at the upstream and downstream sections respectively (ft),

y_1 and y_2 = depths of flow at the upstream and downstream sections respectively (ft),

V_1 and V_2 = average velocity of flow at the upstream and downstream sections respectively (ft/sec),

h_L = head losses between sections 1 and 2,

g = the acceleration due to gravity 32.2 ft/sec^2.



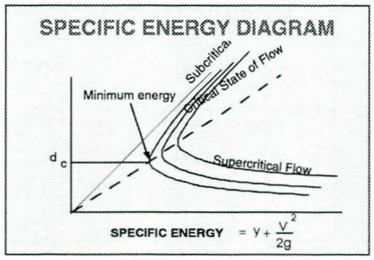
3.5

The energy grade line (EGL) represents the total energy at any given section, defined as the sum of the three components of energy represented on each side of the energy equation. These components of energy are often referred to as the:

1. Velocity head
2. Pressure head
3. Elevation head

The hydraulic gradeline (HGL) is below the EGL by the amount of the velocity head, or is the sum of just the pressure head and elevation head.

The specific energy is the energy relative the to channel bed (no elevation head).



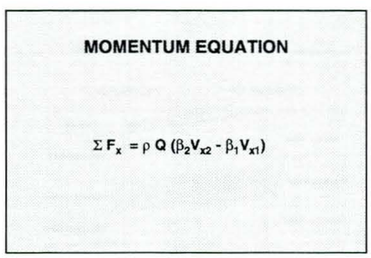
3.6

The specific energy is defined as:

$$H = y + \frac{V^2}{2g} \quad \text{......} 3.2b$$

where: H = specific energy (ft),
y = depth of flow (ft),
V = average velocity of flow (fps)
g = acceleration of gravity (32.2 ft/s^2)

C. Momentum



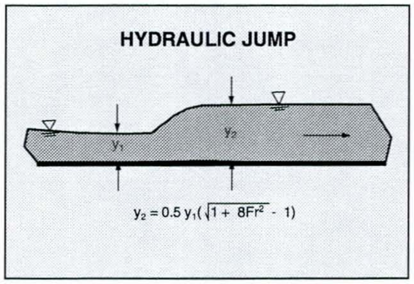
3.7a

The momentum equation is

$$\Sigma F_x = \rho\, Q\, (\beta_2 V_{x2} - \beta_1 V_{x1}) \quad \text{......} 3\text{-}3$$

where F_x = Forces in the x direction
ρ = density of water
Q = discharge
β = Momentum coefficient, normally assumed to be one
V = velocity in the x direction

The momentum equation is derived from Newton's second law, which states that the summation of all external forces on a system is equal to the change in momentum. The equation is a vector relationship and the form shown is for the x-direction, with a similar form in the y and z directions.



3.7b

The momentum concept is important in grate design, hydraulic jump analysis, analysis of paved channels intersecting at angles and in design of energy dissipators.

3.3 MANNING'S EQUATION

The culvert hydraulic operation often is a direct function of the unconstricted channel flow characteristics. One of the most common methods of analyzing open channel flow is the Manning's Equation.

MANNING'S EQUATION (MERGED WITH CONTINUITY)

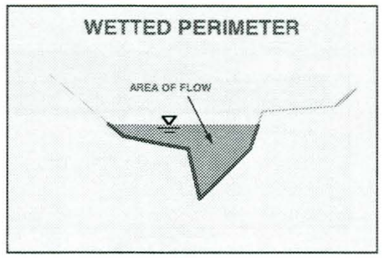
$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2}$$

3.8

Manning's Equation describes uniform flow in a prismatic conveyance or channel. The depth of flow associated with uniform flow is termed normal depth. The original equation described uniform velocity. However, in combination with the Continuity Equation, its more familiar format is given as follows.

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2} \qquad \text{......} 3\text{-}4$$

where: Q = discharge (cfs),
n = roughness coefficient (dimensionless),
A = cross-sectional area of flow (ft^2),



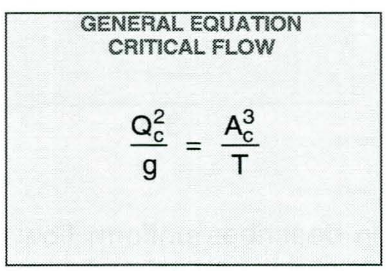
3.9

R = hydraulic radius [area (A) divided by wetted perimeter] (ft),
S = longitudinal slope of water surface (ft/ft).

Uniform flow can occur when discharge, channel geometry, roughness characteristics, and water surface slope are constant for a significant reach of stream. In natural stream settings, uniform flow is not likely. However, for many practical applications Manning's Equation is often appropriate.

Normal depth of flow sometimes is referred to as uniform depth and is the depth at which uniform flow would occur.

3.4. CRITICAL DEPTH EQUATION



3.10

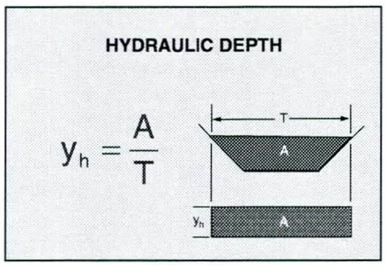
Critical depth of flow occurs at a critical state of flow. Critical depth is defined by the general equation:

$$\frac{Q_c^2}{g} = \frac{A_c^3}{T} \quad \text{.......... 3-5}$$

where: Q_C= Critical discharge (cfs),
A_C= Cross-sectional area of flow (ft^2),
T = Width of water surface (ft),
g = acceleration due to gravity (32.2 ft/s^2).

3.5. OTHER DEPTH RELATIONSHIPS

A. Hydraulic Depth



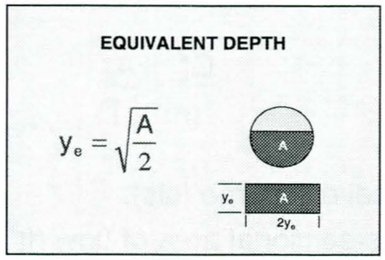
3.11

The hydraulic depth, or mean depth, is often used to define an average depth condition in open channel flow. It is equal to the area of flow divided by the top width of flow:

$$y_h = \frac{A}{T} \quad \text{.......... 3-6}$$

where: y_h = hydraulic depth (ft),
A = Cross-sectional area of flow (ft^2),
T = Top width of water surface (ft),

B. Equivalent Depth



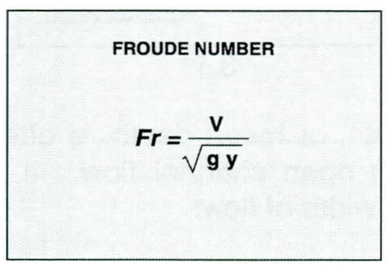
3.12

The equivalent depth is often used as an approximate depth of flow in energy dissipator calculations. It is the depth corresponding to an area of flow which has a width that is twice the depth:

$$y_e = \sqrt{\frac{A}{2}} \quad \text{..........} 3\text{-}7$$

where: y_e = equivalent depth (ft),
A = Cross-sectional area of flow (ft^2).

3.6 FROUDE NUMBER



3.13a

A. The Froude number is defined as

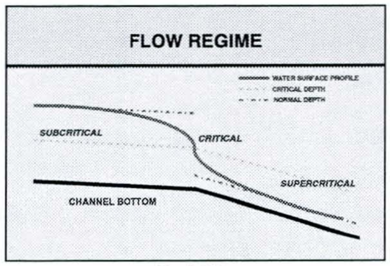
$$Fr = \frac{V}{\sqrt{g\,y}} \quad \text{..........} 3\text{-}8$$

where Fr = Froude Number
V = Flow velocity (fps)
g = acceleration of gravity (32.2 ft/s^2)
y = flow depth (ft).

For irregular sections, y is the mean or hydraulic depth (y=A/T) and for circular sections it is the equivalent depth ($y=(A/2)^{1/2}$)

B. The Froude number can be used to define subcritical, critical, and supercritical flow:

$Fr < 1$ subcritical
$Fr = 1$ critical
$Fr > 1$ supercritical



3.13b

1. Subcritical

Subcritical flow occurs when the depth of flow, velocity, and orientation of flow is dependent upon factors from the point in question to downstream. The flow usually has a low velocity and is described as tranquil.

Normal depth of flow is defined according to Manning's Equation for Uniform Flow (Equation 3-4). Subcritical flow can also be defined as the condition when normal depth is greater than critical depth

2. Supercritical

Supercritical flow occurs when the depth of flow, velocity, and orientation of flow is dependent upon factors from the point in question to upstream. The flow usually has a high velocity and may be described as rapid, shooting, and torrential.

Supercritical flow can also be defined as the condition when normal depth is less than critical depth.

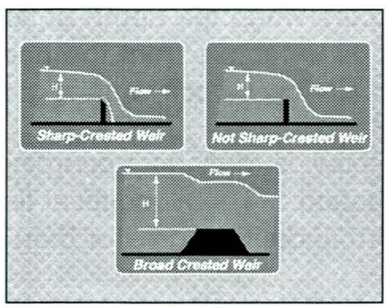
3.7 WEIR AND ORIFICE FLOW

WEIRS

- TYPICALLY A NOTCH OF REGULAR SHAPE
- WEIR CREST IS THE EDGE OR SURFACE OVER WHICH WATER FLOWS

3.14

A. A weir is typically a notch of regular shape (rectangular, square, or triangular) with a free surface.
   - the edge or surface over which water flows is called the crest
   - a weir with a crest where the water springs free of the crest at the upstream side is called a sharp-crested weir



3.15

- if water does not spring free and the crest length is short, the weir is called a not sharp-crested weir, round edge weir, or suppressed weir
- if the weir has a horizontal or sloping crest sufficiently long in the direction of flow that the flow distribution is hydrostatic it is called a broad-crested weir

WEIR EQUATION

- DISCHARGE ACROSS A WEIR:

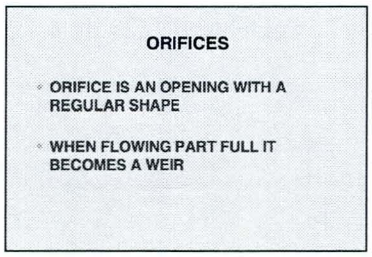
$$Q = C_D L H^{3/2}$$

3.16

- the discharge across a weir (sharp-crested or broad-crested) is:

$$Q = C_D L H^{3/2} \qquad \text{3-9}$$

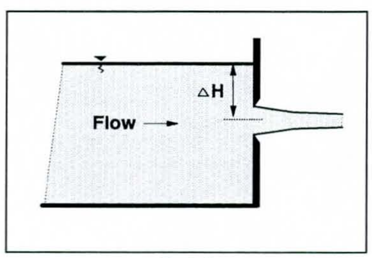
where Q = discharge (cfs)
C_D = coefficient of discharge for weirs
L = flow length along the weir (ft)
H = the depth of flow above the weir crest (ft), typically measured a distance 2.5H upstream of the weir



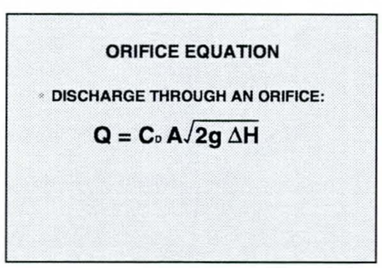
3.17

B. An orifice is an opening with a regular shape (circular, square or rectangular) through which water flows in contact with the total perimeter.

- if the opening is flowing only partially full, the orifice becomes a weir
- an orifice with a sharp upstream edge is called a sharp-crested weir



3.18



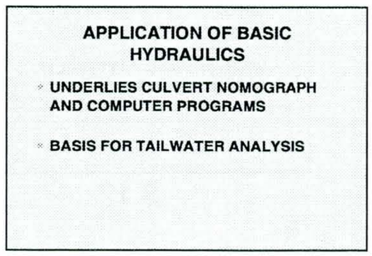
3.19

the discharge through an orifice is:

$$Q = C_D A\sqrt{2g\,\Delta H} \quad \text{.......... 3-10}$$

where Q = discharge (cfs)
C_D = coefficient of discharge for orifices
A = area of the orifice (ft^2)
g = acceleration of gravity (32.2 ft/s^2)
ΔH = difference in head across the orifice (ft)

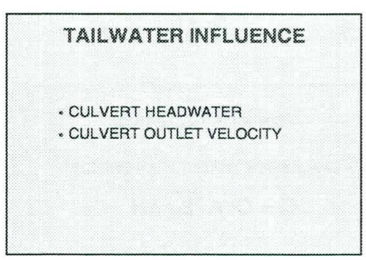
3.8. APPLICATION OF BASIC HYDRAULICS IN CULVERT DESIGN



3.20

The application of basic hydraulic concepts and equations, as reviewed above, is essential in any culvert design. These basic equations and concepts underlie the culvert nomographs and computer programs that are used in design. The proper application, understanding and interpretation of the design results is predicated on a comprehensive understanding of these basic principles and equations.

Additionally, the application of basic hydraulics is necessary to evaluate the tailwater conditions in the channel downstream of the culvert. The tailwater level may be influential on both the headwater and the outlet velocity characteristics of the culvert flow.



3.21

A. Influence On Culvert Headwater

Depending upon the conditions of flow through the culvert, the headwater required to force water through the culvert may be directly influenced by the level of the tailwater.

B. Influence On Outlet Velocity

- Culvert outlet velocity may be directly controlled or at least affected by the tailwater level.
- In some instances for inlet control, the tailwater can cause a hydraulic jump. Velocity is affected directly in such instances.

C. Strategies for defining tailwater conditions

TAILWATER STRATEGIES

- MEASURED RATING CURVE
- NEGLIGIBLE TAILWATER
- CONSTANT TAILWATER LEVEL
- STAGE-DISCHARGE CURVE

3.22

1. Measured Rating Curve

   If measured data is available, a rating curve may be used to describe the tailwater characteristics.

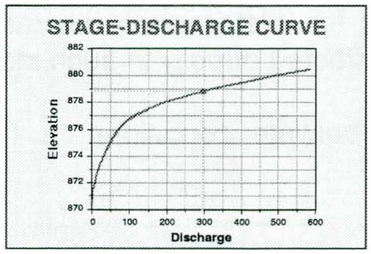
2. Negligible Tailwater

   Where flow is not concentrated or there is small discharge with indefinite outfall channels, tailwater may be found or assumed as negligible.

3. Constant Tailwater Level

- In instances of irrigation channels or constant level outfall situations, a constant value for the tailwater may be used.
- A properly developed culvert performance curve usually should be supported by a stage-discharge relationship.

4. Stage vs. Discharge Curve



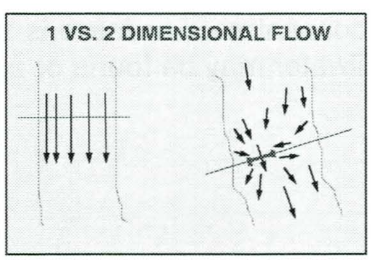
3.23

When a measured rating curve does not exist and tailwater may not be neglected or assumed constant, it usually is necessary to develop a stage-discharge curve.

Estimating a stage vs. discharge curve requires some simplifying assumptions. The difficulty in making a channel analysis is associated with the highly variable nature of flow during flood events. There are wide variations in:

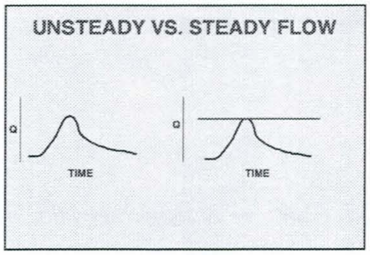
- directions of flow,
- resistance to flow,
- and channel geometry.

- One dimensional flow usually is assumed.



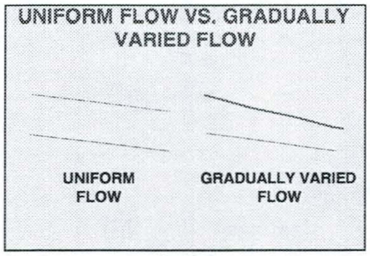
3.24

- Steady flow usually is assumed.

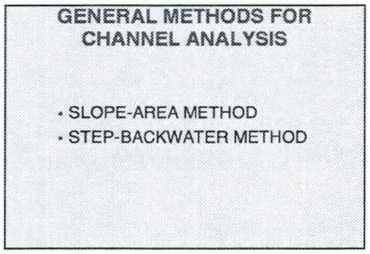


3.25

- Uniform flow may be assumed in many instances.



3.26



3.27

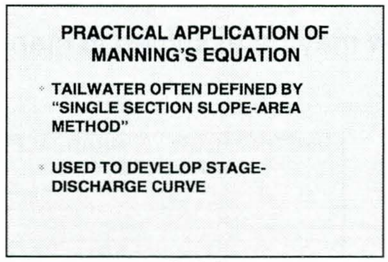
a. Slope area Method (application of Manning's equation)

The use of the slope-area method depends upon an assumption of uniform flow in the channel. The analysis is based on the Manning's Equation.

b. Step-backwater Method

The step-backwater method can be used to develop gradually varied backwater profiles which can be used as bases for a stage-discharge curve.

3.9 PRACTICAL APPLICATION OF THE MANNING'S EQUATION



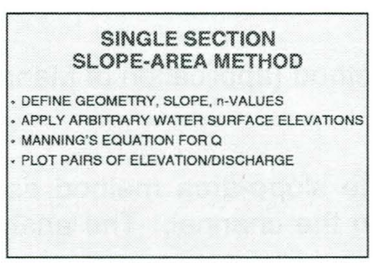
3.28

Most culvert designs merit a relatively simple approach for estimating stage-discharge relations. The single section slope-area method, based on the Manning's equation, is straightforward and simple.

A. General Approach

Manning's equation does not allow a direct solution of depth of flow, given the discharge. For this reason, either an iterative or graphical solution is necessary. The stage-discharge curve represents a graphical solution.

B. Slope-area Procedure Illustration

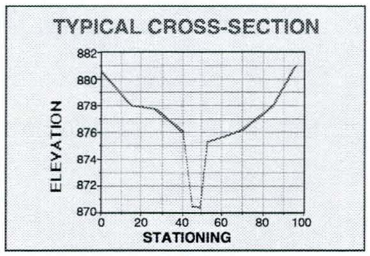


3.29

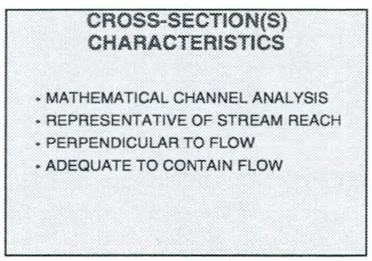
- Using a typical representation of the channel downstream of the culvert, define the geometry, longitudinal slope, and roughness characteristics.

- Apply arbitrary water surface elevations to the typical cross-section, calculating total discharges using Manning's Equation (across the cross-section).
- Plot or tabulate the assumed elevations with respect to their associated total discharges. This will constitute the stage-discharge curve.
- For each subject discharge; graphically (or by tabular interpolation) extract the associated water surface elevation.

C. Typical Cross-sections



3.30



3.31

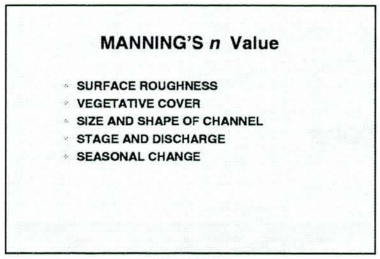
Typical cross-sections used for channel analysis with Manning's Equation should be:

- Used when a mathematical channel analysis is to be made.
- Representative of the subject stream reach.
- Oriented normal (perpendicular) to the flow at flood stage.
- Adequate to contain flow.

D. Roughness Characteristics

The roughness characteristics or elements which resist flow are quantified in Manning's Equation as the "n-value".

a. Influences on the n-value



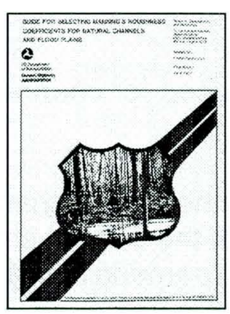
3.32

The roughness coefficient "n" is significant in Manning's Equation and varies with:

- surface roughness,
- vegetative cover,
- size and shape of channel,
- stage and discharge,
- seasonal change,

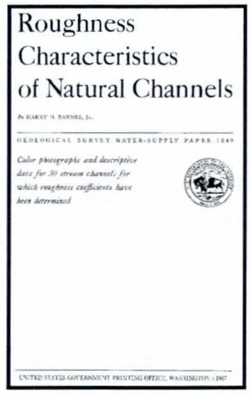
b. Methods of n-value Assignment.

- Designers usually rely upon guide tables and experience
- FHWA HDS No. 3, "Design Charts for Open-Channel Flow"



3.33a

- Useful systematic approach in Report No. FHWA-TS-84-204, "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains".

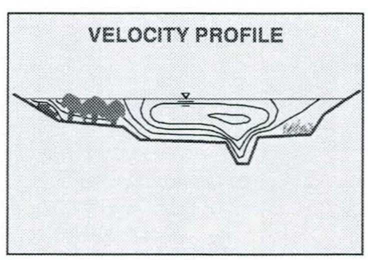


3.33b

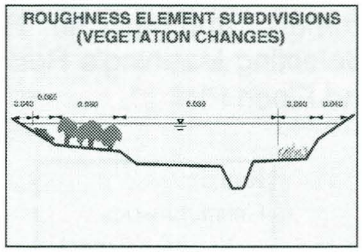
- USGS. Water-Supply Paper 1849, "Roughness Characteristics of Natural Channels", Harry H. Barnes, Jr.
- The n-value assignment is subjective.

c. Subdivision n-value Assignment

In order to simulate actual flow conditions and the velocity variations accurately, and to avoid discontinuity in the stage-discharge curve, it usually is necessary to subdivide a cross-section on the basis of roughness elements and geometry.

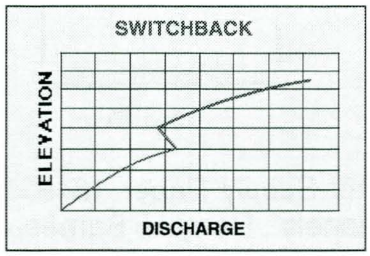


3.34



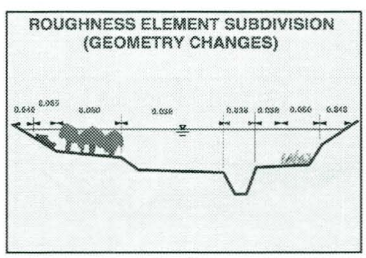
3.35

If the typical cross-section is improperly subdivided, a discontinuity (known as a switchback) in the stage-discharge curve may appear. A switchback can occur.



3.36

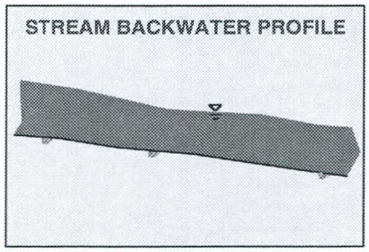
In a switchback, the discharge appears to decrease with an associated increase in elevation. With a minor increase in water depth, there is a large increase of wetted perimeter. Simultaneously, there is a small increase in cross-sectional area This results in a net decrease in the hydraulic radius. The combination of the lower hydraulic radius and the slightly larger cross-sectional area, may cause a discontinuity in the discharge or conveyance.



3.37

- More subdivisions within the cross-sections should be used in order to avoid this discontinuity.
- The cross-section usually should be subdivided with respect to both vegetation and geometric changes.

3.10. WATER SURFACE PROFILES



3.38

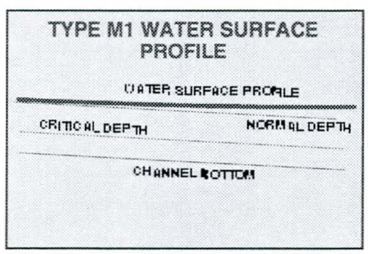
A. When a uniform flow assumption and the application of Manning's equation is not appropriate, the gradually varied flow water surface profile must be calculated.

B. Several different types of water surface profiles are possible for natural stream flow. The type of profile is governed by the flow's position on the specific energy diagram. This may be determined by comparison of critical depth of flow and normal depth of flow.

C. Subcritical Flow in the Channel

   1. Mild Slope Streams

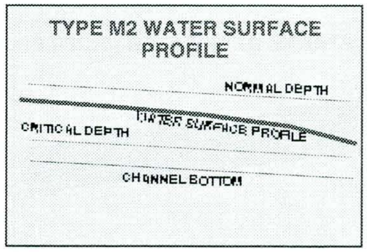
   2. M1 Backwater Curve



3.39

The M1 backwater curve occurs as backwater from a location where flow is impeded (for example, the impoundment in a reservoir). The downstream depth is greater than normal depth in the channel.

3. M2 Backwater Curve



3.40

The M2 backwater curve occurs where the downstream control section represents a "free fall" situation. The downstream depth is less than normal depth but greater than critical depth in the channel.

4. Backwater Control

Mild slope curves are controlled by downstream conditions. Therefore, water surface profiles must be calculated from downstream to upstream.

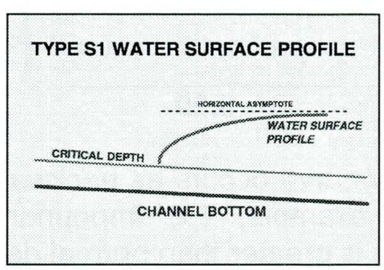
5. M Curve Tendencies

Curves tend to approach and converge with normal depth of flow for the channel (from the downstream direction).

D. Supercritical Flow in the Channel.

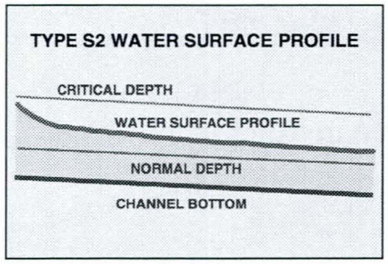
1. Steep Slope Streams

2. S1 Backwater Curve



3.41a

2. S2 Backwater Curve



3.41b

The S2 backwater curve is the most commonly encountered of the supercritical water surface profiles.

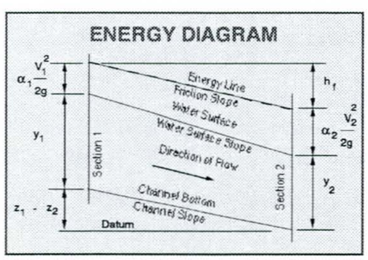
3. Upstream Control

Supercritical backwater surface profiles must be calculated from upstream to downstream.

4. S Curve Tendencies

The water surface profile for an S2 backwater curve tends to approach and converge with normal depth of flow for the channel (from the upstream direction).

E. A gradually varied water surface profile can be estimated by the standard step-backwater method of channel analysis. Gradually varied flow is a type of non-uniform flow in which the area of the stream cross-section changes so slowly that the energy losses can be computed for various reaches in the same manner as for uniform flow. Therefore, apply the step-backwater method when uniform flow cannot be assumed.



3.42

The energy diagram of two adjacent cross-sections in a stream reach illustrates the constituents and relationships of the various parameters in the Energy Equation.

1. Procedure

   a. Direction of Computations

      - Calculate in an upstream direction for subcritical flow.
      - Calculate in a downstream direction for supercritical flow.

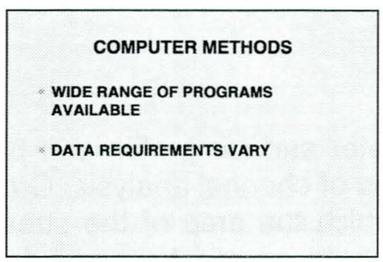
   b. Beginning Elevation

      A known (or assumed) water surface elevation must be used as a starting point.

2. Data Requirements

   The step-backwater method is a data intensive method. Cross-section geometries, stream reach distances, and roughness characteristics are necessary for computation.

3.11. COMPUTER METHODS

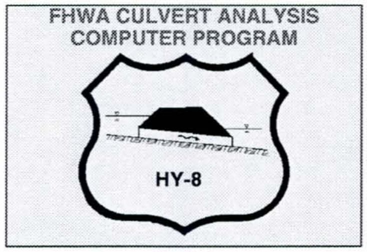


3.43

Computer methods for channel flow analysis vary from simple slope-area methods to highly sophisticated two-dimensional flow analysis.

The character, quantity, and quality of the data required for each channel flow computer model varies considerably. For most culvert design situations, themost productive and usually justifiable method is the single section slope area method.

A. Single Section Slope Area Analysis with HY-8



3.44

The single section slope-area method algorithm in the computer program HY-8 is effective and productive for typical culvert design. The method is useful if uniform flow can be assumed.

1. HY-8 Options

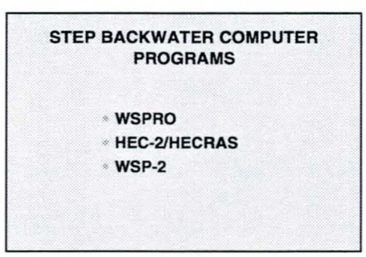
   Within HY-8, there are several different approaches available; ranging from:

   - Simple assignment of a single tailwater level associated with a single discharge.
   - Up to a more comprehensive stage vs. discharge development algorithm which may require a moderate amount of input data.

2. Embedded Algorithm

   The single section slope-area algorithm in HY-8 is accessible after supplying various data concerning a culvert analysis.

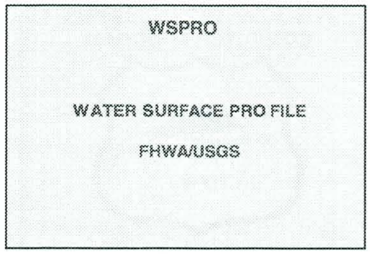
B. Step Backwater Computer Programs



3.45

The intensive data manipulation involved in the step-backwater method has led to the development of several useful computer programs.

1. WSPRO



3.46

Developed by FHWA and US Geological Survey. WSPRO (**W**ater **S**urface **Pro**file) was specifically developed for use in highway drainage analysis.

2. HEC-2/HECRAS

These programs were developed and are administered by the US. Army Corps of Engineers. HECRAS is a newer windows based version with improved calculation features, such as calculating both subcritical and supercritical profiles within the same reach.

3. WSP-2

Developed and administered by the Soil Conservation Service

4. Training Requirements

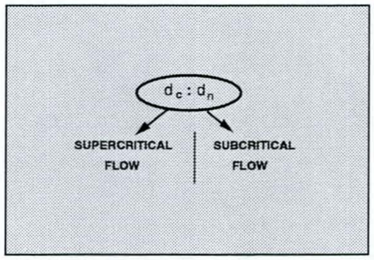
WSPRO requires extensive input and some training and/or experience of the user for successful application.

5. Use for Culvert Design

Most routine culvert design developments do not justify the use of WSPRO.

3.12 WORKSHOP 3A - CRITICAL/NORMAL DEPTHS

FLOW TYPE DETERMINATION



Differentiation of flow between supercritical and subcritical is possible by comparing critical depth (d_c) and normal depth (d_n).

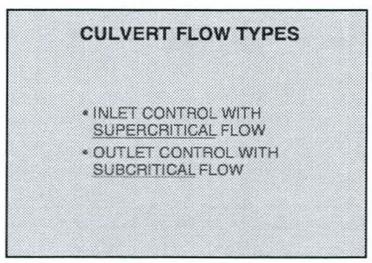
A. Supercritical Flow

Technically, if $d_c > d_n$, there is supercritical flow.

- Usually, supercritical flow implies inlet control in the culvert hydraulics for the subject discharge.
- In some instances, slug flow may occur.

B. Subcritical Flow

Technically, if $d_c < d_n$, there is subcritical flow.



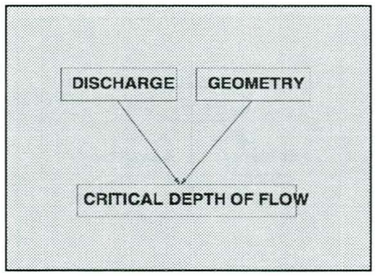
Subcritical flow always indicates an outlet control situation for the subject discharge.

C. Threshold - Supercritical/Subcritical Flow

In general, if normal depth of flow is within about 5% of critical depth of flow, the distinction between supercritical flow and subcritical flow is not clear. Reference to the energy head diagram will confirm this. In such an unclear situation, culvert hydraulics may fluctuate between inlet control and outlet control. This is called slug flow.

REVIEW OF DEFINITIONS - CRITICAL AND NORMAL DEPTHS

A. Critical Depth of Flow



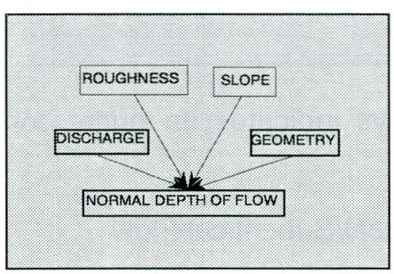
Critical depth of flow is a function of discharge and geometry alone. The general equation for critical flow (equation 3-5) can be manipulated algebraically for a rectangular cross-section (box culvert) to allow direct solution for the critical depth (d_c):

$$d_c = \sqrt[3]{\frac{q^2}{g}}$$

where: q = Q/W (discharge per foot of width of the box culvert) (cfs/ft),
g = Acceleration due to gravity (32.2 ft/s^2).

Manipulation of the critical flow equation (Equation 3-5) for other shapes such as circular and arch-pipe yield indeterminate relations which require iterative solution. Alternatively, graphical solutions can be used (e.g. Chart 4, HDS#5 or various charts provided in HDS #3), or various computer programs are available and can be used to solve for critical depth in different geometrical cross sections.

B. Normal Depth of Flow



Normal depth is a function of discharge, geometry, roughness characteristics, and slope of the conduit. Using Manning's equation for uniform flow, an iterative procedure is necessary to solve for normal depth of flow.

The Manning's Equation can be rearranged so that geometric parameters appear on one side of the equation. The other side of the equation comprises constant values which can be converted to a single constant value.

$$A\,R^{2/3} = \frac{Q\,n}{1.49\,S^{1/2}} = \text{Constant Value (K)}$$

By iteration, try various depths of flow which can be used to develop area (A) and hydraulic radius (R) until a tolerable match between $A\,R^{2/3}$ and the Constant Value (K) is made.

A graphical solution for normal depth is possible by use of an appropriate chart in HDS #3.

CRITICAL DEPTH PROBLEMS

Critical depth of flow may be determined directly for rectangular shapes by use the equation provided above. Chart No. 14 in HDS#5 is a graphical depiction of this equation.

Critical depth of flow for circular and other shapes requires an iterative solution of a form of the general critical flow equation (3-5). Chart No. 4 in HDS#5 can be used for this determination for circular pipe. HDS#3 also can be used for such determinations.

A. Rectangular Shape

Find the critical depth of flow for a box culvert with a span = 8 feet and rise = 6 feet for discharges of 100, 200, and 400 cfs.

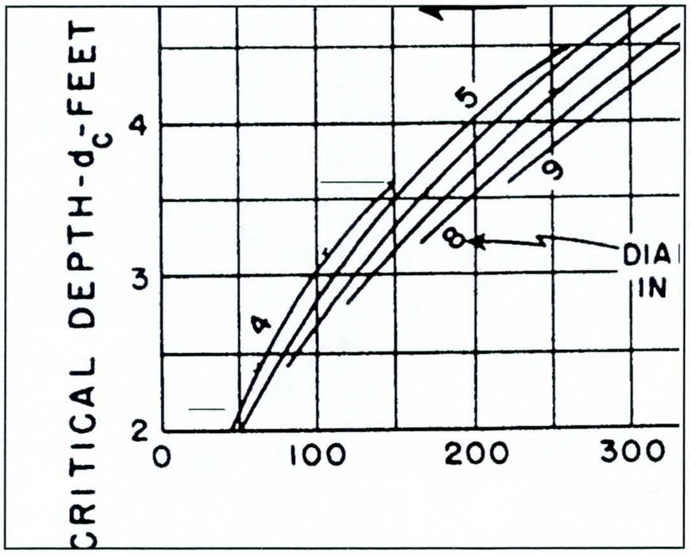
Use the equation:

$$d_c = \sqrt[3]{\frac{q^2}{g}}$$

B. Circular Shape

Find the critical depth of flow for a circular concrete pipe, diameter = 48" for discharges 50, 100, and 150 cfs.

Use Chart 4 in HDS#5 or Chart 56 in HDS#3:



NORMAL DEPTH PROBLEMS

Normal depth of flow must be determined by an iterative or graphic solution to Manning's Equation. Graphic solutions to Manning's Equation for several culvert barrel shapes are found in HDS#3.

A. Rectangular Shape

Find the normal depth of flow for a box culvert with dimensions span = 8 feet and rise = 6 feet for a discharge of 100 cfs. Culvert slope = 0.002 ft/ft. Use an n value (Manning's roughness coefficient) of 0.012 for this problem.

A mathematical rearrangement of Manning's Equation for this determination is

$$\frac{Q\,n}{1.486\,S^{1/2}} = A\,R^{2/3} = K = \frac{(W\,d_n)^{5/3}}{(2d_n + W)^{2/3}}$$

K=

This relation requires an iterative solution for d_n.

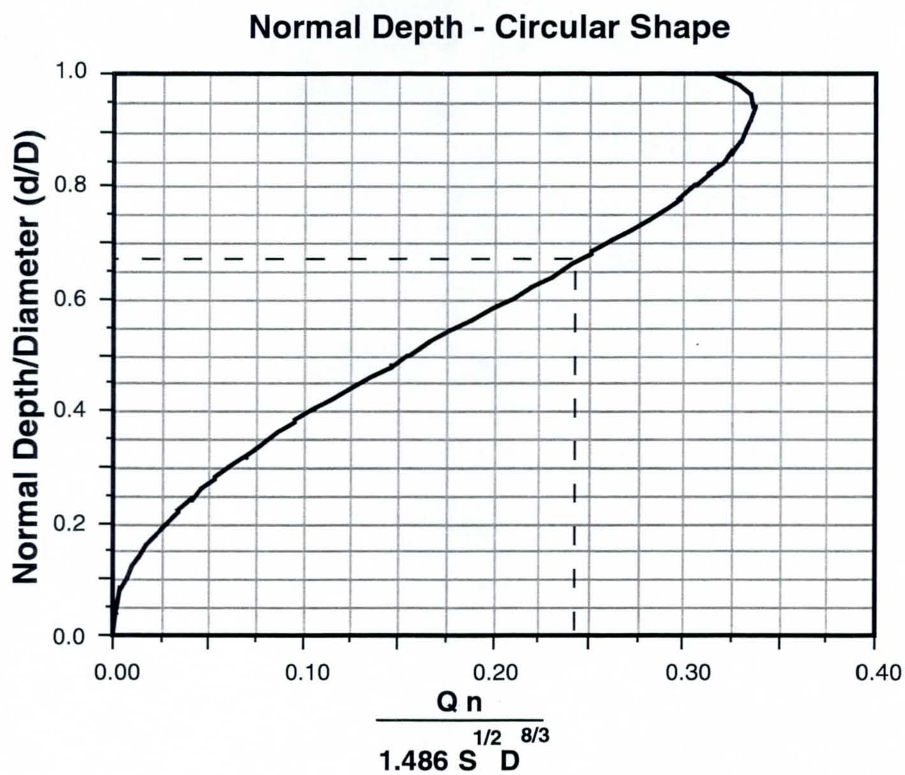
Use the following table for the iterative calculations necessary.

d_n	$(Wd_n)^{5/3}$	$(2d_n + W)^{2/3}$	K(trial)	d_c

B. Circular Shape

Find the normal depth of flow for a circular concrete pipe, diameter = 48" for discharges 50, 100, and 150 cfs. Culvert slope - 0.006 ft/ft.

Use the following chart as one means for determination of normal depth of flow for a circular shape. Other charts are available for this solution in HDS#3.



Example:
Q = 10 cfs, n = 0.013, S = 0.001 ft/ft, diameter = 30" (2.5 ft)

Abscissa value = 0.24
Normal depth / Diameter = 0.67
Normal depth of flow = 0.67 x 2.5 = 1.68'

CALCULATIONS

DISCUSSION OF OTHER SHAPES

The solution of critical depth and normal depth for most other commonly used culvert shapes is based similarly. Iterative or graphical methods are usually necessary. Iterative solutions are simple for computer calculations. HY-8 builds a table of values in D/10 increments.

Graphical solutions to the indeterminate equations for critical depth and normal depth for various barrel shapes may be found in HDS#3.

A. Critical Depth

The basis for critical depth for any shape is associated with the general critical flow equation, (Equation 3-5). Usually, some iterative process based upon this equation must be devised and used for critical depth of flow determination.

B. Normal Depth

The basis for normal depth for any shape is Manning's Equation. Usually, some iterative process based upon this equation must be devised and used for normal depth of flow determination.

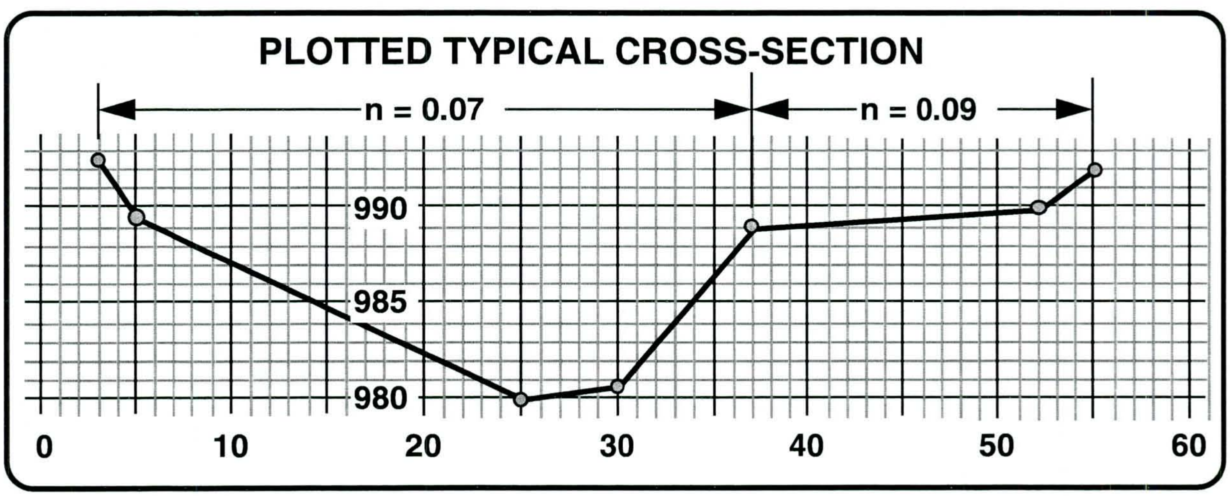
3.13. WORKSHOP 3B - SLOPE AREA METHOD

Problem Statement

An irregular, heavily vegetated channel exists at the downstream end of a culvert to be designed. The slope of the channel in this reach of stream is estimated by reference to the contours on a USGS 15 minute quadrangle as 0.07% (0.0007 ft/ft). A culvert will be designed and a performance curve will be developed covering discharges ranging from Q_2 = 100 cfs to Q_{100} = 500 cfs. Based upon a field survey, the coordinate points of the typical section best representing the conditions at this site are as follows:

Point	Station	Elevation
1	3	992.5
2	5	989.5
3	25	980.0
4	30	980.7
5	37	989.0
6	52	990.0
7	55	992.0

The points are plotted below at a vertical and horizontal scale of 1" = 10' for convenience in measuring areas and wetted perimeters.



Reference is made to Table 11 in HDS#5 to estimate Manning's n-value for the main channel (from point 1 to 5) at 0.07. The estimated n-value for the right overbank (from point 5 to 7) is 0.09 from FHWA TS-84-204.

By means of the single-section slope-area method, develop and construct a stage-discharge curve for this channel location. Begin with an assumed water surface elevation of 984.0 and use 2 foot elevation increments for additional calculations. The water surface elevations for the various discharges then can be extracted for use in the culvert performance curve development.

DISCUSSION

A. Slope-Area Method Basis

This method is based upon the use of the Manning's Equation, a uniform flow equation involving channel characteristics, water-surface profiles, and roughness coefficients. Manning's Equation was developed to describe uniform flow in which the water surface profile and the energy gradient are parallel to the stream bed. Furthermore, Manning's Equation assumes no change in area, hydraulic radius, nor depth throughout a given reach. Natural channels rarely, if ever, present such a set of circumstances. Therefore, since there is no reasonable alternative, it is assumed that Manning's Equation is valid for application to natural channels.

Given a discharge, Manning's Equation is indeterminate for depth of flow. Therefore, its use depends on a series of assumed depths of flow from which associated total discharges are derived. This series of assumed water surface elevations with their associated discharges calculated by use of Manning's Equation comprises a "stage vs. discharge" curve. Such a curve can be used very productively in comprehensive culvert design, particularly when a culvert hydraulics performance curve is to be developed.

B. Uses and Limitations

- Useful if uniform flow is assumed.
- Simple in application.
- Used by USGS for indirect measurement calculations.
- Results susceptible to water surface slope, calculation cross-section, and subjectivity of roughness coefficient (n-value) assignment.
- Usually reliable enough for most culvert designs/analyses.

C. Conveyance Calculations

Manning's Equation

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2}$$

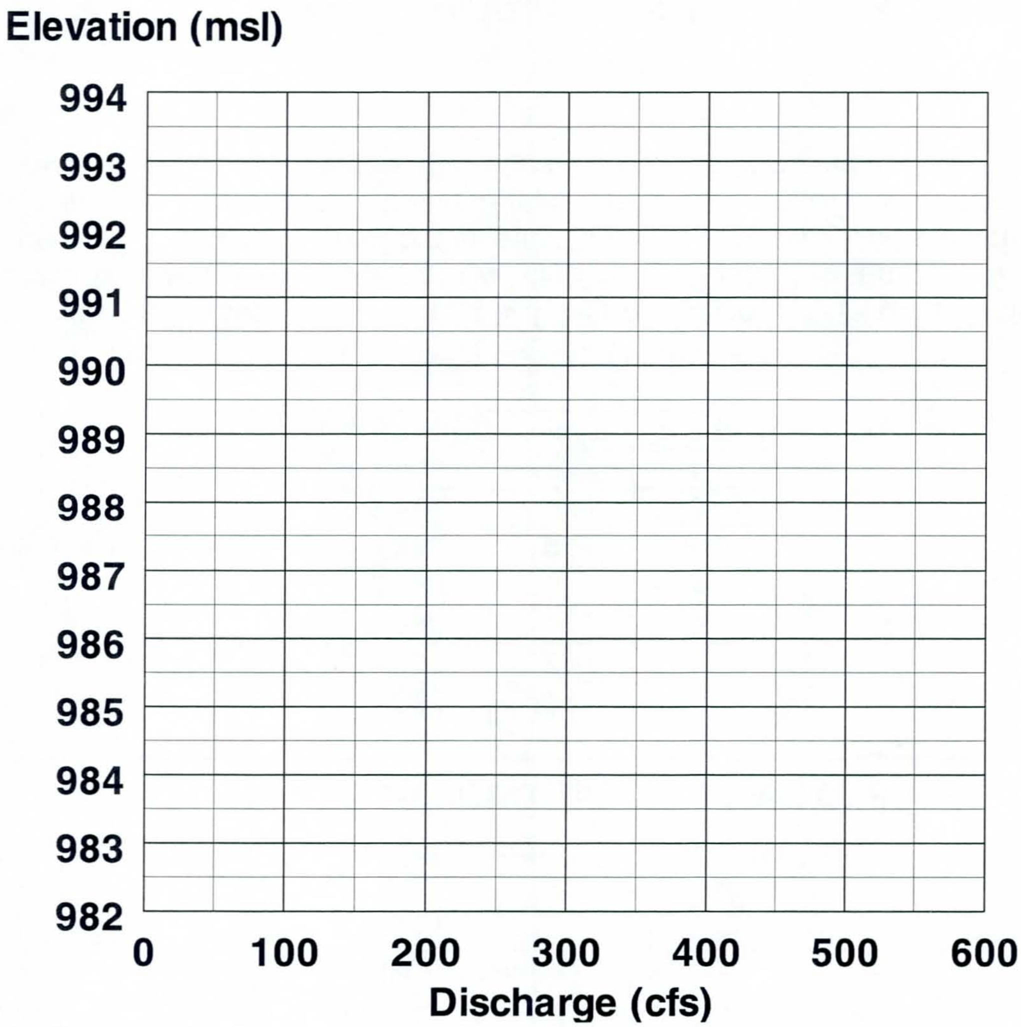
where:
Q = discharge (cfs),
n = roughness coefficient (dimensionless),
A = cross-sectional area of flow (ft^2),
R = hydraulic radius (A divided by wetted perimeter) (ft),
S = longitudinal slope of water surface (ft/ft).

D. Procedure

- Assume a series of water surface elevations to be imposed on the calculation cross-section.
- For each assumed water surface elevation:
  - Calculate the cross-sectional area of flow, wetted perimeter, and hydraulic radius for each subdivision of the cross-section.
  - For each subdivision use the applicable n-value in Manning's Equation and calculate the subdivision discharge increment.
  - Total all subdivision discharge increments to represent the total discharge for each assumed water surface elevation.

Elev	A_{s1}	WP_{s1}	R_{s1}	Q_{s1}	A_{s2}	WP_{s2}	R_{s2}	Q_{s2}	Q_{Total}
984.0	*39.7*	*18.7*			-	-	-	-	
986.0	*78.0*	*26.0*			-	-	-	-	
988.0	*128.1*	*33.2*			-	-	-	-	
990.0	*189.4*	*38.6*			*7.5*	*15.0*			
992.0	*255.4*	*41.1*			*40.5*	*18.6*			

- Tabulate or plot (on linear graph provided below) each pair of assumed water surface elevation/calculated discharge to form a stage-discharge relationship.

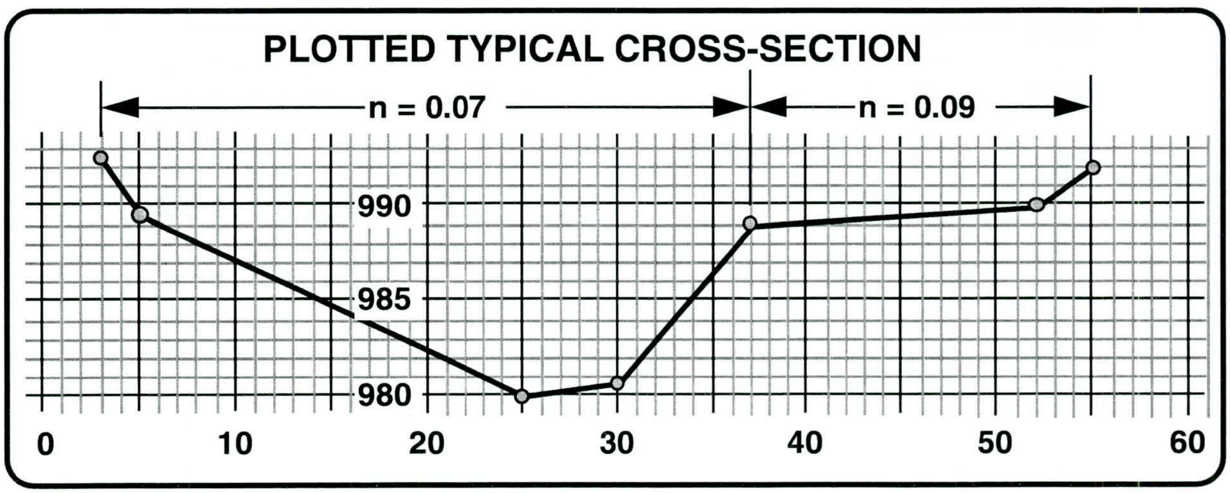

Elevation (msl)
994
993
992
991
990
989
988
987
986
985
984
983
982
0
100
200
300
400
500
600
Discharge (cfs)

3.14. WORKSHOP 3C - SLOPE AREA METHOD BY HY-8

Problem Statement

Using the same data as in Workshop 3B, access the slope-area algorithm contained in HY-8 and perform the same calculations. This will be demonstrated. The slope of the channel is 0.07% (0.0007 ft/ft). A culvert will be designed and a performance curve will be developed covering discharges ranging from Q_2 = 100 cfs to Q_{100} = 500 cfs. The coordinate points of the typical section best representing the conditions at this site are as before:

Point	Station	Elevation
1	3	992.5
2	5	989.5
3	25	980.0
4	30	980.7
5	37	989.0
6	52	990.0
7	55	992.0



The roughness coefficients are estimated at 0.07 for the main channel and 0.09 for the right overbank.

Discussion

A. Culvert Analysis/Design

The program (HY-8) is written to accommodate culvert hydraulic analysis and design.

The tailwater algorithm within HY-8 consists of several options and is encountered by menu after the specification of certain basic parameters for culvert analysis. The program first displays screens which allow the input of:

- minimum discharge,
- design discharge,
- maximum discharge,
- embankment toe or culvert invert data,
- specifications for the type of site data,
- culvert shape,
- culvert dimensions,
- culvert material,
- culvert inlet type,
- culvert inlet condition,
- ending with a data summary.

In order to facilitate the demonstration, necessary input (to be discussed in subsequent lessons) will be provided to bring the program to the tailwater algorithm.

B. Tailwater Option Screen

A tailwater rating curve option screen is then offered. There are six choices.

```
TAILWATER RATING CURVE

PRESS NUMBER OF OPTION

<1>      RECTANGULAR CHANNEL

<2>      TRAPEZOIDAL CHANNEL

<3>      TRIANGULAR CHANNEL

<4>      IRREGULAR CHANNEL (MAX. 15 COORDINATES)

<5>      ENTER RATING CURVE (11 POINTS)

<6>      ENTER CONSTANT TAILWATER ELEVATION
```

- Rectangular channel - This could be a simple box shaped channel or a simulation of a channel into the rectangular form.
- Trapezoidal channel - This is one of the most common types of constructed channels because of its hydraulic effectiveness, economy, and ease of maintenance.
- Triangular channel - Often used for median ditches and other conveyances where discharges are relatively small.
- Irregular channel - This option allows up to 15 ground points (or coordinates) to define the shape of the channel.

  - Natural channels associated with culvert design can usually be described with this option.
  - ***For this workshop, this will be the option selected.***
- Enter rating curve - An 11 point rating curve can be entered if already known (or assumed). Usually, a measured rating curve will not be known, but there may be circumstances where one could be assumed reliably.
- Enter constant tailwater elevation - This option should be used with care because the tailwater level has a great influence on most culvert hydraulics.
  - If a constant pool level in the channel is anticipated.
  - If a very low depth for the full range of discharges is anticipated.

C. Create File

A file will be established under a user-specified name (or an existing file could be edited).

```
IRREGULAR CHANNEL MENU


PRESS LETTER OF CHOICE

<E>   EDIT OR USE EXISTING TAILWATER

<C>   CREATE A TAILWATER FILE


<ESC>   TO RETURN TO MAIN PROGRAM MENU
```

The file name for this demonstration will be SLP-AREA.TW.

D. Channel Data Screen

```
NO.          ITEM                                       VALUE
<1>   SLOPE OF CHANNEL (FT/FT)                          0.0007

<2>   NUMBER OF CROSS-SECTION COORDINATES
           (MAX = 15, MIN = 3)                            7

<3>   SUBCHANNEL OPTION (4 POSSIBLE)                      3
     (1)   LEFT OVER BANK AND MAIN CHANNEL
     (2)   LT & RT OVER BANKS & MAIN CHANNEL
     (3)   RIGHT OVER BANK AND MAIN CHANNEL
     (4)   SINGLE MAIN CHANNEL

COORDINATE NUMBER OF CHANNEL BOUNDARIES
                              LEFT OVERBANK         0
                              RIGHT OVERBANK        5

                 <NUMBER>  TO EDIT ITEM
                  <ENTER>  TO CONTINUE
```

- slope,
- number of cross-section coordinates,
- subchannel option;
  - left overbank and main channel,
  - left and right overbanks and main channel,
- right overbank and main channel,
- single main channel,
- coordinate numbers. This option will define the left and right overbanks and the main channel to assign the corresponding Manning's n-values.
- Note that many screens have additional options at the bottom of the menu. One of the more useful of these is the data revision option.

E. Coordinates

The user then can specify the X and Y values.

```
     IRREGULAR CHANNEL CROSS-SECTION
CROSS-SECTION          X           Y
COORD. NUMBER         (FT)        (FT)

    1                  3.00      992.50
    2                  5.00      989.50
    3                 25.00      980.00
    4                 30.00      980.70
    5                 37.00      989.00
    6                 52.00      990.00
    7                 55.00      992.00

     <NUMBER>    TO EDIT COORDINATES
     <I>  <D>    TO INSERT OR DELETE
      <ENTER>    TO CONTINUE
          <P>    TO PLOT CROSS-SECTION
```

- X = horizontal distance from one side within cross-section
- Y = elevation above some specified datum, (usually mean sea level).

F. Manning's n-values

The Manning's n-values for the respective subchannels are input on the next screen.

```
              MANNING'S N MENU
        (NORMAL N VALUES 0.001 TO 0.2)

  NO.              ITEM                 VALUE

  (2)    MANNING N MAIN CHANNEL          .07
  (3)    MANNING N RIGHT OVER BANK       .09

           <NUMBER>  TO EDIT ITEM
            <ENTER>  TO CONTINUE
```

G. Computation Mode

The final screen before calculation allows the choice of:

- Simple computation of a stage vs. discharge curve (termed rating curve).
- Curve Computation/Interpolation

The interpolated values are based on the user's specification of a particular discharge to obtain the water surface elevation, shear stress or velocity, or to specify a particular elevation to obtain discharge..

Output Screen

A. Compute Stage-Discharge Curve

For this workshop, the choice will be the simple computation of a stage vs. discharge curve. The resulting tabulation lists eleven points, including the specified design discharge, on the generated curve:

```
                IRREGULAR CHANNEL FILE: SLP-AREA

NO.    FLOW(CFS)    T.W.E.(FT)    DEPTH(FT)   VEL.(FPS)    SHEAR(PSF)
 1       0.00        980.00         0.00        0.00          0.00
 2      50.00        984.64         4.63        1.01          0.11
 3     100.00        986.27         6.27        1.20          0.14
 4     150.00        987.48         7.47        1.33          0.16
 5     200.00        988.46         8.45        1.43          0.18
 6     250.00        989.27         9.26        1.51          0.19
 7     300.00        989.91         9.91        1.61          0.21
 8     350.00        990.46        10.46        1.69          0.23
 9     400.00        990.97        10.96        1.76          0.24
10     450.00        991.44        11.43        1.83          0.26
11     500.00        991.89        11.89        1.89          0.27

             PRESS:
                <D>     FOR DATA
                <P>     TO PLOT RATING CURVE
              <ESC>     FOR CHANNEL SHAPE MENU
            <ENTER>     TO CONTINUE
```

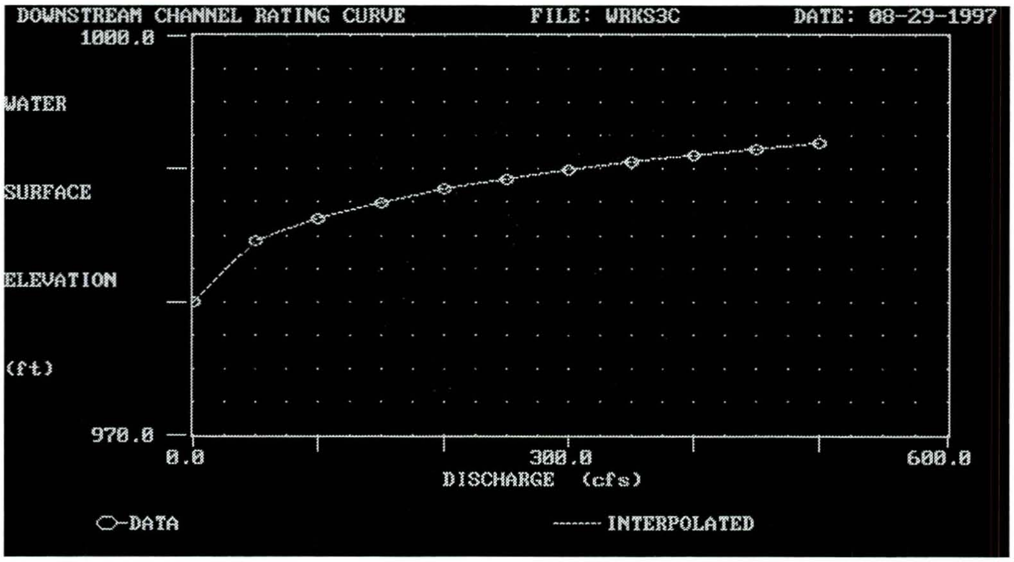
- Flow
  - The flow increments are in arbitrary 10% increments.
  - The specified design discharge is listed in place of the next 10% increment.
- Tailwater Elevation (T.W.E.) - The algorithm iterates calculations to 'home in' on an elevation corresponding to the 10% increment of discharge or the specified discharge, as the case may be.
- Depth (ft) - The difference between the T.W.E. and the low point in the cross-section is given here.
- Velocity - Based upon the simple calculation of discharge divided by cross-sectional area of flow.
- Shear - This is the boundary shear stress defined as γRS

where: γ = specific gravity of water (62.4 lb/ft^3),
R = hydraulic radius (ft),
S = slope of the channel (ft/ft).

The boundary shear stress should be compared with the critical shear stress (from HEC-15) to determine whether or not an energy dissipator or rock riprap is needed in the channel.

B. Stage-Discharge Plot

The program will generate an onscreen plot of water surface elevations vs. discharges. Rescaling of both the ordinate and abscissa for screen plots are possible within HY-8.



3.15. WORKSHOP 3D - DEMONSTRATION FLUME

CONTINUITY AND MANNING'S EQUATIONS

A steady, uniform flow condition will be created in the main channel of a compound channel section. The class will be divided into groups and each group will use a different procedure to estimate velocity and discharge:

1. Calculate the discharge from bucket/stop watch measurements and the velocity from the continuity equation.

2. Calculate the velocity from Manning's equation (n=0.009) and discharge from the continuity equation.

3. Calculate the velocity from float measurements and discharge from the continuity equation.

On the flip chart, write out the necessary equations and your solution. Be prepared to discuss your results and compare your answers with the other groups.

SUBDIVIDING CROSS SECTIONS

The discharge will be increased slightly, causing flow in the overbank of the compound section. The discharge and velocity will again be calculated from:

1. Bucket/stop watch measurements, and a float measurement with continuity.

2. Manning's equation without subdividing the cross section.

3. Manning's equation with subdividing of the cross section.

SUBCRITICAL, CRITICAL AND SUPERCRITICAL FLOW

To illustrate subcritical, critical, and supercritical flow conditions, a broad-crested weir will be inserted into the flow. The class will be divided into groups and each group will calculate the critical depth and evaluate flow conditions at different locations in the flume:

1. Calculate critical depth for the rectangular channel using

$$d_c = \sqrt[3]{\frac{q^2}{g}}$$

2. Compare the flow depth *before* the weir with the calculated critical depth and evaluate the flow condition.

3. Compare the flow depth *after* the weir with the calculated critical depth and evaluate the flow condition.

4. By measuring the flow depth along the weir, find where critical depth occurs.

WEIR AND ORIFICE FLOW

Both broad- and sharp-crested weir flow conditions will be demonstrated. By adjusting tailwater condition, both free overall and submerged weir flow conditions will be created. For a given discharge, the differences in headwater will be observed between broad- and sharp-crested weirs (remember that a sharp-crested weir is one where the water springs clear of the crest). The weir equation is $\mathbf{Q = C_D\, L\, H^{3/2}}$.

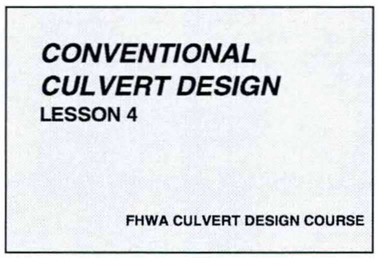
Orifice flow conditions will be demonstrated for a small orifice with a free discharge. For a given discharge, the change in headwater will be measured between a sharp-edged orifice and an orifice with a rounded inner face to illustrate the importance of inlet condition. The orifice equation is $\mathbf{Q = C_D\, A\sqrt{2g\,\Delta H}}$.

LESSON 4

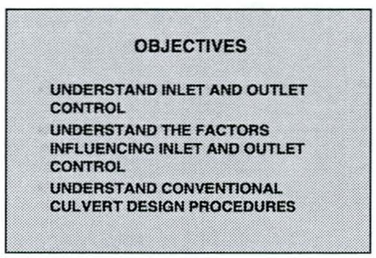
CONVENTIONAL CULVERT DESIGN

OVERVIEW:

Method of Instruction:	Lecture
Lesson Length:	90 minutes
Resources:	Student Workbook Graphics



4.0a



4.0b

OBJECTIVES: At the conclusion of this lesson, the participant shall be able to:

1. Understand the definitions of inlet and outlet control and the relationships to subcritical and supercritical flow.
2. Understand the factors that influence inlet and outlet control.
3. Understand conventional culvert design procedures.

LESSON OUTLINE

4. CONVENTIONAL CULVERT DESIGN

   4.1. INTRODUCTION

   4.2. CULVERT NOMENCLATURE

   4.3. ANALYSIS PROCEDURES

   4.4. INLET AND OUTLET CONTROL

   4.5. TYPES OF FLOW CONDITIONS IN INLET AND OUTLET CONTROL

   4.6. FACTORS INFLUENCING CULVERT PERFORMANCE

   4.7. FACTORS INFLUENCING OUTLET CONTROL

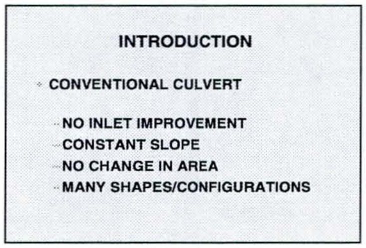
   4.8. FACTORS INFLUENCING INLET CONTROL

   4.9. CULVERT ANALYSIS - CONCEPTUAL EXAMPLE

   4.10. CULVERT DESIGN PROCEDURE

   4.11. WORKSHOP 4 - CONVENTIONAL CULVERT DESIGN

4.1 INTRODUCTION



4.1

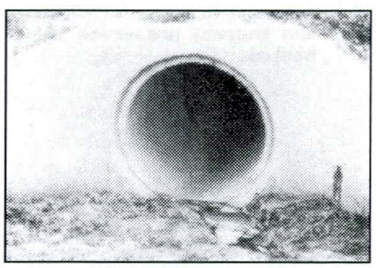
A. A conventional culvert is one that has had no significant effort directed at improving the inlet flow hydraulics.

B. Generally, they have an invert on a constant slope and have the same cross section thoughout the culvert length.

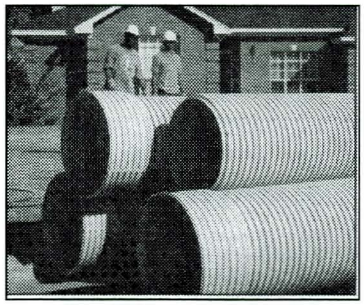
C. Culverts are manufactured using a variety of materials, and they are of many shapes and configurations:

Circular Culverts:

4.2a Circular CMP.

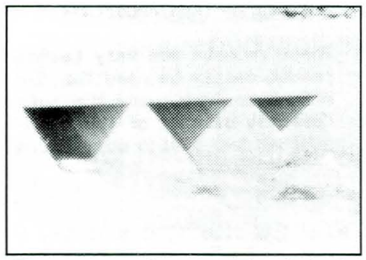


4.2b Circular concrete



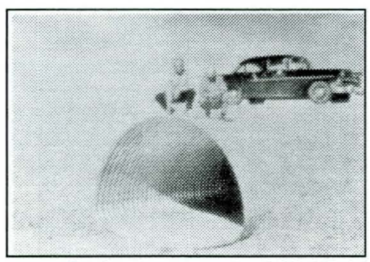
4.2c Circular Plastic

Box Culverts:



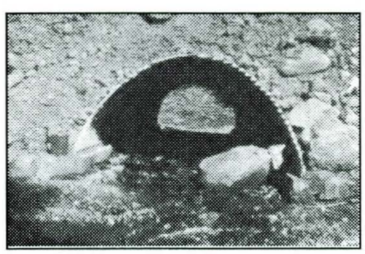
4.3 Concrete box with debris fins

Arch Culverts:



4.4 CM pipe arch (CMPA)

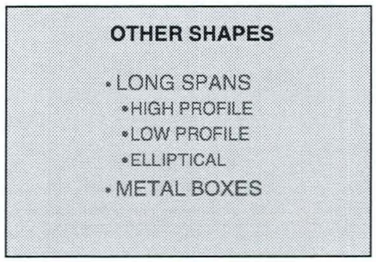
Open bottom arch culverts:



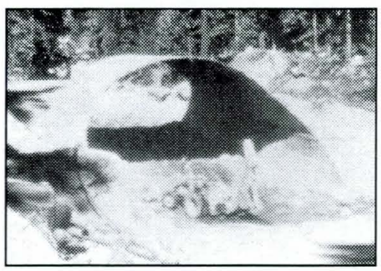
4.5a CM arch with no bottom

4.5b Concrete arch with open bottom

Long Span Culverts:

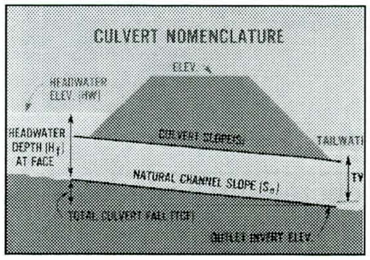


4.6a



4.6b Corrugated metal ellipse, long-span

4.2 CULVERT NOMENCLATURE



4.7

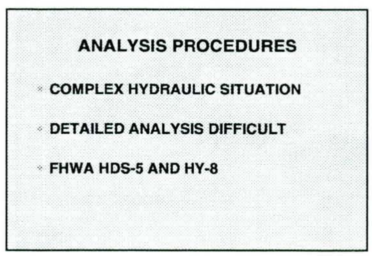
A. Natural channel slope vesus culvert slope.

B. Headwater depth and headwater elevation.

C. Tailwater depth.

D. Total culvert fall.

4.3 ANALYSIS PROCEDURES



4.8

A. The hydraulics of culverts are quite complex. Nearly every hydraulic phenomena is involved.

- detailed analysis of the actual flow situation is difficult.
- The only method of culvert design in the past was the use of standard hydraulic texts.
- recognizing the difficulties involved in culvert design and the need for improved hydraulic analysis, the FHWA developed design procedures (HDS-5) and computer programs (HY-8) to facilitate culvert design

B. Two important ideas in culvert design are

DESIGN CONCEPTS

- IGNORE TRANSIENT CONDITIONS
- ASSUME WORST CASE CONDITION

4.9

- Miminum performance, that is, transient conditions which may improve the flow conditions temporarily are neglected.

- Culverts may operate in several types of control and it is simpler to check each type of control and design for the worst condition than to try to determine how the culvert is actually flowing, which is variable in time.

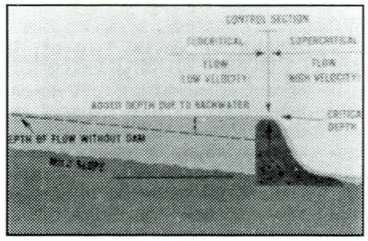
4.4 INLET AND OUTLET CONTROL

INLET AND OUTLET CONTROL

- FUNDAMENTAL CONCEPT IN CULVERT HYDRAULICS
- OGEE SPILLWAY EXAMPLE

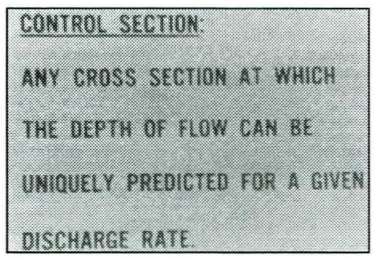
4.10

A. To better understand basic culvert hydraulics, particularly the concepts of inlet and outlet control, consider flow over an ogee spillway.



4.11

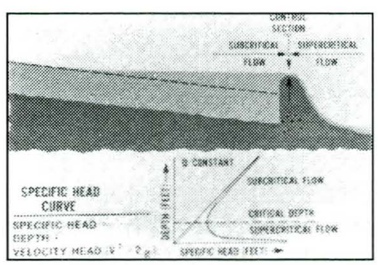
- The flow downstream of the crest is is termed supercritical while the upstream flow is subcritical. Generally, supercritical flow is a high velocity, shallow flow, and subcritical is deep with a low velocity.



4.12

- The dividing point is called a control section: A control section is any cross section at which the depth of flow can be uniquely predicted for a given discharge rate.

- The specific energy concept:

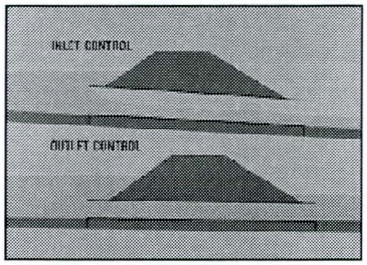


4.13

- For any given specific energy, with constant discharge, there are two depths-- subcritical and supercritical. For subcritical flow, most of the energy is in terms of the depth or potential energy. While for supercritical flow, the majority of the flow's energy is in its velocity head or kinetic energy.

- Also, recall that for supercritical flow, the control section is upstream (downstream obstructions have no effect on an upstream point). It is obvious that placing an obstruction at the spillway toe will have no effect at the spillway crest.
- However, an obstruction placed upstream of the dam control section would result in a higher backwater. The control section for subcritical flow is downstream.

B. These characteristics of supercritical flow and subcritical are the reason for the two basic types of culvert control -- *inlet control and outlet control.*



4.14

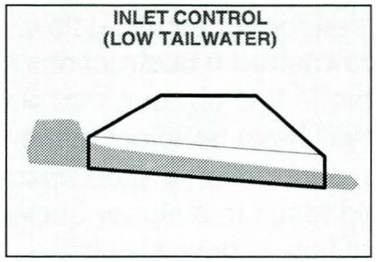
- When the barrel is full or on a subcritical slope, control is downstream or at the outlet.
- When the slope is supercritical or steep, control is at the face, or inlet.
- Basically, in inlet control the culvert opening permits less flow to enter the culvert than the barrel could carry, and in outlet control the barrel is restricting the flow.

4.5 TYPES OF FLOW CONDITIONS IN INLET AND OUTLET CONTROL

A. Inlet Control Variations

The FHWA recognizes certain basic cases of flow for inlet control. These are described as follows (see also Figure III-1, HDS 5).

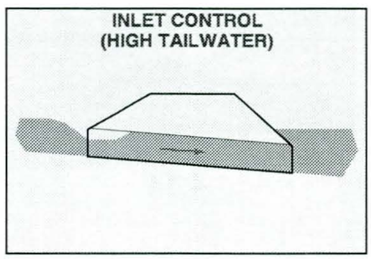
1. With low tailwater the inlet may be submerged or unsubmerged:



4.15

- Typically, critical depth occurs at or immediately downstream of the culvert entrance.
- An S2 water surface profile describes flow through the culvert barrel.
- Outlet depth approaches normal depth of flow.
- Flow is at partial depth throughout the culvert length.

2. Submerged Outlet (High Tailwater)



4.16

When the tailwater is high but does not submerge the entrance, the headwater is still governed by entrance conditions and is in inlet control.

If the tailwater elevation submerges the entrance, the culvert will flow full and will no longer be in inlet control.

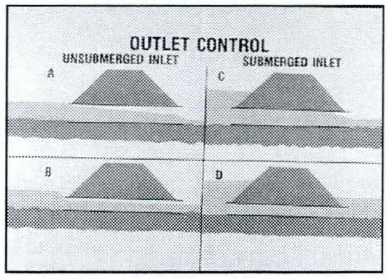
Inlet control with a high tailwater is a relatively unusual situation.

B. Outlet Control Variations

In outlet control, discharge can enter and flow through the culvert only as fast as the conduit and its physical characteristics, the tailwater level, and to a minor extent, the entrance configuration will allow it.

Outlet control implies subcritical flow.

The FHWA recognizes certain basic cases of flow for outlet control. These are described as follows (see also Figure III-7, HDS 5).



4.17

In outlet control the culvert can have free surface flow throughout as shown in A and B, or full flow as shown in C and D.

Outlet control usually occurs in areas of flat terrain where the culvert is on a mild slope. Some outlet control culvert operations include those where flow is partially full, either throughout the culvert length or through a significant portion of the culvert length.

4.6 FACTORS INFLUENCING CULVERT PERFORMANCE

FACTORS INFLUENCING CULVERT PERFORMANCE

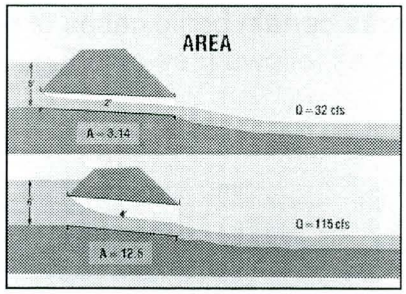
OUTLET CONTROL	INLET CONTROL
HEADWATER DEPTH	HEADWATER DEPTH
TAILWATER DEPTH	————
INLET EDGE CONFIGURATION	INLET EDGE CONFIGURATION
CROSS SECTIONAL AREA	CROSS SECTIONAL AREA
BARREL SHAPE	BARREL SHAPE
TOTAL CULVERT FALL	————
BARREL LENGTH	————
BARREL ROUGHNESS	————

4.18

A. Note that, as the name implies, inlet control is only influenced by inlet conditions, while outlet control is governed by the barrel conditions and the tailwater as well.

B. There are eight factors that influence culvert performance in outlet control, and four factors in inlet control.

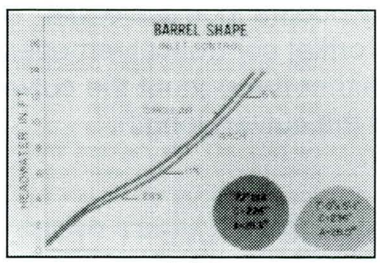
4.7 FACTORS INFLUENCING OUTLET CONTROL



4.19

A. AREA - all other factors being equal, a larger area conveys more flow.

B. SHAPE-With the same total area, the pipe-arch conveys more flow than the circular pipe.

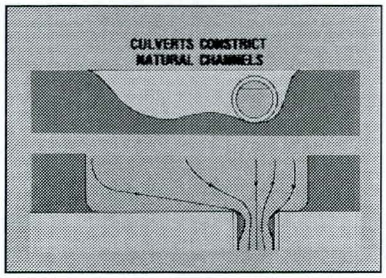


4.20

- However, note that the perimeter of the pipe-arch is larger than that of the circular pipe for the same area. This means that the pipe arch will cost more than the circular pipe.
- These conduits are recommended only when there is a vertical restriction.
- Note that this method of depicting culvert operation, flow rate vs. headwater, is called a performance curve. This type of curve comes in handy in visualizing the operation of a culvert over a range of flow rates, and is strongly recommended.

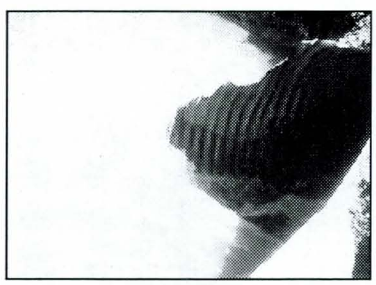
C. INLET EDGE CONFIGURATION.-the inlet condition influences the amount of contraction of flow into the culvert and the energy loss that occurs.

- A culvert generally has a smaller area than the natural channel it replaces. (Slide 4.21 Culvert Constriction)

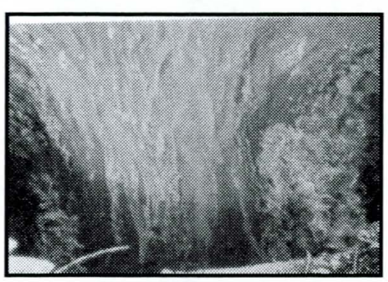


4.21

- The best method of conveying the design storm would be to preserve the natural drainage area and bridge every stream.
- This, however, is not economically feasible. Highway engineers, therefore, use culverts which have an area less than that of the natural stream.
- The channel is constricted and the smaller culvert area conveys the same discharge at a higher velocity with some increase in backwater.

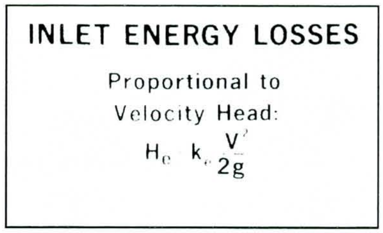


4.22



4.23

- Contraction of flow reduces the effective area of flow, and the barrel area is thus not fully used. If the inlet conditions were more favorable, this contraction, and the associated energy losses, could be reduced and the culvert would convey more flow.

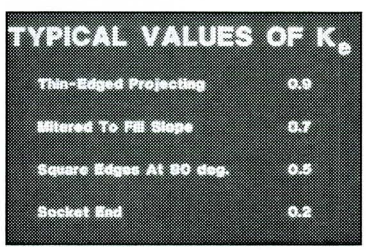


4.24

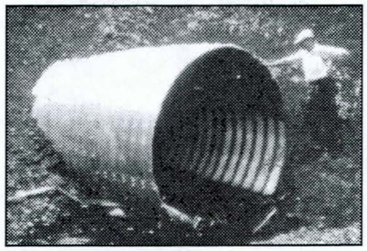
- Inlet energy losses are proportional to the velocity head. Where V in this expression is the full barrel velocity.
- The entrance head loss is a function of velocity head based upon the entrance loss coefficient K_e. K_e may be found in Table 12, Appendix D of HDS#5.

Typical values of K_e are:

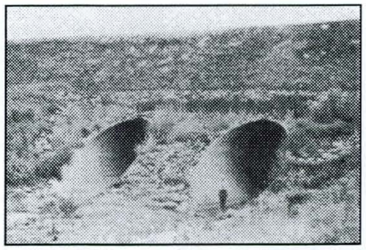
• Thin-Edged Projecting	0.9
• Mitered to Fill Slope	0.7
• Square Edges at 90 deg.	0.5
• Socket End	0.2



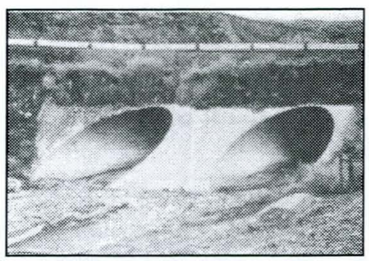
4.25



4.26 Thin edge projecting, $k_e = 0.9$.

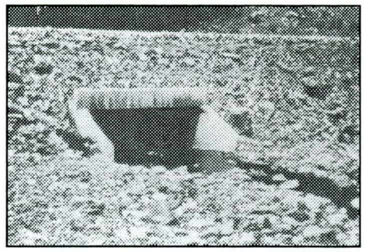


4.27 Mitered end, $k_e = 0.7$

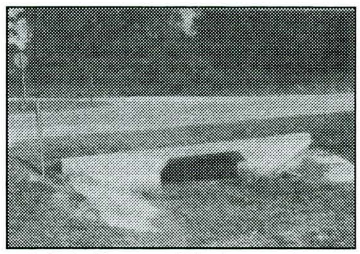


4.28 Mitered end, anchored at sides with paved slope, $k_e = 0.7$.

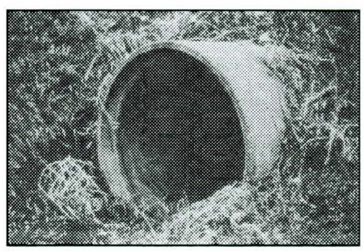
4.29 Pipe culvert with square edges or headwall. Wingwalls added to a circular pipe have no significant hydraulic effect, $k_e = 0.5$.



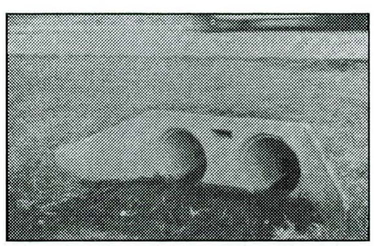
4.30 Box culvert with wingwalls at 10° to 25° to barrel, square top edge, k_e = 0.5.



4.31 Box with bevel on top and sides, k_e = 0.2.

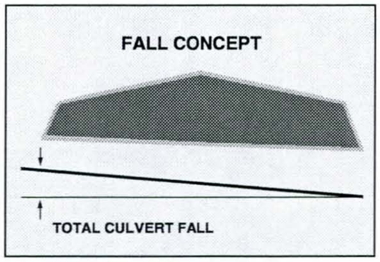


4.32 Concrete pipe, groove end projecting, k_e = 0.2.

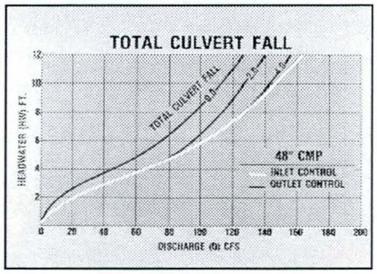


4.33 Concrete pipe with groove end in headwall, double barrel, Ke still 0.2.

E. TOTAL CULVERT FALL-The effect of total available culvert fall is somewhat more difficult to depict, but can be understood by consideration of a set of performance curves for a particular culvert.



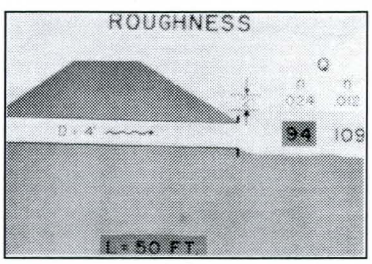
4.34



4.35

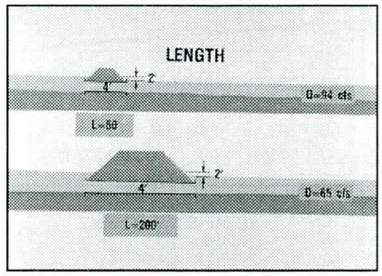
- Note that for the same headwater (use 7 ft.), as total culvert fall is increased, the flow increases, moving from curve to curve if all other conditions are held constant.
- However, if the total fall of this culvert is increased past 4 ft., control shifts to inlet control and further steepening has no effect. The barrel is no longer influencing the flow.
- Obviously, any given culvert site has only one total culvert fall available. Therefore, to increase total fall, different sites must be compared.

F. BARREL ROUGHNESS-All other things being equal, increasing the barrel roughness decreases the flow rate, through friction losses.

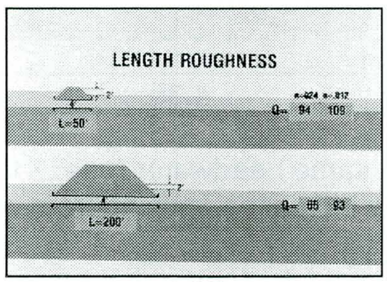


4.36

G. BARREL LENGTH-flow rate decreases with increasing barrel length. Barrel length and roughness go together, since the longer the culvert barrel, the more roughness is encountered by the flow.

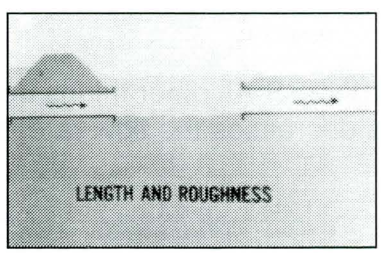


4.37



4.38

- The length effect is illustrated by example. The culvert under the two-lane existing roadway on the left has not posed flooding problems throughout the life of the facility.

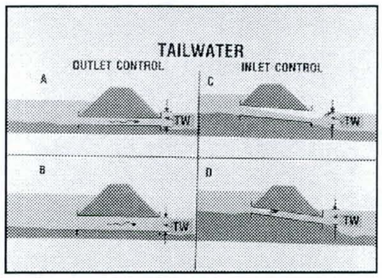


4.39

- Arbitrarily selecting the same sized culvert for use in the new four lane highway without considering the increased length of the new structure, and the fact that the grade line of the new facility is lower than that of the existing one may result in the headwater overtopping the new roadway.

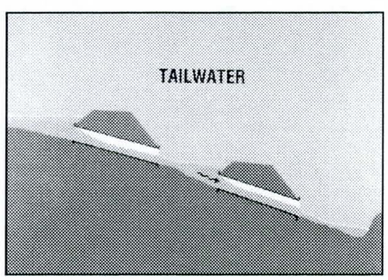
- Certainly the size of existing nearby culverts should be considered in selecting those needed for a new facility, however, not to the exclusion of other factors.

H. TAILWATER-tailwater conditions can influence the type of control, and changing tailwater conditions can change control from inlet to outlet, or vice-versa.

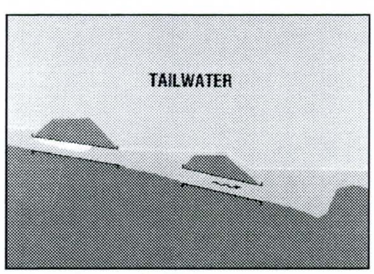


4.40

- In outlet control with high tailwater (example A), changes in tailwater are directly reflected in the headwater. At low tailwater conditions (when flow passes through critical depth at the outlet), this is not true (example B).
- In inlet control the effect of tailwater is not important, unless the tailwater becomes high enough to cause outlet control.



4.41

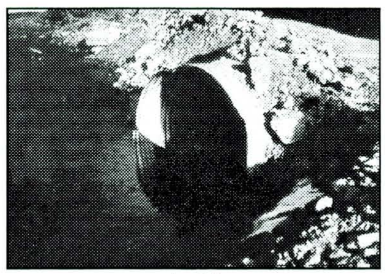


4.42

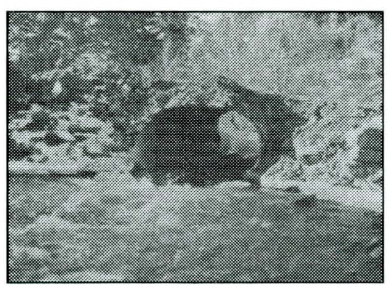
- This illustrates the importance of determining the correct tailwater. The tailwater is normally estimated to be the normal depth in the outlet channel as shown in Slide 4.41. However, if the culvert discharges into another stream as shown on the right, the depth of flow in that stream may be the controlling tailwater.

- Other downstream controls such as dams, wiers, etc., may also influence tailwater, and should be considered in culvert design (Slide 4.42).

I. HEADWATER-The headwater is central to culvert design. A certain amount of energy is required to force the water through a culvert, overcoming entrance and barrel losses and accelerating the flow through the channel constriction. This energy is produced by the headwater on the upper end of the culvert.



4.43

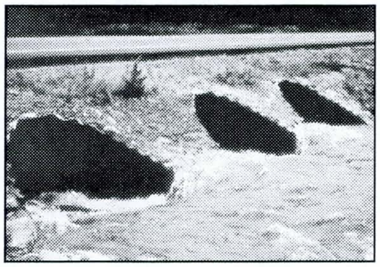


4.44

- The headwater is assumed to be a quiet pool for reasons of conservative design. (Actually, the approach velocity helps "push" the water into the culvert.)

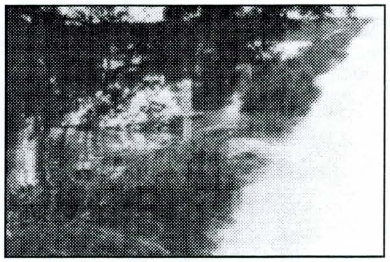
- To design a culvert the headwater depth is determined and then enough culvert area is provided to convey the discharge using this available headwater.

  If the headwater depth is limited, such as in this example, the area cannot be provided in one culvert.



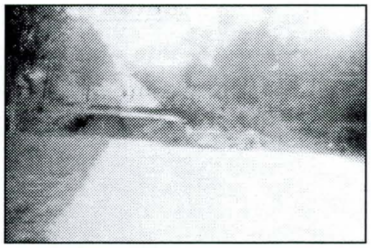
4.45

- The consequence of choosing incorrectly is, of course,



4.46

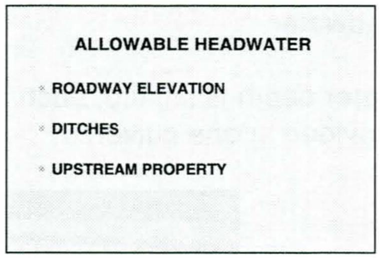
flooding the road and adjacent property. This does not mean we should design to prevent overtopping; however, we should design to prevent major damage such as



4.47

washing the roadway out entirely. For when this occurs, the damage to roadway, vehicles, and property can make the culvert cost appear small.

- The maximum feasible headwater is called the allowable headwater.

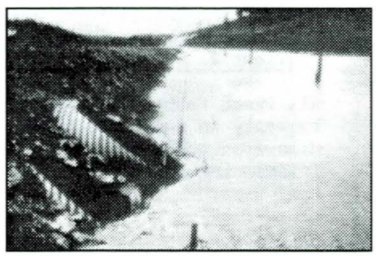


4.48

It is the engineer's job to design a culvert to pass the design discharge without exceeding the allowable headwater.

- In choosing the AHW, consideration must be given to the elevation of: the roadway centerline profile, ditches to adjacent drainages, and upstream property.

- Here is a case where the allowable headwater was determined based on the roadway elevation immediately above the culvert



4.49

- The designer forgot to check the entire roadway profile and therefore missed a low point up the road where the water goes over the road long before the allowable headwater is reached. As a result, the embankment is eroded

4.50

- Headwater must increase as the culvert is lengthened if all other factors remain the same.

4.8 FACTORS INFLUENCING INLET CONTROL

FACTORS INFLUENCING CULVERT PERFORMANCE

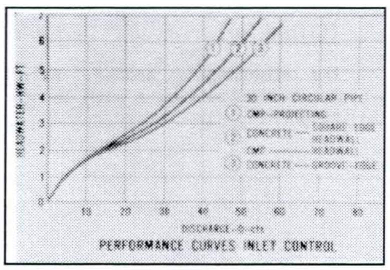
OUTLET CONTROL	INLET CONTROL
HEADWATER DEPTH	HEADWATER DEPTH
TAILWATER DEPTH	————
INLET EDGE CONFIGURATION	INLET EDGE CONFIGURATION
CROSS SECTIONAL AREA	CROSS SECTIONAL AREA
BARREL SHAPE	BARREL SHAPE
TOTAL CULVERT FALL	————
BARREL LENGTH	————
BARREL ROUGHNESS	————

4.51

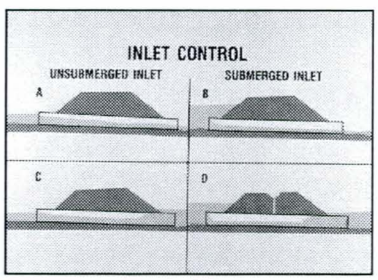
A. All factors affecting culvert capacity in outlet control have been reviewed.

B. Four of these factors also influence inlet control. It is clear that area, shape, and headwater will cause flow variation as in outlet control.

C. Inlet edge configuration behaves in the same manner, but is more important in inlet control, as illustrated by the following inlet control performance curves:



4.52

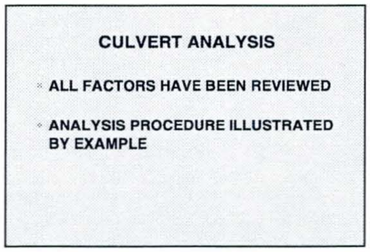


4.53

D. It may be useful to think of inlet control as orifice flow, where the inlet is the orifice and the barrel has excess capacity, and therefore, does not affect the culvert flow capacity. The flow is always free surface downstream of the inlet, and the entrance and outlet may be submerged or unsubmerged.

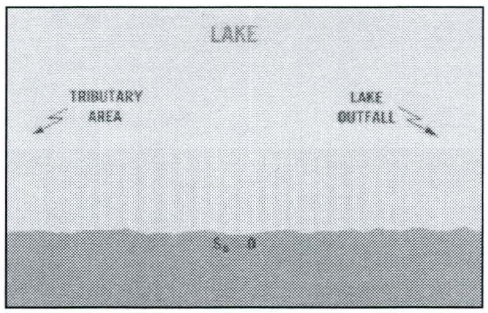
E. Consequently, even if the outlet is submerged with high tailwater, the culvert should be checked for inlet control.

4.9 CULVERT ANALYSIS-CONCEPTUAL EXAMPLE



4.54

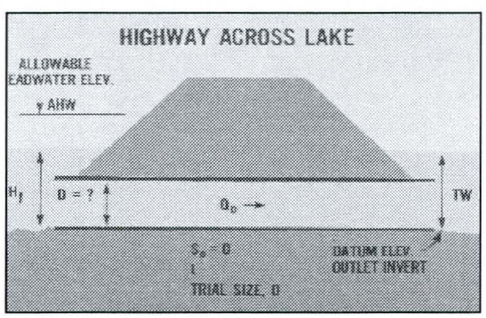
A. All the factors affecting culvert flow have been reviewed. To understand how to systematically analyze a culvert, consider a lake with with a tributary and an outfall. A culvert will connect the upstream and downstream sides of a roadway to be built across the lake.



4.55

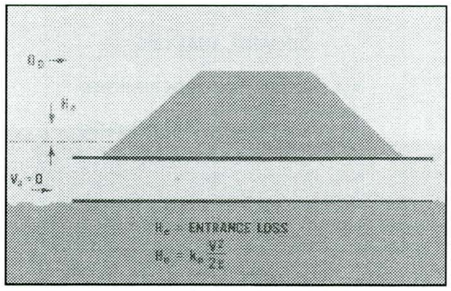
B. To design the culvert, determine the culvert size (D) that will convey the design discharge (Q_D) and will pond the water only to the allowable headwater depth (AHW) for this culvert on a flat slope (So = 0).

C. In order for the flow to pass through the culvert, enough energy must be available at the entrance to overcome the culvert losses. This energy is provided in potential energy or depth in the headwater pool.



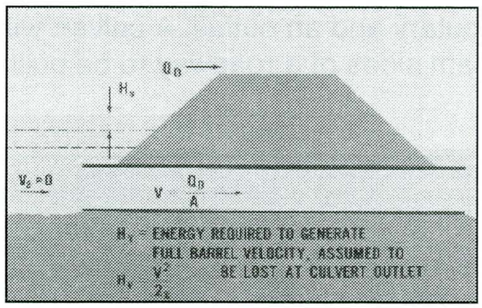
4.56

The first loss to overcome is the entrance loss, which requires an increment of energy (He).



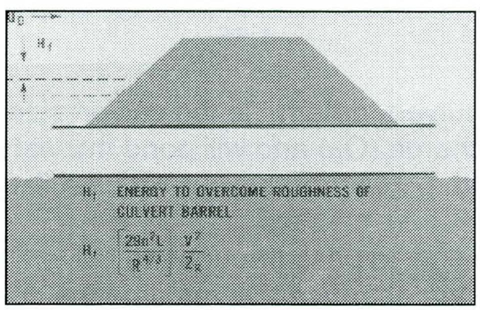
4.57

The next increment is (Hv) the energy necessary to generate full barrel velocity.



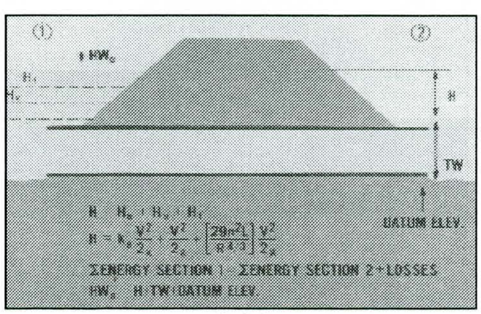
4.58

The third major loss to overcome is the friction loss in the barrel, which is determined by using a form of Manning's equation.



4.59

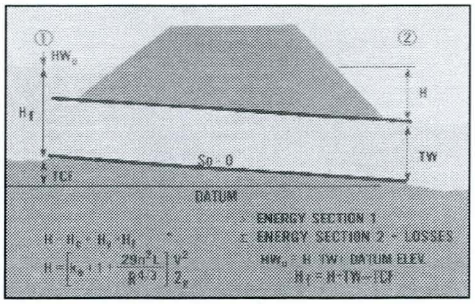
Adding these losses together results in the total loss from the inlet to the outlet of the culvert (H). Note that this calculation is for outlet control, since the barrel is contributing to the required headwater.



4.60

D. To find the required headwater pool elevation (HWo, where the "o" is for outlet control), the *energy equation* will be applied from the outlet to the inlet by adding the tailwater level (TW) and the total loss (H) to the known elevation at the outlet (control section).

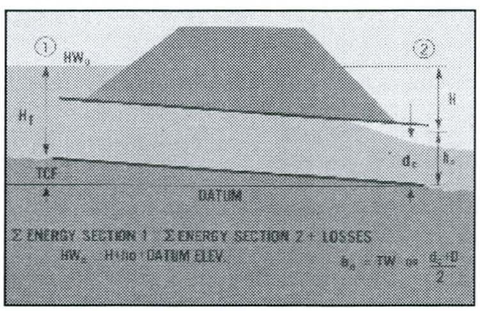
E. Now consider the effect of sloping the culvert barrel.



4.61

- The headwater elevation is determined in the same way: elevation at control section plus TW plus H = HWo.
- Note that the pool elevation has not changed. The only thing that is different is the headwater depth (Hf) is smaller by the amount SoL.
- Also note that as the slope is increased, Hf will get smaller until a minimum is reached, where Hf = the inlet control headwater depth. If the slope is increased even more, Hf stays constant and headwater will rise with the culvert entrance and the culvert will operate in inlet control.

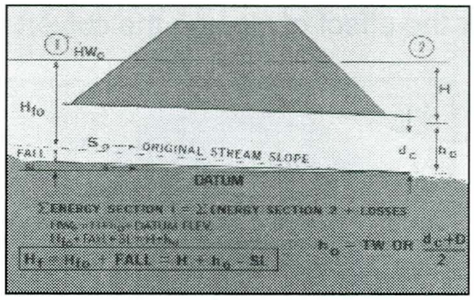
F. If the tailwater is low, flow in outlet control will pass through critical depth near the culvert outlet.



4.62

- In this case, a value, ho, is used in the energy balance: where ho = TW or (dc + D)/2 whichever is larger.
- ho is an empirical value determined from test results which enables one to use HDS 5, developed for full flow conditions, for partly-full culvert flow without tedious backwater calculations.

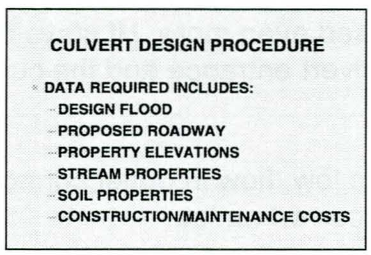
G. Before leaving this example, the concept of fall (different from total culvert fall) can also be illustrated. When a culvert is placed with the inlet invert below the streambed a drop, or fall, is created at the entrance of the culvert.



4.63

- Notice that the headwater pool elevation (HWo) has not changed. Looking at the outlet we see that the elevation is equal to datum elevation plus (ho) plus (H) the same as before.
- The new headwater depth (H_{fo}) is now equal to the fall plus the depth above the original streambed (H_{fo}).

4.10 CULVERT DESIGN PROCEDURE

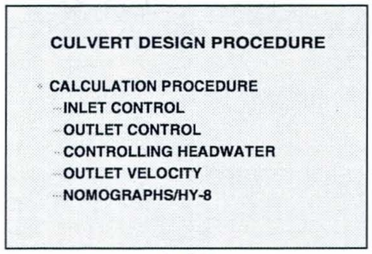


4.64

A. In order to design a culvert, the following information must be collected:

- Design flood
- Proposed roadway
- Elevations of surrounding property
- Natural stream properties
- Soil properties
- Construction costs
- Maintenance costs

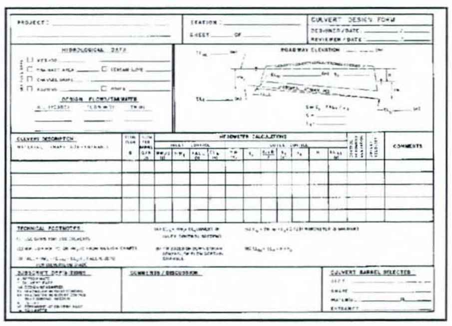
B. To facilitate the hydraulic design process, a computation sheet was developed and is provided in HDS-5. This computation sheet identifies the sequence of major design steps and provides for a documented culvert design. The major design steps are:



4.65

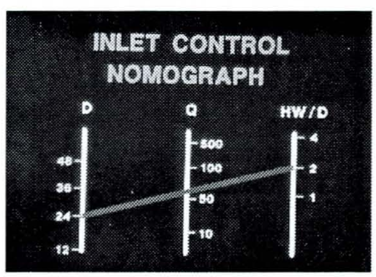
- Inlet control calculation
- Outlet control calculation
- Identification of the controlling headwater
- Evaluation of outlet velocity

HDS-5 also provides nomographs for completing the inlet control and outlet control calculations.



4.66

INLET CONTROL NOMOGRAPHS. The inlet control nomographs are simple to use and provide a direct solution for the headwater depth:

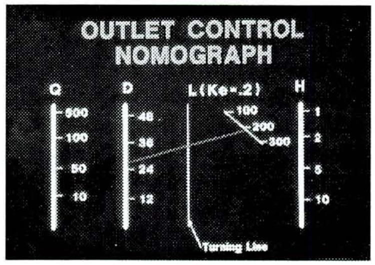


4.67

- A diameter is chosen (in our example, 24 inches).
- A line is then drawn from this point through the design discharge (in our example, 30 cfs) to find (Hf/D) or headwater depth to diameter ratio of 2.

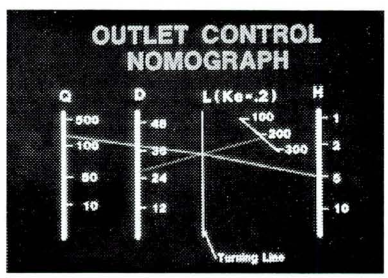
- Multiplied by (D) we find that a head- water depth of 48 inches is required if a 24-inch pipe is used to convey 30 cfs.

C. OUTLET CONTROL NOMOGRAPHS. The outlet control headwater depth is determined in the same manner. However, since more factors influence outlet control, the nomograph is a little more complicated and is a two step process.



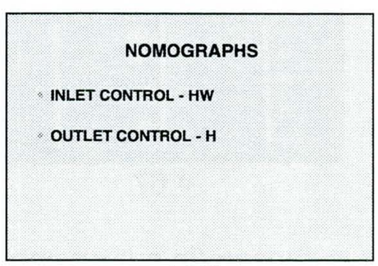
4.68

- Choose an entrance type (for our example a beveled entrance). The associated ke value of 0.2 determines which length scale we should use.
- Start at the known culvert length 100 ft. and draw a line to the trial culvert size 60 inches to establish a point on the turning line.



4.69

- Then draw a line from the discharge 140 cfs through the point on the turning line to the (H) scale the sum of the losses.



4.70

- It is important to realize that the outlet control nomographs solve for H (headloss) which is then used to to calculate the headwater condition by application of the energy equation (unlike the inlet control nomographs that solve directly for HW).

- To apply the energy equation, the hydraulic grade line at the outlet (control location) must be determined.

OUTLET CONTROL

- ENERGY EQUATION USED
- HGL BASED ON TW OR ho

4.71

This will be the greater of either the tailwater depth in the downstream channel or the empirical value ho (which is the average of critical depth and culvert size).

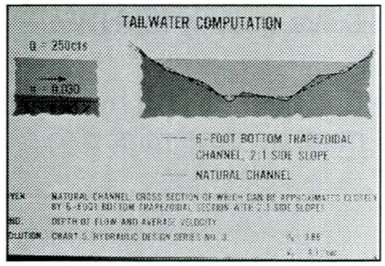
CRITICAL DEPTH

- NOMOGRAPHS
- EQUATION
- COMPUTER

4.72

- Critical depth is typically determined from nomographs, but can be solved by equation 3-5.

- The tailwater is taken to be normal depth in the outlet channel and can be computed by a single section slope area calculation (based on the Manning's equation as reviewed in Lesson 3).

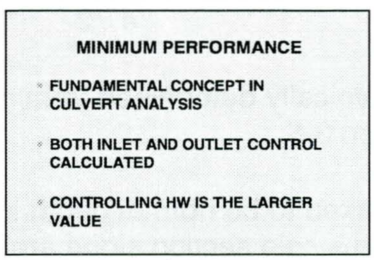


4.73

This means of determining the tailwater depth is extremely simplified, and it should be recognized that normal depth in the downstream channel will not exist at the culvert outlet. Also, it may be difficult to define the natural stream in terms of a prismatic channel. However, considering the computational difficulities and channel data required to perform actual channel backwater or drawdown calculations, it is considered a reasonable method of estimating tailwater influence on the culvert.

- The controlling HGL is then determined and the energy equation is applied to calculate the headwater elevation.

D. CONTROLLING HEADWATER ELEVATION.



4.74

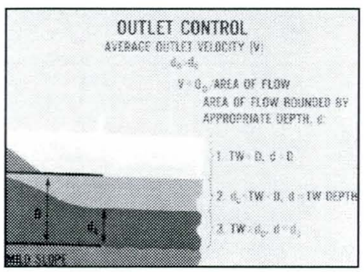
Based on the concept of minimum performance, the controlling headwater elevation is the larger of either the inlet control or outlet control headwater elevations.

E. EVALUATION OF OUTLET VELOCITY. The outlet velocity is defined by the area of flow just inside the culvert at the outlet.

4.75

To find the velocity, we first determine the depth of flow at the outlet which defines the area of flow. The velocity is then obtained by dividing the discharge by the area (according to the continuity equation).

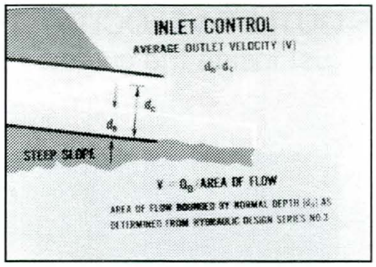
- Deciding what depth to use depends on the type of flow. In outlet control the three possibilities are high, moderate, and low tailwater.



4.76

For high tailwater, above the top of the culvert, the cuvlert will flow full to the outlet; so the culvert height (D) is used in calcualting the outlet velocity. For low tailwater (below dc), the flow will pass through (dc) near the outlet, so (dc) is used. If the tailwater is in between (dc) and (D), use the tailwater depth for the velocity calculation.

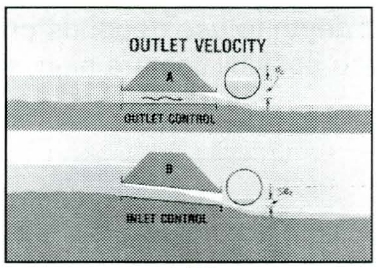
- For inlet control, the outlet velocity is defined by normal depth.



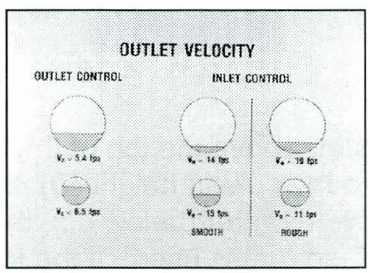
4.77

This is a good assumption if the culvert is long and is conservative if the culvert is short.

- It is often incorrectly believed that increasing the size will substantially decrease the outlet velocity, and thus reduce downstream scour. This fallacy is illustrated by slide 4.78



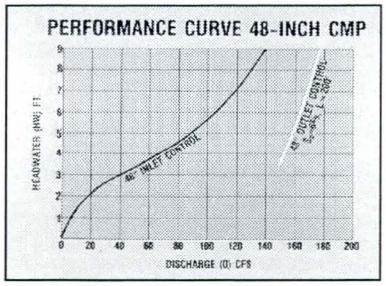
4.78



4.79

- A far more practical and economic solution would be to use a rougher pipe if velocity reduction is necessary. As shown, the velocity is reduced from 15 to 25 percent by using a rough rather than a smooth pipe.

F. After the culvert size is selected, performance curves should be drawn for inlet and outlet control. Performance curves are used to depict the operation of a particular culvert over a range of flow rates.



4.80

- Note that the outlet control curve is to the right of the inlet control curve, or that the barrel is conservative.
- By improving the inlet, the inlet control curve may be shifted to the right to better use the existing culvert capacity. This will be discussed more fully in the Improved Inlet presentation.

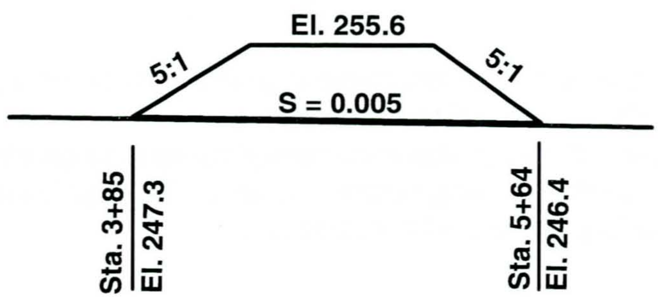
4.11 WORKSHOP 4 - CONVENTIONAL CULVERT DESIGN

PROBLEM STATEMENT

A culvert crossing must be designed for a new roadway. The site survey project file contains:

- USGS, site, and location maps,
- roadway profile, and
- embankment cross section.

From this information, the following schematic drawing of the roadway embankment was prepared:



Site visit notes indicate:

- no significant debris potential from the watershed to be served by the culvert
- no nearby structures.

The design criteria for this project is:

- 50-year frequency for design
- allowable headwater elevation = 252.00 due to the elevation of a different roadway upstream of the subject culvert.
- 100-year frequency for check.

The Rational method was used to determine the following values on a flood-frequency curve:

- Q_{50} = 93 cfs
- Q_{100} = 175 cfs

The rating curve for the downstream channel was calculated by normal depth analysis:

Q(cfs)	TW (ft)	V (ft/sec)
0	0.00	-
50	4.00	2.5
93	4.50	2.9
150	4.84	3.2
175	4.95	3.8

Note that the maximum average stream velocity (for 175 cfs) is 3.8 fps.

REQUIRED SOLUTION:

Complete all necessary calculations and and plot the performance curve for the following assumed culvert configuration:

Shape: Circular
Size: 4 - 36" CSP
Material: Steel
Entrance: headwall - square edge

SOLUTION PROCEDURE:

Complete the Culvert Design Form, using the printed nomographs in HDS No. 5.

GENERAL SOLUTION PROCEDURE

Step 1. Select a culvert size, type of material, number of barrels, and inlet condition to analyze. For our problem, this information was given.

Step 2. Complete the top portion of the Culvert Design Form, filling in all known information.

Note that when given embankment data, the length of the culvert and the invert and outlet elevations must be calculated based on the size and slope of the barrel and embankment sideslope. The length of the barrel is based on where the crown of the barrel intersects the embankment fill. Therefore, the barrel length is shorter than distance between the upstream and downstream embankment toe-of-slope, and the barrel invert elevations are slightly different from the toe-of-slope elevations.

Step 3. Complete the inlet control calculations for the design discharge by filling in the appropriate spaces on the Culvert Design Form, following the instructions given in the footnotes. For our problem, use Chart 2 to calculate the inlet control headwater depth.

Step 4. Complete the outlet control calculations for the design discharge by filling in the appropriate spaces on the Culvert Design Form, following the instructions given in the footnotes. For our problem, use Chart 6 to calculate the outlet control headloss.

Step 5. Based on the concept of minimum performance, select the controlling headwater elevation.

Step 6. Calculate the outlet velocity.

Step 7. Based on the headwater elevation and outlet velocity, evaluate the hydraulic performance of the culvert. If not acceptable, select another configuration and complete the analysis again.

Step 8. Repeat the calculations for other discharges to evaluate the culvert performance curve, and plot the performance curve.

PROJECT : ______________________

STATION : ______________

SHEET ______ OF ______

CULVERT DESIGN FORM

DESIGNER / DATE : ________ / ________

REVIEWER / DATE : ________ / ________

HYDROLOGICAL DATA

SEE ADD'L. SHTS.

☐ METHOD : ______________________

☐ DRAINAGE AREA : ________ ☐ STREAM SLOPE : ________

☐ CHANNEL SHAPE : ______________________

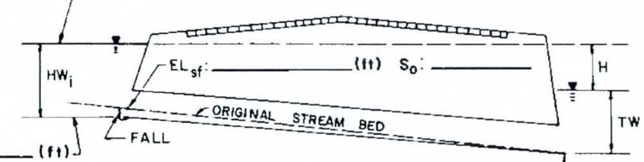
☐ ROUTING : ________ ☐ OTHER : ________

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)

EL_{hd} : ______ (ft)

ROADWAY ELEVATION : ________ (ft)



EL_i ________ (ft)

EL_o : ________ (ft)

$S \approx S_o - FALL / L_a$

S = ________

L_a = ________

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i / D = HW / D$ OR HW_i / D FROM DESIGN CHARTS

(3) $FALL = HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2 / 2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS :

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION :

CULVERT BARREL SELECTED :

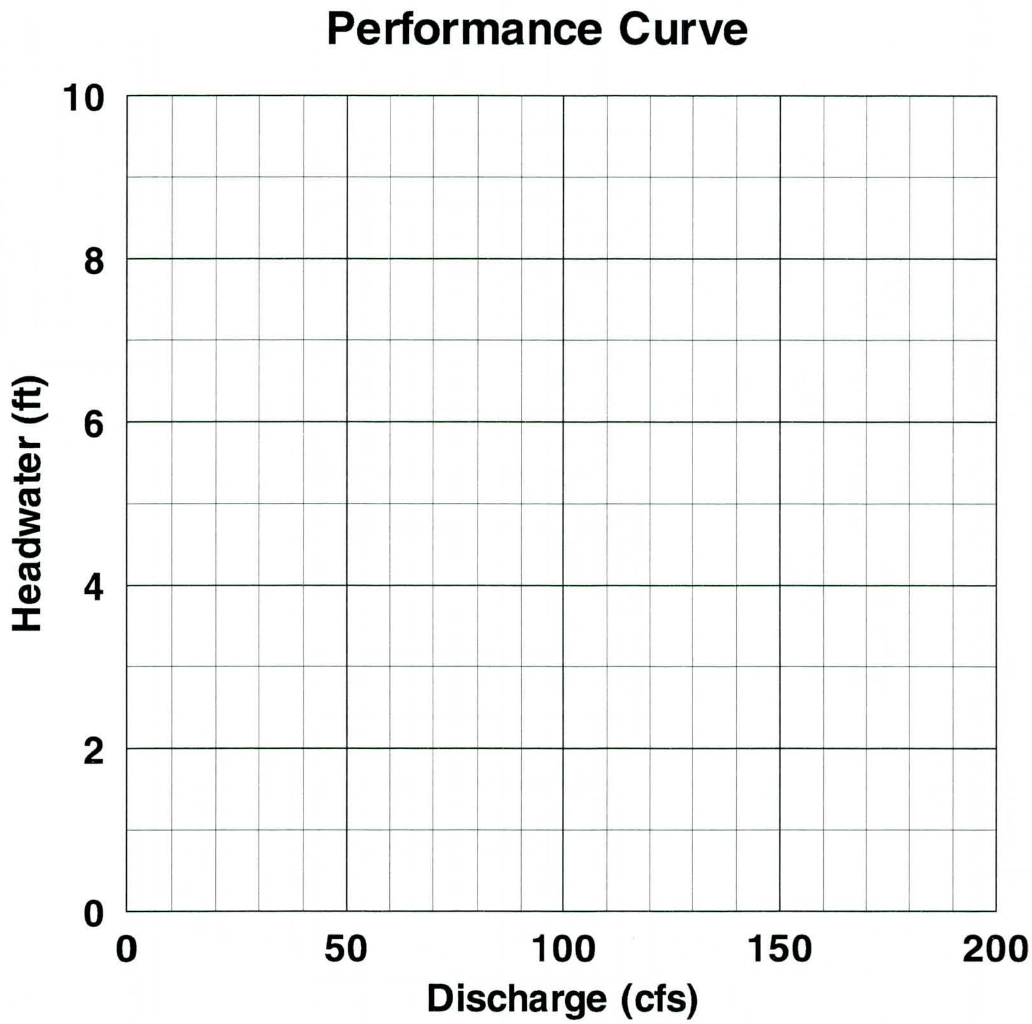
SIZE : ________

SHAPE : ________

MATERIAL : ________ n: ________

ENTRANCE : ________

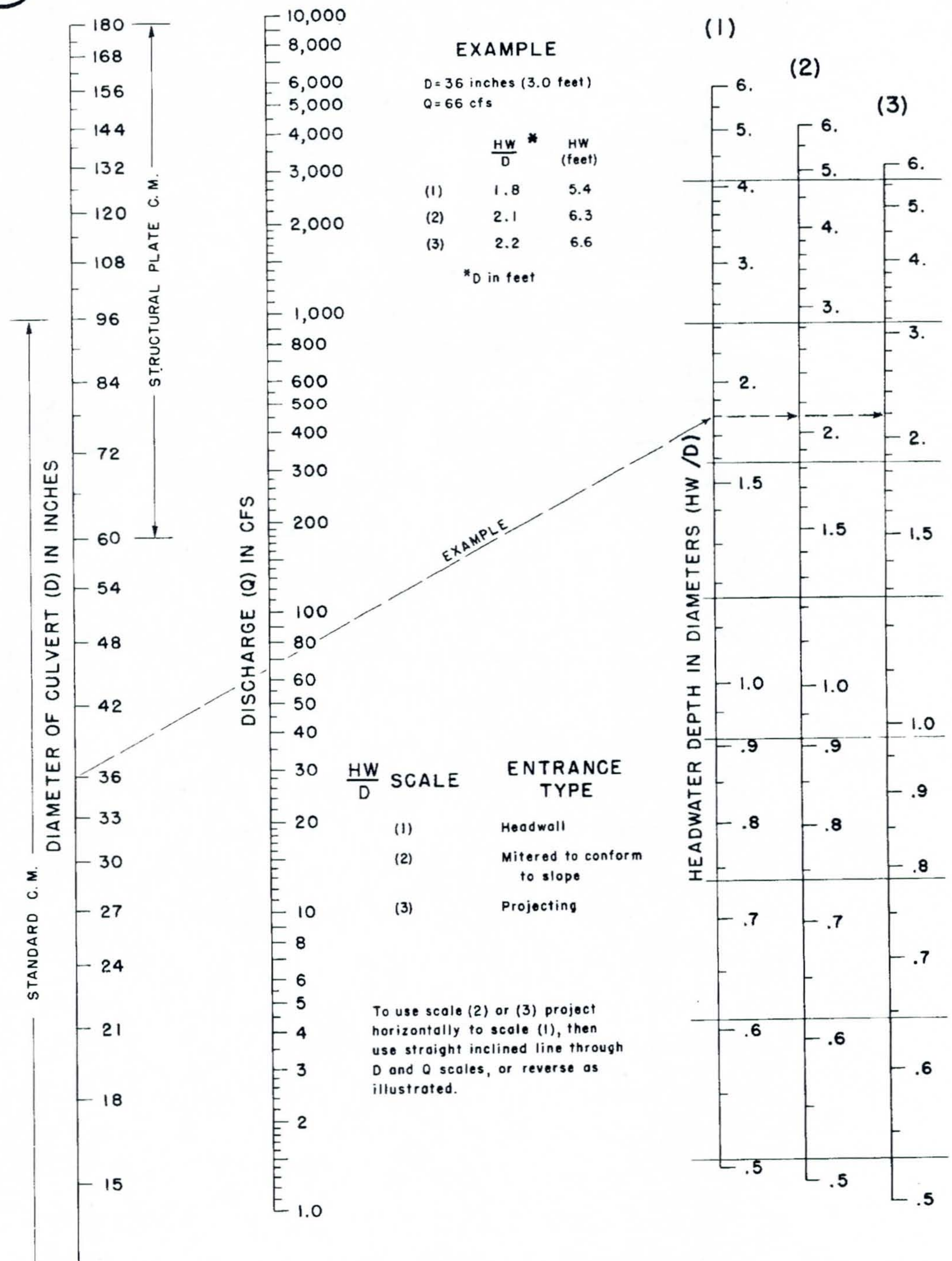
Performance curve:



DISCUSSION:

- Culverts are normally designed for a HW/D of 1.1 or 1.2 for the design discharge.
- Tapered inlets are not justified since the culvert operates in outlet control throughout the considered performance curve.
- Energy dissipators are not needed because of the relatively low outlet velocities.
- No apparent sedimentation or fishery problems.
- Remember to document all assumptions and calculations, and file accordingly.

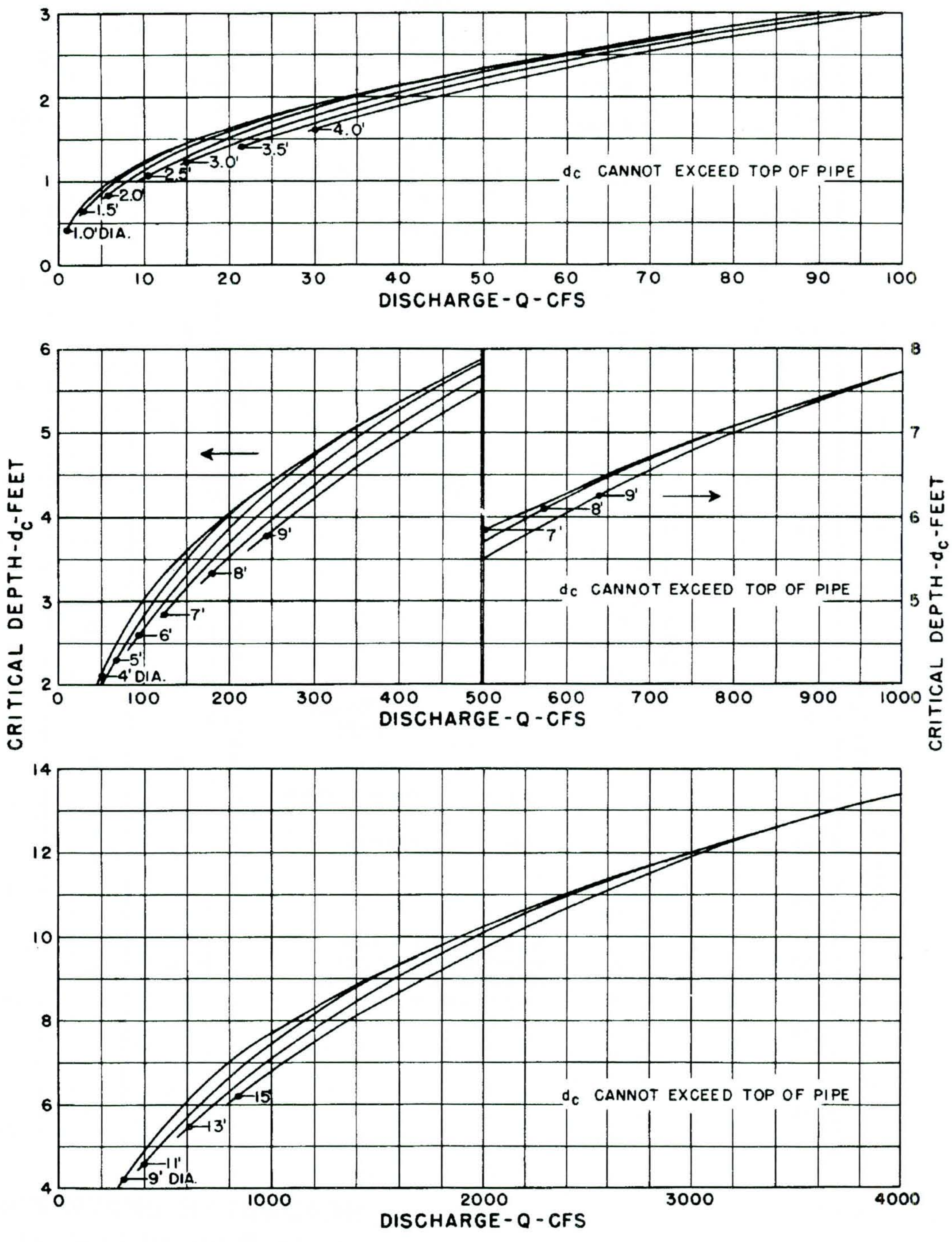
CHART 2



HEADWATER DEPTH FOR
C. M. PIPE CULVERTS
WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

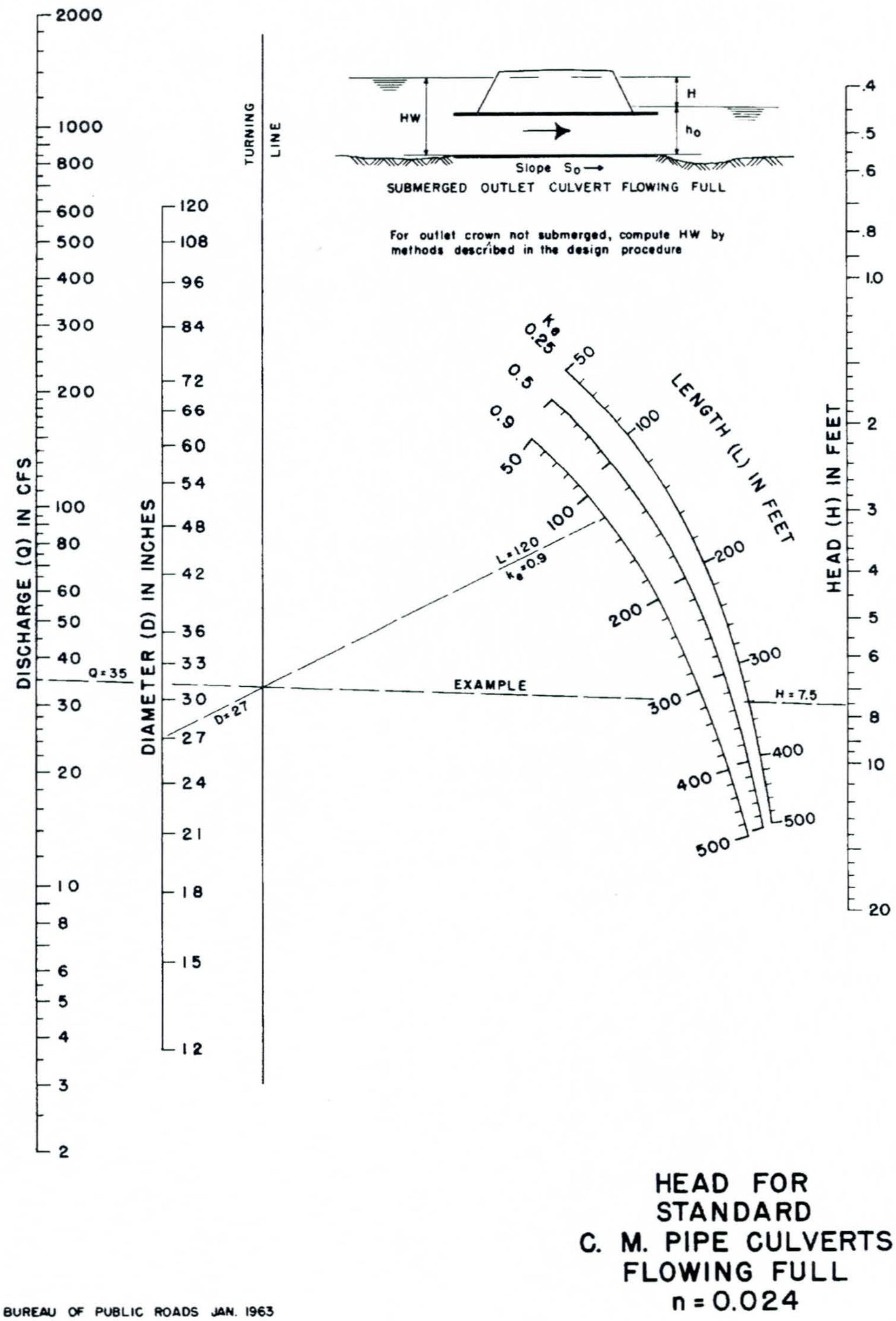
CHART 4



BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
CIRCULAR PIPE

CHART 6



HEAD FOR
STANDARD
C. M. PIPE CULVERTS
FLOWING FULL
n = 0.024

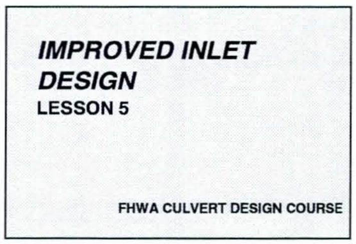
NOTES:

LESSON 5

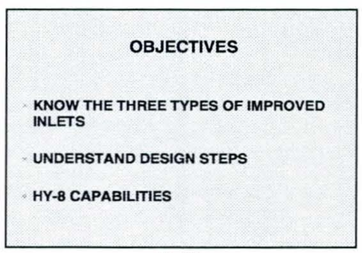
IMPROVED INLET DESIGN

OVERVIEW:

Method of Instruction:	Lecture
Lesson Length:	60 minutes
Resources:	Student Workbook Graphics



5.0a



5.0b

OBJECTIVES: At the conclusion of this lesson, the participant will be able to:

1. Recognize the three different types of improved inlets: bevels, side-tapered inlets and slope-tapered inlets.
2. Understand the design steps and their sequence for improved inlets.
3. Be acquainted with the capabilities of HY-8 for design and analysis of improved inlets.

LESSON OUTLINE

5. IMPROVED INLET DESIGN

   5.1. INTRODUCTION

   5.2. INLET IMPROVEMENT

   5.3. IMPROVED INLET DESIGN - BOX CULVERT

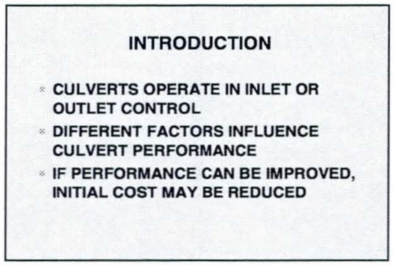
   5.4. IMPROVED INLET DESIGN - PIPE CULVERT

   5.5. GENERAL DESIGN CONSIDERATIONS

   5.6. STANDARD DESIGNS

   5.7. WORKSHOP 5 - IMPROVED INLET DESIGN

5.1. INTRODUCTION

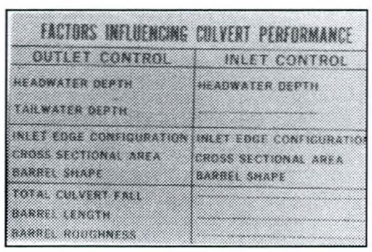


5.1

As discussed in Lesson 4, culverts operate in either outlet or inlet control. Furthermore, various culvert characteristics influence culvert performance under these two conditions. If performance can be improved, the initial cost of the culvert may be reduced.

A. Culvert Performance Factors

Eight factors are involved in outlet control, but only four in inlet control. For either case, what can be done to improve culvert performance?



FACTORS INFLUENCING CULVERT PERFORMANCE

OUTLET CONTROL	INLET CONTROL
HEADWATER DEPTH	HEADWATER DEPTH
TAILWATER DEPTH	
INLET EDGE CONFIGURATION	INLET EDGE CONFIGURATION
CROSS SECTIONAL AREA	CROSS SECTIONAL AREA
BARREL SHAPE	BARREL SHAPE
TOTAL CULVERT FALL	
BARREL LENGTH	
BARREL ROUGHNESS	

5.2

1. Outlet Control Factors

- Headwater depth - usually fixed.
- Tailwater depth - usually fixed.
- Inlet edge configuration - Entrance loss coefficient varies from 0.2 to 0.9.
- Cross sectional area - Performance improves with larger cross sectional area.
- Barrel shape - A "short, fat" culvert offers better performance.

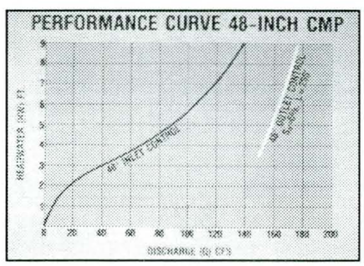
- Total culvert fall - Usually fixed.
- Barrel length - Usually not subject to change.
- Barrel roughness - Smoother conduit improves performance.

Outlet control culvert operations are not subject to much improvement by adjustment of any factors.

2. Inlet Control Factors

- Headwater depth - Usually fixed.
- Cross sectional area - Any increase in area usually entails an increase in initial cost.
- Barrel shape - Same as for outlet control.
- Inlet edge configuration - Only the inlet configuration may profitably be improved to enhance hydraulic performance and ultimately decrease initial cost.

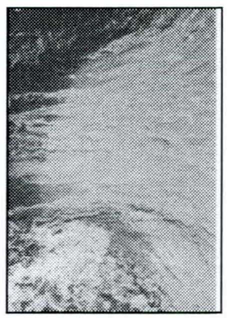
- This performance curve illustrates the problem. For a given HW the outlet control condition passes more water. The inlet is preventing the barrel from reaching its capacity. If the entrance can be improved so that it more nearly matches that of the barrel, a better design will result.



5.3

5.4

B. Flow Constriction caused by inlet edge condition

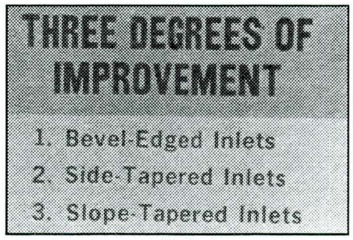


5.5

Flow constriction due to inlet causes turbulence. Eddies represent areas where flow is not being conveyed. Only about one-half the culvert area is being used for flow conveyance.

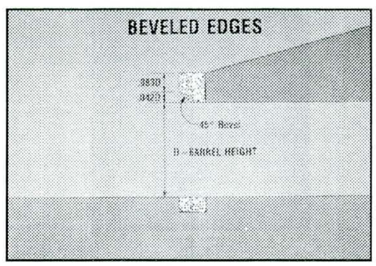
5.2. INLET IMPROVEMENT

There are three degrees of inlet improvement discussed in HDS#5. These are bevel, side, and slope-tapered inlets.



5.6

A. Bevel-Edged Inlets



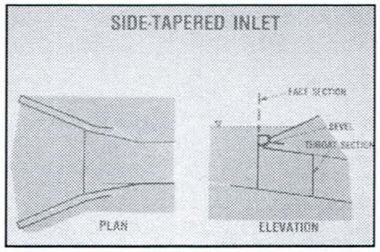
5.7

The first degree of inlet improvement is a beveled edge. This operates by increasing the area of flow and reducing the contraction effect at the inlet. Adding bevels to a conventional culvert design increases culvert capacity by 5 to 20 percent.

Although bevels are typically plane surfaces, rounded edges that approximate bevels would also be acceptable.

Bevels should be considered when designing all culverts.

B. Side-Tapered Inlets



5.8

The second degree of improvement is the side-tapered inlet. Such an improvement can increase the flow capacity from 25 to 40 percent over that of a conventional culvert with a square-edge inlet. This type of inlet has an enlarged face area with a tapered transition to the smaller culvert barrel. The inlet face has the same height as the barrel and its top and bottom are extensions of the top and bottom of the barrel. Two control sections are possible:

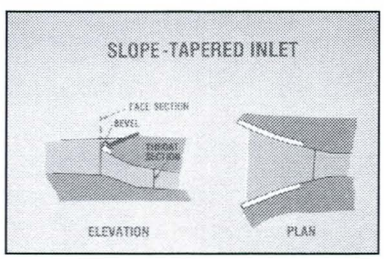
1. Face Control

   Face control implies that capacity is limited by the initial opening in the culvert (at the face).

2. Throat Control

   Throat control implies that the capacity of the culvert occurs at the throat (at the narrow part of the taper). The face has more capacity.

C. Slope-Tapered Inlets



5.9

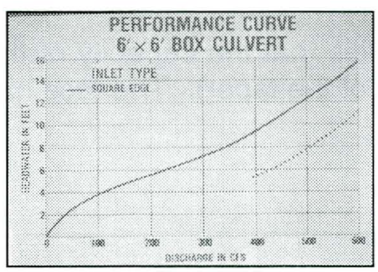
The third degree of improvement is the slope-tapered inlet. Its advantage over the side-tapered inlet is that more head is made available at the control (throat) section. This is accomplished by incorporating a sloped fall in the enclosed entrance section. As a result of this fall, the barrel slope of a culvert with a slope-tapered inlet is flater than the barrel slope of a conventional or side-tapered culvert at the same site.

This type of inlet can have a capacity over 100 percent greater than a conventional culvert with square edges.

The face and throat are both possible control sections in a slope-tapered inlet. The inlet face should be designed to have more capacity than the throat. This will minimize the barrel size necessary for the culvert.

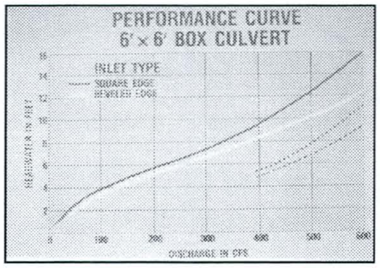
D. Comparative Example

Using a 6 X 6 box as an example, note the improvements in capacity shown in the following tables going from a conventional (non-improved) design to a slope-tapered inlet. The inlet and outlet performance curves for the conventional culvert are shown first:



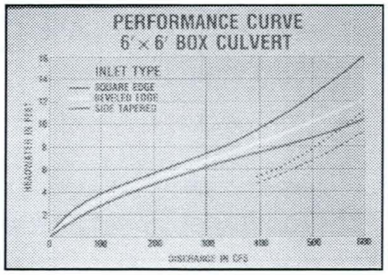
5.10

Adding a bevel at the entrance shifts both inlet and outlet curves to the right. The bevel improves the capacity of a culvert in both inlet and outlet control. However, additional inlet improvements will not measurably change outlet performance.



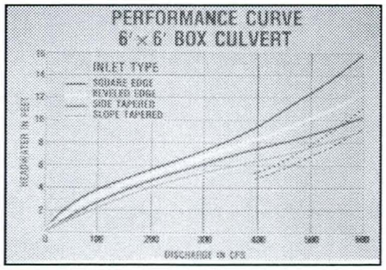
5.11

With a side-taper the inlet control curve shifts further to the right:



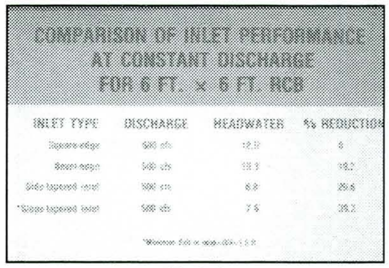
5.12

Adding a slope-taper provides even more improvement:



5.13

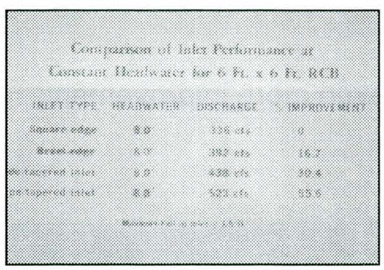
The various changes can be understood by evaluating headwater reductions for a given discharge:


COMPARISON OF INLET PERFORMANCE AT CONSTANT DISCHARGE FOR 6 FT. × 6 FT. RCB

5.14

Inlet Type	Discharge	Headwater	% Reduction
Square Edge	500 cfs	12.5 ft.	0
Bevel-Edge	500 cfs	10.1 ft.	19.2
Side-Tapered Inlet	500 cfs	8.8 ft.	29.6
Slope-Tapered Inlet	500 cfs	7.6 ft.	39.2

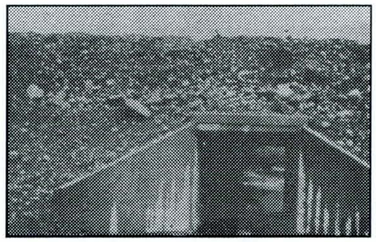
And, by evaluating increased discharge capacity for a given headwater:


Comparison of Inlet Performance at Constant Headwater for 6 Ft. x 6 Ft. RCB

5.15

Inlet Type	Headwater	Discharge	% Improvement
Square Edge	8.0 ft.	336 cfs	0
Bevel-Edge	8.0 ft.	392 cfs	16.7
Side-Tapered Inlet	8.0 ft.	438 cfs	30.4
Slope-Tapered Inlet	8.0 ft.	523 cfs	55.6

5.3. IMPROVED INLET DESIGN - BOX CULVERT



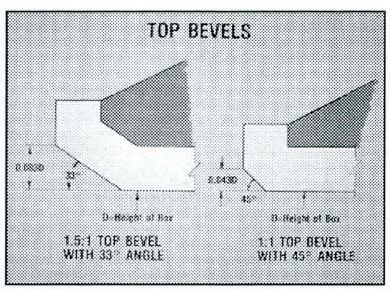
5.16

A. Bevel-Edged Treatment

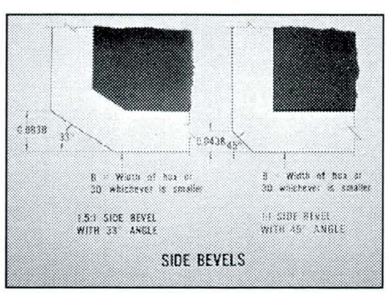
A bevel treatment is relatively inexpensive and should be considered for all box culvert designs. The bevel should be on both the top and the two sides to a culvert barrel.

If wingwalls are used, a side bevel is not necessary if the wingwall is 30-75 degrees. If the wingwalls are flared more than 75 degrees, a bevel should be used.

1. Top and Side Bevel Dimensions



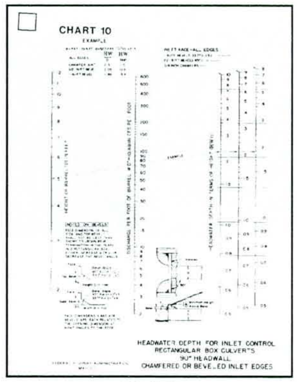
5.17



5.18

1.5 to 1 (33°) and 1 to 1 (45°)

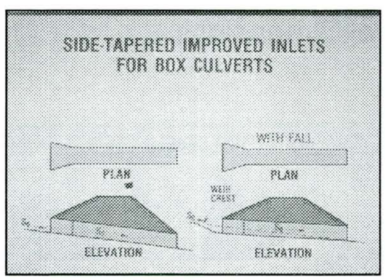
2. Hydraulic Capacity



5.19

HDS#5 Charts 9 through 11.

B. Side-Tapered Entrance Types: Conventional and with Fall

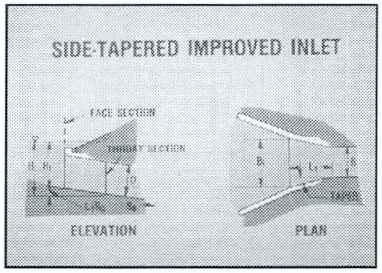


5.20

To achieve fall, the culvert is rotated about the outlet invert so that the face and throat are depressed below the stream bed. This puts more head on the control section and increases culvert capacity.

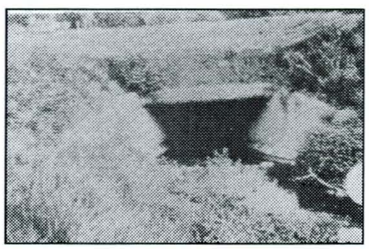
1. Conventional Side-tapered Design Procedure

Slide 5.21 illustrates the design parameters for a conventional side-tapered inlet. The first step in the design is to find the culvert width, and then use the appropriate design chart to define the face width B_f. Given these two widths and a transition taper of either 4:1 or 6:1, the entrance length L_1 is defined.



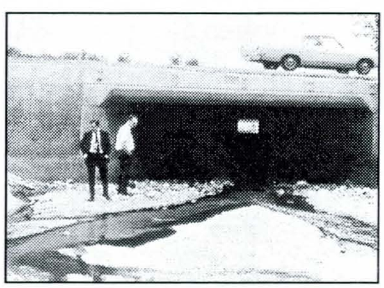
5.21

Slide 5.22 illustrates an early side-tapered entrance built in Virginia. The top bevel was built as a radius, which performs essentially the same as a bevel, and the wingwall angle eliminated the need for side bevels.



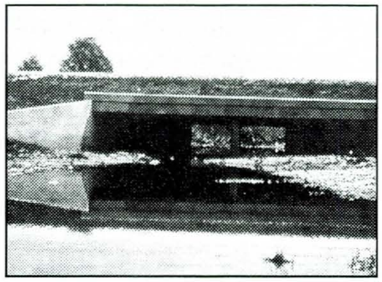
5.22

This structure, built on Interstate 95 north of Washington, D.C., shows a much larger side-tapered structure.



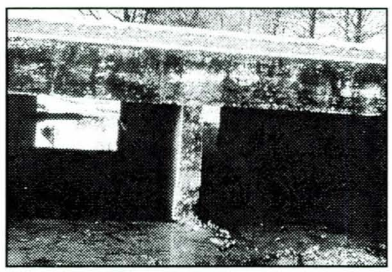
5.23

Side-tapered inlet in Tennessee:



5.24

This is the outlet of the same culvert - note the old concrete. The highway department took advantage of widening the roadway to add on the side-tapered entrance and thus increase the capacity of the existing double barrel culvert. This can be viewed as a maintenance improvement.

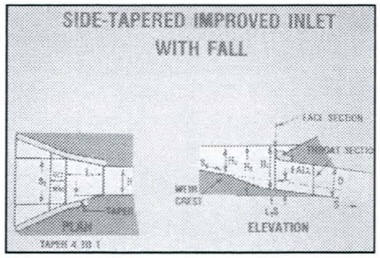


5.25

2. Design Procedure for a Side-tapered Entrance with Fall

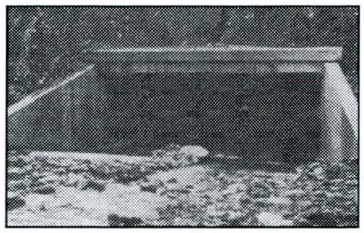
By introducing a fall, the culvert slope S is flatter than the channel slope. The culvert is bascially rotated about the outlet to achieve the fall so that the face and throat are depressed below the stream bed. This provides a greater depth of water in the control section and an increase in culvert capacity.

The culvert slope should extend upstream of the culvert for a distance D/2, before transitioning back to the streambed at a slope of 2:1 or 3:1. The length of the crest at the channel should be long enough that the crest does not control the flow.



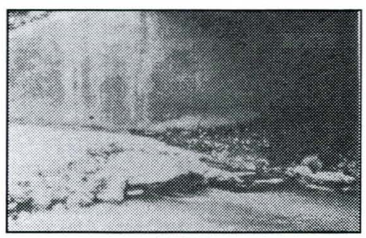
5.26

Side-tapered entance with fall. This apron does not extend D/2 upstream, as this culvert was built before that criteria.



5.27

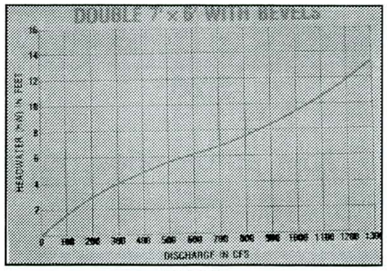
Note the sediment deposition in the bottom of the culvert. This may or may not be a problem, depending on the circumstances.



5.28

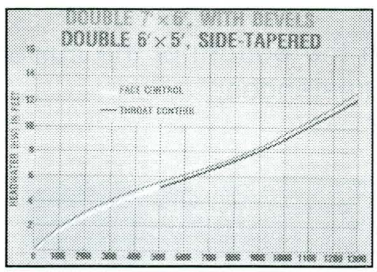
3. Performance Curves (Examples)

Initial design:



5.29

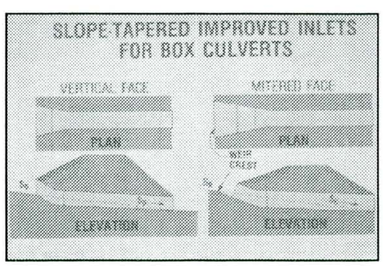
With a side-tapered entrance, the performance can be increased to the point that only a double 6x5 is necessary to match the performance of the original double 7x6:



5.30

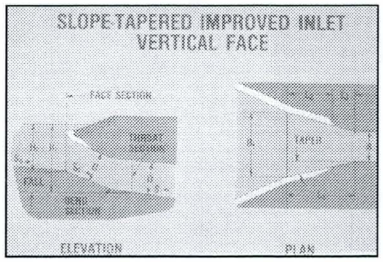
C. Slope-Tapered Entrance Type

Slope-tapered entrances can have a vertical face or a mitered face:



5.31

1. Vertical Face

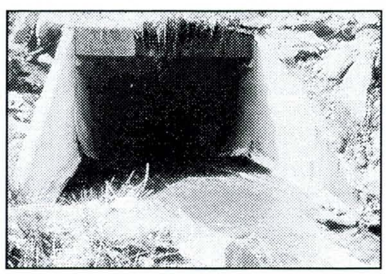


5.32

Additional parameters for this type of entrance are:

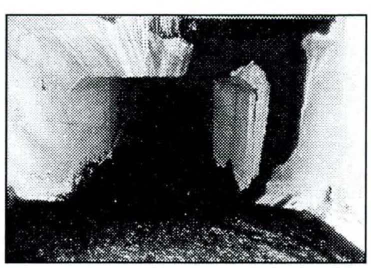
- Stream bed slope (S_o),
- Total length of the slope-tapered inlet (L_1),
- Distance between the face and the top of the bend section (L_2),
- Distance from the bend to the throat (L_3). L_3 is the distance along the top of the culvert from the bend to the throat and has to be a minimum of 1/2 of the width of the culvert (B/2). L_3 is used to define L_1 and L_2.

Example of a slope-tapered inlet:



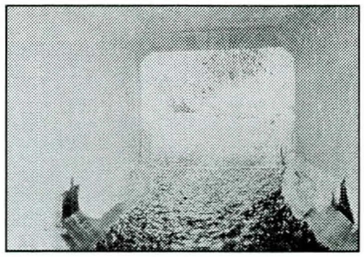
5.33

A closer look shows the top of the bend section and the throat section:



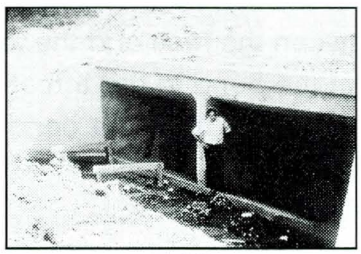
5.34

On the inside, the details of the breaks can be seen.



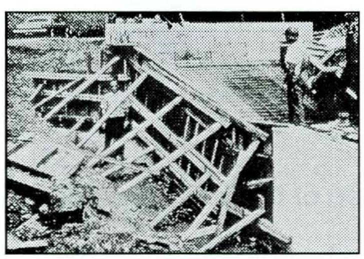
5.35

A slope-tapered inlet can be used on a double barrel culvert. The middle wall may be treated in any way (square, rounded, beveled) as the hydraulics are unaffected; however, the face width must be increased by the width of the wall.



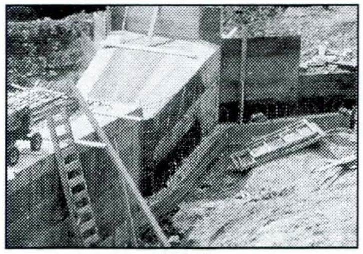
5.36

Construction may not be complicated or costly. The additional costs of construction may be averaged into the bid prices for all concrete and steel on the job.



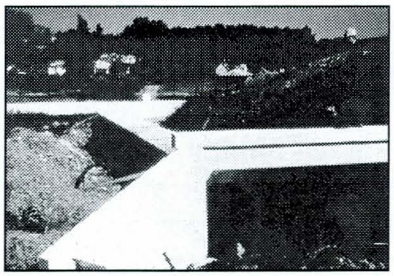
5.37

From the side, the form height is the same height as the barrel of the culvert. The contractor could use the same forms in both positions with a little bit of odd form work at the junction of the two:



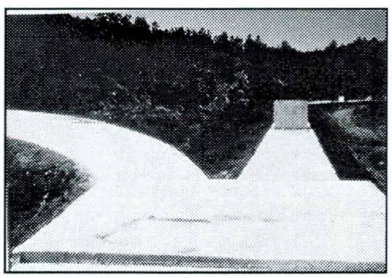
5.38

Slope-tapered example in Georgia, where two slope-tapered entrances come together in a junction:



5.39

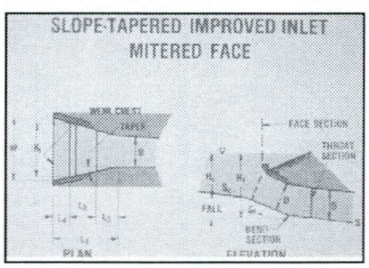
and then use the same outlet box:



5.40

2. Mitered Face

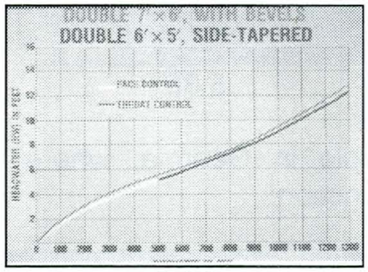
   The crest width (W) on a mitered face provides an additional possible control location. It is important to make the crest width on a mitered slope-tapered inlet conservative so that it cannot be the controlling section. The throat should control the flow.



5.41

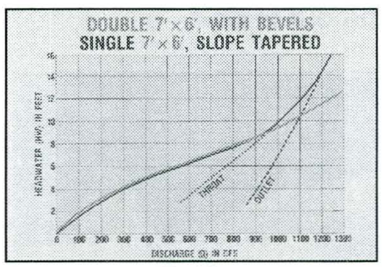
3. Slope-tapered Performance Curves (Examples)

Starting where the side-tapered inlet left off:



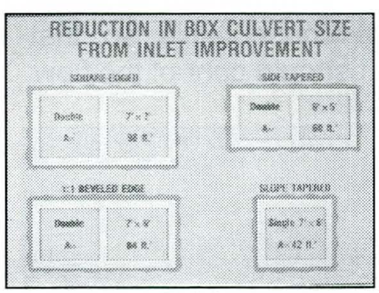
5.42

Adding all the curves for a slope-tapered inlet...the outlet control curve (for the barrel, which ultimately controls culvert performance) is the dashed line on the far right. The throat control curve is the dotted line just to the left. For low flows the face will control culvert performance.



5.43

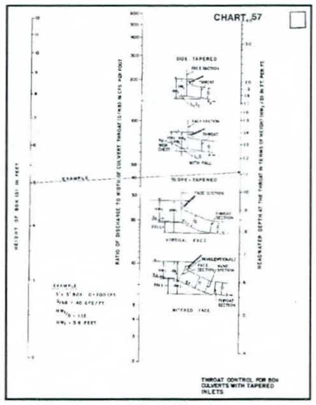
The end result is that with a slope-tapered inlet performance is increased to the point that only a single 7x6 culvert is required. Slide 5.44 illustrates the change in area that results when using inlet improvements:



5.44

4. Slope-tapered Inlet Design Procedure

A slope-tapered inlet is designed by first determining the minimum barrel size which will pass the design discharge in outlet control. One nomograph then defines the throat elevation, or fall, required, and a second is used to conservatively size the face.



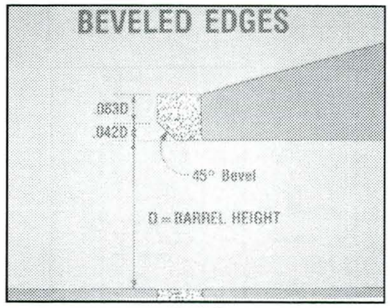
5.45

Refer to Chart No. 57 in HDS #5 for a graphical relation of headwater, geometry, and discharge for box culverts with tapered inlets.

5.4. IMPROVED INLET DESIGN - PIPE CULVERT

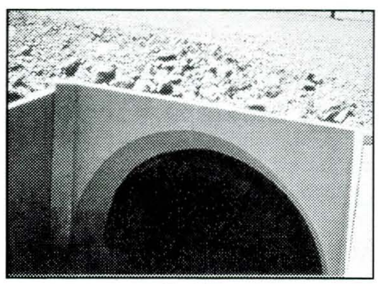
A. Bevel-Edged Treatment

The size of the bevel is a function of pipe diameter (D):



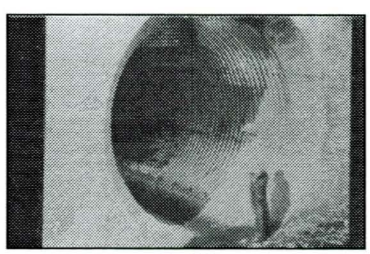
5.46

Example of a bevel:



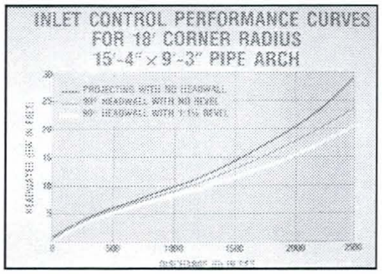
5.47

Example of a bevel on a large, structural plate arch culvert:



5.48

Example of the improvement by using a bevel:

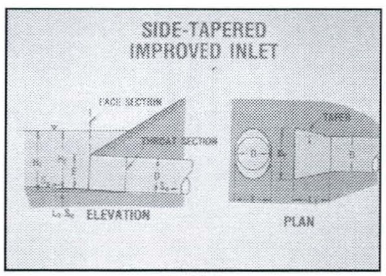


5.49

Bevels for pipe are similar as those for box culverts. Bevels can also be applied profitably to other shapes (arches and ovals, e.g.).

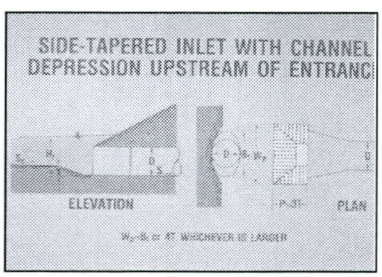
B. Side-Tapered Entrance

A side-tapered entrance for a pipe is similar to that for a box culvert. The only difference is that the shape is elliptical and the face height (E) is limited to 10 percent greater than the pipe diameter (D):



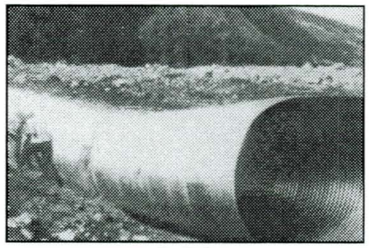
5.50

For a side-tapered inlet with fall, the sump dimensions must be as indicated:



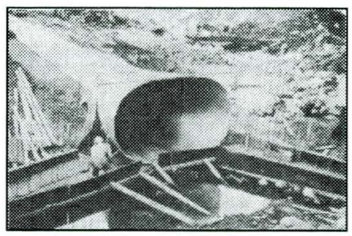
5.51

Side-tapered inlet on a 78-inch CMP:

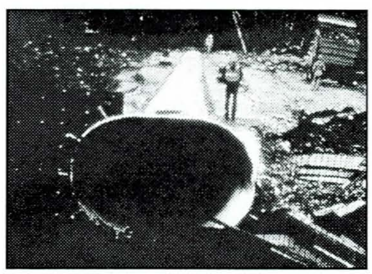


5.52

The face of this inlet is 124 inches by 83 inches:



5.53

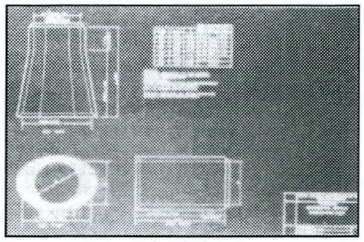


5.54

Example of a side-tapered inlet on RCP:

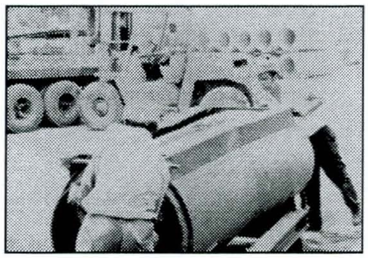
5.55

Concrete pipe manufacturers are reluctant to supply side-tapered entrances of varying dimensions. Therefore, standards and/or shop drawings must be provided so that local manufacturers will only have to build one set of forms for each pipe diameter.



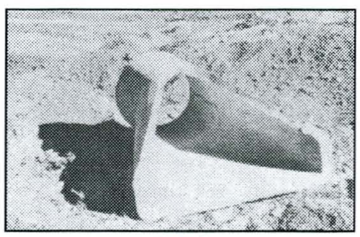
5.56

Example of forms used in a Georgia fabrication plant:



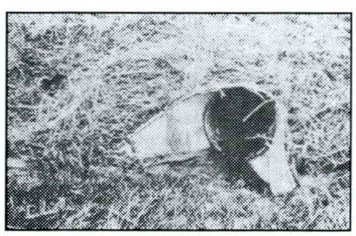
5.57

Note that this is not an improved entrance; rather, it is a terminal end section:



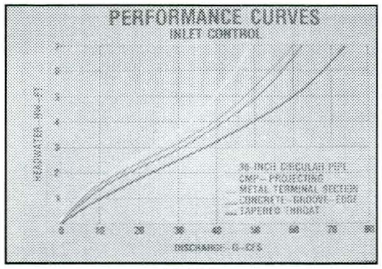
5.58

This is also not an improved end section. Terminal end sections can improve performance, but not as much as a side-tapered entrance.



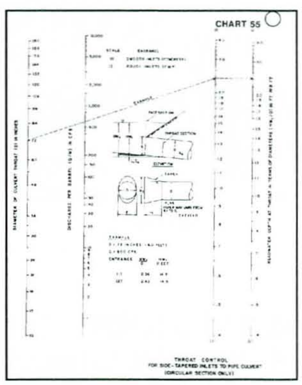
5.59

To illustrate the differences, consider the following performance curves for 30 inch circular pipe. Shown here are performance curves for the different end sections on a 30" circular pipe. Using headwater of 3 feet, or 6 inches over the top of the pipe, we see on curve number one that the metal pipe projecting out of the fill, will carry around 25 cfs. If we add the terminal end section curve 2, we find we have increased the capacity up to about 29 cfs. Now, if we had taken the same area of concrete pipe--the groove end being a very efficient end section-- we find that the pipe will carry 32 cfs. If we add a side-tapered entrance to either one of these, the pipe will carry about 36 or 37 cfs.



5.60

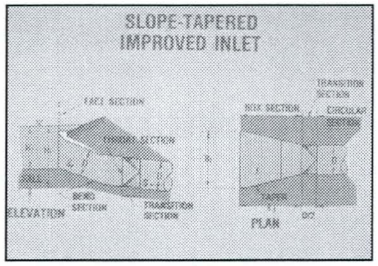
Side-tapered inlets for pipe culverts are designed the same as for box culverts. The barrel is sized assuming outlet control, full barrel flow and then the appropriate throat control curve is used to size the inlet.



5.61

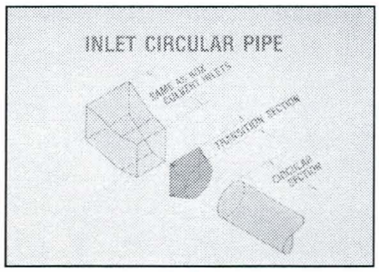
C. Slope-Tapered Entrance

A slope-tapered inlet for circular pipe is geometrically complex and difficult to construct. To simplify design and construction, a standard box culvert slope-tapered inlet is used with a transition section to the circular pipe.



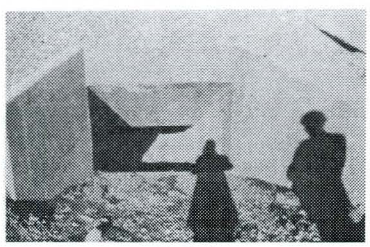
5.62

The design concept can be illustrated by a schematic:



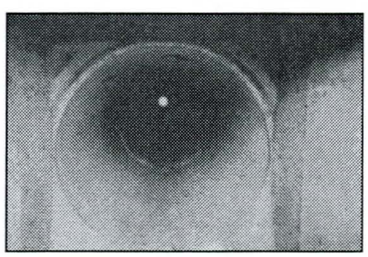
5.63

An example of a pipe culvert slope-tapered inlet in Nevada:



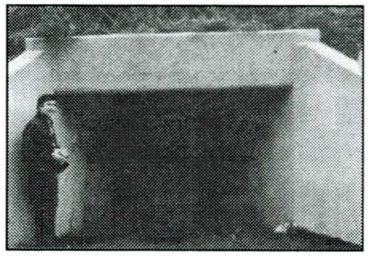
5.64

A close up view shows the transition to 48 inch RCP:



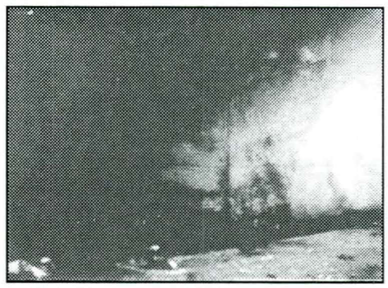
5.65

An example of a slope-tapered inlet to a circular RCP in Kentucky:



5.66

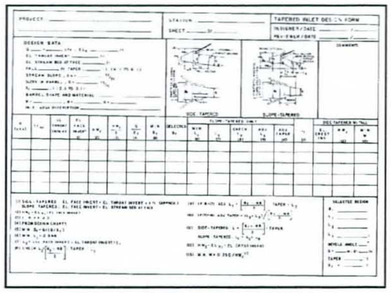
A close up view show the sloping floor and the fall slope:



5.67

5.5. GENERAL DESIGN CONSIDERATIONS

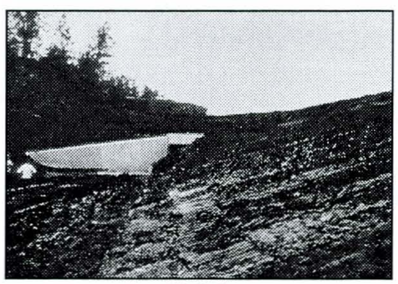
A. Inlet Control Computation Sheet. To aid in design of improved entrances a set of design computation sheets is used, one of which is the inlet control computation sheet (see forms on pages 241 and 242 in HDS 5).



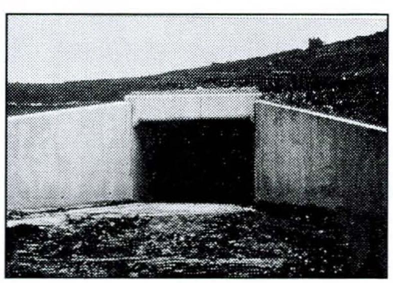
5.68

The first step is to select the size of the throat to be used. Then design either a side-tapered face or a slope-tapered face using the Inlet Control computation sheet.

B. Skewed Culverts. The face of a culvert with an improved inlet must be perpendicular to the flow (and, therefore, to the conduit). For a culvert that is skewed to the roadway, some warping of the embankment material may be necessary. This may require some special construction efforts and techniques:

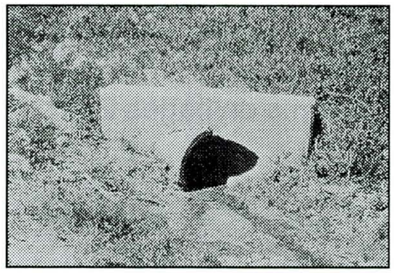


5.69



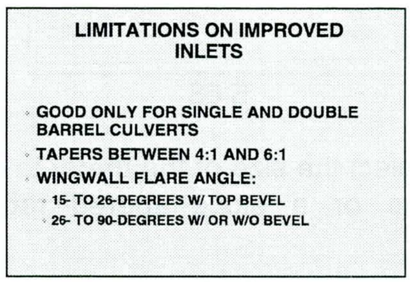
5.70

Some unusual designs may result:



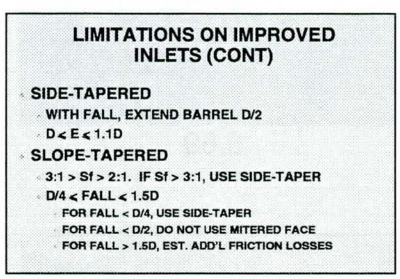
5.71

C. Limitations on improved inlets.



5.72

- Improved inlets are only good for single and double barrel culverts. If the W/D > 3, the benefits of an improved entrance decline since the contraction effect becomes less significant.
- taper must be between 4:1 and 6:1. Less divergent tapers may be used, but performance will be underestimated.
- Wingwall flare angle range from 15- to 26-degrees with top edge beveled, or from 26- to 90-degrees with or without bevels



5.73

- Side-tapered inlets:
  - ⇒ If FALL is used upstream of the face, extend the barrel invert slope upstream fro the face a distance of D/2 before sloping upward more steeply. The maximum vertical slope of the apron is 2:1.
  - ⇒ The height of the taper should be between D and 1.1D.

- Slope-tapered inlets:
  - ⇒ S_f must be between 2:1 and 3:1. If S_f > 3:1, use side-tapered design.
  - ⇒ Min L_3 = 0.5B
  - ⇒ Allowable fall is between D/4 and 1.5D. For fall < D/4, use side-tapered design. For fall < D/2, do not use a mitered face. For fall > 1.5D, estimate friction losses between the face and throat, and add these losses to Hw_t.

5.6. STANDARD DESIGNS

5.74

Standard structural designs for tapered inlets are found in the FHWA publication Structural Design Manual for Improved Inlets and Culverts, FHWA-IP-83-6

Included designs are:

- Side-tapered Single Cell Box Inlets.
- Side-tapered Two Cell Box Inlets.
- Slope-tapered Single Cell Box Inlets.
- Slope-tapered Two Cell Box Inlets.
- Side-tapered Pipe Inlet (Concrete).
- Side-tapered Corrugated Metal Inlet.
- Headwall Details for Box Inlets.
- Headwall Details for Pipe Inlets.
- Cantilever Wingwall Designs.

- Miscellaneous Improved Inlet Details.
  - Apron with Wingwalls < 60°.
  - Apron with Wingwalls at 60° - 90°.
  - Circular to Square Transitional Detail.
  - Skewed Headwall Details.

Also included in FHWA-IP-83-6 are structural design methods and related design computer programs (e.g. BOXCAR and PIPECAR).

5.7 WORKSHOP 5 - IMPROVED INLET DESIGN

PROBLEM STATEMENT

A new culvert has been designed to provide cross drainage for a realignment project. The design discharge was the 50-yr event with a discharge of 400 cfs. The inlet invert elevation was set at elevation 90 ft because of a utility line crossing at the upstream face. The maximum allowable headwater elevation was 100 ft. because of an existing commercial area on the right bank upstream of the new alignment. The culvert will be 160 ft long on a slope of 0.04, and so the outlet invert elevation will be at 83.6 ft.

The project was originally designed for a 6x6 RCB culvert with a square edge entrance, which resulted in inlet control with a headwater elevation of 99.6, and an outlet velocity of 29 fps. The tailwater condition is a grass-lined channel with an 8-ft bottom width, 2:1 sideslope, 4 percent bed slope and Manning's n = 0.032. Normal depth calculations determined a tailwater depth of 2.4 ft for the design discharge. The outlet velocity from the culvert is too high for a grass lined channel, and so an energy dissipator is currently under design.

A quality control review has suggested that an improved inlet may be cost effective for this crossing. The quality control reviewers have suggested the following three alternatives be considered:

1. 6x5 RCB with a beveled edge entrance.
2. 5x5 RCB with a side-tapered entrance.
3. 5x4 RCB with a slope-tapered entrance.

REQUIRED SOLUTION

For the given conditions, evaluate culvert performance for each suggested alternative.

GENERAL SOLUTION PROCEDURE

Step 1. Complete the inlet and outlet control calculations for the new alternatives. These calculations can be added to the Culvert Design Form completed for the original design.

Step 2. If the hydraulic analysis completed in Step 1 for the 6x5 beveled entrance meets the allowable headwater criteria, complete the calculations to size the bevels.

Step 3. If the hydraulic analysis completed in Step 1 for either tapered alternative (5x5 side-tapered or 5x4 slope-tapered) meet the allowable headwater criteria, complete the Tapered Inlet Design Form to size the taper.

PROJECT : WORKSHOP 5

STATION : ______

SHEET ____ **OF** ____

CULVERT DESIGN FORM

DESIGNER / DATE : ______ / ______

REVIEWER / DATE : ______ / ______

HYDROLOGICAL DATA

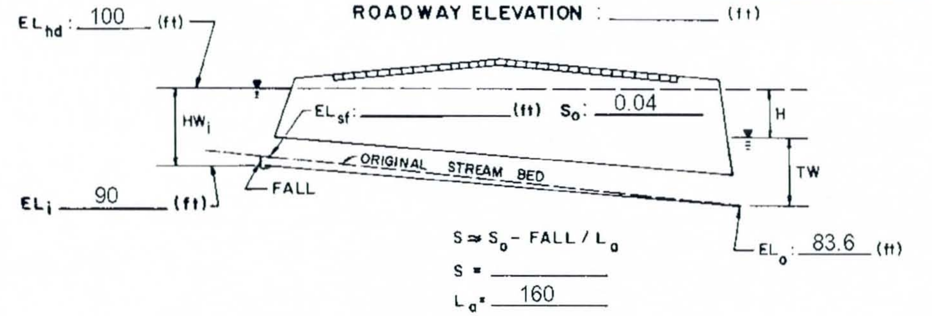
SEE ADD'L SHTS.

- ☐ METHOD: ______
- ☐ DRAINAGE AREA: ______ ☐ STREAM SLOPE: ______
- ☐ CHANNEL SHAPE: ______
- ☐ ROUTING: ______ ☐ OTHER: ______

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	400	2.4

ROADWAY ELEVATION : ______ (ft)



$S = S_o - FALL / L_a$

S = ______

L_a = 160

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c + D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
RCB 6X6 SQ EDGE	400	67	1.6	9.6	--	99.6	2.4	5.2	5.6	5.6	0.5	3.8	93.0	99.6	29	INLET CONTROL
RCB 6X5 1:1 BEVEL																
RCB 5X5 SIDE TAPERED																
RCB 5X4 SLOPE TAPERED																

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW/D$ OR HW_f/D FROM DESIGN CHARTS

(3) $FALL = HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS :

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION :

CULVERT BARREL SELECTED :

SIZE: ______

SHAPE: ______

MATERIAL: ______ n: ______

ENTRANCE: ______

PROJECT: ______________________

____

STATION: ______________________

SHEET ______ OF ______

TAPERED INLET DESIGN FORM

DESIGNER / DATE: __________ / __________

REVIEWER / DATE: __________ / __________

DESIGN DATA:

Q ______ = ______ cfs ; EL_{hi} __________ ft

EL. THROAT INVERT __________ ft

EL. STREAM BED AT FACE __________ ft

FALL __________ ft TAPER __________ : 1 (4:1 TO 6:1)

STREAM SLOPE, So = __________ ft/ft

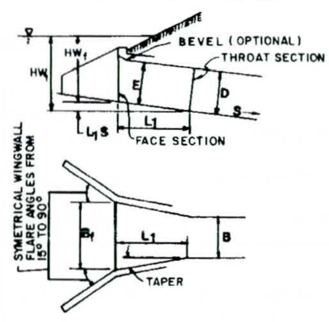
SLOPE OF BARREL, S = __________ ft/ft

S_f __________ : 1 (2:1 TO 3:1)

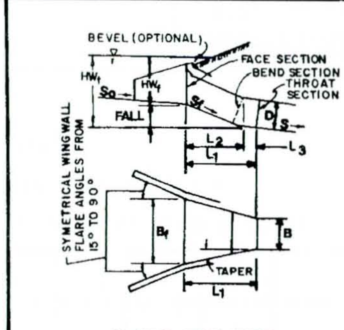
BARREL SHAPE AND MATERIAL: __________

N = __________, B = __________, D = __________

INLET EDGE DESCRIPTION __________



SIDE-TAPERED



SLOPE-TAPERED

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hi}$ - EL. FACE INVERT

(3) $1.1D \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_3 = 0.5NB$

(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot TAPER - L_3$

(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot TAPER - L_2$

(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot TAPER$
SLOPE-TAPERED: $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = 0.35Q / HW_c^{1.5}$

SELECTED DESIGN

B_f __________

L_1 __________

L_2 __________

L_3 __________

BEVELS ANGLE ______°

b = ______ in ; d = ______ in

TAPER ______ : 1

S_f = ______ : 1

PROJECT: ____________	STATION: ____________ SHEET ______ OF ______	TAPERED INLET DESIGN FORM DESIGNER / DATE: ________ / ________ REVIEWER / DATE: ________ / ________

DESIGN DATA:

Q _____ = _____ cfs ; EL_{hi} __________ ft

EL. THROAT INVERT __________ ft

EL. STREAM BED AT FACE __________ ft

FALL ________ ft TAPER ________ : 1 (4:1 TO 6:1)

STREAM SLOPE, So = __________ ft/ft

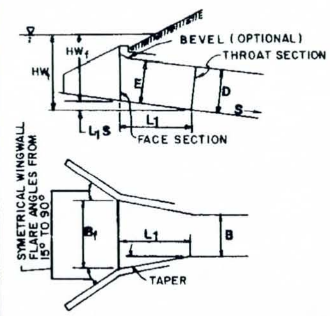
SLOPE OF BARREL, S = __________ ft/ft

S_f ________ : 1 (2:1 TO 3:1)

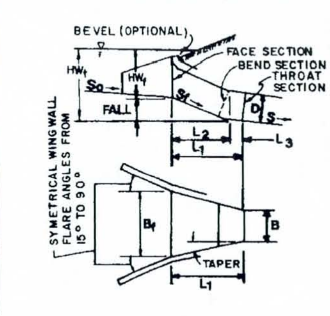
BARREL SHAPE AND MATERIAL: ______________

N = __________, B = __________, D = __________

INLET EDGE DESCRIPTION ______________



SIDE-TAPERED



SLOPE-TAPERED

COMMENTS

									SLOPE-TAPERED ONLY						SIDE-TAPERED W/ FALL		
Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	MIN. B_f (5)	SELECTED B_f	MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED: EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE-TAPERED: EL. FACE INVERT = EL. STREAM BED AT FACE

(2) HW_f = EL_{hi} - EL. FACE INVERT

(3) $1.1D \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_3 = 0.5NB$

(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot TAPER - L_3$

(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot TAPER - L_2$

(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED: $L = \left[\frac{B_f - NB}{2}\right] \cdot TAPER$
SLOPE-TAPERED: $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = 0.35Q / HW_c^{1.5}$

SELECTED DESIGN

B_f __________

L_1 __________

L_2 __________

L_3 __________ (

BEVELS ANGLE ______ °

b = _____ in; d = _____ in

TAPER ________ : 1

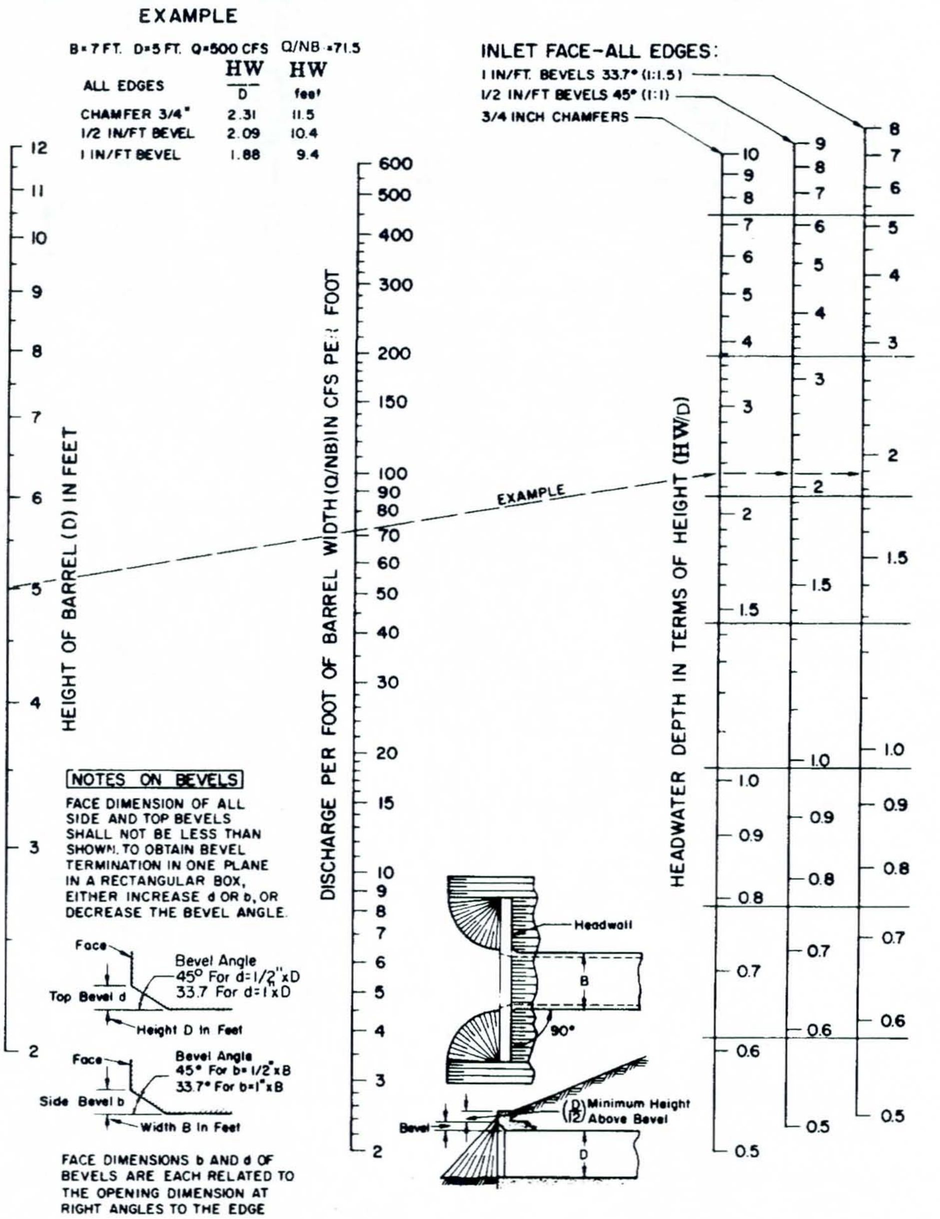
S_f = ________ : 1

DISCUSSION

The resulting headwater elevation for all three alternatives are very similar, and all three provide acceptable hydraulic performance. However, note that something as simple as adding a bevel allowed the culvert to be downsized from a 6x6 to a 6x5, which would result in a significant savings in construction cost. The value of the tapered inlet alternatives must be evaluated, in part, by comparing the cost of building a tapered inlet with the cost savings by further downsizing the barrell.

☐

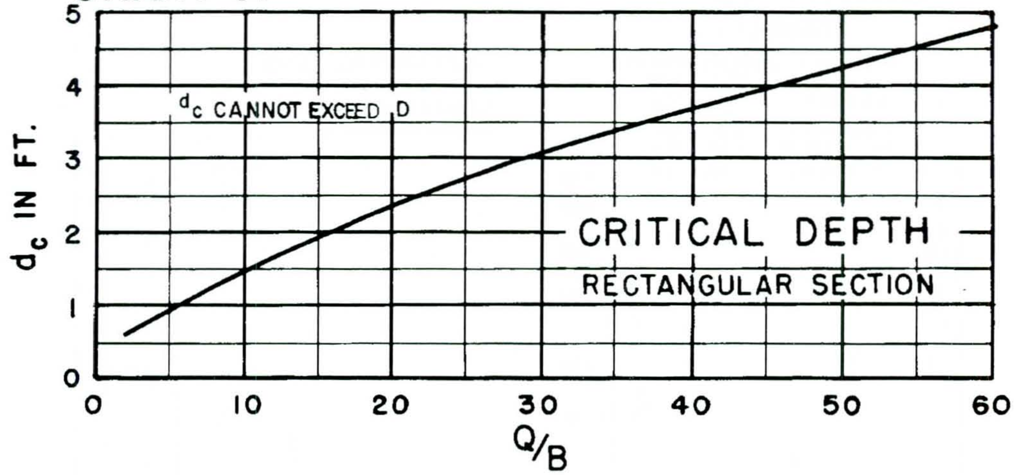
CHART 10

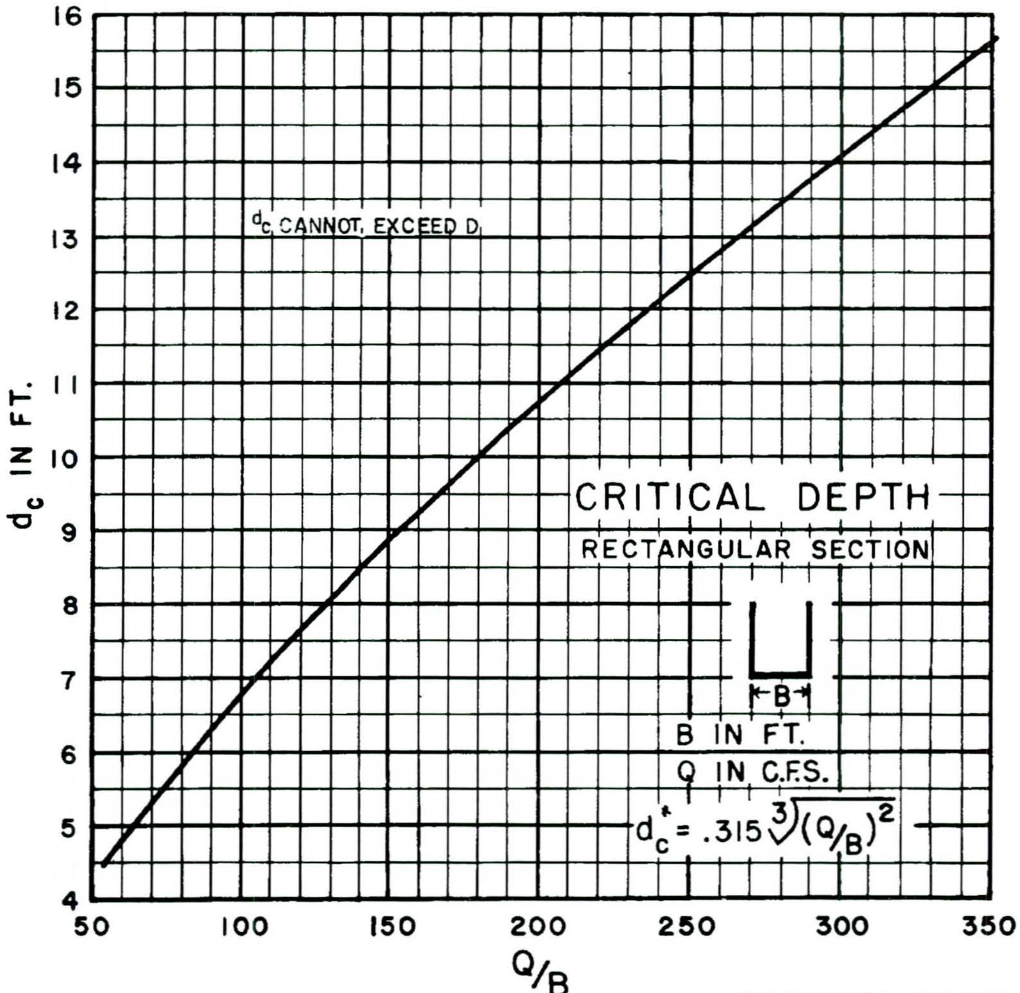


HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
90° HEADWALL
CHAMFERED OR BEVELED INLET EDGES

FEDERAL HIGHWAY ADMINISTRATION
MAY 1973

CHART 14



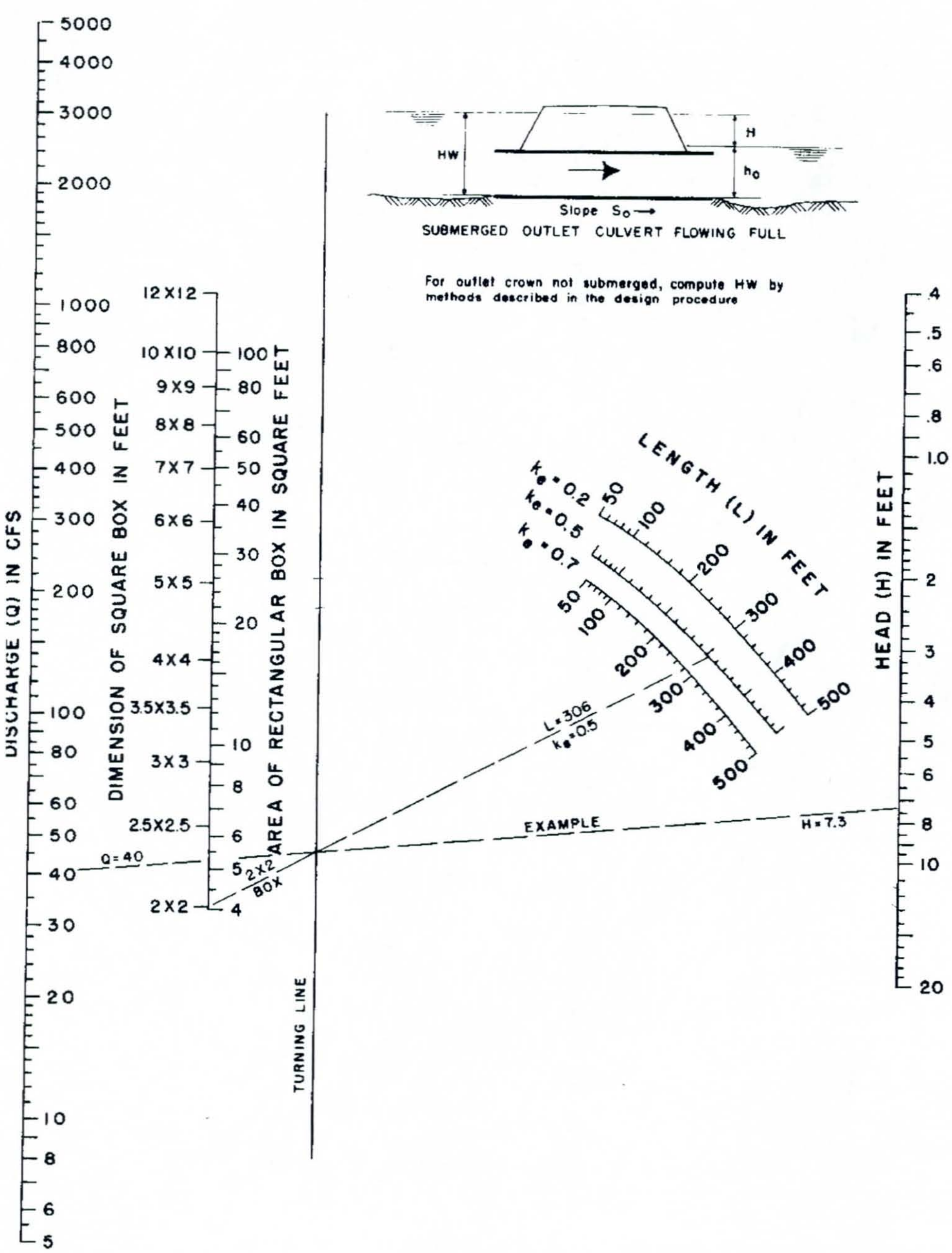


BUREAU OF PUBLIC ROADS JAN. 1963

5-38

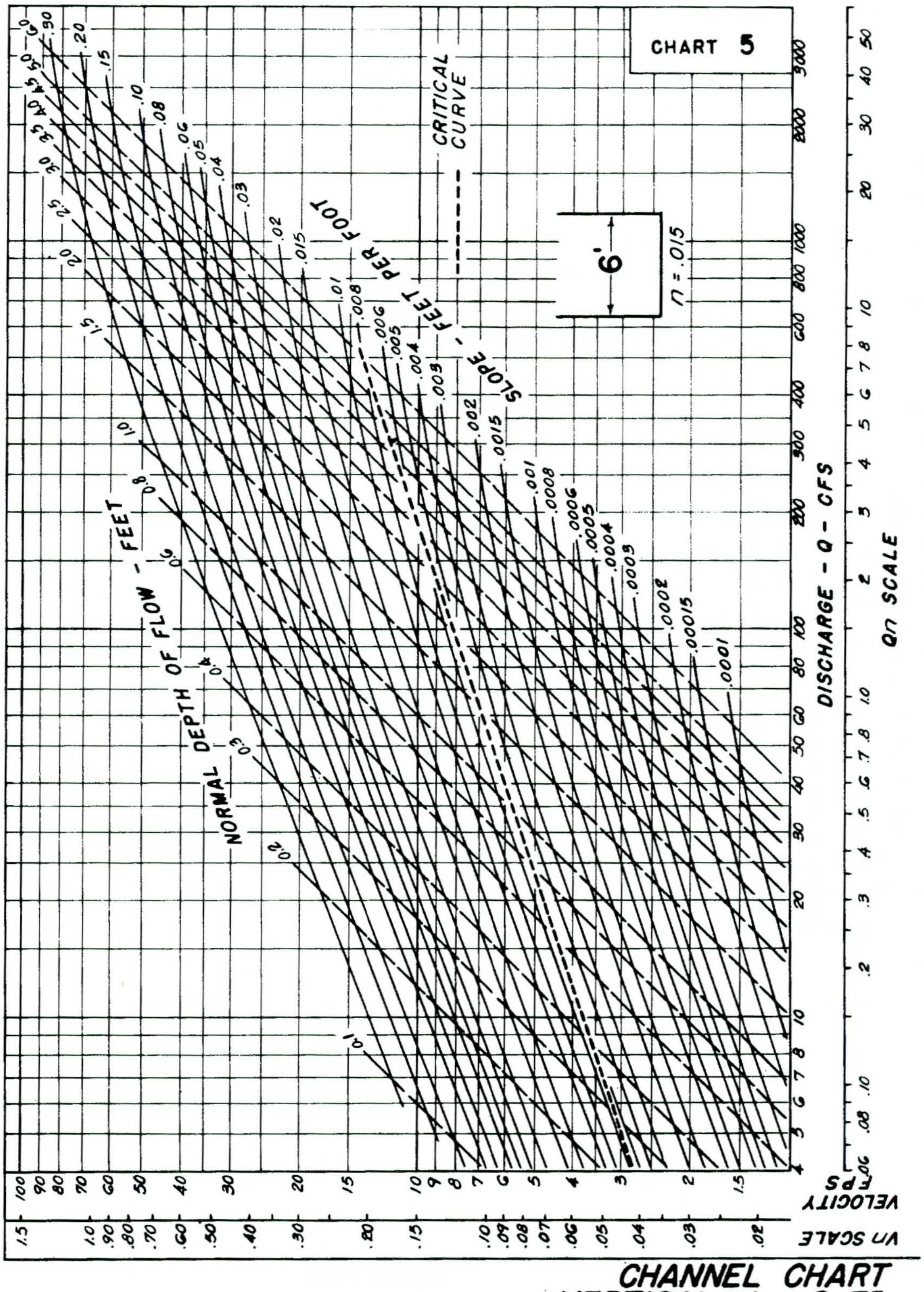
CRITICAL DEPTH
RECTANGULAR SECTION

CHART 15



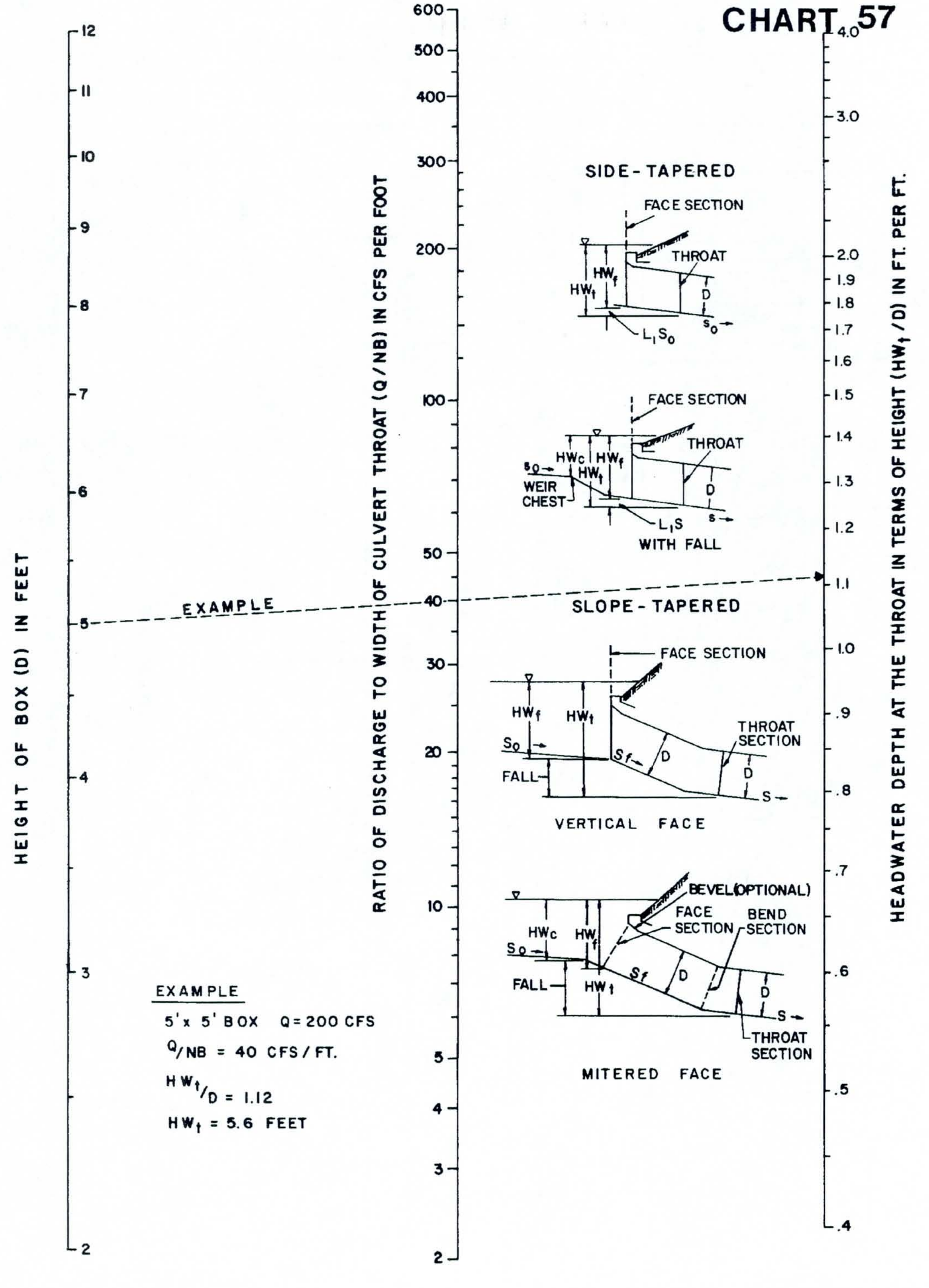
AU OF PUBLIC ROADS JAN. 1963

HEAD FOR
CONCRETE BOX CULVERTS
FLOWING FULL
n = 0.012

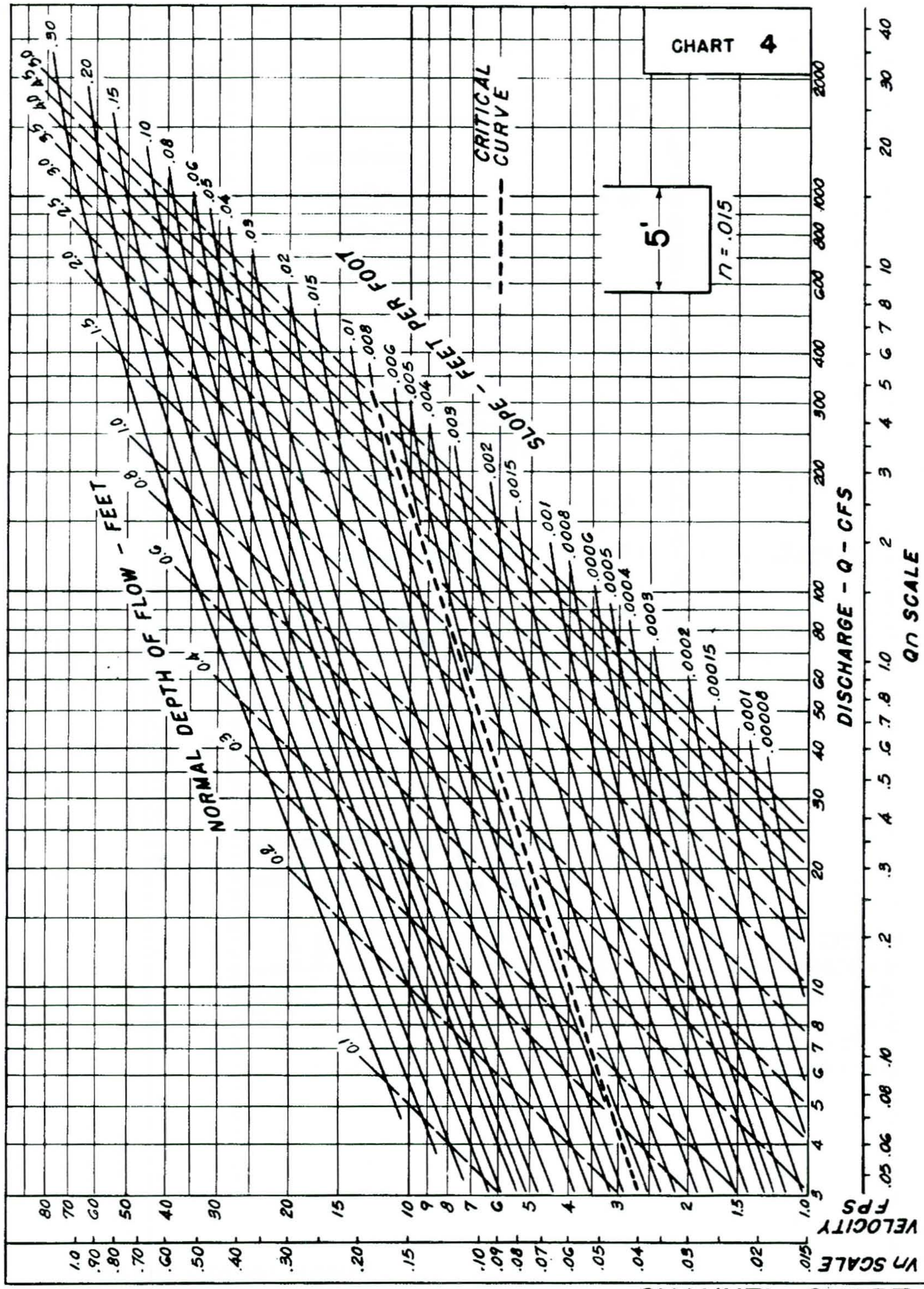


CHANNEL CHART
VERTICAL b = 6 FT.

CHART 57

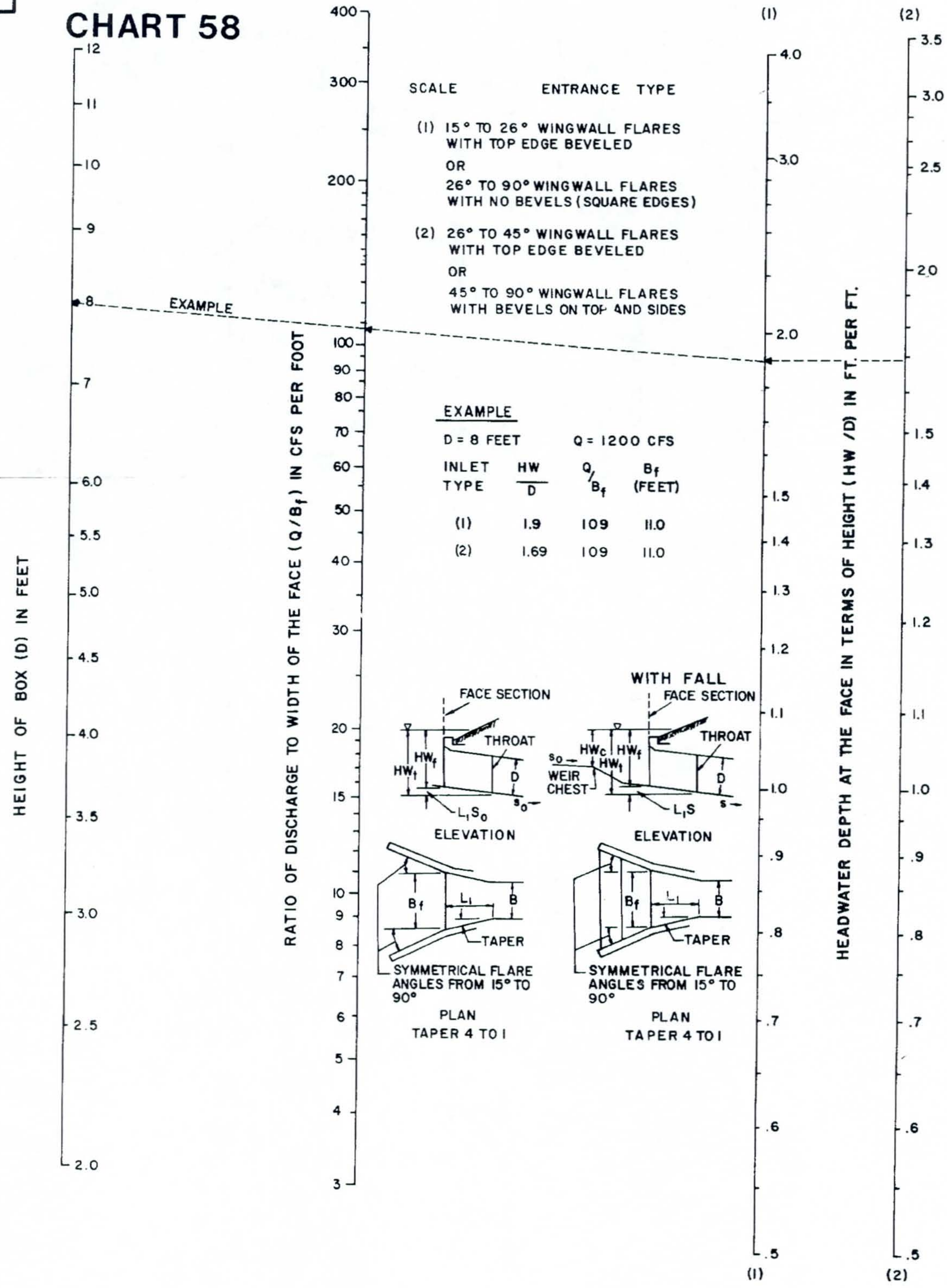


THROAT CONTROL FOR BOX CULVERTS WITH TAPERED INLETS



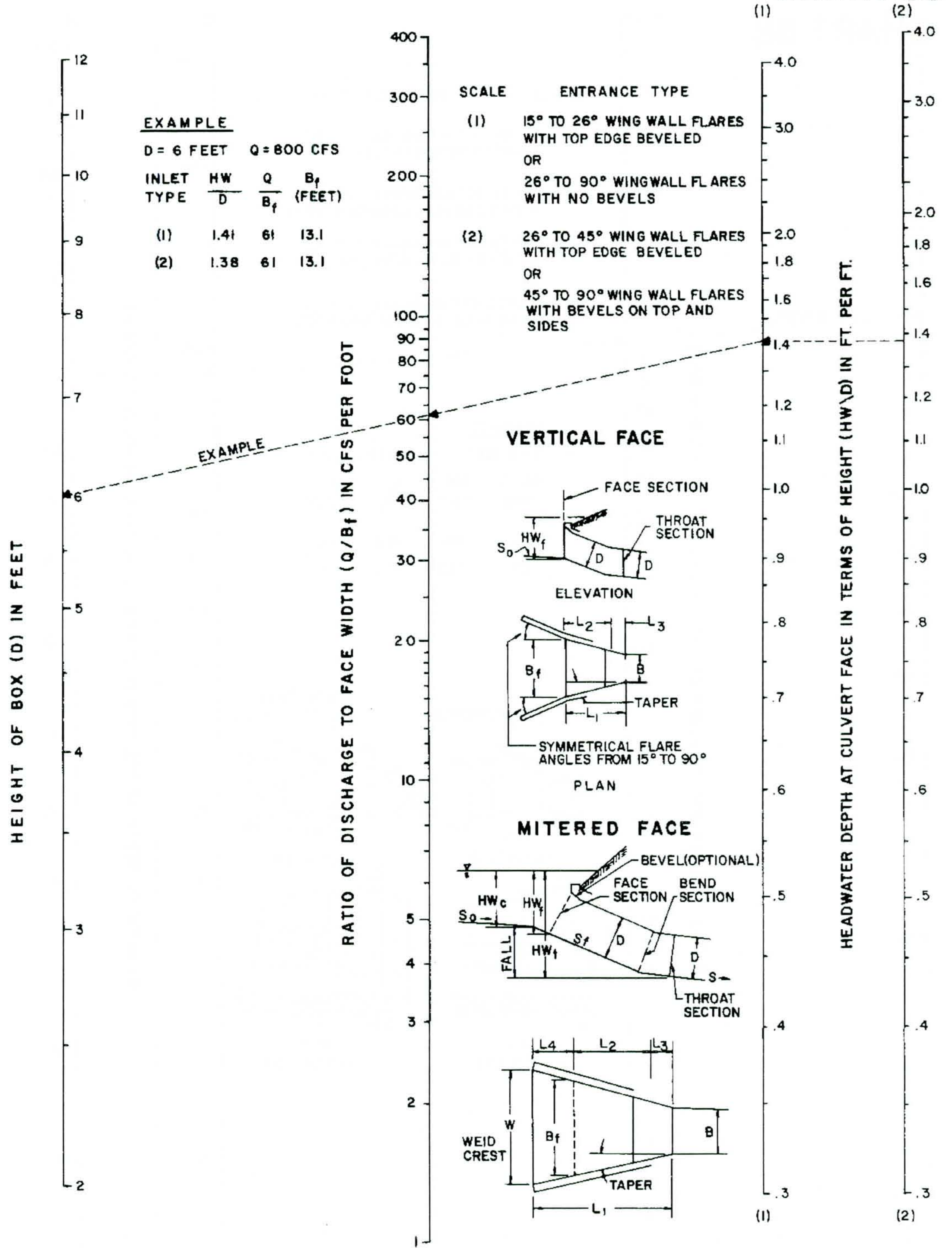
CHANNEL CHART
VERTICAL b = 5 FT.

CHART 58



FACE CONTROL FOR BOX CULVERTS WITH SIDE TAPERED INLETS

CHART 59



FACE CONTROL FOR BOX CULVERTS WITH SLOPE TAPERED INLETS

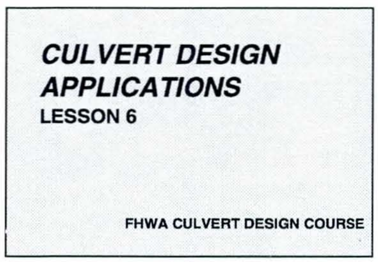
LESSON 6

CULVERT DESIGN APPLICATIONS

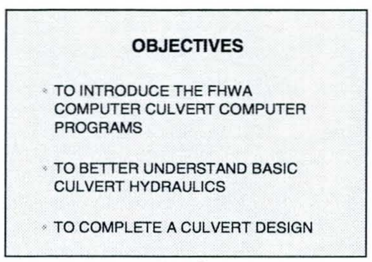
OVERVIEW: Method of Instruction: Lecture

Lesson Length: 300 minutes

Resources: Student Workbook
Computer Demonstration
Demonstration Flume



6.0a



6.0b

OBJECTIVES: At the conclusion of this lesson, the participant:

1. Will be familiar with FHWA computer programs commonly used to design culvert crossings.
2. Will better understand basic culvert hydraulic principles and design concepts that have been introduced in lecture, through the observation of flume demonstrations.
3. Will have an opportunity to design a culvert.

LESSON OUTLINE

6. CULVERT DESIGN APPLICATIONS

   6.1. INTRODUCTION

   6.2. COMPUTER APPLICATIONS: HDS-5 CD-ROM AND HY8

   6.3. WORKSHOP 6A - CONVENTIONAL CULVERT DESIGN USING CD-ROM AND HY8

   6.4. WORKSHOP 6B - IMPROVED INLET DESIGN USING CD-ROM AND HY8

   6.5. WORKSHOP 6C - FLUME DEMONSTRATION

   6.6. WORKSHOP 6D - DESIGN WORKSHOP

6.1 INTRODUCTION

A. This lesson is organized around three basic elements:

- a computer demonstration workshop,
- a flume demonstration, and
- a design workshop.

B. In the computer demonstration workshop, the conventional and improved inlet design problems from Workshops 4 and 5 will be solved using the CD-ROM version of HDS-5 and the computer program HY8.

C. In the flume demonstration the basic principles of culvert flow will be demonstrated and the impacts of various design considerations and decisions will be observed. This demonstration should solidify your understanding of basic culvert hydraulics and the design procedures for conventional and improved inlet design.

D. In the design workshop, you will divide into design teams and design a culvert crossing.

6.2 COMPUTER APPLICATIONS: HDS-5 CD-ROM AND HY8

A. The CD-ROM version of HDS-5 provides electronic equation boxes that solve the various design charts and nomographs in HDS-5. Note that the CD does not provide a complete culvert design solution, but only the results from the design charts and nomographs that must then be entered on the Culvert Design Form (this may be done electronically) to complete the design.

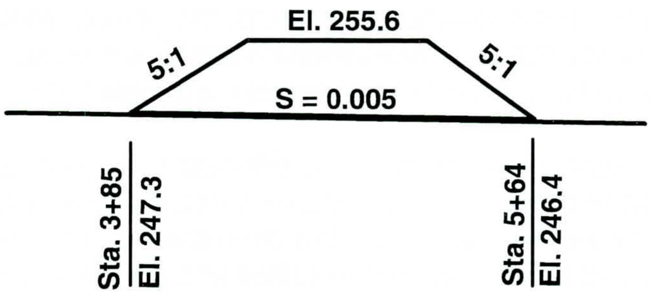
The use of the electronic equation boxes will be illustrated by solving several of the nomographs used in the previous workshop problems.

The CD-ROM has other media-media capabilities, including video, and a comprehensive english to metric conversion utility that will also be briefly illustrated.

B. The HY-8 module of HYDRAIN provides complete culvert design features. The conventional and improved inlet culvert workshops previously analyzed using the design charts will now be completed using the computer program HY-8.

6.3 WORKSHOP 6A - CONVENTIONAL CULVERT DESIGN USING CD-ROM AND HY8

The conventional culvert design completed in Workshop 4 will be re-visited, using the Electronic Design Charts in the CD-ROM version of HDS-5 and HY8. This problem involved a culvert crossing for a new roadway. The schematic drawing of the roadway was:



The design criteria for this project was:

- 50-year frequency for design (93 cfs)
- allowable headwater elevation = 252.00 due to the elevation of a different roadway upstream of the subject culvert.
- 100-year frequency for check (175 cfs)

The rating curve for the downstream channel is:

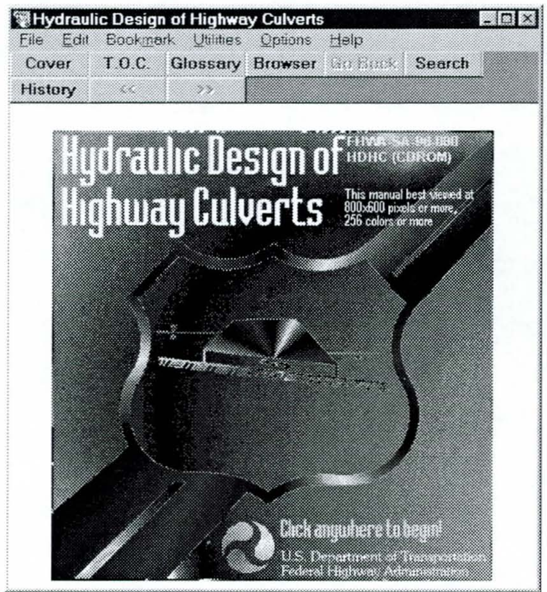
Q (cfs)	TW (ft)
0	246.61
17.5	249.73
35.0	250.22
52.5	250.51
70.0	250.71
87.5	250.87
93.0	250.91
122.5	251.10
140.0	251.20
157.5	251.28
175.0	251.35

The culvert configuration selected and analyzed in Workshop 4 was a four-barrel CMP with a square-edge headwall inlet.

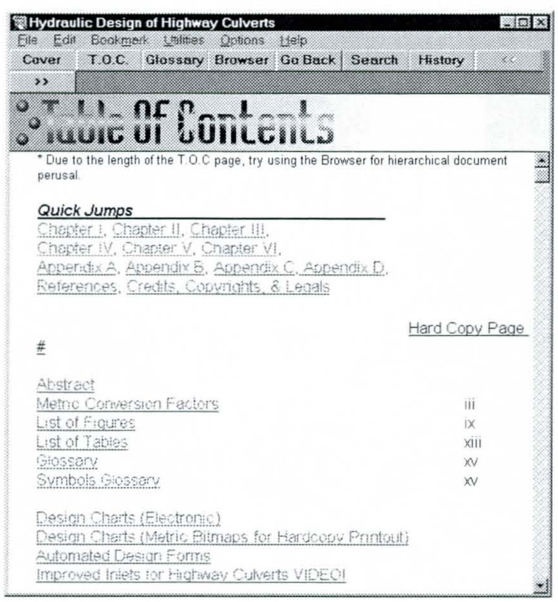
Using the Electronic Design Charts in the CD-ROM version of HDS-5, verify the workshop 4 results for the design discharge.

PART 1. SOLUTION USING CD-ROM.

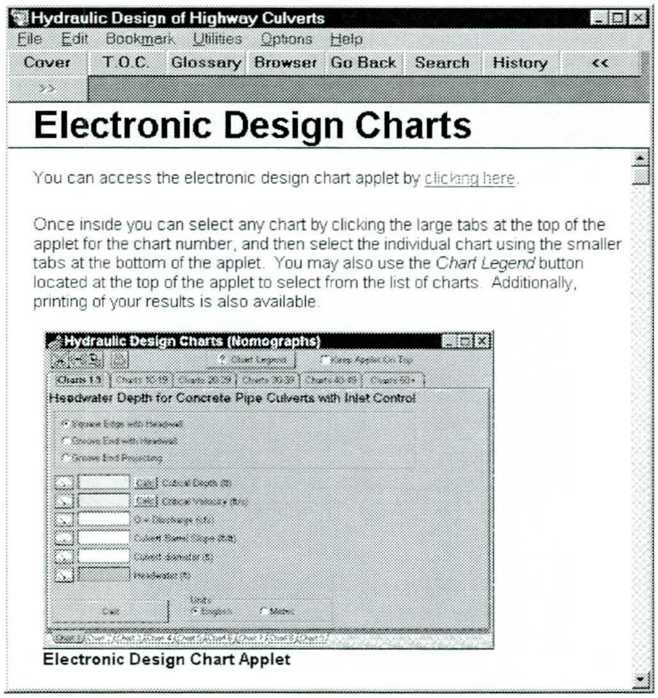
Step 1. Access the electronic verision of the document by clicking anywhere on the opening menu...



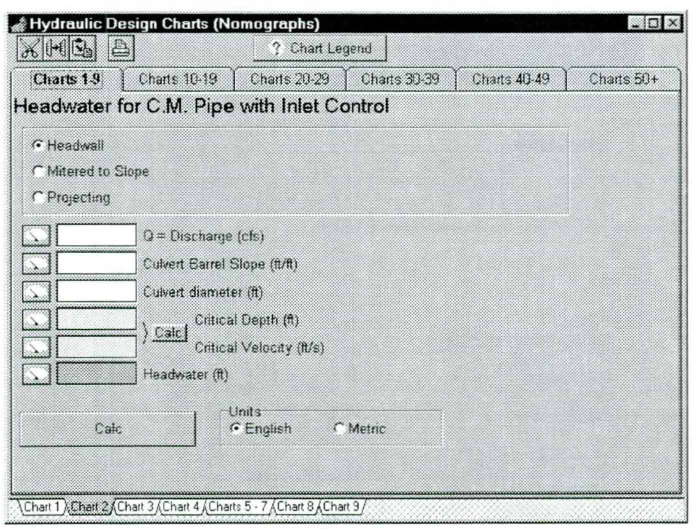
Step 2. On the Table of Contents page, click on *Design Charts (Electronic)*



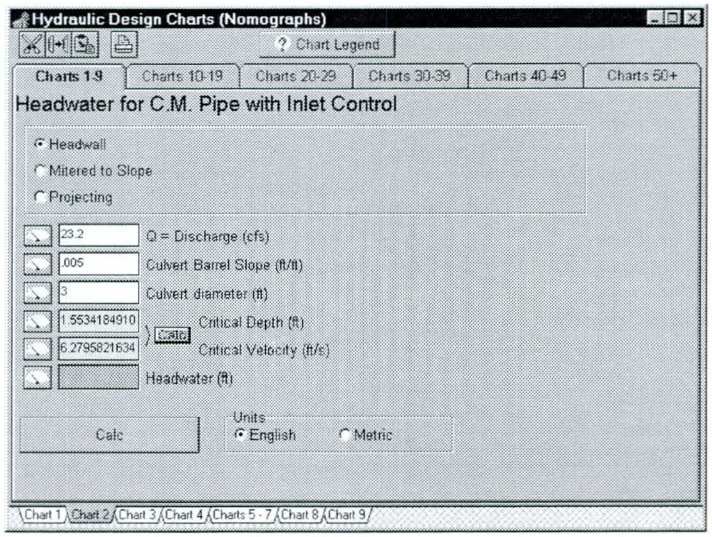
Step 3. Click on "...*clicking here*" to access the Design Charts



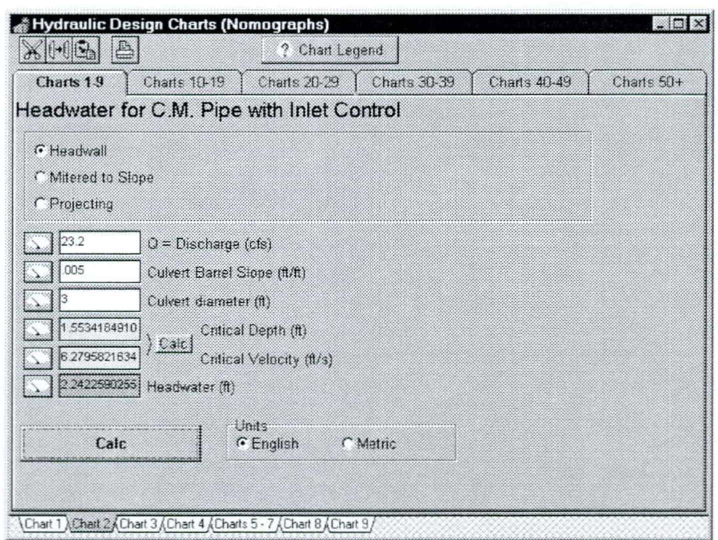
Step 4. At the bottom of the screen, select the inlet control nomograph for CMP pipe (Chart 2)



Step 5. Fill in the *design discharge, culvert slope and culvert diameter*, and calculate the critical depth parameters by clicking the *calc* buttom adjacent to the critical depth values.

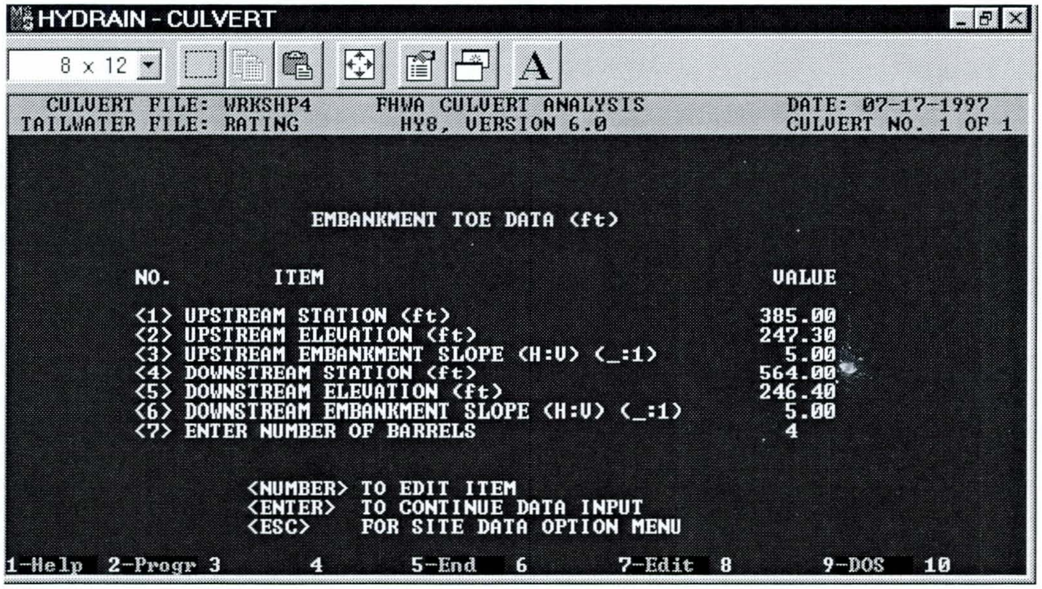


Step 6. Calculate the inlet control headwater by clicking the large *Calc* button at the bottom of the screen.

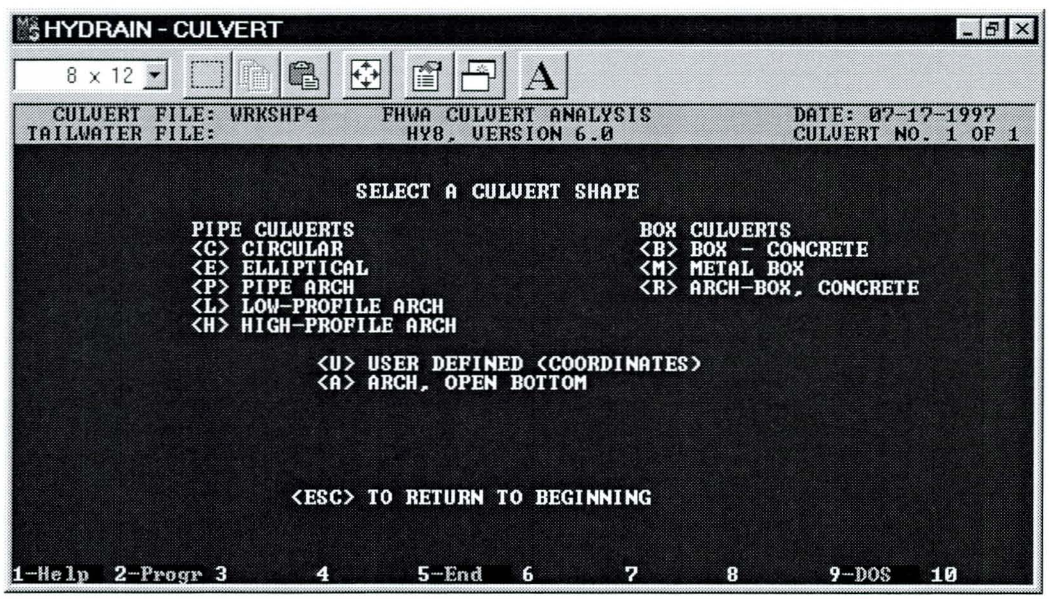


For the design discharge of 93 cfs, the inlet control headwater depth is 2.24 ft, which compares favorably with the value determined in Workshop 4 using the printed nomograph in the paper copy of HDS-5.

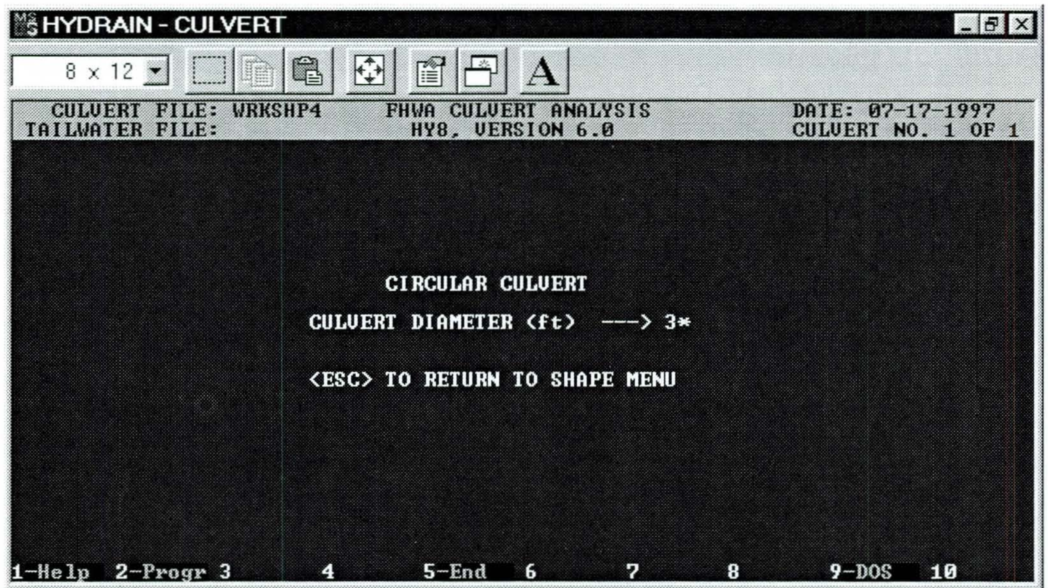
Step 7. On the "EMBANKMENT TOE DATA" menu, enter the given *stationing, elevations* and the selected *number of barrels* being analyzed:



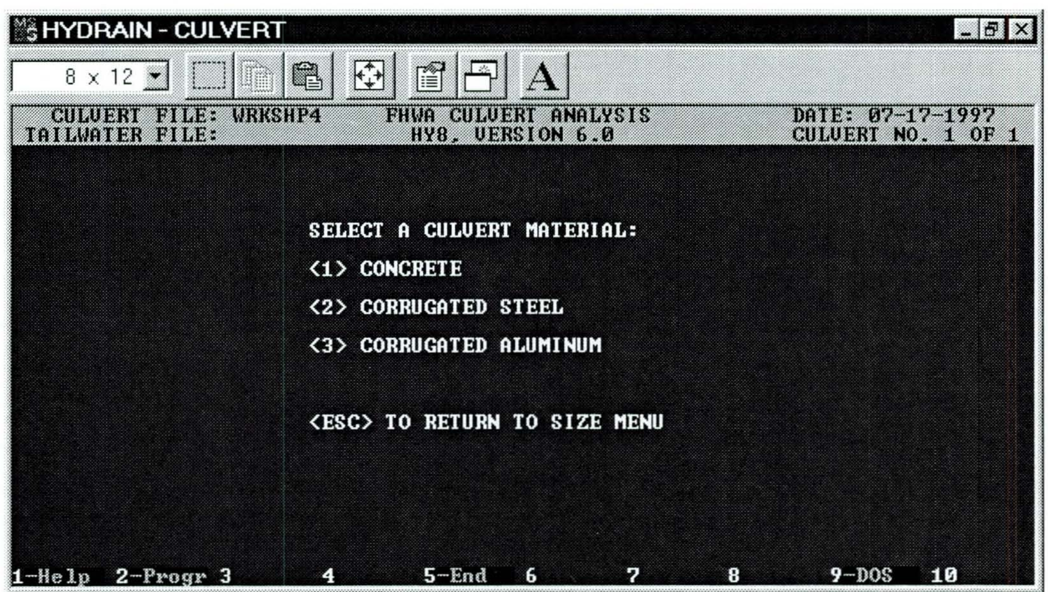
Step 8. On the ""SELECT A CULVERT SHAPE" menu, select *Circular*.



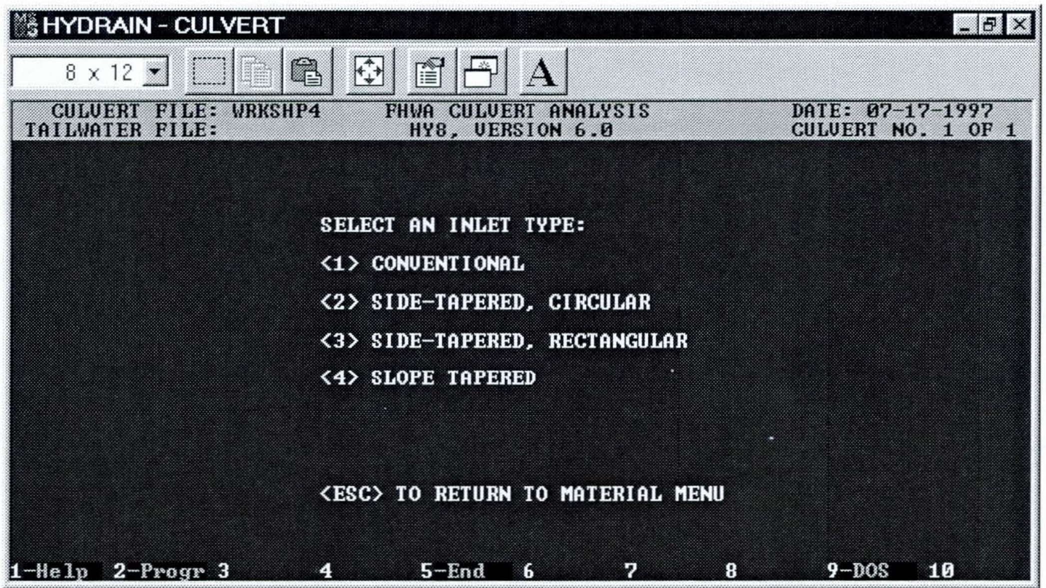
Step 9. On the "CIRCULAR CULVERT" menu, enter *culvert diameter*:



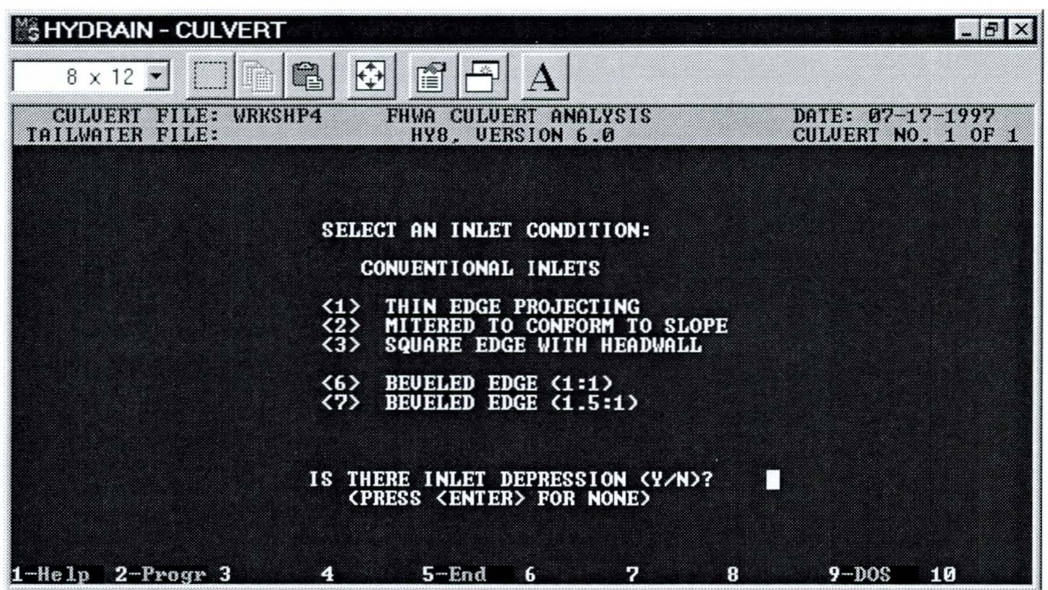
Step 10. On the "SELECT A CULVERT MATERIAL" enter the culvert material being considered (*Corrugated Steel*):



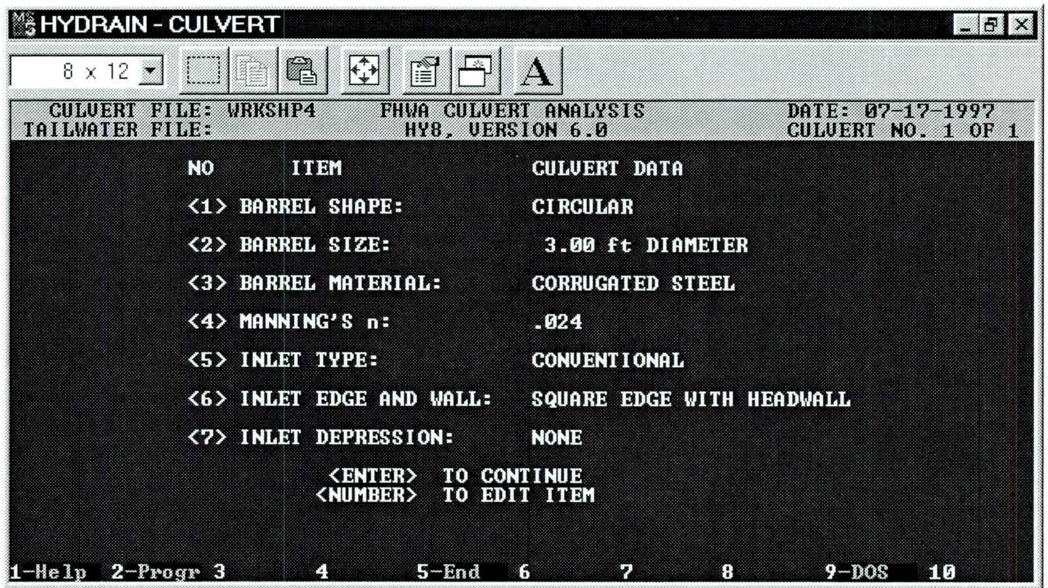
Step 11. On the "SELECT AN INLET TYPE" menu select *conventional* for our workshop problem:



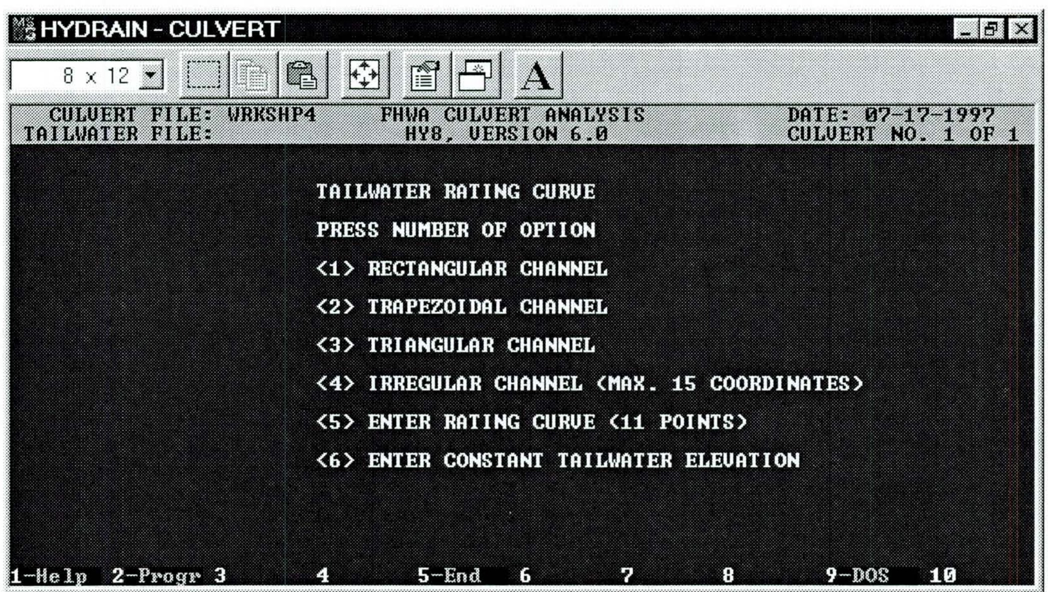
and on the next menu, select *square edge with headwall*



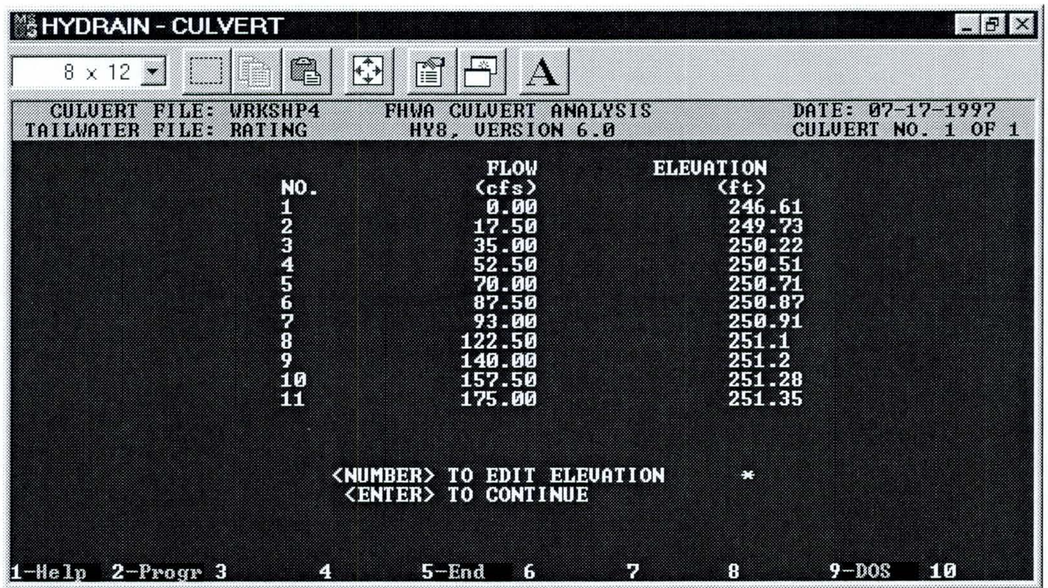
After entering this data, a summary screen appears. Make any necessary corrections or revisions at this time...



Step 12. We were given rating curve data, so use *Enter a Rating Curve* on the "TAILWATER RATING CURVE" menu:



and on the next menu, enter the *tailwater data.* HY8 divides the performance curve discharge data range, previously entered (0-175 cfs), into eleven equal increments, and so additional rating curve points from those given in the problem are required:


HYDRAIN - CULVERT

8 x 12

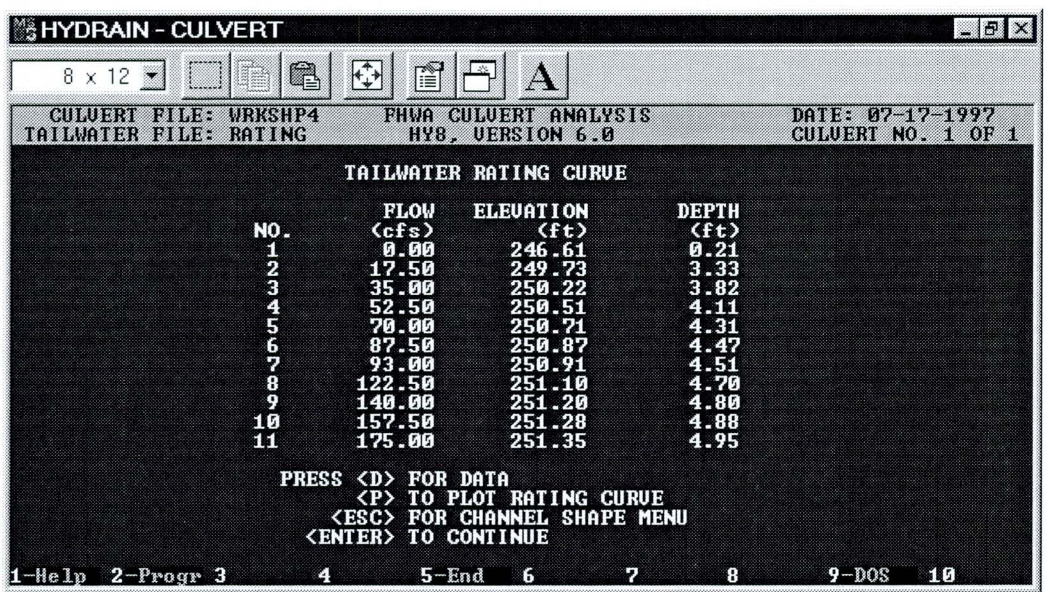
CULVERT FILE: WRKSHP4 FHWA CULVERT ANALYSIS DATE: 07-17-1997
TAILWATER FILE: RATING HY8, VERSION 6.0 CULVERT NO. 1 OF 1

NO.	FLOW (cfs)	ELEVATION (ft)
1	0.00	246.61
2	17.50	249.73
3	35.00	250.22
4	52.50	250.51
5	70.00	250.71
6	87.50	250.87
7	93.00	250.91
8	122.50	251.1
9	140.00	251.2
10	157.50	251.28
11	175.00	251.35

<NUMBER> TO EDIT ELEVATION *
<ENTER> TO CONTINUE

1-Help 2-Progr 3 4 5-End 6 7 8 9-DOS 10

after entering the tailwater elevations for the tabulated discharges, the following screen showing tailwater depths appears:


HYDRAIN - CULVERT

8 x 12

CULVERT FILE: WRKSHP4 FHWA CULVERT ANALYSIS DATE: 07-17-1997
TAILWATER FILE: RATING HY8, VERSION 6.0 CULVERT NO. 1 OF 1

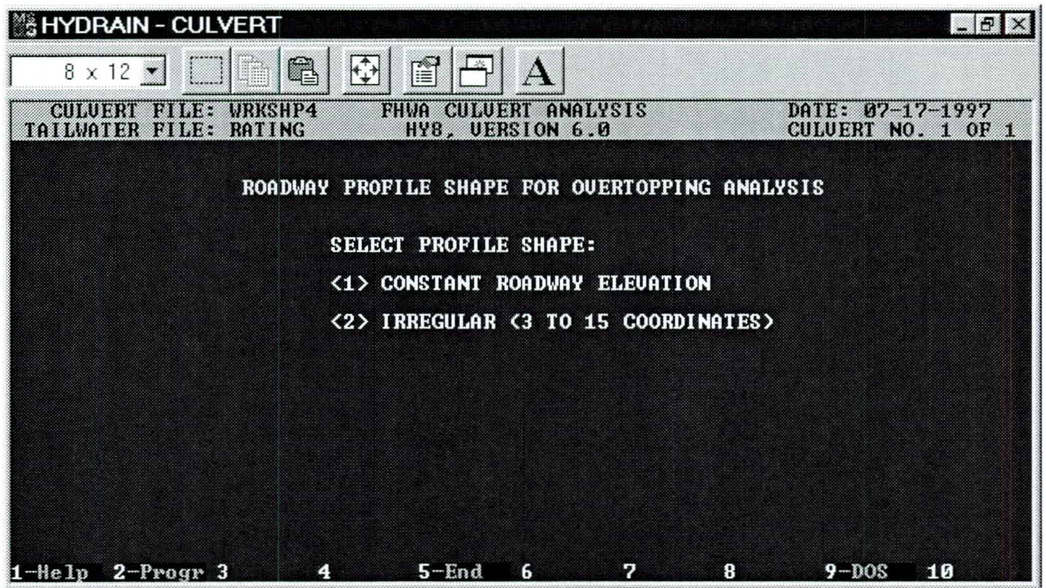
TAILWATER RATING CURVE

NO.	FLOW (cfs)	ELEVATION (ft)	DEPTH (ft)
1	0.00	246.61	0.21
2	17.50	249.73	3.33
3	35.00	250.22	3.82
4	52.50	250.51	4.11
5	70.00	250.71	4.31
6	87.50	250.87	4.47
7	93.00	250.91	4.51
8	122.50	251.10	4.70
9	140.00	251.20	4.80
10	157.50	251.28	4.88
11	175.00	251.35	4.95

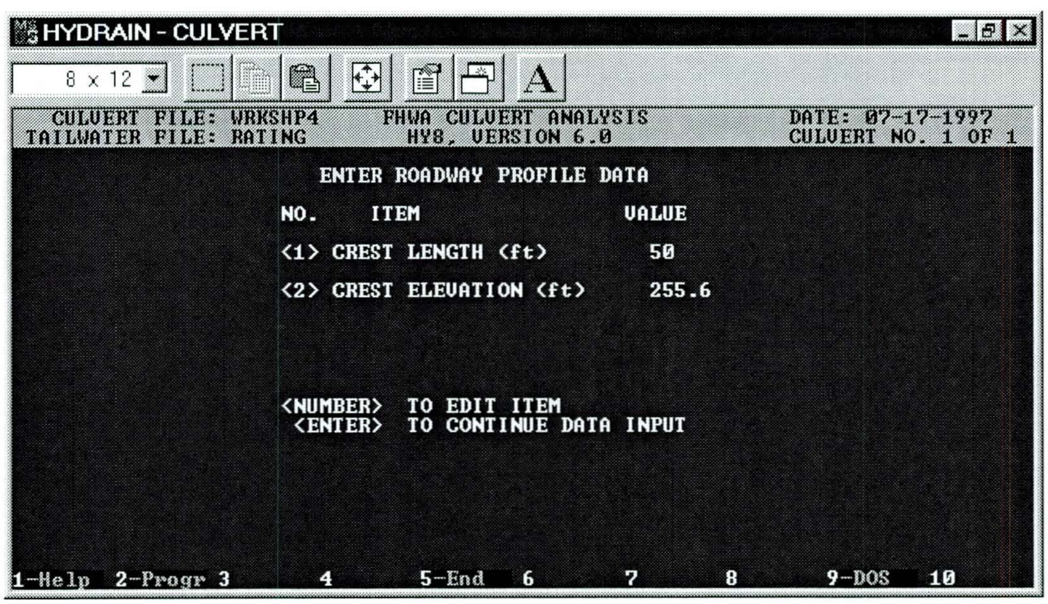
PRESS <D> FOR DATA
<P> TO PLOT RATING CURVE
<ESC> FOR CHANNEL SHAPE MENU
<ENTER> TO CONTINUE

1-Help 2-Progr 3 4 5-End 6 7 8 9-DOS 10

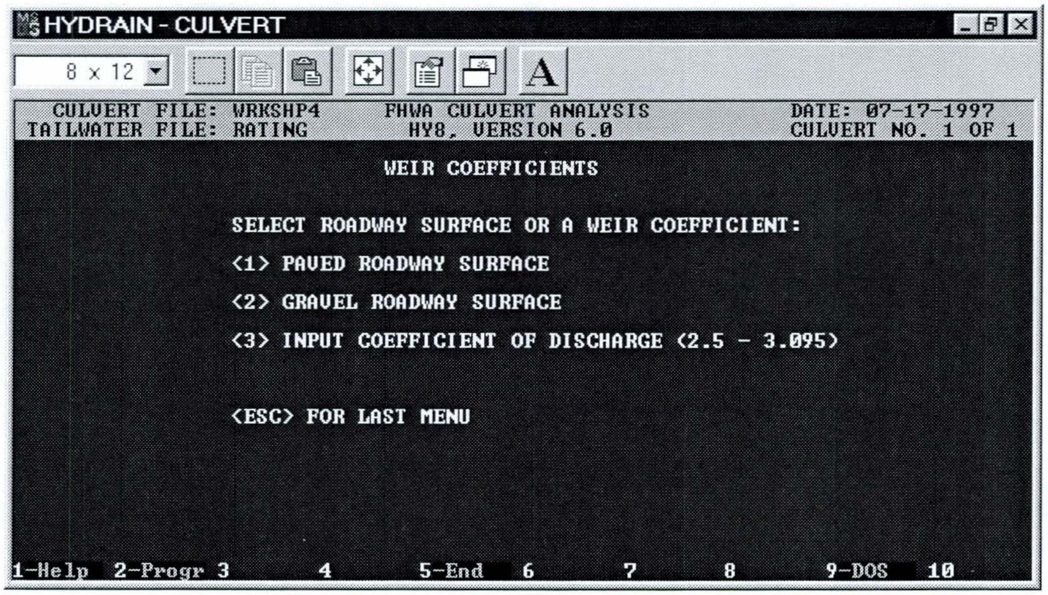
Step 13. On the "ROADWAY PROFILE SHAPE FOR OVERTOPPING ANALYSIS" select a roadway profile option. We are not designing for overtopping; however, this data must still be entered. We will use a *Constant Roadway Elevation:*



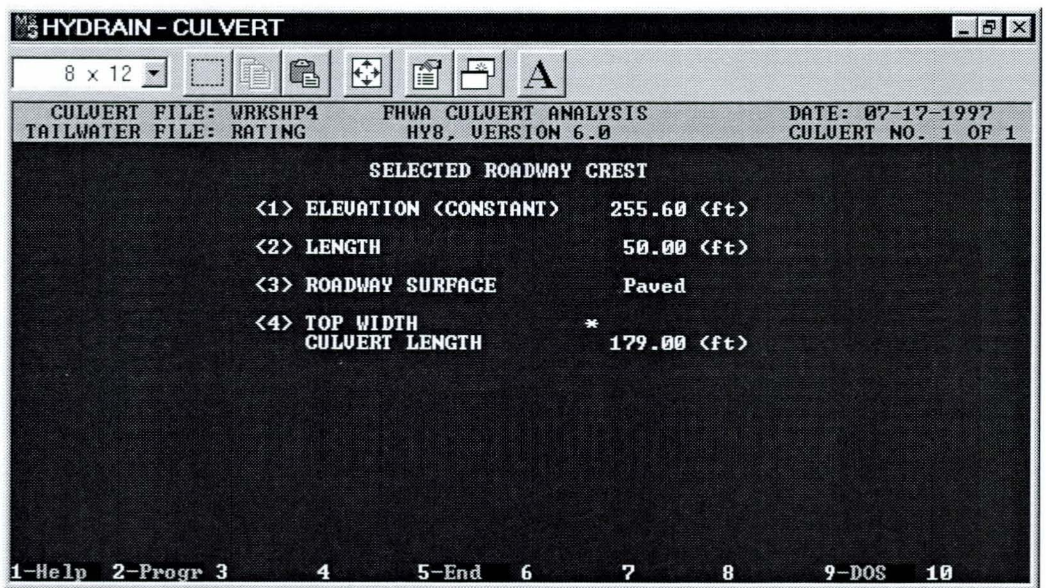
and enter the constant elevation, 255.6. The crest length is used in the weir equation to calculate the overflow discharge. For purposes of our analysis, we will use a crest length of 50:



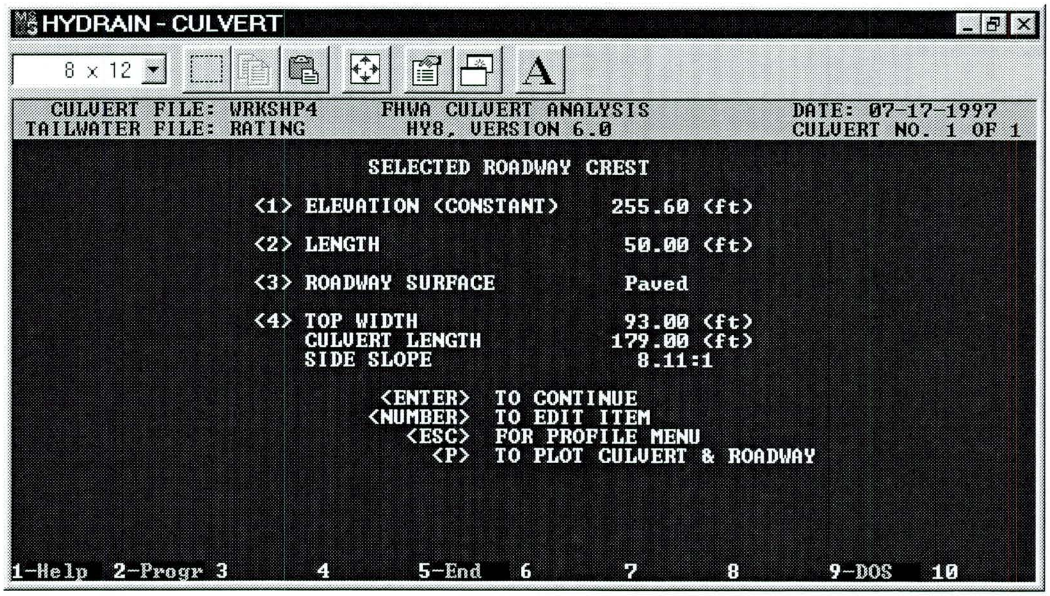
On the "WEIR COEFFICIENTS" menu, we will assume a paved roadway surface:



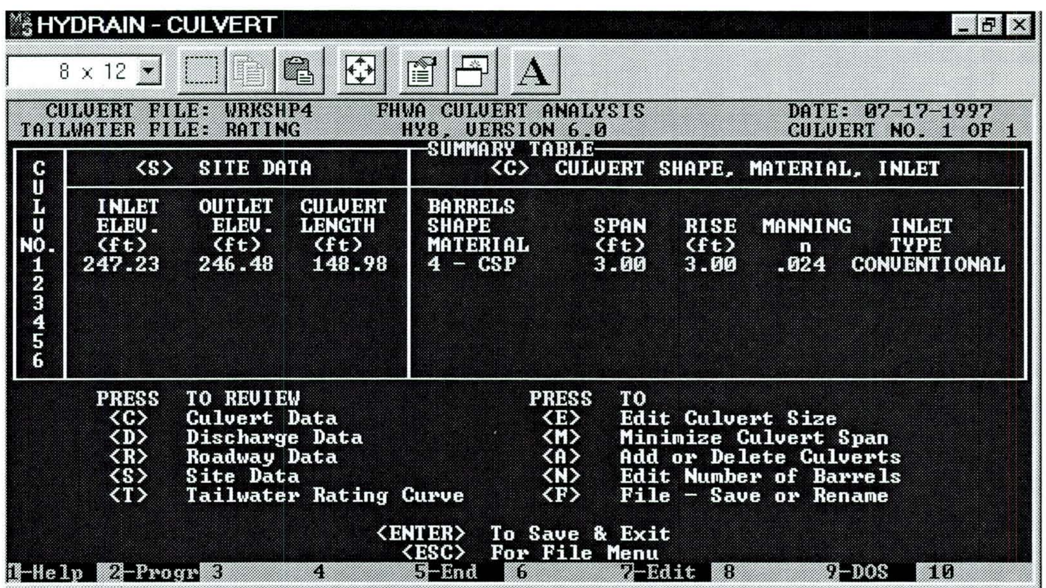
after which the following menu appears:



Enter the embankment top width (93 ft) and the following menu appears:

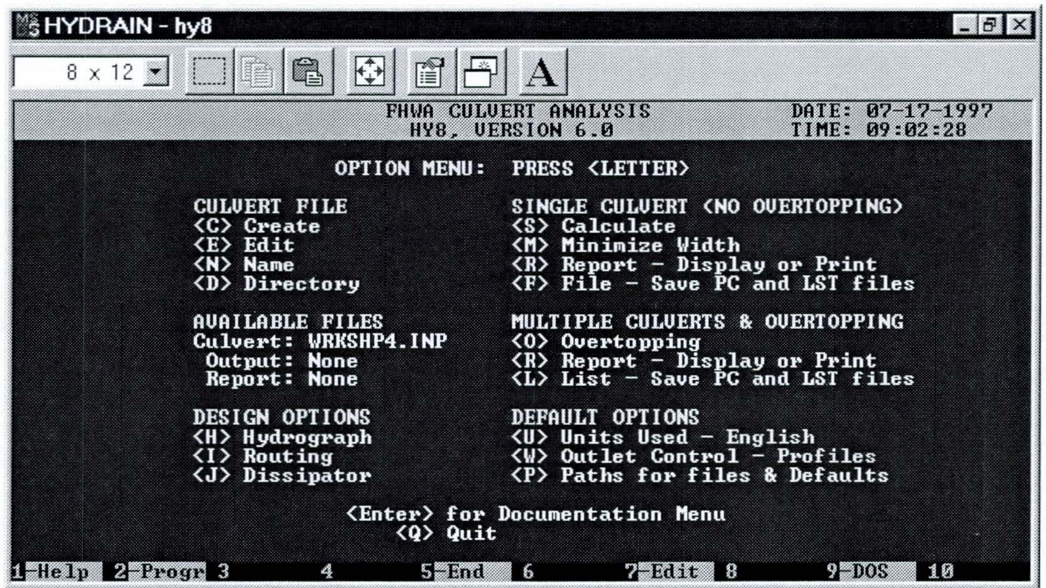


and a summary table appears:

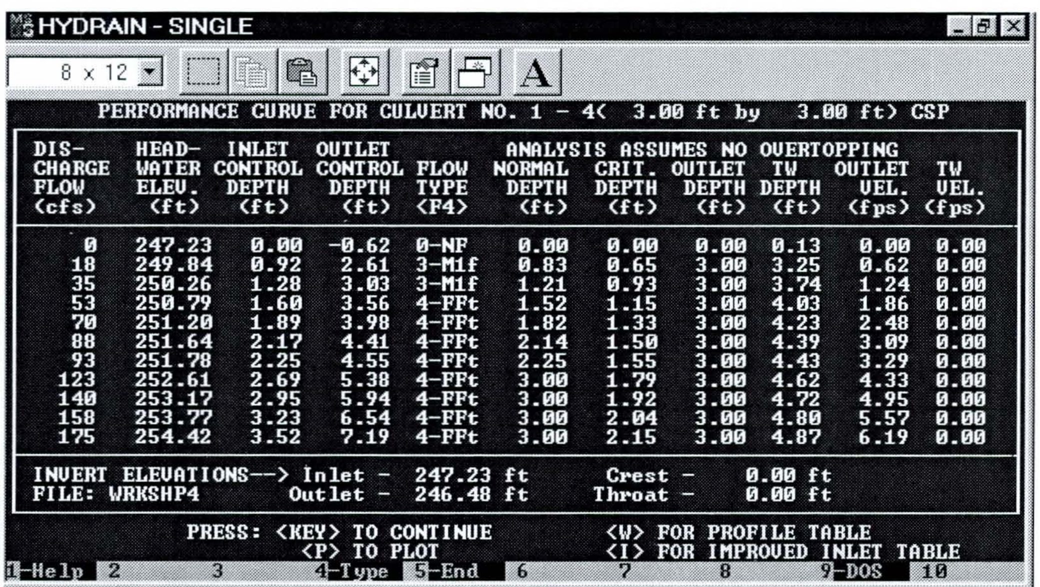


press *enter* to save and exit this input file creation.

Step 14. The "OPTION MENU" now reappears, from which the culvert analysis can now be completed.

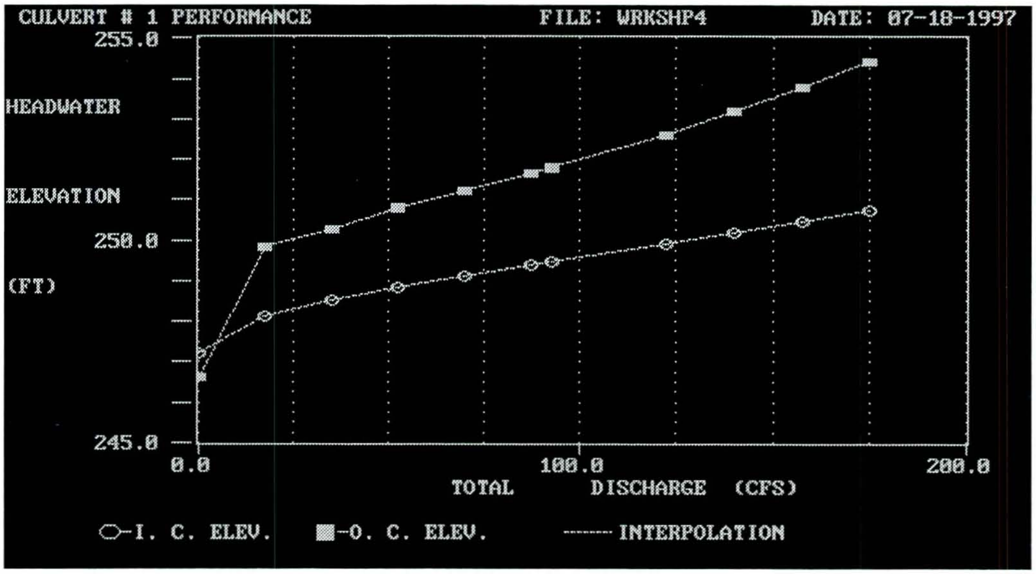


Under "SINGLE CULVERT (NO OVERTOPPING)" select *Calculate* and the following table of results appears (Note that even through we have a multiple barrel installation, all barrels are the same size. HY8 considers this a single culvert, as shown on the summary table, above. A multiple culvert installation on the Option Menu refers to a site where several different types of barrels are installed):



DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (fps)	TW VEL. (fps)
0	247.23	0.00	-0.62	0-NF	0.00	0.00	0.00	0.13	0.00	0.00
18	249.84	0.92	2.61	3-M1f	0.83	0.65	3.00	3.25	0.62	0.00
35	250.26	1.28	3.03	3-M1f	1.21	0.93	3.00	3.74	1.24	0.00
53	250.79	1.60	3.56	4-FFt	1.52	1.15	3.00	4.03	1.86	0.00
70	251.20	1.89	3.98	4-FFt	1.82	1.33	3.00	4.23	2.48	0.00
88	251.64	2.17	4.41	4-FFt	2.14	1.50	3.00	4.39	3.09	0.00
93	251.78	2.25	4.55	4-FFt	2.25	1.55	3.00	4.43	3.29	0.00
123	252.61	2.69	5.38	4-FFt	3.00	1.79	3.00	4.62	4.33	0.00
140	253.17	2.95	5.94	4-FFt	3.00	1.92	3.00	4.72	4.95	0.00
158	253.77	3.23	6.54	4-FFt	3.00	2.04	3.00	4.80	5.57	0.00
175	254.42	3.52	7.19	4-FFt	3.00	2.15	3.00	4.87	6.19	0.00

The performance curve may be plotted by pressing *"P"*:



6.4 WORKSHOP 6B - IMPROVED INLET DESIGN USING CD-ROM AND HY8

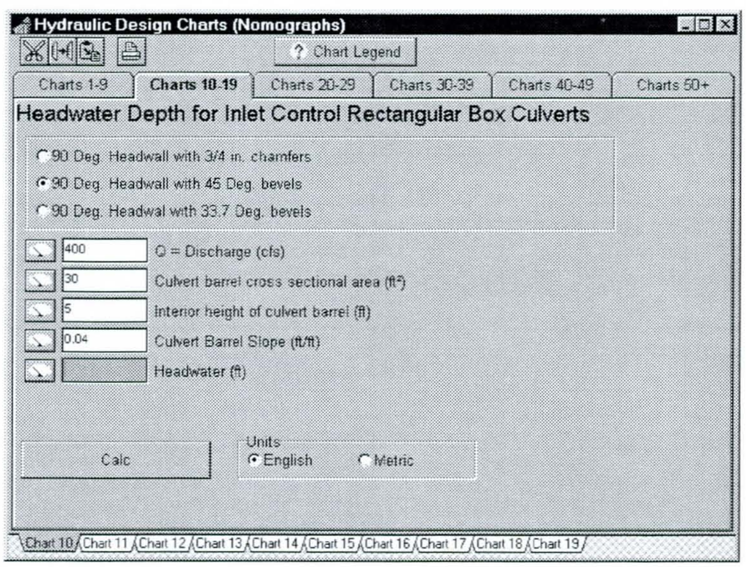
The improved inlet culvert design completed in Workshop 5 will be re-visited, using the Electronic Design Charts in the CD-ROM version of HDS-5 and HY8. This problem required evaluation of three improved inlet alternatives for a roadway realignment: a 6x5 RCB with a 90 degree headwall with beveled inlet edges, a 5x5 RCB side-tapered inlet and a 5x4 slope-tapered inlet.

The design discharge was 400 cfs and the allowable headwater was 100 ft. The length of the culvert was 160 feet on a 4 percent slope, and the inlet and outlet invert elevations were 90.0 ft and 83.6 ft, respectively. The tailwater channel was an 8 ft bottom, 2:1 side slope, grass lined trapezoidal channel on a 4 percent slope with a Manning's n value of 0.032.

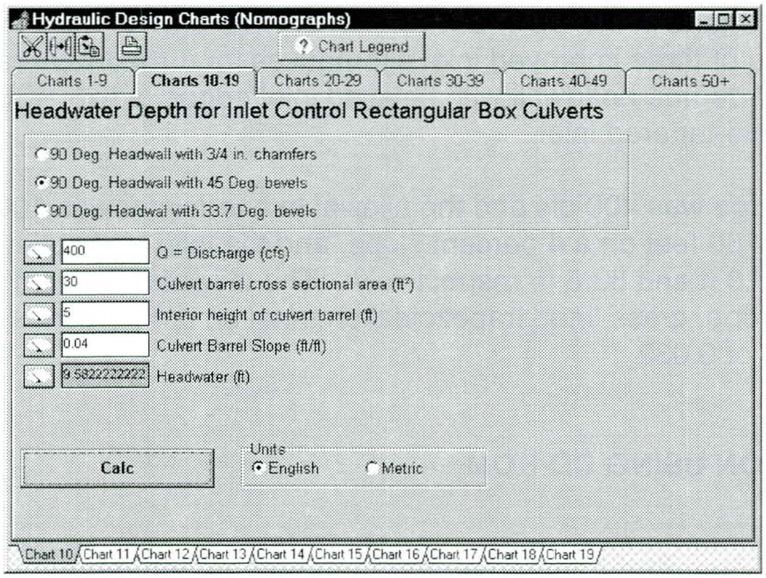
PART 1. SOLUTION USING CD-ROM

Step 1. Access the electronic design charts, as previously demonstrated, selecting Chart 10 for the bevel edge improved inlet alternative.

Step 2. Fill in the *discharge, cross sectional area, barrel height and slope*:

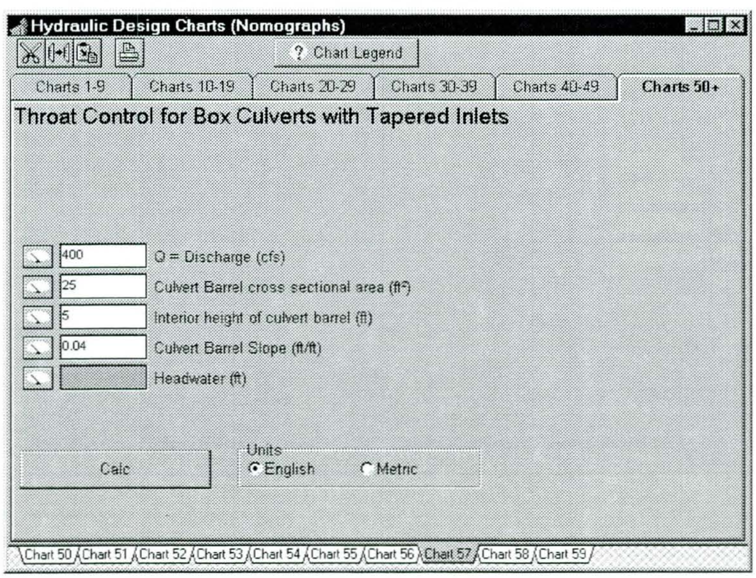


Step 3. Click on the large *Calc* button at the bottom of the screen:

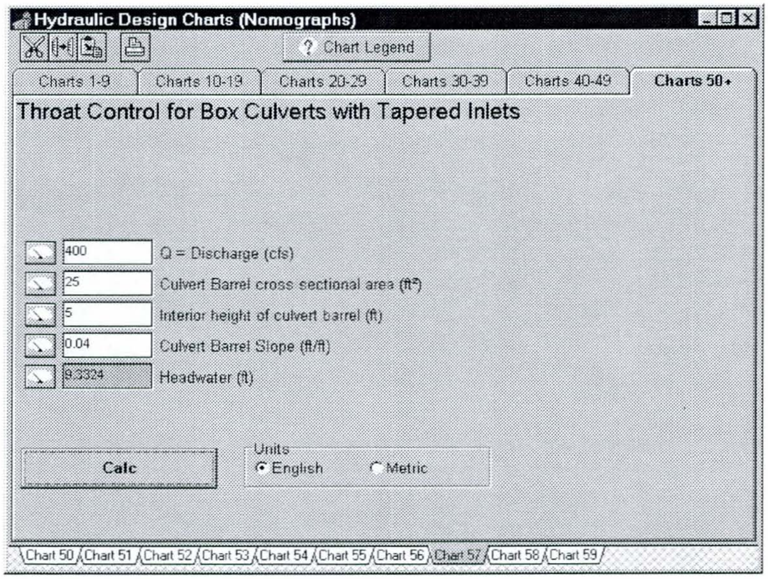


The calculated headwater is 9.58 ft, which compares favorably with the results from the paper charts in Workshop 5.

Step 4. For the side-tapered improved inlet alternative, select Chart 57 for throat control analysis and fill in the *discharge, cross sectional area and barrel height and slope*:

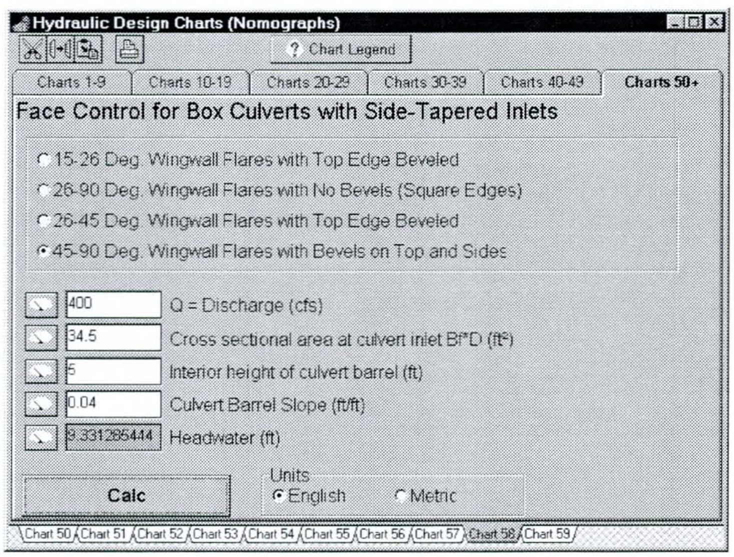


Step 5. Click on the large *Calc* button at the bottom of the screen



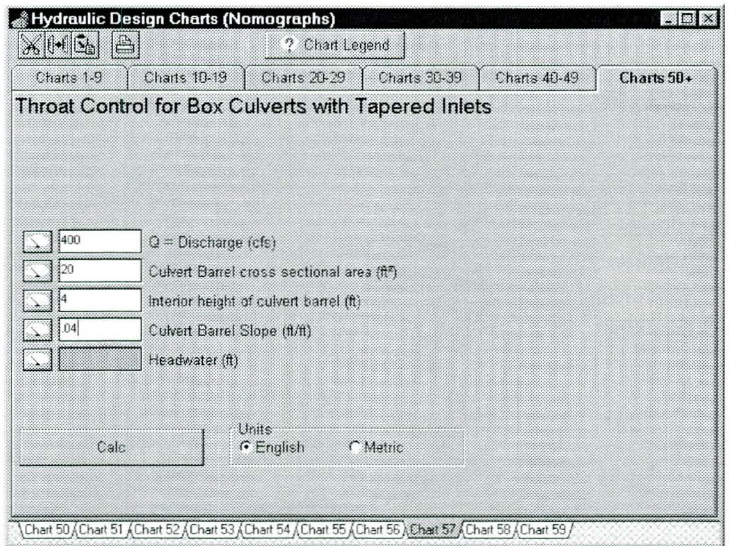
The calculated headwater depth of 9.33 compares favorably with the results computed in Workshop 5.

Step 6. Similarly, select Chart 58 for face control analysis. This chart requires a trial and error solution for B_f , obtained by filling in the known *discharge, barrel height and slope* and trying different values of B_f*D. In order for the throat to control, and not the face, the resulting headwater must be less than the value calculated for throat control (9.33).

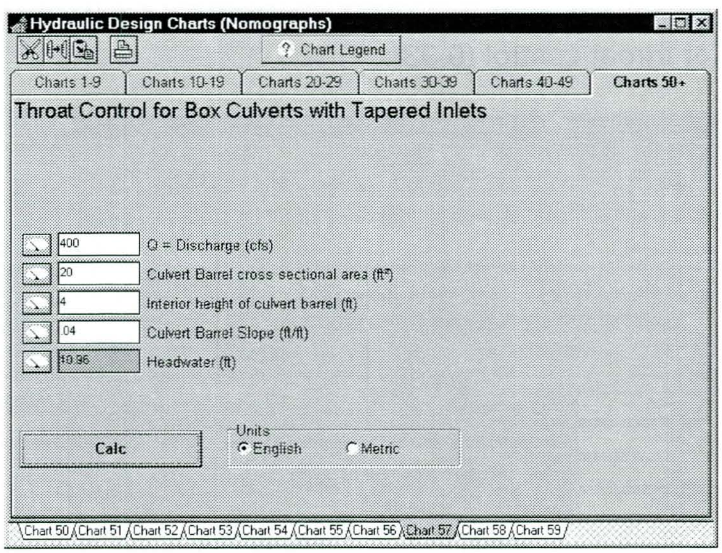


By trial and error, the minimum value of B_f*D is 34.5, so that the minimum value of B_f is 6.9. This compares favorably with the results from Workshop 5.

Step 7. For the slope-tapered inlet, again select Chart 57 for throat control analysis and fill in the *discharge, cross sectional area and barrel height and slope:*

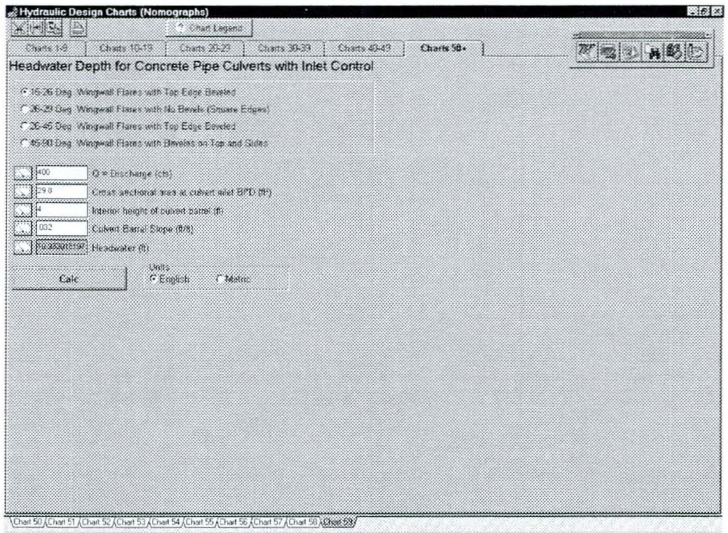


Step 8. Click on the large *Calc* button at the bottom of the screen:



The calculated headwater depth of 10.96 compares favorably with the results computed in Workshop 5.

Step 9. Select Chart 59 for face control analysis and again use a trial and error approach to solve for B_f by trying different values of B_f*D. In order for the throat to control, and not the face, the resulting headwater must be less than the value calculated for throat control (10.96). The slope value used has been recomputed to account for the 1.5 ft fall used in the slope-tapered inlet design. (Note that the Chart is labeled wrong, but the answers are correct...)

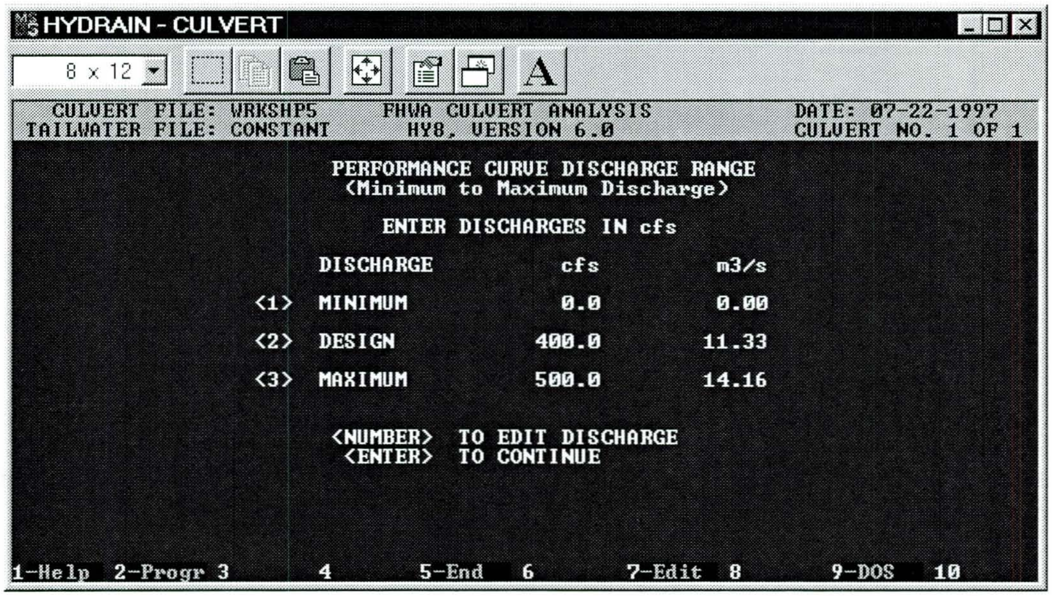


By trial and error, the minimum value of B_f*D is 29.8, so that the minimum value of B_f is 7.45. This compares favorably with the results from Workshop 5.

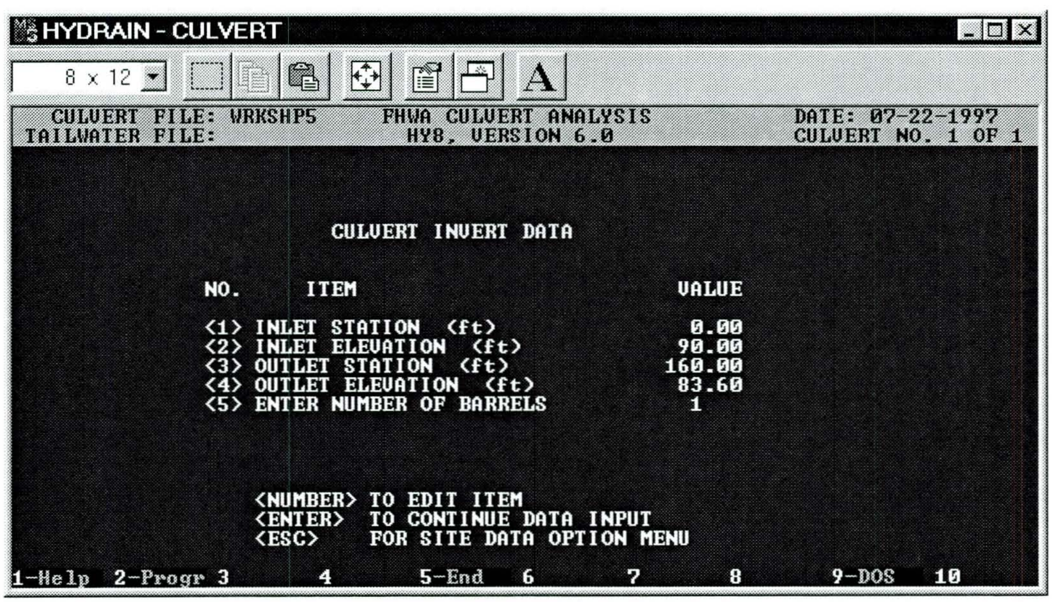
PART 2. SOLUTION USING HY8

Much of the HY8 data input for an improved inlet analysis is similar to previously shown in the conventional inlet demonstration. Therefore, some of the intermediate menu's are not shown below.

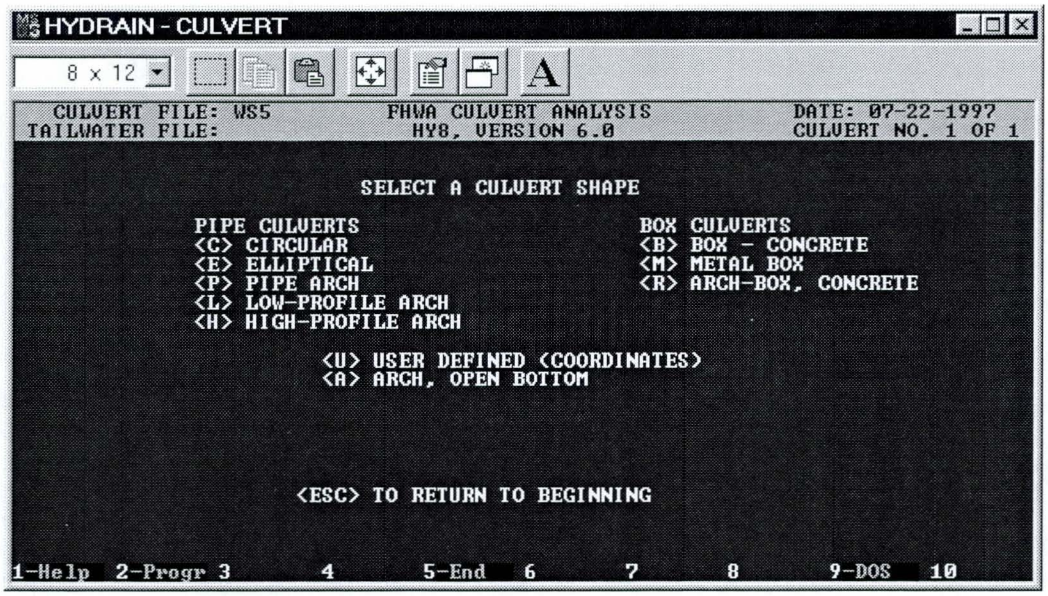
Step 1. Begin HY8 and *create and name* a file, as previously demonstated, and enter the discharge data. Use a maximum discharge of 500 cfs for the performance curve range:



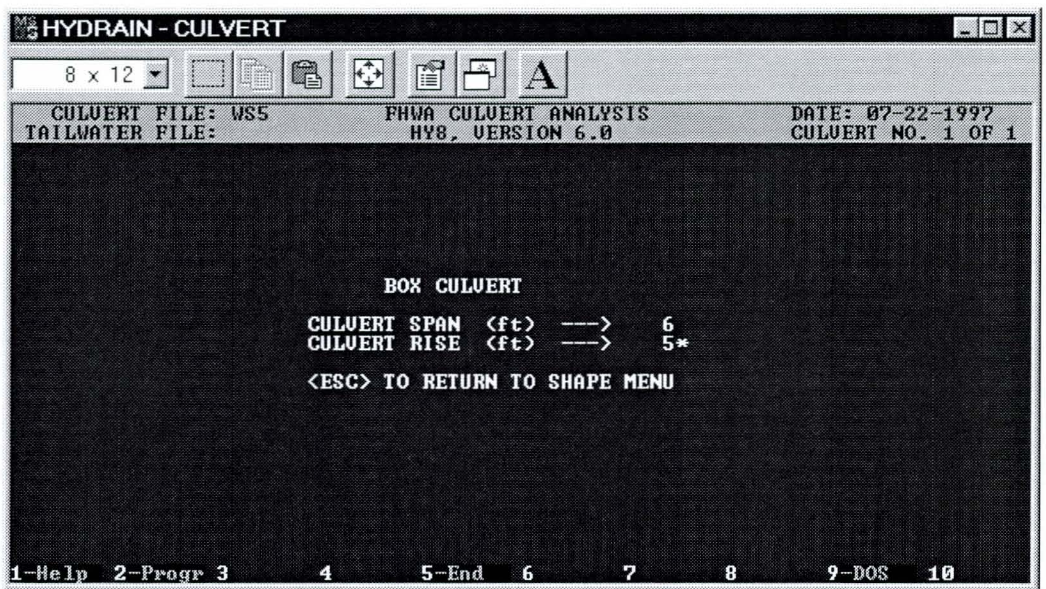
Step 2. Enter the geometric data, using the *culvert invert* option:



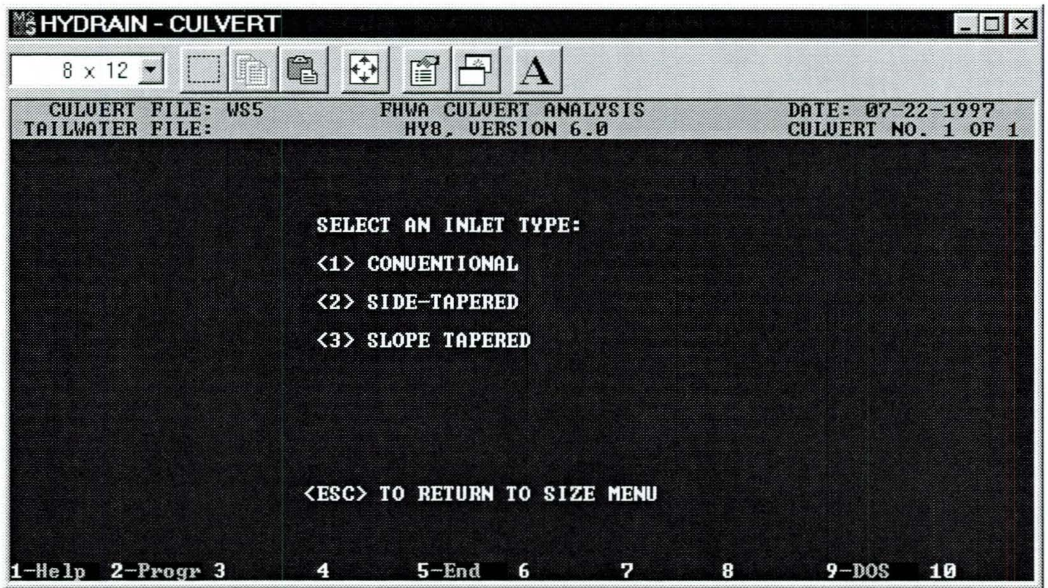
Step 3. Enter the *culvert shape, size and material* (analyze the 6x5 RCB with 90 degree headwall and beveled inlet edges first):



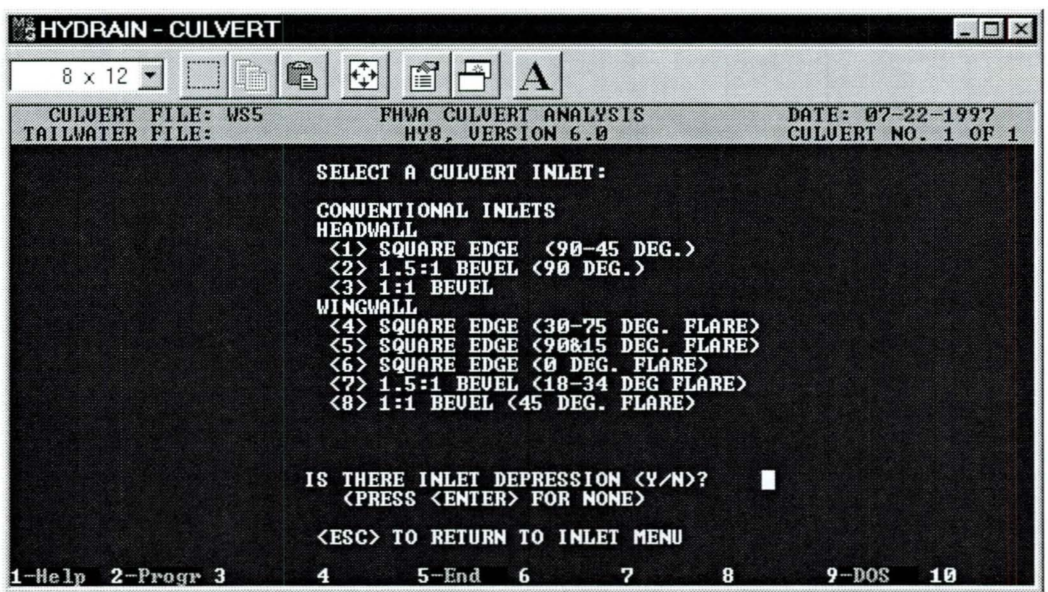
After selecting *box - concrete*, the following menu appears:



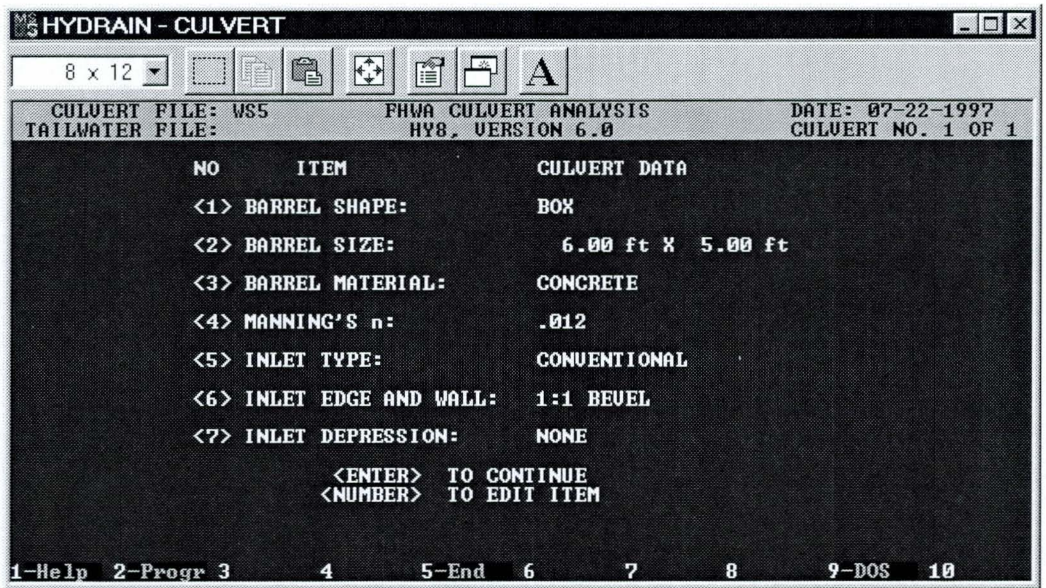
Then select *conventional* inlet:



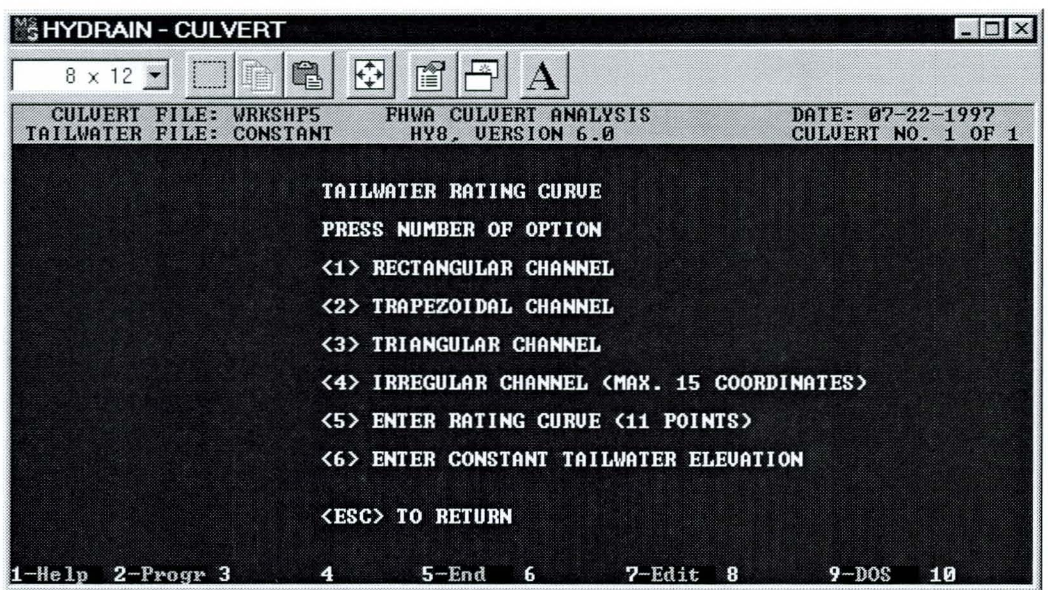
and then *Headwall, 1:1 Bevel* (option 3) with *no inlet depression*:



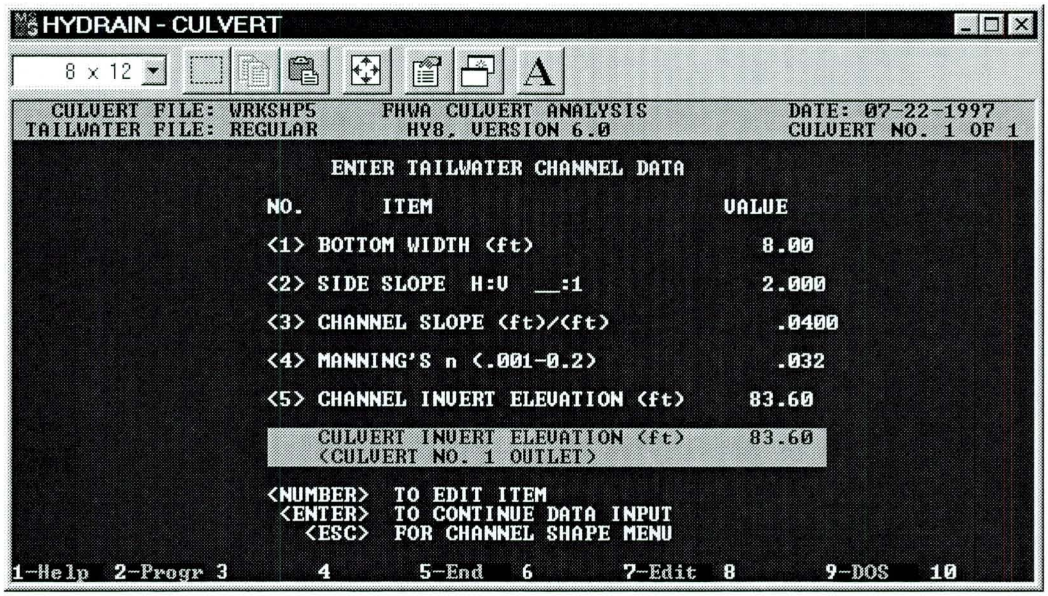
and the following summary screen appears:



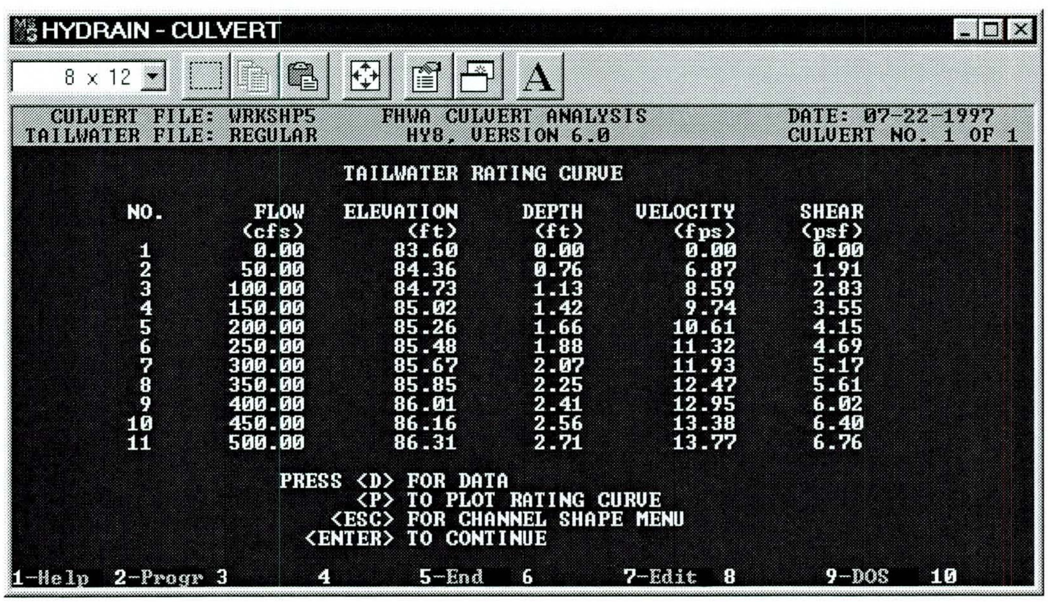
Step 4. For tailwater conditions, use the *trapezoidal channel* option to calculate a rating curve based on normal depth assumptions:



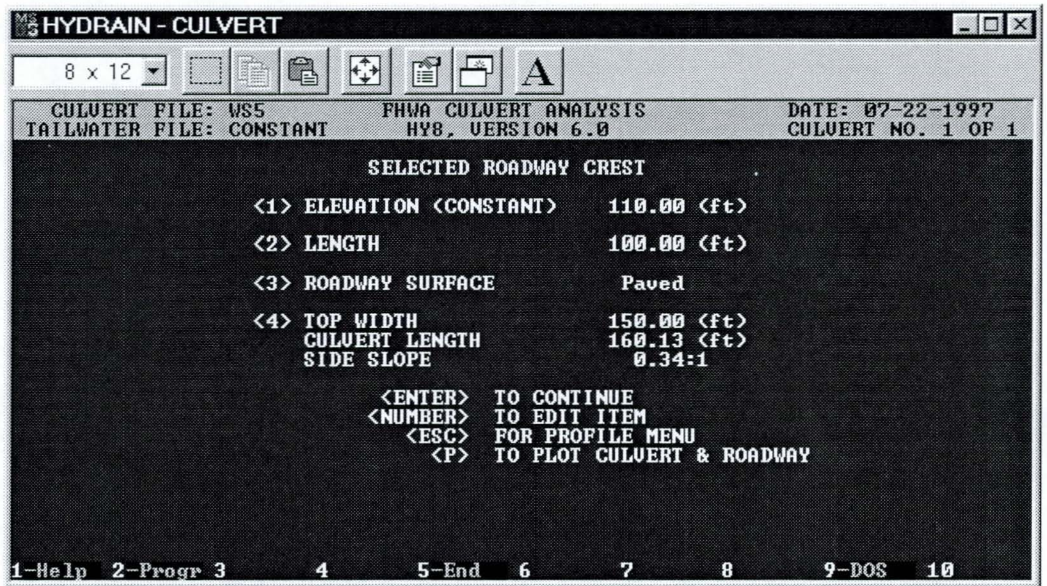
and enter the given *channel geometry* and *Manning's n* information:



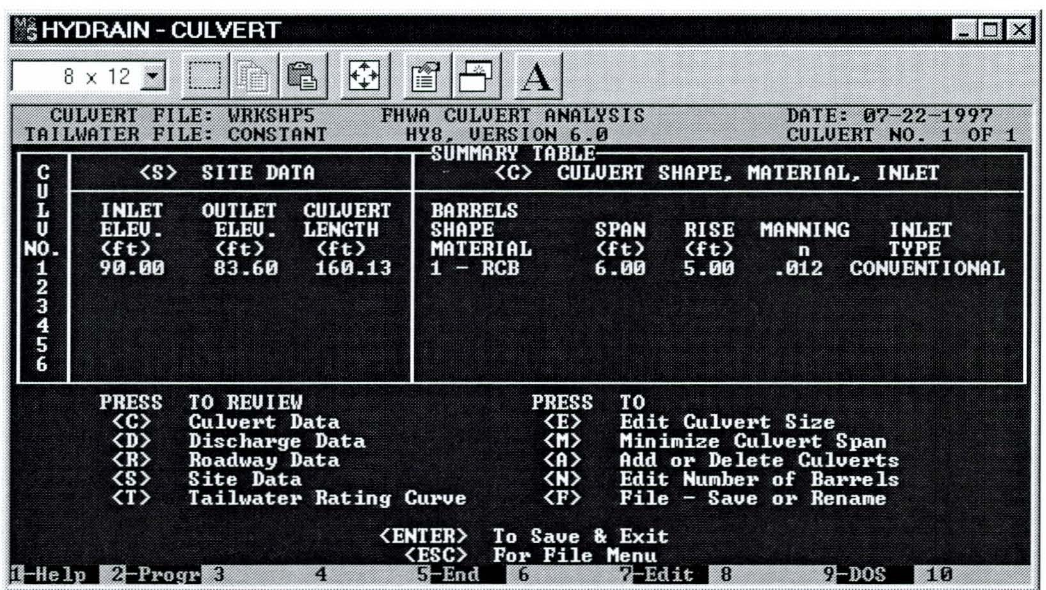
The calculated rating curve is then displayed:



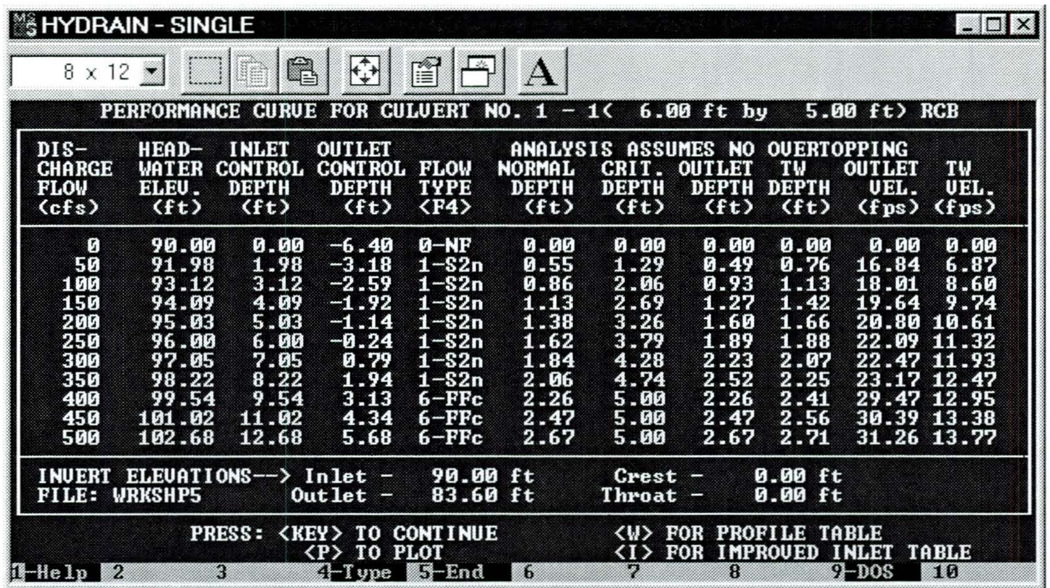
Step 5. For the overtopping analysis, use a *constant roadway elevation*. The design will not be based on overtopping, so any reasonable values may be input for the overtopping analysis. Assume 110 ft elevation, crest length of 100, paved surface, and embankment length of 150. After working through the overtopping analysis menus and inputting these values, the following summary menu appears:



Step 6. The following summary menu then appears for the 6x5 beveled inlet edge alternative:



after saving this file, complete the analysis by entering "*S*" and the results are displayed:



HYDRAIN - SINGLE

PERFORMANCE CURVE FOR CULVERT NO. 1 - 1(6.00 ft by 5.00 ft) RCB

ANALYSIS ASSUMES NO OVERTOPPING

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (fps)	TW VEL. (fps)
0	90.00	0.00	-6.40	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50	91.98	1.98	-3.18	1-S2n	0.55	1.29	0.49	0.76	16.84	6.87
100	93.12	3.12	-2.59	1-S2n	0.86	2.06	0.93	1.13	18.01	8.60
150	94.09	4.09	-1.92	1-S2n	1.13	2.69	1.27	1.42	19.64	9.74
200	95.03	5.03	-1.14	1-S2n	1.38	3.26	1.60	1.66	20.80	10.61
250	96.00	6.00	-0.24	1-S2n	1.62	3.79	1.89	1.88	22.09	11.32
300	97.05	7.05	0.79	1-S2n	1.84	4.28	2.23	2.07	22.47	11.93
350	98.22	8.22	1.94	1-S2n	2.06	4.74	2.52	2.25	23.17	12.47
400	99.54	9.54	3.13	6-FFc	2.26	5.00	2.26	2.41	29.47	12.95
450	101.02	11.02	4.34	6-FFc	2.47	5.00	2.47	2.56	30.39	13.38
500	102.68	12.68	5.68	6-FFc	2.67	5.00	2.67	2.71	31.26	13.77

INVERT ELEVATIONS--> Inlet - 90.00 ft Crest - 0.00 ft
FILE: WRKSHP5 Outlet - 83.60 ft Throat - 0.00 ft

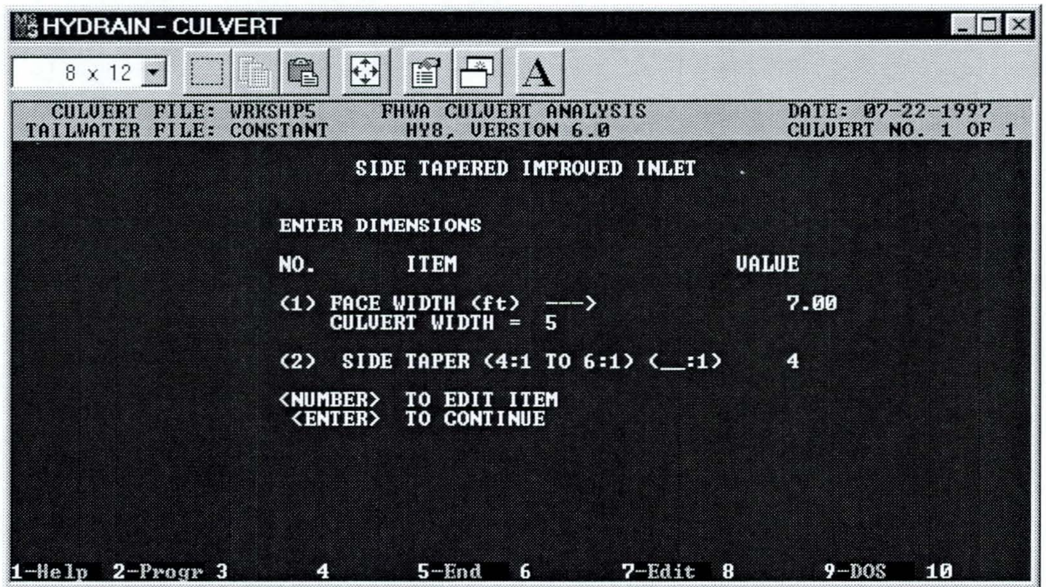
PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

1-Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

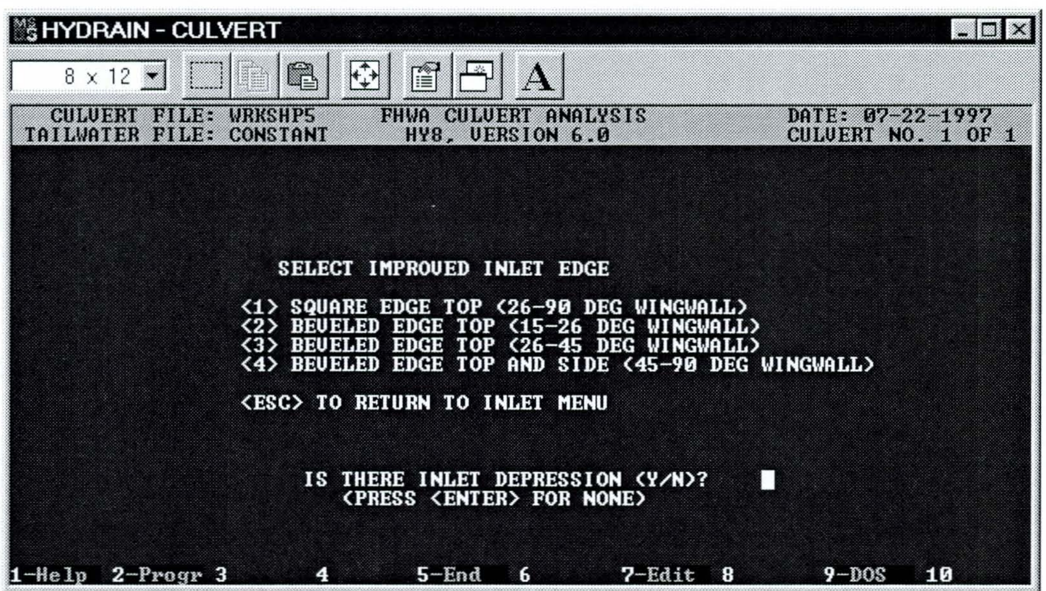
The calculated headwater elevation for the design discharge (99.54) compares favorably with the results from Workshop 5.

Side Tapered Alternative

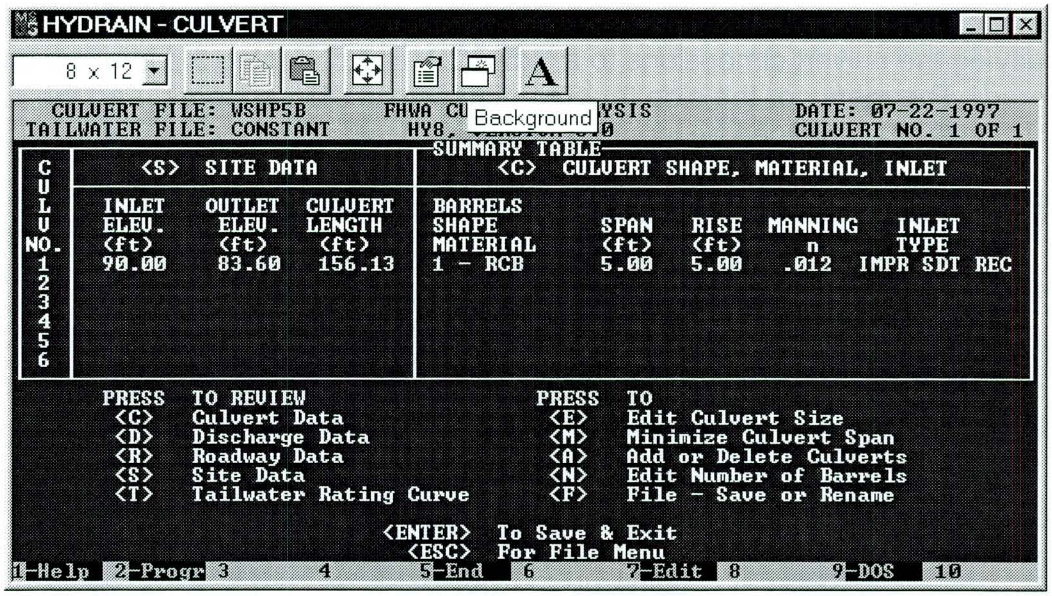
The side tapered alternative can be analyzed by selecting *edit* on the options menu and then modifying the culvert dimensions to a 5x5 RCB, and changing the inlet condition to side tapered. The menu for the side tapered dimensions then appears, and the *face width of 7 ft with 4:1 taper* can be input for analysis:



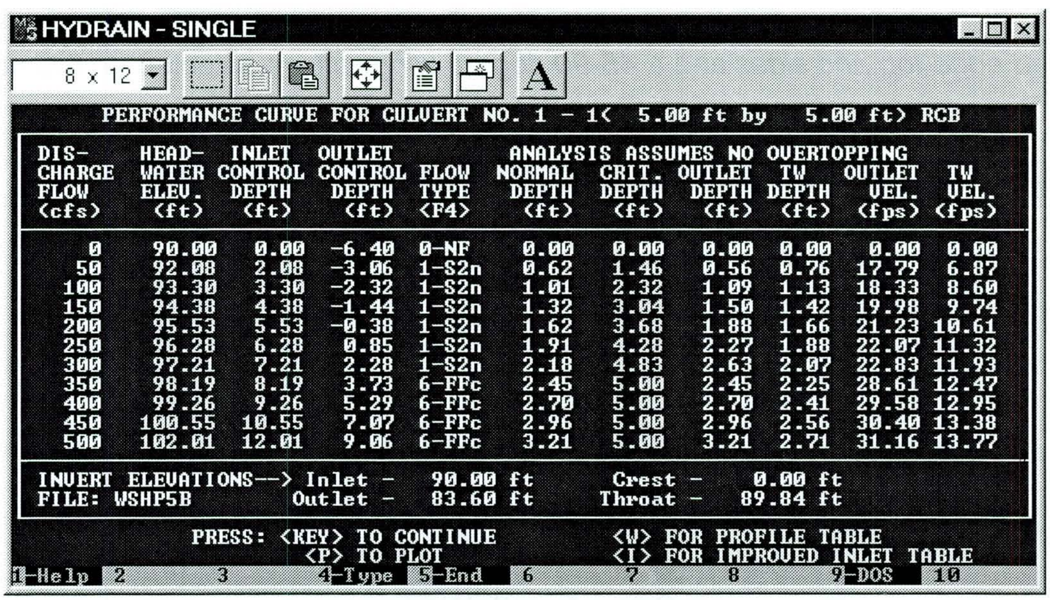
A *beveled edge top and sides* and a *45-90 degree wingwall* are selected on the next menu:



After entering this data, the summary table appears, showing the new configuration:

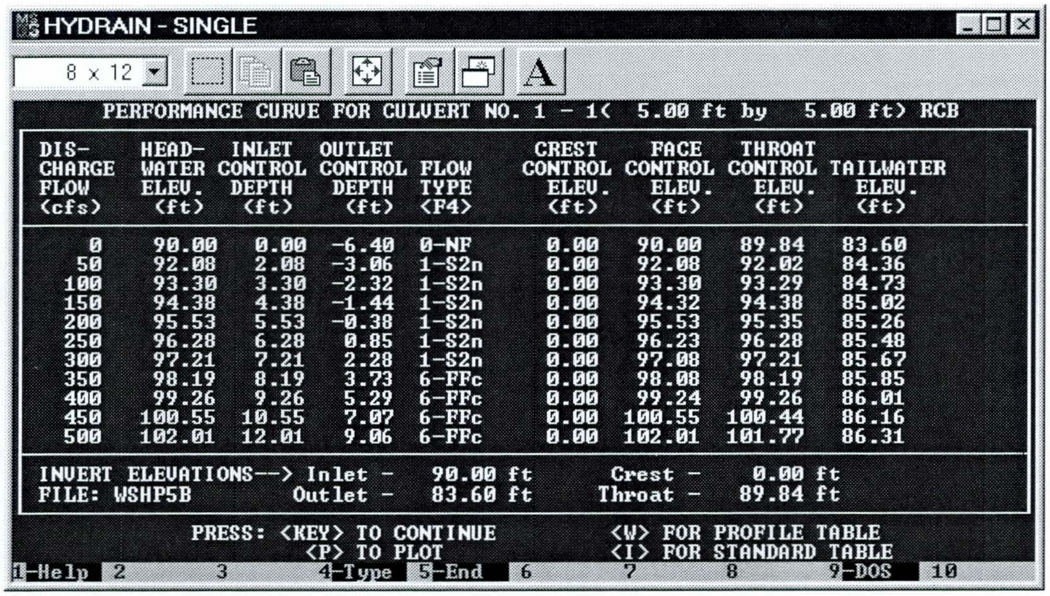


After saving and exiting, the options menu appears again and this configuration can be analyzed:



The calculated headwater elevation (99.26) compares favorably with the results from Workshop 5.

Entering "*I*" then displays the improved inlet table:


HYDRAIN - SINGLE

PERFORMANCE CURVE FOR CULVERT NO. 1 - 1(5.00 ft by 5.00 ft) RCB

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE (F4)	CREST CONTROL ELEV. (ft)	FACE CONTROL ELEV. (ft)	THROAT CONTROL ELEV. (ft)	TAILWATER ELEV. (ft)
0	90.00	0.00	-6.40	0-NF	0.00	90.00	89.84	83.60
50	92.08	2.08	-3.06	1-S2n	0.00	92.08	92.02	84.36
100	93.30	3.30	-2.32	1-S2n	0.00	93.30	93.29	84.73
150	94.38	4.38	-1.44	1-S2n	0.00	94.32	94.38	85.02
200	95.53	5.53	-0.38	1-S2n	0.00	95.53	95.35	85.26
250	96.28	6.28	0.85	1-S2n	0.00	96.23	96.28	85.48
300	97.21	7.21	2.28	1-S2n	0.00	97.08	97.21	85.67
350	98.19	8.19	3.73	6-FFc	0.00	98.08	98.19	85.85
400	99.26	9.26	5.29	6-FFc	0.00	99.24	99.26	86.01
450	100.55	10.55	7.07	6-FFc	0.00	100.55	100.44	86.16
500	102.01	12.01	9.06	6-FFc	0.00	102.01	101.77	86.31

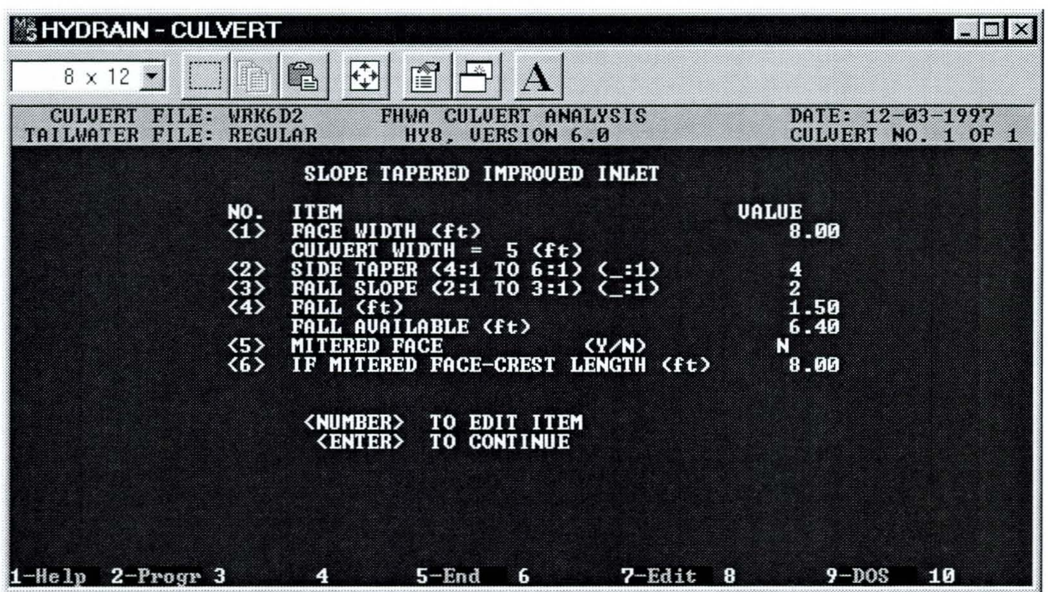
INVERT ELEVATIONS--> Inlet - 90.00 ft Crest - 0.00 ft
FILE: WSHP5B Outlet - 83.60 ft Throat - 89.84 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR STANDARD TABLE

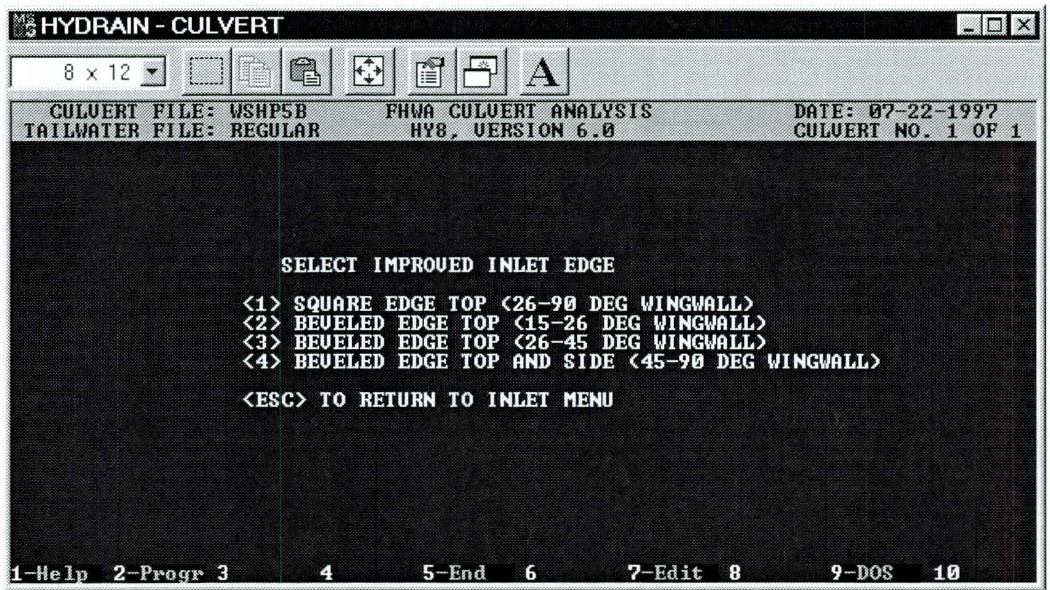
1-Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

Slope-tapered Alternative

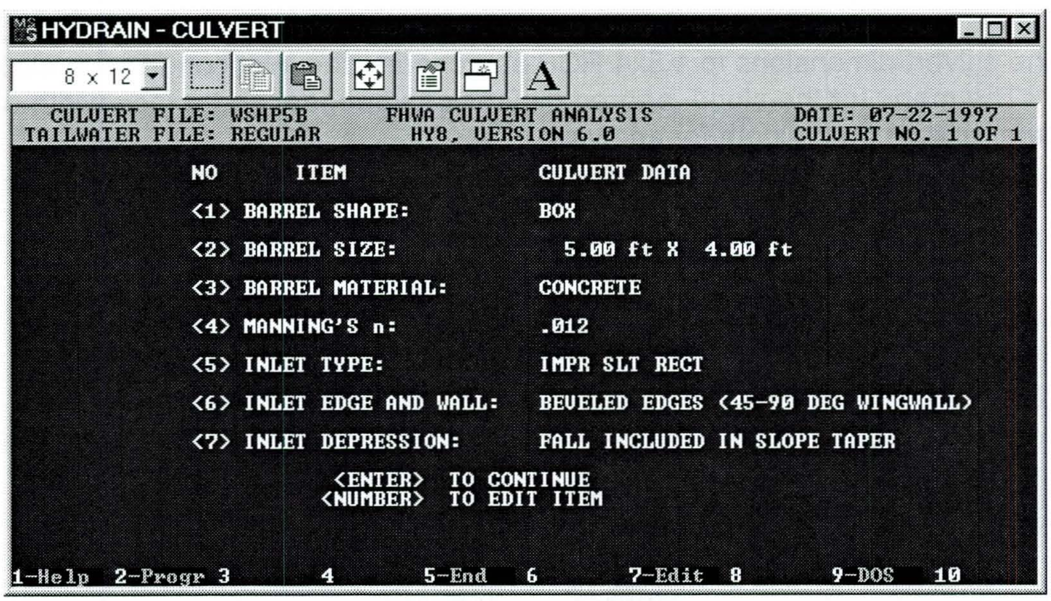
Analyze the slope-tapered alternative by again selecting *edit* on the options menu, and modify the culvert dimensions to a 5x4 RCB and change the inlet condition to slope-tapered. The menu for the slope-tapered dimensions appears and a face width of *8 ft with a taper of 4:1* can be input for analysis:



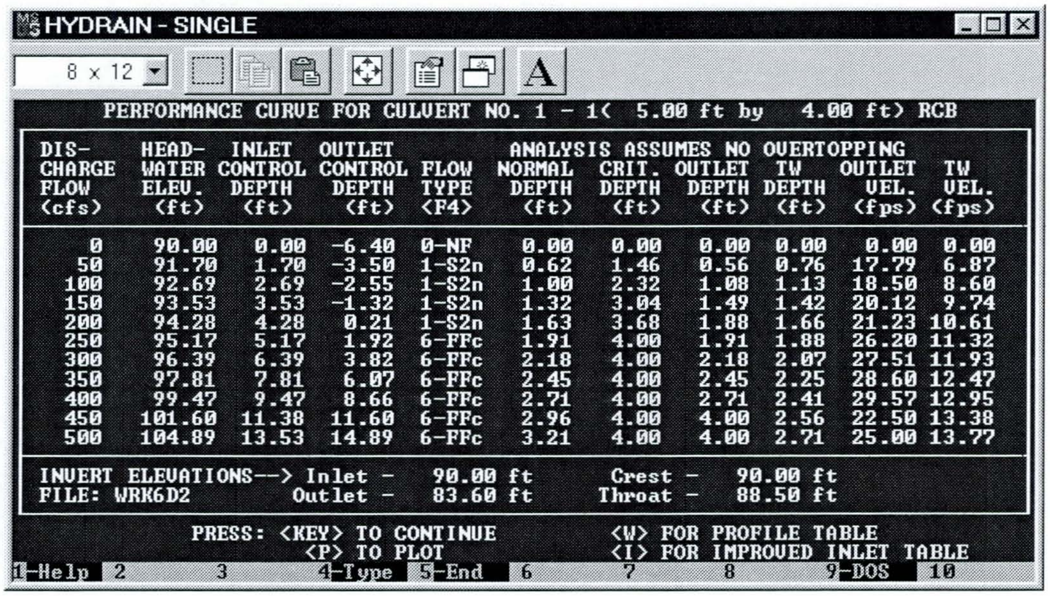
A *beveled edge top and sides and a 45-90 degree wingwall* are selected on the next menu:



After entering this data, the summary table appears showing the new configuration:



After saving and exiting, the options menu appears again and this configuration can be analyzed:



PERFORMANCE CURVE FOR CULVERT NO. 1 - 1(5.00 ft by 4.00 ft) RCB

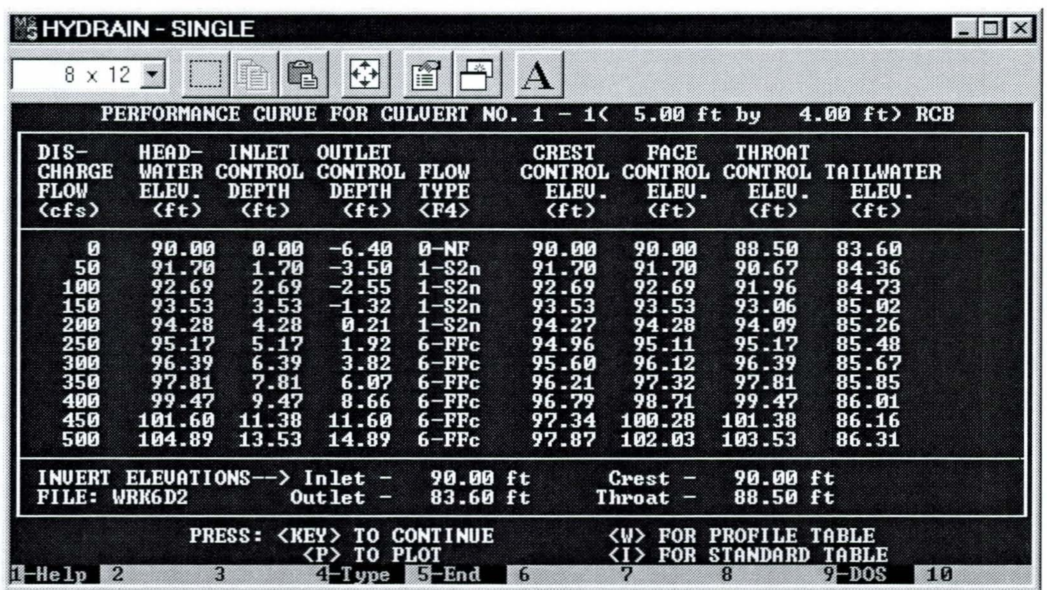
ANALYSIS ASSUMES NO OVERTOPPING

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET VEL. (fps)	TW VEL. (fps)
0	90.00	0.00	-6.40	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50	91.70	1.70	-3.50	1-S2n	0.62	1.46	0.56	0.76	17.79	6.87
100	92.69	2.69	-2.55	1-S2n	1.00	2.32	1.08	1.13	18.50	8.60
150	93.53	3.53	-1.32	1-S2n	1.32	3.04	1.49	1.42	20.12	9.74
200	94.28	4.28	0.21	1-S2n	1.63	3.68	1.88	1.66	21.23	10.61
250	95.17	5.17	1.92	6-FFc	1.91	4.00	1.91	1.88	26.20	11.32
300	96.39	6.39	3.82	6-FFc	2.18	4.00	2.18	2.07	27.51	11.93
350	97.81	7.81	6.07	6-FFc	2.45	4.00	2.45	2.25	28.60	12.47
400	99.47	9.47	8.66	6-FFc	2.71	4.00	2.71	2.41	29.57	12.95
450	101.60	11.38	11.60	6-FFc	2.96	4.00	4.00	2.56	22.50	13.38
500	104.89	13.53	14.89	6-FFc	3.21	4.00	4.00	2.71	25.00	13.77

INVERT ELEVATIONS--> Inlet - 90.00 ft Crest - 90.00 ft
FILE: WRK6D2 Outlet - 83.60 ft Throat - 88.50 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR IMPROVED INLET TABLE

Entering "I" then displays the improved inlet table:



PERFORMANCE CURVE FOR CULVERT NO. 1 - 1(5.00 ft by 4.00 ft) RCB

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	CREST CONTROL ELEV. (ft)	FACE CONTROL ELEV. (ft)	THROAT CONTROL ELEV. (ft)	TAILWATER ELEV. (ft)
0	90.00	0.00	-6.40	0-NF	90.00	90.00	88.50	83.60
50	91.70	1.70	-3.50	1-S2n	91.70	91.70	90.67	84.36
100	92.69	2.69	-2.55	1-S2n	92.69	92.69	91.96	84.73
150	93.53	3.53	-1.32	1-S2n	93.53	93.53	93.06	85.02
200	94.28	4.28	0.21	1-S2n	94.27	94.28	94.09	85.26
250	95.17	5.17	1.92	6-FFc	94.96	95.11	95.17	85.48
300	96.39	6.39	3.82	6-FFc	95.60	96.12	96.39	85.67
350	97.81	7.81	6.07	6-FFc	96.21	97.32	97.81	85.85
400	99.47	9.47	8.66	6-FFc	96.79	98.71	99.47	86.01
450	101.60	11.38	11.60	6-FFc	97.34	100.28	101.38	86.16
500	104.89	13.53	14.89	6-FFc	97.87	102.03	103.53	86.31

INVERT ELEVATIONS--> Inlet - 90.00 ft Crest - 90.00 ft
FILE: WRK6D2 Outlet - 83.60 ft Throat - 88.50 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
<P> TO PLOT <I> FOR STANDARD TABLE

6.5 WORKSHOP 6C - FLUME DEMONSTRATION

INLET AND OUTLET CONTROL

The differences between inlet and outlet control will be demonstrated using a double barrel culvert model. The barrels are the same size; however, one is smooth and one is rough. Only one barrel will be used at a time.

Remember under inlet control the conditions at the inlet govern how much water can enter the culvert, while under outlet control conditions downstream of the inlet predominate.

With the flume on a flat slope, the discharge will be increased to create full flow conditions in the pipe. The factors influencing outlet control will be evaluated and discussed during the demonstration.

Inlet control conditions will be demonstrated by increasing flume slope. Note that initially, as the slope increases, the headwater remains constant and the culvert continues to operate in outlet control. However, eventually the headwater begins to increase and a free surface condition develops, indicating a change to inlet control. The factors influencing inlet control will be evaluated and discussed. Note that in the field, inlet control can occur at about a half of one percent slope for a smooth barrel.

In particular, note the effect of pipe roughness on flow conditions between inlet and outlet control.

What are the relationships between inlet and outlet control and supercritical and subcritical flow?

NOTES:

NOTES:

CULVERT INLETS

The effect of inlet configuration will be demonstrated with the single-barrel culvert model operating in inlet control. The inlets demonstrated include a sharp edge, miter, thick wall, headwall, groove end, headwall with a bevel, and side- and slope-tapered improved inlets. Note the changes in headwater for different inlet conditions.

NOTES:

6.6 WORKSHOP 6D - DESIGN WORKSHOP

PROBLEM STATEMENT

A new bypass has been proposed around a small rural community. The project includes a culvert crossing of a stream channel with a 50-year discharge of 1,000 cfs. The Project Manager has requested a conceptual design and cost estimate for the culvert by tomorrow morning, in preparation for a budget meeting later that day.

Review of the preliminary roadway plans indicate that the barrel length will be about 350 ft on a 5 percent slope. The outlet invert elevation is 172.5 ft. The allowable headwater elevation is 200.0. Available mapping indicates that the stream channel slope upstream and downstream of the crossing can be approximated by an 8 ft bottom, 2:1 sideslope trapezoidal channel with an n value of 0.03. The calculated tailwater rating curve is:

DISCHARGE (cfs)	TW (ft)
200	1.50
400	2.25
600	2.75
800	3.25
1000	3.50
1200	3.80

REQUIRED SOLUTION

Complete preliminary design for a box culvert at the proposed crossing. Begin with a conventional culvert design (may be a multiple barrel configuration); however, if inlet control exists also evaluate an improved inlet design. The project is located in a rural area where the allowable headwater elevation is not to critical; that is, the damages are low due to exceeding that elevation at infrequent times. Therefore, the culvert should have the smallest possible barrel to pass the design discharge without exceeding the allowable headwater elevation.

Estimate barrel cost assuming a wall thickness of 12 inches and a unit cost of $300/cy for concrete and steel. If an improved inlet is used, estimate the inlet cost based on a wall thickness of 12 inches and a unit cost of $500/cy for concrete and steel. Include a 10 percent contingency in your final estimate to account for headwall/wingwall requirements that will be designed at a later date. If an energy dissipator is required, it will also be designed at a later date and will be included as a separate line item on the cost estimate, to be determined by others. A blank culvert design form and taper design form have been provided for the design, and any required nomographs can be found in HDS-5.

CALCULATIONS:

CALCULATIONS:

CALCULATIONS:

CULVERT DESIGN FORM

PROJECT: ______________________________

STATION: ______________ SHEET ______ OF ______

DESIGNER / DATE: ________ / ________

REVIEWER / DATE: ________ / ________

HYDROLOGICAL DATA

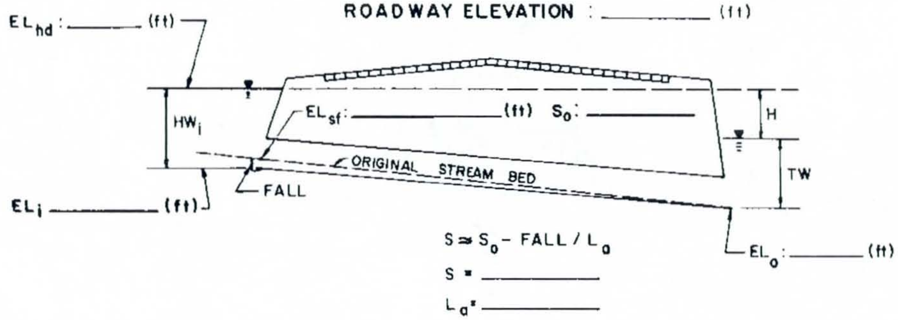
SEE ADD'L. SHTS.

- ☐ METHOD: ____________
- ☐ DRAINAGE AREA: ________ ☐ STREAM SLOPE: ________
- ☐ CHANNEL SHAPE: ____________
- ☐ ROUTING: ________ ☐ OTHER: ________

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)

ROADWAY ELEVATION: ________ (ft)



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL: TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW/D$ OR HW_f/D FROM DESIGN CHARTS

(3) $FALL = HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2 / 2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

CULVERT BARREL SELECTED:

SIZE: ____________

SHAPE: ____________

MATERIAL: ________ n: ________

ENTRANCE: ____________

PROJECT: ______________________________	STATION: ______________ SHEET ______ OF ______	TAPERED INLET DESIGN FORM DESIGNER / DATE: ________ / ________ REVIEWER / DATE: ________ / ________

DESIGN DATA:

Q ____ = ____ cfs ; EL_{hi} ________ ft

EL. THROAT INVERT ________ ft

EL. STREAM BED AT FACE ________ ft

FALL ________ ft TAPER ________ : 1 (4 : 1 TO 6 : 1)

STREAM SLOPE , S_o = ________ ft/ft

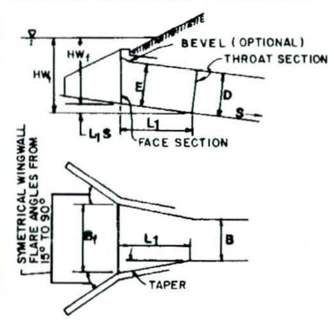
SLOPE OF BARREL , S = ________ ft/ft

S_f ________ : 1 (2 : 1 TO 3 : 1)

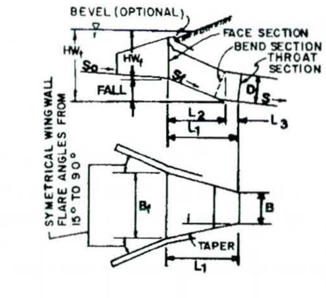
BARREL SHAPE AND MATERIAL : ________________

N = ________ , B = ________ , D = ________

INLET EDGE DESCRIPTION ________________



SIDE - TAPERED



SLOPE - TAPERED

COMMENTS

Q (cfs)	EL_{hi}	EL. THROAT INVERT	EL. FACE INVERT (1)	HW_f (2)	HW_f / E (3)	Q / B_f (4)	MIN. B_f (5)	SELECTED B_f	SLOPE-TAPERED ONLY: MIN. L_3 (6)	L_2 (7)	CHECK L_2 (8)	ADJ. L_3 (9)	ADJ. TAPER (10)	L_1 (11)	SIDE-TAPERED W/ FALL: EL. CREST INV.	HW_c (12)	MIN. W (13)

(1) SIDE - TAPERED : EL. FACE INVERT = EL. THROAT INVERT + 1 ft (APPROX.)
SLOPE - TAPERED : EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hi}$ - EL. FACE INVERT

(3) $1.1 D \geq E \geq D$

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q/(Q/B_f)$

(6) MIN. $L_3 = 0.5 NB$

(7) L_2 = (EL. FACE INVERT - EL. THROAT INVERT) S_f

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_3$

(9) IF (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER $- L_2$

(10) IF (7)>(8), ADJ. TAPER $= (L_2 + L_3) \Big/ \left[\frac{B_f - NB}{2}\right]$

(11) SIDE - TAPERED : $L = \left[\frac{B_f - NB}{2}\right] \cdot$ TAPER
SLOPE - TAPERED : $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = 0.35 Q / HW_c^{1.5}$

SELECTED DESIGN

B_f ________

L_1 ________

L_2 ________

L_3 ________ (

BEVELS ANGLE ____ °

b = ____ in ; d = ____ in

TAPER ________ : 1

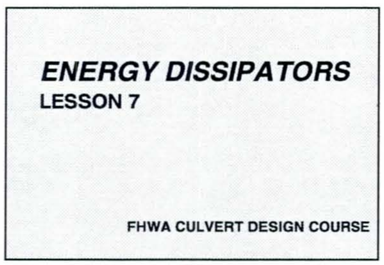
S_f = ________ : 1

LESSON 7

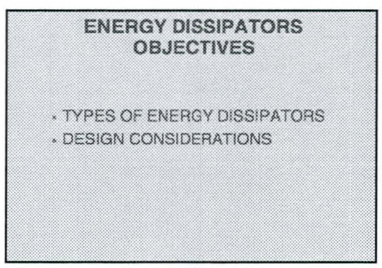
ENERGY DISSIPATORS

OVERVIEW:

Method of Instruction:	Lecture
Lesson Length:	75 minutes
Resources:	Student Workbook Graphics



7.0a



7.0b

OBJECTIVES: At the conclusion of this lesson, the participant shall be able to:

1. Understand the different types of energy dissipators and the application.
2. Understand general design considerations for each type of energy dissipator.

LESSON OUTLINE

7. ENERGY DISSIPATORS

   7.1. INTRODUCTION

   7.2. EROSION PROBLEMS

   7.3. GENERAL PROTECTION

   7.4. DESIGN CONCEPTS

   7.5. TYPES OF ENERGY DISSIPATORS

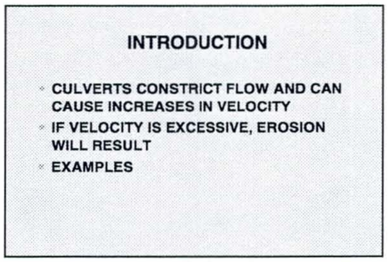
   7.6. WORKSHOP 7A - ENERGY DISSIPATOR VIDEO AND DISCUSSION

   7.7. WORKSHOP 7B - FLUME DEMONSTRATION

   7.8. WORKSHOP 7C - ENERGY DISSIPATOR DESIGN

7.1. INTRODUCTION

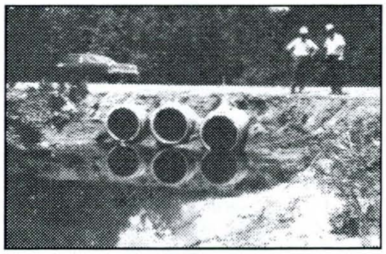
A. Since a culvert represents a constriction in the flow, due to the fundamentals of continuity of flow, velocity of flow increases.
B. If the flow velocity of water as it exits the culvert is excessive, damaging erosion and impacts on culvert, roadway, and property may result.



7.1

C. Examples of culverts impacted by erosion:

Scour hole at the outlet of a culvert installation on the Long Leaf Trail in Louisiana..



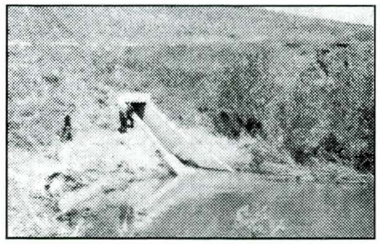
7.2

Slide 7.3 shows a barrel that has been undermined and dropped down into the scour hole.

7.3

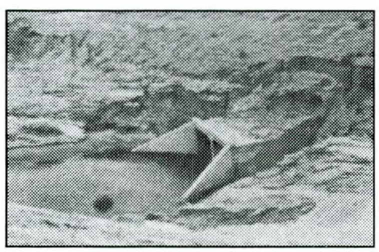
This is a typical failure for concrete pipe, losing the last section of pipe. The contractor will have to pick up this section and rebed it before building the headwall. If the contractor was off the job, this type of failure would lead to losing the end of the pipe which tends to be a progressive failure. Additional sections of pipe are lost with time. The use of U-bolts or ties on the culvert tops can minimize the repair work required for this type of failure. If the end of the culvert is undermined, maintenance forces can jack up the culvert since it is tied together and rebed it without special equipment.

A scour hole can get quite large if left unchecked. Here a scour hole is encroaching upon the highway embankment and with time it could even cause undermining and failure of the embankment and possibly failure of the roadway.



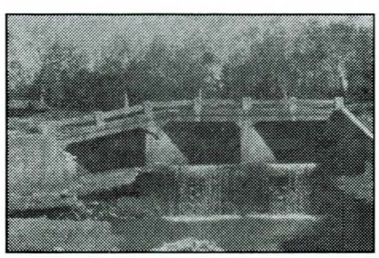
7.4

A large scour hole has formed at the end of the culvert in Slide 7.5. However, this is even more severe than it appears. The scour hole has undermined the end of the culvert. About 15 feet back in the barrel, the culvert is broken off. The whole culvert end has dropped down into the hole. This will be very expensive to fix. The only thing that can be done is to break up and reform the whole end of the box.



7.5

Slide 7.6 shows an RCB failure is in Oklahoma due to head cutting.



7.6

Or you can lose the whole culvert end, as shown in Slide 7.7, due to headcutting or degradation. This is a more severe problem than can be handled with energy dissipators. An energy dissipator is not going to help with an unstable channel over a long reach. Head-cutting or long term channel degradation cannot be corrected by slowing the water down at the outlet of the culvert. Channel degradation must be analyzed by looking at the whole channel reach to see if it is stable, which is a more complicated analysis than just analyzing the culvert.

7.7

D. The designer has two basic options to handle high velocity flow from a culvert. One is to simply do nothing in the hope that the potential for damage is not serious or will naturally rectify itself. The other is to provide some type of protection to directly rectify the damage potential. This protection may be in the form of an energy dissipator.

7.2. EROSION PROBLEMS

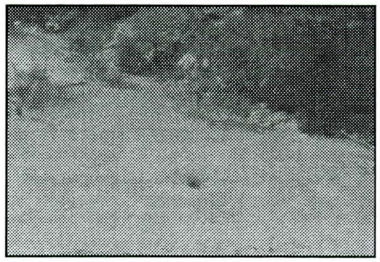
Erosion problems can occur both upstream and downstream of the culvert. Excessive velocities at the downstream end of the culvert tend to cause the more extensive and expensive damages.

A. Downstream

Typically, scour holes form which may develop into culvert or even highway embankment failure, as illustrated above. Extensive scour holes may encroach on private property off the roadway right-of-way.

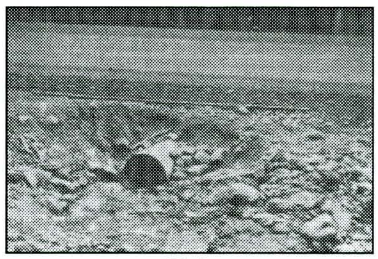
B. Upstream

It is commonly thought the vortex or whirlpool at the entrance of the culvert causes a severe amount of erosion. This really is not the case. The vortex causes a minor amount of erosion at the entrance to the culvert.



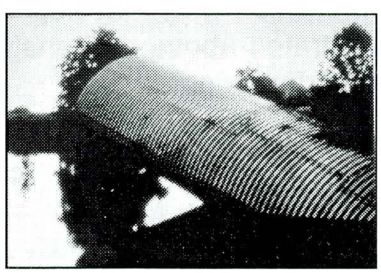
7.8

More problems at the inlet are caused by misalinement of the culvert. As shown in Slide 7.9, the stream approaches the roadway at a skew. In order to provide the least expensive culvert, culverts are frequently constructed perpendicular to the roadway. So the stream approaches at an angle which causes the stream to make an abrupt turn. In Slide 7.9, the whirling action has removed quite a bit of material even in this very cobbly soil. If the cobbles were not present even more material would have been lost.



7.9

A problem can also be caused by buoyancy. A thin edge projecting culvert sticking out of the fill with water over the top of it has nothing to hold the culvert down. It can be lifed up vertical like a stove pipe. Some very dramatic failures of this type have been experienced, as shown in Slide 7.10. This problem can be corrected with a headwall. The culvert must have its leading edge anchored into the headwall with bolts.



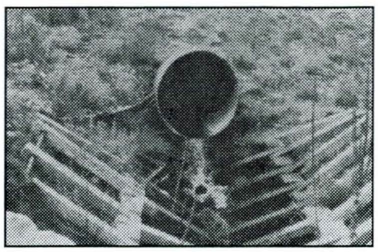
7.10

Erosion, impact, and associated damages at the upstream end of a culvert are not as common a problem as those at the downstream end. Often, local erosion at the upstream end of the culvert can be addressed by routine maintenance.

7.3. GENERAL PROTECTION

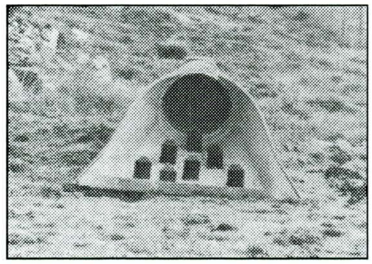
A. All kinds of things have been tried to slow water down. The following examples illustrated things that have *not worked*...

B. Slide 7.11 shows an articulated mattress that was built on a Federal highway project in the west. The articulated mattress should break up the jet of flow coming out of the culvert and slow the water down; however, it did not work very well. The mattress was originally constructed on the same grade as the culvert, but is now 6 or 7 feet depressed below that flow line. The reason was that there was no filter below the mattress and so the soil was eroded from under the mattress causing it to sink, leaving a big scour hole. Some large rock was added afterwards to try to hold it in place but it was not very successful. Another complication was that the mattress was designed to be two times longer than shown, but construction personnel decided that was not necessary, so they shortened it...



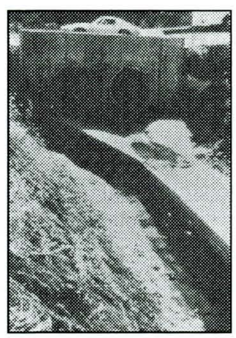
7.11

C. Slide 7.12 shows roughness elements put on a terminal end section to slow the water down. In this case there are too few elements, they are too close to the entrance, and the section is not wide enough.. A row of roughness elements or a couple of rows of roughness elements will only slow the water down a minor amount.



7.12

D. The limited paving shown in Slide 7.13 will not be effective for any flows of signficance. As a minimum, it is better to pave the mean annual or the normal flow of the channel. If you want to protect for the design flow, pave the whole channel with freeboard.

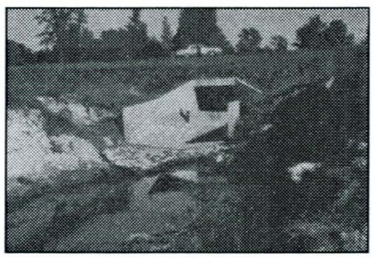


7.13

E. Endsills are not energy dissipators and they do not slow the water down. Slide 7.14 shows an endsill in California that was used to direct low flows over a sacked riprap roughness element dissipator. For very low flows, this design may be adequate, but a single endsill would be ineffective under high flows..

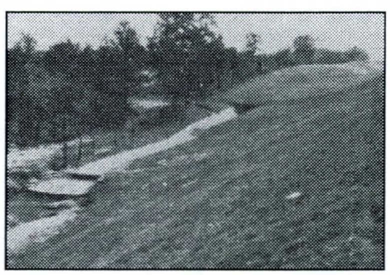
7.14

F. After the culvert in slide 7.15 was constructed, a scour hole formed causing a problem with the culvert. Concrete was added to the end of the culvert with a drop. As can be seen the problem has just been shifted from the end of the culvert to the end of the concrete. The scour hole is now undermining the grouted riprap and it will not be long until the concrete is undermined. After it falls in, you are right back to where you started from. Smooth concrete does not slow the water down. A paved apron at the culvert exit is only a delaying measure and should not be used in place of a good energy dissipator.



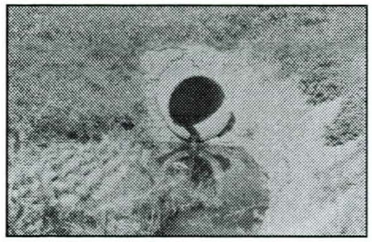
7.15

G. Slide 7.16 illustrates the same problem, only in this case one failure did not convince the maintenance crew. They kept chasing the problem downstream at least three stages until they ran out of right-of-way...



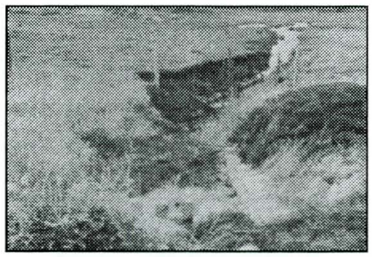
7.16

H. Slide 7.17 shows a stable environment at the culvert exit. Unfortunately, this was accomplished with essentially rigid paving. The paving will be satisfactory only if a good terminus is used such as stopping at another



7.17

culvert, another paved lining, or a dissipator of some type. None of these three exist at this site. So, the obvious place to stop the paving is at the ROW fence... Of course, the water should be released in substantially the same condition it was in before the highway was built and then this would not happen.

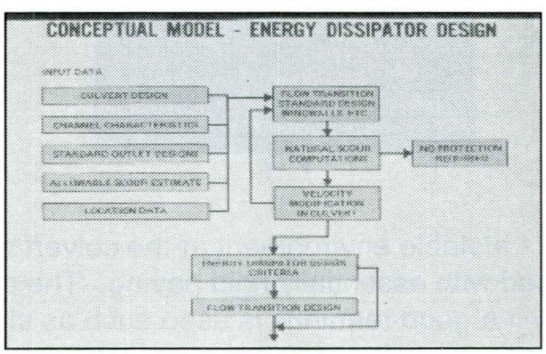


7.18

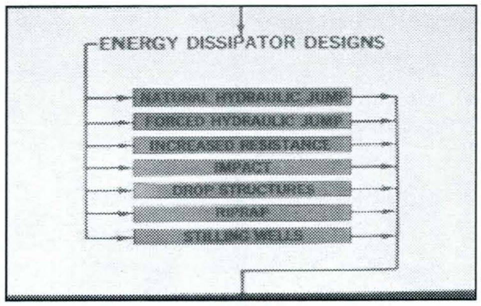
7.4. DESIGN CONCEPTS

A. The subject of energy dissipators is covered extensively in HEC #14, "Hydraulic Design of Energy Dissipators for Culverts and Channels". About 20 types of energy dissipators are addressed in this publication.

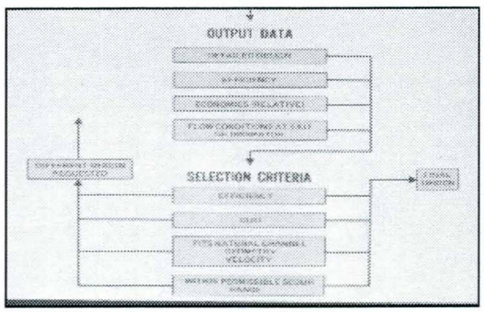
B. Design Concepts



7.19



7.20



7.21

The design consideration of when and what type of energy dissipator to use is a function of:

- the culvert design,
- down stream channel configuration,
- standard outlet design,
- available scour,
- distance to right-of-way fence,
- proximity of the roadway embankment,
- potential for culvert undermining,
- rural or urban character of the culvert location.

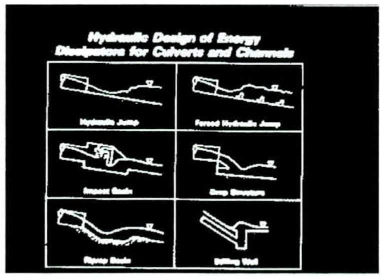
1. Outlet Velocity

   The designer's judgment of whether or not the culvert outlet velocity is excessive is subjective. Comparisons to natural stream velocity should be made. The potential for erosion or other damage must be estimated.

2. Velocity Reduction

   If a velocity reduction is judged to be in order, the designer must decide just how to reduce the velocity.

7.5. TYPES OF ENERGY DISSIPATORS

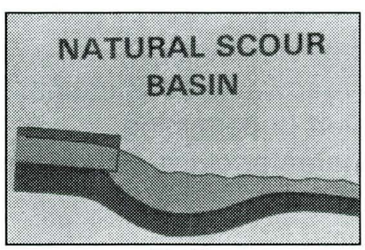


7.22

Energy dissipator types include:

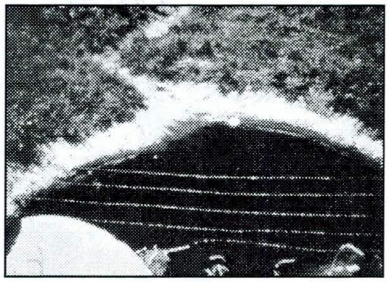
- Natural hydraulic jump,
- Forced hydraulic jump,
- Increased resistance,
- Impact,
- Drop structures,
- Riprap,
- Stilling wells.

A. Scour Holes. The most economical solution is the do-nothing alternative, or allow the natural scour hole to form at the outlet of the culvert and let the scour hole act as the energy dissipator.



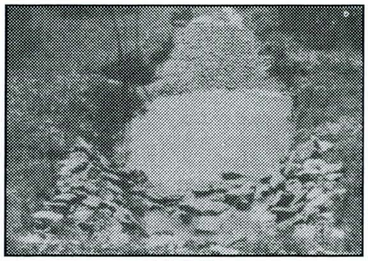
7.23

In erosion resistant material with a large amount of clay in the soil or in a rocky soil, the scour hole will armor itself and be a pretty good energy dissipator. If pure sand exists at the outlet of the culvert, the scour dimensions may exceed your criteria, and cause a problem.



7.24

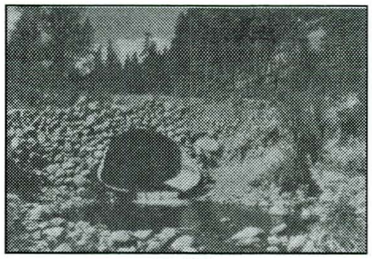
One way to evaluate scour potential is to look at culverts in the area where the flow conditions are known. Calculate the scour that is expected at the outlet of the culvert and compare it with what actually occurred. If the scour holes are not excessive, they may be adequate energy dissipators. Alternatively, a riprap basin can be installed in a preformed scour hole.



7.25

Slide 7.25 shows a culvert which runs underneath a canal and exits on a rock riprap pad. The rock riprap pad was ineffective in slowing the water down. The velocity went over top of the pad and scoured this hole downstream of the riprap. Fortunately, there was a considerable amount of gravel in the underlying soil. The gravel armored the scour hole, and we now have an energy dissipator that is working fine...

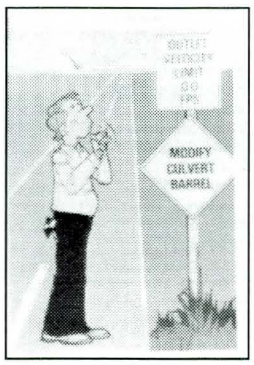
Another example is the small scour hole shown in Slide 7.26 that armored itself with cobbles that were placed around the culvert exit and it appears to be effective for low flows. However, with a large flow the scour hole may get larger and maybe even wash out.



7.26

A natural scour hole can be a cost-effective dissipator. The designer's choice may be to do nothing and let nature control the potential for damage by letting the water dig its own scour hole which, in turn, may serve as an effective energy dissipator.

However, if you cannot live with a natural scour hole, or if the velocity coming out of the culvert is excessive, you are going to have to consider an energy dissipator. To design the dissipator, accept the velocity coming out of the culvert, and design the energy dissipator to handle that velocity.

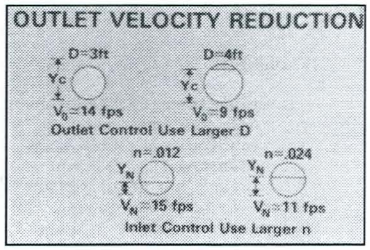


7.27

The question is, what velocity do we design for coming out of the dissipator? An outlet velocity limit of zero feet per second is certainly not reasonable, nor is any other aribitrary velocity criteria that we could place on this sign. What is a reasonable range to design for? 4 to 6 feet per second? 6 to 8 feet?

Whatever range you choose, this is not really the approach you should use for design. You should design for whatever velocity will occur naturally in the downstream channel: normal depth and normal velocity in the downstram channel. These are the conditions you should design for coming out of the energy dissipator. If the water leaves the dissipator slower than normal velocity in the downstream channel, at some point downstream the water is going to return to normal velocity. Therefore, our criteria will be normal velocity in the downstream channel.

B. Internal Velocity Reduction. The first step is to look at slowing the water down within the culvert barrel. The first thing that comes to mind is to use a rougher barrel.

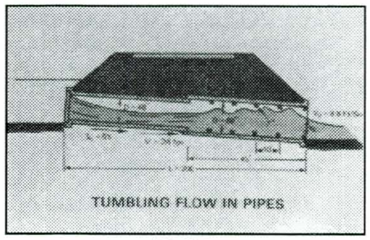


7.28

In the bottom example shown here, the culvert is in inlet control. On the left is a smooth barrel, similar to a concrete pipe. On the right is a rough barrel, similar to a corrugated metal pipe. Notice that the velocity has been reduced by using a larger roughness pipe, from 15 to 11 feet per second, in inlet control. If using the rougher barrel did not provide enough reduction, the cuvlert barrel can be artifically roughened. That alternative will be considered next. At no time in inlet control will using a larger barrel culvert substantially reduce the outlet velocity.

In outlet control, there is one special case where a larger barrel culvert will reduce the outlet velocity. The special case shown as the upper example is for the barrel flowing full all the way to the end of the culvert. In other words, the barrel is in pressure flow to the end of the barrel.

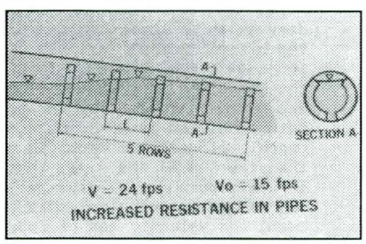
You can artifically roughen the culvert barrel and reduce the outlet velocity by using roughness rings. There are two types of designs using roughness rings: tumbling flow and increased resistance.



7.29

The diameter of the rings, inside diamater, is equivalent to the approach diameter of the culvert. The height of the rings is 1/10 the diameter of culvert. The ring spacing is approximately one culvert diameter. One spacing should be provided beyond the last roughness ring as a landing area (this is not shown in the diagram). Notice, that with tumbling flow free surface flow occurs throughout the culvert. The exit is at critical depth and critical velocity.

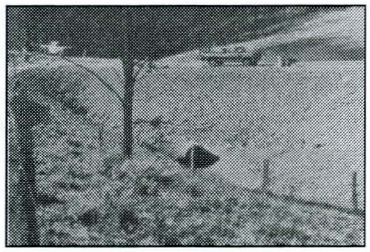
The other type of flow for roughness rings is to fill up the end of the barrel of the culvert by forcing a hydraulic jump to occur in the area of the roughness field. This is referred to as increased resistance.



7.30

The notches are provided in the bottom for low flow drainage. The notch is provided in the top to prevent the hydraulic jump from moving upstream and filling up the barrel. Without the notches the culvert has a tendency to fill up and force the barrel into outlet control. Whenever you place anything within the culvert barrel, the culvert is very susceptible to switching into outlet control or filling up for larger discharges. Therefore, you should have a good idea of the design discharge. Or at least be on the conservative side when designing within the culvert barrel. Another check is to look at the performance curve for your culvert. If the design discharge is close to the intersection of the inlet and outlet control curve, the culvert design is close to forcing the barrel to flow full. Once in outlet control, the headwater will rise quite rapidly. This will force you to look upstream to check what your safety factor is, i.e., how much safety factor you have in your headwater upstream, before the allowable headwater is exceeded. This type of design will probably be used more often in an urban area where a right-of-way constraint is present, where the dissipator cannot be hung on the outside of the culvert, or outside of the fill.

Slide 7.31 shows the inlet of a culvert with a roughness ring dissipator in Ohio. Notice this is a rural area and a fairly high fill (30 to 40 feet).

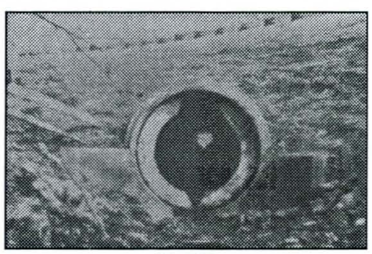


7.31

Slide 7.32 is the outlet before the roughness rings were added

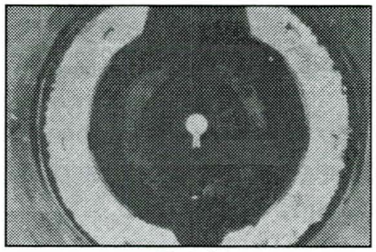
7.32

This is a large diameter culvert. Since the roughness rings were so large, they were fabricated in a yard, pulled in on a sled, and then jacked into place.



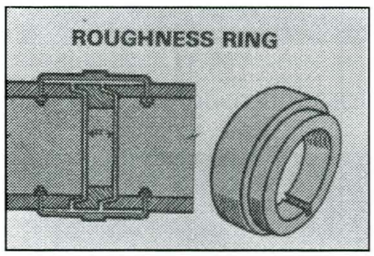
7.33

The rings were fabricated in halves. A series of five rings were put into place. They were bolted and epoxied into place. Roughness rings can also be fabricated as part of a section of pipe.



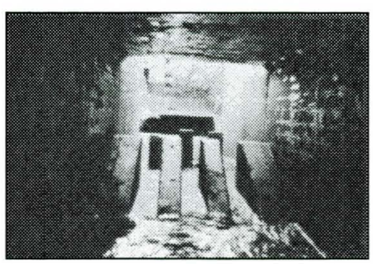
7.34

For example, one manufacturer supplies a section of pipe (12 inches long) as shown in Slide 7.35. U-bolts are used to bolt them in place. This type of energy dissipator can then be provided fairly cheaply. Furthermore, with this design the roughness rings can be used to slow the water down some, and then another dissipator could be added at the outlet to slow the water down to the velocity that exists in the downstream channel.



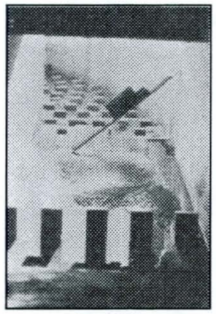
7.35

The same sort of design can be used for box culverts. The installation in Slide 7.36 was not designed using HEC #14. If a roughness ring was designed for a box culvert to create tumbling flow, the sill will be approximately half the height of the culvert or higher as shown. This will cause you to build a higher culvert and raise the roof. The recommended design is to build a complete sill all the way across the bottom, with small slots in it for drainage, not large slots as shown. Also, a series of 5 sills are required.



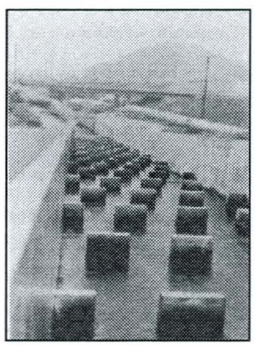
7.36

For increased resistance in box culverts, the height of the roughness elements will be similar to the height shown in Slide 7.37. Isolated roughness elements like this are not recommended. The sill should extend all the way across the culvert bottom. With box culverts you have the flexibility to design the length of roughness element that you need. You can put a roughness element just on the bottom with small slots for low flow drainage. If more resistance is needed, the roughness element can be extended up the wall on both sides. For the most resistance, it can be placed all the way around. The number of roughness elements that are required is determined by the momentum equation using a conservative coefficient of drag. For just roughness on the bottom of a culvert of this size, a small roughness element, it is possible to require as many as 80 or 90 rows of roughness elements, which is not practical.



7.37

Slide 7.38 shows a design called "large roughness elements on steep slopes." It is not included in HEC 14, but is detailed in Nomograph 25 from the Bureau of Reclamation. It is primarily for irrigation return flow and is not commonly used for culvert installations.

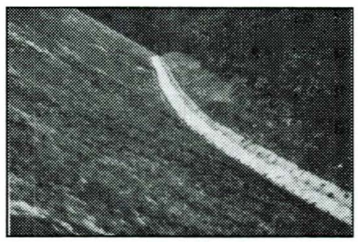


7.38

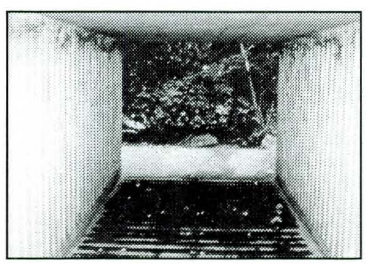
Also not included in HEC 14 is determining the effect of using natural material such as rock to slow the water down as was used in this installation on the Tellico-Robinsville Scenic Highway in Tennessee.

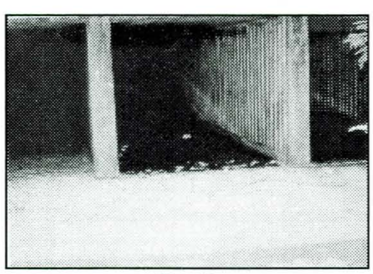

7.39

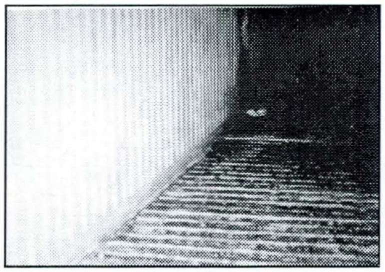
The channel in Slide 7.40 is at the toe of a fill slope and is on a 13 percent grade.


7.40

Another non-conventional approach is to increase surface roughness with cast-in-place roughness elements (2x4's inserted into casting forms):

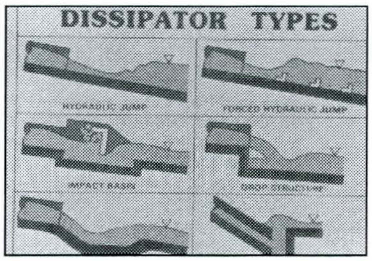

7.41


7.42



7.43

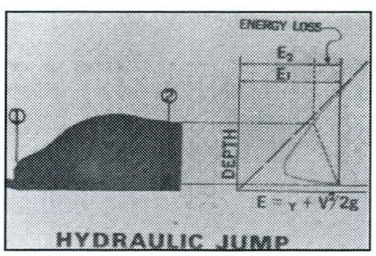
C. External Energy Dissipators. External energy dissipators are broken into six classes:



7.44

Several types of external energy dissipators are possible. For a given situation of excessive culvert outlet velocity, any of the several types may be effective. The designer should select the most cost-effective.

1. Natural Hydraulic Jump. The hydraulic jump is a natural energy dissipator. It is not very often used along the highway for various reasons: it takes a long length to be accomplished, a free hydraulic jump is not stable over a range of discharges, and it is hard to calculate where a hydraulic jump will occur.



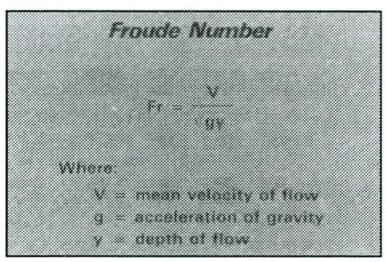
7.45

An hydraulic jump is a fast moving jet or super critical flow approaching the jump area and a slow moving jet or subcritical flow leaving the jump area. On the right is deep, slow moving water which is necessary to force the hydraulic jump to occur.

In all cases, you have to have sufficient tailwater depth downstream in order to force the jump to occur. Just changing the slope, for example in a broken back culvert, is not going to cause the jump to occur (a broken back culvert is a culvert which comes down on a steep slope, and then near the end of the culvert the slope is flattened out).

If tailwater is not present, another way to force the jump to occur is put roughness elements in the culvert. If this is done, the size of the downstream culvert must be larger in order to accommodate the jump without causing undue pressure on the downstream section of the culvert.

The operation of the hydraulic jump is dependent on the force of the flow and can be indicated with the Froude number which has the formula:



7.46

Another reason you do not see free hydraulic jumps near the highways is that culvert outlet velocity does not have sufficient energy to form a good hydraulic jump. The Bureau of Reclamation recommends that the Froude number be in the order of 4-1/2 to 9 to form a good hydraulic jump. Typically along the highway, Froude numbers are down in this range, 3 or less. Also, hydraulic jumps are only stable for the design discharge. If a discharge higher than your design discharge is received, the free hydraulic jump is swept out of the basin. If the discharge is less, the jump is submerged on the slope with a rough water surface.

HYDRAULIC JUMP

Fr	JUMP FORM
1.7 to 2.5	PRE-JUMP—OSCILLATING JET
2.5 to 4.5	ROUGH WATER SURFACE
4.5 to 9.0	RANGE OF GOOD JUMPS
> 9.0	EFFECTIVE BUT ROUGH

7.47

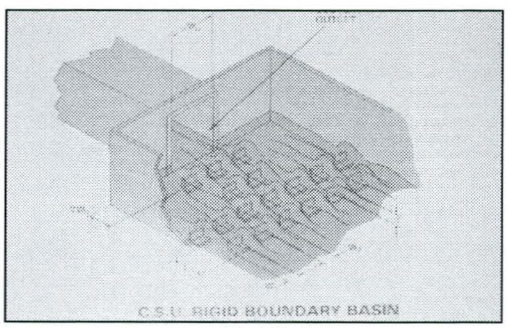
For these reasons, a forced hydraulic jump will normally be used.

2. Forced Hydraulic Jump

For a forced hydraulic jump, some appurtenance is added to a stilling basin which helps to stabilize the jump over a range of discharges and forces it to occur in a shorter distance. Thus they are cheaper to build.

a. CSU Rigid Boundary Basin

The basin that was researched is shown in Slide 7.48, and is called an abrupt expansion basin.



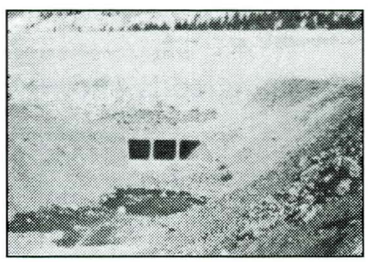
7.48

However, the recommended basin is flaired from the exit of the culvert through the edges of the roughness element. The flair angle is similar to Blaisdell's Criteria: 1 divided by 3 times the Froude number is equal to the tangent of the flair angle.

The minimum width of the basin is four culvert widths. The maximum basin width is eight culvert widths. The minimum number of rows as shown here is four. The maximum number of rows is six. Notice that the basin is symmetrical about the center line. The roughness elements are all the same size and they are staggered--one row behind another. The length (L) is the spacing between the rows of roughness elements.

Notice that the first row of roughness elements occurs two culvert widths away from the end of the culvert, followed by four to six rows of roughness elements spaced "L" apart. To design one of these basins, the momentum is calculated at the outlet of the culvert. The momentum in the downstream channel is also known by using the depth and velocity that is desirable in the channels. A roughness field is then chosen that will cause the necessary amount of momentum loss between the exit of the culvert, and the exit of the basin. Therefore, this basin can be tailor-made to yield whatever velocity that is required from the structure.

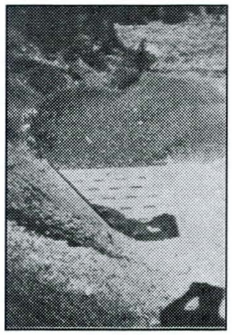
The first one of these in the country was built in central Oregon. Slide 7.49 shows the the entrance of the culvert.



7.49

Notice that it is under a fairly high fill. The culvert is 8 feet high with a slope tapered entrance, an improved entrance. The barrel is an 8x8 single barrel that runs through the fill. The face shown here is about three times that wide or about 24 feet. The divider walls are not carried all the way into the throat of the culvert. They are used only as support at the entrance of the culvert and to keep debris from getting into the culvert. The walls extend only one or two diameters into the culvert, and stop before the throat. By dividing the face area, any debris that comes to this site either passes the entrance and goes through the barrel or will hang up at the face. Maintenance then has a little easier time removing it.

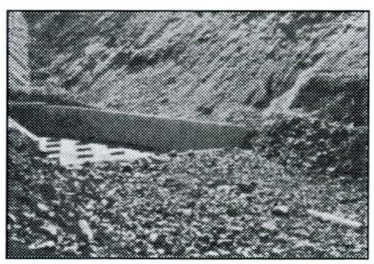
The exit looks like this: and it is bigger than it looks (remember, you are standing at the top of a high fill). This is 5 culvert widths wide or about 40 feet.



7.50

There are six rows of roughness elements. Notice that the roughness elements all appear to be the same size, staggered, and symmetrical. The configuration of roughness elements is exactly as recommended in HEC 14. You cannot change the configuration. The momentum loss coefficients are based on the whole roughness field, not the sum of the individual element. The research indicates that the coefficient of drag for one roughness element cannot be multiplied by the number of roughness elements to determine the coefficient of drag for the whole field. A coefficient of drag has to be measured for the whole basin and, therefore, only those configurations for which we have coefficients can be used for design.

Notice that this basin is depressed below the streambed by using an endsill that is about 3 feet high.



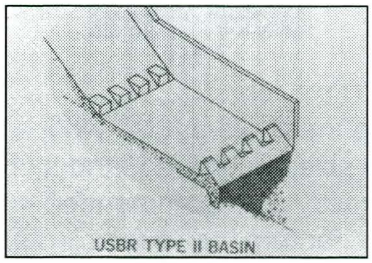
7.51

The reason for the endsill is so that sufficient tailwater downstream is generated to force a hydraulic jump to occur within the basin, resulting in subcritical flow leaving the basin. Notice the large riprap field downstream from the roughness element basin. Riprap is recommended for a distance of 4 culvert diameters downstream from dissipators, since the flow from all the dissipators is very turbulent.

Note that the roughness elements are not concrete blocks. They are steel angles. The angle is a 6x12 angle and bolted into place. This makes it very easy for maintenance to replace the element.

b. USBR Type 2 Basin

Another forced hydraulic jump basin is the Bureau of Reclamation basin. There are three of these: Type 2, 3, and 4. Each is good for a different range of Froude number. The Type 2 basin shown here is good for Froude numbers from 4 to 14, has chute blocks which are equal to the depth of the incoming flow, and a dentated endsill.

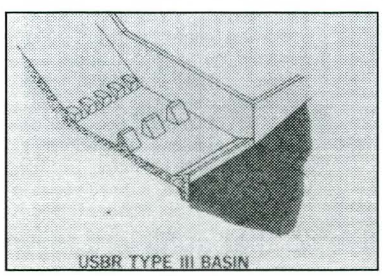


7.52

Even with the Bureau of Reclamation basin, you have to have tailwater. In most cases, not very much tailwater exists downstream from the highway, therefore the basin must be depressed or lowered below the streambed.

c. USBR Type 3 Basin

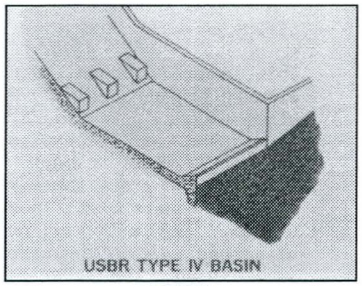
The Type 3 Bureau of Reclamation basin has 3 appurtenances in the bottom of it: chute blocks equal to the height of the incoming flow, baffle blocks twice the height of the incoming flow, and 2:1 sloping endsill. The Type 3 basin is also good for a large range of Froude number (4.5-17).



7.53

d. USBR Type 4 Basin

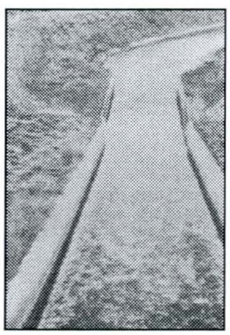
The Type 4 basin is essentially a free hydraulic jump basin. It is good for a lower range of Froude number, from between 2.5 to 4.5.



7.54

The problem with this basin is that it is very long. Since it is a free hydraulic jump, the length of the basin that is required is considerable. In HEC No. 14 all three of the basins, the Type 2, 3, and 4, are compared for the same inflow conditions and the same Froude number to illustrate the difference in length required. The Type 4 is almost twice as long as the Type 3.

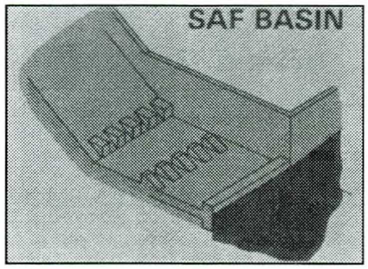
A Bureau of Reclamation basin looks like this. They are typically a rectangular steep chute that enters the jump area. The appurtenances are below the water and convert the flow to the proper conditions in the downstream channel.



7.55

e. SAF Basin

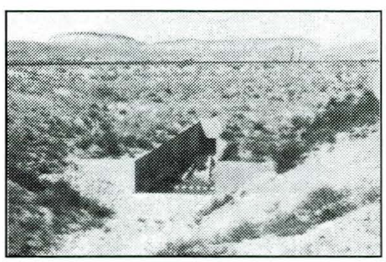
The SAF basin, St. Anthony Falls Silling basin, was developed by the Soil Conservation Service. The research was accomplished by the SAF laboratory at the University of Minnesota.



7.56

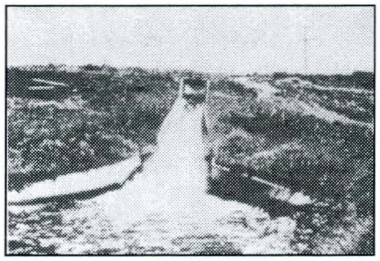
This basin is very similar to the Type 3 Bureau of Reclamation basin. It has chute blocks the same height as the incoming flow, and an endsill that is square. If you compare the Bureau of Reclamation basin and the SAF basin, you will find that the SAF basin is always shorter. The Bureau of Reclamation designs for 110 percent of the theoretical hydraulic jump height, whereas the Soil Conservation Service designs for 85 percent of the theoretical jump height. Therefore, they are allowing more of the jump to occur outside the basin. This is a little less conservative design assumption to yield a shorter basin.

This is an SAF basin, constructed on a Wyoming highway project.



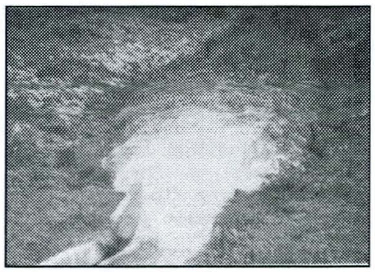
7.57

Notice the steep chute, chute blocks, baffle blocks and an endsill. Riprap is placed downstream from the basin for a short distance. The ribs are concrete stiffeners on the basin bottom. Generally, this basin will not fail structurally when the water is running. It fails when the water has stopped running. The soil around the basin is saturated, and the hydrostatic uplift pressure cracks the bottom slab. By using these stiffeners on the bottom for support, the bottom slab is strengthened without affecting the hydraulics.



7.58

You can use stilling basins effectively, even when good vegetation is not present in the downstream channel.



7.59

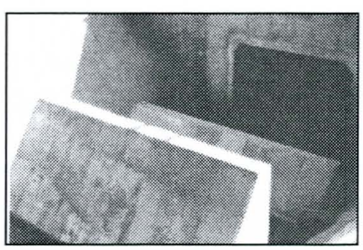
The vegetation along this channel is sparse. However, no erosion is apparent alongside the dissipator, and the dissipator does not appear to be undermined.

3. Impact Basins

   An impact basin is effective by forcing a hydraulic jump with the use of a combination of turbulence and impact. Generally, these types of dissipators are more cost-effective than the preceding series of dissipators.

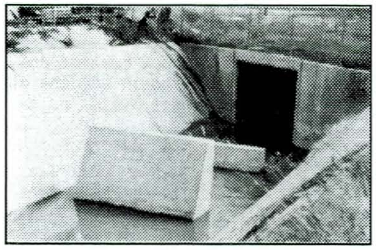
   a. Contra Costa

Contra Costa basins are built with a couple of large blocks at the outlet of the culvert (little block first and the big block behind which forces an hydraulic jump to occur).



7.60

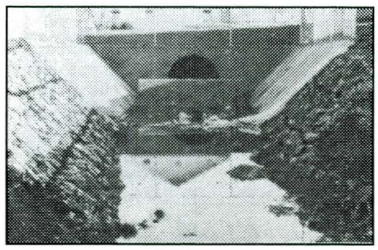
The flow out of this basin is very turbulent and it is only good for minor velocity reduction. Riprap may be required downstream for low tailwater conditions.



7.61

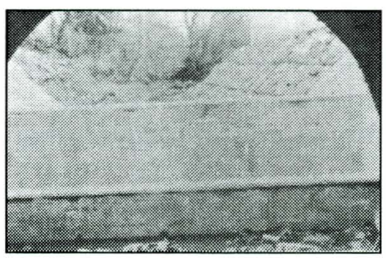
If a paved lining exists, this type of energy dissipator can be cost-effective.

This Contra Costa basin is located in Liberty, Missouri. The pipe is a 72-inch CMP that discharges 300 cfs with a velocity of 16 fps.



7.62

This is the same basin viewed from the culvert,



7.63

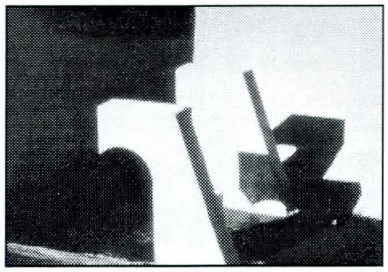
The Contra Costa energy dissipator is intended to:

- reestablish natural channel flow conditions downstream from the culvert outlet,
- have self cleaning and minimum maintenance properties,
- drain by gravity when not in operation,
- be constructed easily and economically,
- be applicable for a wide range of culvert sizes and operating conditions.

This dissipator is best suited for small and medium size culverts where the depth of flow at the outlet is less than the culvert height.

b. Hook

The Hook energy dissipator was developed for Caltrans by the University of California at Berkeley. There are two types of hook basins: one is called a trapezoidal basin and the other one a warped wing wall basin.



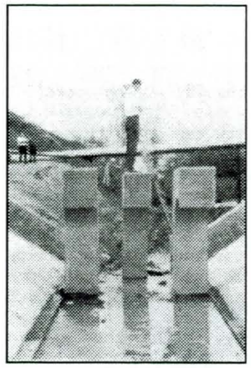
7.64

A trapezoidal basin has a cross section that is a trapezoid. It is not very long. The length of the basin is 3 culvert widths long, from the end of the culvert to the end of the basin.

7.65

The height of the hook is equal to the depth of flow from the culvert. These hooks are approximately equal to the height of the culvert for this installation in Georgia. A series of 3 hooks must be used in the design. A single hook is not effective.

There are two possible basin widths for a trapezoidal basin. This one is equal to the width of the culvert, from outside edge of hook to outside edge.

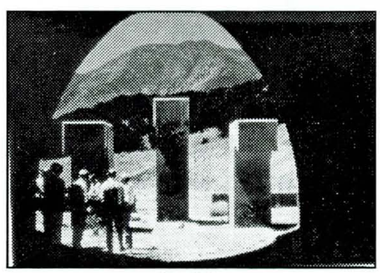

7.66

The basin width can also be twice the width of the culvert, but the hooks stay in the same place.

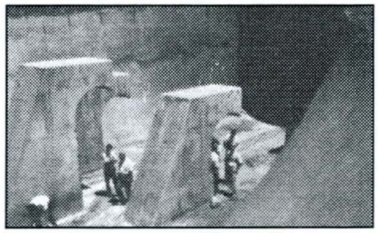
In warped wing wall basin, the walls are curved and the basin flares or gets larger as it leaves the culvert. The walls are constructed of air blown mortar.


7.67

Slide 7.68 shows a hook energy dissipator on a large arch culvert in southern California

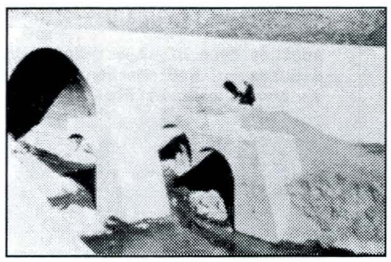

7.68

For large installations, a laboratory physical model study may be valuable to aid in design.



7.69

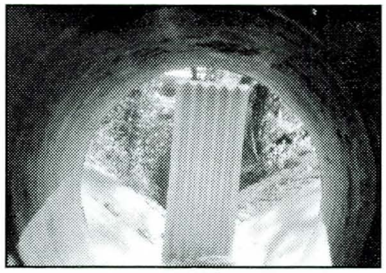
Whenever an obstruction is placed in the flow, sediment may be dropped out.



7.70

Note that the obstruction may not be caused by the hooks, but rather some control downstream. It is possible build an energy dissipator at the culvert only to find that the control is actually a grove of trees downstream that eliminated the need for an energy dissipator. However, trees or willows can also slow the water down enough so that it deposits it's bedload. The material can then build up and plug the culvert from downstream.

Single hooks were originally used, but they did not work well. A single hook acts as a flow divider creating severe turbulence.

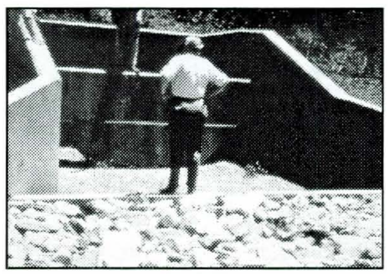


7.71

In this case, sack riprap was required downstream and way up on the slope for protection. If the flow carries abrasive material, hooks can be armored with metal plates as shown in Slide 7.71.

c. USBR Type 6 Basin

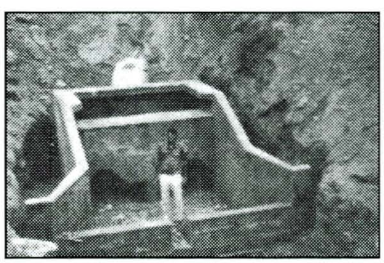
Another type of impact basin is the USBR Type 6 basin, which is a hanging baffle type of basin.



7.72

The culvert is behind the baffle in slide 7.72. The flow comes out of the culvert, impacts on the baffle , turns and goes underneath and over the endsill.

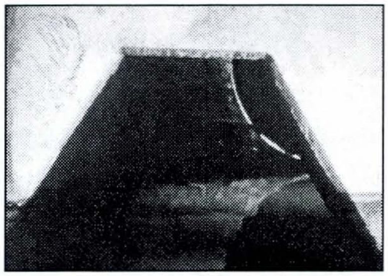
The pipe must be normal to the dissipator to function properly,



7.73

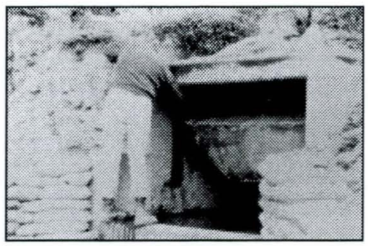
and it is also recommended that the culvert be flat for 3 or 4 diameters before it enters the impact basin. If it cannot be flat, turn the impact wall so that it is perpendicular to the end of the culvert so that the flow impacts it directly.

The notches are provided to help the basin clean deposited sediment,



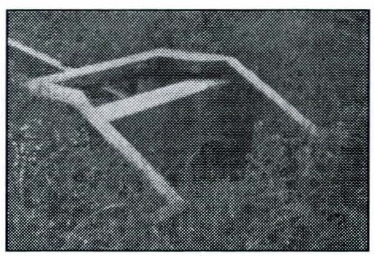
7.74

and a roof is not recomended. Slide 7.75 is an old design of the Bureau of Reclamation Type 6. The roof is left off purposely so that if the culvert gets plugged, all of the design flow can come over the top of the wall.



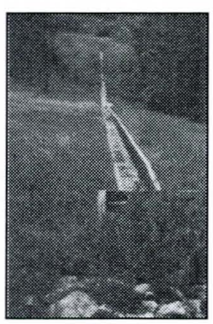
7.75

This is an interesting installation located on a tunnel portal in Virgina on an interstate project,



7.76

which is at the end of an open channel,



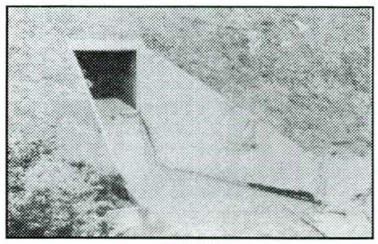
7.77

The Type 6 impact-type energy dissipator comprises a relatively small box-like structure which requires no tailwater for successful performance. The hanging baffle in the Type 6 energy dissipator intercepts and deflects the flow from the culvert. The deflection is upstream and downward, causing horizontal eddies. The resulting turbulence dissipates the energy.

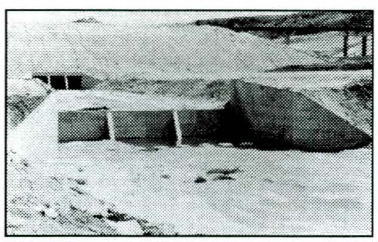
4. Drop Structures

Another class of dissipators is the drop structure. Drop structures are not energy dissipators. Drop structures are grade control structures that change a steep slope into a series of flat slopes and drops.

Examples of a drop structures at the outlet of a culverts:

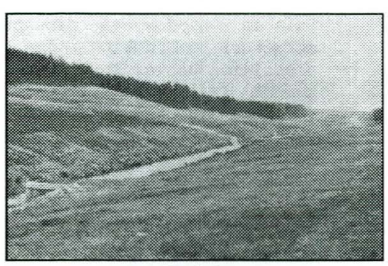


7.78



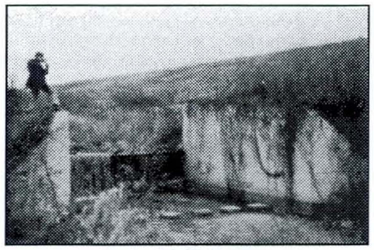
7.79

Typically, a whole series of drop structures are used, as shown in this installation in Alabama,



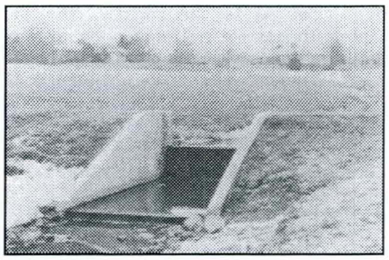
7.80

Slide 7.81 shows a closeup of one of these drop structures,



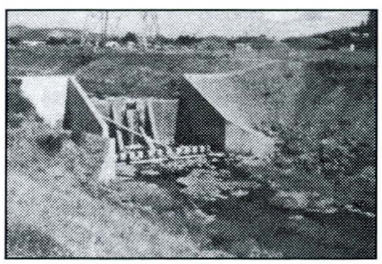
7.81

Slide 7.82 shows a small drop structure in Iowa used for channel stabilization



7.82

Slide 7.83 shows a good energy dissipator drop structure combination. The design uses a stilling basin, and the downstream channel tailwater to reduce the outlet velocity from the dissipator. The design of a drop structure is based on the weir equation.



7.83

Notice that above the weir is a trapezoidal section provided as an overflow section and as a cutoff wall.

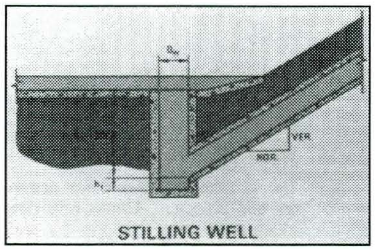
Drop structures can be constructed at the exit of the culvert or in the downstream channel. Drop structures control the slope of the channel in such a way that the high, erosive velocities usually do not develop. The kinetic energy or velocity gained by the water as it drops over the crest of the structure is dissipated by a specially designed apron or stilling basin.

5. Corps of Engineers Stilling Well

There are two types of stilling wells, the manifold stilling well which is not often used in highway engineering and the Corp of Engineers stilling well, which is quite useful on downdrains.

Stilling wells dissipate kinetic energy by forcing flow to travel vertically upward to reach the downstream channel. They are highly effective but require considerable and constant maintenance attention.

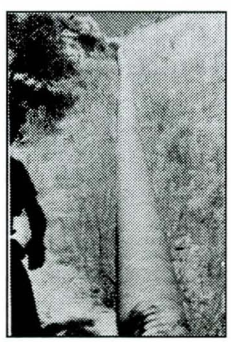
The Corps of Engineers Stilling Well is illustrated as follows.



7.84

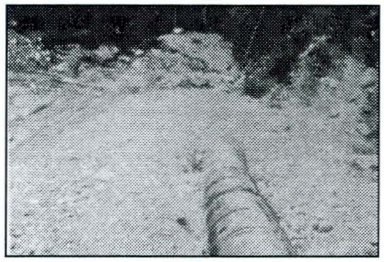
Stilling wells can be used in northern climates if a vent is provided (holes in the bottom or a filter to allow water to trickle out).

Slide 7.85 shows a 24 inch downdrain to take water from a high hill to the bottom,



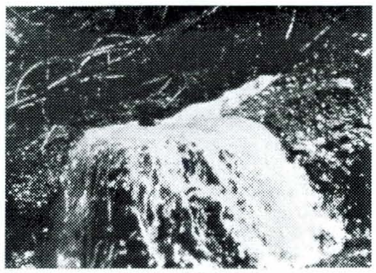
7.85

At the bottom is a COE stilling well,



7.86

The stilling well must be adequately anchored using collars, pins and deadmen.

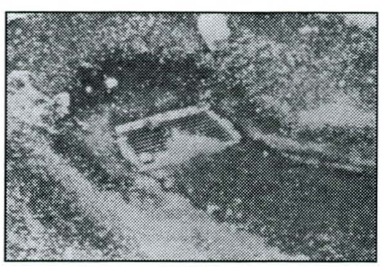


7.87

Riprap or concrete can be used around the end of the well, and in urban areas it is better to design the basin to be self draining

7.88

A grate inlet at the upstream end is useful in intercepting debris which might otherwise be trapped in the stilling well downstream.



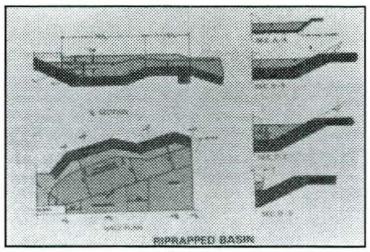
7.89

This type of stilling well is useful at the downstream end of downdrains or overside drains. Often, the stilling well is placed up on the slope sufficiently to allow draining during low flows.

6. Riprap Basin

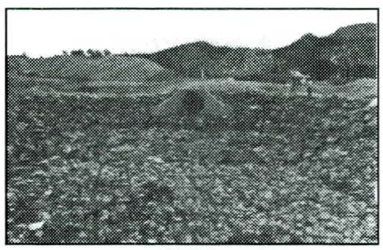
The riprap basin is recommended for effectiveness and economy. It takes advantage of a natural feature (the scour hole) to provide a location and configuration so that high velocity flow can return to an equilibrium state of flow.

The recommended design is shown in Slide 7.90,



7.90

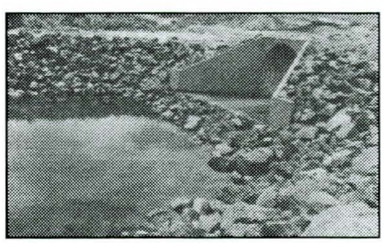
Slide 7.91 shows a basin in Utah that follows the recommended design parameters.



7.91

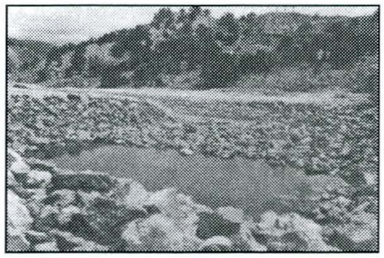
Riprap is placed on the fill slope and underneath the end of the culvert. Berms are used on both sides to enclose the flow. A depressed section will probably fill in during periods of low flows with soil and vegetation. A landing area is provided on the end to transition the flow back to the natural channel.

Slide 7.92 shows a closeup of the outlet. The median stone size is 1.25 ft.



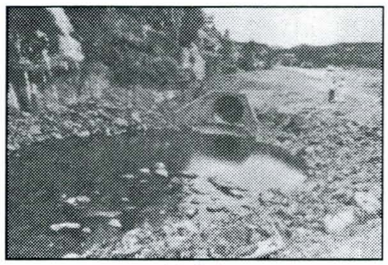
7.92

The depth of the scour hole is designed to be 3.5 ft:



7.93

Slide 7.94 shows a similar installation in Utah



7.94

Riprap is recommended as a first consideration because of its relatively low expense of installation and maintenance. Riprap is effective as an energy dissipator when used in conjunction with a preformed scour hole. Riprap also has been used in many locations as a protective device to allow high velocity flow to return to an equilibrium stream flow without damaging or eroding threatened features.

7.6. WORKSHOP 6A - ENERGY DISSIPATOR VIDEO AND DISCUSSION

A. VIDEO

B. Hydraulic Theory

Certain basic hydraulic and flow momentum relationships are associated with the analysis of energy dissipators. These relationships were introduced in Lesson 3, and are reviewed in HEC 14.

- Continuity Equation - The rate of discharge is equal to the cross-sectional area of flow multiplied by the average velocity of flow.

$$Q = V_1 A_1 = V_2 A_2 = V_n A_n \quad \text{.......... 3-1}$$

where: Q = discharge (cfs),
A_1 = cross-sectional area at location 1 (ft^2),
V_1 = average velocity of flow at location 1 (fps),
A_2 = cross-sectional area at location 2 (ft^2),
V_2 = average velocity of flow at location 2 (fps),
A_n = cross-sectional area at location n (ft^2),
V_n = average velocity of flow at location n (fps),

- Energy Equation - The energy equation relates all of the energy components of flow from one point in a conveyance reach to another.

$$y_1 + z_1 + \frac{V_1^2}{2g} = y_2 + z_2 + \frac{V_2^2}{2g} + h_{L(1-2)} \quad \text{.......... 3-2a}$$

where: y_1 = depth of flow at location 1 (ft),
z_1 = datum at location 1 (ft),
V_1 = average velocity of flow at location 1 (fps),
y_2 = depth of flow at location 2 (ft),
z_2 = datum at location 2 (ft),
V_2 = average velocity of flow at location 2 (fps),
g = acceleration due to gravity (32.2 ft/sec^2),
$h_{L(1-2)}$ = total head loss between locations 1 and 2 (ft),

- Natural Hydraulic Jump - A hydraulic jump is where flow which has been in supercritical flow abruptly changes to subcritical flow. The triggering mechanism for this change is a downstream depth (sometimes referred to as sequent depth or conjugate depth). Momentum relations (described below) will define the necessary sequent depth for the occurrence of the hydraulic jump.

- Equivalent Depth of Flow - An approximate depth of flow for energy dissipator calculations is expressed as:

$$y_e = \sqrt{\frac{A}{2}} \qquad \text{3-7}$$

where: y_e = equivalent depth of flow (ft),
A = cross-sectional area of flow (ft^2),

- Froude Number - This number is used as a shorthand description of flow regime. Depending upon its intended use, the Froude number (Fr) is expressed mathematically in several ways. For use in analyzing energy dissipators, the relation is:

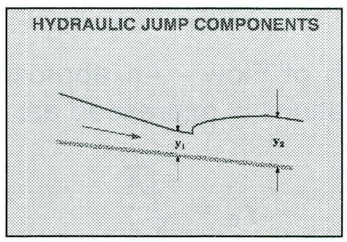
$$Fr = \frac{V}{\sqrt{gy}} \qquad \text{3-8}$$

where: Fr = Froude number (dimensions not usually given),
V = average velocity of flow (fps),
g = acceleration due to gravity (32.2 ft/sec^2),
y = equivalent depth of flow (ft).

- Momentum Equation - Momentum is defined as the product of mass and velocity. However, for the purpose of analysis or design of energy dissipators, a transformed momentum equation referred to as a hydraulic jump equation (for flat slopes) is given as:

$$y_2 = 0.5\, C_1\, y_1 \left(\sqrt{1 + 8\,Fr^2} - 1\right) \quad \text{7-1}$$

where: y_2 = depth of flow at location 2 (ft),
y_1 = depth of flow at location 1 (ft),
C_1 = adjustment coefficient specific to different types of stilling basins,
Fr = Froude number,
z_2 = datum at location 2 (ft),
V_2 = average velocity of flow at location 2 (fps),
g = acceleration due to gravity (32.2 ft/sec^2),



- Specific Energy - Specific energy is the energy at a specific point or location in the flow. It is expressed as:

$$H = y + \frac{V^2}{2g} \quad \text{3-2b}$$

where: H = specific energy (ft),
y = depth of flow (ft),
V = average velocity of flow (ft),
g = acceleration due to gravity (32.2 ft/sec^2).

7.7 WORKSHOP 7B - FLUME DEMONSTRATION

A variety of energy dissipators will be demonstrated in the flume. The effect of each energy dissipator on velocity, turbulence and the transition to the downstream channel will be observed and discussed.

The demonstation is primarily based on visual observations, but should provide a good understanding of the different types of energy dissipators available and their performance.

7.8. WORKSHOP 7C - ENERGY DISSIPATOR DESIGN

OVERVIEW

HY-8 includes an option for the design of internal and external energy dissipators of various types as well as an approximation of geometric dimensions of a scour hole.

External dissipator categories accommodated by HY-8 are:

- Drop structures.
- Stilling basins.
- At-streambed-level structures

Stilling basins accommodated by HY-8 are

- USBR Types 2, 3, and 4,
- St. Anthony Falls basin.

At-streambed-level structures which can be designed by use of HY-8 are

- USBR Type 6,
- CSU basin,
- Riprap basin,
- Contra Costa impact,
- Hook impact.

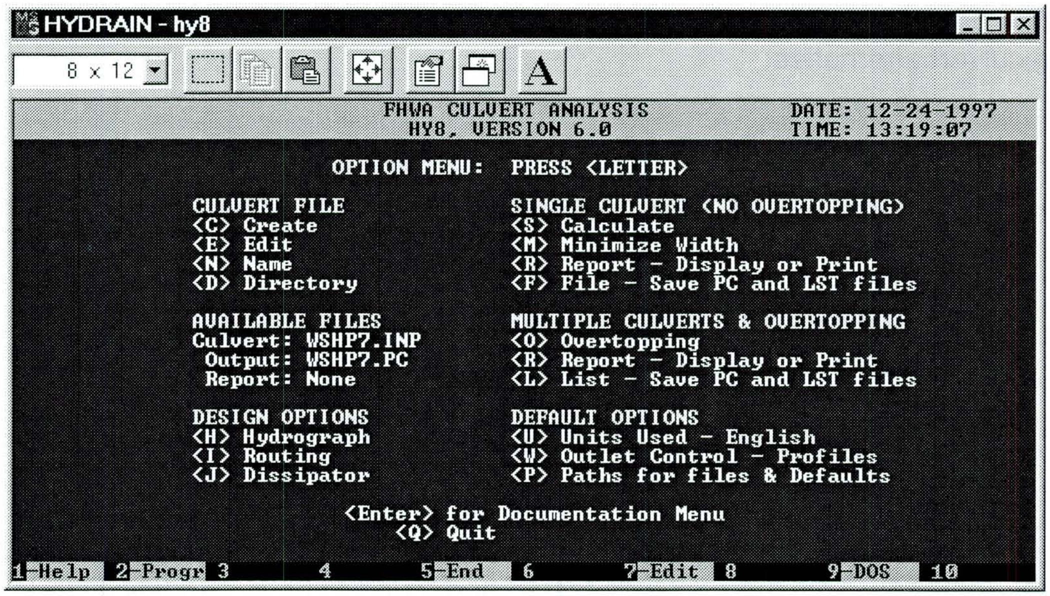
PROBLEM STATEMENT

HY8 will be used to evaluate and design several alternative energy dissipators for the following culvert alternative:

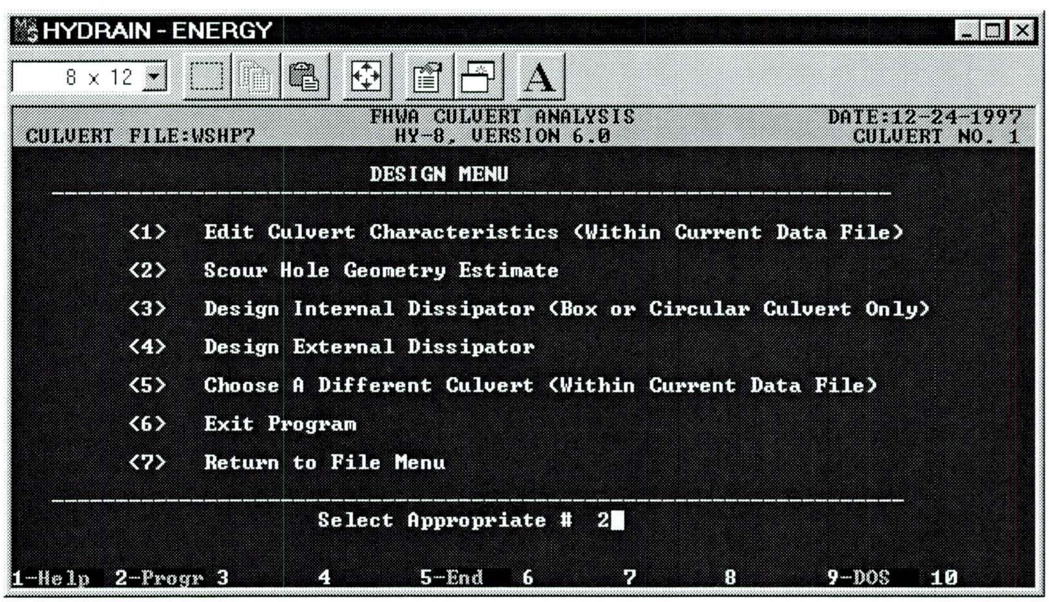
- Design discharge = 500 cfs, maximum = 750 cfs
- Single barrel 5x5 RCB with side-tapered inlet (B_f = 8, taper 4:1, top and side beveled)
- Inlet station = 0.00
- Inlet elevation = 100.0
- Outlet station = 250.00
- Outlet elevation = 93.0
- Downstream channel: 8 ft bottom, 2:1 sideslope, S = 0.03, n = 0.04

To evaluate the scour geometry, assume that the tailwater conditions are a cohesive sandy-clay material. This material was tested and found to have a Plasticity Index (PI) of 12 and a saturated shear strength (Sv) of 240 psi.

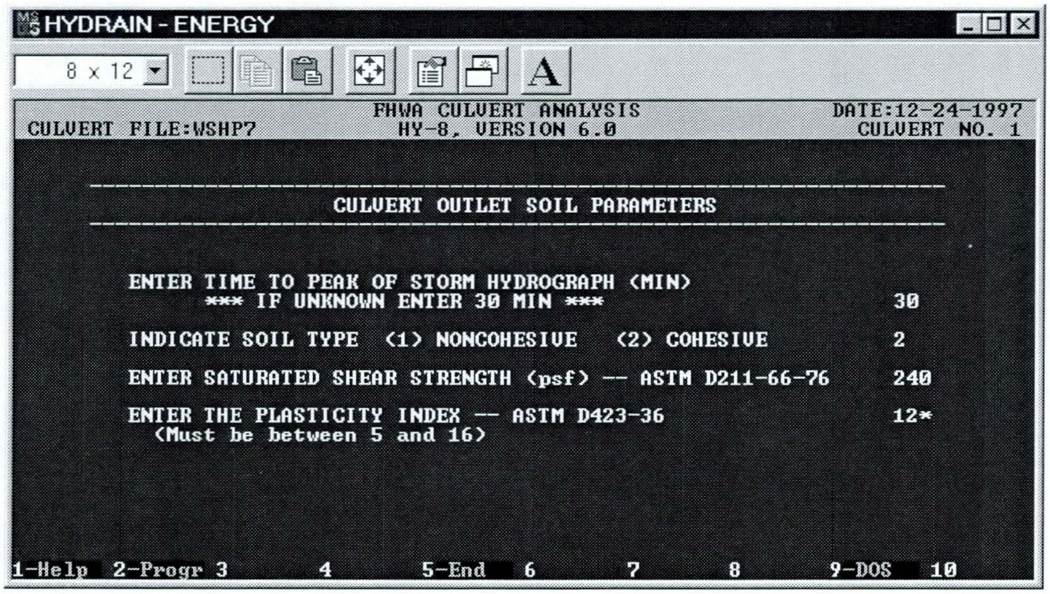
Step 1. From the Options Menu, select *"J"* for the energy dissipator module:



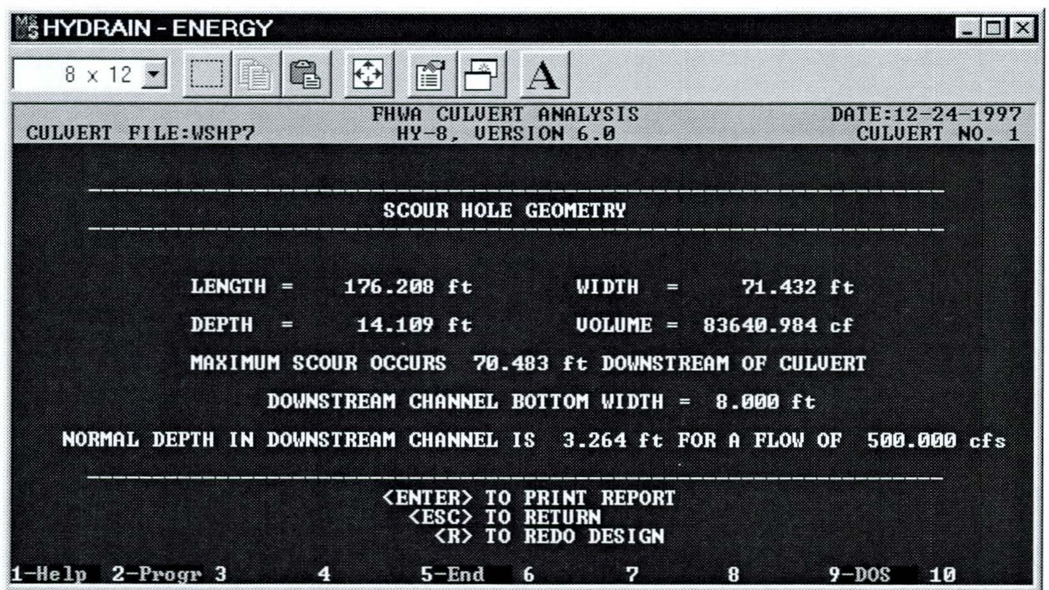
and follow the directions/menus for selecting the culvert input file to reach the *Design Menu File* and select the *Scour Hole Geometry Estimate:*



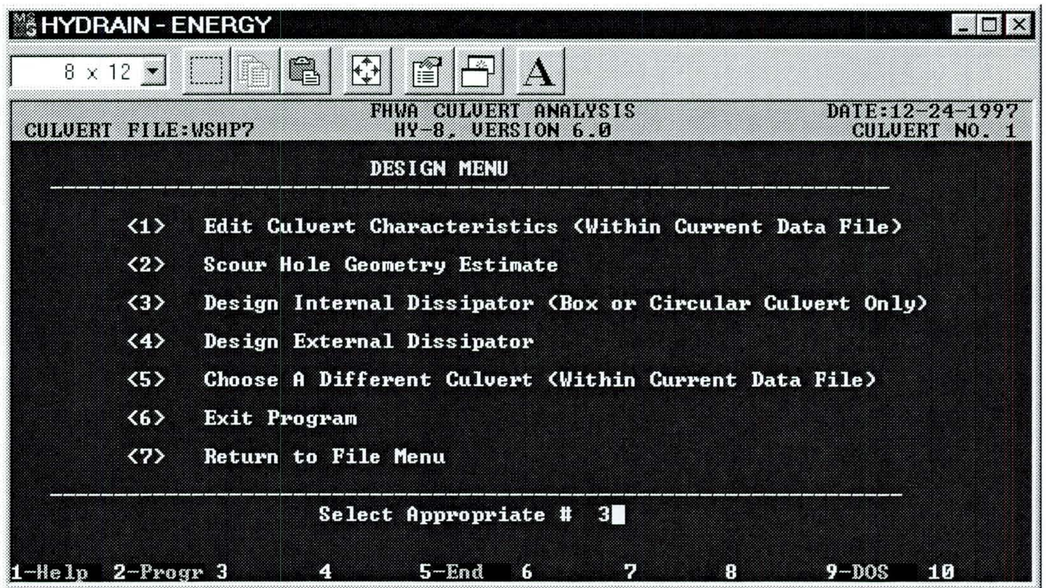
Input the soil parameter information:



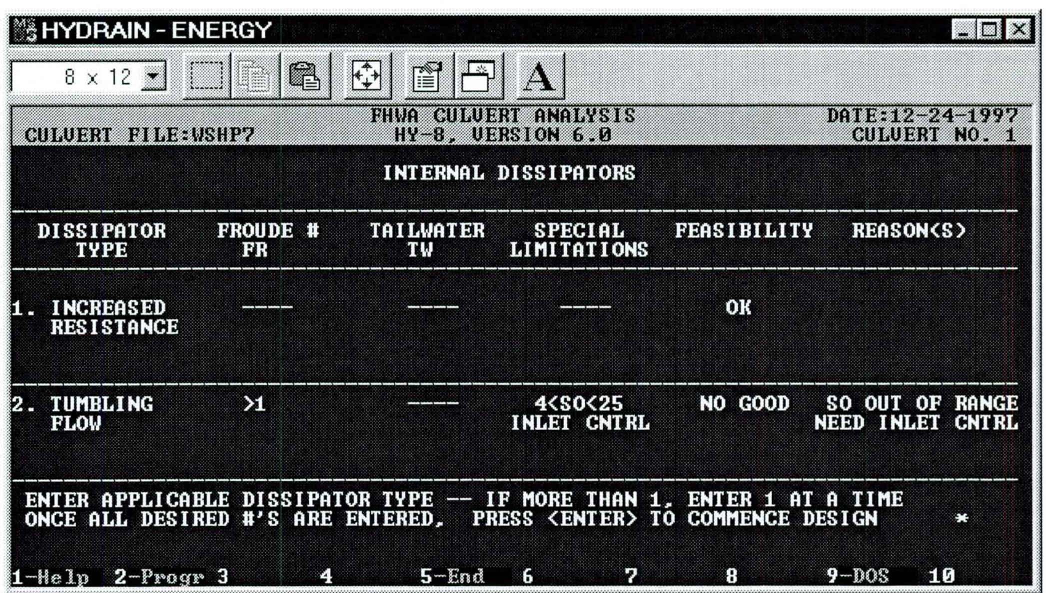
and the scour hole estimate is computed:



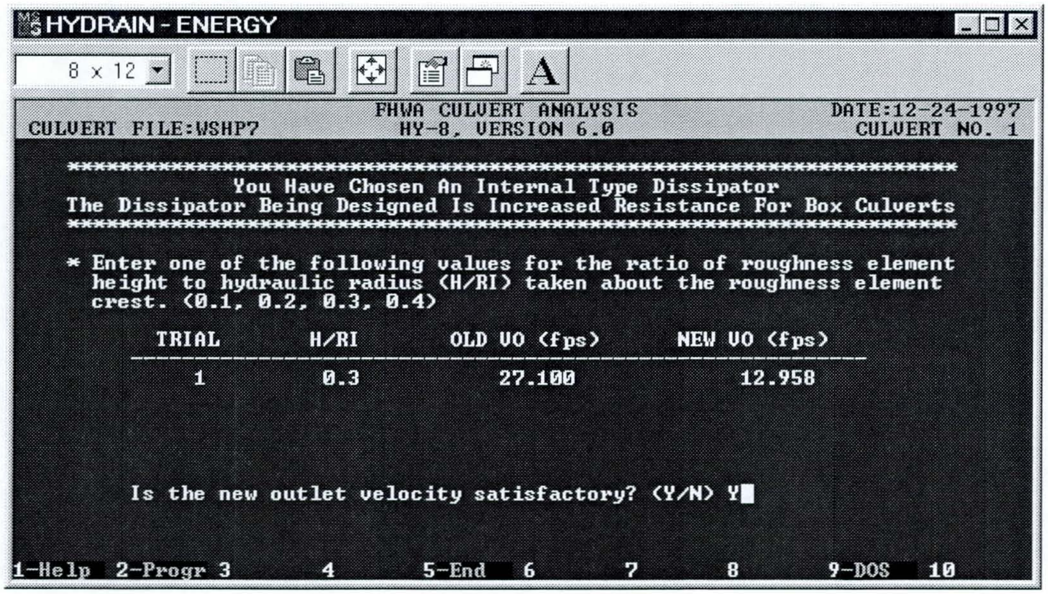
Step 2. Return to the design menu and select *Design Internal Dissipator*.



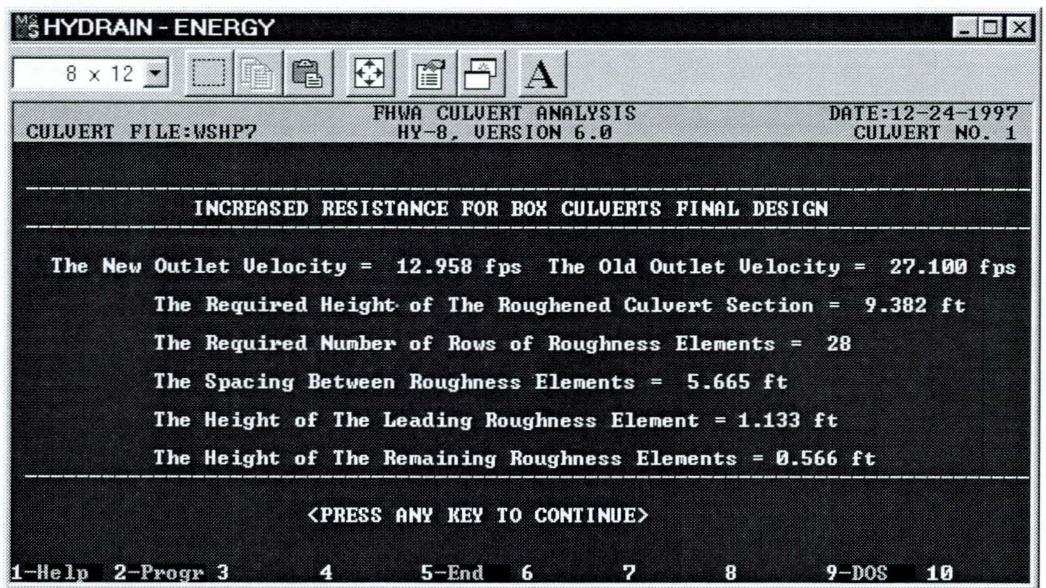
which indicates that increased resistance is a viable option:



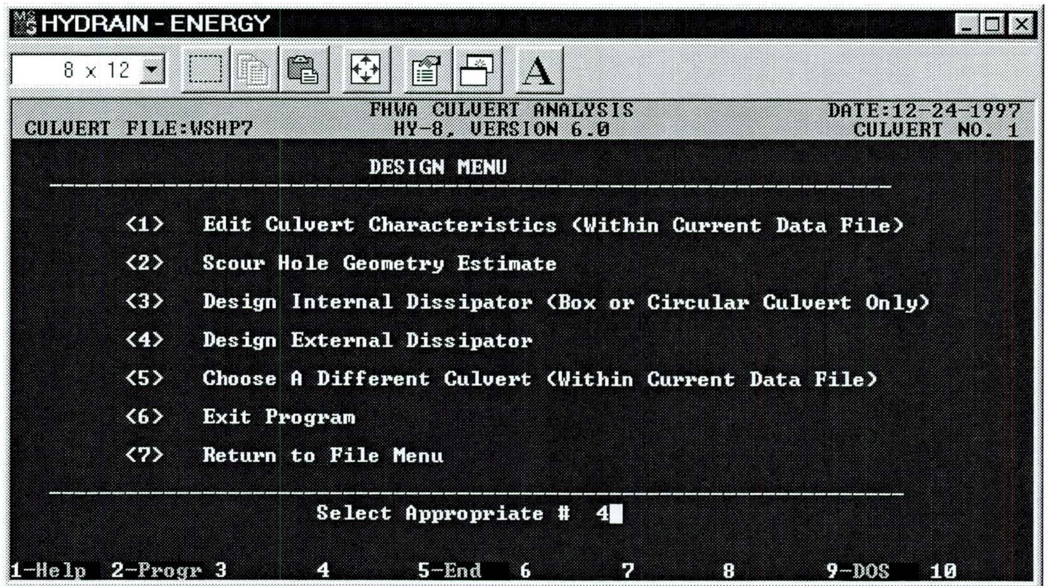
Selecting the *Increased Resistance*, and entering an H/*RI ratio of 0.3*:



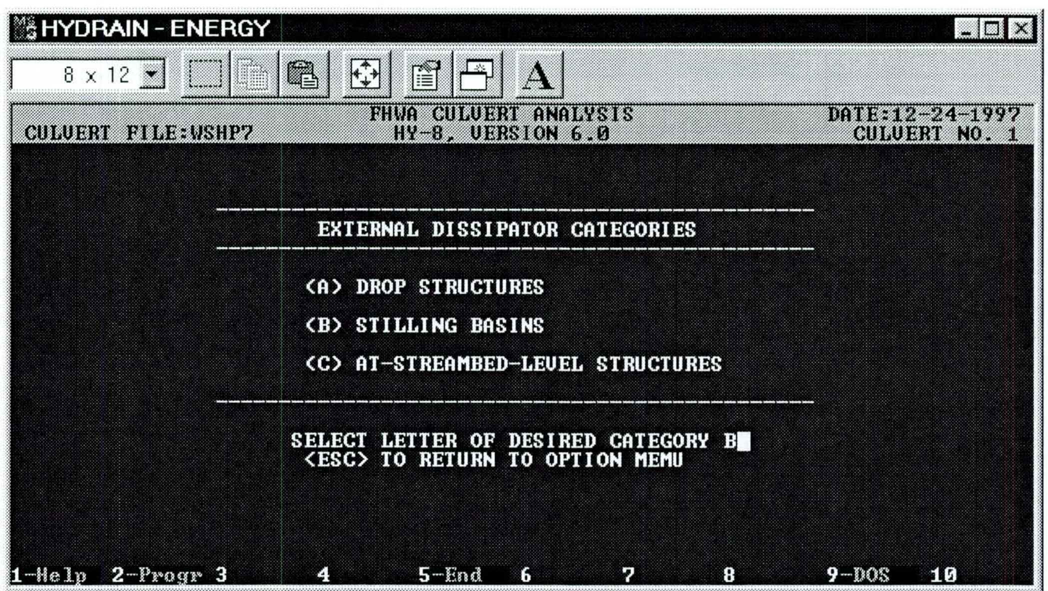
The new outlet velocity of 13 fps is satisfactory compared to the outlet channel velocity, and the following menu provides the dimensions of the roughness elements:



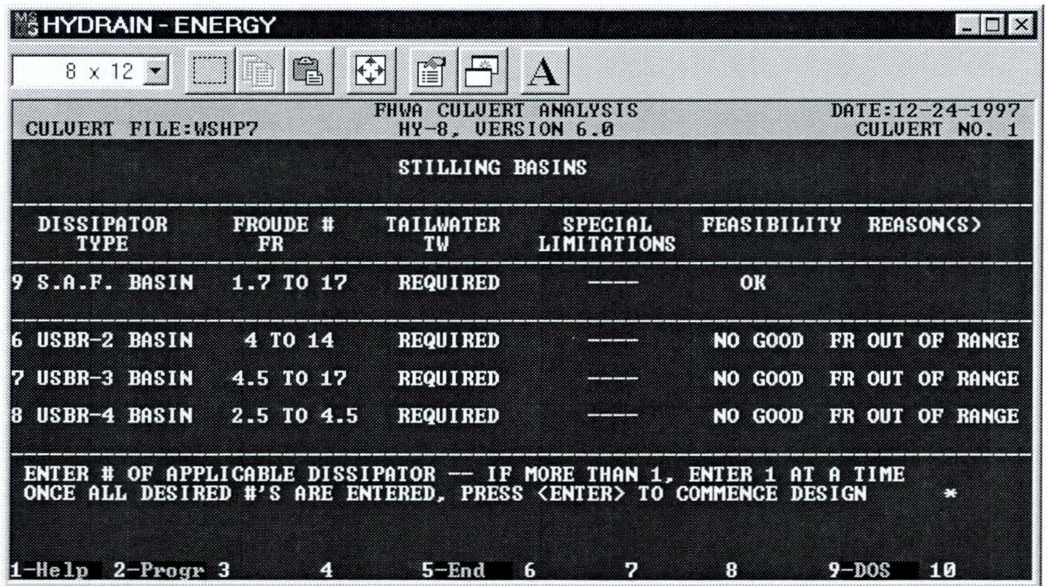
Step 3: Return to the Design Menu and select *Design External Dissipator*.



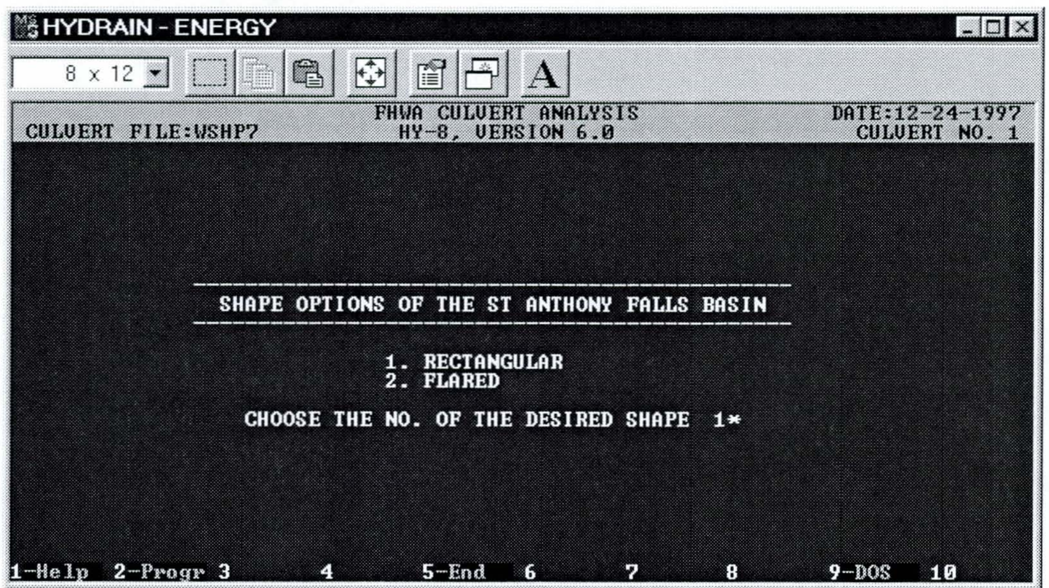
and select *Stilling Basins*:



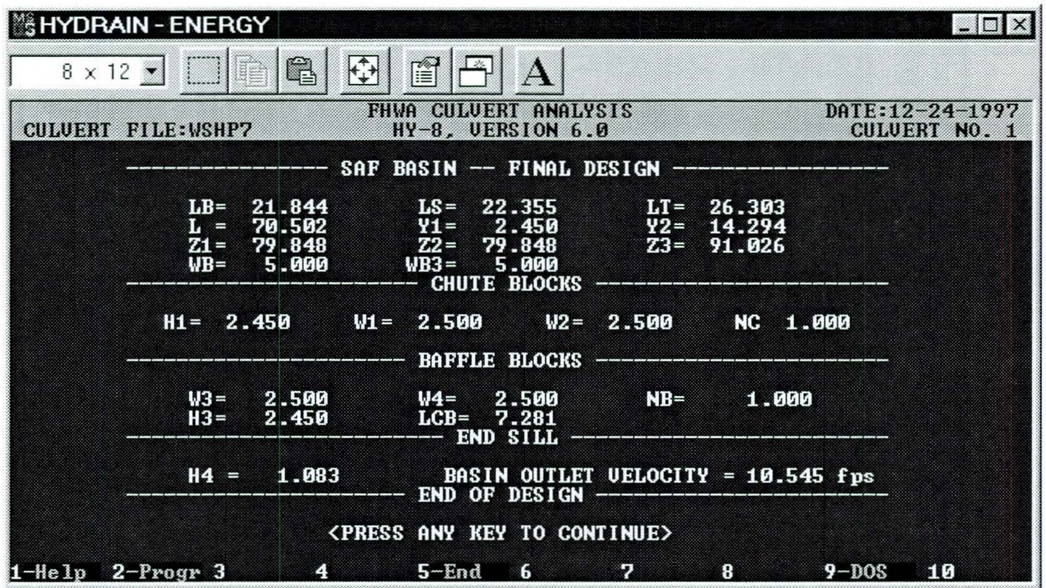
Of the available options, only the SAF is *OK*:



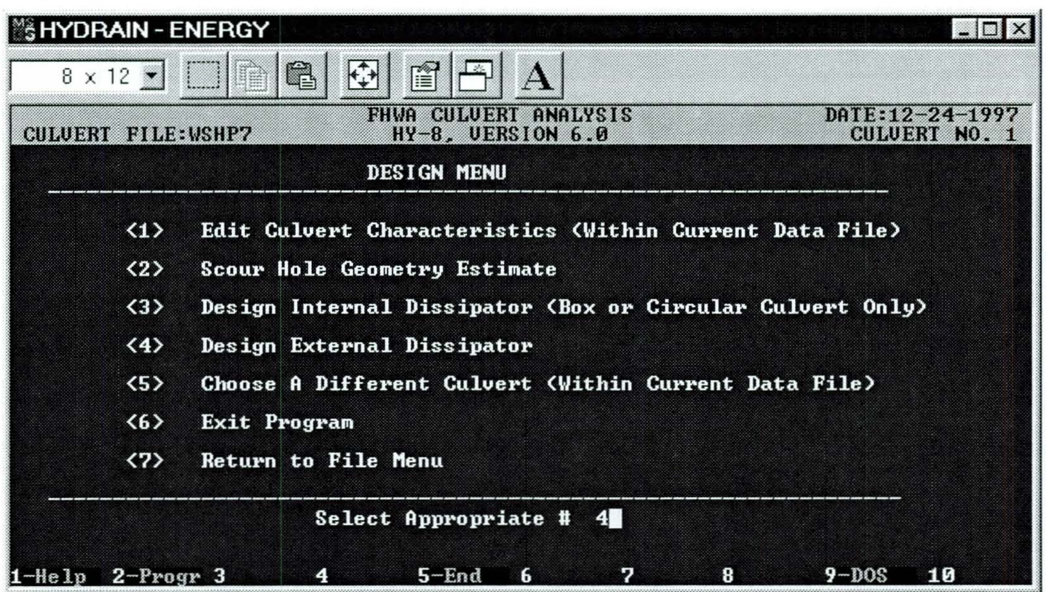
Selecting a *Rectangular* SAF:



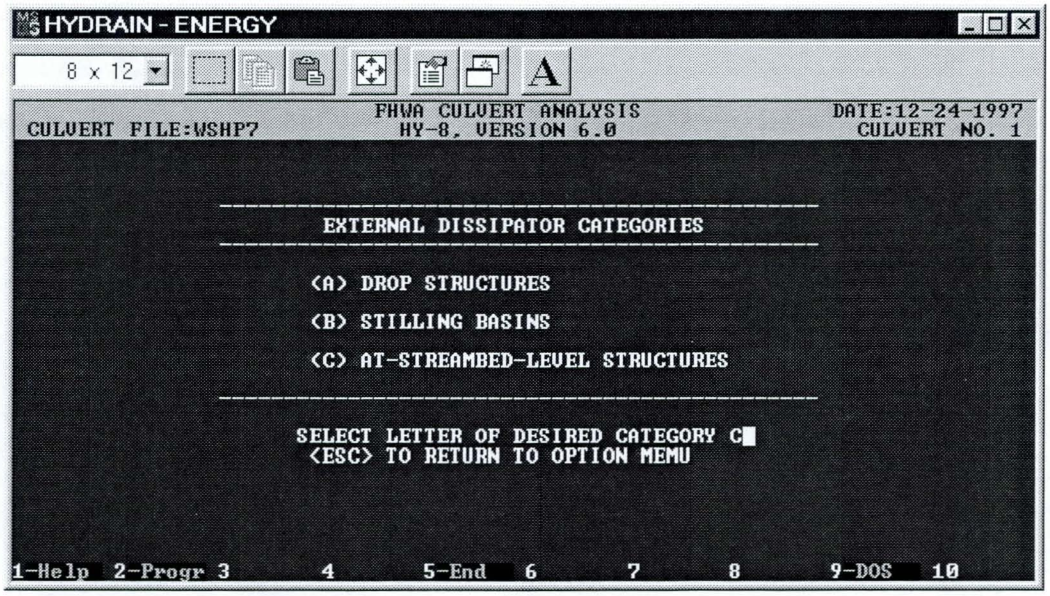
the following design is computed:



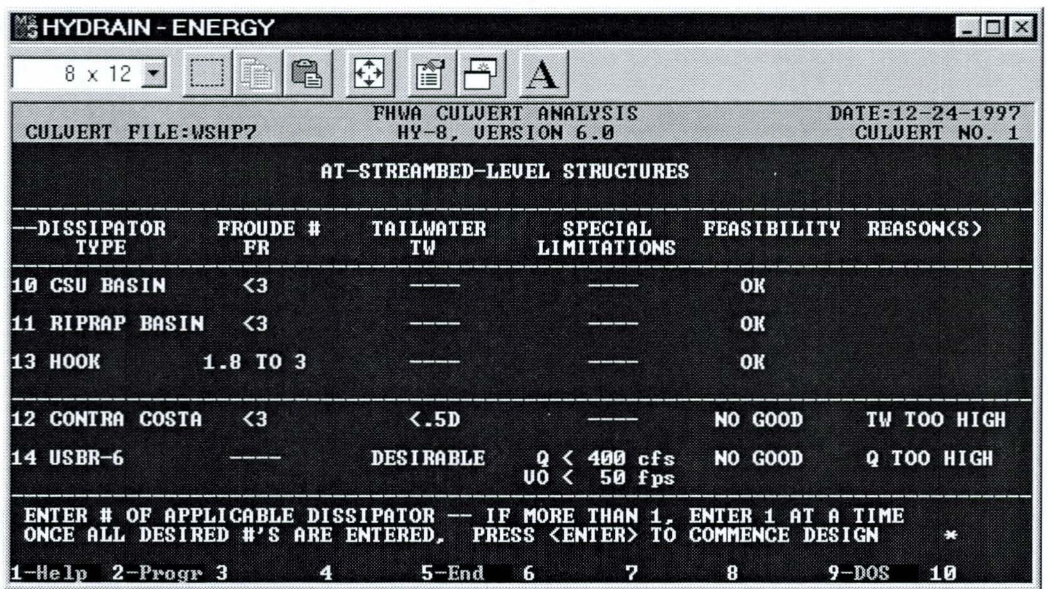
Step 4. Return to the Design Menu and again select *External Dissipator*.



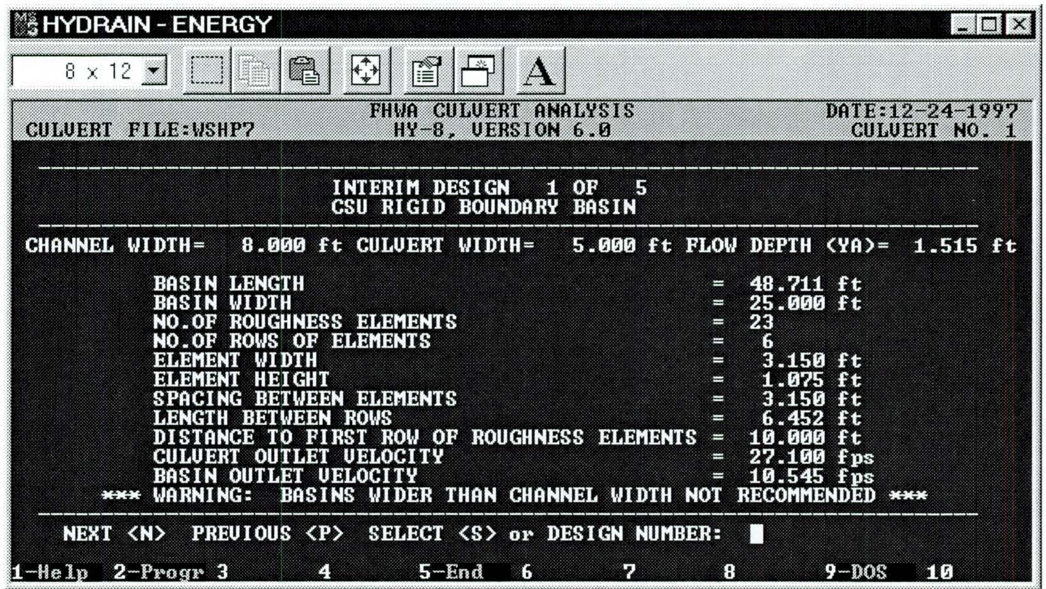
and select *at-streambed-level* structures:



which indicates that the CSU, Riprap Basin and Hook are all viable options:

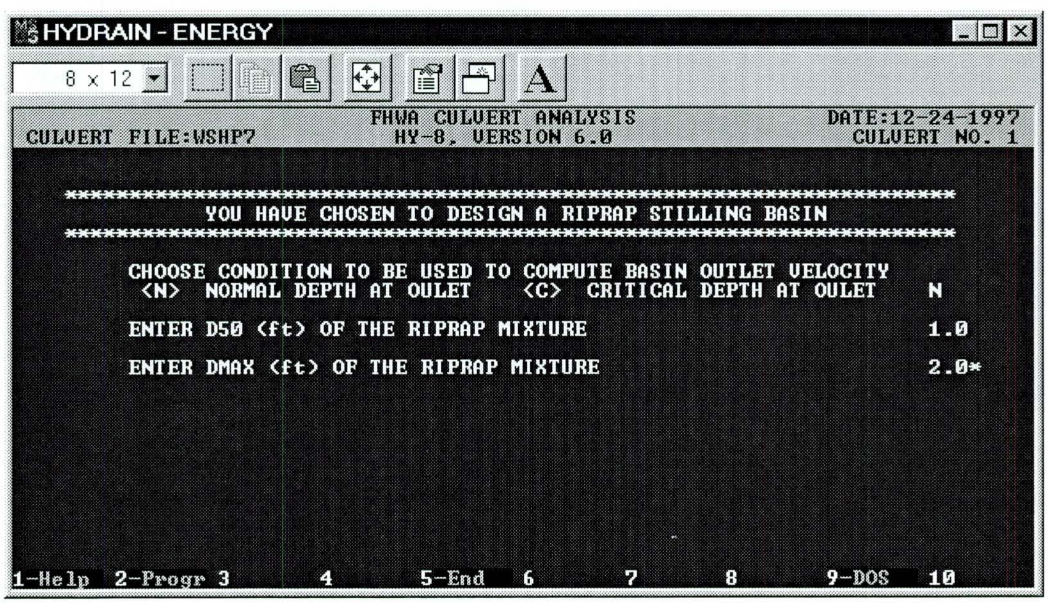


The CSU basin design is calculated first. A number of different configurations are possible, any of which may be viewed by using *Next, Previous or Design Number* options at the bottom of the screen (only the first configuration is shown):

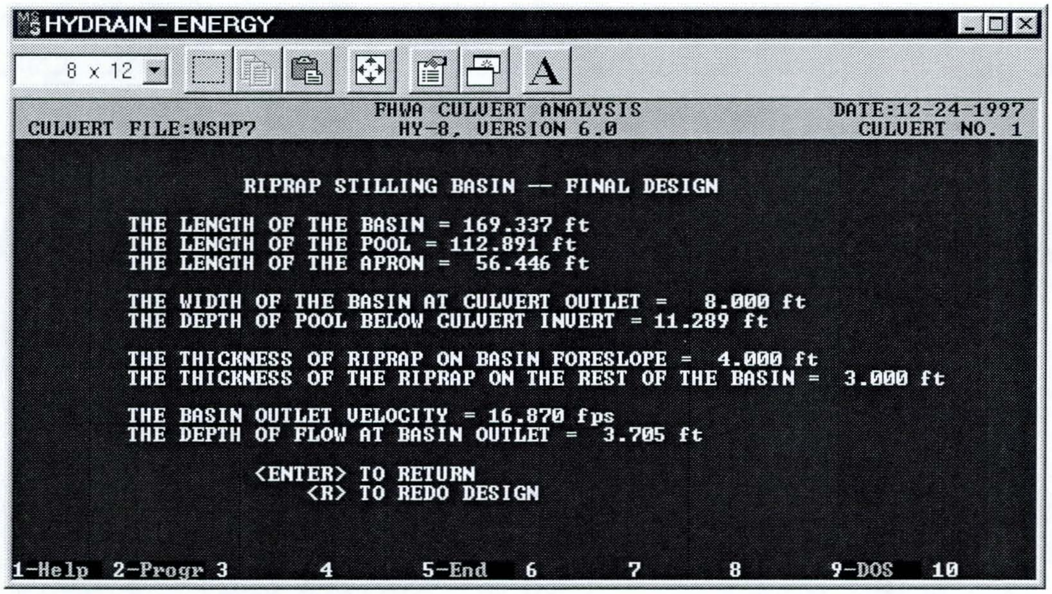


Note that the basin outlet velocity (10.5 fps) is OK compared to the tailwater channel velocity, and so this design is acceptable.

The next type of dissipator (Riprap Stilling Basin) is selected by using the *Select* option. The *normal depth* option will be used for computing the outlet velocity based on the assumption that with a long culvert (250 ft), normal depth at the outlet will be reached. A *1.0 ft D50* and a *2.0 ft Dmax* will be assumed:

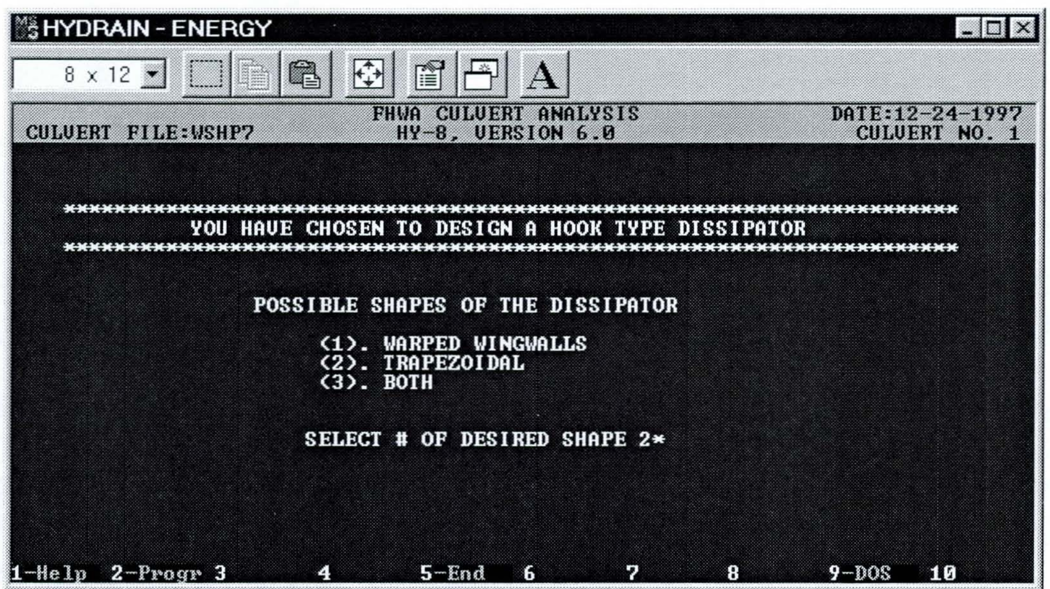


and the final design is provided:

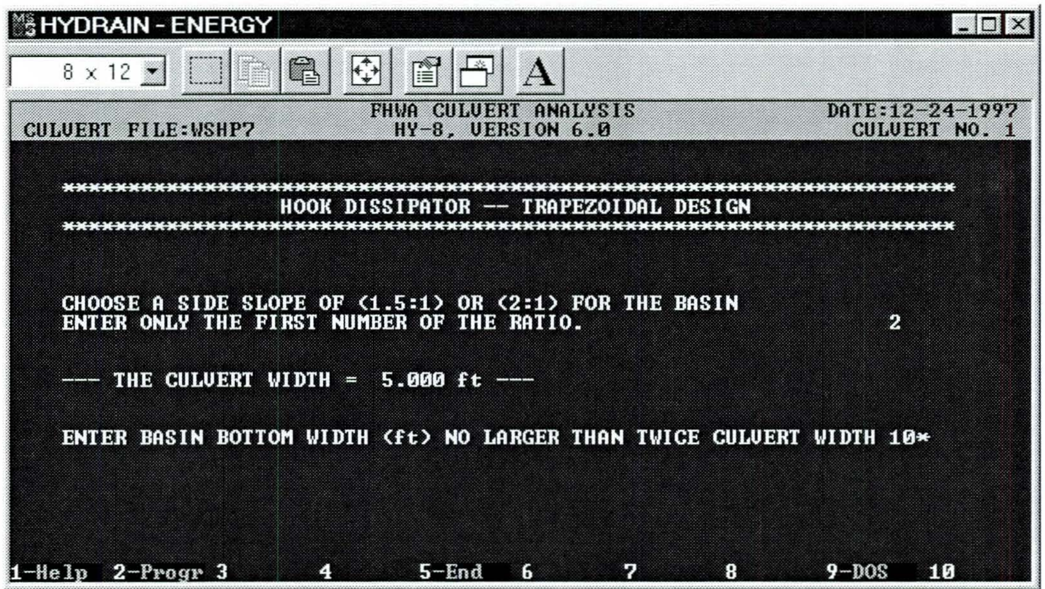


Note that the outlet velocity is higher than the tailwater channel velocity.

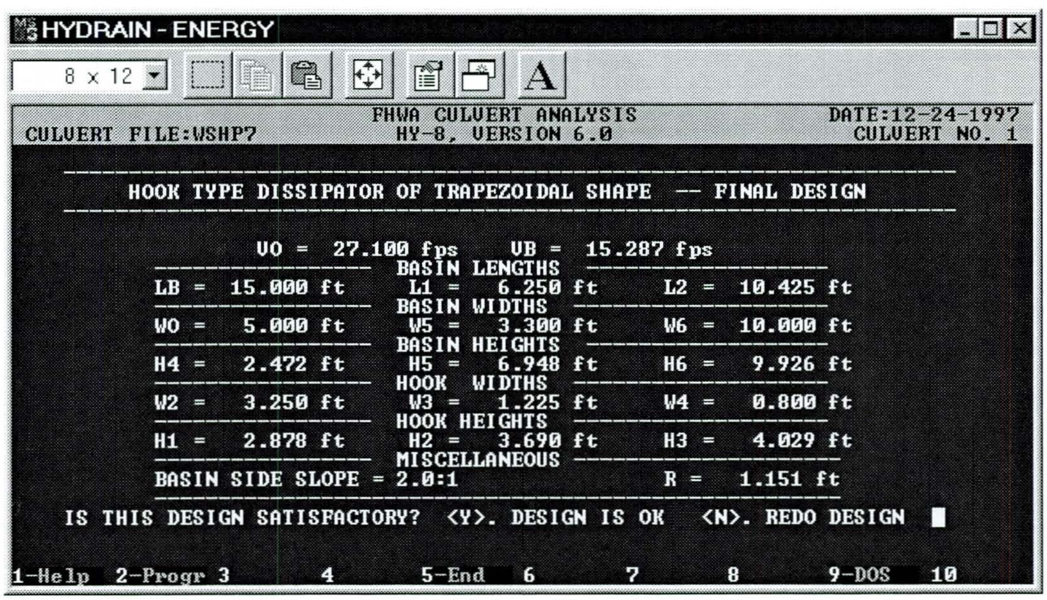
The final type to be designed is the Hook. Selecting a *trapezoidal shape*:



with a *2:1 side slope* and a *bottom width of 10 ft* (which matches the outlet channel bottom width):



and the results are provided:



The outlet velocity for the Hook basin is also higher than the tailwater channel. Investigation of alternative designs did not change the basin outlet velocity significantly, and the CSU basin may be the best streambed level structure.