Culvert Hydraulics and Section 50 Consent

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Abstract

Road culverts, despite their apparent simplicity, are complex engineering structures from a hydraulic as well as a structural viewpoint. The functional adequacy of a culvert is no better than the estimate of the design flood it is intended to convey. This paper attempts to give an understanding of hydrological estimation for catchments and culvert hydraulics but is not to be considered a treatise on same. Information is taken from numerous sources and a degree of knowledge is assumed. It also outlines the information required for an application to the Office of Public Works for Section 50 consent and the most frequent errors encountered in applications for same.

Introduction

There is a statutory obligation under Section 50, Arterial Drainage Act 1945 to obtain consent from the Commissioners of Public Works in Ireland to construct or alter any bridge or culvert over any watercourse.

No local authority, no railway company, canal company, or other similar body, and no industrial concern shall construct any new bridge or alter, reconstruct, or restore any existing bridge over any watercourse without the consent of the Commissioners or otherwise than in accordance with plans previously approved of by the Commissioners.

For many years very few applications for same were received by the OPW despite the ever-growing number of culverts being constructed.

Hydrology

The functional adequacy of a culvert is no better than the estimate of the design flood it is intended to convey. The estimation of a design flow rate is based on an understanding of the hydrological catchment and climatological characteristics. The following are the most commonly applied methods:

- Rational Method

  Simplistic relationship between rainfall intensity and runoff of the form

  $$Q = C \cdot i \cdot A$$

  where Q is the peak runoff rate, i is the rainfall intensity, A is the catchment area, and C is the runoff coefficient.

Culvert Hydraulics and Section 50 Consent

- Modified Rational Method

$$Q = 2.78 \cdot C_v \cdot C_r \cdot i \cdot A$$

with the units : Q in l/s, i in mm/hr, A in hectares, and where C_v is the volumetric runoff coefficient, C_r is the routing coefficient (normally taken as 1.3).

The recommended equations for determining C_v as given in the Wallingford Procedure (applicable to catchments up to 150 hectares in size), Volume 1, is

$$C_v = PR / 100$$

$$PR = 0.829 PIMP + 25\, SOIL + 0.078\, UCWI - 20.7$$

where PR is the (urban) percentage runoff

        SOIL is the soil index from FSR

        PIMP is the percentage of impermeable area to total catchment area

        UCWI is the urban catchment wetness index (mm)

- Flood Studies Report 1975 *Catchment Characteristics / No Data Equations*
One of the major aspects of the FSR was the derivation of techniques which allow flood prediction for ungauged catchments. This involved finding quantitative relationships between catchment characteristics and flood magnitudes for large numbers of gauged catchments, and the application of these results to ungauged catchments by the use of multiple regression techniques. However it should be highlighted that when using the catchment characteristics method of FSR a design factor for standard error as outlined in 4.3.10 Volume 1 must be taken into account. For example the most commonly used relationship for large rural catchments, the six variable equation:

$$Q_{Bar} = 0.0172 \cdot A^{0.94} \cdot F_s^{\,0.27} \cdot G^{1.23} \cdot R_{smd}^{\,1.03} \cdot W^{-0.85} \cdot S_{1085}^{\,0.16}$$

where Q_{Bar} Mean Annual Flood, which has a return period of 2.33 years

        A   Catchment Area

      F_s Stream Frequency

    G   Soil index, vol. V Fig. II 3.1 of FSR

      R_{smd} Climate Characteristic

      W   Lake Index

      S_{1085} Slope of Channel between the 10 and 85 percentiles of length

has a standard factorial error of 1.47. Effectively for two thirds of catchments the percentage error would fall between +47% and -32% and that in 1 in 20 cases they could over-estimate by more than 117% or under-estimate by more than 54%.

Culvert Hydraulics and Section 50 Consent

- Flood Studies Report 1975 *Application of Regional Curves to Q_{Bar}*

  For the FSR Ireland was taken as one region and the resulting $Q - T$ (return period) relation is described as follows :

$$Q_T / Q_{Bar} = -3.33 + 4.20 . e^{y/20}$$

  where the extreme value type 1 reduced variate $y = -\ln[-\ln((T-1)/T)]$

  which gives the following table

T years	Q_T / Q_{Bar}
2	0.95
5	1.20
10	1.37
25	1.60
50	1.77
100	1.96
200	2.14

- Flood Studies Report 1975 *BESMAF Map*

  A map which indicates the mean annual flood divided by catchment area for given locations and is expressed as m^3/s per $1000 \, km^2$. (Figure I.4.21 of FSR)

- FSR Supplementary Report No. 5

  Design flood estimation in catchments subject to urbanisation

- FSR Supplementary Report No. 6

  Flood prediction for small catchments

- FSR Supplementary Report No. 16

  The FSR rainfall-runoff model parameter estimation equations updated

- Poots Cochrane

  Paper presented to ICE which used multiple regression techniques and the FSR to produce a three variable equation, however to obtain 95% confidence that predictions are not underestimated, a design factor, F_n, of 2.7 is required. Suitable for small rural catchments, $< 20km^2$

$$Q_{bar} = 0.0136 . F_n . A^{0.866} . R_{smd}^{1.413} . SOIL^{1.521}$$

- Hydrograph

  Relates rainfall to runoff.

Culvert Hydraulics and Section 50 Consent

- Gauged Flow Records, sites monitored by OPW, EPA, ESB etc

  Statistical Determination of design flow

  Annual Maximum

  Peaks over Threshold

  Rating curves

  Records from adjacent catchments

Culvert Hydraulics

Energy is required to force flow through a culvert. This energy takes the form of an increased water surface elevation on the upstream side of the culvert. An exact theoretical analysis of culvert flow is extremely complex because the flow is usually nonuniform with regions of both gradually varying and rapidly varying flow. An exact analysis involves backwater and drawdown calculations, energy and momentum balance, and application of the results of hydraulic model studies. In general 6 different types of culvert flow are accepted to describe the majority of conditions encountered, although it must be highlighted that the U.S. Geological Survey has defined 18 different culvert flow types based on inlet and outlet submergence, the flow regime in the barrel, and the downstream brink depth. The flow types in a given culvert change as the flow rate and tailwater elevations change.
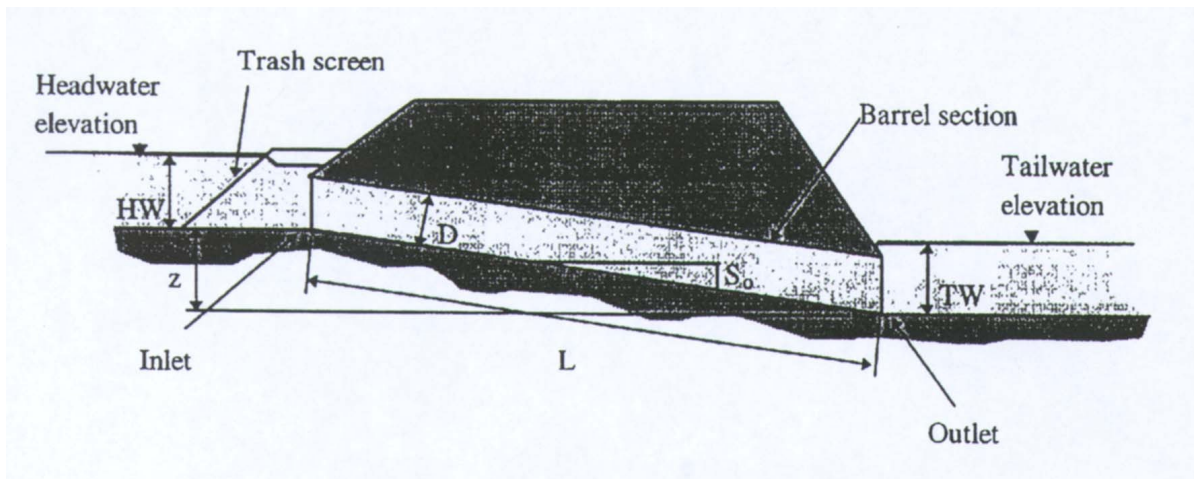

Fig. 1 Outline Diagram of Main Features of a Culvert

A culvert consists typically of an inlet, an outlet and between these a culvert barrel of length L and height D. The barrel is normally on a slope, S_o and the depths of water above the upstream and downstream invert levels are known as the headwater depth (HW) and the tailwater depth (TW) respectively. Fig. 1 illustrates the main features of a culvert:

Culvert Hydraulics and Section 50 Consent

Types of Flow Control

A control section is a location where there is a unique relationship between the flow rate and the upstream water surface elevation. Many different flow conditions exist over time, but at a given time the flow is either governed by the inlet geometry (inlet control) or by a combination of the culvert inlet configuration, the characteristics of the barrel, and the tailwater (outlet control). i.e Inlet control occurs when the culvert barrel is capable of conveying more flow than the inlet will accept. Outlet control flow occurs when the culvert barrel is not capable of conveying as much as the inlet opening will accept. Table 1 presents the geometric and hydraulic characteristics which play a role in determining culvert capacity for a given flow type.

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	X (minor)	X
Tailwater Elevation		X

Table 1 Factors Influencing Culvert Performance

Culvert Performance

Fig. 2 illustrates a typical culvert performance curve, headwater depth plotted against flow rate. The advantage of outlet control is evident. Entrance energy losses defined as $K_i v^2/2g$ where K_i is the coefficient of inlet losses and is a function of inlet configuration. Fig. 3 illustrates types of inlet configurations. Table 2 presents the range of values for K_i.
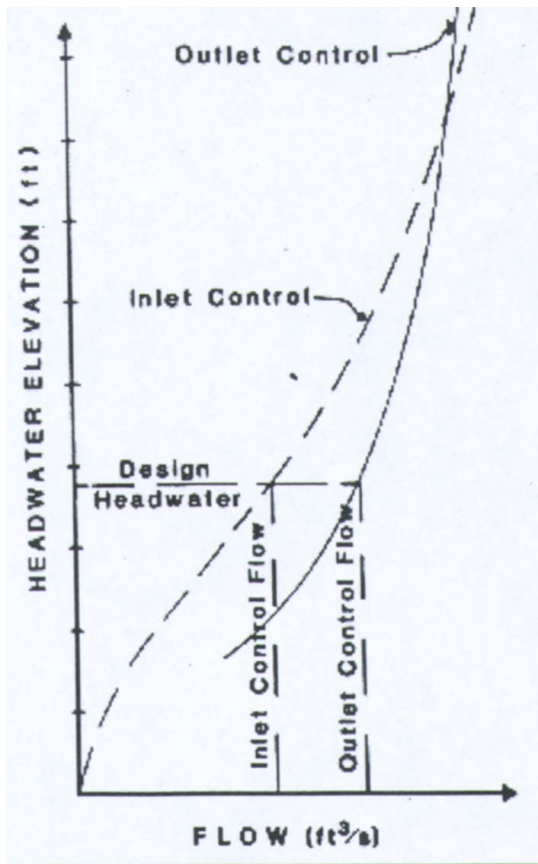
Fig. 2 Culvert Performance Curve
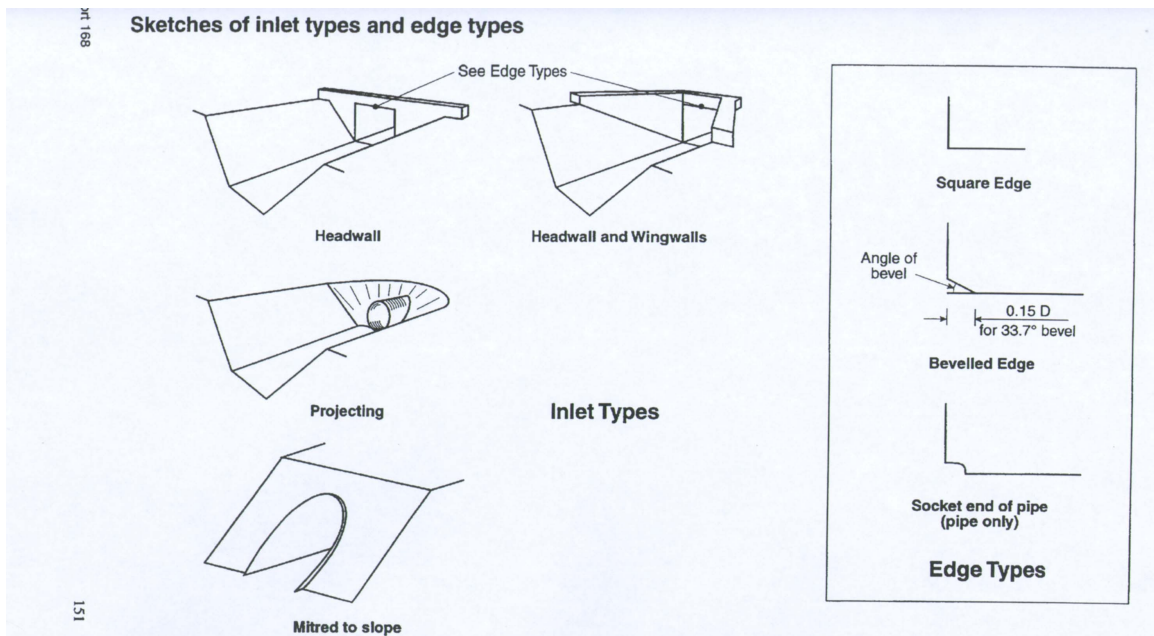
Fig. 3 Inlet Types and Edge Types

Shape	Material	Inlet type / edge type (see sketches below)	Eqn	K	M	c	Y	K_i
Circular	Concrete	Headwall / square edge	A	0.0098	2.0	0.0398	0.67	0.5
		Headwall / socket end of pipe	A	0.0078	2.0	0.0292	0.74	0.3
		Projecting / socket end of pipe	A	0.0045	2.0	0.0317	0.69	0.3
	Corrugated metal	Headwall / square edge	A	0.0340	1.5	0.0553	0.54	0.5
		Mitred to slope	A	0.0018	2.5	0.0300	0.74	0.7
		Projecting	A	0.0018	2.5	0.0243	0.83	0.9
Rectangular	Concrete	Headwall and wingwalls at 30° - 75° to barrel / square edge	A	0.026	1.0	0.0385	0.81	0.3
		Headwall or headwall and wingwalls at 15° to barrel / square edge	A	0.061	0.75	0.0400	0.80	0.5
		Headwall and wingwalls at 0° to barrel / square edge	A	0.061	0.75	0.0423	0.82	0.7
		Headwall / 20mm chamfers	B	0.515	0.667	0.0375	0.79	0.5
		Headwall / 45° bevels	B	0.495	0.667	0.0314	0.82	0.5
	Corrugated metal	Headwall / square edge	A	0.0083	2.0	0.0379	0.69	0.5
		Thick wall projecting	A	0.0145	1.75	0.0419	0.64	0.6
		Thin wall projecting	A	0.0340	1.5	0.0496	0.57	0.6
Pipe Arch	Corrugated metal 450 mm corner radius	Headwall / square edge	A	0.0083	2.0	0.0496	0.57	0.5
		Mitred to slope	A	0.0300	1.0	0.0463	0.75	0.7
		Projecting	A	0.0340	1.5	0.0496	0.53	0.9
		Headwall / 33.7° bevels	A	0.0030	2.0	0.0264	0.75	0.3
	790 mm corner radius	Projecting	A	0.0296	1.5	0.0487	0.55	0.9
		Headwall / square edge	A	0.0087	2.0	0.0361	0.66	0.5
		Headwall / 33.7° bevels	A	0.0030	2.0	0.0264	0.75	0.25
Arch	Corrugated metal	Headwall / square edge	A	0.0083	2.0	0.0379	0.69	0.5
		Mitred to slope	A	0.0300	2.0	0.0463	0.75	0.7
		Thin wall projecting	A	0.0340	1.5	0.0496	0.57	0.6

Notes

(1) Wingwall angle measured from centre-line of culvert barrel(s)
(2) For further details of inlet types and other configurations see Normann, 1985
(3) Coefficients K, c, M and Y used in equations in analysis module 3, K_i is inlet head loss coefficient

Table 2 Inlet Structure Design Coefficients, CIRIA 168

Design Methodologies

The following are the most commonly applied methods:

- Empirical equations

  The discharge of a culvert is determined by the application of the continuity and energy equations between the approach section and a downstream section which is within the culvert barrel. The location of the downstream section depends on the state of the flow within the culvert. Discharge equations for the various types of culvert flow are summarised in Fig. A1, appendix, taken from French. Other authors use different methods.

- Nomographs (US Bureau of Public Roads)

  Over 60 different charts for various culvert types and flow conditions are available.. An example of a nomograph is shown in Fig. A2, appendix.

- CIRIA Report 168 - Culvert Design Guide

  Design manual produced by HR Wallingford in association with the University of Hertfordshire and Mott MacDonald on behalf of CIRIA, Construction Industry Research

and Information Association, UK. Provides a guide to the hydraulic design of culverts. A procedure chart is shown in Fig. A3.

- Software

  Packages such as CulvertMaster® by Haestad Methods now available which are user friendly and can estimate headwater elevations, size culverts or determine maximum flow capacity.

Headloss at Bridges

The calculation of headlosses at existing bridges may be required to establish headwater levels. The following may be of use:
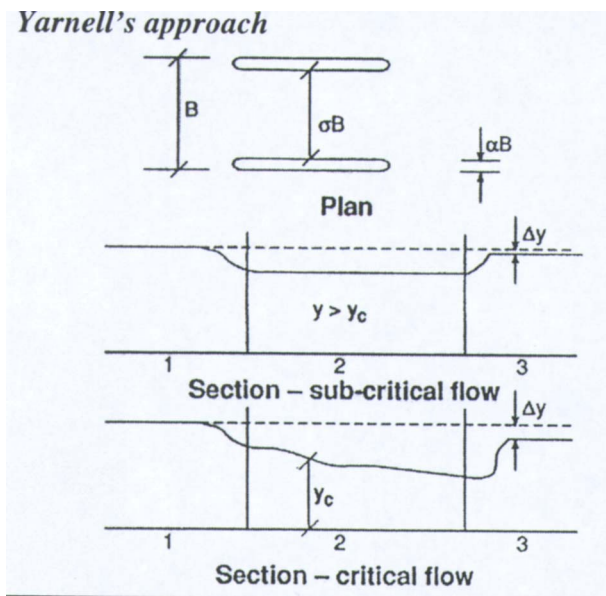
Yarnell's equation for stone arch bridges

Fig. 4 Yarnell's Approach

Super-critical flow:

Estimate head loss by using flume equation.

Sub-critical flow:

To estimate headloss, Δy,

$$\Delta y/y_3 = kF_3^2 [k + 5 F_3^2 - 0.6][\alpha + 15\alpha^4]$$

where F is Froude Number and K varies between 0.9 and 1.25 depending upon pier shape:

0.9 = semicircular nose and tail

1.25 = square nose and tail

USBPR method for modern bridges

To estimate headloss, Δy:

$$\Delta y = k\alpha_2 v_2^2/2g + \alpha_1 [(A_2/A_3)^2 - (A_2/A_1)^2]v_2^2/2g$$

where

α_2 velocity coefficient

α_1 kinetic energy coefficient

k   total backwater coefficient, where:

$$k = k_b + k_p + k_e + k_s$$

k_b = base coefficient k_p = effects of piers

k_e = effect of eccentricity k_s = effect of skew

Risk Analysis

The OPW recommends certain degrees of immunity for various scenarios as set out in its brochure *Guide on Information to Accompany Applications for OPW Consent for Bridges and Culverts*. As a matter of interest if culvert size was to be determined by risk analysis an exercise as detailed in Fig. 5 would give the optimum culvert size.
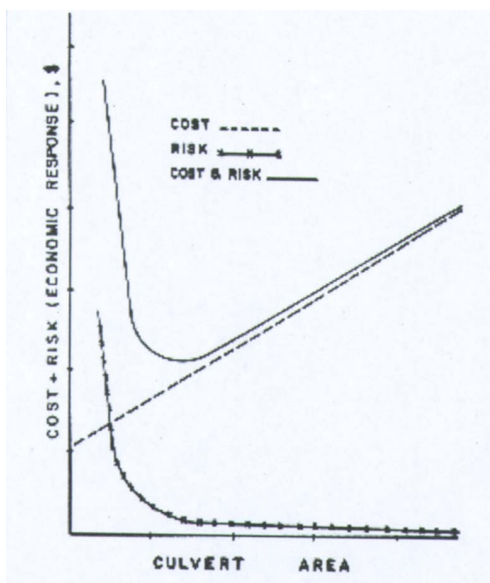

Fig. 5 Risk Analysis Benefit versus Cost Curve

Culvert Hydraulics and Section 50 Consent

Embankments Across Floodplains

As recommended in CIRIA 168 where a newly constructed road embankment crosses a flood plain it is highly desirable to include additional / relief culverts, (with inverts at the flood plain elevation) to give additional flow capacity above that provided by the river crossing itself.

Environmental Requirements

Some watercourses may be of fishery significance and consideration should be given to the ability of the structure to accommodate migrating fish at the design stage. This may include a minimum depth of water in low flow situations and/or the oversizing of the culvert and installation below design bed level to allow a build up of natural bed material. Liaison with the Central or Regional Fishery Boards prior to submission of application is advisable.

Provision for the passage of mammals may be required and can be of the form of a shelf within the culvert or a separate structure at bank elevation. The latter could also incorporate access for anglers / members of the public along river corridor.

Frequent Errors

The following non-exhaustive list contains the most frequent errors made in Section 50 applications :

- The use of Wallingford / manufacturers tables for the capacity of pipes / box culverts. Discharge rates presented are usually calculated using equations estimating barrel friction losses only and assumes the culvert is flowing full under uniform flow conditions.

- No allowance for head loss due to entry and exit. As above only losses due to barrel friction are accounted for.

- Use of incorrect software, i.e. drainage / pipe network design.

- No design factor for standard error when using the catchment characteristics method of FSR as outlined in 4.3.10 Volume 1.

Culvert Hydraulics and Section 50 Consent

- Runoff from proposed impermeable surface not taken into account. Surface runoff from a proposed road discharging to a watercourse may increase the peak discharge at culvert. This applies in particular to small catchments.

- Stormwater retention ponds designed with lower immunity than culverts thereby increasing peak discharge as above.

- Environmental considerations may lead to a change in structure's requirements. This may require resubmission for consent.

Tailwater Calculation in Compound Channel / Floodplain

The tailwater elevation is an important factor in determining culvert capacity under outlet control conditions. The following example calculates the tailwater level for out-of-bank flow via Normal Depth Method.

Solving Manning's eqn for

$$A = (Q.n.P^{2/3}.s^{-1/2})^{3/5}$$

Assuming no floodplain flow and that the Wetted Perimeter, P is constant, therefore only A varies with level. Calculate the cross-sectional area required for the design flow, A_{Total} from the above equation.

$$A_{Total} = A_{Inbank} + A_{Outbank}$$

A_{Inbank} is known cross-section geometry, solve for $A_{Outbank}$, which is defined as Top Width multiplied by z, where z is depth of flow above bank. Calculate tailwater level.

Submission Documents

To summarise, to facilitate the orderly assessment of Section 50 applications the applicant is required to submit the following :

- Completed application form, 50/1
- Site location / overall plan of scheme, if applicable,
- Drainage plan, scale 1:2500 approx.
- Long section of proposed structure, indicating existing channel gradient both upstream and downstream
- Proposed culvert type, size, length and upstream and downstream inverts
- Outline drawing (cross-section) of proposed structure, if non-standard
- Selected design standard with reasoning
- Maximum permissible upstream water level for the design flood
- Hydrological calculations. The applicant is to provide details of the hydrological calculations used to determine the design flow for the proposed structure. These should include method used, assumptions made, design factor for standard error, parameters adopted and other pertinent information.
- Estimated tailwater level for design event
- Hydraulic calculations
- History of flooding

References

(1)   Arterial Drainage Act, 1945.

(2)   Cunnane, C. and Lynn, M.A., Flood Estimation following the Flood Studies Report, presented to the Institution of Engineers of Ireland.

(3)   CulvertMaster® User's Guide, http://www.haestad.com

(4)   Flood Studies Report (1975), Natural Environment Research Council. (available form the Institute of Hydrology, Wallingford

(5)   French, R.H., Open Channel Hydraulics, McGraw Hill

(6)   OPW, Guide on Information to Accompany Applications for OPW Consent for Bridges and Culverts

Appendix

Culvert type flow — **Discharge equation**

Type 1. Critical depth at inlet
$(h_1 - z)/D < 1.5$
$h_4/h_c < 1.0$
$S_0 > S_c$

$$Q = C_D A_c \sqrt{2g\left(h_1 - z + \alpha_1 \frac{\bar{u}_1^2}{2g} - y_c - h_{f1.2}\right)}$$

Type 2. Critical depth at outlet
$(h_1 - z)/D < 1.5$
$h_4/h_c < 1.0$
$S_0 > S_c$

$$Q = C_D A_c \sqrt{2g\left(h_1 + \alpha_1 \frac{\bar{u}_1^2}{2g} - y_c - h_{f1.2} - h_{f2.3}\right)}$$

Type 3. Tranquil flow throughout
$(h_1 - z)/D < 1.5$
$h_4/h_c \leq 1.0$
$h_4/h_c > 1.0$

$$Q = C_D A_3 \sqrt{2g\left(h_1 + \alpha_1 \frac{\bar{u}_1^2}{2g} - h_3 - h_{f1.2} - h_{f2.3}\right)}$$

Type 4. Submerged outlet
$(h_1 - z)/D > 1.0$
$h_4/D > 1.0$

$$Q = C_D A_0 \left[\frac{2g(h_1 - h_4)}{1 + (29C_D^2 n^2 L/R_0^{4/3})}\right]^{1/2}$$

Type 5. Rapid flow at inlet
$(h_1 - z)/D \geq 1.5$
$h_4/D \leq 1.0$

$$Q = C_D A_0 \sqrt{2g(h_1 - z)}$$

Type 6. Full flow free outlet
$(h_1 - z)/D \geq 1.5$
$h_4/D \leq 1.0$

$$Q = C_D A_0 \sqrt{2g(h_1 - h_3 - h_{f2.3})}$$
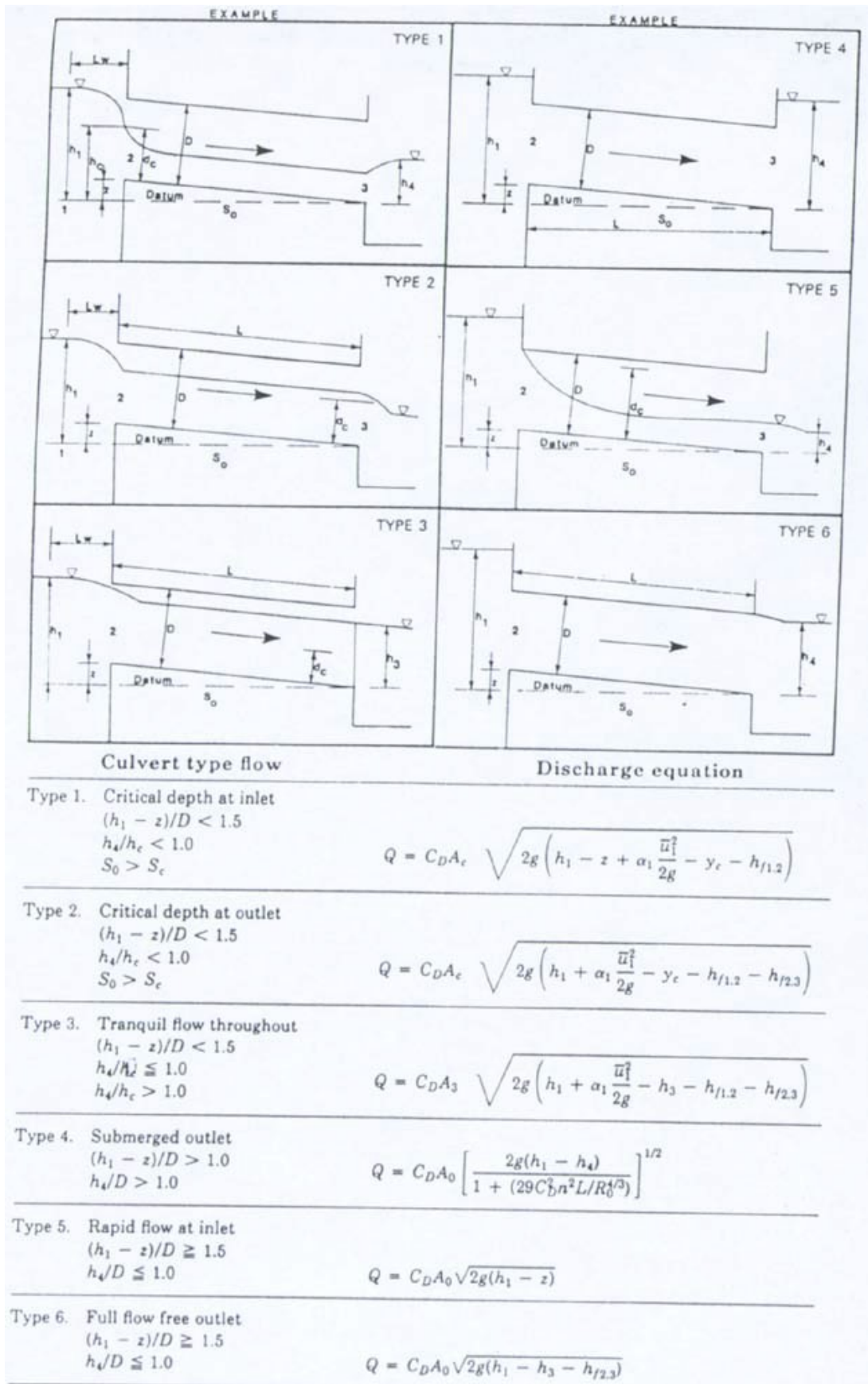
Fig. A1 Classification of Culvert Flow, French
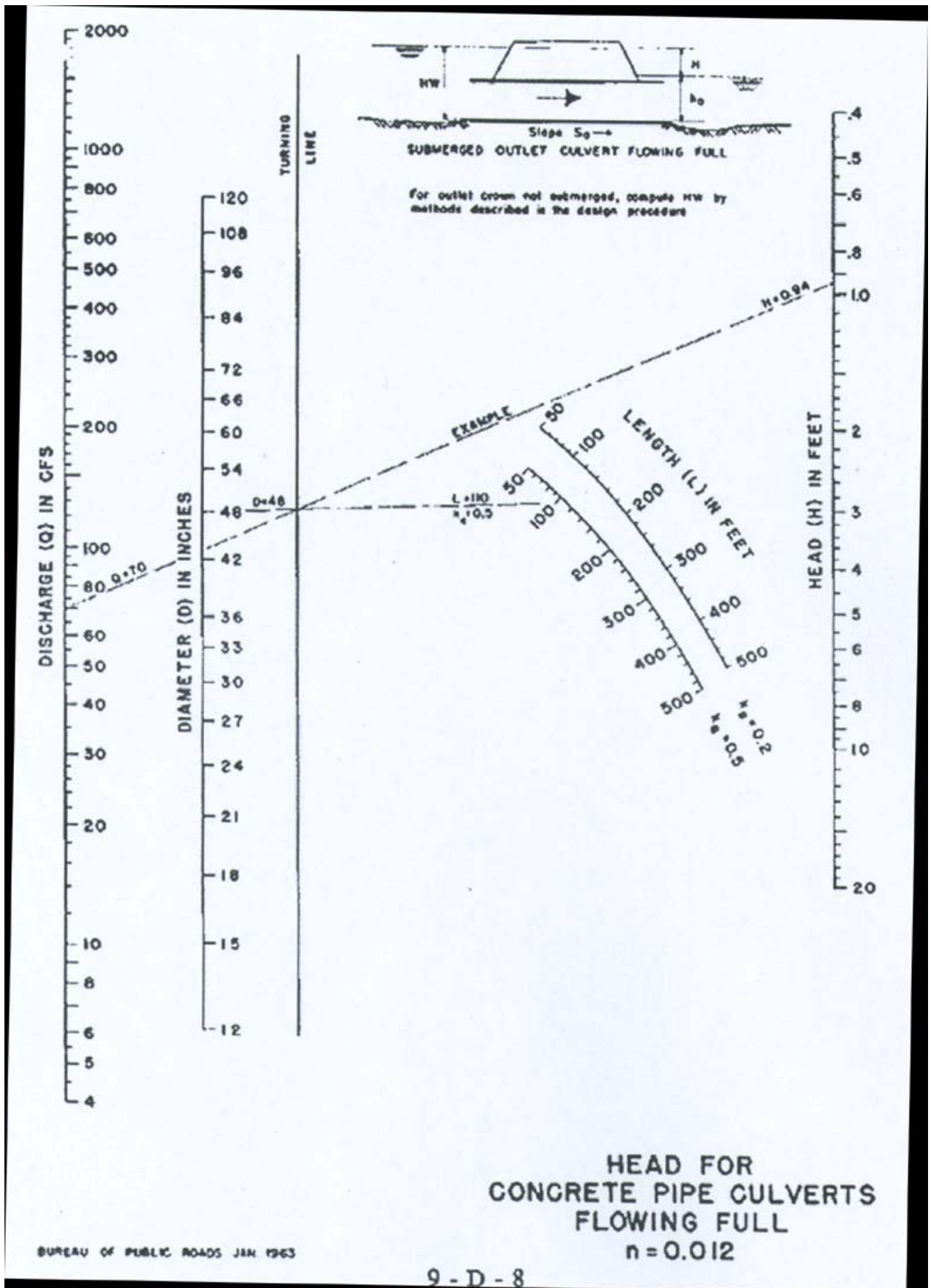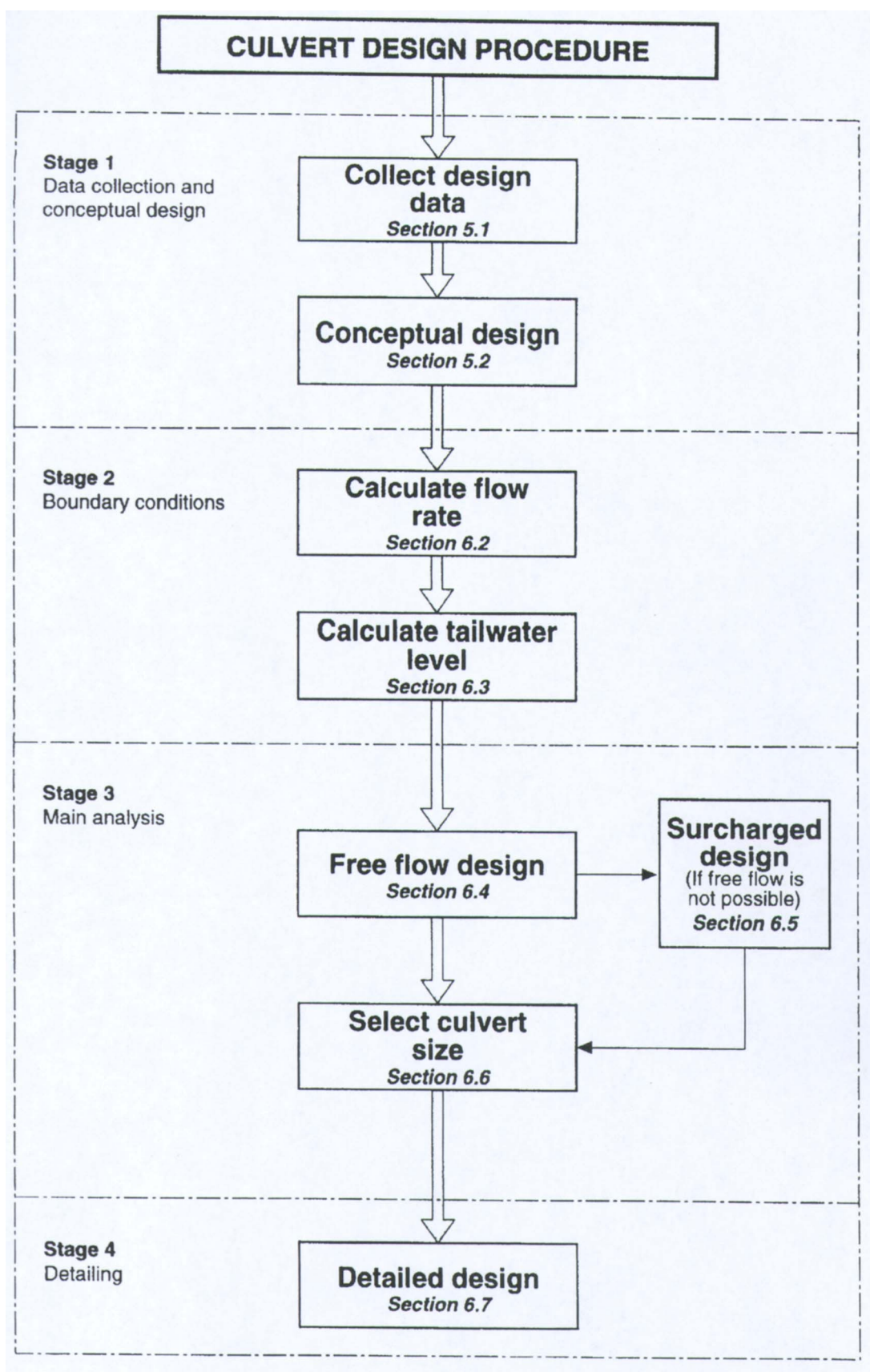
Fig. A2 Typical Nomograph, Bureau of Public Roads

Fig. A3 Outline Design Procedure for New Culverts, CIRIA 168