OPTIMUM SAFE HYDRAULIC DESIGN OF CULVERTS

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in Water Resources Engineering

By
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بِسمِ اللّهِ الرَّحمنِ الرَّحِيمِ

وَقُل رَّبِّ زِدنِي عِلماً

صَدَقَ اللّهُ العَظيم

(طه١١٣)

DEDICATION

To my family, relatives and friends, and special gratitude to my wife and Children Ali and Amani

CERTIFICATION

We certify that this thesis entitled " **Optimum Safe Hydraulic Design of Culverts**", was prepared by **Atheer Zeki Muhsen Al–Qaisi**, under our supervision at the Civil Engineering Department, College of Engineering, University of Babylon, in partial fulfillment of the requirements for the Degree of Master of Science in Water Resources Engineering.

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Optimum Safe Hydraulic Design of Culverts

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ABSTRACT

In view of the importance of culverts whether in irrigation projects or as road–crossings and the high cost they usually form, the subject of the "Optimum Safe Hydraulic Design of Culverts" has been selected, taking into consideration the cost of excavation, bedding, material, compacted fill, hunches, protection works and additionally involved head loss.

Because of numerous shapes and materials of culverts, the wide–fame among them have been selected in this research, namely, reinforced concrete box culverts of both rectangular and squared shape, and pipe culverts of circular shape with materials of reinforced concrete, cast–iron, asbestos–cement, and ductile–steel.

To be close to field conditions, discharges of (0.5, 1.0, 1.5, 2.5, 5.0, 10.0, and 15.0m^3/s) have been selected to represent small, medium, and big discharges; culverts lengths of (5, 10, 15, 20, 25, 35, and 40m) have been selected to represent short, medium, and long structures. However, typical trapezoidal earthen irrigation channels have been considered to accommodate the respective culverts.

To prepare the optimization model, an objective function has been formulated to cover all aforementioned costs. The optimization model involved all structural and hydraulic design constraints. The non–linear optimization model is solved by the modified Hooke and Jeeves direct search approach. A computer program is developed to handle the aimed solution.

The following categories of analyses have been considered:

1. Cost as a function of discharge (for the different selected lengths).

2. Cost as a function of length (for the different selected discharges).

3. The number of vents as a function of discharge (for the different selected lengths).

4. The number of vents as a function of length (for the different selected discharges).

5. The dimensions of the culvert as a function of discharge (for the different selected lengths).

6. The dimensions of the culvert as a function of length (for the different selected discharges).

The results showed the following:

1. The method of solving optimization problem is suitable in giving the results.

2. The optimization process automatically excluded the pipe culverts.

3. For the considered cases, the discharge, rather than length, is the dominant factor controlling costs, number of vents, and dimensions of the culvert.

4. Reinforced concrete box culverts are the optimum types for all considered discharges and lengths as follows:

a) For (Q=0.5,1.0,and1.5m^3/s) and for all considered lengths, the optimum types are single–vent, reinforced concrete square box culverts.

b) For (Q=2.5m^3/s) and (L=5 through 20m), the optimum type is a single–vent, reinforced concrete square box culvert, whereas for (L=25 through 40m), the optimum type is a single–vent, reinforced concrete rectangular box culvert.

c) For (Q=5.0 and 10.0m^3/s) and for all considered lengths, the optimum types are two–vents, reinforced concrete square box culverts.

d) For (Q=15.0 m^3/s) and for all considered lengths, the optimum type is a single–vent, reinforced concrete rectangular box culvert.

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNIT
A	Cross–sectional area of the culvert.	m^2
A_c	Cross–sectional area of the channel.	m^2
B.L.	Bed level.	m
d	Height of the culvert or diameter of a pipe culvert.	m
D	Outer diameter of pipe culverts.	m
1D	One dimensional	
2D	Two dimensional	
D/SWL	Downstream water level.	m
g	Gravitational acceleration.	m/s^2
G.S.	Ground surface.	
h or h_f	Height of compacted fill.	m
H or HW	Headwater depth.	m
H_A	Active head on the culvert.	m
H_T	Effective head on the culvert.	m
H*	Critical headwater.	m
K_1	Entrance loss coefficient of the culvert.	
K_2	Exit loss coefficient of the culvert.	
K_i	Inlet transition loss coefficient.	
K_o	Outlet transition loss coefficient.	
L	Length of the culvert.	m
LP	Linear Programming.	

m	Number of vents of a culvert.	
n	Manning roughness coefficient of the culvert.	
n_c	Manning roughness coefficient of the channel.	
NLP	Non–Linear Programming.	
Q	Discharge through the structure(culvert and channel).	m^3/s
R	Hydraulic radius of the culvert.	m
R.C.	Reinforced concrete.	
S or S_b	Bed slope of the culvert.	m/m
S_c	Bed slope of the channel.	m/m
U/SWL	Upstream water level.	m
V	Velocity within the culvert.	m/s
V_c	Velocity within the channel.	m/s
X_i	The i–th design variable.	
y_c	Critical water depth.	m
y_o	Water depth of the channel.	m
Y_t or TW	Tailwater.	m
ZT_i	Total cost objective function for the i–th selected type of culverts.	$
θ	Angle of inclination of the culvert.	

Note: Some other symbols are explained where they appear in the text.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Water is an important resource to humanity. As a result of the controversial development that is continuously growing in various countries of the world, the demand on this resource is increasing on the various fields of its use, such as industry, agriculture, electric power–generation,…,etc. Therefore, the optimum use of water must be well considered to avoid wastage of water, quantitatively, qualitatively, or as a command head, specially when the water resources are scarce. In Iraq, the irrigation and drainage projects consist of a bulk of various hydraulic structures for the purposes of regulating the passage of water (e.g., the different types of regulators), measurement of the discharge (e.g., weirs), conveying the water in a channel crossing others (e.g., conveyance structures, which include culverts, aqueducts, and siphons), or in road crossings (e.g., bridges, culverts and causeway), beside some other miscellaneous structures which collectively serve to assure the supply of the demanded water quantities. These hydraulic structures usually form an important part of the total cost of the whole project, probably in the range of (10–35) % of the total cost. This calls for special attention to the design of these structures aiming at the 'best' of each type such that it will function satisfactorily, hydraulically, structural, and within acceptable economical performance. This research focuses on the optimum design of culverts as one important type of the aforementioned hydraulic structures, aiming at avoiding wasteful over–designing.

1.2 OBJECTIVES OF THE RESEARCH

The main objectives of this research can be summarized as follows:

1. Building a general model that incorporates the assumptions and methods used in analysis and design of culverts, involving the basic parameters in the processes of construction and maintenance of such structures.

2. Of the possible alternative types of culverts, the most appropriate one (or ones) is (are) to be selected through an optimization approach.

3. Verifying the optimally–selected type (or types) through application to some selected practical case studies.

1.3 METHODOLOGY OF THE RESEARCH

To meet the aforementioned objectives, the methodology adopted in this research is:

1.Formulating the optimization model for selected types of culverts.

2.Adopting a case study that incorporates all important parameters controlling the optimization problem.

3. Solving the optimization problem by an appropriate method of solution.

4.Analyzing the final result to attain the relatively–optimum shape for the respective considered discharges and lengths of culvert.

CHAPTER TWO

REVIEW OF LITERATURE

The review of literature contained in this chapter covers three aspects; the first concerns the definition of the culvert and its appurtenants; the second is the developments of culvert analysis; the third covers developments in the optimum design of culverts.

2.1 THE CULVERT

2.1.1 DEFINITION

A culvert is a closed conduit that provides a means of carrying the flow of water through an embankment. The shape of the cross–section of a culvert may be of any reasonable geometric shape. However, the most common shapes are the circular and the box.

The flow through a culvert may be a pipe (closed–conduit) flow when the culvert flows full under pressure. However, culverts may be designed or analyzed as open channels when they flow partially full.

Culverts may serve two distinguished purposes, namely, as a drainage structure and as an irrigation structure. Culverts serving as drainage structures include road crossing structures that convey water under a road or railway. However, a substitute could be a bridge that passes a road or a railway over a channel. Culverts serving as irrigation structures include conveyance structures such as aqueducts, inverted siphons, drop structures, flumes, and chutes. These structures are used to carry water over obstructions or at changes of the cross section or grade of a channel.

2.1.2 CULVERT TYPES AND MATERIALS

Culverts may be constructed with different shapes and materials:

Metal and reinforced concrete pipe culverts are shop–manufactured products available in a range of sizes in the standard shapes. Metal pipes (Aluminum and steel) are available in round and arch shapes. Reinforced concrete pipes are available in round and elliptical shapes. Round shapes are generally more economical due to their greater strength [NJDOT (2003)].

Box culverts are either precast or cast–in–situ. They may be constructed to any desired size in either square or rectangular shapes. These designs may be easily altered to allow for site conditions. The flow characteristics of the reinforced concrete box culverts, (RCBC), are very good as their barrels provide smooth flow and their inlet may be designed for extra efficiency where needed. The more common culvert types and the materials of which they are made are shown in Fig. (2.1).

2.1.3 THE TRANSITION COMPONENTS

A channel transition may be defined as a local change in cross section which produces a variation in flow from one uniform state to another. In many hydraulic structures, the main reason for constricting or fluming at the inlet is to reduce the cost of construction of the structure and in some cases can provide an expedient device for measurement of discharge in the main body of the structure. It is important that transitions to and from structures are properly designed when head losses are critical [Pencol (1983)].

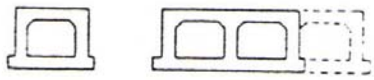
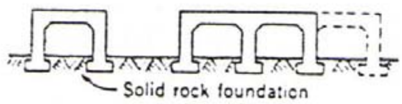
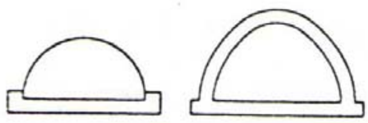
Culvert type	Typical cross sections	Common material
Pipe, single or multiple, circular		**Corrugated metal, plain or reinforced concrete, vitrified clay, cast iron**
Ovalt		**Concrete**
Pipe arch, single or multiple span		**Corrugate metal, precast reinforced concrete**
Box culvert, single or multiple span		**Reinforced concrete**
Bridge culvert, single or multiple span		**Reinforced concrete**
Arch		**Reinforced concrete, corrugated metal or stone masonry arch on reinforced concrete**

Figure (2.1): Common culvert types and materials (Note: Metal include galvanized iron, steel and aluminum alloy) [After Oglesby (1975)].

Transitions can serve several other functions, namely:

(a) Minimize canal erosion.

(b) Increase the seepage path and thereby provide additional safety against piping.

(c) Retain earth fills at the ends of structures.

All transitions may be classified as either inlet (contraction) or outlet (expansion) transition. The various types of transitions are [Pencol (1983)]:

a- Straight–line headwall .

b- Broken–back to rectangular or pipe opening.

c- Cylinder quadrant.

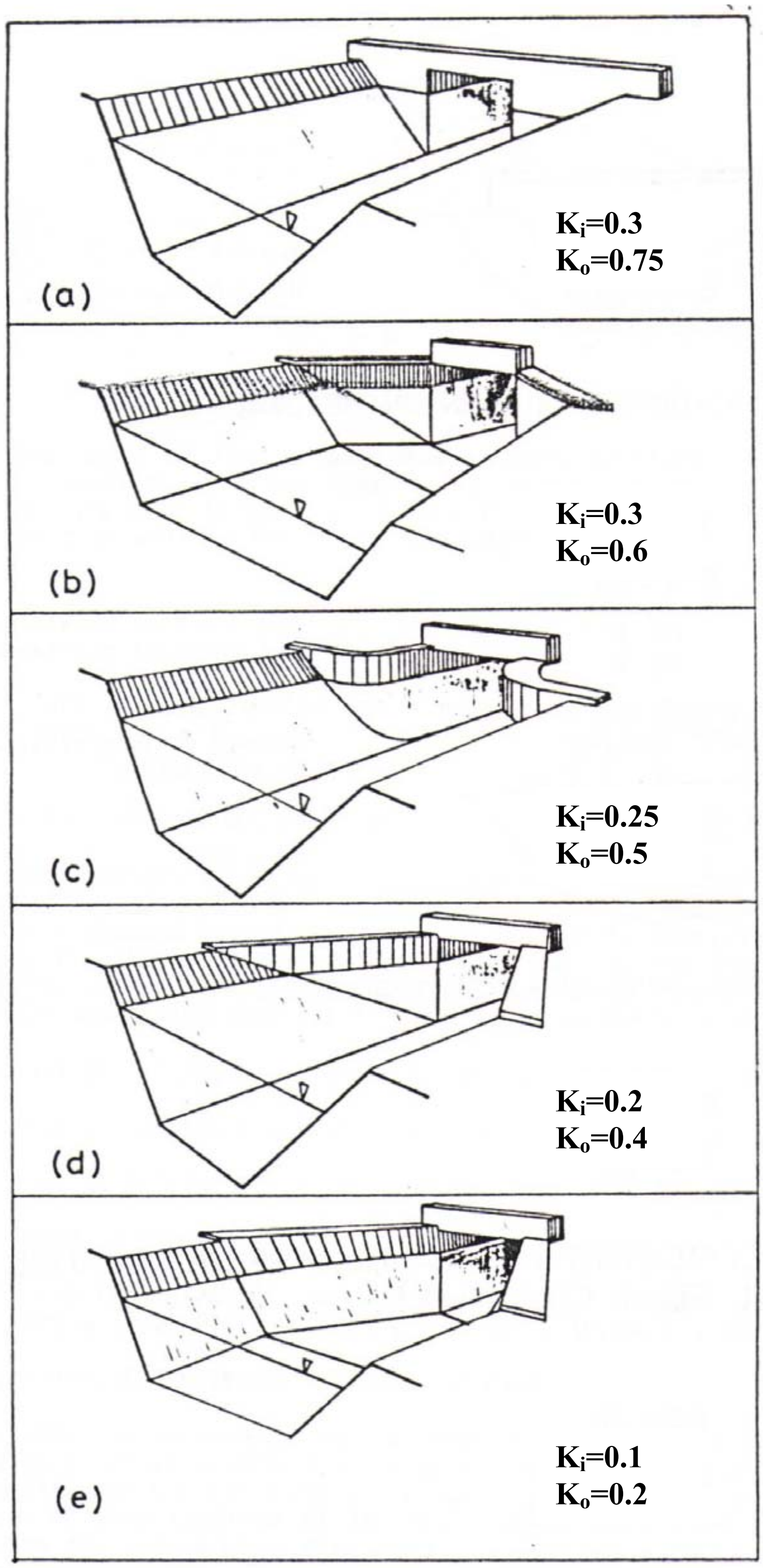
d- Straight warp to rectangular or pipe opening.

e- Streamlined warp to rectangular opening.

The aforementioned types of transitions are shown in Figs. (2.2) and (2.3), together with their respective inlet and outlet loss coefficients. Table (2.1) gives a range of loss coefficients for pipes and box sections under partial and full flow conditions.

As stated in Pencol [1983], the following comments apply to the transitions shown in Figs. (2.2) and (2.3):

(a) The straights–line headwall transition, Fig. (2.2a), is suitable for small short structures in watercourses and where head loss is not a problem. It is relatively cheap and easy to construct. Both inlet and outlet transitions can take this form. It is also used extensively on small pipe culverts flowing full.



Straight line headwall

Broken back (Dog leg)

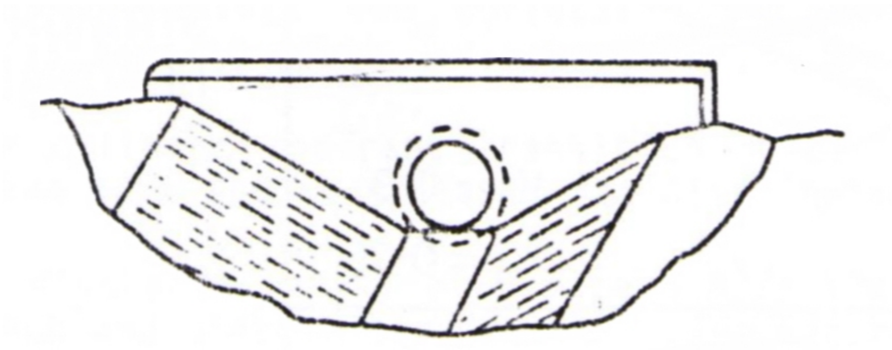
Cylinder quadrant

Straight warp

Streamlined warp

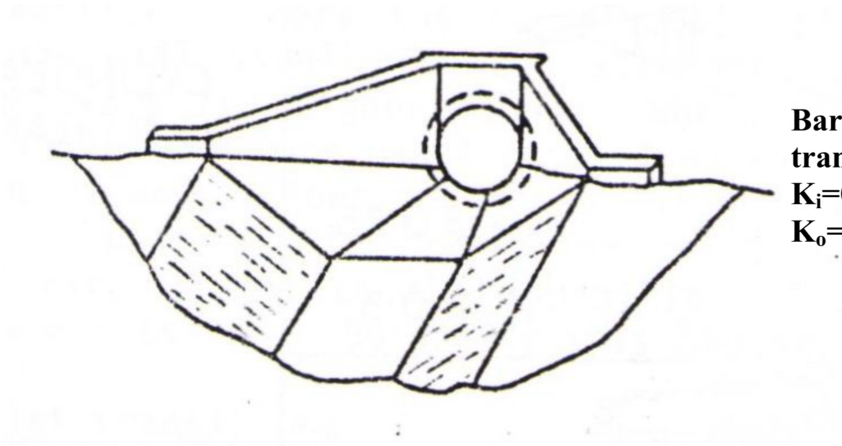
Note: K_i = Inlet loss coefficient.
K_o= Outlet loss coefficient (free water surface in box section).

Figure (2.2): Transition types for box culverts [After Pencol (1983)].



K_i=0.5
K_o=1.0

a) Pipe transition termination in headwall.



Barrel of pipe attached to transition
K_i=0.4
K_o=0.7

b) Conventional broken–back transition.

Figure (2.3): Transition types for pipe culverts [After Pencol (1983)].

Table (2.1): Loss coefficients for transitions [After Pencol (1983)].

Transition type	Pipe				Box			
	Full flow		Partial flow		Full flow		Partial flow	
	inlet	outlet	inlet	outlet	inlet	outlet	inlet	outlet
a	0.5	1.0	0.4	0.8	0.5	1.0	0.3	0.75
b	0.4	0.7	0.3	0.6	0.4	0.7	0.3	0.6
c	*	*	*	*	0.3	0.6	0.25	0.5
d	0.2	0.4	0.2	0.4	0.25	0.5	0.2	0.4
e	0.2	0.4	0.1	0.2	0.2	0.4	0.1	0.2

* Not used for a pipe.

(b) For discharge range of (0.5 to 5.0 m^3/s), the broken–back (or dog log) transition is used for inlet and outlet, Fig. (2.2b). It is also suitable for transition to pipes under pressure, Fig. (2.3b).

(c) The cylinder quadrant transition gives slightly lower loss coefficients than the broken–back and is suitable for distributary canals, Fig. (2.2c).

(d) For a discharge range of (2.5 to 5.0 m^3/s), the straight warp transition is preferred on branch and distributary canals, Fig (2.2d).

(e) Where canal discharge exceeds (5.0 m^3/s), the streamlined warp transition is most suitable, especially for inlets. Construction is however more complicated and the transition would be longer than for the other types. For reasons of economy, this transition is often paired with the straight line warp as an outlet. It has been found that the most suitable convergence angle is about 1:4 or (14°), Fig. (2.2e).

As a conclusion from what is mentioned hereinabove, the selection of the most appropriate type of transition based solely on discharge is impractical when considering head loss and cost (as will be shown later). Each case must be considered on its merits and it is not possible to provide solutions of completely general applicability. Where the conservation of head is not of great importance, the best solutions will usually be the straight–line headwall for the smaller flows and the straight warp for higher flows. Where minimizing of head loss is of importance (and this is the more usual situation), then the use of a straight–line headwall should be limited to small flows and the straight warp and streamlined warp is to be used for the higher flows.

2.2 CULVERT ANALYSIS

2.2.1 CULVERT HYDRAULICS

The culvert hydraulics had been the subject of research by many researchers. In studying the flow through culverts, Chow [1959] stated that the characteristics of the flow are very complicated because the flow is controlled by many variables, including the inlet geometry, slope, size, roughness, approach and tail water conditions,…,etc. Hence, an adequate determination of the flow through a culvert should be made by laboratory or field investigations. Many researchers worked on box and pipe culverts depending on experimental investigation.

As mentioned in Sec. (2.1.1), the flow through a culvert is either full or partially full flow. The culvert will flow full when the outlet is submerged or when the outlet is not submerged but the head water is high and the barrel is long. This situation of flow occurs if the head water is greater than a certain critical value, designated by (H*). The value of (H*) varies from (1.2 to 1.5) times the height of the culvert [i.e. H*= (1.2 – 1.5) d; (d) is the culvert height] while the outlet is not submerged. However, if the culvert is sufficiently long to allow the expanding depth of flow below the contraction to rise and fill the barrel, the culvert will flow full and such culvert is considered hydraulically long. Otherwise, the partially–full flow is applicable; such culvert is considered hydraulically short [Chow (1959)].

For practical purposes, culvert flow may be classified into six types as shown in Fig. (2.4). The identification of each type may be explained according to the following outline [Chow (1959)]:

A. Outlet submerged ………………………..………………………Type 1

B. Outlet unsubmerged:

1. Headwater greater than the critical value:

   a. Culvert hydraulically long ………………..…………..…..…Type 2

   b. Culvert hydraulically short…………………………......……Type 3

Type | **Profile**

(1) Outlet submerged
H>d
y_t>d
Full flow

(2) Outlet unsubmerged
H>H^*
y_t<d
Full flow

(3) Outlet unsubmerged
H>H^*
y_t<d
Partially-full

(4) Outlet unsubmerged
H<H^*
y_t> y_c
Subcritical flow

(5) Outlet unsubmerged
H<H^*
y_t< y_c
Subcritical flow
Control at outlet

(6) Outlet unsubmerged
H<H^*
y_t< y_c
Supercritical flow
Control at entrance

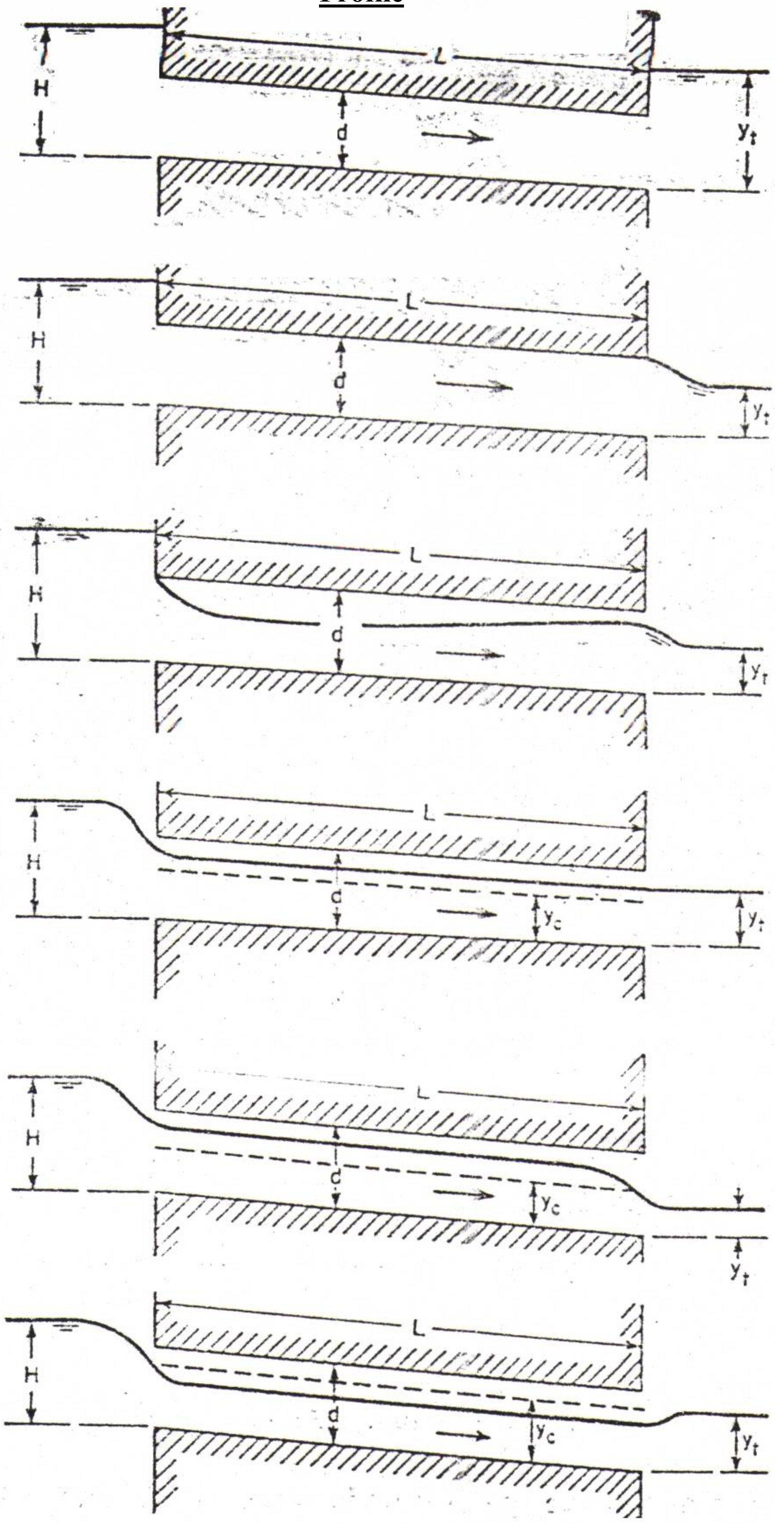


Figure (2.4): Types of culvert flow [After Chow (1959)].

2.Headwater less than the critical value:

a. Tailwater higher than the critical depth ………………………..Type 4

b. Tailwater lower than the critical depth:

i. Slope subcritical ..……………..……...…………………..……Type 5

ii. Slope supercritical ………………..………………………..Type 6

Pencol [1983] mentions several modes of flow through the culvert similar to the previous classification. These modes can be summarized as follows [with the aid of Fig. (2.5), where (D) is the culvert height and (H) is the head above the culver Invert].

A. Partially – full flow

1. Inlet not submerged (H/D<1.2):

   a. Outlet control:

      i. Mild slope (s< critical); subcritical flow……….……..…...Mode 1

      ii. Critical slope; subcritical flow ………..…..........................Mode 2

   b. Inlet control; steep slope(s>critical); supercritical flow……….Mode3

2. Inlet submerged (H/D>1.2); free outlet; inlet control (hydraulically short):

   a. Mild slope; supercritical flow; orifice flow................................Mode 4

   b. Steep slope; supercritical flow; orifice flow…………………...Mode 5

B. Full flow, inlet and outlet submerged (H/D>1.2):

a. Outlet control (hydraulically long):

   i. Mild slope ....Mode 6

   ii. Steep slope ....Mode 8

b. Control switching between inlet and some section within.…... Mode 7 the conduit; steep slope; supercritical pulsating slug flow.

However, the aforementioned classifications could be summarized into more brief one, namely, ‘inlet control’ and ‘outlet control’.

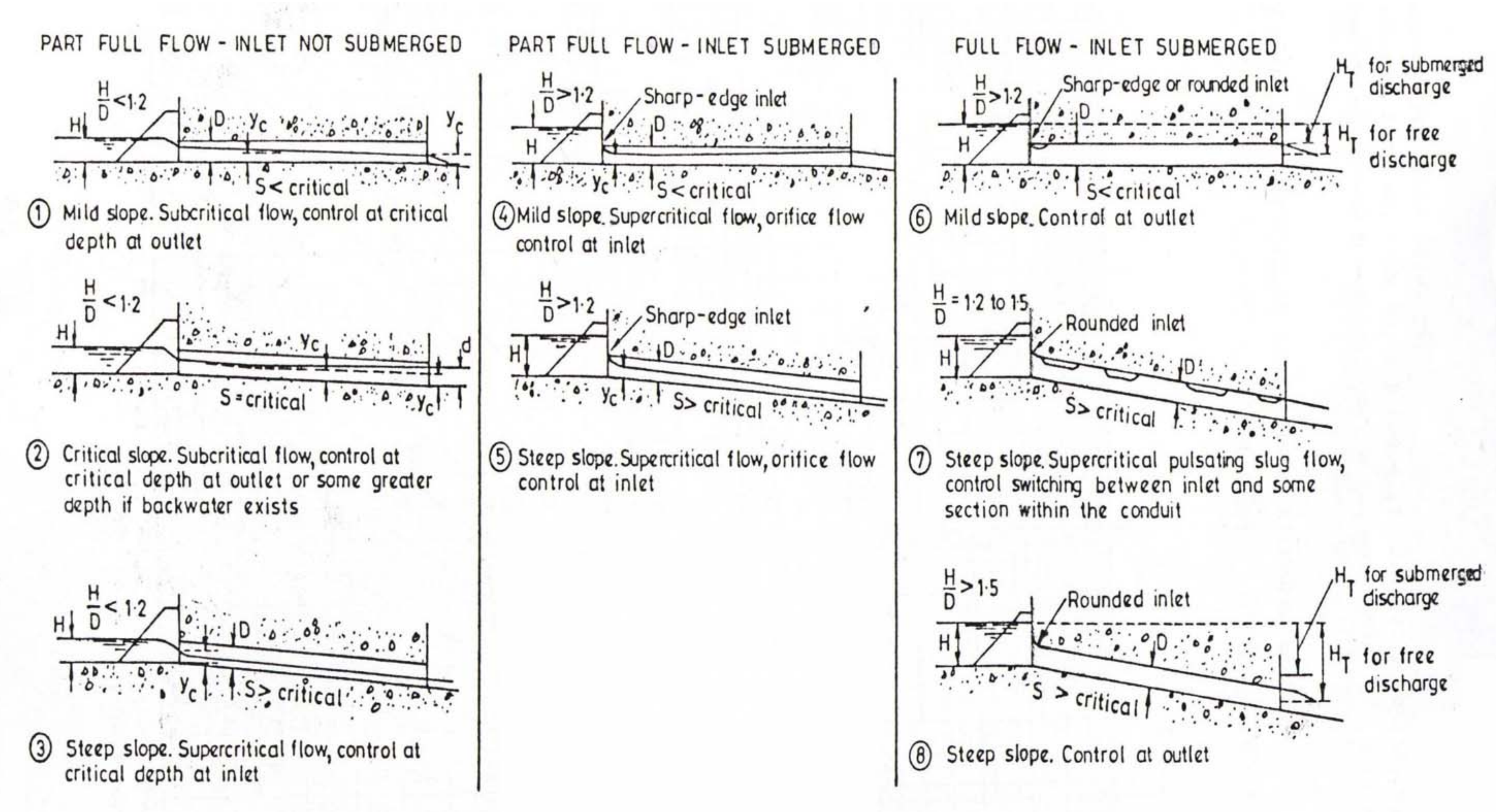


Figure (2.5): Typical flow conditions in conduits on mild and steep slopes [After USBR (1977)].

[A] Inlet control

A culvert is considered to operate under inlet control when the control section is located near the inlet of the culvert. It occurs when the culvert barrel is capable of conveying more flow than the culvert inlet will accept. Water can flow out of the culvert faster than it can enter the inlet. Critical depth occurs at or near the entrance to the culvert, and the flow downstream from the inlet is supercritical. Hydraulic characteristics of the downstream channel don't affect culvert capacity. Most culverts, except in flat terrain (slope is less than 3 percent), are designed to operate under inlet controlled conditions [Ballinger and Drake (1995)].

At the inlet, in this case, discharge is independent of slope, roughness, length, outlet type, and shape and size of the barrel. It depends entirely on the inlet geometry and the headwater elevation [Pencol (1983)].

A culvert may operate under 'Inlet control ' in two distinguished states:

1. Unsubmerged

Such a state occurs when the headwater is not sufficient to submerge the top of the culvert and the culver invert slope is super–critical. The culvert acts like a weir, as shown in Fig. (2.4–type 6) and Fig. (2.5–mode 3).

2. Submerged

Under this state, the headwater submerges the top of the culvert but it does not flow full. The culvert inlet acts like an orifice as shown in Fig. (2.4–type 3) and Fig. (2.5–modes 4 and 5); the culvert under such a state is entitled as "hydraulically short".

[B] Outlet control

Outlet control is physically more complex than inlet control. Outlet control occurs when the control section is near the outlet of the culvert, where the control section is a point in the channel that establishes either the upstream or downstream depth, depending on the state of flow. Moreover, the culvert barrel is not capable of conveying as much flow as inlet opening will accept; water can enter the culvert faster than it can flow through the culvert.

At the outlet, the discharge depends on inlet geometry and headwater elevation in addition to shape and size of the barrel, its roughness, slope and length. This can be the case for a culvert flowing partly full on a subcritical slope. When a culvert flows full, the control is always considered to be at the outlet unless it is very short. If the outlet is submerged, the tailwater elevation must be considered also [Pencol (1983)].

When a culvert is operating under outlet control, changes in barrel characteristics or tailwater elevation will affect its capacity. Hence, friction must be considered in calculating discharge and velocity [AISI (1994)].

Outlet control will govern if the headwater and /or tailwater is deep enough, the culvert slope is relatively flat, and the culvert is relatively long.

There are three cases under which outlet control of a culvert may occur:

1. The headwater submerges the culvert top, and the culvert outlet is submerged by the tailwater. The culvert will flow full as shown in Fig. (2.4–type1).

2. The headwater is insufficient to submerge the top of the culvert and the culvert is unsubmerged by the tailwater as shown in Fig.(2.4–types 4and 5) and Fig. (2.5–modes 1 and 2).

3. The headwater submerges the top of the culvert and the culvert is unsubmerged by the tailwater (hydraulically long) as shown in Fig. (2.4–type2) and Fig. (2.5–modes 6 and 8).

Most of Middle and Southern Iraq has a relatively flat topography. Under such circumstances, head losses have to be minimized. Consequently, flow of types (6) and (8) of Fig. (2.5) would be applicable [Pencol (1983)].

2.2.2 HYDRAULIC DESIGN OF CULVERTS

2.2.2.1 GENERAL

The principal goal of culvert's design is to determine the size, alignment, and functionality of the culvert with respect to passage requirements. In addition to the flow of water, a culvert must pass woody debris and sediment and allow passage of aquatic species. The term ‘size’ refers to the dimensions of the barrel, including the length and diameter of a pipe–shape or width and height of a box–shape. Alignment considers the culvert placement, usually horizontal, respective to stream flow direction and road centerline. Functionality refers to the culvert operation under given conditions and includes culvert hydraulic capacity. Additional goals of design include structural stability, durability, cost, ease of maintenance and safety [Gribben (1997)].

2.2.2.2 DESIGN PROCEDURE

For flow types (6 and 8) of Fig. (2.5), the discharge–head relationship of both pipe and box sections of a culvert could be set with the aid of Fig. (2.6) as follows [Given similarly in Pencol (1983)]:

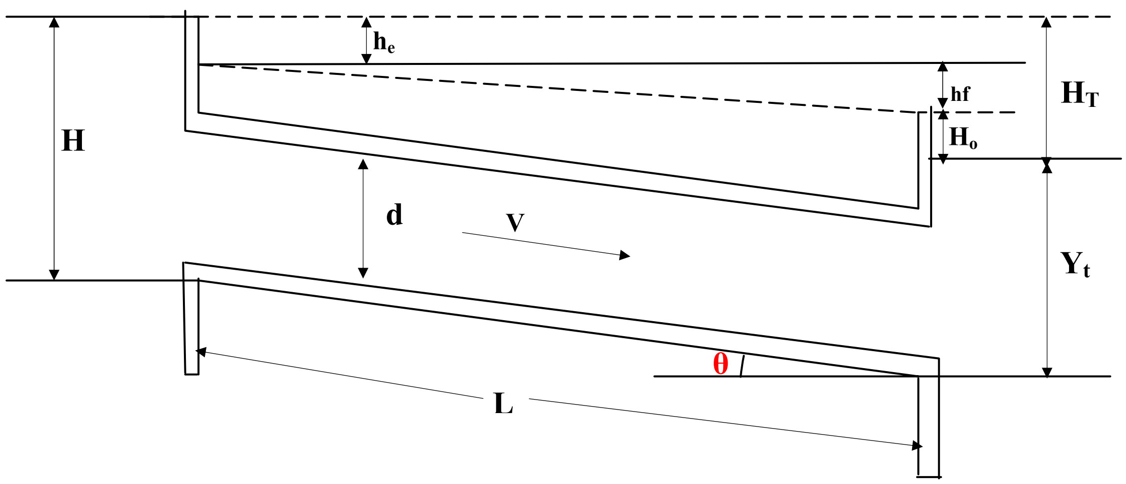


Figure (2.6): Notation for full flow in circular and box sections.

The effective head (H_T) may be written as:

$$H_T = h_e + h_\circ + h_f \tag{2.1}$$

where:

h_e = entrance loss; (L), $h_e = \dfrac{K_1 V^2}{2g}$ (2.2)

$h_\circ$ = outlet loss; (L), $h_\circ = \dfrac{K_2 V^2}{2g}$ (2.3)

h_f = friction loss; (L). It is calculated as follows:

If the culvert is running full, then recalling that $\left(S = {h_f}/{L}\right)$, the Manning equation may be used to calculate the friction loss . Thus:

$$\mathrm{h_f} = \left(\frac{2gn^2L}{R^{4/3}}\right)\frac{\mathrm{V}^2}{2\mathrm{g}} \tag{2.4}$$

Then:

$$H_T = \left(K_1 + K_2 + \frac{2gn^2L}{R^{4/3}}\right)\frac{V^2}{2g} \tag{2.5}$$

On equating upstream and downstream energy head in Fig. (2.6), the following relationship is obtained.

$$\mathrm{H} + \mathrm{LSin}\theta = Y_t + \mathrm{H_T} \tag{2.6}$$

On substituting (H_T) by its calculated equivalent and substituting (V) by $\left({Q}/{A}\right)$, the result will be:

$$\mathrm{H} - \mathrm{Y_t} + \mathrm{L\,Sin}\theta = (K_1 + K_2 + \frac{2gn^2L}{R^{4/3}})\frac{Q^2}{2gA^2} \tag{2.7}$$

In Iraq where slopes are generally flat, the $(L\,Sin\theta)$ term is generally ignored; then the head through the culvert barrel, (h_{LC}), would be:

$$\mathrm{h_{LC}} = \left(\mathrm{K_1} + K_2 + \frac{2gn^2L}{R^{4/3}}\right)\frac{\mathrm{Q}^2}{2\mathrm{gA}^2} \tag{2.8}$$

where:

Q = discharge of the culvert, (L^3/T);

A = cross–section of waterway (area of culvert), (L^2);

L = length of culvert, (L);

R = hydraulic radius, (L). $R = A/P$, where (P) is the wetted perimeter;

K_1 and K_2 = inlet and outlet loss coefficients as given in Table (2.2);

n = Manning roughness coefficient, given in Table (2.3).

Table (2.2a): Inlet and outlet loss coefficients of pipe culverts [After Pencol (1983)].

Type of entrance (inlet)		K_1
1	Square-edged inlets flush with vertical walls	0.5
2	Rounded inlet, radius(r) where r/D≤0.15	0.1
3	Grooved or socket ended pipes	0.15
4	Projecting steel pipes	0.85
5	Projecting concrete pipes	0.2
Values of (K_2)are taken as (1.0) for most outlets.		

Table (2.2b): Inlet and outlet loss coefficients of box culverts [After Pencol (1983)].

Type of entrance (inlet)		K_1
1	Square –edged entrance	0.5
2	Bell –mouthed and rounded entrance	0.16
Values of (K_2)are taken as (1.0)for most outlets.		

Table (2.3): Manning roughness coefficient (n) of culverts [After Pencol(1983)].

Type of culvert	Type of material	n
pipe	Concrete	0.013
	Metal (steel, iron, aluminum…etc.)	0.022
Box	Concrete	0.015
Note: Metals are not used with box culverts.		

2.2.2.3 EFFECT OF TRANSITIONS

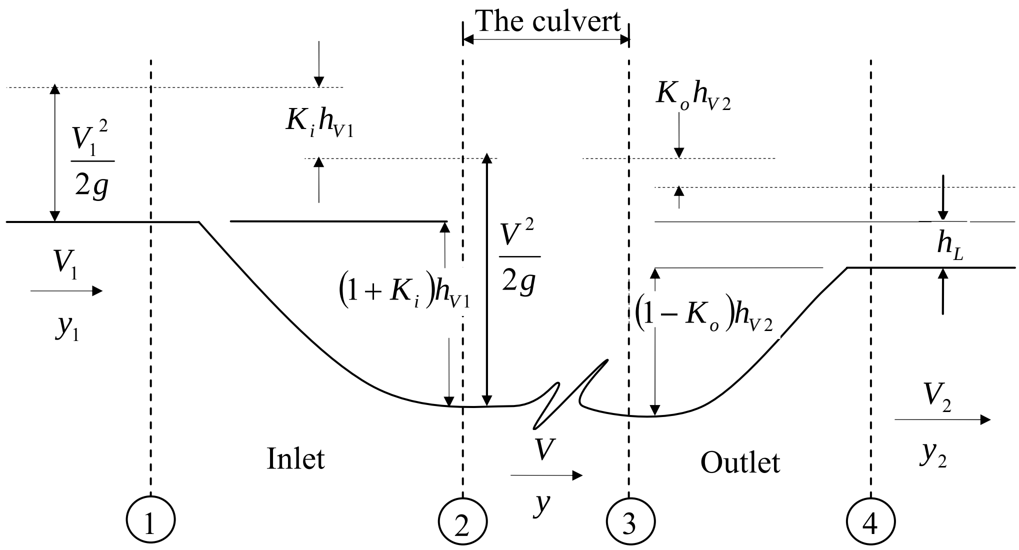
The general method of computating the effect of transitions on the culvert involves the use of the specific and total energy principle [Pencol (1983)]. The zone of analysis could be divided into three parts, namely, (1–2), (2–3), and (3–4), as shown in Fig. (2.7).

The velocity and depth of flow through the culvert, part (2–3), are denoted by (V) and (y), respectively. Part (1–2) is the inlet transition and part (3–4) is the outlet transition. In this case, it is assumed that the velocity and depth of flow downstream of the outlet transition will be equal to that upstream of the inlet transition, i.e., (V_2=V_1) and (y_2=y_1).

The head loss in part (1–2) is [K_i (V^2-V_1^2)/2g = K_i .h_{V1}] and in part (3–4) is [K_o(V^2-V_2^2)/2g=K_o.h_{V2}], where (K_i) and (K_o) are inlet and outlet transition loss coefficients as given in Figs.(2.2) and (2.3) and Table (2.1).

Since (V_1=V_2=V_c), (where V_c=velocity in the canal), then (h_{V1}=h_{V2}). Thus, the total head loss due to inlet and outlet transitions, denoted as (h_{Lt}), would be:

$$h_{Lt} = \frac{(K_i + K_O).(V^2 - V_C^2)}{2g} \qquad (2.9)$$



Figure(2.7): Notation for transitions problem [After Pencol(1983)].

From Eqs.(2.8) and (2.9), the overall head loss through the structure would be:

$$h_L = (K + \frac{2gn^2L}{R^{4/3}})\frac{Q^2}{2gA^2} - \frac{kQ^2}{2gA_c^{\ 2}} \tag{2.10}$$

where:

$$K = K_i + K_{\circ} + K_1 + K_2 \tag{2.11}$$

$$k = K_i + K_{\circ} \tag{2.12}$$

2.2.3 DEVELOPMENT OF CULVERT STUDIES

As mentioned in Henderson [1966], the culvert is called "hydraulically long" if it runs full and "hydraulically short" if it does not, depending on the culvert's length as one of the important factors among other factors that affect the flow of the culvert such as size, roughness, headwater, and tailwater levels. However, the importance of the culvert's length as a factor in making the culvert run full had rather been diminished. Figure (2.8) illustrates the effectiveness of the various factors governing culvert performance. It shows the effect of each of headwater, tailwater and slope on the flow of culvert. As shown in Fig. (2.8a), the three lowermost profiles are the types that would occur when the culvert is short and steep; in these cases the discharge is determined by the culvert entry and the flow at the entry will be critical. It is noteworthy that in one of these cases, (H) is greater than (D), but not so much greater as to make the water surface to touch the "soffit" (i.e., the highest point of the culver periphery). In the same figure, the culvert is running completely full when the tailwater level is high (i.e., greater than D) and the culvert will fill the downstream end of the culvert, then a hydraulic jump will move upstream.

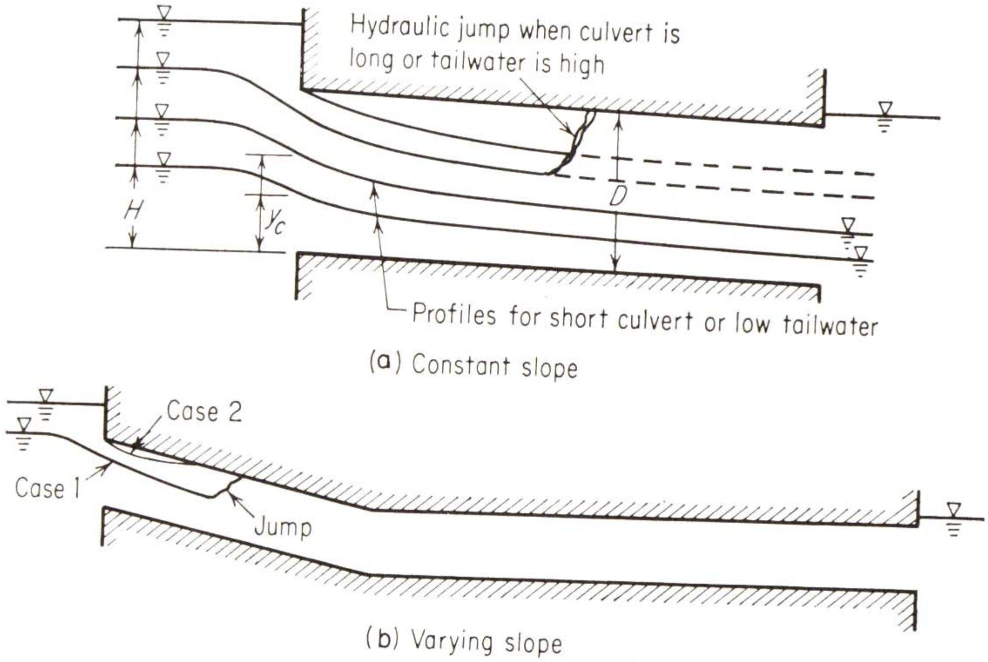


Fig. (2.8): Typical culvert flow profiles [After Henderson (1966)].

A slightly different situation will appear when having a broken slope (a short steep upstream length and a long flat downstream length) with tailwater above the soffit level, as shown in Fig.(2.8b). Clearly, the downstream length will run full, as will some of the upstream length. The full portion extends for enough distance up the steep length to supply the head needed for the downstream length. Consequently, such a situation may reveal two cases; at low discharges, the submergence will extend only a short distance and the culvert entry will be running free and undrowned; however, when the discharge increases, the hydraulic jump advances forwards and the part of culvert flowing full will move further and further upstream until finally the entry is drowned and the whole culvert will be running full. In this case, the discharge is determined by the culvert resistance, whereas in the former, it is controlled by the entry conditions only.

Blaisdell [1960] {quoted in [Henderson (1966)]} showed that even a short steep culvert can be made to run full at low head if the inlet is formed by cutting the culvert at an angle so that the soffit projects beyond the invert, as shown in Fig. (2.9). This design had been described as the "hood–inlet" which is usable with circular culverts only. However, the hood–inlet principle is basically applicable to the box culvert as well, but there are no sufficient relevant experimental studies to support such an application.

HEC10 [1972] involves capacity charts for the hydraulic design of highway culverts of both pipe and box sections with different shapes, material, and types of entrance. The culvert capacity charts are designed to provide an easy method for the direct selection of culvert size. When designing so, many requirements and limitations for the direct use of the charts must be considered. This, sometimes, makes problems unfit for a direct solution by the charts. In many cases, such problems can be solved by finding a chart for a culvert of similar characteristics (and, therefore, the same hydraulic performance) or by modification of the problem so that one of the charts would be applicable.

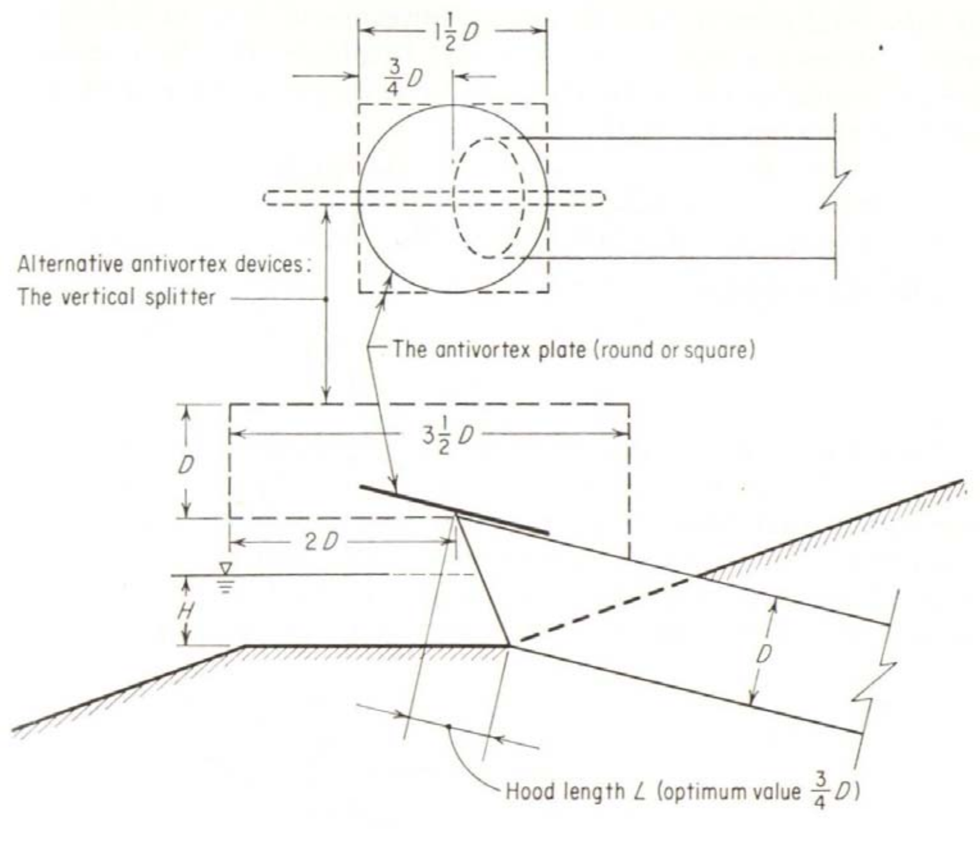


Fig. (2.9): A circular culvert with hood-inlet [(After Henderson (1966)].

HEC13 [1972] presented a circular on hydraulic design of improved inlet for culverts. The circular incorporates the results of the NBS (National Bureau of Standards) on improved inlets into a new culvert design procedure. The circular demonstrated that improved inlets, with their more efficient flow characteristics and better utilization of available head, may greatly improve the performance of culverts operating in inlet control.

Al–Zubaidy [1976] studied energy loss in culvert outlets. The study explained the effect of wall types (transitions) of the culvert on energy loss. Laboratory experiments were performed for different types of sloping splayed–walls by using varied values of expansion ratio; the energy equation was used to calculate energy loss; a comparison was done with that of using a 90°–wing wall of sudden expansion. It is concluded that using a sloping splayed–walls is better than the 90°–wing wall. Consequently, this type of walls may serve two goals; the hydraulic performance through energy loss, and the reduction of cost.

Al–Khafagi [1983] studied the scour downstream of a circular culvert outlet depending on experimental investigation, both with and without protection, aiming at minimizing the scour. Experimental work involved two main parts; the first was investigating the nature of scour in the unprotected movable bed of channel downstream culvert outlet; the second was testing several classes of rigid basin and outlet basins stabilized with rock riprap for protection at culvert outlet for minimizing scour. For the type of flow encountered at culvert outlet, the Froude law was tested in the model and found to be sufficient for scaling results to prototype installation.

McVay [1986] studied the long–term behavior of buried large–span culverts. He stated that "A study is reported on the modeling of large–span flexible corrugated culverts in the centrifuge environment with emphasis on simulating the construction sequence and long–term viscous consolidation behavior in cohesive backfills". In this study, a fully instrumented prototype was selected, which reported both stresses and strains in the culvert and soil mass both during construction and for the long–term; a technique was developed in which placement of soil lifts followed by compaction was carried out in the centrifuge under increased acceleration; correlation between prototype and model deflections, stresses and strains in the culvert wall and the surrounding soil mass was obtained at the end of construction for repetitive tests under various levels of acceleration. Finally, long–term (four months)correlation of model versus prototype behavior : culvert stresses and soil stress–strain is reported. It is concluded that centrifuge modeling is both an economical and viable means of studying short–and long–term behavior of flexible large–span culverts, if the construction sequence with the inclusion of the compaction process is undertaken.

Fabian et al. [1988] discussed the durability and service life of concrete pipe culverts in a study including the analysis of important enabling and triggering events that have caused or have the potential to cause the deterioration of concrete pipes. Regression analyses were used to predict equations for the expected service life of culverts. It was concluded that the service life reported may be of value to cost engineers performing life–cycle cost studies of these types of culverts.

Weisman [1989] used a physical model to design a safety grating for a culvert inlet. The objectives of such a grating are: **(1)** To prevent a person who falls into the drainageway from being carried into and through the culvert; and **(2)** To prevent the person from being pained against the grating. The basic design of the grating, recommended by previous researches, was tested using a 1:10 scale model. In this study, testing was performed over a wide spectrum of flood flows, including flows that exceed the culvert capacity. The grating has only a minor effect on the head–discharge relationship, causing a slight increase in the headwater required to pass a given discharge. However, the grating may act as a debris control structure and vigilant maintenance may be required to prevent clogging of the culvert inlet. Neutrally buoyant objects were introduced to the flow to assess the performance of the grating. Because of the parabolic shape of the grating, an object carried to the culvert tends to be pushed up the grating and out of the flow.

Baltaian [1997] presented a study of Iraqi circular reinforced concrete pipes (ICPC) as highway culverts, taking into account laboratory and in–situ strength of pipes. Different pipe sizes were chosen for this study. Laboratory strength for these pipes was determined by the three–edge bearing test method. The required in–situ strength of each concrete pipe culvert was determined. In order to help the engineer in selecting the proper pipe for each given situation, design charts for the required three–edge bearing strength for (ICPC) of interest in this study, were developed.

Al–Azzawi [1998] analyzed structurally a reinforced concrete inverted U–shape culverts by grillage analogy and finite element methods, aiming to show the behavior of culverts under loads. It is found that the analysis is accurate when the plates forming the culverts are open into one plane to form a continuous plate, and the U–shape culvert is symmetric. The results of different methods of analysis are compared. The method of grillage analogy is found to be fast and economical, and its result is acceptable for preliminary design purposes, and for quick analysis when compared to the sophisticated but more accurate method of the finite shell element.

Al–Sammaraey [1999] tackled the design of highway drainage with computer assessment. The research considered the design of a pipe culvert used as a drainage device to collect storm water on a highway.

O'Donaill [2001] stated that: “There is a statutory obligation under section 50, Arterial Drainage Act 1995, to obtain consent from the commissioners of Public Works in Ireland to construct or alter any bridge or culvert over any watercourse”. A paper was presented as an attempt to give an understanding of hydrological estimation for catchments and culvert hydraulics. Information was taken from numerous sources and a degree of knowledge is assumed.

Langdon [2002] discusses using a culvert for closures and access control for mines and caves. Although a culvert use for mine closures has been uncommon until recently and references for design and construction are sparse, it has become more common. Culvert materials cover corrugated steel, stainless steel with smooth walls, corrugated aluminum, plastic (both corrugated and smooth wall), and concrete. The most common material is corrugated steel. Installation includes: excavating a foundation or bed, placing the culvert and closure device, and backfilling. Considerations in selecting a culvert as an alternative to conventional steel closure structure include: safety, visual appearance, long–term stability, costs, acceptance by bats, and maintenance. A typical (54 inch) (137cm) diameter and (14foot) (427cm) long culvert installed with an excavator by a contractor costs about ($3000). Caving and sloughing of dirt and rock and corrosion will probably be a bigger long–term maintenance problem than vandalism at most sites. Construction details are important to reduce corrosion in humid environments.

Barnard [2003] stated that: "More than (50) stream simulation culverts have been constructed in Washington State since 1995". The paper summarizes monitoring conducted on (19) of these culverts in various settings. The monitoring goal was to compare the physical characteristics of the adjoining upstream channel with those of the culvert bed. Results showed that when designed and constructed according to stream simulation design criteria (culvert bed width=1.2(channel width) + 60cm, and slope of culvert <1.25(channel slope)), stream simulation culverts are reliable and create similar passage conditions compared to the adjoining channel.

As mentioned in Joe et al. [2003], when box culverts are located under engineering structures, the overtopping foundation loading may induce considerable soil pressure on the culverts causing excessive culvert deformation. A research was performed to minimize possible adverse effect of foundation loading on the culvert performance; the soil pressures induced by the foundation loading need to be properly considered. It is concluded that the soil pressure distribution around a box culvert induced by the overtopping footing is strongly dependent on soil–culvert interactions. Thus, an optimal structural design of box culverts may require iteration procedures. The results of research have provided an insight into soil–culvert interaction mechanism. More data are needed, however, not only for better understanding of the interaction mechanism but also for the development of a rational method for structural design of square box culverts overlain by strip footings.

From the preceding review, it is clear that there is no detailed study that deals with the hydraulic design for all types and shapes of culverts. In the present research, all the basic concepts and parameters involved in culvert design shall be considered. This includes different flow types, culvert shapes and materials, inlet and outlet properties of the entrance and exit, transition components, in addition to the amount of discharge, length of culvert, and headwater.

2.3 OPTIMIMIZATION IN THE FIELD OF CULVERT DESIGN

Optimization is a mathematical technique that selects the best solution from a set of feasible alternatives. Studies that use optimization in the design of culverts are scarce. However, the case is somehow different with problems of the design of hydraulic structures, in general. Some of such studies are given subsequently.

Reddy and Clyma [1981] generalized a geometric programming technique as one method for solving a non–linear problem to find the optimal design of border and level basin irrigation systems. The presented technique provides guidelines for improving existing on–farm irrigation systems for better management of the scarce resources of agricultural production.

Hamed [1996] used Rosenbrock constrained optimization and Sequential Unconstraint Minimization Technique (SUMT) methods to find the optimum design of a barrage floor (area of concrete and reinforcement).

Sauvaget et al. [2001] solved the problem of the A89 motorway in the Dordogne–Isle confluence plain which is regularly flooded under the effect of both river discharges and ocean tides by using optimum design of large flood relief culverts under this motorway. In order to optimize the cost–efficiency ratio of these culverts, the task had been fulfilled, thanks to complementary sophisticated physical and 2D numerical models. 2D numerical modeling of flood flows proved to be extremely efficient in this optimization and hydraulic impact study. The major advantages offered by this approach, as compared to the traditional 1D modeling technique, are the great accuracy of the results produced and the realism guaranteed by enhanced graphical post – treatment of the results. 2D modeling also gives access to detailed knowledge of the flow field, particularly in the flood plains, which is not possible with 1D modeling. In fact, a 2D model lies on much less empirical coefficients than 1D model of the same area, such as for modeling the exchanges between the main river course and the flood plain for instance. The accurate representation of alternately flooded and exposed areas in a river valley is also an important advantage of the 2D model.

Al–Musawi [2002] solved the problem of seepage under hydraulic structures by formulating a non–linear problem (NLP) as an optimization model and solving by using the Lagrange–Multiplier method to find the minimum costs of control devices with safe exit gradient and uplift pressure.

Al–Janabi [2003] used the direct search method for solving the (NLP) to get the best design (minimum total cost) for reinforced concrete (plane or space) frames.

In the present work, the formulation of the optimization problem with all related details (as will be described in Chapter Three) is performed for optimum safe hydraulic design of culverts.

CHAPTER THREE

FORMULATION OF THE OPTIMIZATION PROBLEM

3.1 THE OPTIMIZATION PROCESS

The purpose of optimization is to find the best possible solution among many potential solutions satisfying the chosen criteria. Designers often base their designs on the minimum cost as an objective, taking into account mainly the costs of the structure itself, safety, and serviceability .

An optimization process involves the following :

1. Recognizing the parameters involved in the process under study.

2. Defining the decision variables .

3. Formulating the objective function as a function of the decision variables.

4. Specifying the constraints imposed on the process in general and on the named decision variables and on the objectives aimed at, as the case may be .

5. Using an appropriate procedure to solve the formulated optimization problem.

6. Performing sensitivity analyses whenever such analyses are meaningful .

A general mathematical model of the optimization problem can be represented in the following form :

A certain function (Z), called the objective function ,

$$Z = f\{X_i\} \qquad i = 1,2,\ldots,n \tag{3.1}$$

which is usually the expected benefit (or the involved cost), involves (n) decision variables $\{X\}$. Such a function is to be maximized (or minimized) subject to certain equality or inequality constraints in their general forms :

$$g_h\{X_i\} = b_h \qquad i = 1,2,...,n; h = 1,2,...,H \qquad (3.2a)$$

$$q_j\{X_i\} \geq b_j \qquad j = H+1, H+2,..., H+J \qquad (3.2b)$$

$$q_k\{X_i\} \leq b_k \qquad k = H+J+1, H+J+2,...,H+J+K \qquad (3.2c)$$

The constrains reflect the design and functional requirements. The vector $\{X\}$ of the decision variables will have optimum values when the objective function reaches its optimum value.

3.2 METHODS OF OPTIMIZATION

In the last three decades, most of the development in the field of optimization theory and methods have occurred due to the explosive growth of large computers.

The available methods of optimization can be divided into three basic categories as briefly discussed below .

3.2.1 THE LINEAR PROGRAMMING (LP)

The main characteristic of a linear programming (LP) problem is that the objective function and all the constraints are linear relationships of the decision variables. Although a relatively few design problems in water – resources engineering can be directly formulated as (LP) problems, the method is widely used .

Of the several algorithms to solve LP–problems, the simplex method developed by C.B. Dantzig in 1946, is the most widely used [Dantzig (1963)]. Some other methods are available such as graphical methods, revised simplex method and transportation method [Phillips et al. (1976)].

3.2.2 THE NON–LINEAR PROGRAMMING (NLP)

If the objective function or any of the constraints is non–linear, the optimization problem is termed a non–linear problem. A variety of real–world design problems are in fact non–linear.

There are several algorithms and techniques for solving NLP-problems. Some of these are briefly reviewed hereinafter.

3.2.2.1 THE ANALYTICAL APPROACH

In this approach the problem is represented by mathematical relationships (equations) which aid in the search for an optimum. The solution usually requires the use of differential calculus and the optimum exact solution is found theoretically [Gallapher and Zienkiewicz(1973)]. The most familiar methods, underlying this approach are :

a. Differential calculus

This method is generally used to solve simple unconstrained NLP–problems by using the laws of differential calculus to find the optimum solution .

b. Lagrange multiplier

This method is used to solve constrained non–linear optimization problems with equality constraints and can be extended to the case of inequality constraints [Bunday (1984)].

c. Geometric programming

Geometric programming is one branch of (NLP) which aims at obtaining the optimum solution for a non–linear objective function subjected to non–linear constraints. It differs from other methods in that it tries to distribute the total cost among the various terms of the objective function before finding the corresponding design variables [Duffin et al. (1967)].

3.2.2.2 THE NUMERICAL APPROACH

In this approach, a near optimum solution is automatically generated in an iterative manner. An initial guess is used as a starting point for search of better solutions. The search continues until no further improvement in the objective function is possible or until a certain convergence criterion is satisfied, which indicates that the optimum solution has been achieved within the desired accuracy. Since most of practical design problems can not be solved by analytical methods, numerical techniques are of great importance.

Two such approaches, namely, the direct search and the gradient search, are discussed briefly hereinafter.

a. The direct search

Here, the search proceeds with evaluation of the objective function only in an iterative manner until a local or an approximate optimum solution is reached. The step sizes and the direction of moves at each iteration represent the main features of this approach. Many methods are proposed as standard algorithms such as Rosenbrock method [Rosenbrock (1960)], the pattern search of Hooke and Jeeves [Hooke and Jeeves (1961)], the complex method [Bunday (1984)], and Fletcher and Powell method [Bunday(1984)].

b. The gradient search

The basic idea here is to evaluate the gradient of the objective function at a point and utilize it to improve and accelerate the search. The acceleration is attained by finding the direction of the steepest descent, following this direction until no further improvement is possible, then the direction is changed again. The search continues until the gradient becomes zero, indicating that the optimum solution is reached.

The most widely used methods following this approach are the Rosen method [(Rosen(1960)], the Sequential Unconstrained Minimization Technique (SUMT) [Fiacco and McCormick (1968)] and Fletcher and Powell method [Bunday (1984)]. These methods require smaller number of iterations than the direct search methods; however, Carpenter and Smith [1975] showed that the high order derivatives of these methods are more expensive, needing longer computer time than the direct search methods.

3.2.3 DYNAMIC PROGRAMMING

Dynamic programming is used to solve special types of optimization problems which involve multistage decision processes. The optimization of each stage will affect the next stage and the final optimum decision is ensured to be the sum of all the optimization decisions of all stages.

The method is very powerful and used to solve continuous and discrete non–linear programming [Slaby(1987)].

3.3 OPTIMUM DESIGN OF CULVERTS

3.3.1 BASICS

The design of a culvert is based on the hydraulic provisions and then the structural provisions. However, a 'good' design should take into consideration the overall cost of the designed structure. While safety is the major aim of the structural design, the hydraulic design would aim at passing the specified discharge with the least head loss in order to maintain most of the available command head. For this, a reasonable and practical survey in this respect would delineate the following constituents of a cost objective function :

1. Excavation.

2. Bedding (blinding) layer.

3. The material the culvert will be constructed from such as reinforced concrete, steel,...,etc.

4. Compacted fill.

5. Hunches.

6. Protection works.

7. Additionally–involved head loss .

Several design constraints related to safety, functioning, and constructional requirements do control the optimization process and, consequently, should be taken into account in the formulation of the optimization problem.

Figure (3.1) shows a typical culvert. The basic parameters involved in a culvert–design problem are:

1. Q= Discharge flowing through the culvert, (L^3/T); it comes from an irrigation or a drainage channel, whether hypothetical or actual, depending on the considered case study .

2. L = Length of the culvert, (L); it depends on the width of the considered road or railway of the respective case study.

3. W = Top width of embankment, (L).

4. H = Active head on the culvert, (L).

5. h = Height of the compacted fill above the culvert, (L).

6. n = Manning roughness coefficient.

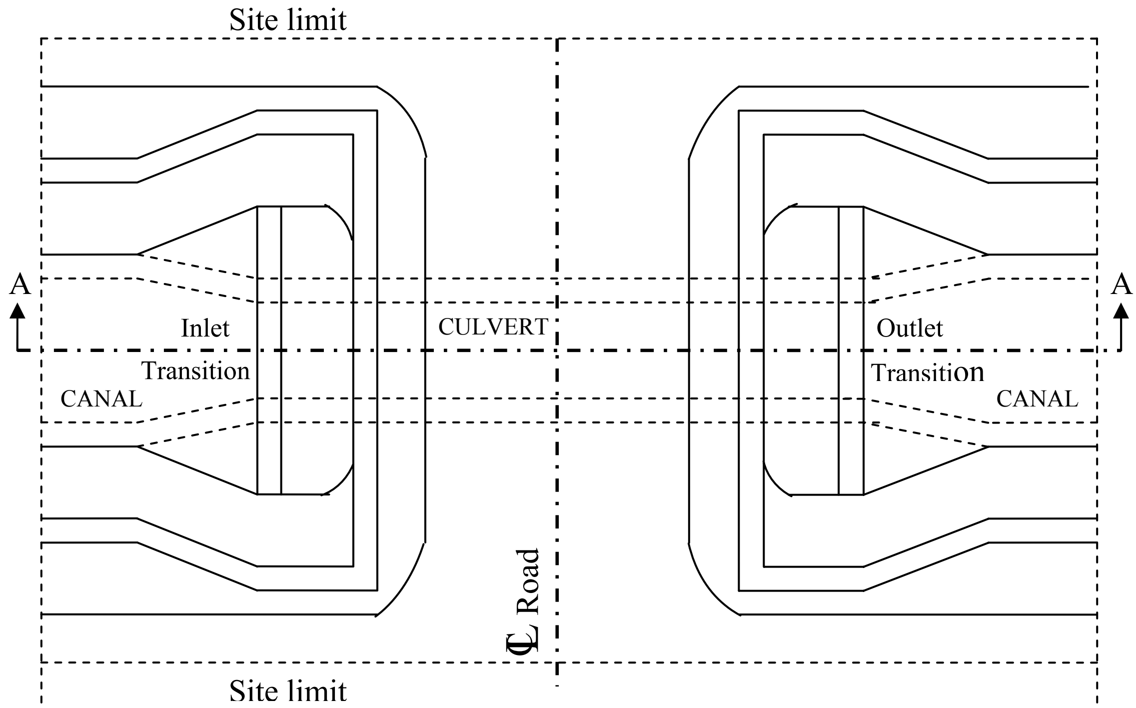
7. A_C = Cross – sectional area of a channel, (L^2).

8. K_1 and K_2 = Inlet (entrance) and outlet (exit) loss coefficient of culverts.

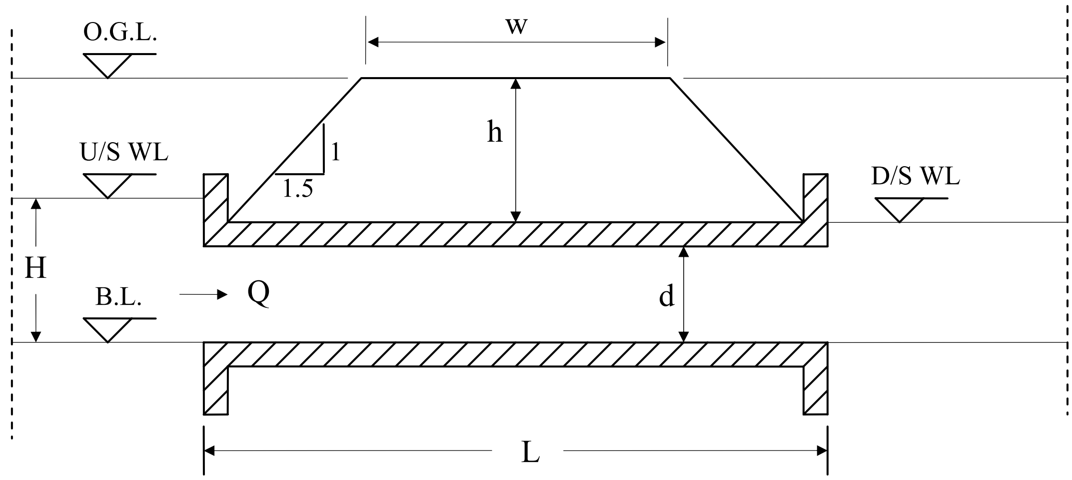
9. K_i and K_o = Inlet and outlet loss coefficient of transitions.

3.3.2 THE DESIGN VARIABLES

The design variables (which are virtually the decision variables in the optimization model) represent the dimensions that characterize the respective



[a]:PLAN



[b]: SECTION A-A

Figure(3.1): Typical culvert [After SC (1982)].

sectional shape. The vector of design variables $\{X_i\}$, $(i = 1,2,...,n)$, may be chosen as follows:

1. For a box culvert:

a. Rectangular shape

The design variables of a rectangular box culvert are $(X_1 = b)$, $(X_2 = d)$, where (b) is the width of a single box–vent, and (d) is the respective height. The optimum solution will give the optimum shape. If $(b > d)$, then the optimum shape shall be denoted as a horizontal rectangle; the optimum shape of the reverse is a vertical rectangle.

b. Squared shape

A special case of the rectangular shape is the squared shape (i.e., $b = d$). In such a case, there would be a single design variable, $(X_1 = d)$, where (d) is the dimension of a single box–vent.

2. For a pipe culvert:

The shape of a pipe culvert may be circular, elliptical or as an arch, among some others. Generally, the more commonly used is the circular shape (which is the one considered in this research). In this case, the design variable will be $(X_1 = d)$, where: d =diameter of a single pipe–vent.

3.3.3 THE OBJECTIVE FUNCTION

The research considers two basic types of culverts, namely, the reinforced–concrete box culvert and the pipe culvert. The box culvert involves rectangular and squared shape. The pipe culvert involves the circular shape with different material, namely, reinforced concrete, cast iron, ductile steel, and asbestos–cement.

As mentioned in Item (3.3.1), the cost objective function (Z) of the present research involves the cost of excavation, bedding, material of the culvert, compacted fill, hunches, protection works and additional head loss. The general procedure to arrive at the aforementioned itemized costs for each of the mentioned types of culverts are discussed hereinafter.

3.3.3.1 THE OBJECTIVE FUNCTION OF THE REINFORCED CONCRETE BOX–CULVERT (RECTANGULAR SHAPE)

According to the details shown in Fig.(3.2), the objective function (ZT_1) for a reinforced–concrete, rectangular box–culvert is formulated as follows:

[A] Cost of excavation, (Z_1)

The dimensions of the excavated trench depend on culvert's size as shown in Fig.(3.2–b). The cost of excavation (Z_1) is:

$$Z_1 = C_1 V_1 \tag{3.3}$$

where:

C_1 = unit cost of excavation expressed in American Dollars per cubic meter, ($/m^3);

V_1 = volume of excavation, (m^3).

The volume (V_1) is calculated as:

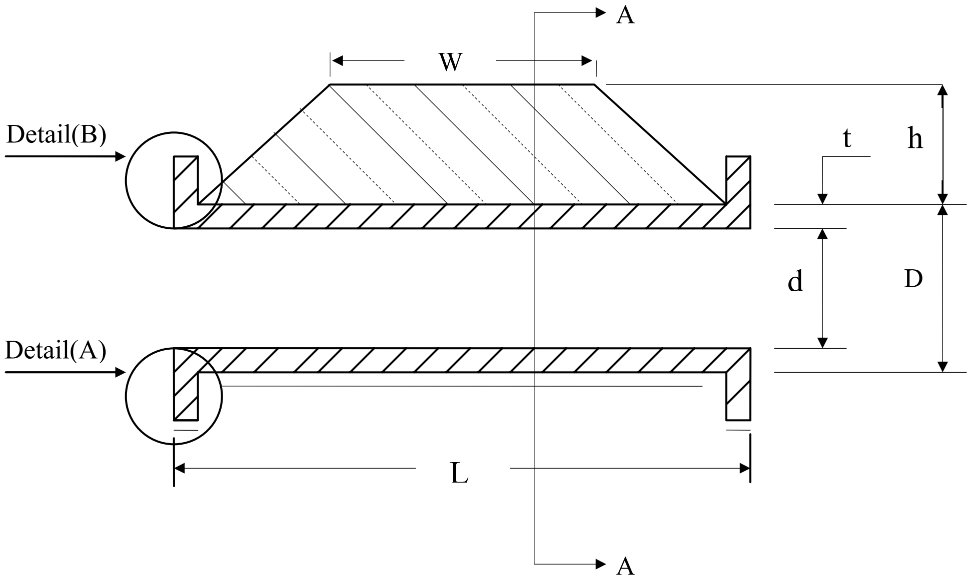
$$V_1 = [(h + s + d + 2t_1 + e + a)(b + 2t_2)]L \tag{3.4}$$

where:

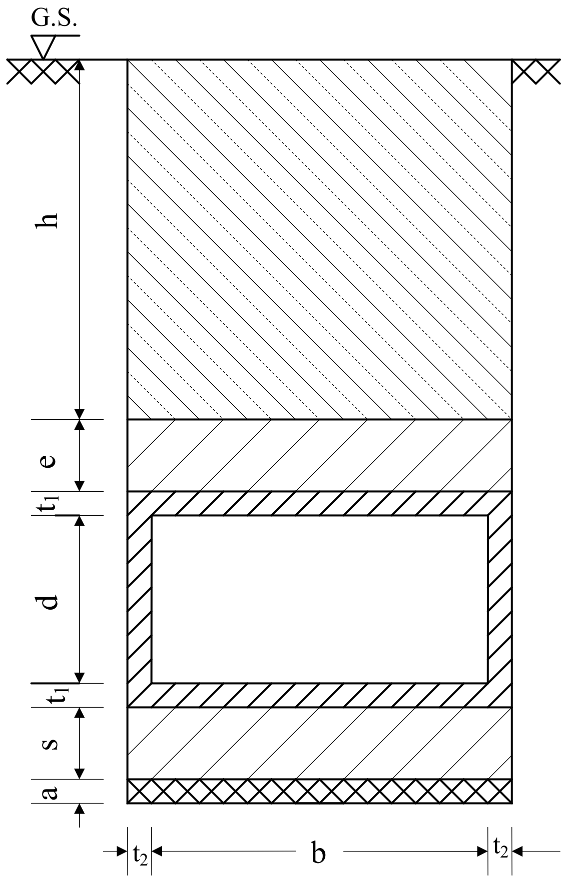
(s), (e), and (a) are to be determined for the respective case study (as given later);

t_1 = thickness of slabs (deck), (L); t_2 = thickness of walls.

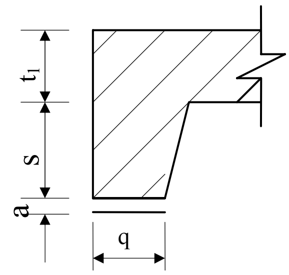
b = width of the culvert, (L); d = the respective height.



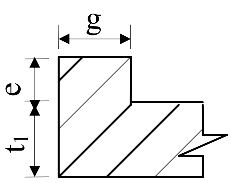
[a]: Typical longitudinal section of culvert



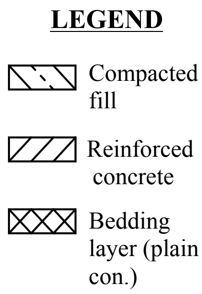
[b]:Section(A-A) Rectangular box culvert trench



[c]:Detail (A) Lower hunch



[d]:Detail (B) Upper hunch



Figure(3.2):Typical works of box culverts[After SC(1982)].

As stated in Al–Janaini [1980], the thickness of slabs and walls of the culvert are taken structurally from the following empirical equations:

$$t_1 = \frac{b}{6} \tag{3.5}$$

$$t_2 = \frac{d}{6} \tag{3.6}$$

According to the Indian Standard Code IS:458-1971, Raju [1986], the thickness of slabs and walls of the culvert are taken as (100mm/meter span); that is:

$$t_1 = \frac{b}{10} \tag{3.7}$$

$$t_2 = \frac{d}{10} \tag{3.8}$$

In this research, Eqs.(3.7) and (3.8) have been adopted as they are the latest and a code references is more dependable.

Substituting Eqs.(3.7) and (3.8) in Eq.(3.4), gives:

$$V_1 = \frac{L}{25}\left[5\left(b^2 + d^2\right) + 5\left(h + s + e + a\right)\left(5b + d\right) + 26bd\right] \tag{3.9}$$

Consequently:

$$Z_1 = \frac{C_1 L}{25}\left[5\left(b^2 + d^2\right) + 5\left(h + s + e + a\right)\left(5b + d\right) + 26bd\right] \tag{3.10}$$

[B] Cost of bedding, (Z_2)

Bedding is a layer, usually of plain concrete of uniform thickness along the width of the culvert to form a base under the culvert. The cost of bedding can be determined as:

$$Z_2 = C_2 V_2 \tag{3.11}$$

where:

C_2 = unit cost of plain concrete for bedding, (\$/m^3);

V_2 = volume of material of bedding, (m^3).

Calculating (Z_2) proceeds similar to that of $(Z_1)$of the preceding item (cost of excavation). Thus:

$$V_2 = [a(b + 2t_2)]L \tag{3.12}$$

where:

a = thickness of the bedding, (m).

Substituting (t_2) by its equivalent from Eq.(3.8), gives:

$$V_2 = \frac{aL}{5}[(5b + d)] \tag{3.13}$$

Consequently:

$$Z_2 = \frac{C_2 aL}{5}[5b + d] \tag{3.14}$$

[C] Cost of material, (Z_3)

Cost of material of the culvert can be calculated as:

$$Z_3 = C_3 V_3 \tag{3.15}$$

where:

C_3= unit cost of reinforced concrete material, ($/m^3);

V_3= volume of material, (m^3), which is calculating by:

$$V_3 = AL \tag{3.16}$$

where:

A= cross–section area of material, which is:

$$A = 2[(b + 2t_2)t_1 + dt_2] \tag{3.17}$$

Substituting (t_1 and t_2) by their equivalents from Eqs.(3.7 and 3.8), give:

$$A = \frac{5b^2 + 5d^2 + bd}{25} \tag{3.18}$$

Thus:

$$Z_3 = \frac{C_3 L}{25}\left[5b^2 + 5d^2 + bd\right] \tag{3.19}$$

[D] Cost of compacted fill, (Z_4)

According to Figs.(3.2–b) and (3.3), (Z_4) can be formulated as:

$$Z_4 = C_4 V_4 \tag{3.20}$$

where:

C_4 = cost of unit compacted fill expressed in (\$/m^3);

V_4 = volume of compacted fill (m^3).

$$V_4 = \left[\frac{(b+2t_2)L + (b+2t_2)W}{2}\right] h_f \tag{3.21}$$

Substituting (t_2) by its equivalent from Eq.(3.8), gives:

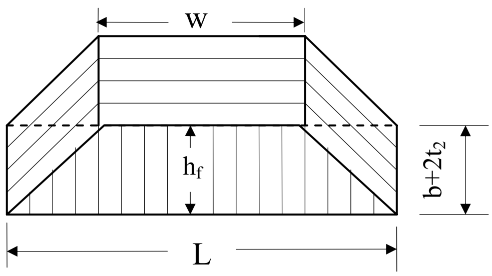
$$V_4 = \left[\frac{(5b+d)(L+W)}{10}\right] h_f \tag{3.22}$$

Consequently:

$$Z_4 = \left(\frac{C_4 h_f (L+W)}{10}\right)(5b+d) \tag{3.23}$$

[E] Cost of hunches, (Z_5)

Hunches are complementary parts of the culvert. They are divided into two types, namely, lower and upper hunches. Lower hunches are like supports to the culvert on both sides, as shown in Fig.(3.2–c); they are made of reinforced concrete. Upper hunches are structurally similar to the lower hunches, Fig.(3.2–d), but functionally different; they are used to support and protect the compacted fill over the culvert from U/S and D/S water effect and, consequently, protect the culvert from hazard of failure. The cost of hunches is:



Figure(3.3): Compacted fill prism.

$$Z_5 = C_5 V_5 \tag{3.24}$$

where:

C_5 = unit cost of reinforced concrete forming the hunches, (\$/m^3);

V_5 = volume of reinforced concrete material of both lower and upper hunches, (m^3), where:

$$V_5 = 2(V_{5L} + V_{5U}) \tag{3.25}$$

and (V_{5L}) and (V_{5U}) denote volume of reinforced concrete material of one lower hunch, and one upper hunch, (m^3), respectively.

In this respect :

$$V_{5L} = qs(b + 2t_2) \tag{3.26}$$

where:

(q) and (s) concern the respective case study (as given later).

Substituting (t_2) by its equivalent from Eq.(3.8), gives:

$$V_{5L} = \frac{qs}{5}[5b + d] \tag{3.27}$$

Similarly, for (V_{5U}):

$$V_{5U} = \frac{eg}{5}[5b + d] \tag{3.28}$$

Substituting Eqs.(3.27 and 3.28) in Eq.(3.25), gives:

$$V_5 = \frac{2}{5}(qs + eg)(5b + d) \tag{3.29}$$

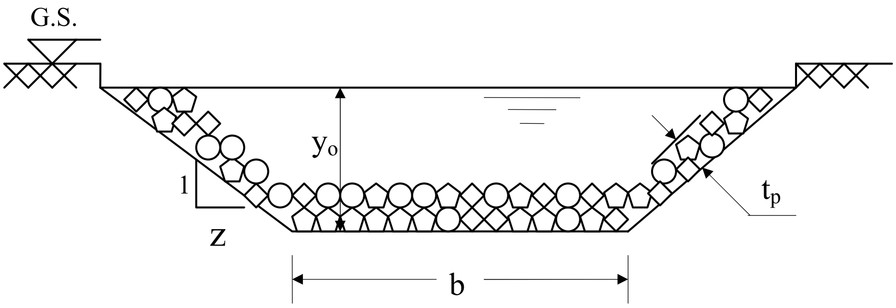
Thus:

$$Z_5 = \frac{2C_5}{5}(qs + eg)(5b + d) \tag{3.30}$$

[F] Cost of protection works, (Z_6)

Protection works are required at the outlet of the culvert to prevent erosion and scouring due to outlet velocity. Erosion protection is one of several types of protection works such as transitions and energy dissipaters which includes riprap and gravel protection . This is often used adjacent to structures and at other locations in earth–surfaced canals where erosion may occur. It is provided in the bed and up the side slopes as shown in Fig.(3.4).

USBR (1974) mentions several types of erosion protection, namely, **Type1**, **Type2**, **Type3**, and **Type4**, depending on the discharge or outlet velocity as given in Table (3.1).



Figure(3.4): Erosion protection works.

Table(3.1): Erosion protection works[After USBR(1974)].

Q,(cfs)(m^3/s)	Type of protection	Length, (ft)(m)	Descriptions
0–30(0–0.81)	Type 1	8 (2.4)	6″(≈15cm) coarse gravel
31–90(0.84–2.43)	Type 2	12 (3.6)	12″(≈30cm) coarse gravel
91–40(2.46–6.48)	Type 3	16 (4.8)	12″(≈30cm) riprap on 6″(≈15cm) sand and gravel bedding
> 40(6.48)	Type 4	>16 (4.8)	18″(≈45cm) riprap on 6″(≈15cm) sand and gravel bedding

Local conditions must be considered in determining the type and the amount of protection to be provided. These conditions include the cost of riprap, cost of gravel, danger to structures and crops or to human life should scour occur, repent damage, type of soil, and velocity of water .

The cost of these protection works, (Z_6), can be calculated as follows :

$$Z_6 = C_6 V_6 \tag{3.31}$$

where :

C_6 = cost of erosion protection works, ($/m³);

V_6 = volume of material forming the protection works, (m³).

$$V_6 = t_P w_P L_P \tag{3.32}$$

where :

t_P = thickness of protection, depending on size of gravel and riprap, (m)

w_P = width of protection including width of canal and side slope ≈ wetted perimeter, (m)

L_P = length of protection, (m)

Pencol [1983] specified a length of protection as three times the height or diameter of the barrel. This can be expressed as follows:

$$L_P = 3d \tag{3.33}$$

where :

d = diameter or height of the barrel of the culvert, (m)

In this research, Eq.(3.33) has been considered because it is more specific as compared to the values given in Table (3.1).

It is worth mentioning that (Z_6) will be calculated with the aim of Table (3.2) and added as a constant to the total cost involved in the overall objective function.

Table (3.2): Designation of protection works.

Type of protection works	Designation
Type 1	Z_{61}
Type 2	Z_{62}
Type 3	Z_{63}
Type 4	Z_{64}

[G] Cost of head loss, (Z_7)

The primary objective of the hydraulic design of structures involved in irrigation networks is the determination of the appropriate waterway section with minimizing head loss playing a major role. Increasing head loss will cause decrease of the total active head of the downstream water, i.e., loss of command, which would result in less area under command and, thus, less production return. Such a loss may be expressed as :

$$Z_7 = C_7 h_L \tag{3.34}$$

where :

C_7 = unit loss of return due to additional head loss ($/m of head loss);.

h_L = overall head loss in (m). This can be calculated as follows :

On substituting (R) in Eq.(2.10) by its equivalent in terms of the decision variables, the result will be :

$$h_L = \frac{KQ^2}{2g(bd)^2} + \frac{2.52Q^2n^2L(b+d)^{4/3}}{(bd)^{10/3}} - \frac{kQ^2}{2gA_C{}^2} \tag{3.35}$$

Consequently:

$$Z_7 = \frac{C_7KQ^2}{2g(bd)^2} + \frac{2.52C_7Q^2n^2L(b+d)^{4/3}}{(bd)^{10/3}} - \frac{C_7kQ^2}{2gA_C{}^2} \tag{3.36}$$

All the aforementioned sub–objective cost functions are summarized in Table (3.3).

The total cost (ZT_1) is the summation of all aforementioned sub–cost functions calculated in the previous items and given in Table (3.3) .That is :

$$ZT_1 = \sum Z_i \qquad i = 1,2,...,7 \tag{3.37}$$

Thus, the overall cost objective function may be written in the form:

$$ZT_1 = [C_1L(h+s+e+a)+C_2aL+0.5C_4h(L+W)+C_5(qs+eg)]b+[0.2L(C_1+ C_3)]b^2+[0.2C_1L(h+s+e+a)+0.2C_2aL+0.1C_4h(L+W)+0.4C_5(qs+eg)]d+ [0.04L(C_1+5C_3)]d^2+\left[\frac{C_7KQ^2}{2g}\right](bd)^{-2}+[0.04L(26C_1+C_3)]bd+[2.52C_7Q^2n^2L] (b+d)^{4/3}(bd)^{-10/3}+Z_6-\frac{C_7kQ^2}{2gA_C{}^2} \tag{3.38}$$

Table(3.3): Summary of final cost objective function, (ZT_1).

Cost function	Constant	Terms of the decision variables						
		b	b^2	d	d^2	$(bd)^{-2}$	bd	$(b+d)^{4/3}(bd)^{-10/3}$
Z_1	—	$C_1L(h+S+e+a)$	$0.2C_1L$	$0.2C_1L(h+s+e+a)$	$0.04C_1L$	—	$1.04C_1L$	—
Z_2	—	C_2aL	—	$0.2C_2aL$	—	—	—	—
Z_3	—	—	$0.2C_3L$	—	$0.2C_3L$	—	$0.04C_3L$	—
Z_4	—	$0.5C_4h(L+W)$	—	$0.1C_4h(L+W)$	—	—	—	—
Z_5	—	$2C_5(qs+eg)$	—	$0.4C_5(qs+eg)$	—	—	—	—
Z_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—	—	—
Z_7	$-\frac{C_7kQ^2}{2gA_C{}^2}$	—	—	—	—	$\frac{C_7KQ^2}{2g}$	—	$2.52C_7Q^2n^2L$

3.3.3.2 THE OBJECTIVE FUNCTION OF THE REINFORCED CONCRETE BOX – CULVERT (SQUARED SHAPE)

Generally, in the squared–shape box culvert, $(t_1 \text{ and } t_2)$ and (b) shown in Fig.(3.2) are (t) and (d), respectively .

Similar to the procedure followed in getting (ZT_1), the final formulation of the objective function of the reinforced–concrete, square box–culvert, (ZT_2), is:

$$ZT_2 = \left[6.35C_7Q^2n^2L\right]d^{-16/3} + \left[\frac{C_7KQ^2}{2g}\right]d^{-4} + [1.2C_1L(h+s+e+a) + 1.2C_2aL + 0.6C_4h(L+W) + 2.4C_5(qs+eg)]d + \left[1.44C_1L + 0.44C_3L\right]d^2 + Z_6 - \frac{C_7kQ^2}{2gA_C{}^2} \quad (3.39)$$

The summary of calculated sub–cost objective functions, and the final cost objective function are given in Tables (3.4) and (3.5), respectively .

3.3.3.3 THE OBJECTIVE FUNCTION OF THE REINFORCED–CONCRETE, CIRCULAR PIPE–CULVERT

With Fig.(3.2–a) representing a reinforced–concrete circular pipe culvert as well, nevertheless, section (A–A) and detail (A) for pipe–culvert works are to be as shown in Fig (3.5).

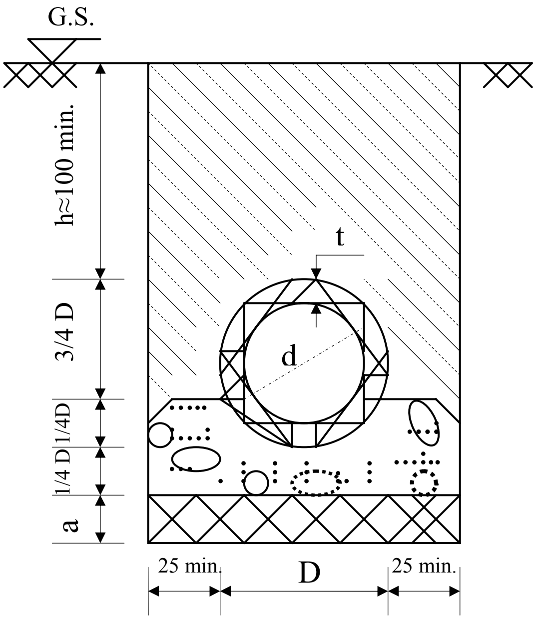
The cost objective function for an optimum design of reinforced–concrete, circular pipe–culvert is formulated in a similar fashion to that of the box culvert and as follows :

Table(3.4):Summary of calculated sub–cost objective functions of the square box culvert.

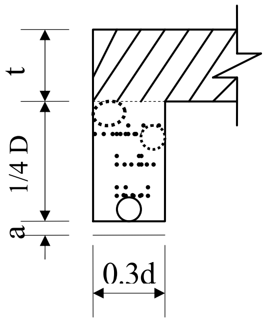
Sub-cost objective function item	Detail of calculation	Results of cost
[A]Cost of excavation, (Z_1)	$V_1 = 1.2L[(h+s+e+a)d + 1.2d^2]$	$Z_1 = 1.2C_1L[(h+s+e+a)d + 1.2d^2]$
[B]Cost of bedding, (Z_2)	$V_2 = [1.2aL]d$	$Z_2 = [1.2C_2aL]d$
[C]Cost of material, (Z_3)	$V_3 = [0.44L]d^2$	$Z_3 = [0.44C_3L]d^2$
[D]Cost of compacted fill, (Z_4)	$V_4 = [0.6h(L+W]d$	$Z_4 = [0.6C_4h(L+W]d$
[E]Cost of hunches (lower and upper), (Z_5)	$V_5 = [2.4(qs+eg)]d$	$Z_5 = [2.4C_5(qs+eg)]d$
[F]Cost of protection works, (Z_6)	As given in Table (3.2)	
[G]Cost of additionally involved head loss, (Z_7)	$h_L = \left[\frac{KQ^2}{2g}\right]d^{-4} + [6.35Q^2n^2 L]d^{-16/3} - \frac{kQ^2}{2gA_C^{\,2}}$	$Z_7 = \left[\frac{KC_7Q^2}{2g}\right]d^{-4} + [6.35C_7Q^2n^2 L]d^{-16/3} - \frac{kC_7Q^2}{2gA_C^{\,2}}$
		$ZT_2 = \sum Z_i \quad (i = 1,2,...,7)$

Table(3.5):Summary of the final cost objective function,(ZT_2).

Cost function	Constant	Terms of the decision variables			
		$d^{-16/3}$	d^{-4}	d	d^2
Z_1	—	—	—	$1.2C_1L$ $(h+S+e+a)$	$1.44C_1L$
Z_2	—	—	—	$1.2C_2aL$	—
Z_3	—	—	—	—	$0.44C_3L$
Z_4	—	—	—	$0.6C_4h$ $(L+W)$	—
Z_5	—	—	—	$2.4C_5(qs+$ $eg)$	—
Z_6	$z_{61}, z_{62}, z_{63,} or z_{64}$	—	—	—	—
Z_7	$-\frac{C_7kQ^2}{2gA_C^{\,2}}$	$6.35C_7Q^2n^2L$	$\frac{C_7KQ^2}{2g}$	—	—



[b]: Section (A-A) Circular pipe culvert



[c]: Detail (A) Lower hunch

LEGEND AND NOTES

Bedding (plain con.)

Hunch (R.C.)

Compacted fill

Pipe material

* Dimensions in centimeters

min. : Minimum dimensions

Figure(3.5):Typical pipe–culvert works[After SC (1982)].

[A] Cost of excavation, (Z_{P1})

$$Z_{P1} = C_1 V_{P1} \tag{3.40}$$

$$V_{P1} = [(0.5 + D)(a + 1.25D + h)]L \tag{3.41}$$

where:

D = outer diameter of pipe, (m);

Considering the structurally–safe value of (t) as recommended by Raju (1986), that is:

$$t = \frac{d}{10} \tag{3.42}$$

where:

t = thickness of pipe, (m)

d = inner diameter, (m)

and with the definition of $(D = d + 2t)$, then Eq. (3.41) becomes:

$$V_{P1} = \left[0.5(a+h) + \left(0.75 + 1.2(a+h)\right) d + 1.8d^2\right] L \tag{3.43}$$

Consequently :

$$Z_{P1} = C_1 L\left[0.5(a+h) + \left(0.75 + 1.2(a+h)\right)d + 1.8d^2\right] \tag{3.44}$$

[B] Cost of bedding, (Z_{P2})

$$Z_{P2} = C_2 V_{P2} \tag{3.45}$$

Then, $V_{P2} = \left[(0.5 + D)a\right]L$ (3.46)

Thus: $Z_{p2} = \dfrac{C_2 La}{2}(1 + 2.4d)$ (3.47)

[C] Cost of material, (Z_{P3})

$$Z_{P3} = C_3 V_{P3} \tag{3.48}$$

where:

V_{P3} = volume of pipe material, (m^3);

With $(V_{P3} = A_P L = \pi DtL)$, $(D = d + 2t)$, and $\left(t = d/10\right)$, Eq.(3.48) becomes :

$$Z_{P3} = \left[\frac{3C_3 L\pi}{25}\right] d^2 \tag{3.49}$$

[D] Cost of compacted fill, (Z_{P4})

$$Z_{P4} = C_4 V_{P4} \tag{3.50}$$

where:

V_{P4}=volume of compacted fill, (m^3).

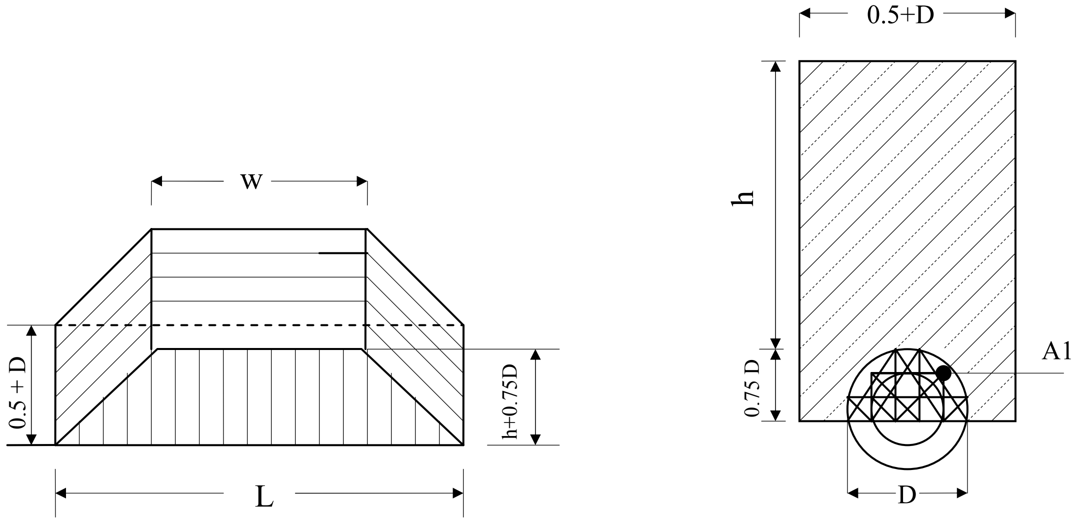
With reference to Fig.(3.6), the compacted fill for a reinforced–concrete pipe culvert would be :

$$V_{P4} = \left(A_{T1} - A_1'\right)L \tag{3.51}$$

where :

A_{T1} = total area (including that of pipe)

$$A_{T1} = \left(\frac{(0.5 + D)L + W(0.5 + D)}{2}\right)(h + 0.75D) \tag{3.52}$$



[a[: Compacted fill prism **[b]: Cross-section**

Figure(3.6):Detail of compacted fill of a reinforced–concrete pipe culvert.

A_1' =area to be deducted from (A_{T1}).

With reference to Fig.(3.6–b), $\left(A_1'\right)$ would be:

$$A_1 = 0.91d^2 \tag{3.53}$$

Thus:

$$Z_{P4} = C_4(0.25h(L+W)) + [C_4(0.6h+0.225)(L+W)]d + [C_4(0.54(L+W)-0.91L)]d^2 \tag{3.54}$$

[E] Cost of lower hunches, (Z_{P5})

The lower hunch of a pipe culvert, Fig.(3.7), forms a base to the pipe and, therefore, it is different from that discussed in Item 3.3.3.1. For (Z_{P5}):

$$Z_{P5} = C_5 V_{P5} \tag{3.55}$$

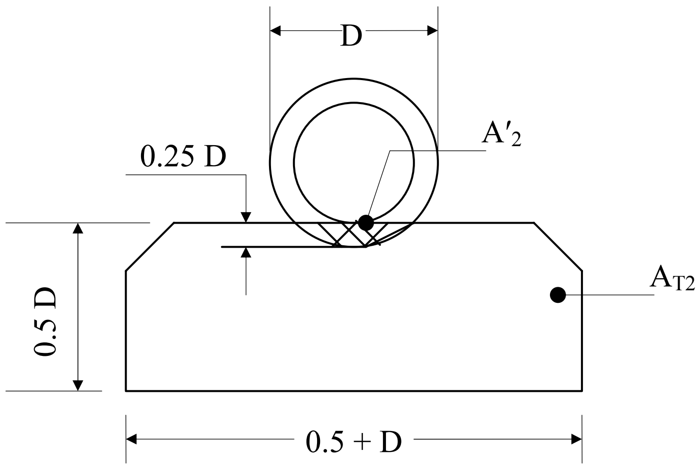
where:

V_{P5} =net volume of the material forming the hunch, (m^3);

$$V_{P5} = \left(A_{T2} - A_2'\right)L \tag{3.56}$$

where:

A_{T2} =total gross area; A_2' =area to be excluded.



Figure(3.7): Details of the lower hunch of a pipe – culvert.

On calculating the respective areas with the aid of Fig.(3.7), the respective cost objective function would be:

$$Z_{p5} = C_5 L\left(0.3d + 0.5d^2\right) \qquad (3.57)$$

[F] Cost of protection works, (Z_{P6})

The concept of protection works of a pipe culvert is similar to that of the box. Thus , $(Z_{P6} = Z_6)$ of Item (3.3.3.1–F).

[G] Cost of additionally–involved head loss, (Z_{P7})

Similar to (Z_7) for a box culvert as discussed in Item (3.3.3.1–G), $(Z_{P7})$for a reinforced–concrete pipe culvert would be:

$$Z_{P7} = \left[\frac{1.621C_7KQ^2}{2g}\right]d^{-4} + \left[10.30C_7Q^2n^2L\right]d^{-16/3} - \frac{C_7kQ^2}{2gA_C{}^2} \qquad (3.58)$$

The sub–cost objective functions with respect to a reinforced concrete pipe culvert, are summarized in Table (3.6).

Table(3.6): Summary of the final cost objective function,(ZT_3).

Cost function	Constant	Terms of the decision variables			
		$d^{-16/3}$	d^{-4}	d	d^2
Zp_1	$0.5C_1L(a+h)$	—	—	$C_1L(0.75+1.2(a+h))$	$1.8C_1L$
Zp_2	$0.5C_2La$	—	—	$1.2C_2La$	—
Zp_3	—	—	—	—	$0.12\pi C_3L$
Zp_4	$0.25C_4h(L+W)$	—	—	$C_4(0.6h+0.225)(L+W)$	$C_4(0.54(L+W)-0.91L)$
Zp_5	—	—	—	$0.3C_5L$	$0.5C_5L$
Zp_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—
Zp_7	$-\frac{kQ^2C_7}{2gA_C^{\ 2}}$	$10.30C_7 Q^2n^2L$	$\frac{1.621C_7KQ^2}{2g}$	—	—

Consequently, the total cost objective function for a reinforced concrete pipe culvert is :

$$ZT_3 = \left[10.30C_7Q^2n^2L\right]d^{-16/3} + \left[\frac{1.621C_7KQ^2}{2g}\right]d^{-4} + [C_1L(0.75+1.2(a+h))+ 1.2C_2La + C_4(0.6h+0.225)(L+W) + 0.3C_5L]d + [1.8C_1L + 0.12LC_3\pi + C_4(0.54(L+W) - 0.91L) + 0.5C_5L]d^2 + Z_6 + 0.5C_1L(a+h) + 0.5C_2La + 0.25C_4h(L+W) - \frac{kC_7Q^2}{2gA_C^{\ 2}} \qquad (3.59)$$

3.3.3.4 THE OBJECTIVE FUNCTION OF PIPE CULVERTS OF MATERIALS OTHER THAN REINFORCED CONCRETE

With respect to the material of a circular pipe culvert other than the reinforced concrete, the most common types in use in Iraq are cast iron, asbestos–cement, and ductile steel. These types will be considered in this research. The unit prices of the aforementioned types for some useful standard sizes {as found in the local market and for Hilla–Market, 2005} are given in Table (3.7).

Table (3.7): Commercial prices of pipes [Hilla–Market(2005)].

Pipe type	Inner diameter(d), (m)	Unit price, ($/m)
Cast iron	0.50	46.67
	0.60	50.00
	0.70	60.00
	0.80	66.67
	1.00	106.67
	1.20	116.67
Asbestos-Cement	0.50	16.67
	0.60	26.67
	0.70	30.00
	0.80	33.33
Ductile-Steel	0.50	33.33
	0.60	43.89
	0.70	83.33
	0.80	111.11
	0.90	133.33
	1.00	155.55

It is necessary to express the cost of pipe per unit of the installed length as a function of its size (diameter). Mohammad [1992] stated that the best function obtained to express such a cost is:

$$Y = K'L + KLd^{m} \tag{3.60}$$

in which:

Y = cost of pipe furnishing in U.S. Dollars per unit length;

L = length of pipe, (m);

d = diameter of pipe, (m);

K', K, m = fitting parameters.

On considering the unit prices listed in Table (3.7) (beside prices for smaller sizes not listed in the table), the regression yielded the following:

[A] The objective function of the cast–iron, circular–pipe culvert

According of Eq.(3.60), and Table (3.7), the cost of cast iron pipe furnishing is:

$$Z_{PC3} = \left(5.325459 + 90.86784 d^{1.30}\right) L \qquad \{R = 0.9880\} \qquad (3.61)$$

where:

Z_{PC3} = cost of cast–iron pipe furnishing, (\$).

The other sub–cost objective functions, i.e., excavation Z_{PC1}, bedding (Z_{pc2}), compacted fill (Z_{pc4}), lower hunch (Z_{pc5}), protection works (Z_{pc6}), and additionally involved head loss (Z_{pc7}), are calculated in the same way of calculating the respective items for the reinforced concrete pipe culvert mentioned before. The summary of the final cost objective function of the cast iron, circular–pipe culvert, (ZT_4) is given in Table (3.8).

Table(3.8): Summary of the final cost objective function,(ZT_4).

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	$d^{1.3}$	d^2
Zpc_1	$0.5C_1L(a+h)$	—	—	$C_1L(0.75+1.2(a+h))$	—	$1.8C_1L$
Zpc_2	$0.5C_2La$	—	—	$1.2C_2La$	—	—
Zpc_3	$5.325459L$	—	—	—	$90.86784L$	—
Zpc_4	$0.25C_4h(L+W)$	—	—	$C_4(0.6h+0.225)(L+W)$	—	$C_4(0.54(L+W)-0.91L)$
Zpc_5	—	—	—	$0.3C_5L$	—	$0.5C_5L$
Zpc_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—
Zpc_7	$-\frac{kQ^2C_7}{2gA_C^2}$	$10.30C_7Q^2n^2L$	$\frac{1.621C_7KQ^2}{2g}$	—	—	—

Then, (ZT_4) would be :

$$ZT_4 = \left[10.30C_7Q^2n^2L\right]d^{-16/3} + \left[\frac{1.621C_7KQ^2}{2g}\right]d^{-4} + [C_1L(0.75 + 1.2(a+h)) + 1.2C_2La + C_4(0.6h + 0.225)(L+W) + 0.3C_5L]d + \left[90.86784L\right]d^{1.30} + [1.8C_1L + C_4(0.54(L+W) - 0.91L) + 0.5C_5L]d^2 + Z_6 + 5.325459L + 0.5C_1L(a+h) + 0.5C_2La + 0.25C_4h(L+W) - \frac{kC_7Q^2}{2gA_C{}^2} \quad (3.62)$$

[B] The objective function of the asbestos–cement, circular–pipe culvert

Similar to (Z_{PC3}) given in Eq.(3.61), the cost of asbestos–cement pipe furnishing is:

$$Z_{Pa3} = \left(51.02211d^{1.535724} - 0.834571\right)L \qquad \{R = 0.9760\} \qquad (3.63)$$

where:

Z_{Pa3} = cost of asbestos–cement pipe furnishing, (\$).

The summary of the final cost objective function of asbestos–cement, circular pipe-culvert, (ZT_5) is given in Table (3.9).

Table(3.9): Summary of the final cost objective function,(ZT_5).

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	$d^{1.535724}$	d^2
Zpa_1	$0.5C_1L(a+h)$	—	—	$C_1L(0.75 + 1.2(a+h))$	—	$1.8C_1L$
Zpa_2	$0.5C_2La$	—	—	$1.2C_2La$	—	—
Zpa_3	$-0.83457L$	—	—	—	$51.02211L$	—
Zpa_4	$0.25C_4h(L+W)$	—	—	$C_4(0.6h + 0.225)(L+W)$	—	$C_4(0.54(L+W) - 0.91L)$
Zpa_5	—	—	—	$0.3C_5L$	—	$0.5C_5L$
Zpa_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—
Zpa_7	$-\frac{kQ^2C_7}{2gA_C{}^2}$	$10.30C_7Q^2n^2L$	$\frac{1.621C_7KQ^2}{2g}$	—	—	—

The total objective function (ZT_5), in its final form is:

$$ZT_5 = \left[10.30C_7Q^2n^2L\right]d^{-16/3} + \left[\frac{1.621C_7KQ^2}{2g}\right]d^{-4} + [C_1L(0.75 + 1.2(a+h)) +$$
$$1.2C_2La + C_4(0.6h + 0.225)(L+W) + 0.3C_5L]d + [51.0211L]d^{1.535724} + [1.8C_1L +$$
$$C_4(0.54(L+W) - 0.91L) + 0.5C_5L]d^2 + Z_6 - 0.834571L + 0.5C_1L(a+h) + 0.5C_2La +$$
$$0.25C_4h(L+W) - \frac{kC_7Q^2}{2gA_C{}^2} \tag{3.64}$$

[C] The objective function of the ductile–steel, circular–pipe culvert

Similar to (Z_{PC3}) and (Z_{Pa3}), the cost of ductile–steel, circular pipe culvert, (Z_{Pd3}) is found to be:

$$Z_{Pd3} = \left(165.2318d^{2.053063} - 3.03502\right)L \qquad \{R = 0.9900\} \tag{3.65}$$

where:

Z_{Pd3} = cost of ductile steel pipe furnishing, ($).

The details of the itemized cost objective function (ZT_6) are summarized in Table (3.10), where (ZT_6) will be in the form:

$$ZT_6 = \left[10.30C_7Q^2n^2L\right]d^{-16/3} + \left[\frac{1.621C_7KQ^2}{2g}\right]d^{-4} + [C_1L(0.75 + 1.2(a+h)) +$$
$$1.2C_2La + C_4(0.6h + 0.225)(L+W) + 0.3C_5L]d + [1.8C_1L + C_4(0.54(L+W) - 0.91L) +$$
$$0.5C_5L]d^2 + [165.2318L]d^{2.053063} + Z_6 - 3.03502L + 0.5C_1L(a+h) + 0.5C_2La +$$
$$0.25C_4h(L+W) - \frac{kC_7Q^2}{2gA_C{}^2} \tag{3.66}$$

Table(3.10): Summary of the final cost objective function,(ZT_6).

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	d^2	$d^{2.053063}$
Zpd_1	$0.5C_1L(a+h)$	—	—	$C_1L(0.75+1.2(a+h))$	$1.8C_1L$	—
Zpd_2	$0.5C_2La$	—	—	$1.2C_2La$	—	—
Zpd_3	$-0.83457L$	—	—	—	—	$165.232L$
Zpd_4	$0.25C_4h(L+W)$	—	—	$C_4(0.6h+0.225)(L+W)$	$C_4(0.54(L+W)-0.91L)$	—
Zpd_5	—	—	—	$0.3C_5L$	$0.5C_5L$	—
Zpd_6	$z_{61}, z_{62}, z_{63}, or\, z_{64}$	—	—	—	—	—
Zpd_7	$-\frac{kQ^2C_7}{2gA_C{}^2}$	$10.30C_7Q^2n^2L$	$\frac{1.621C_7KQ^2}{2g}$	—	—	—

3.3.3.5 THE OBJECTIVE FUNCTION OF CULVERTS OF MULTIPLE – VENTS

A single vent for a certain discharge may be insufficient for many reasons, as will be explained later; therefore, multiple–vents of culverts must be considered to cover the respective discharge .

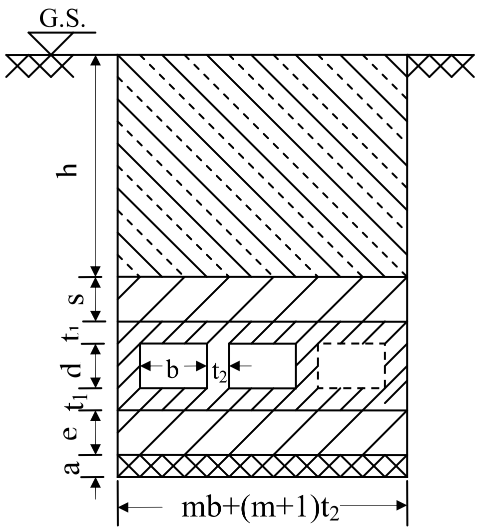
The formulation of the objective functions of multiple–vents culverts are give hereinafter.

[A] The objective function of multiple–vents of reinforced concrete, rectangular–box culverts

The items of sub–objective functions of the multiple–vents of reinforced concrete, rectangular box–culverts are similar to those of single vent culverts, (Sec.3.3.3.1). The formulation of these sub–objective functions are summarized in Table (3.11) with aid of Fig.(3.8).

Table(3.11): Summary of final cost objective function,(ZT′1) for multiple–vents, reinforced concrete rectangular box culverts.

Cost function	Constant	Terms of the decision variables						
		b	b^2	d	d^2	$(bd)^{-2}$	bd	$(b+d)^{4/3}$ $(bd)^{-10/3}$
Z_1	—	mC_1L $(h+S+e+a)$	$0.2m$ C_1L	$0.1C_1L$ $(m+1)$ $(h+S+e+a)$	$0.1C_1L$ $(m+1)$	—	0.02 C_1L $(m+1)$	—
Z_2	—	C_2aLm	—	$0.1C_2a$ $L(m+1)$	—	—	—	—
Z_3	—	—	$0.2m$ C_3L	—	$0.1C_3L$ $(m+1)$	—	0.02 C_3L $(m+1)$	—
Z_4	—	$0.5C_4$ mh $(L+W)$	—	$0.05C_4h$ $(m+1)$ $(L+W)$	—	—	—	—
Z_5	—	$2C_5m(qs+eg)$	—	$0.2C_5$ $(m+1)$ $(qs+eg)$	—	—	—	—
Z_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—	—	—
Z_7	$-\frac{C_7kQ^2}{2gA_C{}^2}$	—	—	—	—	$\frac{C_7K\left(\frac{Q}{m}\right)^2}{2g}$	—	$2.52C_7$ $\left(Q/m\right)^2$ n^2L



Figure(3.8): Section of multiple-vents, reinforced concrete, rectangular box culvert.

The final cost objective function of multiple–vents of a reinforced concrete, rectangular box culvert, (ZT_1') is:

$$ZT_1' = [LC_1 m(h+s+e+a) + C_2 Lam + 0.5hmC_4(L+W) + 2mC_5(qs+ge)]b + [0.2Lm(C_1+C_3)]b^2 + [0.1LC_1(m+1)(h+s+e+a) + 0.1C_2 La(m+1) + 0.05hC_4 (m+1)(L+W) + 0.2C_5(m+1)(qs+ge)]d + [0.1(m+1)L(C_1+C_3)]d^2 + [\frac{C_7 K\left(\frac{Q}{m}\right)^2}{2g}](bd)^{-2} + [0.02L(m+1)(C_1+C_3)]bd + \left[2.52C_7\left(\frac{Q}{m}\right)^2 n^2 L\right](b+d)^{4/3}(bd)^{-10/3} + Z_6 - \frac{C_7 kQ^2}{2gA_C^{\,2}} \qquad (3.67)$$

[B] The objective function of multiple–vents, reinforced concrete, square box culvert

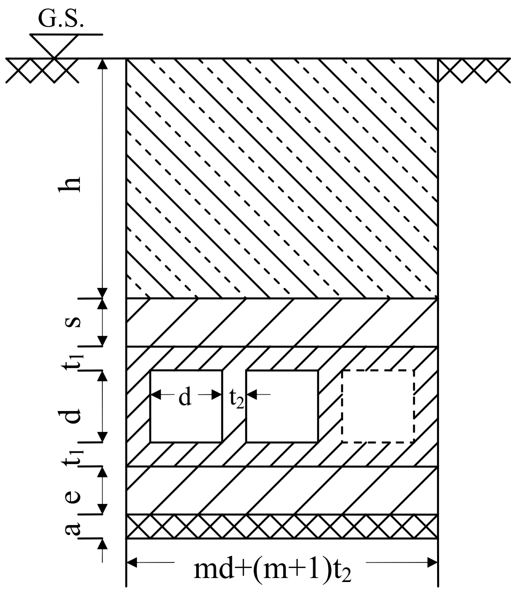
Similar to the rectangular box culvert, the formulation of the objective function of multiple–vents, reinforced concrete, square box culvert, $(ZT_2')$is given as:

$$ZT_2' = \left[6.35C_7\left(\frac{Q}{m}\right)^2 n^2 L\right]d^{-16/3} + \left[\frac{C_7K\left(\frac{Q}{m}\right)^2}{2g}\right]d^{-4} + [(11m+1)(0.1C_2La +$$

$$0.05C_4h(L+W) + 0.2C_5(qs+ge)]d + [C_1L(1.32m+0.12) + (0.32m +$$

$$0.12)LC_3]d^2 + Z_6 - \frac{C_7kQ^2}{2gA_C^{\ 2}} \qquad (3.68)$$

According to Fig.(3.9), the summary of formulation of (ZT_2') is given in Table (3.12).



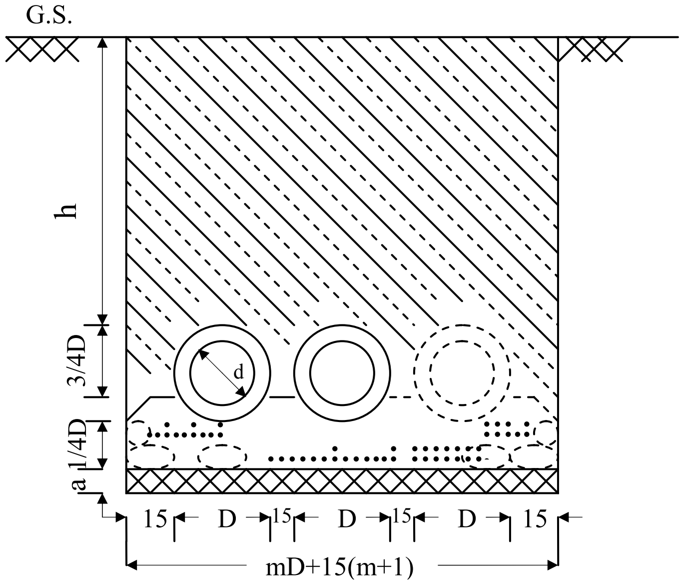
Figure(3.9): Section of multiple–vents, reinforced concrete, square box culvert.

Table(3.12): Summary of final cost objective function,(ZT′2) for multiple–vents, reinforced concrete square box culverts.

Cost function	Constant	Terms of the decision variables			
		$d^{-16/3}$	d^{-4}	d	d^2
Z_1	—	—	—	$0.1C_1L(11m+1)$ $(h+s+e+a)$	$C_1L(1.23m+$ $0.12)$
Z_2	—	—	—	$0.1C_2aL(11m+1)$	—
Z_3	—	—	—	—	$C_3L(0.32m+$ $0.12)$
Z_4	—	—	—	$0.05C_4h(L+W)$ $(11m+1)$	—
Z_5	—	—	—	$0.2C_5(11m+1)$ $(qs+eg)$	—
Z_6	z_{61}, z_{62}, $z_{63}, or z_{64}$	—	—	—	—
Z_7	$-\dfrac{C_7kQ^2}{2gA_C{}^2}$	$6.35C_7\left(\dfrac{Q}{m}\right)^2$ n^2L	$\dfrac{C_7K\left(\dfrac{Q}{m}\right)^2}{2g}$	—	—

[C] The objective function of circular–pipe culvert with multiple vents

The cost objective functions of circular–pipe culverts with multiple vents of (reinforced concrete, cast–iron, asbestos–cement, and ductile–steel), (ZT_3', ZT_4', ZT_5', and ZT_6', respectively) are formulated similar to that of a single–vent mentioned previously, taking into consideration the details given in Fig.(3.10).



Figure(3.10): Section of multiple–vents circular pipe culvert.

The respective objective functions would be:

$$ZT_3' = \left[10.30C_7\left(\frac{Q}{m}\right)^2 n^2 L\right]d^{-16/3} + \left[\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}\right]d^{-4} + [1.2LC_1(m(h+a)+$$
$$0.1875(m+1)) + 1.2aLC_2m + C_4(L+W)(0.6hm + 0.0675(m+1)) + 0.18C_5L$$
$$(m+1)]d + [1.8LC_1m + 0.6C_3Lm\pi + C_4m(0.54(L+W) - 0.91L) + 0.5C_5Lm$$
$$]d^2 + Z_6 + 0.15L(m+1)(C_1(h+a) + aC_2) + 0.075C_4h(L+W)(m+1) - \frac{C_7kQ^2}{2gA_C^{\ 2}} \qquad (3.69)$$

$$ZT_4' = \left[10.30C_7\left(\frac{Q}{m}\right)^2 n^2 L\right]d^{-16/3} + \left[\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}\right]d^{-4} + [1.2LC_1(m(h+a)+$$
$$0.1875(m+1)) + 1.2aLC_2m + C_4(L+W)(0.6hm + 0.0675(m+1)) + 0.18C_5L$$
$$(m+1)]d + [90.8678Lm]d^{1.30} + [Lm(1.8C_1 + 0.5C_5) + C_4m(0.54(L+W) -$$
$$0.91L)]d^2 + Z_6 + 0.15L(m+1)(C_1(h+a) + aC_2) + 5.325459Lm + 0.075C_4h$$
$$(L+W)(m+1) - \frac{C_7kQ^2}{2gA_C^{\ 2}} \qquad (3.70)$$

$$ZT_5' = \left[10.30C_7\left(\frac{Q}{m}\right)^2 n^2 L\right] d^{-16/3} + \left[\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}\right] d^{-4} + [1.2LC_1(m(h+a)+$$

$$0.1875(m+1)) + 1.2aLC_2m + C_4(L+W)(0.6hm + 0.0675(m+1)) + 0.18C_5L$$

$$(m+1)]d + [51.02211Lm]d^{1.535727} + [Lm(1.8C_1 + 0.5C_5) + C_4m(0.54(L+W) -$$

$$0.91L)]d^2 + Z_6 + 0.15L(m+1)(C_1(h+a) + aC_2) - 0.834571Lm + 0.075C_4h$$

$$(L+W)(m+1) - \frac{C_7kQ^2}{2gA_C{}^2} \qquad (3.71)$$

$$ZT_6' = \left[10.30C_7\left(\frac{Q}{m}\right)^2 n^2 L\right] d^{-16/3} + \left[\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}\right] d^{-4} + [1.2LC_1(m(h+a)+$$

$$0.1875(m+1)) + 1.2aLC_2m + C_4(L+W)(0.6hm + 0.0675(m+1)) + 0.18C_5L$$

$$(m+1)]d + [Lm(1.8C_1 + 0.5C_5) + C_4m(0.54(L+W) - 0.91L)]d^2 +$$

$$[165.231mL]d^{2.053063} + Z_6 + 0.15L(m+1)(C_1(h+a) + aC_2) + 0.075C_4h(L+W)$$

$$(m+1) - 3.03502mL - \frac{C_7kQ^2}{2gA_C{}^2} \qquad (3.72)$$

The summary of the formulated respective cost objective functions are given in Tables (3.13), (3.14), (3.15), and (3.16), respectively.

Table(3.13): Summary of the final cost objective function,(ZT′3) for multiple–vents, reinforced concrete circular pipe culverts.

Cost function	Constant	Terms of the decision variables			
		$d^{-16/3}$	d^{-4}	d	d^2
Zp_1	$0.15C_1L(m+1)(a+h)$	—	—	$1.2C_1L(m(a+h)+0.1875(m+1))$	$1.8C_1Lm$
Zp_2	$0.15C_2La(m+1)$	—	—	$1.2C_2Lam$	—
Zp_3	—	—	—	—	$0.6\pi C_3Lm$
Zp_4	$0.075C_4h(L+W)(m+1)$	—	—	$C_4(L+W)(0.6hm+0.0675(m+1))$	$C_4(0.54(L+W)-0.91L)m$
Zp_5	—	—	—	$0.18C_5L(m+1)$	$0.5C_5Lm$
Zp_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—
Zp_7	$-\frac{kQ^2C_7}{2gA_C{}^2}$	$10.30C_7\left(Q/m\right)^2 n^2L$	$\frac{1.621C_7K\left(Q/m\right)^2}{2g}$	—	—

Table(3.14): Summary of the final cost objective function,(ZT′$_4$) for multiple–vents, cast–iron circular pipe culverts.

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	$d^{1.3}$	d^{2}
Zpc_1	$0.15C_1L(m+1)(a+h)$	—	—	$1.2C_1L(m(a+h)+0.186(m+1))$	—	$1.8C_1Lm$
Zpc_2	$0.15C_2La(m+1)$	—	—	$1.2C_2Lam$	—	—
Zpc_3	$5.325459Lm$	—	—	—	$90.86784Lm$	—
Zpc_4	$0.075C_4h(L+W)(m+1)$	—	—	$C_4(L+W)(0.6hm+0.0675(m+1))$	—	$C_4m(0.54(L+W)-0.91L)$
Zpc_5	—	—	—	$0.18C_5L(m+1)$	—	$0.5C_5Lm$
Zpc_6	$z_{61}, z_{62}, z_{63}, or\, z_{64}$	—	—	—	—	—
Zpc_7	$-\frac{kQ^2C_7}{2gA_C^{\,2}}$	$10.30C_7\left(Q/m\right)^2n^2L$	$\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}$	—	—	—

Table(3.15): Summary of the final cost objective function,(ZT′₅) for multiple–vents, asbestos–cement circular pipe culverts.

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	$d^{1.535724}$	d^2
Zpa_1	$0.15C_1L(m+1)(a+h)$	—	—	$1.2C_1L(m(a+h)+0.1875(m+1))$	—	$1.8C_1Lm$
Zpa_2	$0.15C_2La(m+1)$	—	—	$1.2C_2Lam$	—	—
Zpa_3	$-0.83457Lm$	—	—	—	$51.02211Lm$	—
Zpa_4	$0.075C_4h(L+W)(m+1)$	—	—	$C_4(L+W)(0.6hm+0.0675(m+1))$	—	$C_4m(0.54(L+W)-0.91L)$
Zpa_5	—	—	—	$0.18C_5L(m+1)$	—	$0.5C_5Lm$
Zpa_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—
Zpa_7	$-\frac{kQ^2C_7}{2gA_C^2}$	$10.30C_7\left(\frac{Q}{m}\right)^2 n^2L$	$\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}$	—	—	—

Table(3.16): Summary of the final cost objective function,(ZT′$_6$) for multiple–vents, ductile–steel circular pipe culverts.

Cost function	Constant	Terms of the decision variables				
		$d^{-16/3}$	d^{-4}	d	d^2	$d^{2.053063}$
Zpd_1	$0.15C_1L(m+1)(a+h)$	—	—	$1.2C_1L(m(a+h)+0.1875(m+1))$	$1.8C_1Lm$	—
Zpd_2	$0.15C_2La(m+1)$	—	—	$1.2C_2Lam$	—	—
Zpd_3	$-3.03502Lm$	—	—	—	—	$165.232Lm$
Zpd_4	$0.075C_4h(L+W)(m+1)$	—	—	$C_4(L+W)(0.6hm+0.0675(m+1))$	$C_4m(0.54(L+W)-0.91L)$	—
Zpd_5	—	—	—	$0.18C_5L(m+1)$	$0.5C_5Lm$	—
Zpd_6	$z_{61}, z_{62}, z_{63}, or z_{64}$	—	—	—	—	—
Zpd_7	$-\frac{kQ^2C_7}{2gA_C^2}$	$10.30C_7\left(\frac{Q}{m}\right)^2 n^2L$	$\frac{1.621C_7K\left(\frac{Q}{m}\right)^2}{2g}$	—	—	—

3.3.4 THE CONSTRAINTS

The objective function is minimized subject to a set of constraints. Some of these constraints can be explicitly defined in terms of the design variables (i.e., side constraints), such as dimensions, while others are implicitly related to design variables (i.e., head loss, velocity,…,etc). The basic controlling constraints are discussed hereinafter.

3.3.4.1 DIMENSIONS

[A]: The minimum vent dimension of a box culvert is (0.75m) to facilitate inspection, carrying out repairs, and to avoid choking due to debris [Sharma and Sharma (1993)]. This side constraint can be written as:

$$b \geq 0.75 \tag{3.73}$$

$$d \geq 0.75 \tag{3.74}$$

[B]: A box culvert may comprise a single vent or several vents. The span of each vent is not to exceed (3m) [Ahuja and Birdi (1985)]; however, Raju [1986] suggested such a figure to be (4m). The height of the vent generally does not exceed (3m). It is stated in NJDOT (2003) that a maximum span (width), if possible, will be (3.5m) per box.

A maximum span length of (4m) and a maximum height of (3m) have been adopted in this research. This condition can be written as:

$$b \leq 4.0 \tag{3.75}$$

$$d \leq 3.0 \tag{3.76}$$

[C]: To ensure a closed–conduit flow through the culvert, the height of the culvert, (d), must be less than the upstream water depth, (HW), as shown in Fig. (3.11). This can be expressed as:

$$d < HW \tag{3.77}$$

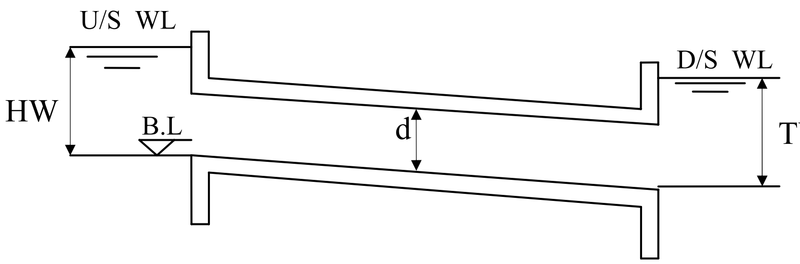
where:

d = height of culvert, (m);

HW = upstream water depth, (m).

As stated in Chow [1959], the culvert will flow completely full if the head water is greater than a certain critical value designated by (H*). The value of (H*) varies from (1.2) to (1.5) times the height of the culvert. This is denoted by the following expression:

$$HW \geq H^{*}\left[= (1.2 \ to \ 1.5)d\right] \tag{3.78}$$



Figure(3.11): Schematic representation of a closed-conduit flow of a culvert.

Chow [1959] recommends using $(H^* = 1.5d)$ for preliminary analysis, whereas Pencol [1983] recommends using the limit $(1.2d)$. The limit $(H^* = 1.5d)$ has been adopted for use in this research.

[D]: As mentioned in Sec.(3.3.3.5), when the design enforces violating one or both of condition [B] and [C] mentioned hereinbefore, multiple–vents may be used. This condition has been involved in the optimization program.

[E]: It is stated in USBR [1974] that to avoid plugging with debris, the minimum diameter of a pipe culvert is usually considered as (60cm). Dutta [1991] mentioned that the diameter of pipe for pipe culvert should not be less than (30cm), as smaller diameter pipe is likely to be chocked. However, City of Greeley [2000] specifies that in a pipe culvert with a circular shape, the minimum diameter is (60cm) in a road side ditch culvert and for driveways, the minimum diameter is (30cm).

A culvert of (60cm) as a minimum diameter is considered in this research because it is more acceptable than the (30cm), particularly for the Iraqi field conditions. The constraint that covers this limit can be written as:

$$d \geq 0.60 \qquad (3.79)$$

[F]: Similar to the box culvert, the condition, $\left(HW/d \geq 1.5\right)$ which was mentioned in item [C], also must be checked in the case of pipe culvert, where (d) is the diameter of the pipe.

3.3.4.2 HEAD LOSS

The minimum net outlet submergence (h_N) is (0.05m) [Pencol(1983)], as shown in Fig.(3.12). The constraint covering this case is:

$$h_N \geq 0.05 \tag{3.80}$$

where:

h_N = net active head on culvert at the D/S. This is the minimum necessary command head for irrigation; $h_N = y_o - d - h_L$, (m);

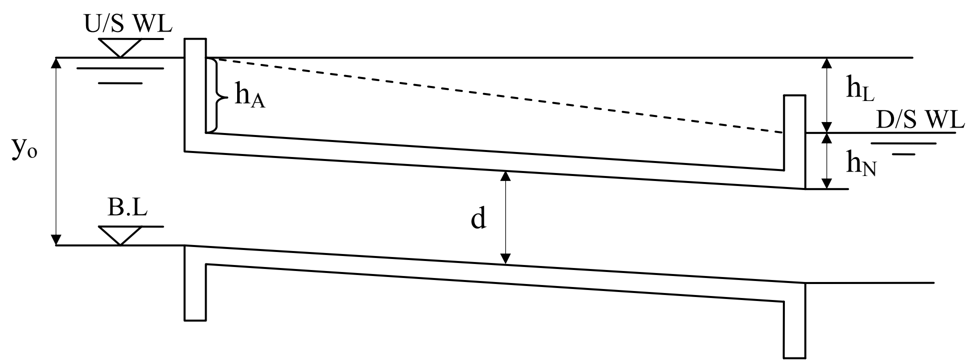
y_o = head water of the culvert; y_o = U/S WL-B.L, (m);

d = diameter of the circular pipe–culvert or the height of box– culvert, (m);

h_L = overall head loss, Eq.(2.10).

3.3.4.3 LIMITING VELOCITY

In the design of culvert, both minimum and maximum velocities must be considered. Increasing outlet velocity will probably cause erosion and scouring of the D/S channel; thus, D/S protection works will be necessary, the cost of which is to be added.



Figure(3.12):Schematic illustration of head loss within a culvert flowing full.

However, the minimum velocity is related to the slope or grade of the culvert and the maximum velocity is dictated by the channel conditions at the outlet.

In practice, and for assumed steady–uniform flow, it has been found satisfactory to use a minimum slope of (0.005) to prevent sedimentation (non–silting) [USBR(1974)]. This can be expressed as:

$$S_b \geq 0.005 \tag{3.81}$$

where:

S_b = bed slope of the culvert.

This, with Manning formula gives:

$$\frac{V^2 n^2}{R^{4/3}} \geq 0.005 \tag{3.82}$$

With $\left(V = Q/A\right)$, A (for a fully–flowing box culvert)= bd , $P(= 2(b+d))$, and $\left(R = A/P\right)$, then Eq.(3.82) could be written as :

$$\frac{(bd)^{10/3}}{(b+d)^{4/3}} \leq 503.96 Q^2 n^2 \tag{3.83}$$

Equation (3.82) for a square box – culvert will read:

$$d^{16/3} \leq 1270 Q^2 n^2 \tag{3.84}$$

and for a circular pipe culvert will be :

$$d^{16/3} \leq 2058.72 Q^2 n^2 \tag{3.85}$$

3.3.5 METHOD OF OPTIMIZATION

The formulated non–linear objective function is so complex that its differentiation with respect to the design variables would be an arduous task and, thus, the gradient method for solving non–linear optimization, such as SUMT method, cannot be used. Moreover, the large number of constraints will make the use of the Lagrange Multiplier method very difficult. However, the modified Hooke and Jeeves of direct search method [Bundy(1984)] has been found to be the appropriate choice in this regard.

Accordingly, the search consists of a sequence of exploration steps about a base point which, if successful, are followed by pattern moves. The modification made to the method was to take account of constraints.

It has been suggested that merely giving the objective function a very large positive value (in a minimization problem) (usually $Z=1\times10^{30}$), whenever the constraints are violated [Bunday (1984)]. Certainly, this idea has an obvious intuitive appeal and it is easy to program .

The procedure may be summarized in the following steps [Bunday (1984)]:

(A) Choose an initial base point $\mathbf{b_1}$ and a step length $\mathbf{h_j}$ for each variable $\mathbf{x_j}$, $\mathbf{j=1,2,\ldots,n}$.

(B) Carry out an exploration about $\mathbf{b_1}$. The purpose of this is to acquire knowledge about the local behavior about the function. This knowledge is used to find a likely direction for the pattern move by which it is hoped to obtain an even greater reduction in the value of the function. The exploration about $\mathbf{b_1}$ proceeds as indicated in the following steps:

1. Evaluate $\mathbf{f(b_1)}$.

2. Each variable is now changed in turn, by adding the step length. Thus, the value of $\mathbf{f(b_1+h_1e_1)}$ where $\mathbf{e_1}$ is a unit vector in the direction of the $\mathbf{x_1}$–axis is then calculated. If this reduces the function replace $\mathbf{b_1}$ by $\mathbf{b_1+h_1e_1}$. If not, find $\mathbf{f(b_1-h_1e_1)}$ and replace $\mathbf{b_1}$ by $\mathbf{b_1-h_1e_1}$ if the function is reduced. If neither step gives a reduction leave $\mathbf{b_1}$ unchanged and consider changes in $\mathbf{x_2}$, i.e, find $\mathbf{f(b_1+h_2e_2)}$, etc. When all $\mathbf{n}$ variables are considered, a new base point $\mathbf{b_2}$ is obtained.

3. If $\mathbf{b_2=b_1}$, i.e., no function reduction has been achieved, the exploration is repeated about the same point $\mathbf{b_1}$ but with a reduced step length.

Reducing the step length to one tenth of its former value appears to be satisfactory in practice.

4. If $\mathbf{b_2} \neq \mathbf{b_1}$ a pattern move can be made.

(C) Pattern moves utilize the information acquired by exploration and accomplish the function minimization by moving in the direction of the established pattern. The procedure of pattern moves is as follows.

1. A sensible moving further from the base point $\mathbf{b_2}$ in the direction $\mathbf{b_2}$-$\mathbf{b_1}$ since that move already led to a reduction in the function value. So, the function value is evaluated at the next pattern point.

$$P_1 = b_1 + 2(b_2 - b_1) \qquad (3.86)$$

In general

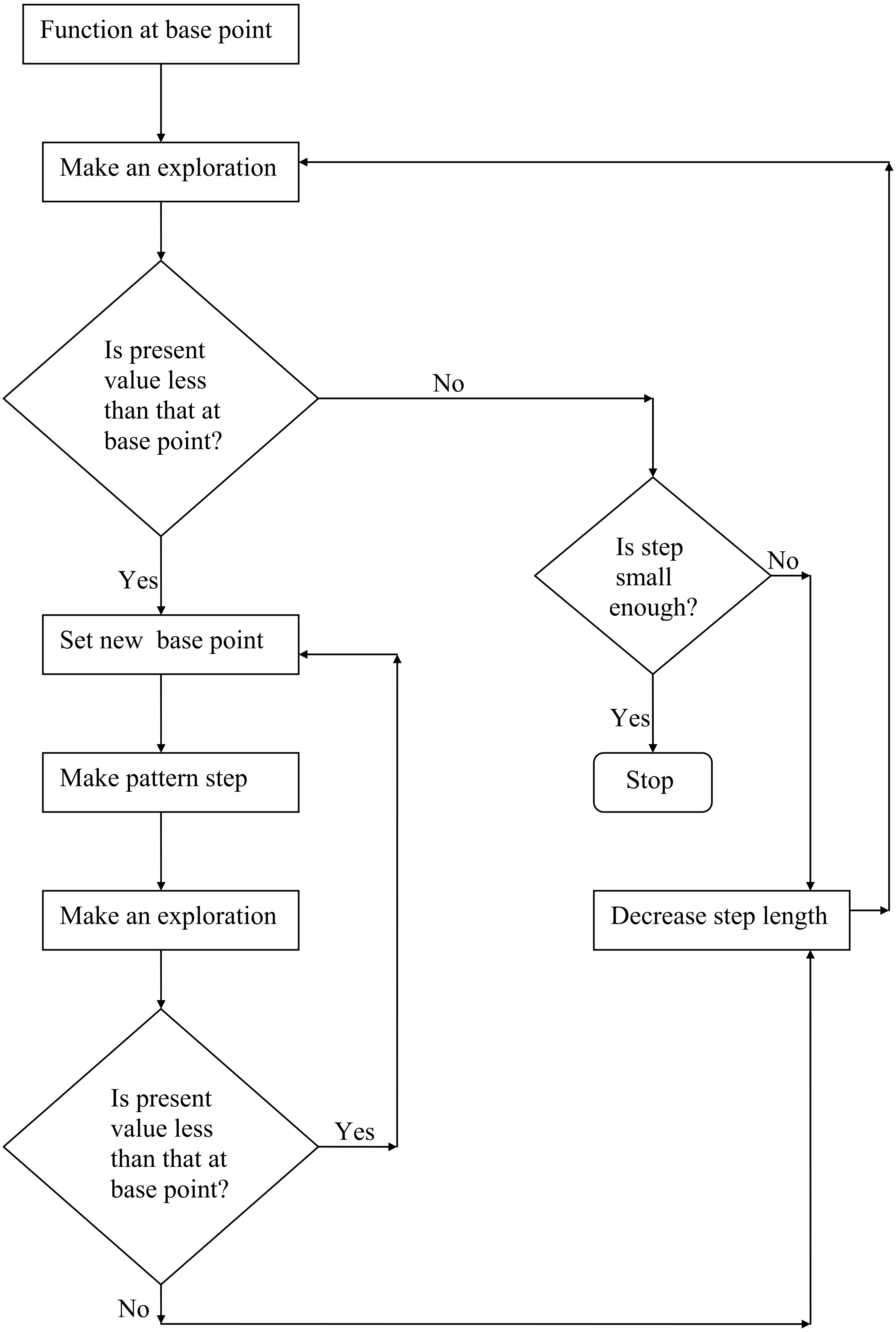
$$P_i = b_i + 2(b_{i+1} - b_i) \qquad (3.87)$$

2. Then continue with exploratory move about $\mathbf{P_1}$($\mathbf{P_i}$).

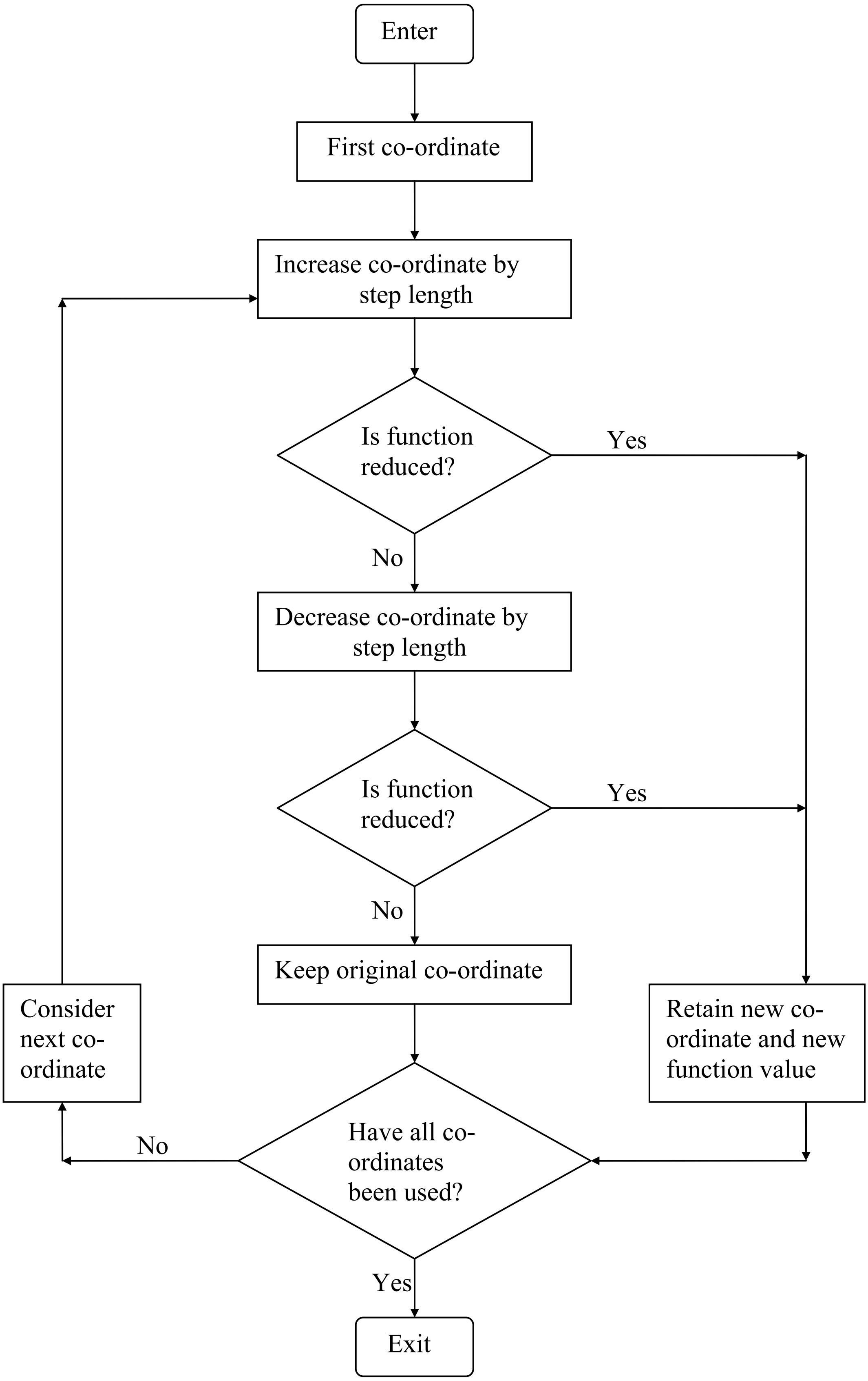
3. If the lowest value at step **C(2)** is less than the value at the base point $\mathbf{b_2}$ ($\mathbf{b_{i+1}}$) then a new base point $\mathbf{b_3}$($\mathbf{b_{i+2}}$) has been reached. In this case, repeat **C(1)**. Otherwise abandon the pattern move from $\mathbf{b_2}$($\mathbf{b_{i+1}}$) and continue with an exploration about $\mathbf{b_2}$($\mathbf{b_{i+1}}$).

(D) Terminate the process when the step length has been reduced to a predetermined small value, [usually less than (1×10^{-8})].

The method is schematically shown in the flow charts given in Figs. (3.13) and (3.14).



Figure(3.13):Flow chart for Hooke and Jeeves method [After Bunday(1984)].



Figure(3.14):Flow chart for an exploration[After Bunday(1984)].

CHAPTER FOUR

APPLICATIONS

In this chapter, unit prices which are mentioned in Chapter Three are determined; a hypothetical case study is suggested, which include all parameters of operating the culvert hydraulically, such as discharge, headwater, section of channel U/S and D/S of the culvert, the specified values of length, the specified coefficients of Manning roughness (n) of culverts; structural parameters, such as constant dimensions of hunches, thickness of bedding, height of compacted fill, top width of embankment; and the appurtenant parameters representing in inlet and outlet loss coefficients of entrance and exit of culverts, and inlet and outlet transitions loss coefficients. The aforementioned parameters are introduced in the constructed optimization problems. Finally, the obtained results for the considered cases are analyzed.

4.1 UNIT PRICES

The unit prices [i.e., C_1, C_2,…, etc. in Eqs. (3.3), (3.11), (3.15), (3.20), (3.24), (3.31), and (3.34)] applied in the research are given in Table (4.1).

4.2 THE CASE STUDY

Beside some other minor factors, the basic controlling factors in deciding on the size and shape of a culvert are: the discharge (Q), the length (L), the height of compacted fill (h_f), top width of embankment (W), cross–sectional area of the channel (A_c), the headwater (HW), constant dimensions

Table (4.1):Applied unit prices [After DWRBG(2005)].

Symbol and units	Definition or Details	Value
C_1 ($/m^3)	Excavation (including finishing).	1
C_2 ($/m^3)	Plain concrete (materials, framework, and labor).	200
C_3 and C_5 ($/m^3)	Reinforced concrete (materials, framework, and labor).	350
C_4 ($/m^3)	Compacted fill (including flattening works).	10
C_{61} and C_{62} ($/m^3)	Implementation of protection works (with coarse gravel, Type 1 and Type 2; Table(3.1)).	85
C_{63} ($/m^3)	Implementation of protection works (with riprap, sand and gravel, Type 3; Table(3.1)).	150
C_{64} ($/m^3)	Implementation of protection works (with riprap, sand and gravel, Type 4; Table(3.1)).	225
C_7 ($/m of head loss)	Losses of return due to additional head loss.	10

of hunches, (s, q, e, and, g), thickness of bedding (a), Manning roughness coefficient of respective material of the culvert (n), inlet and outlet loss coefficients (K_1) and (K_2), and inlet and outlet transition loss coefficients (K_i) and (K_o).

In real–life problems, some of the aforementioned basic parameters have limited alternatives; however, others may vary within a very wide range of values.

To make the research as close as possible to reality, an actual land reclamation project, namely, Hilla–Kifl project, has been considered as a guide in this respect. The respective actual data of the project are summarized in Table(4.2).

In view of the data of Table (4.2), the followings have been chosen for application in the research.

4.2.1 THE DISCHARGE(Q)

With respect to the discharge (Q), values of (0.5, 1.0, 1.5, 2.5, 5.0, 10.0, and 15.0 m^3/s) are suggested.

4.2.2 THE LENGTH (L)

Generally in actual projects, the length of culvert (L) depends on the width of the road or any cross–way and height of its surface with respect to the prevailing water level. To cover a reasonable range, values of (L) of (5, 10, 15, 20, 25, 35, and 40 m) are suggested for the hypothetical case study.

4.2.3 THE HEIGHT OF COMPACTED FILL (h_f)

Height of compacted fill (h_f), over the culvert depends mainly on the difference between level of road's (or any cross–way) surface and level of the culvert (or level of channel bed). However, the minimum height of compacted fill over the culvert have been proposed by investigators; e.g., SC[1982] specified the minimum height of compacted fill over the culvert as (1m), while MDSL [1992] stated that the height of compacted fill over a pipe should not be less than (30cm) or one–third of diameter for large culverts. FHWA [2003] specifies a minimum of (60cm) to prevent pipe crushing by heavy truck.

A height of compacted fill over the culvert of (1m) has been considered in this research .

Table(4.2):Selected actual data of some culverts of Hilla-Kifl project[After SC(1982)].

Name	Discharge (Q), m^3/s	Type	Shape	No. of vents and size, (m)	Length (L)(m)	Height of compacted fill (h_f),(m)	U/Swater depth (Y_o),(m)
BC_1/1R CR1	0.225	Pipe	Circular	1Ø0.60	6.60	1.40	0.46
KC_8L_3 CU_1	0.330	Pipe	Circular	1Ø0.90	6.60	1.10	0.62
HC/4R CR1	0.900	Pipe	Circular	2Ø0.90	6.60	1.10	0.93
HC/4R CR1	1.350	Pipe	Square	1(2.00×2.00)	18.50	3.75	1.05
BC_1 /6R/ CU1	1.505	Box	Square	1(1.50×1.50)	16.70	3.30	0.93
HC CU6	2.625	Box	Rectang-ular	2(2.42×2.50)	16.00	2.20	1.48
HC CU5	7.800	Box	Square	3(2.00×2.00)	17.90	1.83	2.46
KC CU3	8.000	Box	Square	4(2.00×2.00)	10.00	0.90	1.66
KC CU4	8.000	Box	Rectang-ular	3(2.50×1.60)	8.00	0.40	1.66
HC CU4	9.450	Box	Square	3(2.00×2.00)	15.60	1.00	2.29
HC CU2	10.700	Box	Square	3(2.00×2.00)	22.10	2.77	2.71
HC CU1	12.000	Box	Square	4(2.00×2.00)	16.90	0.83	2.89
KC CU1	15.000	Box	Square	5(2.00×2.00)	17.42	0.84	2.19
KC CU2	15.00	Box	Square	5(2.00×2.00)	15.00	1.70	2.19
BD1 CU2	1.890	Pipe	Circular	1Ø0.90	20.00	4.00	1.40
BD4 CU1	1.140	Pipe	Circular	2Ø0.90	28.00	4.67	0.98
BD10 CU1	0.102	Pipe	Circular	1Ø0.90	24.00	3.67	0.40
BD18 /4 CU1	0.256	Pipe	Circular	1Ø0.60	40.00	3.67	0.98
MD CU12	0.700	Pipe	Circular	2Ø0.90	34.00	4.33	0.94

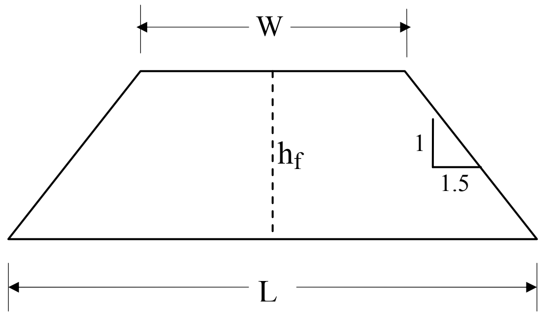
4.2.4 THE TOP WIDTH OF EMBANKMENT (W)

Generally, the top width of embankment (W) depends on both length of culverts(L) and the height of compacted fill (h_f) as shown in Fig.(4.1). It is calculated as:

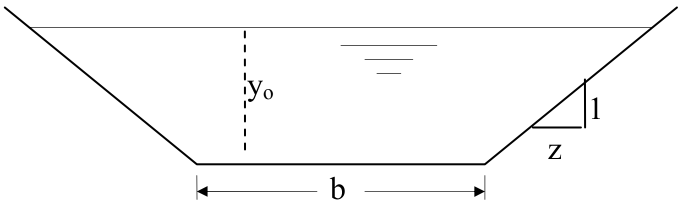
$$W = L - 3h_f \qquad (4.1)$$

4.2.5 CROSS–SECTIONAL AREA OF THE CHANNEL (A_C)

Channel cross–sectional area is a function of the respective discharge. On assuming steady–uniform flow through an open channel, Manning formula is applied in this regard. The best hydraulic section of a trapezoidal shape Fig. (4.2), is [Streeter and Wylie (1983)]:



Figure(4.1):Calculation of the top width of embankment.



Figure(4.2): Typical trapezoidal cross-section of a channel.

$$P = 2\sqrt{3}y_{\circ}, \qquad b = \frac{2\sqrt{3}y_{\circ}}{3}, \qquad A_C = \sqrt{3}y_{\circ}^{2}, \quad Z = \frac{\sqrt{3}}{3} \tag{4.2}$$

where:

P = wetted perimeter, (L) ;

$y_{\circ}$ = depth of flow, (L) ;

b = bottom width, (L) ;

A_C = cross–sectional flow area, (L^2);

Z = side slope.

On substituting $R\left(= A/p\right)$, where (R) is the hydraulic radius, in Manning equation, the result will be :

$$Q = \frac{1}{n_c}\sqrt{3}y_\circ^{2}\left(\frac{y_\circ}{2}\right)^{2/3} S^{1/2} \tag{4.3}$$

where:

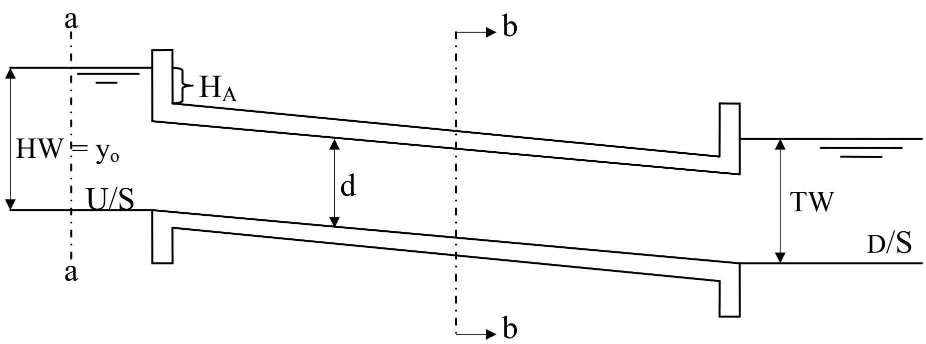
n_c = Manning roughness factor ;

S = the slope of the energy grade line, $(S = S_c)$,where (S_c is bed slope).

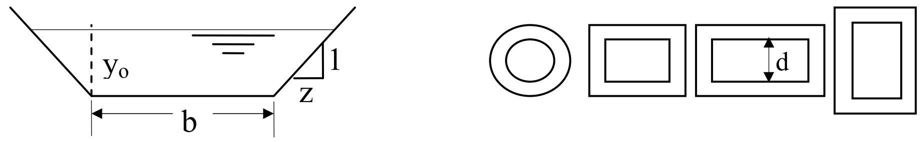
In this research, (n_c) has been taken as (0.025). As for (S_c), it has been taken as (0.00005) {as it is practically found in Hilla–Kifl project}.

4.2.6 THE HEADWATER (HW)

The headwater upstream of culvert serves in generating an active head (H_A) on the culvert. Actually, headwater represents the water depth of the upstream channel (y_o) as shown in Fig.(4.3), where (y_o) is taken from the cross–section of the respective channel. In the hypothetical case study of this research, (y_o) is calculated from Eq.(4.3).



[a]:Longitudinal section



[b]:Section(a-a) **[c]:Section(b-b)**

Figure(4.3): Section presentation of the headwater of the culvert.

4.2.7 CONSTANT DIMENSIONS OF HUNCHES (s, q, e, and g)

Referring to Figs.(3.2–c and d), the constant dimensions of lower and upper hunches, (s, q, e, and g), are taken equal to (50,30,20,and 30 cm), respectively [as suggested by Raju (1986)].

4.2.8 THICKNESS OF BEDDING (BLINDING LAYER) (a)

The thickness of bedding, [Figs.(3.2 and 3.5)] is usually taken as a specified value in the same project. It is equal to (10cm) in SC(1982) and Raju (1986). This same value has been considered in this research.

4.2.9 MANNING ROUGHNESS COEFFICIENT OF THE CULVERT(n)

In the suggested case study of this research, the Manning roughness coefficient of the culvert (n) is selected depending on culvert shape and materials as given in Table (2.3).

4.2.10 INLET AND OUTLET LOSS COEFFICIENTS (K_1 AND K_2)

In the suggested case study of this research, (K_1) and (K_2) have been taken as given in Tables (2.2 a and b).

4.2.11 INLET AND OUTLET TRANSITION LOSS COEFFICIENTS (K_i AND K_o)

Similar to (K_1) and (K_2), the respective values of (K_i) and (K_o) considered in this research were as given in Figs. (2.2), (2.3) and Table (2.1).

The aforementioned adapted values for the involved parameters are summarized in Table (4.3).

Table (4.3):Summary of suggested values of the parameters involved in the optimization process.

a- Variable parameters									b- Constant parameters		
Symbol	**Units**	**Values**							**Symbol**	**Units**	**Values**
Q	**(m^3/s)**	**0.5**	**1.0**	**1.5**	**2.5**	**5.0**	**10.0**	**15.0**	**h_f**	**(m)**	**1**
									a	**(m)**	**0.10**
y_o	**(m)**	**1.20**	**1.55**	**1.81**	**2.19**	**2.84**	**3.68**	**4.29**	**s**	**(m)**	**0.50**
									q	**(m)**	**0.30**
									e	**(m)**	**0.20**
A_c	**(m^2)**	**2.50**	**4.20**	**5.67**	**8.32**	**14.00**	**23.52**	**31.88**	**g**	**(m)**	**0.30**
L	**(m)**	**5**	**10**	**15**	**20**	**25**	**35**	**40**	**n**	—	**As given in Table (2.3).**
W	**(m)**	**2**	**7**	**12**	**17**	**22**	**32**	**37**	**$K_1$and K_2**	—	**As given in Tables (2.2a and b).**
									K_i and K_o	—	**As given in Figs. (2.2),(2.3) and Table(2.1)**

4.3 THE APPLIED OBJECTIVE FUNCTION

The final total objective functions, given by Eqs.(3.38, 3.39, 3.59, 3.62, 3.64, 3.66, 3.67, 3.68, 3.69, 3.70, 3.71, and 3.72) could be represented by the general form :

$$ZT_i = C_i + f\{X_i\} \qquad i = 1,2,...,n \tag{4.4}$$

In the optimization program, the process will consider minimizing $(Z'T_i)$ given by:

$$Z'T_i = ZT_i - C_i \tag{4.5}$$

Then the following matrices could be prepared :

$$[Z'T]_{i\times j} = [a]_{i\times k} . [X]_{k\times j}$$

where :

$Z'T$ = final total objective function used in the optimization process;

a = respective cost coefficients;

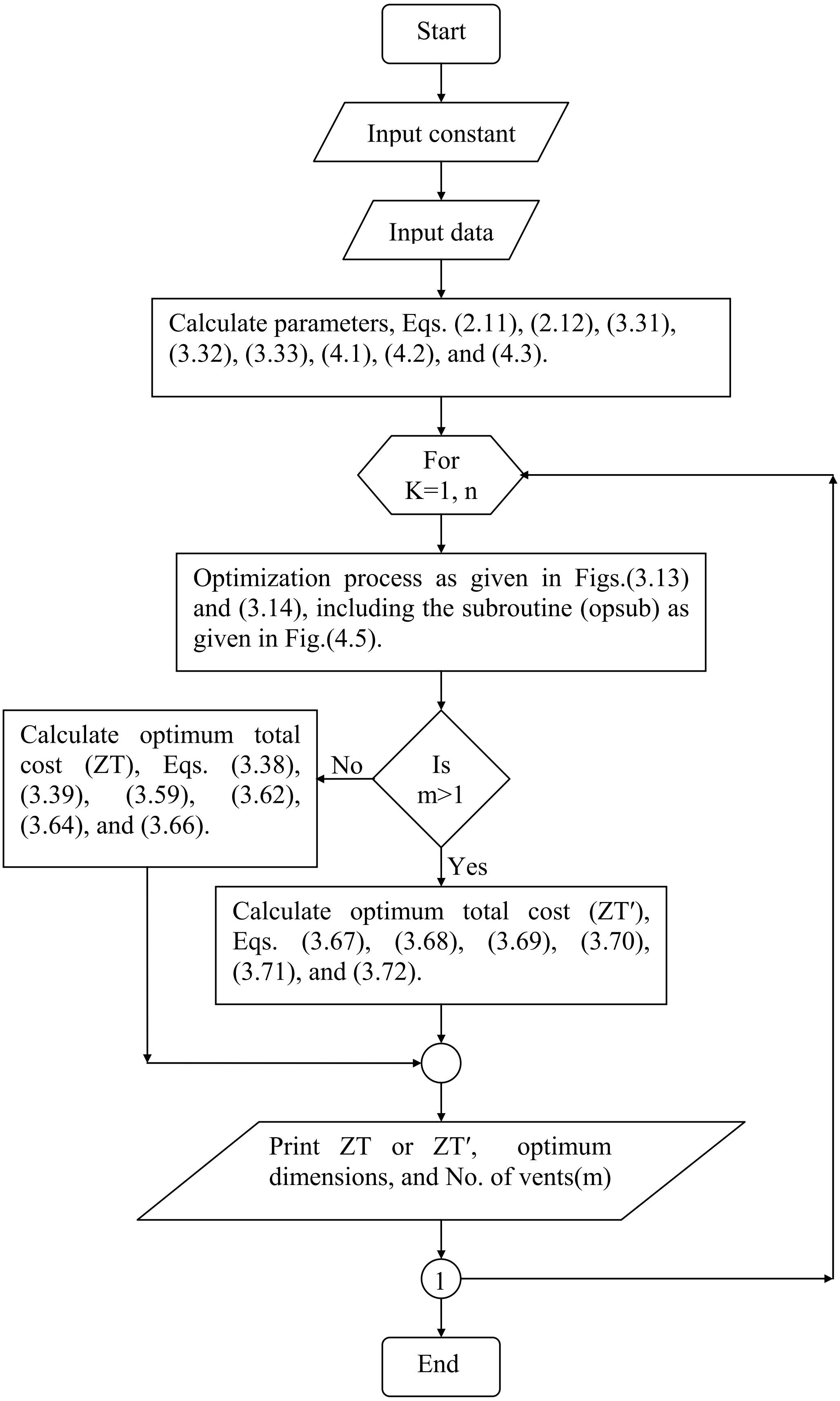
X = design variables.

4.4 THE COMPUTER PROGRAM

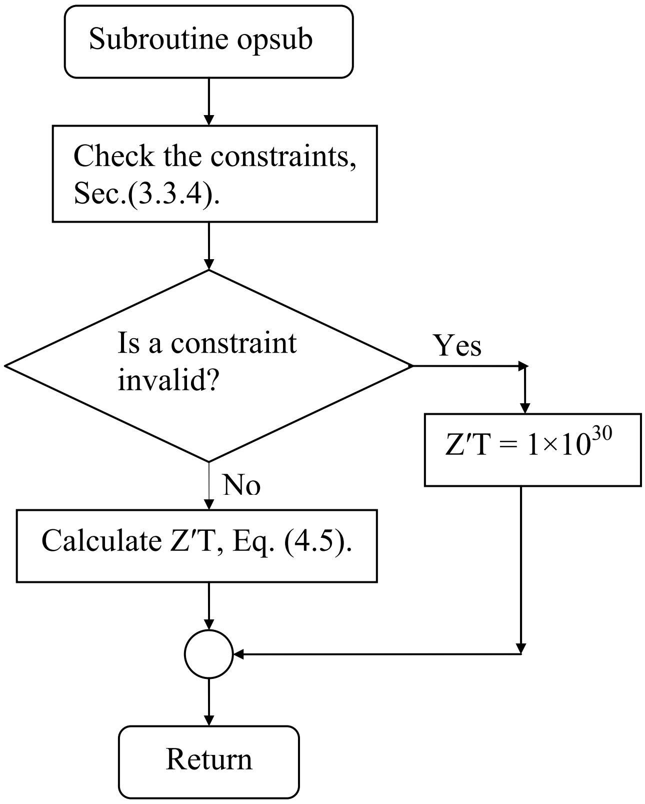
A computer program is developed to get the results from the input data. The flow chart of the respective program is shown in Figs.(4.4) and (4.5).

4.5 SOLUTION BY THE MODIFIED DIRECT SEARCH METHOD OF HOOKE AND JEEVES

The solution of the optimization problem by this method involves estimating of initial point (base point) and step length which must be within the range of constraints. However, more trial attempts should be made to get the optimum solution (minimum in this research), especially when the objective function has a local minimum and global minimum. This could be viewed from the sample data given in Table(4.4).



Figure(4.4):Flow chart of main program of the optimization process.



Figure(4.5): Flow chart of the subroutine program.

4.6 THE RESULTS

Sample results (indicating the optimum designs) are given in Table (4.5) for (Q=15.0 m^3/s) and for values of (L) in the range (5–40 m); the dimensions are set to the nearest (1cm) and costs to the nearest (\$10). Results for selected values of (Q) other than (15.0 m^3/s) are given in Appendix (A).

Table(4.4): Sample results of solution by modified Hooke and Jeeves of direct search method.

$Q(m^3/s)$	L(m)	Shape	Initial point estimate(m) b	d	Step	No. of exploration process	Optimum dimensions (m)	ZT($)
1.0	40	R.C. (rectangle)	0.75	0.75	0.4	169	0.75× 0.75	5070*
			0.75	0.77	0.7	715	0.75×0.75	5070
			0.77	0.75	0.4	585	0.75×0.75	5070
			0.75	0.75	0.7	169	0.75×0.75	5070
			0.75	0.75	0.2	169	0.75×0.75	5070
		R.C. (square)	0.75		0.4	169	0.75×0.75	5070*
			0.77		0.7	715	0.75×0.75	5070
			0.75		0.7	169	0.75×0.75	5070
			0.77		0.4	585	0.75×0.75	5070
			0.75		0.2	169	0.75×0.75	5070
		R.C. (circle)	0.60		0.2	169	1Ø0.82	14120*
			0.67		0.7	212	1Ø0.82	14120
			0.60		0.4	169	1Ø0.60	1×10^{30}***
		Cast-iron (circle)	0.90		0.7	760	1Ø0.93	16300*
			0.90		0.4	539	1Ø0.93	16300
		Asbestos-cement (circle)	0.67		0.7	756	1Ø0.82	12040*
			0.60		0.2	169	1Ø0.82	12040
			0.60		0.4	169	1Ø0.60	1×10^{30}***
		Ductie-steel (circle)	0.90		0.7	760	1Ø0.93	18360*
			0.90		0.4	539	1Ø0.93	18360
5.0	25	R.C. (rectangle)	1.20	1.20	0.4	646	1.42×1.07	9780*
			1.00	1.20	0.4	473	1.35×1.50	9870 }
			1.20	1.00	0.4	516	1.55×0.95	9890 } **
			2.20	1.00	0.4	429	1.66×0.87	10190 }
		R.C. (square)	0.80		0.7	713	2(0.80×0.80)	8430*
			1.00		0.4	735	2(0.80×0.80)	8430 }
			0.78		0.4	689	2(0.80×0.80)	8430 } **
			1.00		0.7	626	2(0.80×0.80)	8430 }
			2.20		0.3	169	(2.20×2.20)	1×10^{30}***
		R.C. (circle)	1.90		0.4	648	2Ø1.04	54720*
			2.00		0.7	169	1Ø2.00	1×10^{30}***
15.0	5	R.C. (rectangle)	2.20	1.00	0.4	602	2.51×1.00	9590*
			2.20	1.40	0.7	558	2.10×1.24	10450 }
			1.00	2.20	0.7	3821	1.75×1.58	12290 } **
			2.20	2.20	0.4	498	1.67×1.68	12900 }
			1.00	2.20	0.4	162	1.00×2.20	1×10^{30}***
		R.C. (square)	1.20		0.4	650	2(1.31×1.31)	11324*
			1.68		0.7	520	2(1.31×1.31)	11324
			1.75		0.4	672	2(1.31×1.31)	11324
		R.C. (circle)	2.30		0.4	802	3Ø1.13	25150*
			2.20		0.2	584	3Ø1.13	25150
			0.77		0.7	735	3Ø1.13	25150

* : Global minimum.

** : Local minimum.

*** : Out of range of constraints.

Table(4.5): Sample of final optimum results(Q=15.0m^3/s).

L(m) / Q(m^3/s)		5			10			15		
		Shape and material	Dimensions, (m), and No. of vents	Cost ($)	Shape and material	Dimensions, (m), and No. of vents	Cost ($)	Shape and material	Dimensions, (m), and No. of vents	Cost ($)
15.0	1	R.C.	1(2.51×1.00)	9590	R.C.	1(2.74×0.93)	13220	R.C.	1(1.84×1.54)	17370
	2	R.C.	2(1.31×1.31)	11320	R.C.	2(1.33×1.33)	14700	R.C.	2(1.36×1.36)	18230
	3	R.C.	3Ø1.13	25150	R.C.	3Ø1.14	44110	R.C.	3Ø1.15	63690
	4	Cast-iron	3Ø1.15	14470	Cast-iron	3Ø1.18	22660	Cast-iron	3Ø1.20	31340
	5	Asbestos cement	3Ø1.13	13400	Asbestos-cement	3Ø1.14	20180	Asbestos-cement	3Ø1.15	27150
	6	Ductile-Steel	3Ø1.15	16020	Ductile-Steel	3Ø1.18	25980	Ductile-Steel	3Ø1.12	36630

Continued …

20			25			35			40		
Shape and material	Dimensions, (m),and No. of vents	Cost ($)	Shape and material	Dimensions, (m), and No. of vents	Cost ($)	Shape and material	Dimensions, (m),and No. of vents	Cost ($)	Shape and material	Dimensions, (m),and No. of vents	Cost ($)
R.C. ▭	1(2.10×1.33)	19390	R.C. ▭	1(2.12×1.34)	22480	R.C. ▭	1(2.10×1.41)	28860	R.C. ▭	1(2.12×1.42)	32140
R.C. □	2(1.38×1.38)	21910	R.C. □	2(1.40×1.40)	25710	R.C. □	2(1.42×1.42)	33670	R.C. □	2(1.44×1.44)	37800
R.C. ○	3Ø1.16	83850	R.C. ○	3Ø1.17	104580	R.C. ○	3Ø1.19	147700	R.C. ○	3Ø1.20	170050
Cast-Iron ○	3Ø1.23	40460	Cast-Iron ○	3Ø1.25	50010	Cast-Iron ○	4Ø1.12	72950	Cast-Iron ○	4Ø1.14	84210
Asbestos -cement ○	3Ø1.16	34280	Asbestos-cement ○	3Ø1.17	41590	Asbestos cement ○	3Ø1.19	56700	Asbestos cement ○	3Ø1.20	64480
Ductile-Steel ○	3Ø1.23	47930	Ductile-Steel ○	3Ø1.25	59850	Ductile-Steel ○	4Ø1.12	86150	Ductile-Steel ○	4Ø1.14	100000

4.7 ANALYSIS OF THE RESULTS

4.7.1 CASES OF COMPARISON

In analyzing the results, the following cases of comparison have been considered:

[A] The optimum cost as a function of (Q) for different (selected) values of (L). The results are shown graphically in Figs.(4.6) to (4.12).

[B] Ditto, as a function of (L) for different specified values of (Q). The results are shown graphically in Figs. (4.13) to (4.19).

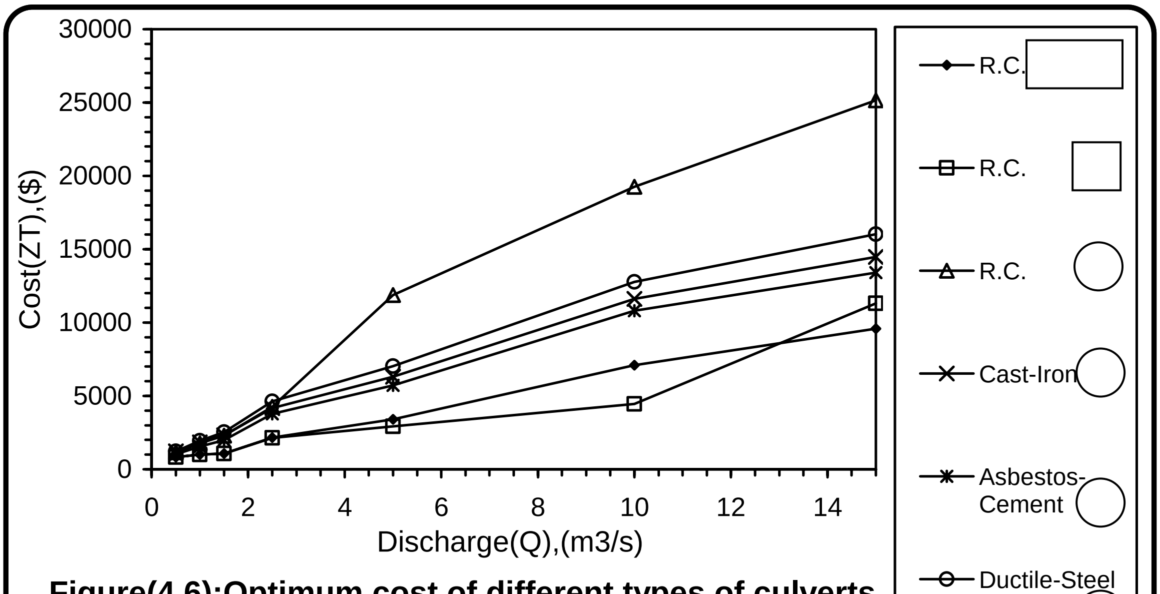
[C] Same as in [A] to find optimum number of vents. The results are shown graphically in Figs. (4.20) to (4.26).

[D] Ditto, but for the analysis in [B]. The results are shown graphically in Figs.(4.27) to (4.33).

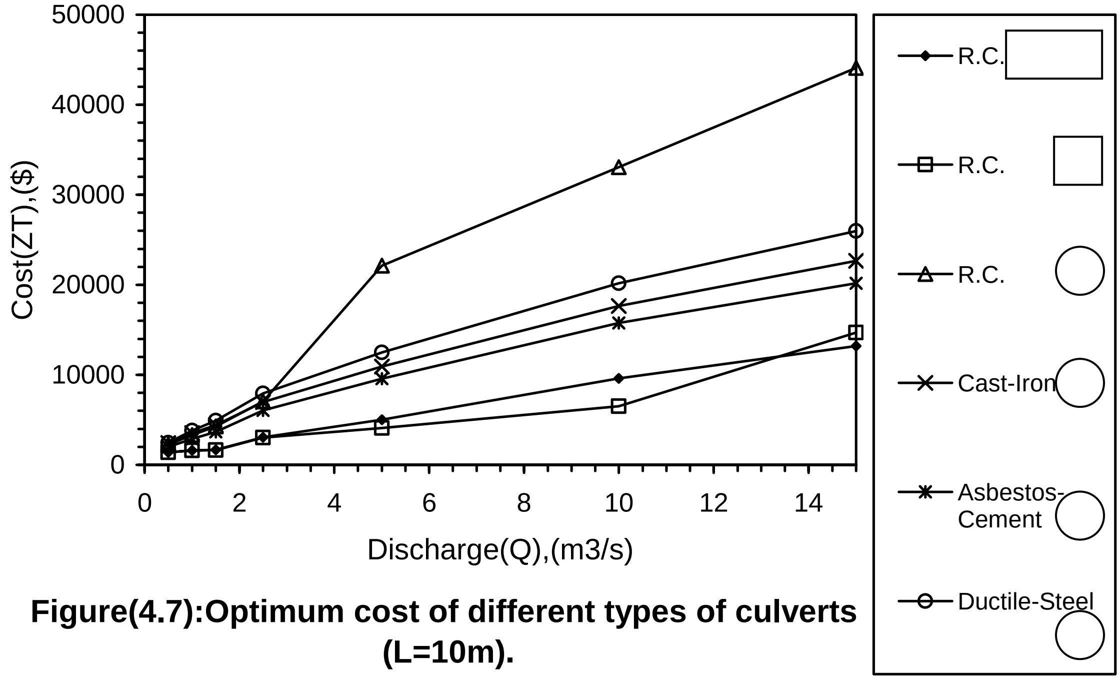
[E] Same as in [A] to find the optimum dimensions of different types of Culvert. The results are shown graphically in Figs.(4.34) to (4.39).

[F] Ditto, but for the analysis in [B]. The results are shown graphically in Figs.(4.40) to (4.45).

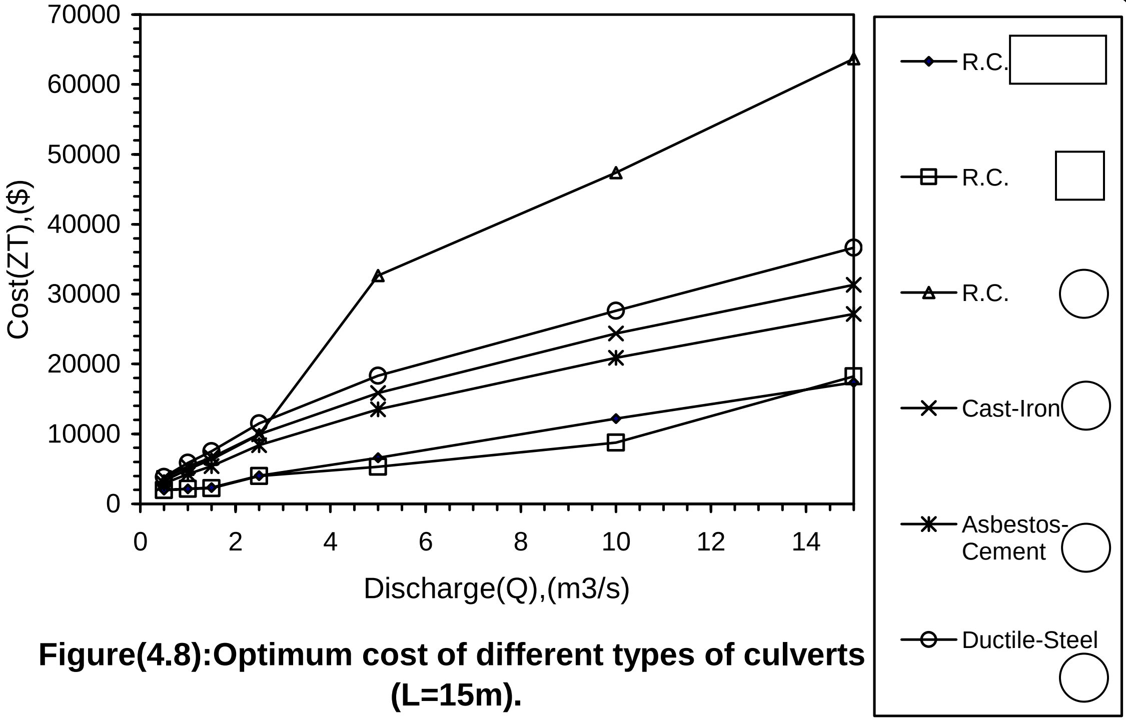
[G] Final summary of optimum results is given in Table (4.6).



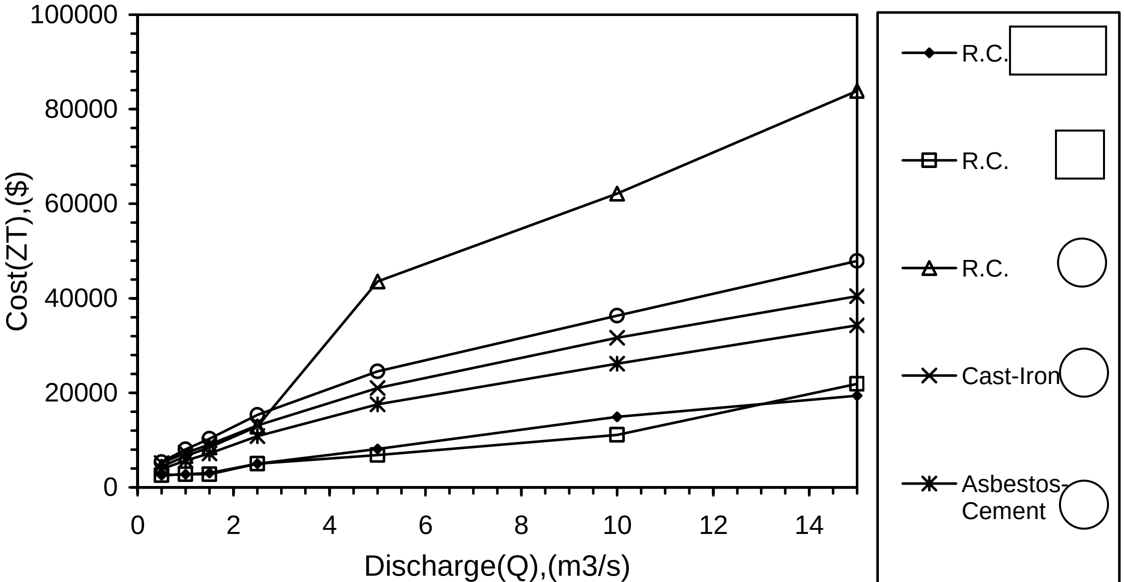
Figure(4.6):Optimum cost of different types of culverts (L=5m).



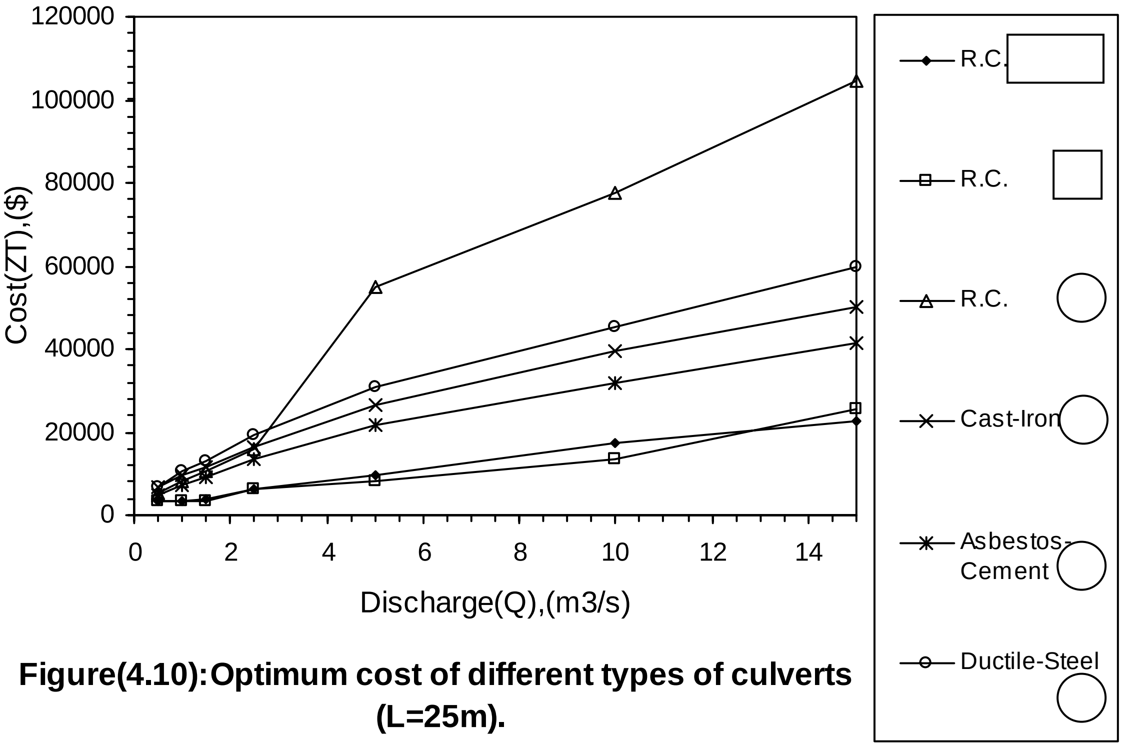
Figure(4.7):Optimum cost of different types of culverts (L=10m).



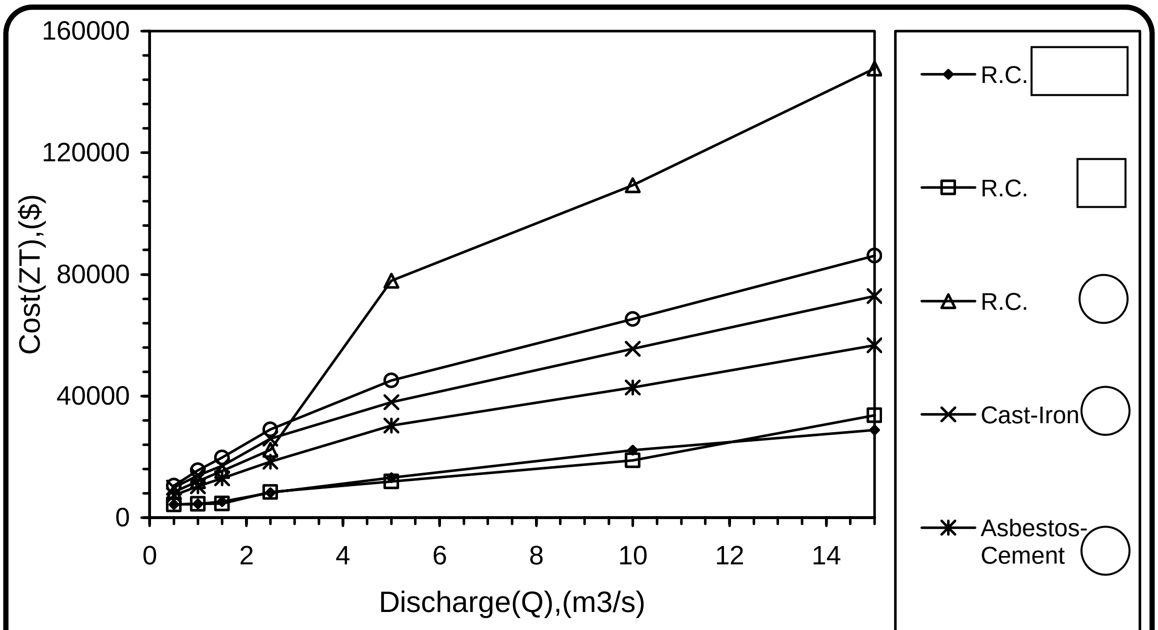
Figure(4.8):Optimum cost of different types of culverts (L=15m).



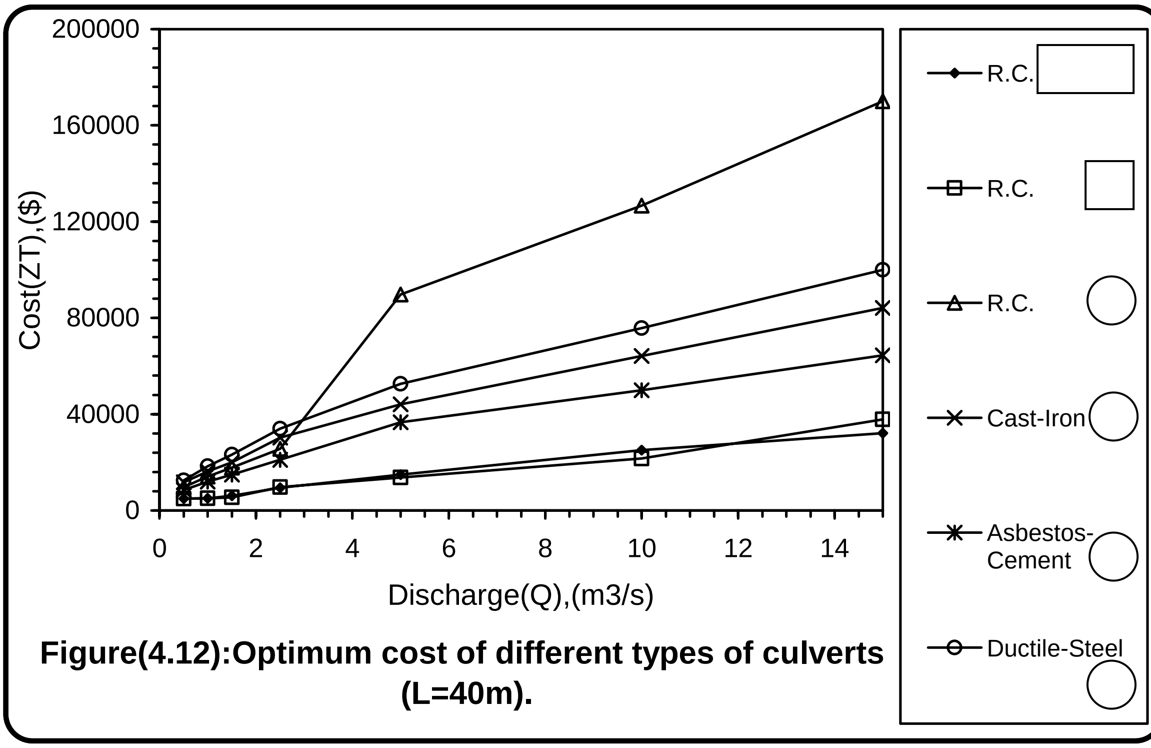
Figure(4.9):Optimum cost of different types of culverts (L=20m).



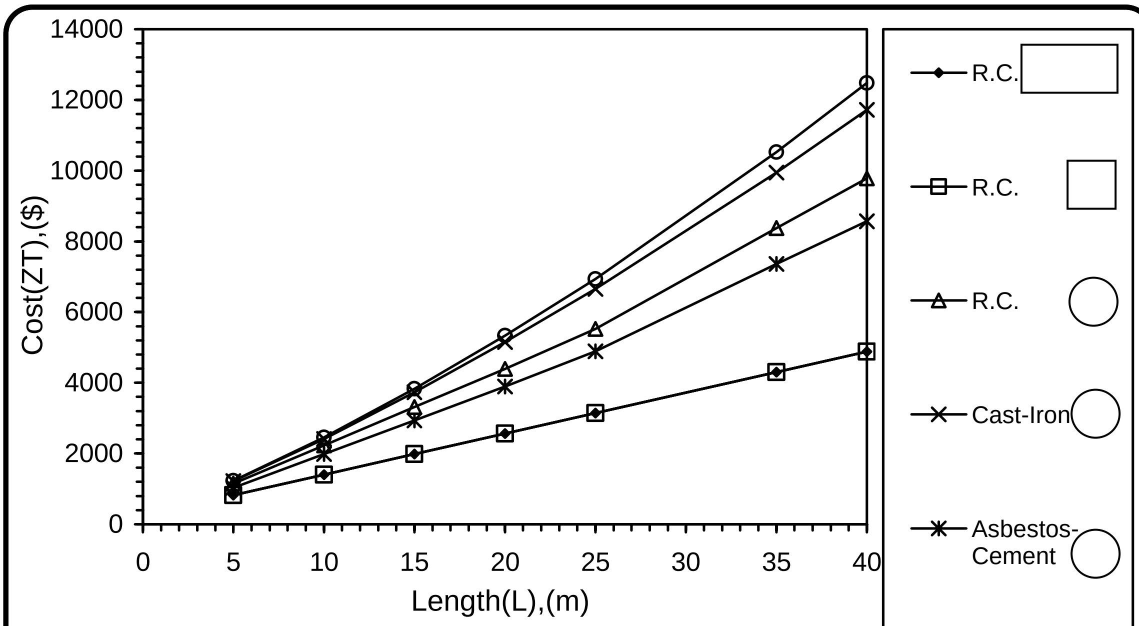
Figure(4.10):Optimum cost of different types of culverts (L=25m).



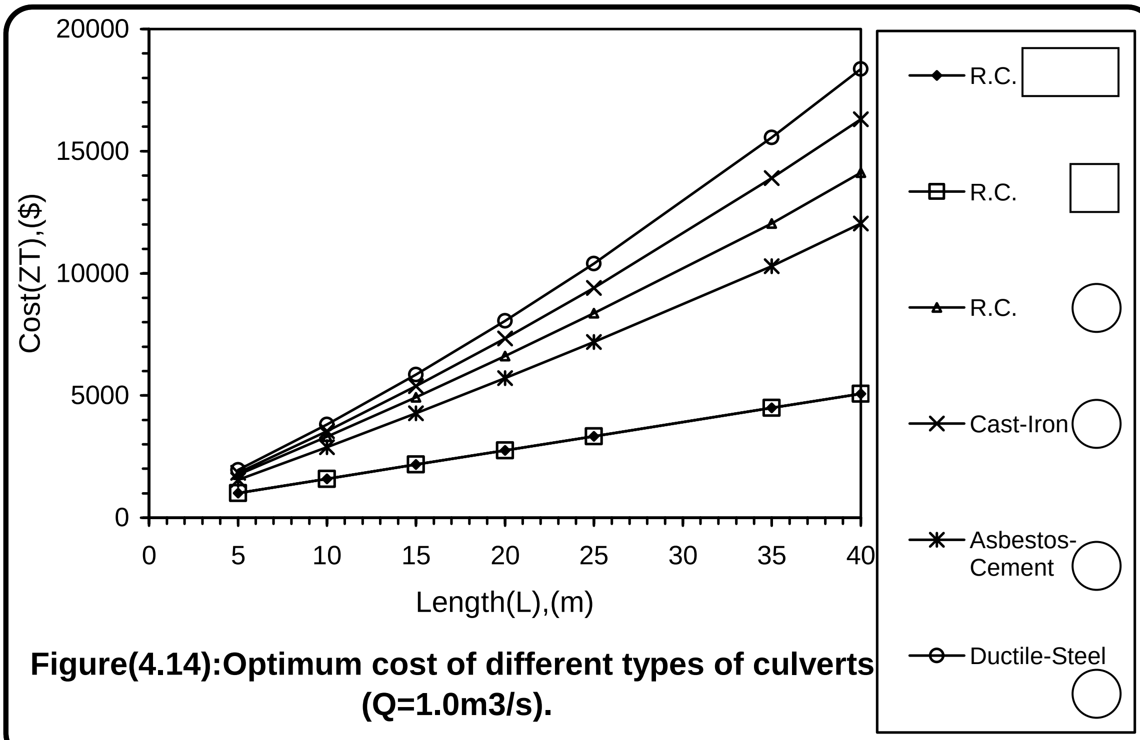
Figure(4.11):Optimum cost of different types of culverts (L=35m).



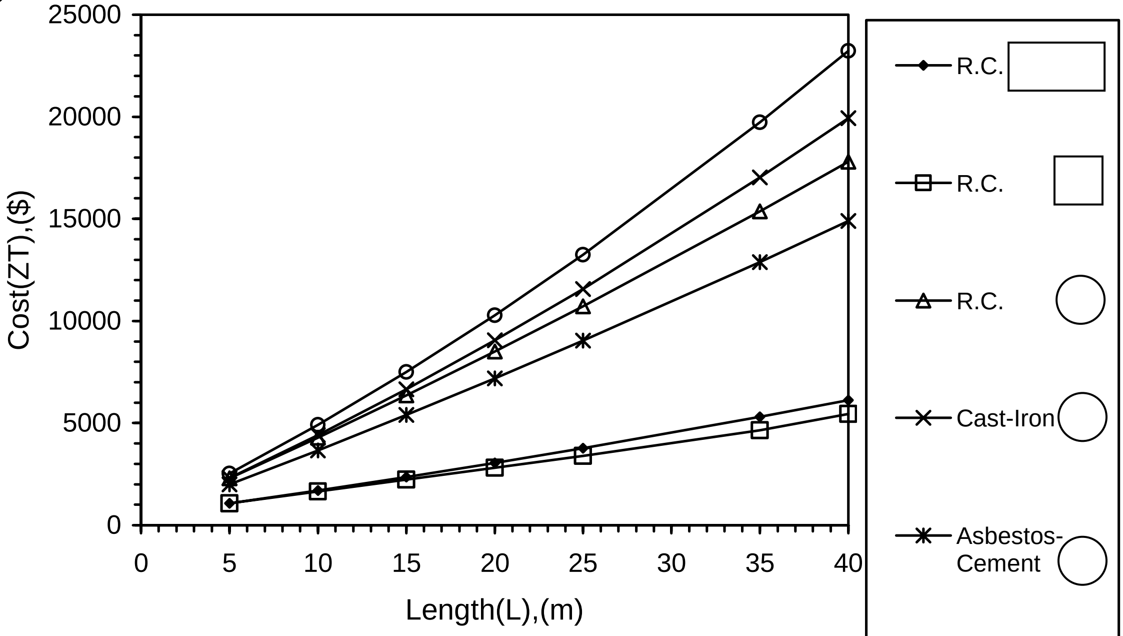
Figure(4.12):Optimum cost of different types of culverts (L=40m).



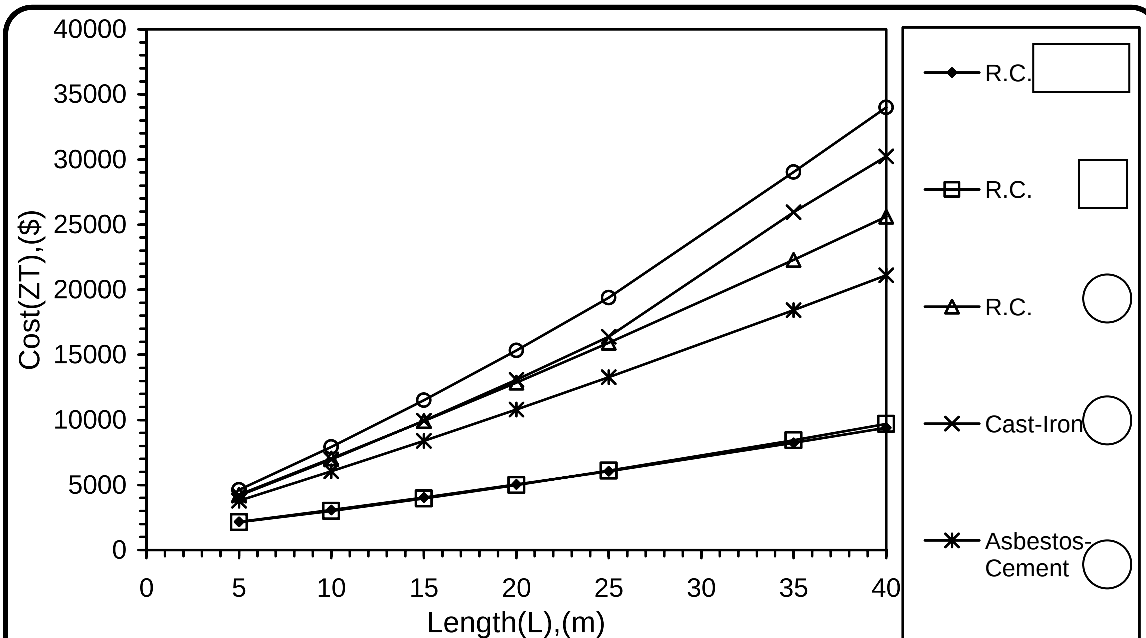
Figure(4.13):Optimum cost of different types of culverts (Q=0.5m3/s).



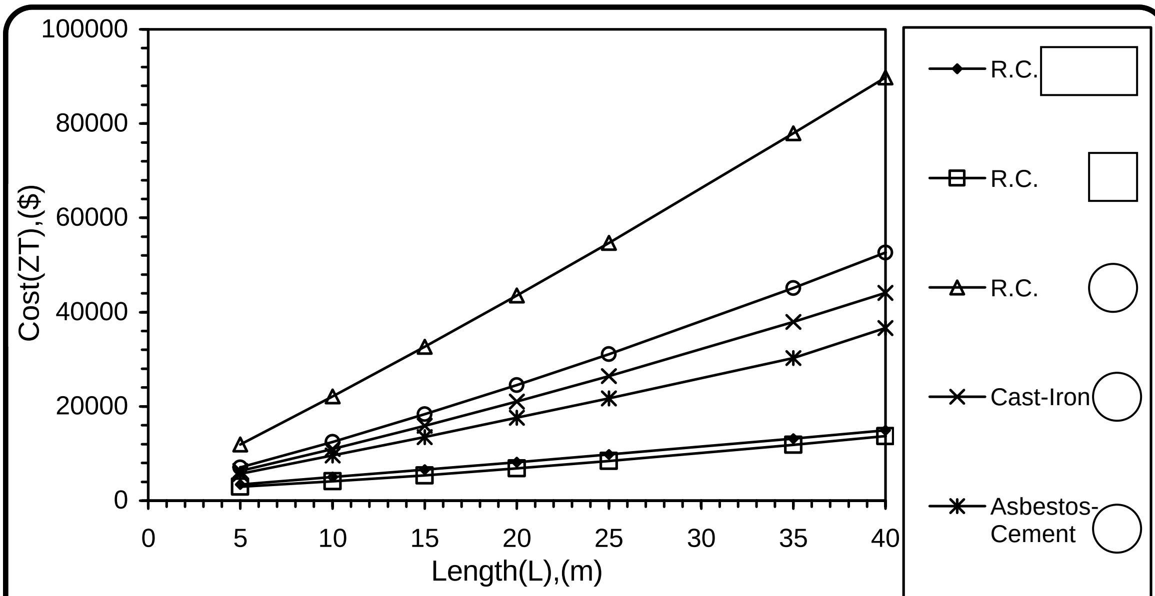
Figure(4.14):Optimum cost of different types of culverts (Q=1.0m3/s).



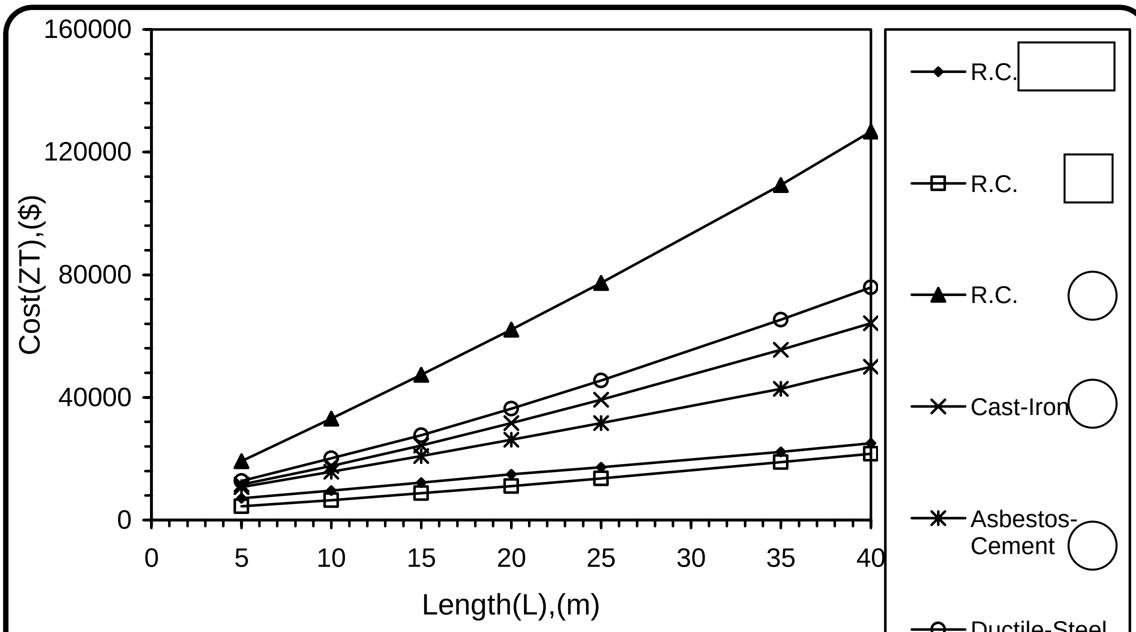
Figure(4.15):Optimum cost of different types of culverts (Q=1.5m3/s).



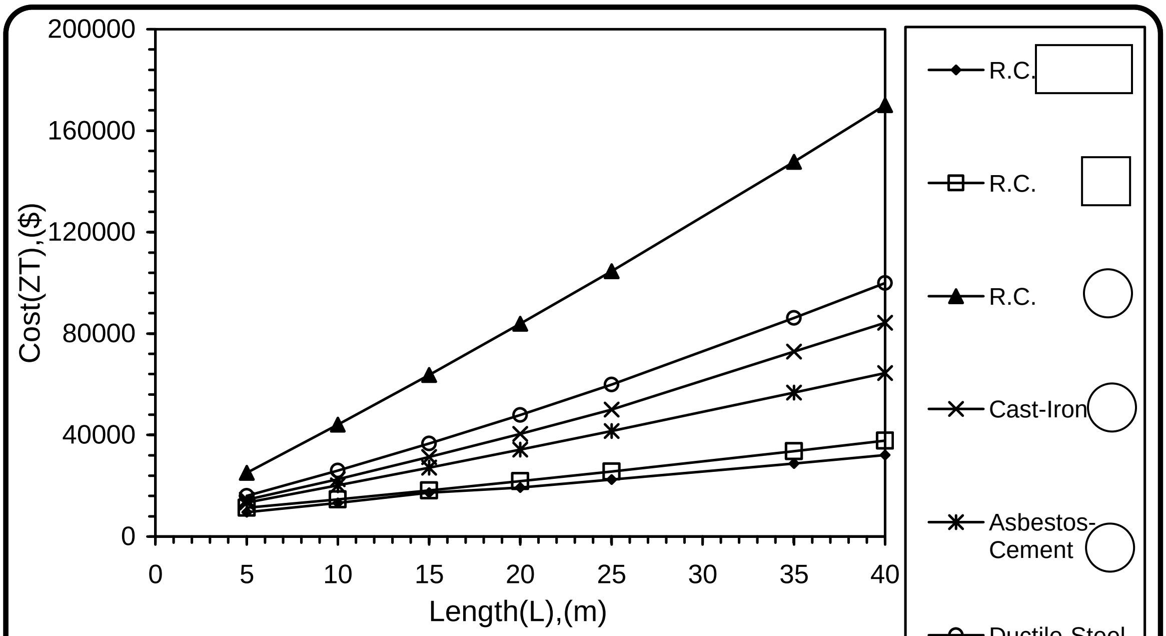
Figure(4.16):Optimum cost of different types of culverts (Q=2.5m3/s).



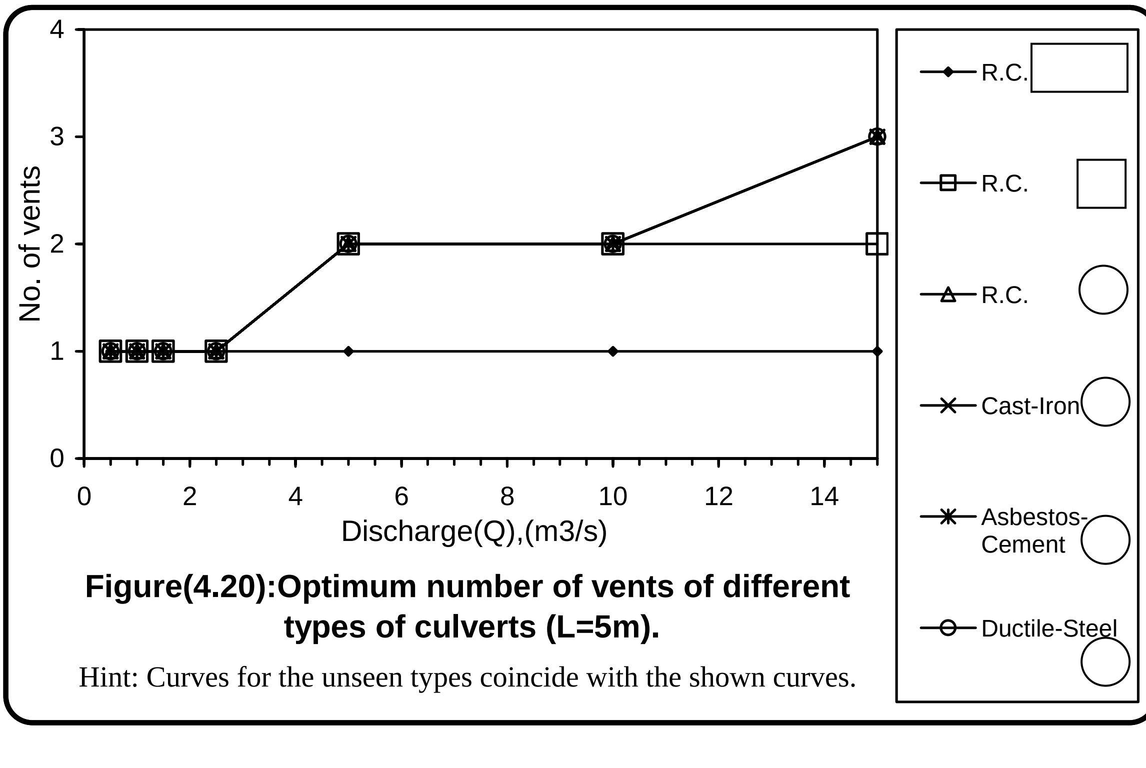
Figure(4.17):Optimum cost of different types of culverts (Q=5.0m3/s).



Figure(4.18):Optimum cost of different types of culverts (Q=10.0m3/s).

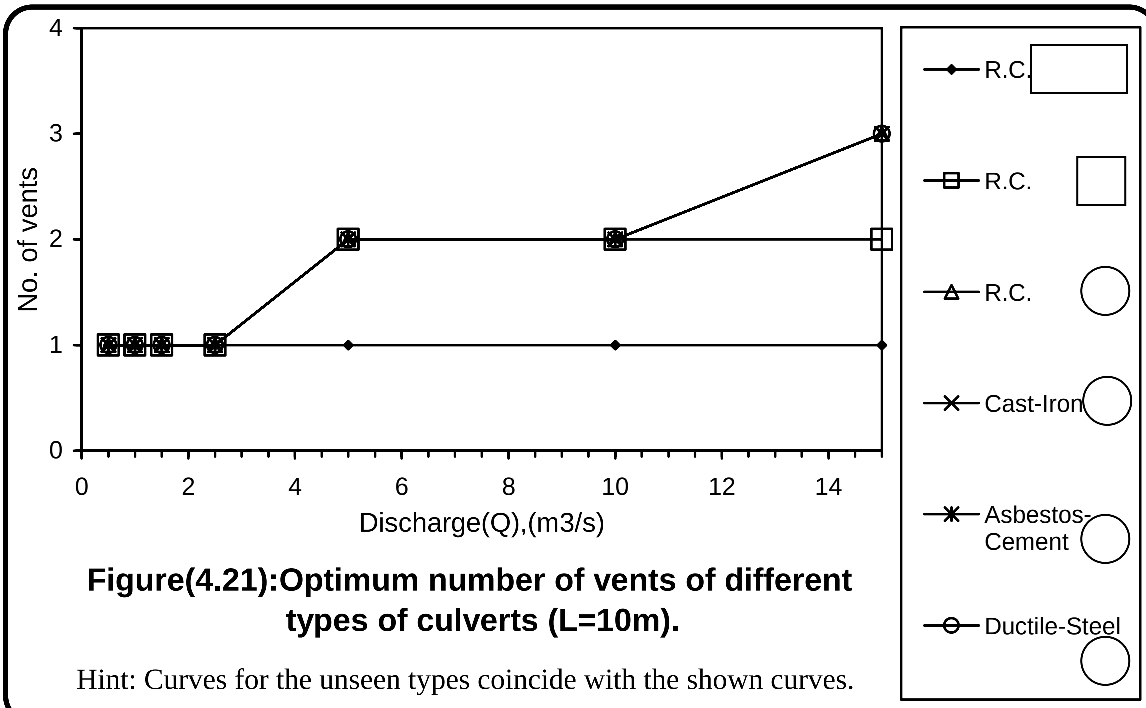


Figure(4.19):Optimum cost of different types of culverts (Q=15.0m3/s).



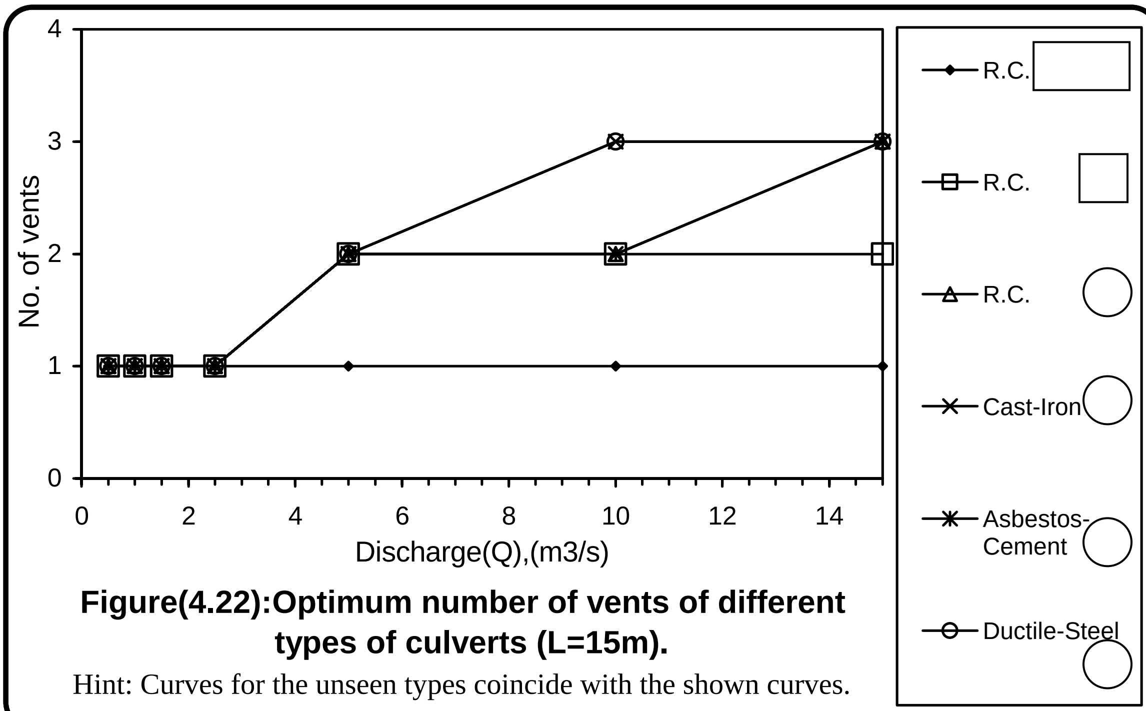
Figure(4.20):Optimum number of vents of different types of culverts (L=5m).

Hint: Curves for the unseen types coincide with the shown curves.



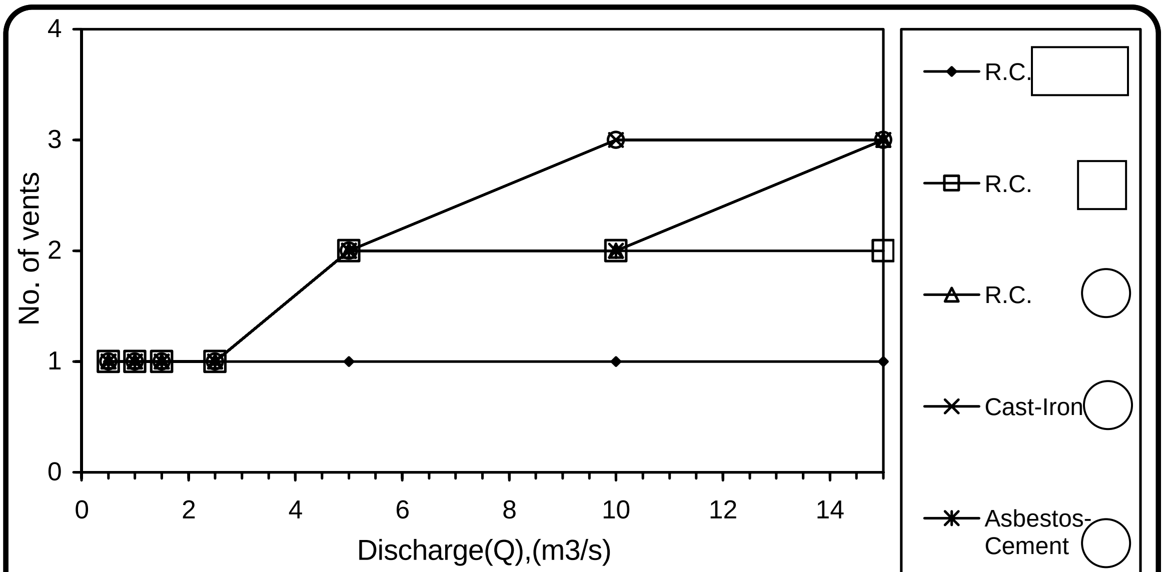
Figure(4.21):Optimum number of vents of different types of culverts (L=10m).

Hint: Curves for the unseen types coincide with the shown curves.



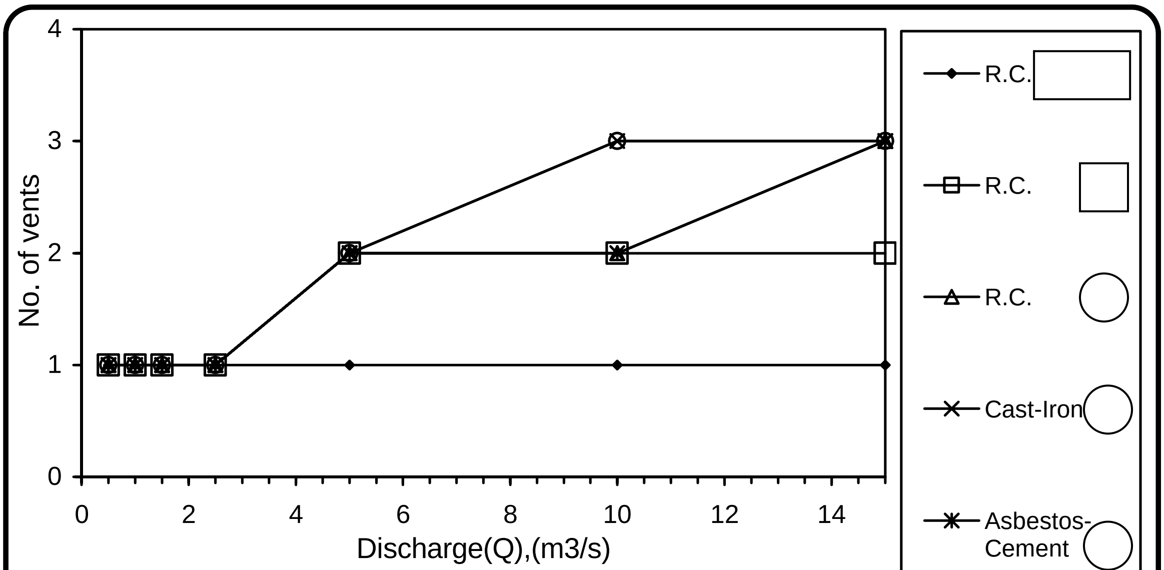
Figure(4.22):Optimum number of vents of different types of culverts (L=15m).

Hint: Curves for the unseen types coincide with the shown curves.



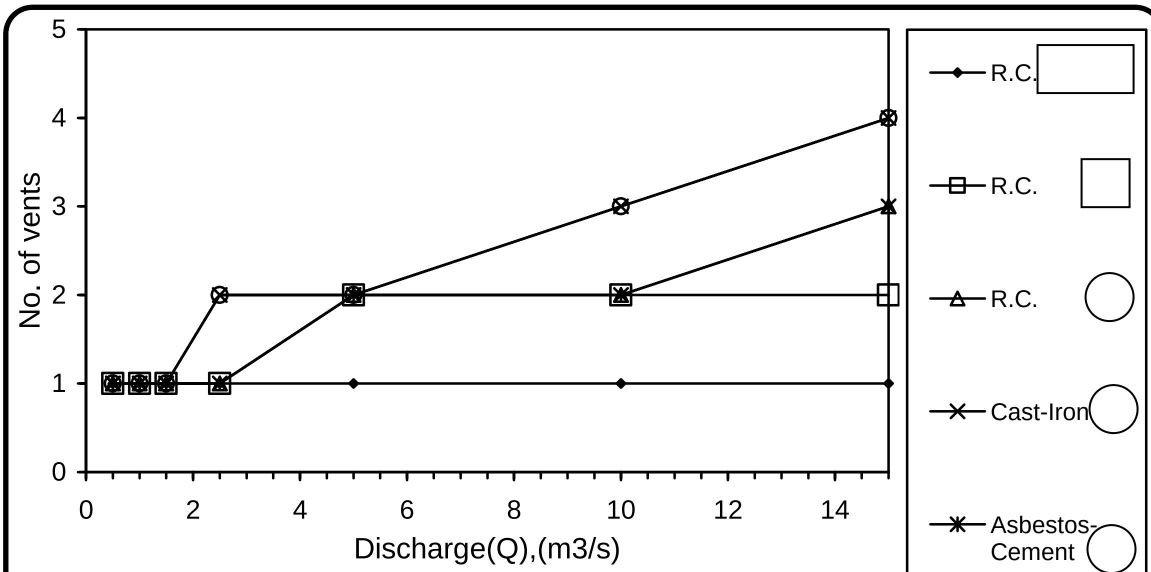
Figure(4.23):Optimum number of vents of different types of culverts (L=20m).

Hint: Curves for the unseen types coincide with the shown curves.



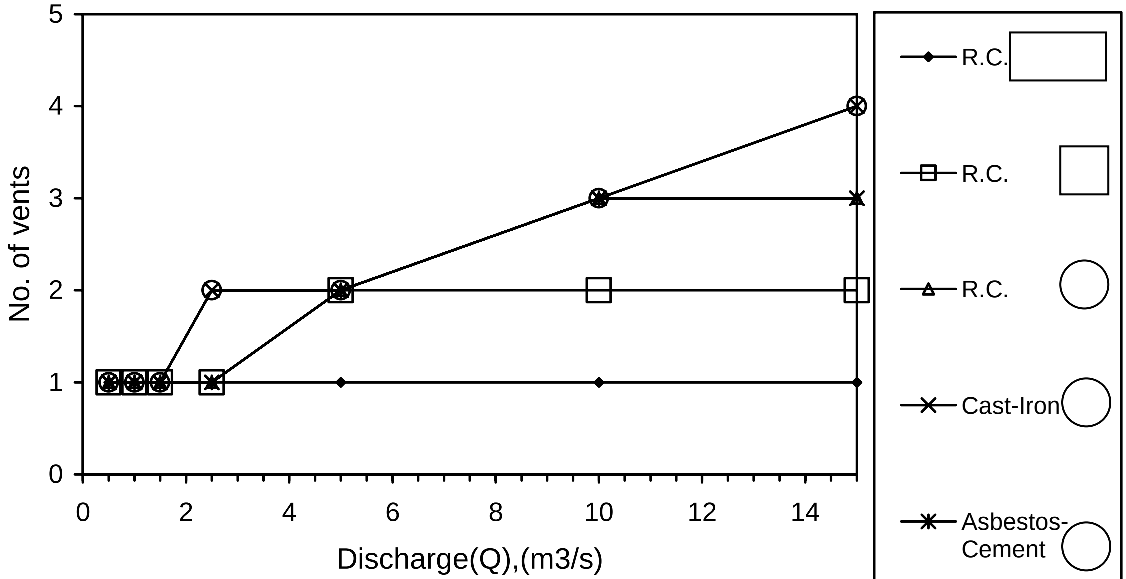
Figure(4.24):Optimum number of vents of different types of culverts (L=25m).

Hint: Curves for the unseen types coincide with the shown curves.



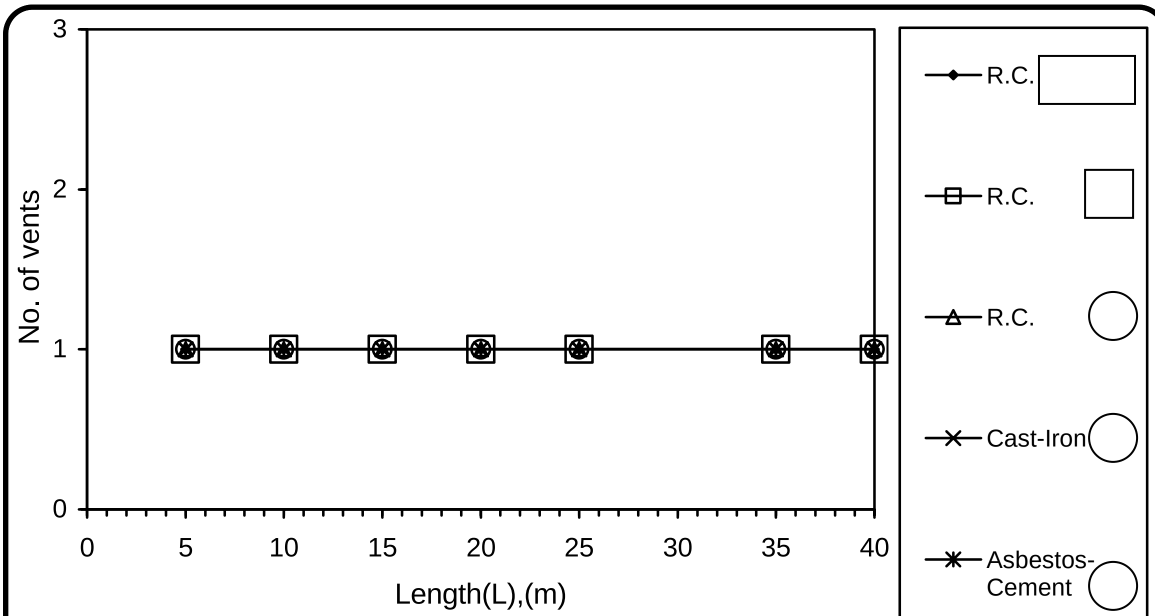
Figure(4.25):Optimum number of vents of different types of culverts (L=35m).

Hint: Curves for the unseen types coincide with the shown curves.



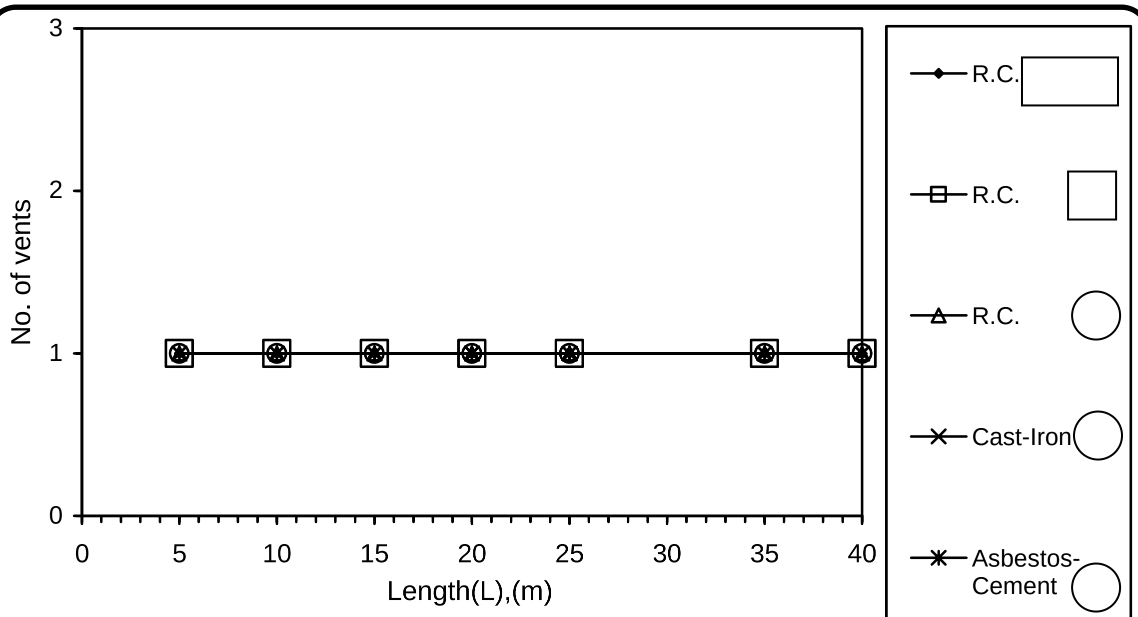
Figure(4.26):Optimum number of vents of different types of culverts (L=40m).

Hint: Curves for the unseen types coincide with the shown curves.



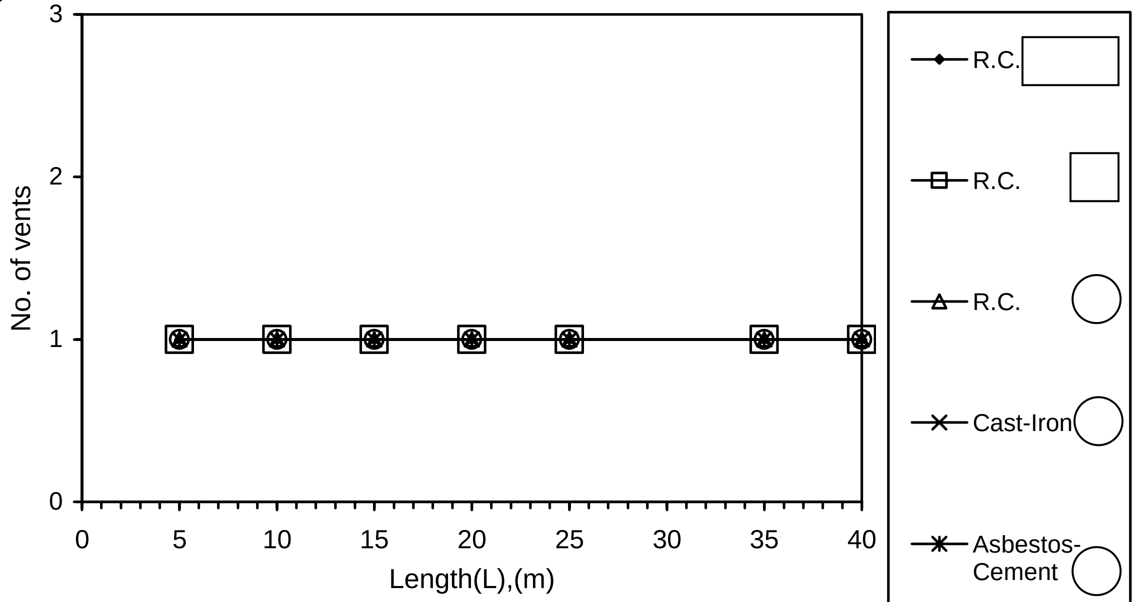
Figure(4.27):Optimum number of vents of different types of culverts (Q=0.5m3/s).

Hint: Curves for the unseen types coincide with the shown curve.



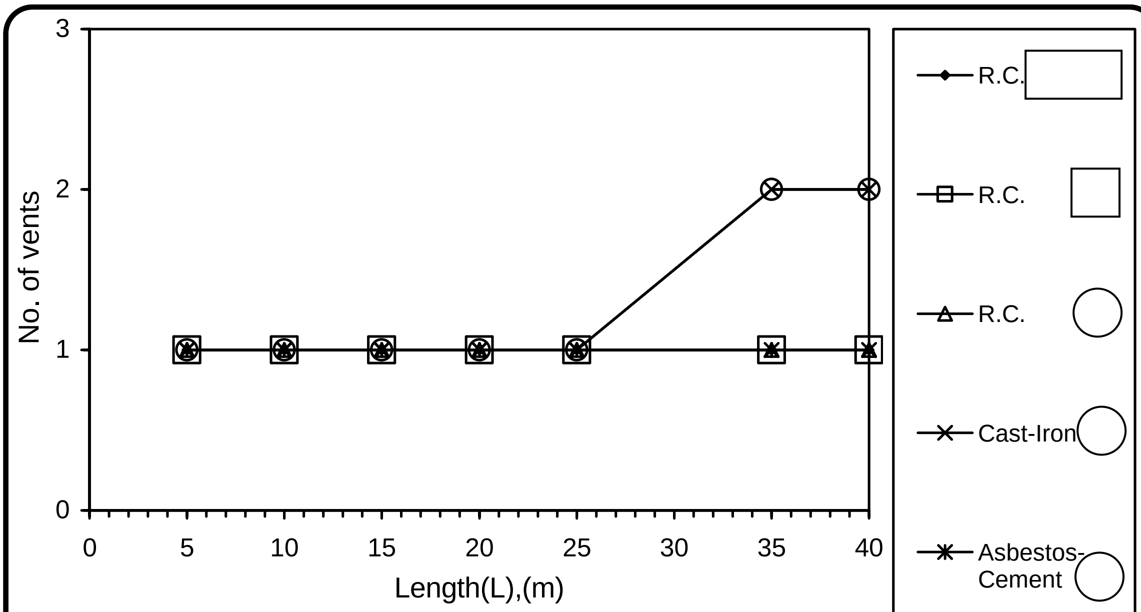
Figure(4.28):Optimum number of vents of different types of culverts (Q=1.0m3/s).

Hint: Curves for the unseen types coincide with the shown curve.



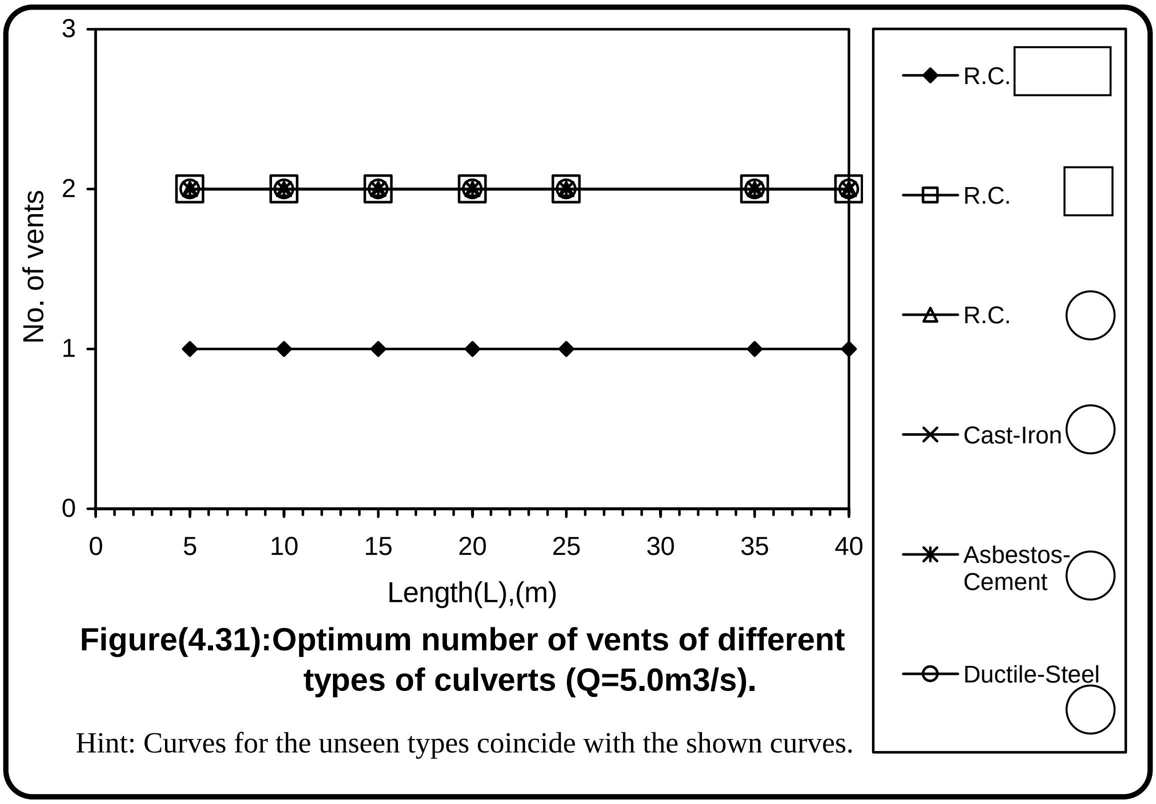
Figure(4.29):Optimum number of vents of different types of culverts (Q=1.5m3/s).

Hint: Curves for the unseen types coincide with the shown curve.



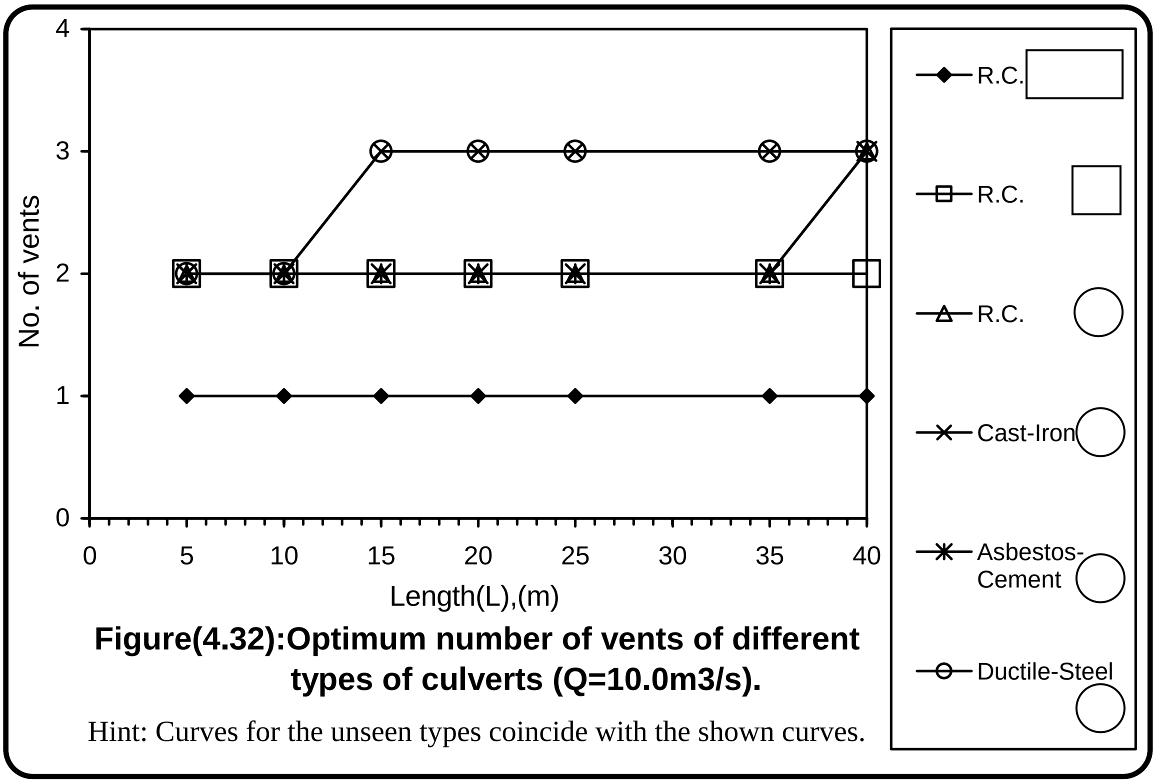
Figure(4.30):Optimum number of vents of different types of culverts (Q=2.5m3/s).

Hint: Curves for the unseen types coincide with the shown curves.



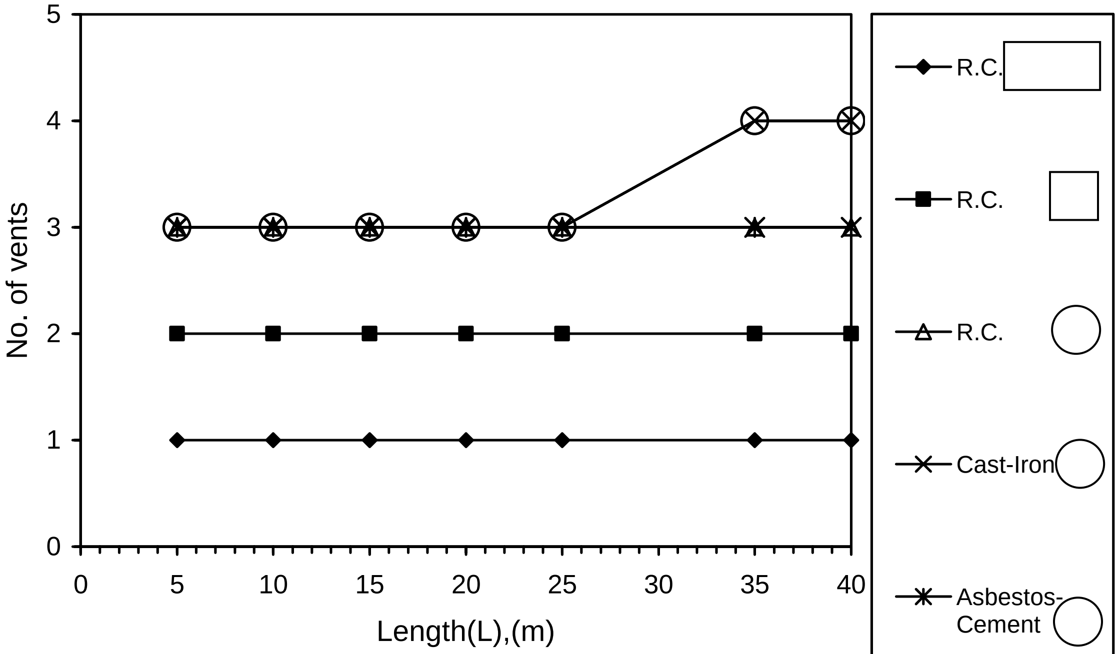
Figure(4.31):Optimum number of vents of different types of culverts (Q=5.0m3/s).

Hint: Curves for the unseen types coincide with the shown curves.



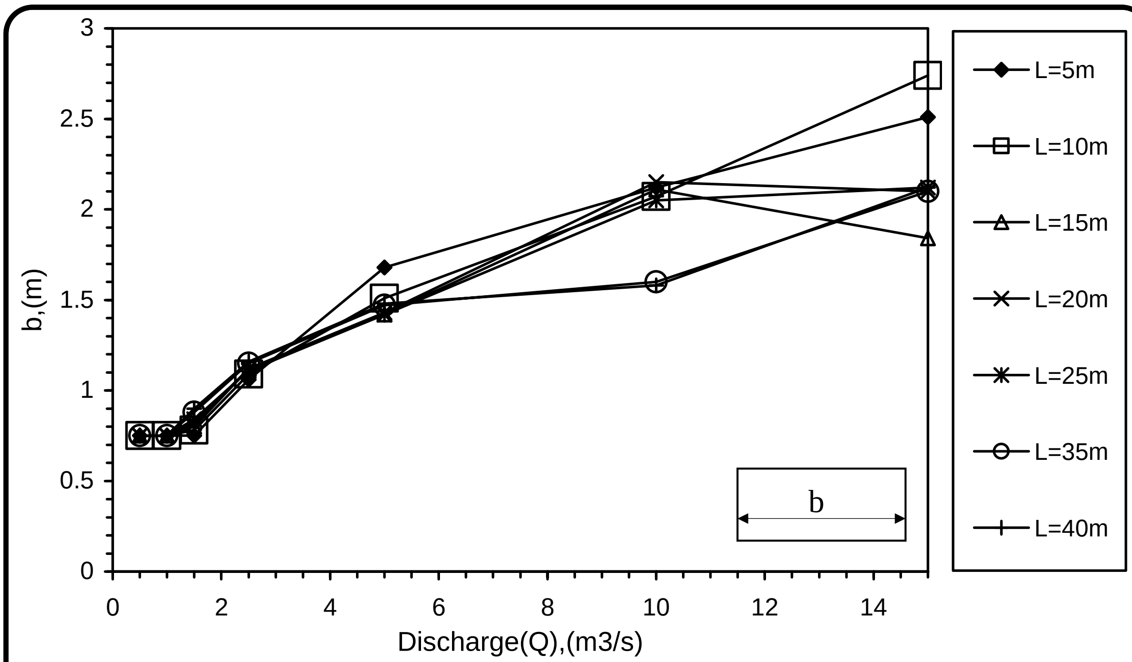
Figure(4.32):Optimum number of vents of different types of culverts (Q=10.0m3/s).

Hint: Curves for the unseen types coincide with the shown curves.

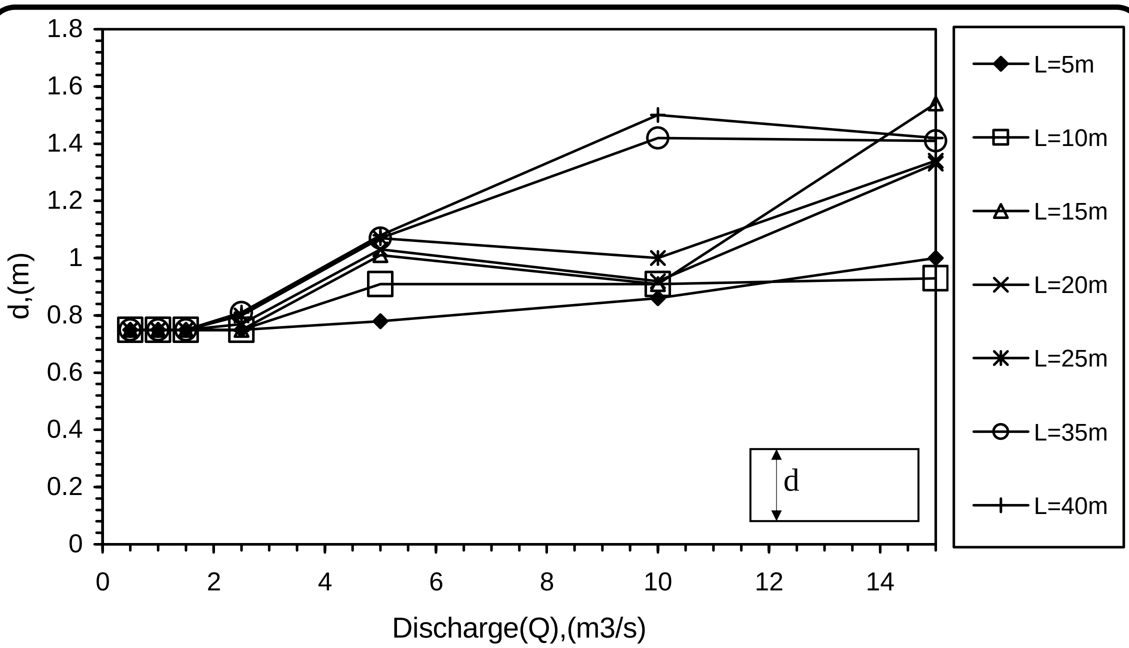


Figure(4.33):Optimum number of vents of different types of culverts (Q=15.0m3/s).

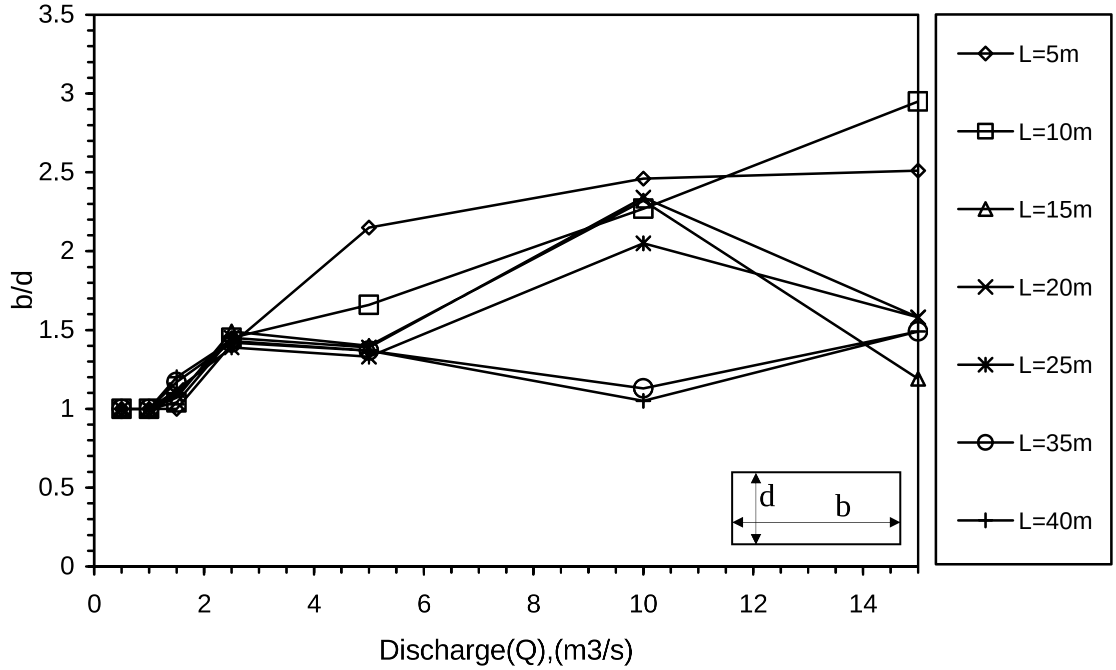
Hint: Curves for the unseen types coincide with the shown curves.



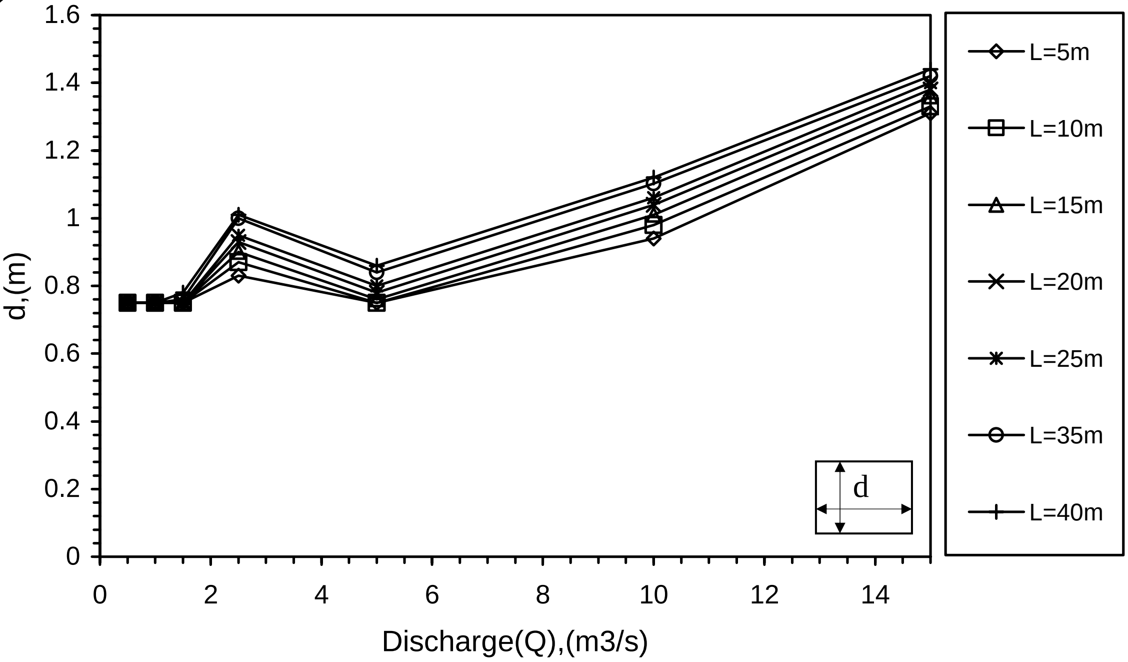
Figure(4.34a):Optimum dimension (b) of R.C., rctangular box culverts.



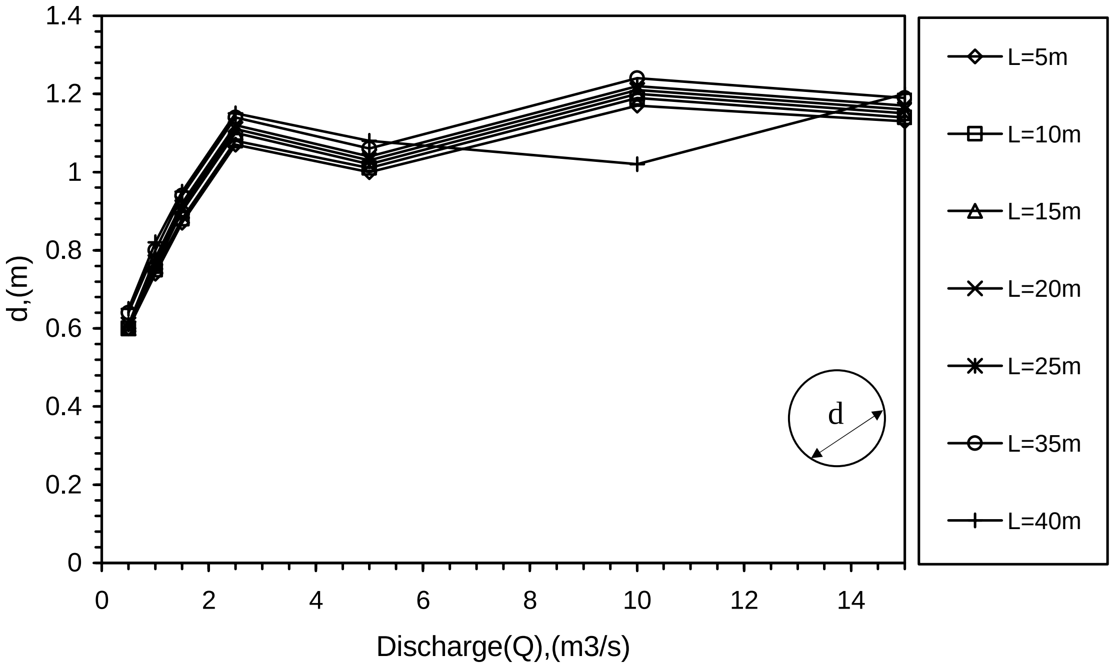
Figure(4.34b):Optimum dimension (d) of R.C., rectangular box culverts.



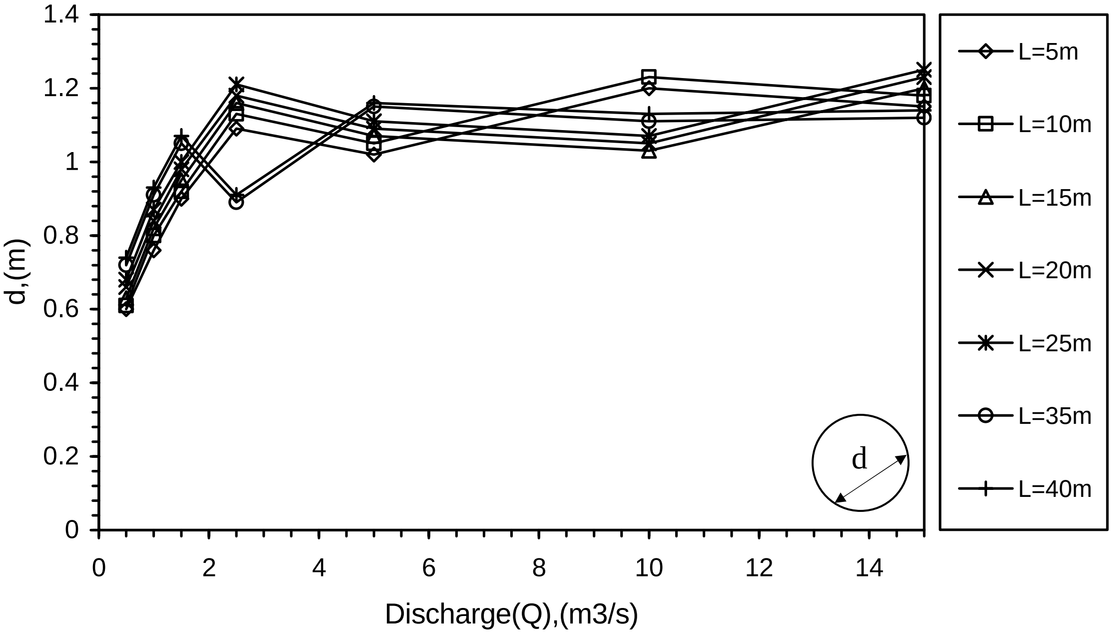
Figure(4.34c):Optimum dimensions ratio (b/d) of R.C., rectangular box culverts.



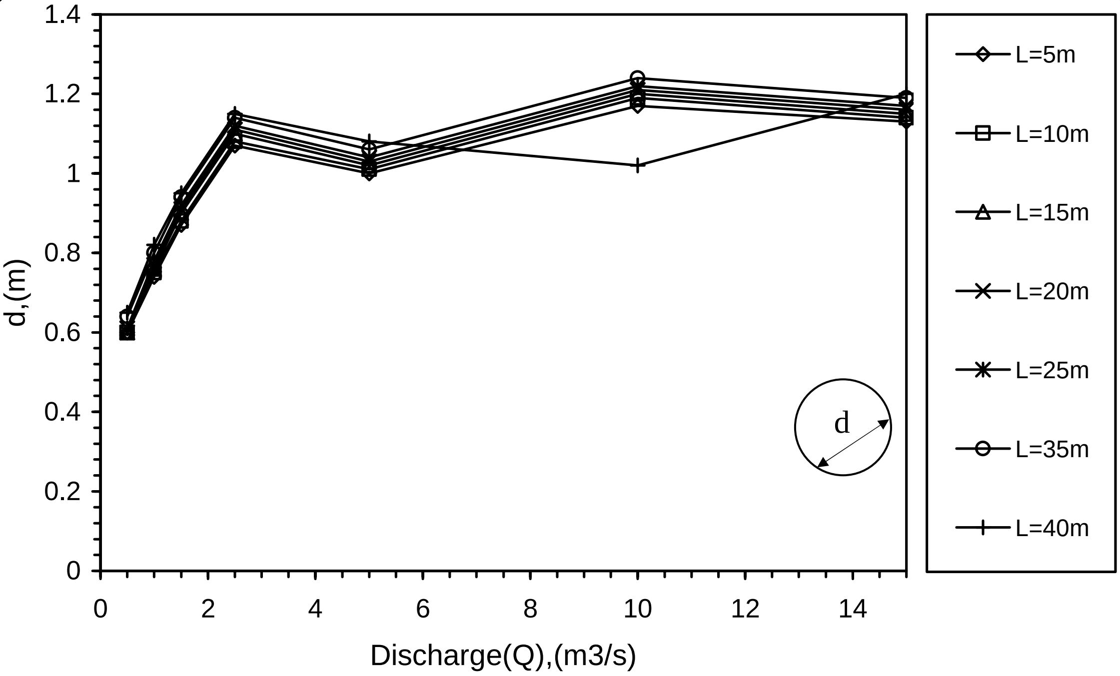
Figure(4.35):Optimum dimension (d) of R.C., square box culverts.



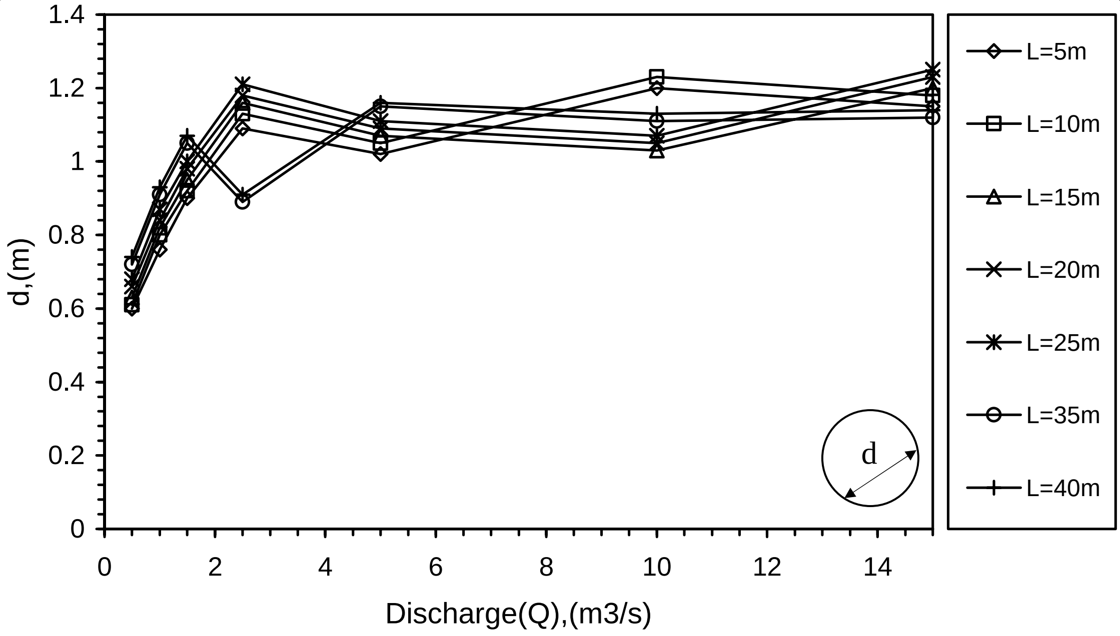
Figure(4.36):Optimum dimension (d) of R.C., circular pipe culverts.



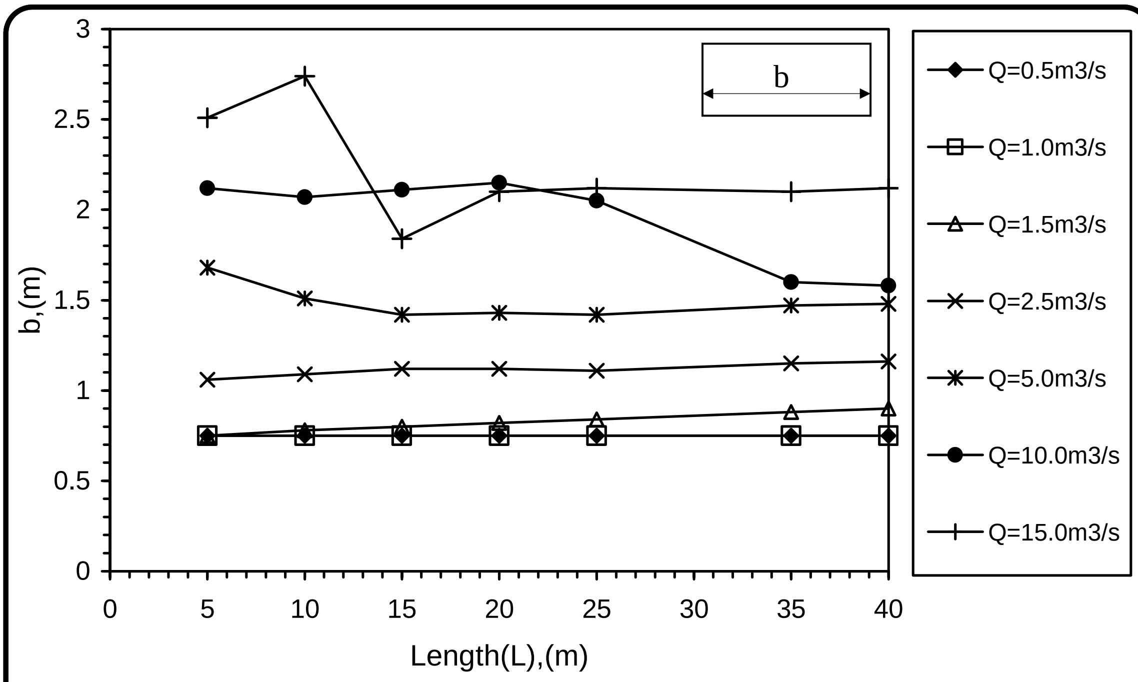
Figure(4.37):Optimum dimension (d) of cast-iron, circular pipe culverts.



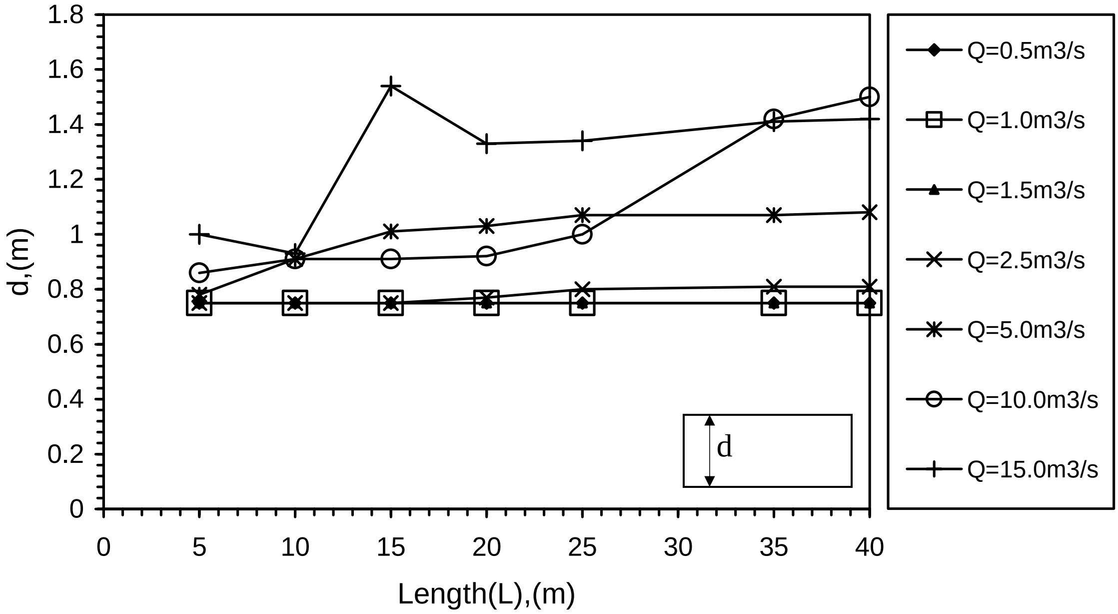
Figure(4.38):Optimum dimension (d) of asbestos-cement, circular pipe culverts.



Figure(4.39):Optimum dimension (d) of ductile-steel, circular pipe culverts.

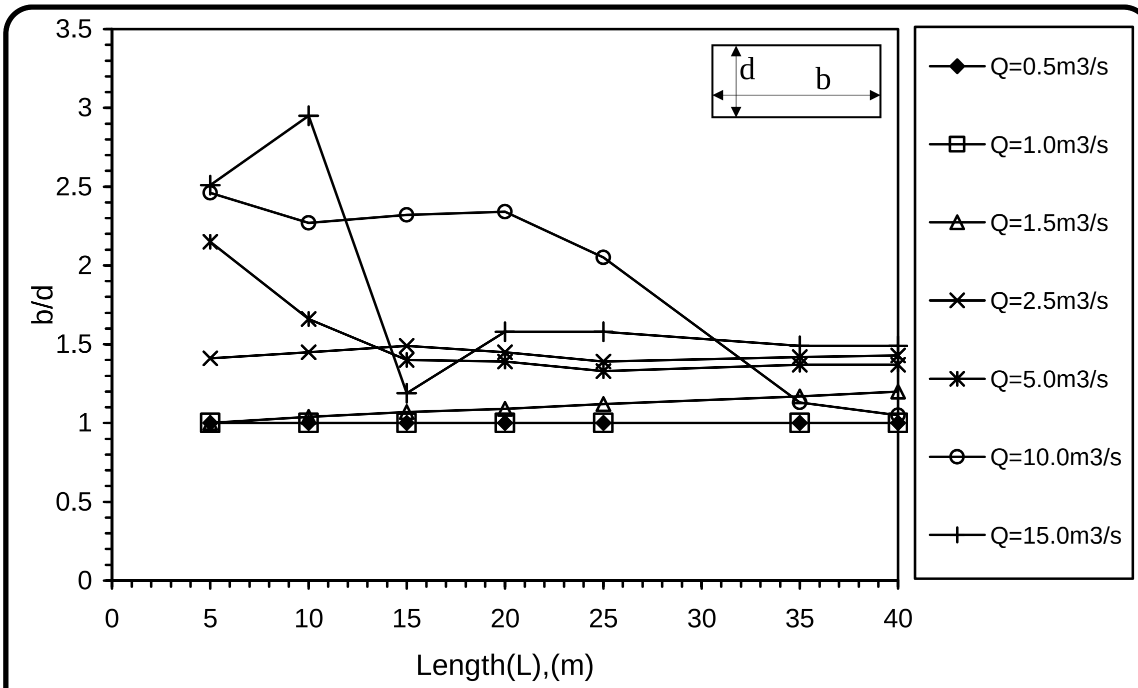


Figure(4.40a):Optimum dimension (b) of R.C., rectangular box culverts.

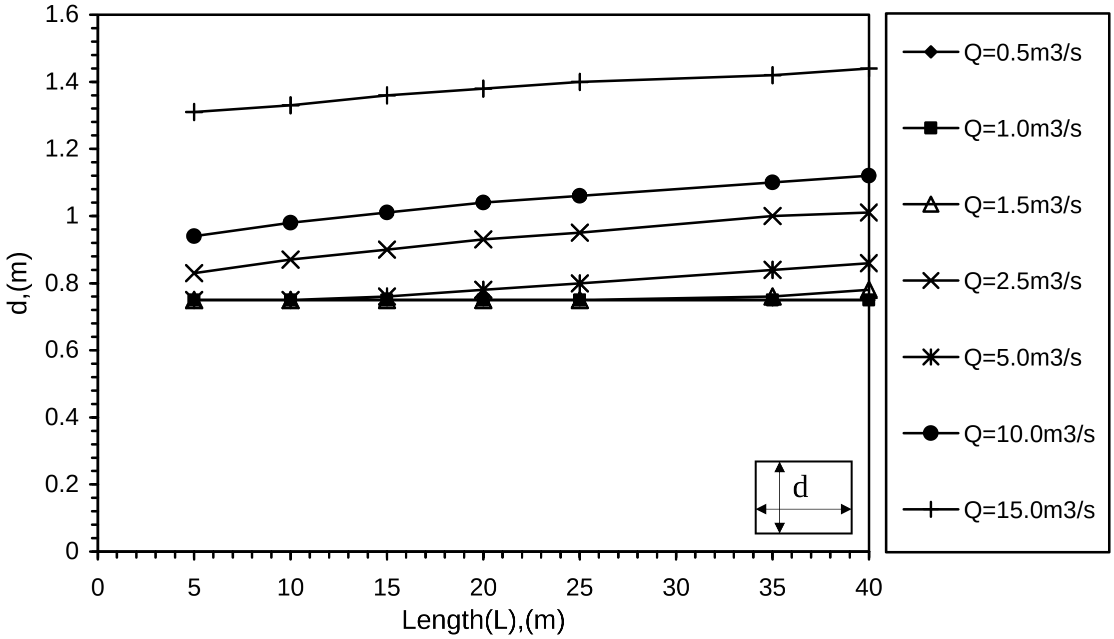


Figure(4.40b):Optimum dimension (d) of R.C., rectangular box culverts.

Hint: Curve for the unseen type coincides with the shown curves.

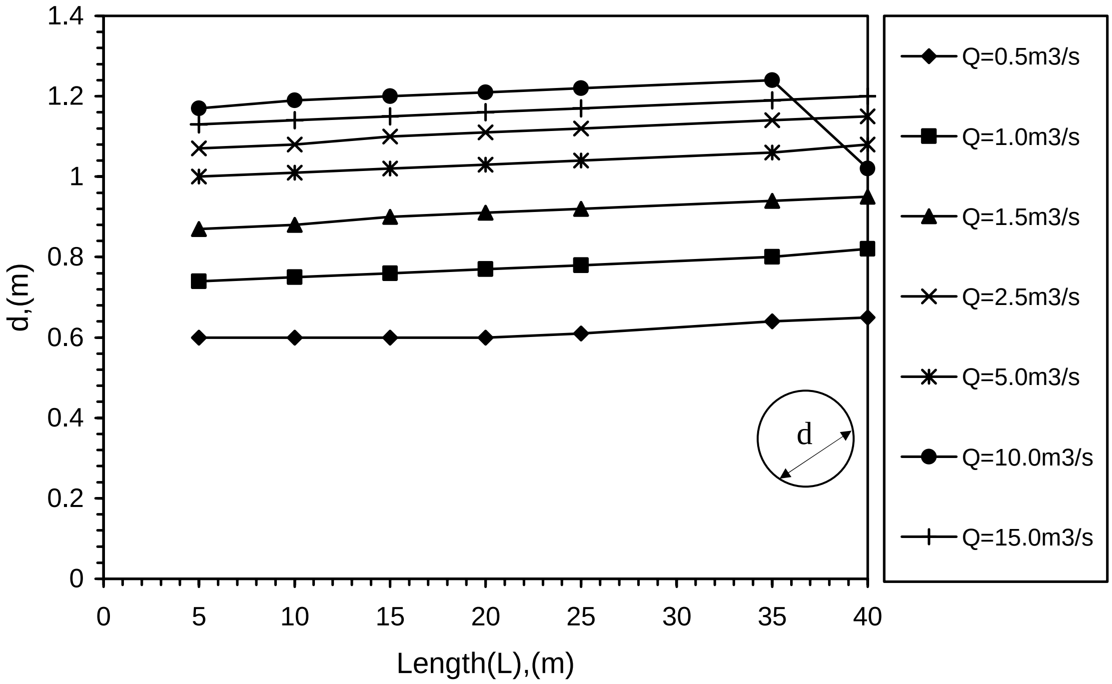


Figure(4.40c):Optimum dimensions ratio (b/d) of R.C., rectangular box culverts.

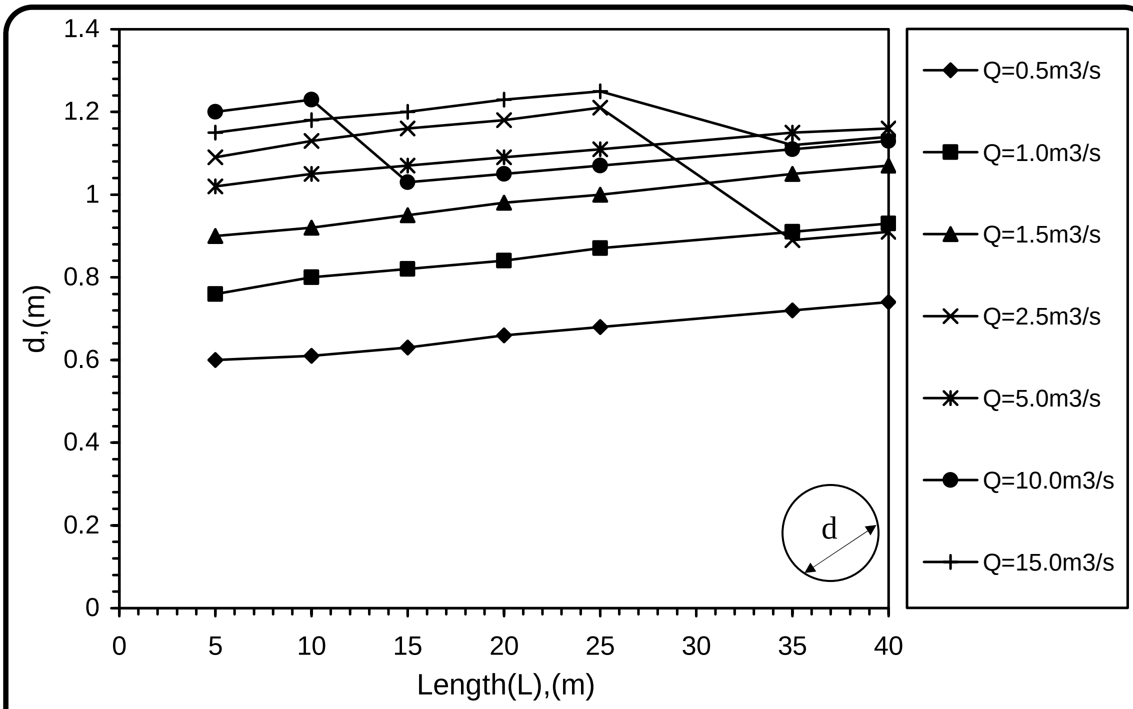


Figure(4.41):Optimum dimension (d) of R.C., square box culverts.

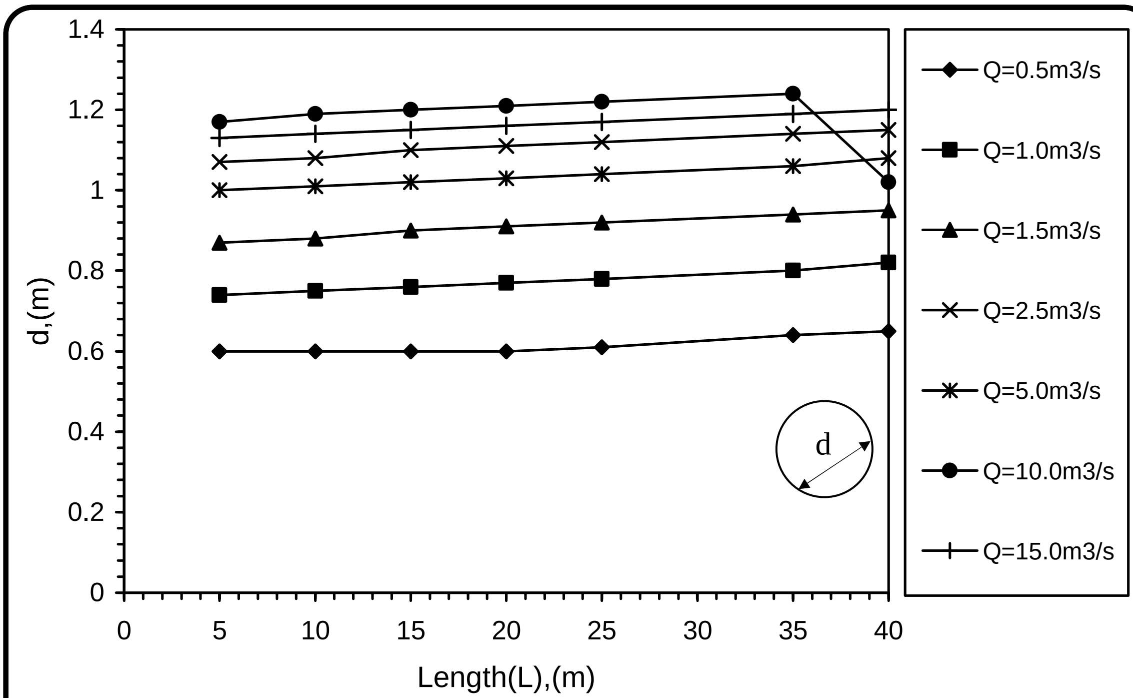
Hint: Curve for the unseen type coincides with the shown curves.



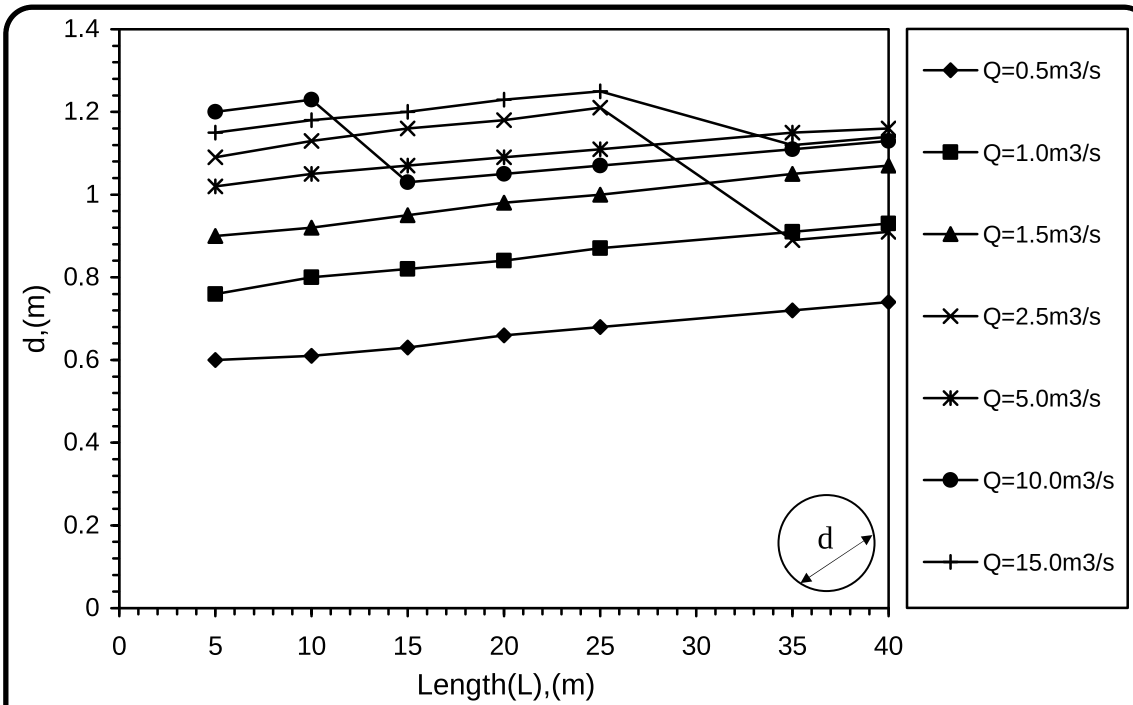
Figure(4.42):Optimum dimension (d) of R.C., circular pipe culverts.



Figure(4.43):Optimum dimension (d) of cast-iron, circular pipe culverts.



Figure(4.44):Optimum dimension (d) of asbestos-cement, circular pipe culverts.



Figure(4.45):Optimum dimension (d) of ductile-steel, circular pipe culverts.

Table (4.6): Final optimum results.

Q (m^3/s)	L (m)	The optimum design				
		Material	Shape	No. of vents	Dimensions (mm)	Overall cost($)
0.5	5	R.C.	□*	1	(750×750)	820
	10	R.C.	□*	1	(750×750)	1400
	15	R.C.	□*	1	(750×750)	1980
	20	R.C.	□*	1	(750×750)	2560
	25	R.C.	□*	1	(750×750)	3140
	35	R.C.	□*	1	(750×750)	4300
	40	R.C.	□*	1	(750×750)	4880

Continued…

1.0	5	R.C.		1	(750×750)	1010
	10	R.C.		1	(750×750)	1590
	15	R.C.		1	(750×750)	2170
	20	R.C.		1	(750×750)	2750
	25	R.C.		1	(750×750)	3330
	35	R.C.		1	(750×750)	4490
	40	R.C.		1	(750×750)	5070
1.5	5	R.C.		1	(750×750)	1070
	10	R.C.		1	(750×750)	1650
	15	R.C.		1	(750×750)	2230
	20	R.C.		1	(750×750)	2810
	25	R.C.		1	(750×750)	3390
	35	R.C.		1	(760×760)	4650
	40	R.C.		1	(780×780)	5450
2.5	5	R.C.		1	(830×830)	2130
	10	R.C.		1	(870×870)	3010
	15	R.C.		1	(900×900)	3970
	20	R.C.		1	(930×930)	5000
	25	R.C.		1	(1110×800)	6060
	35	R.C.		1	(1150×810)	8250
	40	R.C.		1	(1160×810)	9390

Continued…

5.0	5	R.C.	□	2	(750×750)	2920
	10	R.C.	□	2	(750×50)	4090
	15	R.C.	□	2	(760×760)	5320
	20	R.C.	□	2	(780×780)	6830
	25	R.C.	□	2	(800×800)	8430
	35	R.C.	□	2	(840×840)	11850
	40	R.C.	□	2	(860×860)	13660
10.0	5	R.C.	□	2	(940×940)	4450
	10	R.C.	□	2	(980×980)	6510
	15	R.C.	□	2	(1010×1010)	8730
	20	R.C.	□	2	(1040×1040)	11090
	25	R.C.	□	2	(1060×1060)	13570
	35	R.C.	□	2	(1100×1100)	18840
	40	R.C.	□	2	(1120×1120)	21620
15.0	5	R.C.	▭	1	(2510×1000)	9590
	10	R.C.	▭	1	(2740×930)	13220
	15	R.C.	▭	1	(1840×1540)	17370
	20	R.C.	▭	1	(2100×1330)	19390
	25	R.C.	▭	1	(2120×1340)	22480
	35	R.C.	▭	1	(2100×1410)	28860
	40	R.C.	▭	1	(2120×1420)	32140

*: Final dimensions have been decided according to the constraints dimensions given by Eqs.(3.73) and (3.74).

4.7.2 THE ANALYSIS

The analysis focuses on the effect of discharge and length on the different important choices, e.g., cost, number of vents, and dimensions of the culvert. These effects are summarized hereinafter.

[A] Effect of discharge on the optimum total cost of culverts.

It is clear from Figs.(4.6) through (4.12) that the optimum total cost (ZT) of all selected types of culverts increases progressively with the discharge (Q). In fact, this is a logical and an expected result. However, the increase in (ZT) is not always systematic. This is explained as follows:

(a) The optimum shape:

1. For (Q=0.5 and 1.0m^3/s), all assumed rectangular sections came to be square in the optimum result for all considered lengths of the culvert as given in Tables (A–1) and (A–2) of Appendix A.
2. For (Q=1.5m^3/s), the rectangular section came to be a square for (L=5m) whereas a real rectangular section were the results for other lengths as given in Table (A–3) of Appendix A.
3. For (Q>1.5m^3/s), the rectangular section has been found to be pronounced as given in Tables (4.5) and (A–4) through (A–6) of Appendix A.

(b) The optimum cost:

1. For (Q=5.0m^3/s) for all considered lengths, (ZT) of the R.C. circular pipe culvert unsystematically increased due to division to (2–vents) as given in Table (A–5) of Appendix A.
2. (ZT) of the R.C. square box culvert also unsystematically increased for (Q=15.0 m^3/s) for all considered lengths due to division to (2–vents) as given in Tables (4.5) and (A–6) of Appendix A.

[B] Effect of length on the optimum total cost of culverts.

Figures (4.13) through (4.19) show that (ZT) of all selected types of culverts increases progressively and almost linear with length (L). This is a logical and expected result.

[C] Effect of discharge on the optimum number of vents of culverts.

It is worth mentioning that the optimum number of vents accepts only integer values. Consequently, obtained non–integer values are automatically approximated to the nearest higher value, and the respective dimensions are recalculated and rechecked.

The R.C. square box culvert has been divided to multiple–vents when partially–full flow (open channel flow) case has occurred; all types of circular pipe culverts have been divided to multiple–vents when the size (diameter) exceeds the maximum available size given in Table (3.7), where the maximum available size is taken as (1.25m). These conditions have been involved in the optimization program. Figures (4.20) through (4.26) show the aforementioned notes.

[D] Effect of length on the optimum number of vents of culverts.

Figures (4.27) through (4.33) show that the number of vents for all considered types of culverts increases slightly with (L). The reasons of the division to multiple–vents are mentioned in previous item.

[E] Effect of discharge on the optimum dimensions of culverts.

Figures (4.34) through (4.39) show that for all types of culverts, the dimensions increase progressively with discharge (Q). This, in fact, is a logical and expected result from a hydraulic point of view.

The major notes in this respect are:

(a) Figures (4.34a) and (4.34b) show that for the R.C. rectangular box culvert, the dimensions (b and d) are unsystematically increased with (Q). This depends on the behavior of the optimization process for getting optimum (b and d) with minimum (ZT). The dimensions ratio (b/d) displays this behavior as shown in Fig.(4.34c).

(b) For the R.C. square box culvert, (d) decreased for ($Q=5.0m^3/s$) for all considered lengths due to division to (2–vents) as shown in Fig.(4.35).

(c) Figures (4.36) and (4.38) show that for both R.C. and asbestos–cement circular pipe culverts, the optimum diameter (d) decreased with increased (Q). The explanations for this are:

1. With ($Q=5.0m^3/s$) and for all considered lengths: The decrease is due to division to (2–vents).

2. With ($Q=10.0m^3/s$) and (L=40m): The decrease is due to division to (3–vents).

3. With ($Q=15.0\ m^3/s$) and for (L=5 through 35m): The decrease is due to division to (3–vents).

(d) Figures (4.37) and (4.39) show that for both cast–iron and ductile–steel circular pipe culverts, (d) decreased with increased (Q). the explanations for this are:

1. With ($Q=2.5m^3/s$) and for (L=35 and 40m): The decrease is due to division to (2–vents).

2. With ($Q=5.0m^3/s$) and for (L=5 through 25m): The decrease is due to division to (2–vents).

3. With ($Q=10.0m^3/s$) and for (L=15 through 40m): The decrease is due to division to (3–vents).

4. With ($Q=15.0m^3/s$), for (L=5 through 10m): The decrease is due to division to (3–vents), and for (L=35 and 40m), The decrease is due to division (4–vents).

[F] Effect of length on the optimum dimensions of culverts.

The culvert dimension have been found to increase progressively with (L) for all selected types of culverts. This increasing is slight and almost linear as shown in Figs.(4.40) through (4.45). Several notes could be pointed out as follows:

(a) Figures (4.40a), (4.40b), and (4.40c) show the behavior of (b and d) for the R.C. rectangular culvert in the same way mentioned in {(a) of [E]}.

(b) For (Q=5.0m^3/s) and for all considered lengths, (d) for the R.C. square box culvert decreased due to division to (2–vents) as shown in Fig.(4.41).

(c) For both R.C. and asbestos–cement circular section, Figs. (4.42) and (4.44) show that the:

1. For (Q=5.0m^3/s) and for all considered lengths, (d) decreases due to division to (2–vents).

2. For (Q=10.0m^3/s) and (L=40m), (d) decreases due to division from (3–vents).

3. For (Q=15.0m^3/s) and for all considered lengths, (d) decreased due to division to (3–vents).

(d) For both cast–iron and ductile–steel circular pipe culverts, Figs.(4.43) and (4.45) show that (d) decreases as follows:

1. For (Q=2.5m^3/s) and (L=35 and 40m), the decrease is due to division to (2–vents).

2. For (Q=5.0m^3/s) and all considered lengths, the decrease is due to division to (2–vents).

3. For (Q=10.0m^3/s) and lengths of (L=15 through 40m), the decrease is due to division (3–vents).

4. For (Q=15.0m^3/s) and (L=35 and 40m), the decrease is due to division to (4–vents).

A compact summary in this respect is:

1. (Q), rather than(L), is the dominant factor controlling (ZT), number of vents, and dimensions of the culvert. This is a logical and expected result from a hydraulic point of view.

2. The optimization process automatically excluded the pipe culverts because, e.g., for (Q=0.5m^3/s) and (L=10m), the optimum circular section was the asbestos–cement with the minimum permissible size, i.e., (d=600mm), for which the total cost (ZT=$1980), whereas for the same (Q) and (L), the R.C. box was also with minimum box dimensions of (750×750mm) for which (ZT=$1400).

3. For descriptive purposes under the following classification:

Small **Q** : 0.5 and 1.0m^3/s.

Medium **Q** : 2.5m^3/s.

Moderately big **Q** : 5.0 and 10.0m^3/s.

Big **Q** : 15.0m^3/s.

Short **L** : 5 and 10m.

Medium **L** : 15 and 20m.

Long **L** : 25, 35, and 40m.

The results could be summarized as in Fig.(4.46).

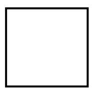
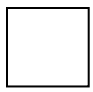
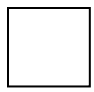
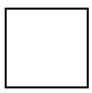
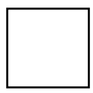
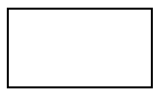
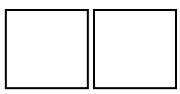
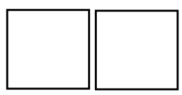
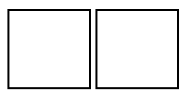
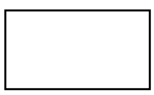
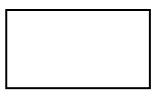
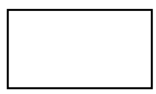
L / Q	Short [5 and 10m]	Medium [15 and 20m]	Long [25, 35, and 40m]
Small [0.5, 1.0, and 1.5 m^3/s]			
Medium [2.5 m^3/s]			
Moderately big [5.0 and 10.0 m^3/s]			
Big [15.0 m^3/s]			

Figure (4.46): Descriptive summary of results.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This research is set out to find the optimum safe hydraulic design of selected types of culverts (i.e., minimum cost of selected shapes and materials).

An optimization model is constructed, taking into consideration several relevant hydraulic and structural requirements. Selected, practically–feasible values of discharge(Q) and length(L) have been adopted, aiming at two categories of findings:

1. Optimum choices as a function of (Q) for different (selected) values of (L).

2. Ditto, as a function of (L) for different specified values of (Q).

5.2 CONCLUSIONS

Based on the obtained results, the following conclusions are abstracted:

1. The computer program for the optimization process represented by the modified Hooke and Jeeves–direct search method has been found suitable in giving the final results.

2. With respect to optimum sizes for the respective discharge values:

(a) For (Q=0.5 and 1.0m^3/s) and for all considered lengths of the culvert, the optimum type is the R.C. square box culvert of (750 × 750 mm).

(b) For ($Q=1.5m^3/s$), the optimum type is the R.C. square box culvert of (750 × 750 mm) for (L=5–25m), (760 × 760 mm) for (L=35m), and (780 × 780 mm) for (L=40m).

(c) For ($Q=2.5m^3/s$), the R.C. square box culvert of (830 × 830 mm), (870×870 mm), (900 × 900 mm), and (930 × 930 mm) are the optimum for the lengths (5, 10, 15, and 20m), respectively; the R.C. rectangular box culvert of (1110×800 mm), (1150×810 mm), and (1160 × 810 mm) are the optimum for (L=25, 35, and 40m), respectively.

(d) For ($Q=5.0m^3/s$), the optimum type is a R.C. with two square vents, each (750×750mm), (750×750mm), (760×760mm), (780×780mm), (800 × 880 mm), (840 ×840 mm), and (860× 860 mm) for the lengths (5, 10, 15, 20, 25, 35, and 40m), respectively.

(e) For ($Q=10.0m^3/s$), the optimum type is a R.C. with two square vents, each (940 × 940 mm), (980 × 980 mm), (1010×1010mm), (1040×1040 mm), (1060 × 1060 mm), (1100 × 1100 mm), and (1120 ×1120 mm) for the lengths (5, 10, 15, 20, 25, 35, and 40m), respectively.

(f) For ($Q=15.0m^3/s$), the optimum type is a R.C. rectangular box culvert of a single–vent, each (2510 × 1000 mm), (2740 × 930 mm), (1840×1540mm), (2100×1330mm),(2120×1340mm), (2100×1410mm), and (2120×1420) for the lengths (5, 10, 15, 20, 25, 35, and 40m), respectively.

3. With respect to optimum sizes for the respective length:

(a) For (L=5m),the optimum types for ($Q=0.5, 1.0, 1.5, and 2.5m^3/s$) are single–vent, R.C. square box culverts with (d=750, 750, 750, and 830 mm), respectively. For ($Q=5.0$ and $10.0\ m^3/s$), the optimum are two–vents, R.C. square box culverts with (d=750 and 940 mm), respectively. The optimum type for ($Q=15.0m^3/s$) is a R.C. rectangular box culvert of a single–vent with (b × d = 2510 × 1000 mm).

(b) For (L=10m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 750, and 870 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d=750 and 980 mm), respectively. The optimum type for (Q=15.0m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 2740 × 930 mm).

(c) For (L=15m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 750, and 900 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d=760 and 1010 mm), respectively. The optimum type for (Q=15.0m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 1840 × 1540 mm).

(d) For (L=20m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 750, and 930 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d=780 and 1040 mm), respectively. The optimum type for (Q=15.0m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 2100 × 1330 mm).

(e) For (L=25m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 750, and 950 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d=800 and 1060 mm), respectively. The optimum type for (Q=15.0m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 2120 × 1340 mm).

(f) For (L=35m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 760, and 1000 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d = 840 and 1100 mm), respectively. The optimum type for (Q=15.0 m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 2100 × 1410 mm).

(g) For (L=40m), the optimum types for (Q=0.5, 1.0, 1.5, and 2.5m^3/s) are single–vent, R.C. square box culverts with (d=750, 750, 780, and 1010 mm), respectively. For (Q=5.0 and 10.0 m^3/s), the optimum are two–vents, R.C. square box culverts with (d = 860 and 1120 mm), respectively. The optimum type for (Q=15.0 m^3/s) is a R.C. rectangular box culvert of a single–vent with (b × d = 2120 × 1420 mm).

4. In the general sense:

a. (Q), rather than (L), is the dominant factor controlling (ZT), number of vents, and dimensions of the culvert. This is a logical and expected result from a hydraulic point of view.

b. The optimization process automatically excluded the pipe culverts.

5.3 RECOMMENDATIONS

The following are recommended for further studies:

1. Solving the optimization problem by techniques other than the one used in this research, e.g., Lagrange multiplier method, SUMT method, Rosenbrock method, complex method or Fletcher and Powell method.

2. Optimizing shapes other than those used in this research, e.g., oval, and arch.

3. Investigating the effect of the case of unsteady flow on the optimization process.

4. Basing the hydraulic design of the culvert on open channel flow throughout the culvert.

5. Studying the design of the culvert with gradually increasing size from the inlet to the outlet.

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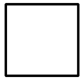
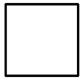
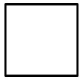
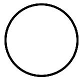
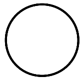
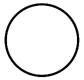
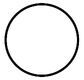
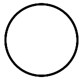
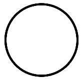
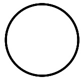
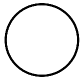
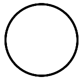
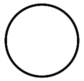
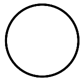
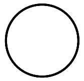
Appendix A

Table(A-1): Final optimum results (Q=0.5m^3/s).

Q(m^3/s) \ L(m)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
0.5	1	R.C.(*) 	1(0.75×0.75)	820	R.C.(*) 	1(0.75×0.75)	1400	R.C.(*) 	1(0.75×0.75)	1980
	2	R.C.(*) 	1(0.75×0.75)	820	R.C.(*) 	1(0.75×0.75)	1400	R.C.(*) 	1(0.75×0.75)	1980
	3	R.C. 	1Ø0.60	1150	R.C. 	1Ø0.60	2230	R.C. 	1Ø0.60	3310
	4	Cast-Iron 	1Ø0.60	1220	Cast-Iron 	1Ø0.61	2410	Cast-Iron 	1Ø0.63	3730
	5	Asbestos-Cement 	1Ø0.60	1030	Asbestos-Cement 	1Ø0.60	1980	Asbestos-Cement 	1Ø0.60	2930
	6	Ductile-Steel 	1Ø0.60	1230	Ductile-Steel 	1Ø0.61	2450	Ductile-Steel 	1Ø0.63	3830

Continued …

20			25			35			40		
Shape and material	Dimensions (m),and No. of vents	Cost ($)	Shape and material	Dimensions (m),and No. of vents	Cost ($)	Shape and material	Dimensions (m),and No. of vents	Cost ($)	Shape and material	Dimensions (m),and No. of vents	Cost ($)
R.C.(*)	1(0.75×0.75)	2560	R.C.(*)	1(0.75×0.75)	3140	R.C.(*)	1(0.75×0.75)	4300	R.C.(*)	1(0.75×0.75)	4880
R.C.(*)	1(0.75×0.75)	2560	R.C.(*)	1(0.75×0.75)	3140	R.C.(*)	1(0.75×0.75)	4300	R.C.(*)	1(0.75×0.75)	4880
R.C.	1Ø0.60	4390	R.C.	1Ø0.61	5520	R.C.	1Ø0.64	8380	R.C.	1Ø0.65	9780
Cast-Iron	1Ø0.66	5150	Cast-Iron	1Ø0.68	6660	Cast-Iron	1Ø0.72	9940	Cast-Iron	1Ø0.74	11720
Asbestos-Cement	1Ø0.60	3890	Asbestos-Cement	1Ø0.61	4890	Asbestos-Cement	1Ø0.64	7360	Asbestos-Cement	1Ø0.65	8570
Ductile-Steel	1Ø0.66	5330	Ductile-Steel	1Ø0.68	6940	Ductile-Steel	1Ø0.72	10520	Ductile-Steel	1Ø0.74	12480

(*): Final dimensions have been decided according to the constrained dimensions given by Eqs.(3.73) and (3.74).

Table(A-2): Final optimum results (Q=1.0m^3/s).

Q(m^3/s) \ L(m)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
1.0	1	R.C.	1(0.75×0.75)	1010	R.C.	1(0.75×0.75)	1590	R.C.	1(0.75×0.75)	2170
	2	R.C.	1(0.75×0.75)	1010	R.C.	1(0.75×0.75)	1590	R.C.	1(0.75×0.75)	2170
	3	R.C.	1Ø0.74	1760	R.C.	1Ø0.75	3310	R.C.	1Ø0.76	4930
	4	Cast-Iron	1Ø0.76	1840	Cast-Iron	1Ø0.80	3540	Cast-Iron	1Ø0.82	5380
	5	Asbestos-Cement	1Ø0.74	1550	Asbestos-Cement	1Ø0.75	2880	Asbestos-Cement	1Ø0.76	4270
	6	Ductile-Steel	1Ø0.76	1950	Ductile-Steel	1Ø0.80	3810	Ductile-Steel	1Ø0.82	5850

Continued …

20			25			35			40		
Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
R.C.	1(0.75×0.75)	2750	R.C.	1(0.75×0.75)	3330	R.C.	1(0.75×0.75)	4490	R.C.	1(0.75×0.75)	5070
R.C.	1(0.75×0.75)	2750	R.C.	1(0.75×0.75)	3330	R.C.	1(0.75×0.75)	4490	R.C.	1(0.75×0.75)	5070
R.C.	1Ø0.77	6620	R.C.	1Ø0.78	8370	R.C.	1Ø0.80	12040	R.C.	1Ø0.82	14120
Cast-Iron	1Ø0.84	7340	Cast-Iron	1Ø0.87	9410	Cast-Iron	1Ø0.91	13900	Cast-Iron	1Ø0.93	16300
Asbestos-Cement	1Ø0.77	5710	Asbestos-Cement	1Ø0.78	7190	Asbestos-Cement	1Ø0.80	10300	Asbestos-Cement	1Ø0.82	12040
Ductile-Steel	1Ø0.84	8050	Ductile-Steel	1Ø0.87	10400	Ductile-Steel	1Ø0.91	15560	Ductile-Steel	1Ø0.93	18360

Table(A-3): Final optimum results (Q=1.5m^3/s).

L(m) / Q(m^3/s)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
1.5	1	R.C.	1(0.75×0.75)	1070	R.C.	1(0.78×0.75)	1690	R.C.	1(0.80×0.75)	2350
	2	R.C.	1(0.75×0.75)	1070	R.C.	1(0.75×0.75)	1650	R.C.	1(0.75×0.75)	2230
	3	R.C.	1Ø0.87	2290	R.C.	1Ø0.88	4280	R.C.	1Ø0.90	6350
	4	Cast-Iron	1Ø0.90	2310	Cast-Iron	1Ø0.92	4410	Cast-Iron	1Ø0.95	6660
	5	Asbestos-Cement	1Ø0.87	1990	Asbestos-Cement	1Ø0.88	3660	Asbestos-Cement	1Ø0.90	5400
	6	Ductile-Steel	1Ø0.90	2530	Ductile-Steel	1Ø0.92	4910	Ductile-Steel	1Ø0.95	7500

Continued …

20			25			35			40		
Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
R.C.	1(0.82×0.75)	3040	R.C.	1(0.84×0.75)	3770	R.C.	1(0.88×0.75)	5310	R.C.	1(0.90×0.75)	6120
R.C.	1(0.75×0.75)	2810	R.C.	1(0.75×0.75)	3390	R.C.	1(0.76×0.76)	4650	R.C.	1(0.78×0.78)	5450
R.C.	1Ø0.91	8500	R.C.	1Ø0.92	10720	R.C.	1Ø0.94	15370	R.C.	1Ø0.95	17800
Cast-Iron	1Ø0.98	9050	Cast-Iron	1Ø1.00	11570	Cast-Iron	1Ø1.05	17020	Cast-Iron	1Ø1.07	19930
Asbestos-Cement	1Ø0.91	7190	Asbestos-Cement	1Ø0.92	9040	Asbestos-Cement	1Ø0.94	12890	Asbestos-Cement	1Ø0.95	14900
Ductile-Steel	1Ø0.98	10280	Ductile-Steel	1Ø1.00	13250	Ductile-Steel	1Ø1.05	19730	Ductile-Steel	1Ø1.07	23230

Table(A-4): Final optimum results (Q=2.5m^3/s).

L(m) / Q(m^3/s)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
2.5	1	R.C.	1(1.06×0.75)	2170	R.C.	1(1.09×0.75)	3070	R.C.	1(1.12×0.75)	4040
	2	R.C.	1(0.83×0.83)	2130	R.C.	1(0.87×0.87)	3010	R.C.	1(0.90×0.90)	3970
	3	R.C.	1Ø1.07	4260	R.C.	1Ø1.08	7040	R.C.	1Ø1.10	9910
	4	Cast-Iron	1Ø1.09	4180	Cast-Iron	1Ø1.13	6960	Cast-Iron	1Ø1.16	9930
	5	Asbestos-Cement	1Ø1.07	3780	Asbestos-Cement	1Ø1.08	6050	Asbestos-Cement	1Ø1.10	8400
	6	Ductile-Steel	1Ø1.09	4620	Ductile-Steel	1Ø1.13	7930	Ductile-Steel	1Ø1.16	11510

Continued …

20			25			35			40		
Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
R.C.	1(1.12×0.77)	5040	R.C.	1(1.11×0.80)	6060	R.C.	1(1.15×0.81)	8250	R.C.	1(1.16×0.81)	9390
R.C.	1(0.93×0.93)	5000	R.C.	1(0.95×0.95)	6090	R.C.	1(1.00×1.00)	8440	R.C.	1(1.01×1.01)	9690
R.C.	1Ø1.11	12870	R.C.	1Ø1.12	15920	R.C.	1Ø1.14	22290	R.C.	1Ø1.15	25600
Cast-Iron	1Ø1.18	13080	Cast-Iron	1Ø1.21	16380	Cast-Iron	2Ø0.89	25960	Cast-Iron	2Ø0.91	30240
Asbestos-Cement	1Ø1.11	10810	Asbestos-Cement	1Ø1.12	13290	Asbestos-Cement	1Ø1.14	18430	Asbestos-Cement	1Ø1.15	21100
Ductile-Steel	1Ø1.18	15330	Ductile-Steel	1Ø1.21	19380	Ductile-Steel	2Ø0.89	29030	Ductile-Steel	2Ø0.91	34000

Table(A-5): Final optimum results (Q=5.0m^3/s).

Q(m^3/s) \ L(m)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
5.0	1	R.C.	1(1.68×0.78)	3410	R.C.	1(1.51×0.90)	5010	R.C.	1(1.42×1.01)	6580
	2	R.C.	2(0.75×0.75)	2920	R.C.	2(0.75×0.75)	4090	R.C.	2(0.76×0.76)	5320
	3	R.C.	2Ø1.00	11880	R.C.	2Ø1.01	22120	R.C.	2Ø1.02	32680
	4	Cast-Iron	2Ø1.02	6310	Cast-Iron	2Ø1.05	10940	Cast-Iron	2Ø1.07	15860
	5	Asbestos-Cement	2Ø1.00	5710	Asbestos-Cement	2Ø1.01	9560	Asbestos-Cement	2Ø1.02	13510
	6	Ductile-Steel	2Ø1.02	7020	Ductile-Steel	2Ø1.05	12480	Ductile-Steel	2Ø1.07	18310

Continued …

20			25			35			40		
Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
R.C.	1(1.43×1.03)	8160	R.C.	1(1.42×1.07)	9780	R.C.	1(1.47×1.07)	13150	R.C.	1(1.48×1.08)	14900
R.C.	2(0.78×0.78)	6830	R.C.	2(0.80×0.80)	8430	R.C.	2(0.84×0.84)	11850	R.C.	2(0.86×0.86)	13660
R.C.	2Ø1.03	43550	R.C.	2Ø1.04	54720	R.C.	2Ø1.06	77940	R.C.	2Ø1.08	89800
Cast-Iron	2Ø1.09	21020	Cast-Iron	2Ø1.11	26430	Cast-Iron	2Ø1.15	37950	Cast-Iron	2Ø1.16	44050
Asbestos-Cement	2Ø1.03	17560	Asbestos-Cement	2Ø1.04	21700	Asbestos-Cement	2Ø1.06	30260	Asbestos-Cement	2Ø1.08	36600
Ductile-Steel	2Ø1.09	24510	Ductile-Steel	2Ø1.11	31050	Ductile-Steel	2Ø1.15	45110	Ductile-Steel	2Ø1.16	52620

Table(A-6): Final optimum results (Q=10.0m^3/s).

L(m) / Q(m^3/s)		5			10			15		
		Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
10.0	1	R.C.	1(2.12×0.86)	7100	R.C.	1(2.07×0.91)	9620	R.C.	1(2.11×0.91)	12190
	2	R.C.	2(0.94×0.94)	4450	R.C.	2(0.98×0.98)	6510	R.C.	2(1.01×1.01)	8730
	3	R.C.	2Ø1.17	19250	R.C.	2Ø1.19	33050	R.C.	2Ø1.20	47350
	4	Cast-Iron	2Ø1.20	11610	Cast-Iron	2Ø1.23	17660	Cast-Iron	3Ø1.03	24360
	5	Asbestos-Cement	2Ø1.17	10800	Asbestos-Cement	2Ø1.19	15780	Asbestos-Cement	2Ø1.20	20910
	6	Ductile-Steel	2Ø1.20	12770	Ductile-Steel	2Ø1.23	20170	Ductile-Steel	3Ø1.03	27620

Continued …

20			25			35			40		
Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)	Shape and material	Dimensions (m), and No. of vents	Cost ($)
R.C. ▭	**1(2.15×0.92)**	14890	R.C. ▭	**1(2.05×1.00)**	17170	R.C. ▭	**1(1.60×1.42)**	22230	R.C. ▭	**1(1.58×1.49)**	25000
R.C. □	**2(1.04×1.04)**	11090	R.C. □	**2(1.06×1.06)**	13570	R.C. □	**2(1.10×1.10)**	18840	R.C. □	**2(1.12×1.12)**	21620
R.C. ○	2Ø1.21	62140	R.C. ○	2Ø1.22	77390	R.C. ○	2Ø1.24	109270	R.C. ○	3Ø1.02	126660
Cast-Iron ○	3Ø1.05	31640	Cast-Iron ○	3Ø1.07	39280	Cast-Iron ○	3Ø1.11	55550	Cast-Iron ○	3Ø1.13	64170
Asbestos-Cement ○	2Ø1.21	26180	Asbestos-Cement ○	2Ø1.22	31600	Asbestos-Cement ○	2Ø1.24	42830	Asbestos-Cement ○	3Ø1.02	49970
Ductile-Steel ○	3Ø1.05	36310	Ductile-Steel ○	3Ø1.07	45500	Ductile-Steel ○	3Ø1.11	65300	Ductile-Steel ○	3Ø1.13	75830

التصميم الهيدروليكي الأمين الأمثل للبرابخ

اثير زكي محسن

بكالوريوس هندسة مدنية ١٩٩٦

باشراف

أ.م.د. عبد الهادي أحمد الدلوي **أ.م.د. عبد الحسن خضير الشكر**

الخلاصة

نظراً للأهمية البالغة للبرابخ سواء في مشاريع الري أو تقاطعات الطرق ولما تمثله من كلفه كبيرة عادة, فقد تم اختيار موضوع التصميم الهيدروليكي الأمين الأمثل للبرابخ, اخذين بالاعتبار كلفة كل من الحفر والأرضية وألماده الأنشائيه والدفن المرصوص والأكتاف (hunches) وأعمال الحماية والزيادة في الشحنة المفقودة.

بالنظر لتعدد أنواع وأشكال والمواد المصنوعة أو ألمنفذه منها البرابخ فقد تم اختيار الأوسع استعمالا ً منها وهي البرابخ ألصندوقيه وبالأشكال ألمستطيلة وألمربعة ألمنفذه من الخرسانة ألمسلحة و البرابخ الأنبوبية بالشكل الدائري المنفذة أوالمصنوعة من الخرسانة ألمسلحة ومن حديد الصب و ألسمنت الأسبستي والفولاذ اللدن.

لربط الناحية ألعمليه بالنظرية فقد انتخبت التصاريف (٠,٥ , ١,٠ , ١,٥, ٢,٥, ٥,٠, ١٠,٠و١٥,٠م٣/ ثا) لتمثل التصاريف ألصغيره والمتوسطه والكبيرة , وتم انتخاب الأطوال (٥,١٠,١٥,٢٠,٢٥,٣٥و٤٠م) لتمثل منشات قصيرة ومتوسطه وطويلة. تم الأخذ بنظر الاعتبار قنوات ري نموذجية مرتبطة بتلك البرابخ.

ولغرض تهيئة نموذج الأمثلية فقد تم إعداد دالة الهدف لتغطي الكلف المذكورة سابقا. نموذج الأمثلية شمل كل المحددات ألتصميميه الأنشائيه والهيدروليكية. نموذج الأمثلية اللاخطي تم حله بأستخدام طريقة (Modified Hooke and Jeeves direct search). تم تطوير برنامج حاسوبي متضمنا كل ما تم ذكره لغرض الحصول على النتائج.

تم تحليل النتائج في ضوء ما يلي:

١. الكلفة كدالة للتصريف لمختلف الاطوال المستعملة.

٢. الكلفة كدالة للطول لمختلف التصاريف المستعملة.

٣. عدد فتحات البربخ كدالة للتصريف لمختلف الاطوال المستعملة.

٤. عدد فتحات البربخ كدالة للطول لمختلف التصاريف المستعملة.

٥. أبعاد البربخ كدالة للتصريف لمختلف الاطوال المستعملة.

٦. أبعاد البربخ كدالة للطول لمختلف التصاريف المستعملة.

لقد بينت النتائج ما يلي:

١.طريقة حل مسألة الأمثلية كفوءة في إعطاء النتائج.

٢. استبعدت عملية الأمثلية البرابخ الأنبوبية تلقائيا.

٣. التصريف هو العامل المسيطر على الكلفة و عدد الفتحات و الأبعاد للبربخ بشكل أوضح من الطول.

٤. البرابخ الخرسانية المسلحة الصندوقية هي أفضل الأنواع تصميما للتصاريف والأطوال المستعملة, وكما يلي:

أ- للتصاريف (٠,٥ , ١,٠ , ١,٥ م^{٣}/ ثا) وللأطوال المستعملة, كان البربخ الصندوقي من الخرسانة المسلحة والشكل المربع ذو فتحة واحدة, الأفضل تصميما.

ب-للتصريف (٢,٥م^{٣}/ ثا) والأطوال (٥–٢٠م), كان البربخ الصندوقي من الخرسانة المسلحة والشكل المربع ذو فتحة واحدة, الأفضل تصميما,أما للأطوال (٢٥–٤٠م), فقد كان البربخ الصندوقي من الخرسانة المسلحة والشكل المستطيل ذو فتحة واحدة, الأفضل تصميما.

ت-للتصاريف (٥,٠ و ١٠,٠ م^{٣}/ ثا) وللأطوال المستعملة, كان الأفضل البربخ الصندوقي من الخرسانة المسلحة والشكل المربع ذو فتحتين.

ث-للتصريف (١٥,٠م^{٣}/ ثا) وللأطوال المستعملة, كان الأفضل البربخ الصندوقي من الخرسانة المسلحة والشكل المستطيل وبفتحة واحدة.