ECONOMICAL DESIGN OF BOX CULVERTS

Alaa Ahmed Yassin

Irrigation and Hydraulics Department

Faculty of Engineering

Alexandria University

Alexandria, Egypt

Abstract

Highway drainage structures may cost up to 25% to 30% of the total highway construction cost. Box culverts are extensively used for the protection of highways against flood activities and for the passage of streams under roads and railways. The main objective of the present study is to present a procedure for the economic sizing of box culverts. To achieve this goal, multiple regression analysis is used to formulate a set of 13 accurate dimensionless equations for the estimation of the cost of 13 different box culvert sizes ranging from 1.0 m * 1.0 m and up to 3.0 m * 3.0 m. The equations are valid for fill heights up to 5 meters above culvert top slab and for number of cells up to 25. Furthermore, design criteria considering geometrical, hydraulical and economical factors are proposed and a computer program called ECOCUL is designed to expedite the lengthy computations. The flow chart and a sample output are given.

Notations

A	=	cross sectional area of one culvert cell,
AHW	=	allowable headwater depth,
APE	=	average percentage error,
AWWF	=	Angle of wing wall flare,
B	=	Channel bed width,
BC	=	Culvert width,
BL	=	Upstream channel bed level,
CC	=	Correlation coefficient,
C_c	=	Cost of one cubic meter of culvert concrete,
C_s	=	Cost of one ton of reinforcing steel,
DH	=	Difference in elevation between highest point on channel and culvert site,
FR	=	fill ratio,
H	=	height of culvert cell,
HW	=	headwater depth ,
HWIC	=	headwater depth according to inlet control design,
HWOC	=	headwater depth according to outlet control design,
HWRIC	=	HWIC/H,
HWROC	=	HWOC/H,
L	=	Channel length up to culvert site,
MPE	=	maximum percentage error,
n	=	Manning's roughness coefficient,
NC	=	Number of cells,
Q	=	Design discharge
q	=	Discharge per unit width of culvert,
RI	=	Rainfall intensity,
RL	=	Road level,
ROC	=	Runoff coefficient,
S	=	Span of culvert cell,
SCR	=	Steel concrete ratio,
TCC	=	Total cost of culvert cells,
TOC	=	Time of concentration,
TW	=	Tailwater depth,
V	=	Velocity through culvert,
VMax	=	Maximum allowable velocity through culvert,
U_c	=	Unit quantity of culvert concrete in cubic meter per meter length of culvert cell,
U_s	=	Unit quantity of reinforcing steel in tons per meter length of culvert cell, and
YC	=	Critical depth through culvert cell.

1. Introduction

In order to study the requirement for an economical design of highway box culverts the following factors which affect the proper and economical sizing of culverts should be considered:

1.1 Hydrologic factors

Which include: a. characteristics of the catchment area which will be drained by the culvert (channel length and profile, top soil characteristics, antecedent moisture, land use... etc) b. rainfall intensity - duration - frequency relationship for the catchment area under consideration, and the design return period for rainfall and c.method used to predict design discharge using above data. Hydrologic factors will govern the estimation of the design discharge which is always the most crucial input parameter in the design of highway culverts due to the uncertainties involved in the assessment of the above mentioned factors.

1.2 Hydraulic factors

Which define the hydraulic criterion used for dimensioning the culvert to pass the design discharge. This may include: a. maximum allowable headwater depth and velocity through culvert, b. type of flow and water surface profile through the culvert and whether the flow is controlled at inlet or outlet of culvert, and c. entrance shape, culvert length, tailwater depth and friction factor of culvert cell.

1.3 Topographic factors

Which include road and channel bed profiles and levels at culvert site and channel bed width. This will determine how much room is available for the culvert height and how many cells can be accomadated in the channel. In many cases topographic conditions dictate the use of minimum box culvert height of 1.0 m. However, hydraulic and topographic factors will normally offer alternative designs for the dimensions and number of cells.

1.4 Structural factors

Which may include a. the design moving loads and cases of loading b. fill height, c. type, condition and proprties of soil surrounding the culvert, d. type and class of culvert concrete and reinforcing steel, and e. level of supervision and quality control.

The size of culvert will be fixed by the three previous factors, while structural factors will give wall and slab dimension and reinforcing steel quantities and arrangement.

1.5 Economic risk factors

Overall risks are due to various uncertainties encounterd in the hydrologic, hydraulic, structural and economic design factors. Economic risks are expected losses and can be divided into : direct damage to roadway and culvert, traffic related losses and losses due to flood damage in the upstream flood plain. Several investigators [1,2,3,4,5] tried to incorporate economic risks into culvert design and relate this economic design to conventional design practice with the objective of maintaining a proper balance between the cost of construction and potential flood damages. To achieve this goal, which complicate the design due to the need for developing a procedure for evaluating an expected annual damage function based on probabilistic function, extensive data are needed and which will be only applicable for a specified region. However, to the author knowledge, none of the existing approaches have succeeded in offering an accurate and practical solution that consider economic risks. Also, it is obvious that hydrologic and topographic factors differ from one culvert site to another and this fact; in addition to the many other interrelated factors affecting the design, explain the difficulty to carry out conventional optimum analysis for the sizing of culverts and which may lead to unpractical solutions that can not be implemented at all culvert sites. Therefore, the present study adopts a different but practical approach for the design of the most economical highway culvert at each culvert site according to its hydrologic, hydraulic and topographic conditions and which is explained hereafter. Economic risks are indirectly considered as the whole design is based on a design return period which controls the determination of the design flow and consequently water levels.

2. Cost Analysis Of Box Culverts

The cost of any culvert structure is composed of the cost of: excavation, concrete blinding, reinforced concrete apron, culvert concrete, culvert steel reinforcement. Based on the cost analysis of several major highway projects implemented in the Sultanate of Oman during the period 1983-1986 inclusive, the author prepared table (1) which summarizes the cost of each of the above elements as percentage of the total box culvert cost. SCR is the ratio of cost of one ton of steel reinforcement to cost of one cubic meter of culvert concrete and which was found to range from 3 and up to 6. It can be seen from table (1) that the cost of culvert cell, i.e. culvert concrete and steel reinforcement, represent about 78% of the total cost of the culvert structure. Also, it is obvious that the cost of excavation, blinding and apron are proportional to the culvert size, i.e. proportional to cost of culvert concrete and steel.

Table (1) Percentage cost of different elements of box culvert.

SCR	Concrete	Steel	Apron	Blinding	Excavation
3	55.64	21.34	15.92	6.53	0.57
4	51.55	26.36	15.43	6.04	0.62
5	47.88	30.60	15.04	5.61	0.87
6	44.70	34.28	14.70	5.24	1.08
AVR.	49.94	28.14	15.27	5.86	0.79

The cost of unit length of any culvert cell is given by:

$$Cost = U_c * C_c + U_s * C_s \qquad (1)$$

$$\text{or} : Cost/ C_c = CR = U_c + SCR * U_s \qquad (2)$$

Values of U_c and U_s, and hence CR, are dependent upon culvert span and height, number of cells, fill height over culvert top slab, type of surrounding soil and the moving live load. To determine the values of U_c and U_s, the results given by Dar Al-Handasa consultants computer program CULVERT [1] is used by the present study. The main output are wall and slab thicknesses, bar schedules and quantities of culvert concrete and reinforcing steel for number of cells up to 6. Hence, for 13 different culvert sizes ranging from 1.0 * 1.0 m to 3.0 * 3.0 m and for number of cells ranging from 1 up to 6, values of U_c and U_s are available corresponding to 5 different fill heights of 1,2,3,4 and 5 meters. Considering each of the 13 culvert sizes, equation (2) is then applied to estimate CR values corresponding to the above ranges for number of cells and fill heights. Four different values of 3,4,5 and 6 are considered for SCR. The obtained values for number of cells up to 6 are then extended to cover the CR values up to 25 cells. Therefore, for each culvert size 500 values for CR are avilable.

Furthermore, in order to utilize the above data in a convenient computerized manner, the following dimensionless equation is proposed to estimate the value of the cost ratio (CR) for each culvert size:

$$CR = a * SCR^{b} * FR^{c} * NC^{d} \qquad (3)$$

in which: FR = (FH + H) / H = fill ratio,

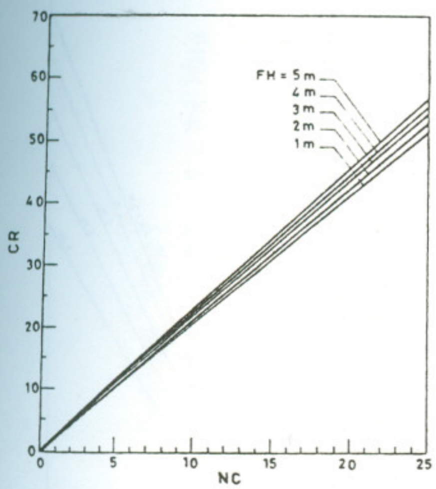
a,b,c and d are regression coefficient to be determined for each culvert size by applying multiple regression analysis. Table (2) shows the estimated values of the 4 regression coefficients, as well as the standard error of estimate (SEE) and the average percentage error (APE) of each equation relevant to the shown size. Correlation coefficients (CC) for all equations are bigger than 0.995. The high values of the correlation coefficient and the low values of the SEE & APE confirm the accuracy of the obtained equations which are used to prepare figure 1 to 3. Figure (1) shows the effect of fill heights on culvert cost for 6 different sizes. As expected, increasing the fill height from 1 to 5 meters will raise the cost. Also figure (2) shows that cost goes up if SCR is increased. Meanwhile, figure (3) illustrates the general rule that square cells are always cheaper than rectangular cells of the same cross sectional area. For example, sizes 1.5*1.5 m, 2.0*2.0 m and 2.5*2.5 m are cheaper than sizes 2.0*1.0 m, 2.5*1.5 m and 3.0*2.0 m respectively. It can also be seen that increasing the ratio of S/H will increase the cost, e.g. size

Table (2) values of four regression coefficients, standard error of estimate and average percentage error for each size equation.

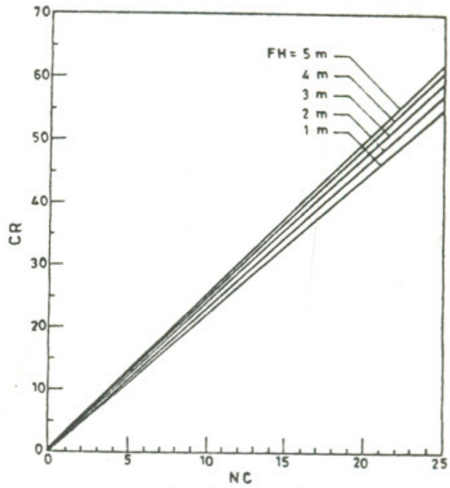
Size S * H	a	b	c	d	SEE	APE
1.0*1.0	0.85885	0.30022	0.00242	0.95340	0.38	2.37
1.5*1.0	1.03504	0.33335	0.00489	0.96356	0.59	2.61
1.5*1.5	1.17846	0.31887	0.03556	0.95204	1.04	3.77
2.0*1.0	1.14756	0.38191	0.08661	0.97083	1.40	4.34
2.0*1.5	1.26712	0.36652	0.12370	0.96903	1.28	3.79
2.0*2.0	1.38351	0.34852	0.23850	0.95015	1.73	4.61
2.5*1.5	1.47724	0.38100	0.20738	0.97719	2.54	5.03
2.5*2.0	1.60122	0.36770	0.31168	0.96518	3.33	5.83
2.5*2.5	1.83451	0.35248	0.39225	0.95624	3.54	5.78
3.0*1.5	1.70327	0.37972	0.32005	0.97621	2.79	4.35
3.0*2.0	1.77308	0.37310	0.43120	0.97328	3.17	4.75
3.0*2.5	2.12024	0.36037	0.44066	0.96183	3.50	4.88
3.0*3.0	2.46520	0.34628	0.51592	0.94910	2.48	3.28

2.0*2.0 m is cheaper than size 2.5*1.5 m which is cheaper than size 3.0*1.5 m. However, it should be emphasized that sometimes topographic and/or hydraulic conditions at the culvert site dictate the use of rectangular culverts.

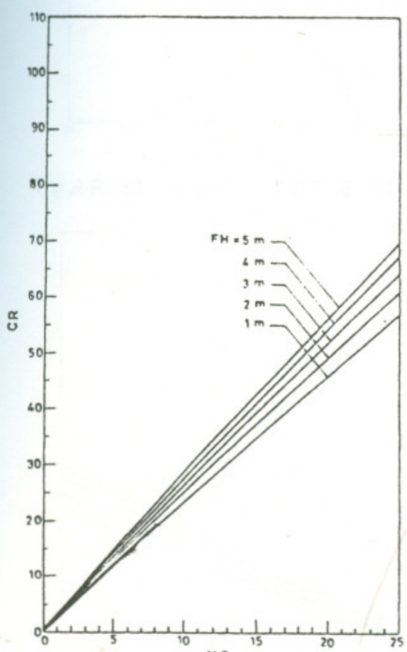
Furthermore, the four regression coefficients are correlated to the culvert span, height and area of one cell (A) by the following best



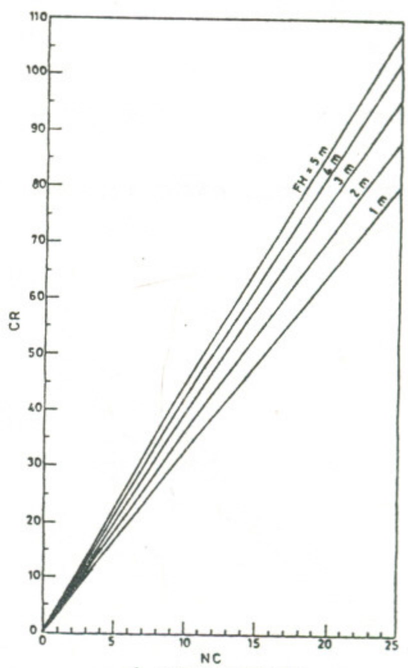
a - SIZE 2.00 × 1.00 m



b - SIZE 2.00 × 1.50 m



c - SIZE 2.00 × 2.00 m



d - SIZE 2.50 × 2.50 m

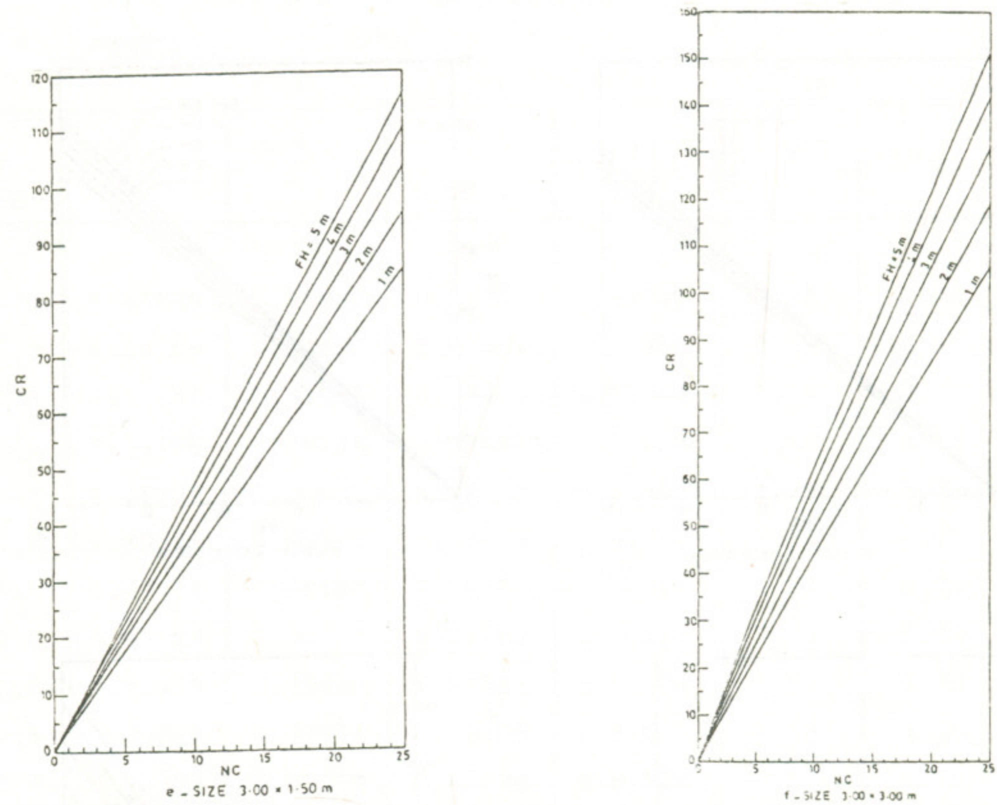


FIGURE (1) COST RATIO VS. NUMBER OF CELSS FOR 5 FILL HEIGHTS (SCR = 5)

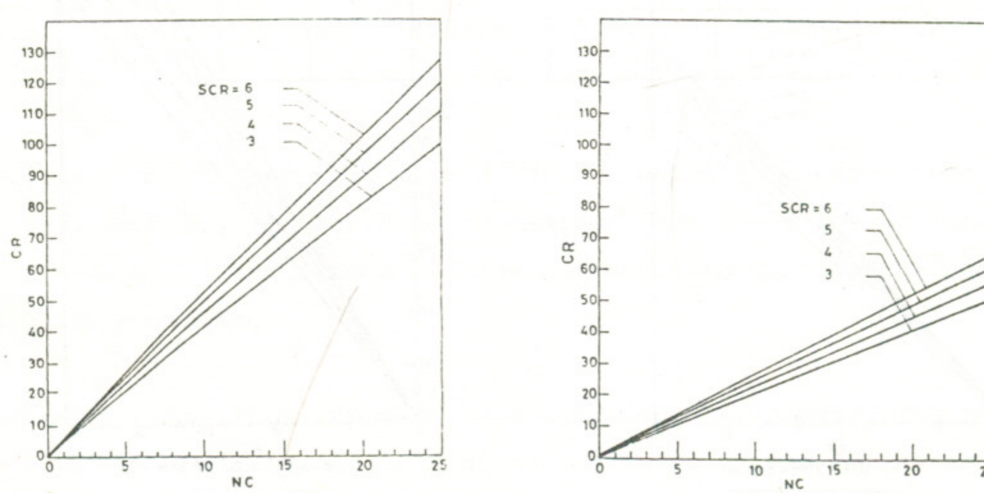


FIGURE (2) COST RATIO VS. NUMBER OF CELLS FOR 4 SCR VALUES (FILL HEIGHT = 2)

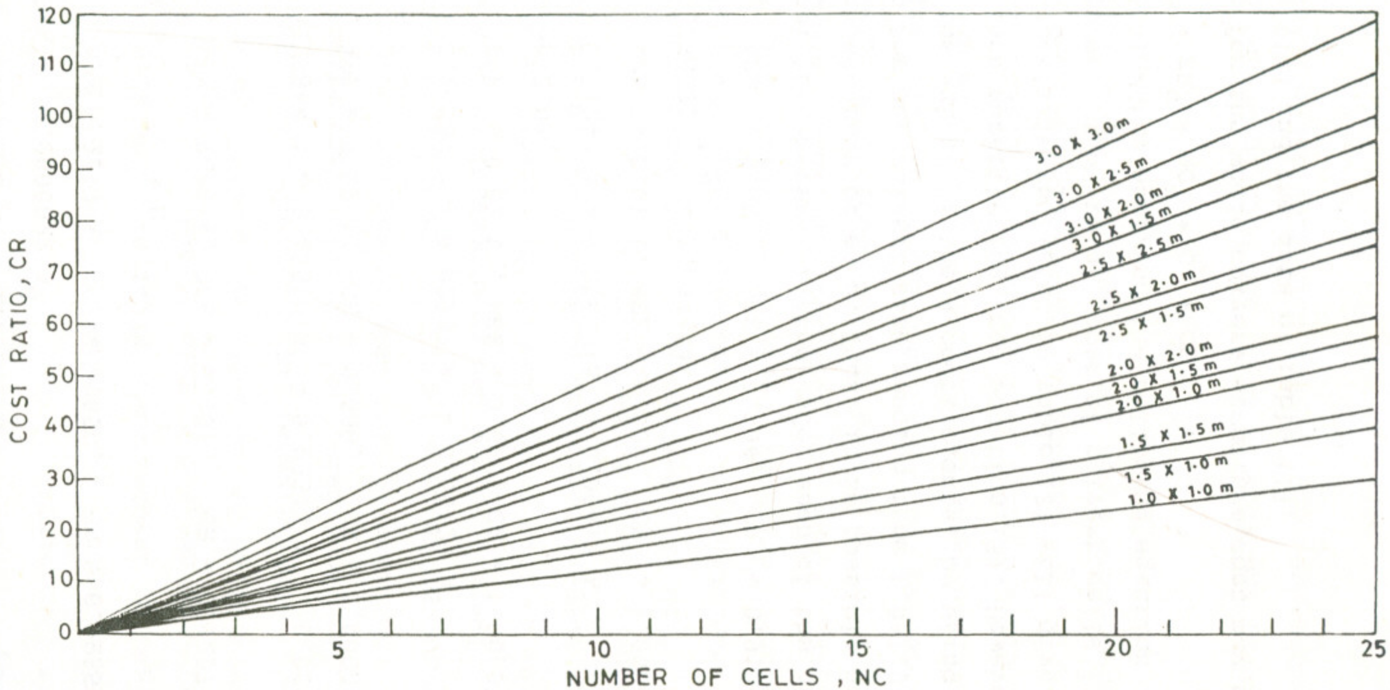


FIGURE (3) COST RATIO VS. NUMBER OF CELLS FOR 13 CULVERT SIZES
(FILL HEIGHT = 2.00 ms. & SCR = 5) .

fit equations:

$$a = -0.43979 + 2.28398\,A - 1.32545\,A^2 + 0.37925\,A^3 - 0.05004\,A^4 + 0.00288\,A^5 - 0.00022\,A^6 + 0.0000388\,A^7 - 0.0000022\,A^8 \quad (4)$$

(MPE = 7.07 % , APE = 2.17 %, SEE = 0.050, CR = 0.9935)

$$b = 0.305994 * S^{0.28230} * H^{-0.14274} \quad (5)$$

(MPE = 4.18 % , APE = 2.43 %, SEE = 0.001, CR = 0.9227)

for S/H = 1 :

$$c = 0.17772 - 0.30884\,A + 0.15555\,A^2 - 0.02314\,A^3 + 0.00113\,A^4 \quad (6)$$

(MPE = 0.07 % , APE = 0.02 %, SEE = 0.000, CR = 1.0000)

for 1.0 < S/H < 2.0 :

$$c = -0.44440 + 0.26587\,A - 0.02937\,A^2 \pm 0.00129\,A^3 \quad (7)$$

(MPE = 0.05 % , APE = 0.03 % , SEE = 0.000, CR = 1.0000)

for S/H = 1.50 or 2.0:

$$c = -0.36599 + 0.32247\,A - 0.05632\,A^2 + 0.00412\,A^3 \quad (8)$$

(MPE = 0.05 % , APE = 0.01 %, SEE = 0.000, CR = 1.0000)

$$d = 0.951282 S^{0.038380} * H^{-0.034314} \quad (9)$$

(MPE = 0.68 %, APE = 0.35 , SEE = 0.004, CR = 0.9120)

The statistical parameters listed under each of the above equations assure the high accuracy of each. Thus, it is possible now to estimate the cost ratio for any culvert size ranging from 1.0*1.0 m to 3.0*3.0m by estimating the values of the 4 coefficients, by using equations (4) to (9) and then substituting into equation (3). However, the direct use of the coefficients listed in table (2) will give more accurate results. Moreover, the total cost of culvert cells (TCC) of length (CL) can be obtained by applying the following equation :

$$TCC = a * SCR^b * FR^c * NC^d * C_c * CL \quad (10)$$

An estimation for the whole culvert structure cost may be obtained by using equation (10) and the data of table (1).

3. Hydraulics of Highway Culvert Flow

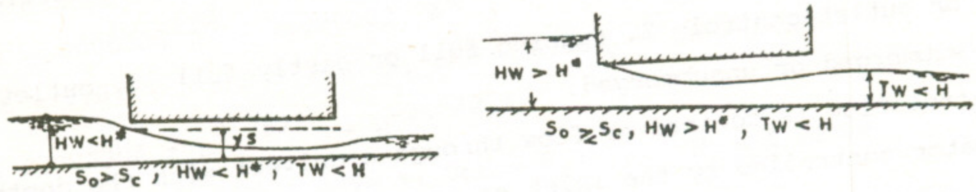
The flow through culvert barrel may be hydraulically classified according to the following:

1. inlet or outlet control 2. running full or partly full 3. outlet or inlet submerged or unsubmerged.

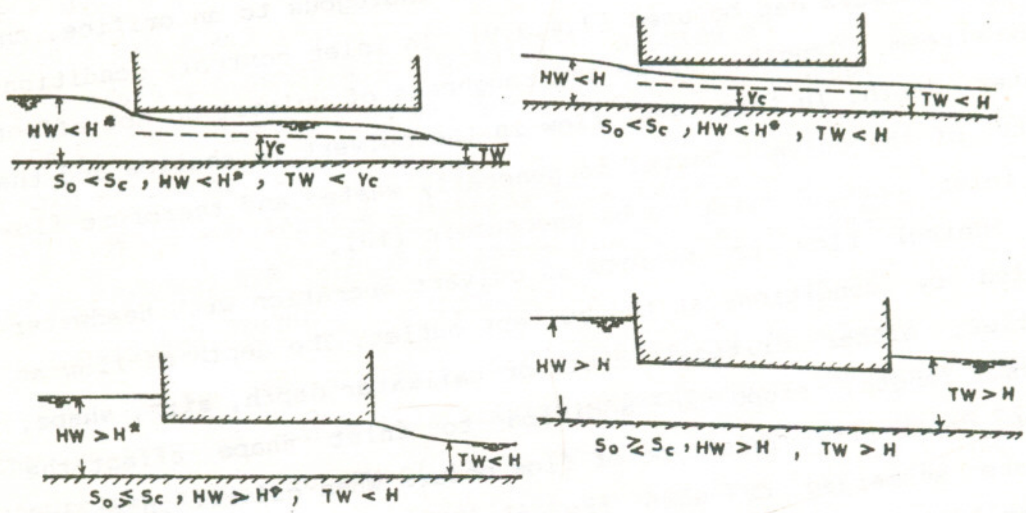
Inlet control flow is defined as flow through a culvert with the depth of headwater controlled by the inlet as is usual for culverts on mild or steep slopes with tailwater below the crown of culvert at outlet. The area, shape, and edge detail of the inlet face affect the depth of headwater. The operation in this case is analogous to an orifice, and an orifice formula can be used [7,4,8,9]. In inlet control, conditions of downstream, length, slope and roughness of culvert do not affect headwater depth. In this case, flow in the culvert is shallow and the capacity of the culvert barrel is generally wasted and therefore flow under inlet control tends to be uneconomic [10].

Outlet control flow is defined as culvert operation with headwater controlled by conditions at the culvert outlet. The depth of flow at the outlet, either critical depth or tailwater depth, size, shape, roughness, length, slope in addition to inlet shape affect the headwater depth [11]. This type of flow occurs when culvert inlet and outlet are submerged or when the slope is flat especially when downstream conditions cause the tailwater depth to be greater than the critical depth.Outlet control is found to be in effect about only 10 % of the time during the passage of flow through highway culverts [4]. Figure (4) shows some cases for culvert flow under inlet and outlet control.

When runoff starts, the flow is small and both inlet and outlet of the culvert are unsubmerged and culvert will flow under inlet control and



EXAMPLES OF INLET CONTROL



EXAMPLES OF OUTLET CONTROL

$H^{*} = 1.2\,H$

FIGURE (4) CULVERT FLOW UNDER INLET AND OUTLET CONTROL.

discharge increases, the headwater depth (HW) may be larger than the culvert height, but not high enough to ensure that culvert will run full. Wheather a culvert run full or not depend on size, length, roughness of culvert as will as both headwater and tailwater levels. Culvert will run full when the outlet is submerged or when the outlet is not submerged but headwater is high and barrel is long. Length is an important factor and a culvert may be called "hydraulically long" if it runs full and "hydraulically short" if it does not. Carter [11,12] prepared charts which may be used to distinguish roughly between hydraulically short and long culverts. Moreover, for unsubmerged outlet, experimental studies concluded that unless headwater depth reach a value of 1.2 to 1.5 the culvert height, water will not touch the culvert soffit at inlet [8,12].

The Bureaue of Public Roads of the U.S.A has published hydraulic charts for the selection of highway culverts [13]. These charts are perhaps the most widely used and accepted culvert design manual in the world [10]. For the case of inlet control, the charts are based on data of laboratory tests of model culvert, while the outlet control charts are based upon culverts flowing full. In 1972 the same bureaue presented additional charts for the capacity of highway culverts [14]. The outlet control curves of these charts are based upon critical depth at the outlet.

4. Proposed Design Criteria

According to the importance and class of the road, a design return period is selected and the design discharge at culvert site is determined. The next step is to fix the size of the culvert, and for this purpose the present study proposes the following design criteria:

this purpose the present study proposes the following design criteria:

4.1. Geometrical Criteria:

1. minimum practical size is 1.0*1.0 m, as smaller sizes will suffer from clogging problems. Maximum size is 3.0 m * 3.0 m,
2. span not greater than double the height, height not greater than span and culvert width is not greater than channel width and
3. for the minimum culvert height of 1.0 m, if the difference in levels between road and top culvert slab is less than 30 cm, raise the road level.

4.2. Hydraulical Criteria:

1. For economical reasons, the present study recommends that headwater depth should not be less than 1.20 the culvert height, unless topographic conditions does not allow this condition.
2. Maximum velocity through the culvert is fixed prior the design, this will control scour downstream. A minimum design velocity of 1.5 m/sec is considered to prevent deposition of debris.
3. the procedure proposed by (13) for estimating the governing headwater depth is to be followed. The present study converted the inlet control nomographs given by (13) into the following equations:

for AWWF = 0 : $HW = 0.82575 * q^{0.76655} * H^{-0.14828}$ (11)

for AWWF = 15 & 90 : $HW = 0.82274 * q^{0.73964} * H^{-0.11876}$ (12)

for AWWF = 30 to 75: $HW = 0.73451 * q^{0.79536} * H^{-0.20537}$ (13)

Also, the energy and Manning's equations are used for the case of outlet control design considering tailwater depth (TW) to be the greater of : TW or (H + YC)/2, in which YC is the critical depth.

4.3. Economical Criteria

For each of the alternative culvert sizes which satisfy the above conditions, the cost ratio is estimated by equation (3) and the coefficients listed in table (2). Hence, the minimum culvert cost at each site may be easily chosen.

5. Computer Program Ecocul

The present study prepared a computer program called ECOCUL which applies the above mentioned design criteria. All culvert sizes which satisfy the proposed design criteria will be given along with the design hydraulic parameters and cost ratio. The data required to run the program are: design discharge, allowable headwater, maximum velocity through culvert, tailwater depth, channel bed width, culvert length and slope, Manning's roughness coefficient for culvert cell, angle of wing wall flare, road level, upstream channel bed level, cost of 1 ton of reinforcement steel and cost of one cubic meter of culvert concrete. Also culvert serial number and chainage are entered. If the design discharge is not available, the program asks for hydrological data and the rational method is applied to compute the design flow. The present program utilize the rainfall intensity - duration - frequency relationship developed by the author for northern Oman [15], and which may be replaced by other equation relevent to other region. A sample output is given below and Figure (5) shows the flow chart of program ECOCUL.

The given example shows four alternatives for the culvert size which will pass the runoff of 73.77 cu.m/sec resulting from rainfall on the 7.55 sq. Km catchment area. Two of these sizes will flow under inlet control and the other two will be flowing under outlet control. It can be seen that the cheapest size which should be implemented is the 7 cell 2.0 * 2.0 m for which CR has a minimum value of 14.730.

NO	CHAINAGE KM	CAT.A SQ.KM	L M	DH M	TOC MIN	ROC	RI MM/HR	RUNOFF CUM/SEC
1	1.750	7.55	4250.	60.	62.	.65	54.07	73.77

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TW =   2.00 M  , AHW =   2.75 M , VMAX =   3.00 M / SEC
B  =  20.00 M  , RL  =  10.00 M , BL   =   6.50 M

OUTLET CONTROL DESIGN : NC= 6  S=3.0  H=1.5  HW= 2.70  HW/H=1.80
                        TW/H= 1.33    V = 2.73  CR= 19.492

INLET  CONTROL DESIGN : NC= 6  S=2.5  H=2.0  HW= 2.53  HW/H=1.26
                        TW/H= 1.00    V = 2.46  CR= 16.095

INLET  CONTROL DESIGN : NC= 7  S=2.0  H=2.0  HW= 2.66  HW/H=1.33
                        TW/H= 1.00    V = 2.63  CR= 14.730

OUTLET CONTROL DESIGN : NC= 8  S=2.0  H=2.0  HW= 2.42  HW/H=1.21
                        TW/H= 1.00    V = 2.31  CR= 16.723
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SAMPLE OUTPUT OF PROGRAM ECOCUL

6. Conclusions

1. A set of 13 accurate dimensionless equations are presented for the estimation of the cost of 13 different box culvert sizes ranging from 1.0 m * 1.0 m up to 3.0 m * 3.0 m. The equations are valid for fill height up to 5 meters above culvert top slab and for number of cells up to 25.
2. Each of the four coefficients used in the formulation of the 13 equations are correlated to the culvert span, height and area of one cell. Thus, a single equation may be used for estimating culvert cost for the 13 sizes.
3. For the economical design of box culverts, design criteria are given considering geometrical, hydraulical and economical factors.
4. A computer program called ECOCUL is designed considering the proposed design criteria. Flow chart and sample output are give.

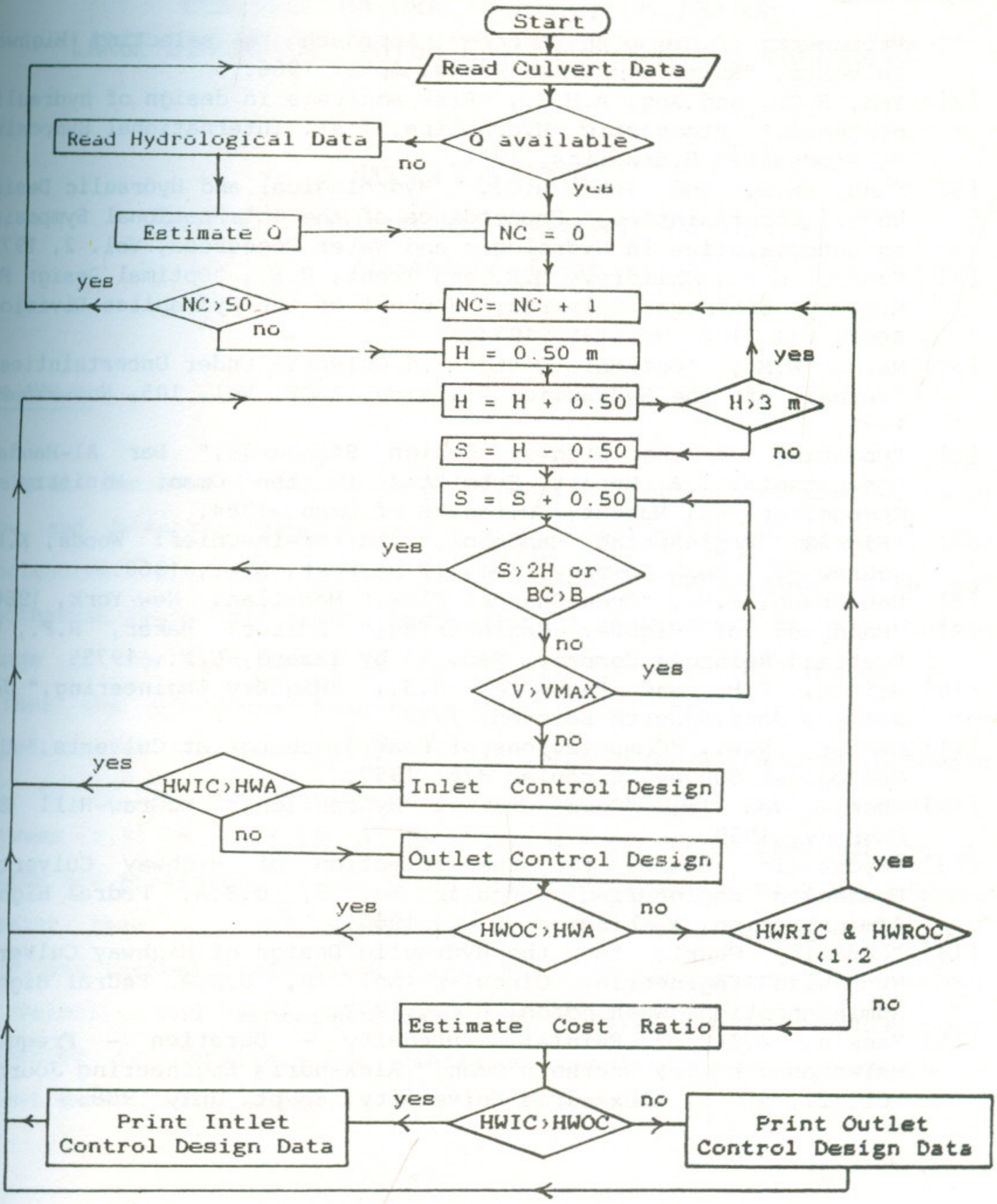

Figure (5) Flow Chart for Program ECOCUL.

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