

HYDROLOGIC & HYDRAULIC CONSIDERATIONS FOR PLANNING AND DESIGN OF CULVERTS FOR ROAD DRAINAGE

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Abstract

Several new road Schemes as well as up-gradation of existing roads are being undertaken by the Govt. of India for better and faster communication amongst the different parts of the country. Drainage of road is an important aspect of road project for the purposes of safety, speed, maintenance and life span of the road. Design of culverts which is an integral part of any road drainage scheme is to be done scientifically for efficient functioning. The paper outlines the various data to be collected from different sources for proper planning and design of culverts and deciding their location, type and size for new roads as well for up-gradation of existing ones. Different hydrological and hydraulic considerations including use of software involved in the design of culverts have been discussed at length.

Key Words: Culvert, Controls, Design Flood, Improved Inlet, Head water, Velocity

1 INTRODUCTION

Govt. of India has an ambitious plan of connecting different parts of our country by constructing a network of national highways, state and village roads under various development schemes e.g. Golden quadrilaterals, North-South & East –West Corridors, Gram Sadak Yojna , NREGP, Bharat Nirman etc. Apart from construction of new roads, the Government's policy is to also upgrade the existing roads for developing an efficient road communication system. Roads and similar other infrastructures, built with public money, are our national assets and they must be preserved and protected for the benefit of the people.

Drainage of road is one of the many components of a road project. The objective of road drainage is to remove the storm water as rapidly as possible so that traffic may move safely and efficiently without any loss of time. Speedy disposal of the storm water runoff likely to be accumulated due to construction of the road embankment is very important for the success of a road project from technical and environmental points of view. Inadequate drainage invariably results in reduction of life span of a road, increase in maintenance cost and drainage congestion in the countryside leading to submergence of land and consequent loss of agricultural and other properties.

Provision of culverts of adequate size and numbers in a road drainage scheme - whether the road is a new one or an up-gradation of an existing one - is intimately related to the health and safety of the road.

Depending on terrain conditions and the magnitude and intensity of rainfall, cost of roadside drains and drainage culverts in Indian road projects is generally around 4% to 5% of the total project cost. However, due importance is generally not given for proper planning, hydraulic design and construction of road drainage and drainage culverts in Indian road projects commensurate with the role the drains and culverts play in protecting the road and safeguarding the interest of the project as a whole.

The main purpose of writing this paper is to emphasize some important hydrologic and hydraulic considerations involved in proper planning and efficient design of drainage culverts. IRC: SP:42 (1994) and IRC:SP:13 (2004) give guidelines for design of road drainage and drainage culverts respectively. IRC: SP:50 (1999) and IRC: SP:48 (1998) are meant for design of urban road drainage and hill road drainage respectively. In an earlier paper (under review by IRC), Mazumder (2009) has discussed about the optimum spacing and design of culverts in a hilly terrain. In this paper, authors have emphasized upon the various hydrologic and hydraulic aspects for proper planning and design of culverts for road drainage.

2. NECESSITY OF DRAINAGE CULVERTS

Construction of a road embankment unavoidably obstructs and interferes with the natural overland flow and flow through the natural channels e.g. rivers, nallas, canals, drains etc. Suitable bridge / culvert openings under the road should, therefore, be provided across these channels with a view to pass the peak discharge through the channels without causing harmful afflux and disturbing the natural flow regime. Provision of adequate numbers of culverts of appropriate size is a prerequisite for a healthy road. Submergence and overtopping of road not only causes damage to the road and road structures, it results in disruption of traffic, loss of travel time and miseries to many of the poor people who take shelter on roads during floods in many parts of our country.

Overland flow, which would otherwise meet the natural stream at some downstream point, must be intercepted in longitudinal drains and discharged back into the nearest natural drainage channel through culverts and bridges. The local drainage arrangements consisting of longitudinal drains and culverts shall have to be designed to carry the runoff from the road surface too.

Where a road runs in an undulating terrain, causeways or dips are often provided in valleys to avoid road in high embankment. Frequent dipping down from high road levels to the ground produces a very undesirable road profile. Constructing bridges and culverts under road in high embankment is a better proposition than providing so many dips and causeways leading to disruption in traffic movement during flood season.

Bridges, culverts and underpasses are often used by local people and livestock to cross the busy roads like national and state highways in high embankments. They also act as passage for up and down movement of fish and other aquatic animals. Sediments and debris carried by the stream, especially during floods, must freely move downstream through these openings to avoid aggradations and other interrelated problems (MOWR,2004). For existing roads, it is not uncommon to find silted barrels of existing culverts and culverts having inadequate capacities causing overtopping of the road embankments.

In a very flat terrain, most of the streams are shallow and the banks are spilled with flood water moving in wide flood plains. In the absence of road, the spill flow moving over the land surface constitutes a substantial amount of peak flood. When a road is built in such a terrain with wide flood plains, the entire flood water has to move across the road through the bridge opening of limited span, resulting in very high afflux and other problems (Mazumder et al,2002). Usually, the spill water is found to move along the toe of the road causing scouring and damage to road embankment. Provision of relief culverts on either side of the bridges in such flood plains are very helpful in the quick disposal of spill flood across the road which results in less afflux and ensures safety of the road embankment.

3 PLANNING OF CULVERTS FOR EFFECTIVE ROAD DRAINAGE

Design of an efficient cross-drainage system is a prerequisite for success of new road projects and for rehabilitation projects as well. Proper planning of culverts is a very important aspect of road design from the point of view of safety of the road - new or existing one. Planning generally covers selection of location, type, numbers and size of culverts.

3.1 Location of Culverts

To be most effective, location of culverts have to be very carefully decided after studying the terrain and collecting relevant information from toposheets and other sources. Field visit and consultation with local people and local authorities conversant with local topography and drainage problem of the area is extremely useful.

3.1.1 Location of Culverts for new road projects

A drainage culvert should be placed in a natural depression or valley points. These locations are easily identifiable in hilly / rolling terrains but very difficult to be identified in plains. An easy method of identifying the depression / valley and direction of flow is contour study of the project road corridor and a site visit to study drainage pattern of the area. The ground level elevations along the toe of the road on upstream and downstream (L-Profile) should identify the natural dips and thus suitable culvert locations and direction of flow. It is mandatory to ensure a path for the runoff to reach the outfall point from culvert outlet either through existing channel or roadside ditches or by overland flow. Flow coming out of the culvert must not get accumulated at its outlet jeopardizing the safety of the road embankment. Downstream canalization, wherever feasible, may also be thought of to avoid such accumulation of water.

In the hilly terrains, culvert locations are identified directly from the presence of streamlets, not big enough to be spanned by a bridge. In the stretches where the road is planned by cutting hill slopes, innumerable streamlets come down the hill slopes cross the proposed road. Runoff water and sediments from such streamlets must be disposed off either directly through culverts at the crossings and/or intercepted by longitudinal drains and disposed off in to the valley through closely spaced intermediate culverts with a view to limit the drain size. Optimum spacing of culverts in a hilly terrain has been worked out in another paper

by the first author (Mazumder,2009).Box or slab type culverts or small bridges are suitable for free movement of the incoming water when it carries a lot of sediments and debris. It is necessary that the span of culverts should be equal to or a little more than the linear waterway at design HFL for such streamlets flowing at supercritical velocity.

In the plains, however, the available longitudinal slope along the proposed alignment is generally very flat and roadside ditches are commonly aligned with available longitudinal slope for economy. If the existing dips are long apart, the distance between an existing dip and an adjacent ridge becomes too long entailing a bigger size of the ditch and acquisition of more land. In such cases, intermediate culverts , also called balancing culverts, are proposed just to reduce the length and size of the roadside ditches. In fact, most of the culverts in plains are balancing in nature. However, all natural dips may not be used as suitable culvert locations. It depends on the available longitudinal slope and consequently the required size of the roadside ditches that govern the locations to be utilized as suitable culvert points. If the available longitudinal slope is good enough to carry the roadside ditches for a longer distance with reasonable size, some intermediate minor dips may be crossed over without having to provide a culvert structure.

For roads planned alongside a major river (say Ganga/Yamuna Expressways), it is frequently observed that spill from the river originates from some upstream point, comes into the countryside and again goes back and meets the river at some downstream point. Each of these spills crosses the proposed road alignment (running almost parallel to river bank) at two points - one at upstream point wherefrom the spill channel originates and comes to the countryside and the other at the downstream point where it goes back and meets the river again. It is a standard practice to plug the upstream crossing points and span the downstream crossing location with suitable culvert or bridge structure, depending on the size of the spill. The countryside length of the spill channel, past the plugging point, shall carry the runoff from the local countryside catchment and the run-off must be disposed into the river through the downstream opening.

The proposed alignment of the new road may also cross some small size irrigation field channels and drains. These small sized canals and drains must be spanned by culverts/syphons at their crossing points with the road.

3.1.2 Location of Culverts for Road Upgrading Projects

For a road upgrading project, the task of selecting culvert locations reduces to selection of locations for additional culverts only. Even if the conveying capacity of some of the existing culverts is not hydraulically adequate, replacement of such culverts by a bigger size culvert or a small bridge shall be made in the existing locations only. For additional culverts, the locations shall be based on the natural dips along the stretches of existing road vulnerable to overtopping. An inventory of existing culverts has to be prepared indicating chainage, type and size of culverts, invert levels at entry and exit of culverts, ground level and stream bed level, condition of culverts, ponding level, submergence of land, overtopping of road and extent of overtopping etc. Such detailed inventory of culverts is very helpful in preparing an adequacy statement

and deciding which of the existing culverts require replacement by larger size culverts or small bridges and to decide whether additional culverts will be needed or not.

3.2 Types and Size of Culverts

Culverts may be of several types and geometry, namely, Pipe Culverts (circular and elliptic), Box culverts (square and rectangular), Slab and Arch culverts (with or without bottom slab) etc. Selection of type and geometry of culverts inter alias depends on the required width and area of opening, height and vertical clearance required, length of culvert and height of embankment decided from geometrics of road design. While it is easier to decide between a pipe culvert and box / slab culvert, selection between box and slab culvert is a matter of cost optimization.

3.2.1 Pipe Culverts

For minor crossings, circular hume pipe culverts suffice hydraulically. However, a pipe culvert has more joints owing to smaller length of precast pipe units manufactured in the market. The more the carriageway width of the road, more will be the length of culvert and consequently more will be the number of joints. As such it has now become a common practice for the major concessionaires to avoid pipe culverts for new major projects like Ganga/Yamuna expressway. However, for many other new projects in India, hume pipes having minimum diameter of 1200 mm are being used.

For mountainous regions, the culverts are generally provided at frequent interval. Pipe culverts are, therefore, very common in hilly stretches of roads. However, in stretches where the streamlets carry large size cobbles and boulders, there is a fair possibility of pipes getting damaged / choked. Pipe culverts are, therefore, avoided in such stretches and either slab type or box type culverts are preferred.

3.2.2 Box & Slab Culverts

For crossings where pipe culverts may not be feasible from hydraulic point of view, box or slab culverts are chosen for installation. From structural definition, a box culvert is a reinforced box structure with rigid joints whereas a slab culvert is one where a simply supported reinforced slab is placed over abutments. Generally, for medium height of embankments, both of the options viz., box culverts with road embankment supported on roof slab and slab culvert with roof slab directly supporting the wheel loads, are feasible. One of the options is chosen on the basis of LTEC (Least Total Expected Cost) method. For high embankments (for example near approach of bridges), however, box culverts are preferred to slab culverts from both structural and economic considerations. Box and slab culverts are suitable for mountainous reaches where the streamlets carry large sized cobbles and boulders. To avoid excessive scour in slab/Arch culverts, bed may be lined or unlined depending on flow velocity and type of bed materials. Lining of bed helps in preventing growth of weeds which drastically reduces the conveying capacity of culvert due to high resistance offered by such weeds and jungles.

3.2.3 Size of Culverts

The size of the culvert is designed on the basis of the following considerations from the points of view of:

- a) peak flow and hydraulic conveyance requirement
- b) ease of maintenance and desilting operation
- c) permissible velocity for fish movement where the channel carries fish
- d) movement of debris, gravels, boulders etc.

The required size of the culvert is decided on the basis of hydrological and hydraulic analysis. However, the minimum size of the culvert is fixed on the basis of ease in maintenance, movement of fish, debris etc. For upgrading projects, hume pipe culverts having diameter less than 900mm are to be replaced with a minimum diameter 1200mm as recommended by IRC: SP:13 (2004).

4 DATA COLLECTION

Data may be collected from site investigation / study of toposheets / Satellite Imagery / local enquiry and from records maintained by Government agencies like CWC, IMD, RDSO and Irrigation / PWDs. Broadly, the several data required for the design of drainage culverts are:

- Topographic maps showing contours, nature and slope of terrain , soil and cover conditions, physical features in the vicinity of the proposed culverts etc.
- Existing stream and canal network in the project area crossing the road indicating direction of flow and the drainage area contributing flow to the culverts.
- Stream data e.g. L-section and cross-sections of the stream upstream and downstream of the point of crossing , gauge-discharge data, if available, HFL from flood marks and local enquiry
- Soil and sub-soil data for computation of run-off from the drainage basins
- Hydro-meteorological data like amount, intensity, duration and frequency of rainfall
- Proposed roadway alignment , L-section and cross-sections of the road near the cross-drainage sites
- Fish passage requirement, if any
- Debris and sediments to be passed through the culverts
- Points of flow accumulation and areas of prolonged submergence, if any
- Nearest human habitation / property, places of worship, places of strategic importance etc.
- In case the proposed alignment runs parallel to any existing major road, it is very helpful to study the drainage particulars and performance of culverts on the existing road to have an idea about the required numbers and size of culverts for the proposed road from the drainage efficiency of the existing road.
- Information regarding likely damage to habitats, crops etc, due to ponding upstream of culverts
- Maximum permissible velocity at the outlets of culvert to determine nature of protective works to be adopted.

Most of the above data are available from toposheets and satellite imageries as well as survey data collected from field and from local enquiry. Flood estimation reports published by Central Water Commission (CWC), Govt. of India and flood estimation methods published by RDSO(1990), Ministry of Railways, Govt. of India, provide valuable hydro-meteorological data for different regions of India.

In case of road up-gradation schemes, the following additional data are to be collected during road survey

- Inventory and condition survey of the existing culverts indicating size, shape, slope, invert levels, siltation (choking), sediments and debris carried by the stream .
- Maximum Pond level and damages upstream and downstream , if any
- Scour and protective measures adopted
- A separate inventory of culverts/syphons carrying irrigation supply and details of irrigation/drainage canals e.g. bed width, FSL, side slope, bank level, ground level etc.
- Stretches of roads where overtopping of flood water takes place during flood season, maximum depth of such overtopping water and its location

4 HYDROLOGICAL CONSIDERATIONS FOR DESIGN OF CULVERTS

Main objective of hydrologic investigation is to determine the peak design flood discharge which the culvert is to carry across the road during flood season. The methodology of flood estimation for culverts is well explained in IRC:SP:13(2004), RDSO (1990), AASHTO(1990), text books (Raghunath-1985, Kings & Brater-1976) and Design Manuals (AASHTO-1975, WSDT-1997). However, some of the important aspects are briefly mentioned underneath.

4.1 Estimation of Design Peak Flood by Rational Formula

The hydrological design of a culvert is governed by the hydrological response of a catchment to the design rainfall over it. Various factors which affect the peak run-off from a drainage basin are

- Physiographic parameters affecting runoff from catchments e.g. size, shape, slope. cover conditions, permeability, antecedent moisture condition etc.
- Rainfall- its magnitude, intensity, duration and frequency (or return period)
- Time of concentration i.e. the time of overland flow and flow through channel from the hydrologically most distant point in the catchment
- Determination of storm duration to be considered depending upon concentration time
- Movement of storm towards or away from the outfall point

Since the catchment area of culverts is small, peak flood for culvert is usually calculated by using Rational formula:

$$Q = 0.028f P_m I_c A \quad (1)$$

where,

Q = peak inflow flood discharge in m^3/sec ,

P_m = mean run-off coefficient of the catchment area contributing flow to the culvert. P_m value can be found by the relation given by equation (2)

$$P_m = \frac{\sum(P_i A_i)}{\sum A_i} \quad (i=1,2,3,\dots) \quad (2)$$

P_i = run-off coefficients for the different types of areas A_i contributing run-off to the drain

$\sum A_i$ = total catchment area in ha ,

I_c = critical design rainfall intensity in cm / hr corresponding to time of concentration, t_c given by

$$I_c = (F/T) [(T+1) / t_c + 1] \quad (3)$$

Where,

F =depth of rainfall in cm over a period of T hours

t_c = time of concentration in hours

4.1.1 Determination of Catchment Area

For mountainous regions, delineation of catchment area may be done either with the help of available toposheets of 20m contour interval or with the help of Google Earth Images. 1:50,000/1:25,000 toposheets are registered in AutoCAD or ArcGIS platform and the ridges can be plotted on it. The Channel length and slope can also be estimated from the available map. Delineation of catchment can be done with more precision with the help of Google Earth images. Polygons can be drawn along the ridges for delineation of catchments with naked eyes with reasonable accuracy. Properties of these polygons can be ascertained either directly (for Google Pro) or by exporting these polygons into AutoCAD / ArcGIS platform. The fall (difference in height) of channel can be ascertained directly from Google Earth image at any desired point with respect to the outfall point at culvert.

For plain regions, toposheets having 20m contour interval may not be at all useful in delineating catchment or determination of fall of the channel. However, the artificial ridge lines like roads, canals etc can be easily traceable on the toposheet/map and these ridges can be considered as catchment boundary for a particular culvert. For plain regions, most of the culverts are designed as balancing ones and do not span any distinct channel. As such, area of catchment applicable for any particular point is governed by the countryside length discharging towards the culvert and the distance between two consecutive cross ridges (natural or artificial) on either side of it. The countryside length may be taken as the distance between the proposed alignment and existing artificial ridges (roads, canals etc), if any, running parallel to it. The distance between the existing cross ridges (running perpendicular to the proposed alignment) can be measured from toposheets or the survey data of the road corridor. However, if the distance between two consecutive cross ridges is so large that it entails unreasonable size of the roadside ditches, the acceptable size of the roadside ditches shall limit

the spacing of the culverts. In such cases, group of culverts at available dips may be required between two cross ridges.

In practice, delineation of catchment is really a problem in plain regions. Delineation of the catchments of rivers is comparatively easier from Toposheets / ArcGIS tools. An innovative method of estimating the catchment for a group of culverts may be as follows:

- Delineate the catchments of the major rivers / streams / streamlets to the extent feasible from ArcGIS or study of Toposheets.
- Measure the area entrapped between two consecutive outfall points of the adjoining streams, which is not a part of the catchments already delineated for the streams.
- Try to plot the artificial ridge lines, if any, running parallel to the proposed alignment within the entrapped area not included in the delineated catchments of the adjoining streams.
- The peak run-off from the area in between the catchments of identifiable streams, will have to be evacuated through the culvert openings to be proposed at natural dips between the two consecutive stream outfall points where bridges are recommended..

4.1.2 Rainfall Analysis

The runoff from a catchment is heavily dependent on the design rainfall. As the catchment area of a culvert is considerably small, the spatial distribution of rainfall over a particular catchment area can be reasonably considered as uniform. However, the times of concentration for such catchments vary widely from as low as 5 minutes (roads on hill cuts) to a few hours (flat terrains). The design intensities of rainfall (corresponding to these varying durations), which are inversely proportional to the time of concentration and directly proportional to the peak discharge, require to be determined with reasonable accuracy.

Determination of Intensity-Duration-Frequency (IDF) curves requires continuous rainfall data for a reasonable length of time. Again, as a road traverses a long distance, different sets of curves may be required to be prepared for different stretches of the roads, depending on the likely variation of rainfall characteristics over varying stretches. In most of the cases, continuous records of rainfall for a reasonably long period are not readily available for carrying out frequency analysis by extreme value distribution method like Gumbel's method, Log Pearson method etc. (Raghunath,1985).

In the absence of such records, the method of determination of the critical intensity of rainfall (I_c) from mean intensity (F/T), as stipulated by eq.3 in IRC:SP:13(2004), is reasonably good. I_c can also be determined from iso-pluvial maps published by CWC and RDSO(1990) where rainfall values (F) are given for 24 hours ($T=24$). Since the time of concentration (t_c) for a culvert is smaller than 24 hours, it is suggested to use storms of smaller durations corresponding to t_c hours (CWC Flood Estimation Reports) to find I_c -value to be used in eq.3

IRC:SP:13(2004) does not specify any return period for rainfall (F) to find design rainfall intensity, I_c . IRC:SP:42 (1994), however, recommends a return period of 25 years for important roads like National and

State highways (50 years for depressed sections) and 10 years for lower category roads. The same may be adopted for the hydrologic design of culverts since culverts are an integral part of road drainage system. WSDT(1997) suggests different return periods for different purposes e.g.10 year peak where there is fish movement, 25year peak for finding maximum head water elevation and 100 year peak to check overtopping of road surface. Approximate values of rainfall frequency factors to convert rainfall of 10 year return period to higher return periods are as follows:

<u>Return Period(years)</u>	<u>Frequency Factor</u>
10	1.0
25	1.10
50	1.20
100	1.25

4.2 SCS Method of Determining Peak Design Flood

A relationship between accumulated rainfall and accumulated run-off was derived by US soil Conservation Service(SCS) from experimental plots for numerous hydrologic and vegetative cover conditions. The relation was developed mainly for small catchments e.g. culverts for which catchment characteristics and daily rainfall data are available. The SCS equation for estimating direct run-off is given by

$$Q = [(P - I_a)^2] / [(P - I_a) + S] \quad (4)$$

where,

Q = Accumulated run-off in mm

P = Accumulated rainfall in mm

I_a =Initial abstraction including surface storage, interception and infiltration prior to run-off in mm

S = Potential maximum retention in mm

The methodology of computing peak flood discharge (in Cumec) by using SCS curves/tables has been explained in hydrology text books (Roberson et al,1993) and Design Manuals (USDA-1973,ERA-2002).

5 HYDRAULIC DESIGN OF CULVERTS

Hydraulic analysis of flow through a culvert is time consuming and complex. Flow conditions vary from culvert to culvert and with time depending upon the quantum of flow passing through the culvert. Culverts may flow full or partially full depending upon its size, upstream and downstream conditions, inlet and outlet geometry, length and slope of culvert barrel, roughness etc. For efficient design of culverts, it is extremely important to know the hydraulics of flow through a culvert as discussed underneath.

5.1 Types of Flow Through Culverts

Depending upon magnitude of flow through a culvert, its size and shape, inlet and outlet geometry, length, bed slope, roughness and tail water conditions, a culvert may run part full or full as illustrated in Figs.1 and 2 respectively. If $HW/D < 1.2$ (HW =head water depth above bottom invert & D is the vertical height of culvert opening at its entry), the inlet is not submerged and the culvert will run part full subject to the condition that the tail water level is below the crown of culvert at its exit end. When $HW/D > 1.2$, the inlet gets submerged (Fig.1) but it may still run part full if the slope is steep. In mild slope, however, the culvert may or may not run full when $HW/D > 1.2$, depending on its length. If the slope is mild (less than friction slope) and downstream flow is sub-critical, hydraulic jump may form inside or outside the culvert where conjugate depth (for momentum balance) condition is satisfied. When the bed slope of culvert is milder than friction slope, depth of water in the culvert increases with length in the direction of flow. In case of very long culvert (as in very wide road or culvert under airport runways), the depth of flow as it approaches exit end may be equal to its height of opening at exit resulting in air lockage and unsteady flow which should be avoided. In the range $1.2 < HW/D < 1.5$, the flow in a culvert with rounded entry and supercritical bed slope will be pulsating as the locked air will be entrained and discharged periodically resulting in vibration and fatigue failure. With $HW/D > 1.5$ and rounded entry, the culvert will run full even if the slope is steep. Culvert will always run full when the tail water elevation is higher than the crown level of the culvert at its exit end.

5.2 Types of Control and Flow Equations

As illustrated in Figs.1&2, the control section (where flow is critical) may be near entry (Fig.1) or exit (Fig.2) of a culvert depending upon its inlet geometry, HW/D -value, length, slope and roughness. If $HW/D < 1.2$ and the inlet is not submerged, control will be at outlet in mild slope but it will shift to inlet in case of steep slope. When $HW/D > 1.2$ and inlet is submerged and the culvert runs part full, the flow becomes orifice type in both mild and steep slope, control is at inlet (Fig.1). When a culvert runs full due to high tail water or high HW/D -value, control is at exit end of the culvert (Fig.2).

5.2.1 Inlet control

In an inlet control culvert with submerged inlet (Fig.1), the flow is orifice type and the discharge through the culvert may be expressed as

$$Q = C_o A_o (2gHW)^{1/2} \quad (5)$$

where,

Q =Flow through culvert in m^3/sec

A_o = Area of conduit at the entrance of culvert normal to flow in Sq. m.

HW = Head water depth in m at inlet measured usually from bottom inert of culvert to pond level

C_o = coefficient of discharge governed by inlet head loss which depends upon type of inlet geometry e.g. square ended, beveled, rounded, abrupt or gradual entry, shape of inlet transition connecting the normal channel section with culvert inlet section, amount of lateral and vertical restriction of waterway etc. C_o -values are given in text books (USBR-1968, Kings & Brater-1976) and design manuals (AASHTO-1975, ERA-2002, FHWA).

Another method of determining head water elevation (HW) for a given flow (Q) in a given culvert is to use nomograph giving discharge against HW/D-values by curves/tables developed from flow measurements for various types of culverts with different inlet and outlet geometry and are available in the text books and manuals cited above.

It may be mentioned here that in a culvert with inlet control, the head water elevation (HW) is governed solely by inlet geometry of the culvert and is independent of losses in friction and outlet loss in the culvert.

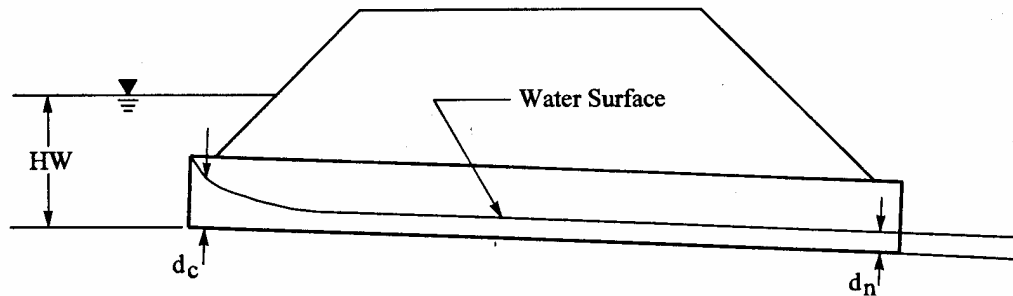


Fig.1 Typical Inlet Control Type Culvert with Orifice Type Flow at Entry

5.2.2 Outlet Control

In a culvert with outlet control, the head water elevation is governed by the head losses at entry (H_e), head loss due to friction (H_f) and head loss at outlet (H_o) of the culvert as illustrated in Fig.2. Headwater depth (HW) can be expressed as

$$HW = h_o + H - LS_o \quad (6)$$

where,

h_o (in m) = approximate height of Hydraulic Grade Line (HGL) measured above bottom invert level of culvert at the outlet ; h_o = tail water depth at culvert exit when TWL is above crown. When TWL is below the crown but the culvert runs full up to exit end, $h_o = D$ and $h_o = (d_c + D/2)$ when the flow is part full at the exit end. Here d_c = critical depth and D = vertical height of conduit at the exit of culvert.

$$H = \text{total head loss at entry, exit and in friction in m} = H_e + H_f + H_o = (K_e + K_f + 1) V^2 / 2g$$

$$H_e = \text{head loss at entry in m} = K_e V^2 / 2g$$

$$H_f = \text{head loss in friction in m} = k_f V^2 / 2g$$

$$H_o = \text{head loss at outlet in m} = V^2 / 2g \text{ (in case of sudden expansion with supported flow only)}$$

L = Length of culvert in m

S_o = Bed slope of culvert

V = Mean velocity of flow through the culvert in m/s = Q/A_f

A_f = Area of flow in the conduit in m^2

K_e = Head loss coefficient at entry (non-dimensional)

K_f = Head loss coefficient in friction (in m unit) = $19.6n^2L/R^{1.33}$

n = Manning's roughness coefficient (treated as constant in both MKS and FPS units)

R = Hydraulic mean depth in m

When $S_o = 0$ i.e. in a horizontal culvert, Equation (6) gives

$$H = (HW - h_0) = \text{afflux} = (1 + K_e + K_f) V^2 / 2g \quad (7)$$

Knowing afflux ($HW - h_0$), velocity of flow in the culvert 'V' can be found from eq.(7) i.e.

$$V = \sqrt{[(2g H) / (1 + K_e + K_f)]} \quad (8)$$

K_e & K_f - values are available in standard text books and design manuals as already referred to under 5.2.1

Equation (8) is applicable only where the flow from culvert is supported and discharges into a regular channel with defined cross-section. When there is a free fall at exit (unsupported as in a valley or culvert flow discharging into a flat terrain with very little tail water depth at exit end), there is no loss at outlet and hence

$$V = \sqrt{[(2g H) / (K_e + K_f)]} \quad (8a)$$

It may be mentioned here that in a freely flowing culvert running full with a free fall at exit (i.e. with unsupported flow at exit), H is to be found from equation (6), depending on h_0 -value at exit and not always from top of conduit as given in Fig.19.1(a) of IRC:SP:13 which is silent about supported and unsupported flow at exit and does not distinguish between inlet and outlet control in finding flow through a culvert.

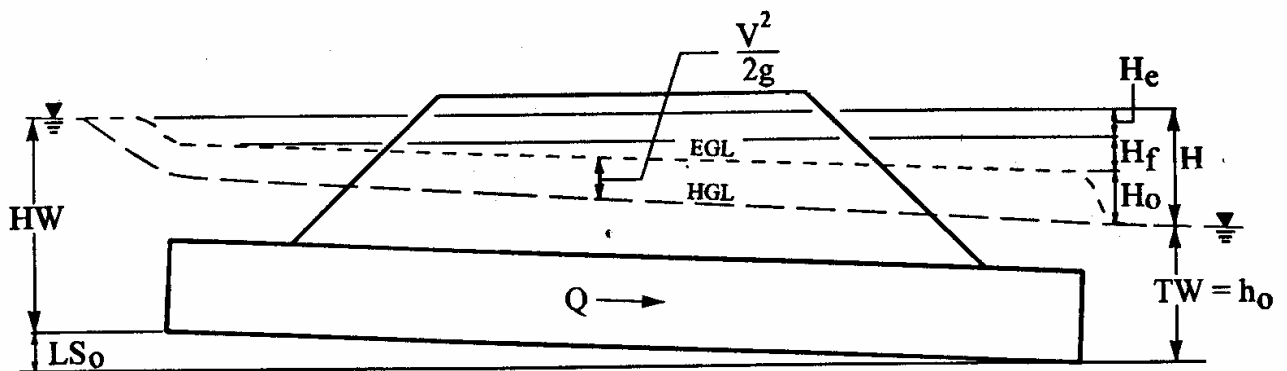


Fig.2 Typical Outlet Control Type Culvert With Supported Flow at Exit

Where the flow at exit is supported as in a channel with defined section and the outlet flow is diffused gradually by providing a suitable transition in order to avoid scour in the tail channel, outlet head loss may be expressed as $H_o = K_o V^2/2g$ and hence equation (8) reduces to

$$V = \sqrt{[(2g H) / (K_o + K_e + K_f)]} \quad (8b)$$

K_o - value in gradual expansion will always be less than 1 and it may vary from 0.2 to 0.8 depending on axial length and shape of transition (Roberson-1993, Mazumder-1967).

5.3 Head Water Rise, Size, Velocity of Flow, Energy Dissipation and Protective Works

Unlike bridges where very little ponding /afflux is permitted, normally ponding is allowed up to a certain limit in a culvert, especially in rural, agricultural, marshy, waterlogged and hilly areas where cultural value of land is not very high. Generally, ponding should be limited up to $HW/D = 1.2$ to 1.5 for easy cleaning of debris which may cause choking of culvert during floods. In any case, head water rise or pond level should be kept below sub-grade level of the road for a flood discharge of 25 year return period and checked against overtopping of road for a flood of 100 year return period.

5.3.1 Head Water Rise

It is apparent from equations (5) and (8) that head water rise is a function of flow (Q), size and geometry of culvert governing losses. Smaller the size, higher will be the head water for a given flow. More is the loss in head (H), more will be the afflux resulting in higher head water rise for a given size of culvert.

5.3.2 Size of Culverts

To decide the culvert size, it is very important to find damages likely to occur due to ponding upstream of the culvert. A minimum size of 1.2m diameter for HP culvert is recommended in IRC:SP:13,2004, for easy cleaning and maintenance of HP culvert. Where large amount of debris move with flood water, culvert size should be increased to ensure that a minimum freeboard is available for free movement of debris across the road. Possibility of constructing racks/detention tanks/flow deflector (WSDA-1997) etc. should be explored against increased size of culvert where there is large quantum of debris including floating matters.

5.3.3 Velocity of Flow Through Culverts

Velocity of flow and hence the discharge ($V.A_f$) in a culvert should be equal to or more than the incoming design flood (Q) which is estimated by methods already discussed under item-4.

In a road up-gradation project, a routine check should be made by comparing the discharging capacity of the culvert(for a given size and permissible maximum head water rise) and the design flood of 25 year return period. In those areas where the road is reported to be overtopped during flood season, culvert size should be

either increased or more culverts should be provided to prevent overtopping of road by peak flood of 100 year return period.

5.3.4 Energy Dissipation and Protective Works

Velocity of flow through culvert should be checked against scouring of footings (in bottomless culverts like slab /arch culverts) and erosion downstream of culvert. Protection work (e.g. Stone pitching) including provision of energy dissipater - usually of baffle type (Haeger-1992, USBR-1968) may have to be provided to prevent downstream erosion. Alternatively, the jet flow emerging out of the culvert has to be diffused by providing suitable outlet expanding transition (Mazumder-1994).

5.4 Tail Water Conditions

For any hydraulic analysis of a culvert, it is essential to know the tail water condition for a given flood and terrain condition. In a flat terrain without any defined channel and in a hilly terrain where the culvert disposes the flood flow in the valley, there is free flow since tail water depth is negligible and there is hardly any tail water effect on the headwater rise. Where the culvert is installed in a defined channel, the tail water depth will be equal to normal depth of flow corresponding to the given flood, channel geometry, slope and roughness. Manning's equation can be used to find the tail water depth (TW). Where no channel data is available, tail water depth (TW) can be approximated by use of Lacey's regime equation. In case there is some control structure on the channel downstream of a culvert, the tail water depth may be governed by the backwater due to the presence of such control structure and the tail water depth (TW) will depend upon the distance of the downstream control structure from the exit end of the culvert.

5.5 Improved Inlet Design to Increase Conveying Capacity of a Culvert

At many a places, the height of embankment is kept low to reduce cost of the road. In the absence of any defined channel, the bottom invert of culverts may often be below the general ground level resulting in a sudden drop at inlet and sudden rise at outlet end of the culvert. That portion of the culvert lying in depression below the ground is likely to be silted up quickly resulting in drastic reduction of conveying capacity of the culvert and consequent rise in head water (HW) for a given flood. Conveyance of such culverts with sudden inlet drop and outlet rise can be improved and the head water elevation (HW) can be lowered substantially, by providing suitable inlet and outlet transition structures. However, such structures add to the cost of culvert. A trade off is needed to decide whether local rise in road elevation (to accommodate culvert with invert at general ground level) or a locally depressed bed culvert (like an inverted siphon) with suitable inlet and outlet transition will be economical. In the former case, however, ride over the local road humps will offer difficulty in driving unless a ruling gradient is adopted as in road bridges. However, it will add to the road cost.

5.6 Use of Software for Hydraulic Design of Culvert

Because of complexity and enormous time required for hydraulic analysis of culverts, software like Culvert Master by Haestad (Bentley) and Hydraflow extension (AutoCAD Civil 3D) etc. are used now-a-days for quick determination of size, head water rise, type of control, flow velocity, flow profile etc. for a given value of design flood. CulvertMaster calculates headwater elevations based on both inlet and outlet control conditions. Inlet control calculations use weir and orifice flow equation (5), depending upon whether inlet is un-submerged or submerged. Outlet control calculations, based on equations (6) to (8), are employed for stable gradually varied flow hydraulic algorithms including hydraulic jumps, mixed gravity and pressure flow; and adverse or horizontal slopes etc. Inputs required are flow, numbers, size and shape of barrels, roughness, inlet and outlet geometry, invert levels, tail water conditions etc. Once these input data are fed to the computer, it uses the inbuilt software and provides complete solution giving all the required information in tabular and graphical forms for taking final decision for the design of culvert.

6 SUMMARY & CONCLUSION

Culverts and bridges are important cross-drainage structures used for disposal of run-off from drainage catchments including the road surface. Although cost of drains and culverts is only 4 to 5 percent of total cost of road project, it is noticed that planning, design and construction of road drainage is often neglected resulting in damage to road, loss in travel time, submergence of land and other associated problems. First step in culvert design is to collect all relevant data from site, toposheets, Google Earth etc. with the objectives of deciding location, type, size and capacity of culverts. Hydro-meteorological data like rainfall-intensity, duration and frequency and physiographic data like size and shape of catchment, its slope, roughness, soil and cover conditions etc. are essentially needed for estimation of design flood of 10, 25 and 100 return periods to be used for deciding size, velocity, headwater rise and checking up overtopping of road. For efficient functioning of culverts, hydraulic analysis must be carried out to find type of flow, type of control, headwater rise, flow velocity etc. for a given size of culvert with given inlet and outlet geometry, length, bed slope and roughness. It is obligatory to determine tail water conditions for proper hydraulic analysis. Because of complexity and enormous time required for proper flow analysis, it is desirable that suitable software like CulvertMaster (Bentley) should be used for hydraulic computations.

ACKNOWLEDGEMENT

Authors wish to thank ICT authorities for the help and encouragement received for writing the paper.

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