Paper No.201

HYDRAULIC DESIGN GUIDELINES OF CULVERTS IN PLANE AND HILLY AREAS

Engr. Dr. Muhammad Mohsin Munir

HYDRAULIC DESIGN GUIDELINES OF CULVERTS IN PLANE AND HILLY AREAS

By

Engr. Dr. Muhammad Mohsin Munir[1]

Abstract:

The primary objective of a culvert or bridge is to convey stormwater flows, based on a design flow rate, through embankments or under roadways without causing damage to adjacent properties and developments, the roadway, or to the drainage structure. The decision of provide culvert barrels in plane and hilly areas govern number of parameters that must be considered while planning. The function of a culvert is to convey surface water under a roadway, railroad, walking path, or other embankment. The hydraulic aspects of culvert design are set forth in this paper. Culverts are available in a variety of sizes, shapes, and materials. These factors, along with several others, affect their capacity and overall performance is discussed in this paper. Sizes and shapes may vary from small circular corrugated plastic pipes for driveways to large multiple side-by-side concrete box sections that can be used in lieu of a bridge.

1. INTRODUCTION

The hydraulic design of a culvert consists of an analysis of the required performance of the culvert to convey flow from one side of an embankment to the other. The designer must select a design flood frequency, estimate the design discharge for that frequency, and set an allowable headwater elevation based on the selected design flood and headwater considerations. A drainage system will commonly address one or more elements, namely:

- Collection and disposal of rainfall on road surfaces
- Subsurface drainage for road pavements
- Overland water flows

The above shall be designed keeping in view:

- Potential for loss of life;
- Effect of potential flooding of important installations (e.g., electrical power plants or substations, chemical plants, refineries, water or sewage treatment plants) on the community;
- Agency liability for potential flood damage;
- Potential for isolation of hospitals or other life support institutions; and Emergency vehicle access and movement.

[1] Principal Engineer, NESPAK

1.1 Hydraulic Considerations in Highway Planning and Location

Following consideration shall be kept in mind while planning of drainage crossings in a Highway:

1. A highway crossing at or near to the confluence of two or more streams is a complex hydrologic and hydraulic location that should be avoided.
2. This includes an analysis of the various combinations of flood events and how they may change flow distributions, hydraulic gradients, headwaters, and velocities.
3. This includes an analysis of the various combinations of flood events and how they may change flow distributions, hydraulic gradients, headwaters, and velocities. Stream stability can also be more critical at confluences because the middle and point bar formation can cause abrupt changes in flow directions.
4. Crossings of tidal waters present the hydraulics engineer with special considerations such as regular changes in water level from astronomically induced tides, storm surges from wind and high waves, or even seismic waves or tsunamis.
5. The use of land adjacent to the stream must be considered. The effects of increased flood stages or increased velocities may affect property land use, both upstream and downstream and the existing property may suffer extensive physical damage from an increased flood stage especially in urban areas.
6. Detailed surveys and comprehensive hydrologic and hydraulic studies are needed to make conclusive recommendations.
7. Longitudinal encroachments, where the highway is located within the stream floodplain boundary and the highway alignment is approximately parallel to the stream, should be avoided wherever practicable and alternative routes outside the floodplain are available.
8. If the encroachment significantly constricts the natural stream and flood conveyance V-shaped section, the possible effects acceleration of flow resulting in attack on the highway embankment potential flooding of upstream property due to backwater effects from the construction accumulation of drift and flooding of road
9. Locations in U-shaped valleys with broad terraces above the channel may be secure from flooding except during rare or infrequent floods
10. It may be necessary to provide additional waterway opening through the constricted section by widening along the opposite bank or providing adequate transition sections into and away from the constriction and sufficient conveyance modification to increase the channel capacity.
11. Channel encroachment locations may require channel modifications such as stream and bank excavation, and replacement of tree and rock cover with lining materials.

12. During the location phase, it is important for the hydraulics engineer to be aware of utility locations and types and their relationship to the proposed highway project.
13. Locations of overhead and underground power lines, underground water and sewer lines, and utility facilities, such as pumping stations or access points to any appurtenant tunnel chambers, will be found by others.

2. SELECTION OF RETURN PERIOD

Table-1: Minimum Design Flood Return Period (Ref: HDS, 2017)

Roadway Classification	Bridges	Culverts	Floodways & Vented Floodways	Channels & Ditches	Storm Sewer Systems	Depressed Road Section (Sag point)
National and Arterial Road	1 in 100 years (1%)	1 in 50 years (2%)	Vented Floodways only to be used	1 in 10 years (10%) 1	1 in 10 years (10%)	1 in 50 years (2%)
Secondary Road	1 in 100 years (1%)	1 in 50 years (2%)	Vented Floodways only to be used	1 in 10 years (10%)	1 in 10 years (10%)	1 in 10 years (10%)
Distributor Road	1 in 100 years (1%)	1 in 25 years (4%)	1 in 25 years (4%) 2	1 in 10 years (10%)	1 in 5 years (20%)	1 in 10 years (10%)
Access Road	1 in 100 years (1%)	1 in 25 years (4%)	1 in 25 years (4%) 3	1 in 5 years (20%)	1 in 2 years 50%	1 in 5 years (20%)

1 Checking for the 25-yr without freeboard should also be performed
2 Vented floodways may be overtopped with a maximum overtopping of 40 cm once in 50 years
3 Vented floodways may be overtopped with a maximum overtopping of 40 cm once in 25 years

2.1 Layout Planning of Culverts

The function of a culvert is to convey surface water across or from the highway right-of-way. culvert locations are predetermined by the intersection of a watercourse and the proposed roadway. In general, culverts should be located to fit natural channels in line and grade, following moderate curvature and natural changes in grade as far as is practical

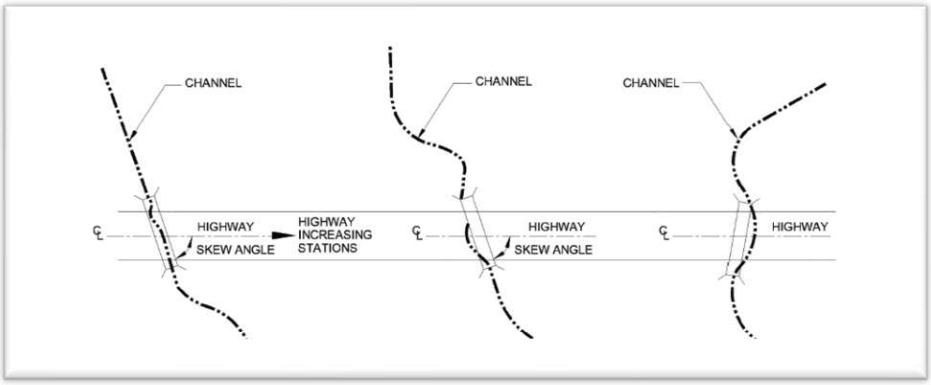


Figure-1: Culvert orientation with Highway

- Establishing the culvert's vertical orientation is usually a matter of placing the upstream flow line and downstream flow line elevations of the culvert at the same elevations as the existing streambed.
- Lowering the upstream flowline can provide an improved hydraulic operation but may create maintenance problems due to a higher potential for both sedimentation and scour.
- Avoid placing the downstream flowline of the culvert at a level higher than the roadway embankment toe of slope. Such a configuration results in a waterfall that increases the potential for erosion.
- Modified culvert slopes other than that of the natural stream, might be used to arrest stream degradation, minimize sedimentation, improve the hydraulic performance of the culvert, shorten the culvert or reduce structural requirements.
- The use of shear keys should be considered for normal soil conditions where culverts are placed at slopes greater than 5%.
- Culvert slope determination is a decision to be taken by a designer depending on location and flow.

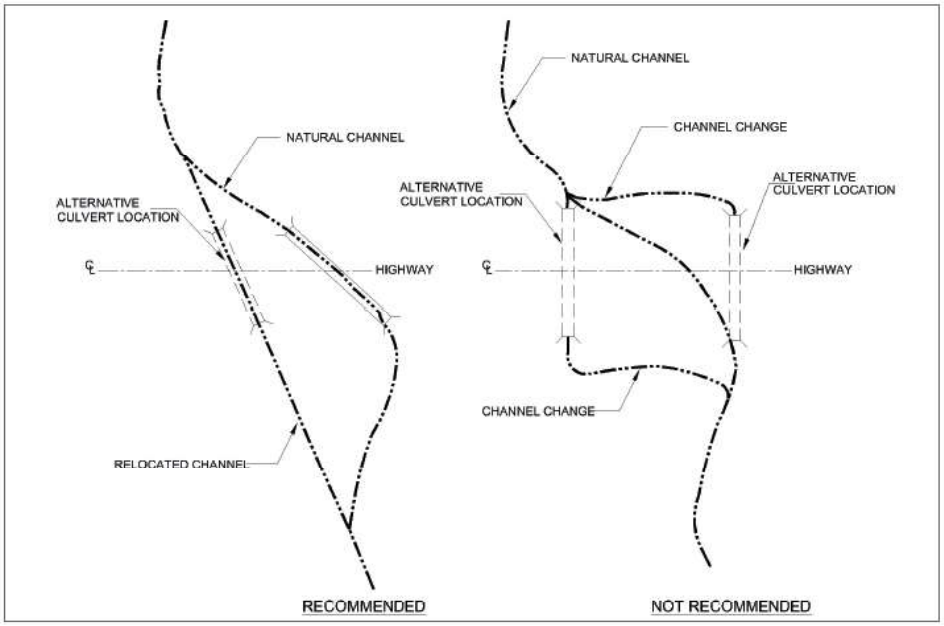


Figure-2: Culvert Located in a Realigned Natural Watercourse

2.2 CULVERT SHAPE SIZE AND MATERIAL CONSIDERATIONS

1. Construction cost, the potential for clogging by debris, limitations on headwater elevation, fill height, and the hydraulic performance of the design alternatives enter into the selection of the culvert shape.
2. A box culvert can be designed to pass large flows and to fit most site conditions. A box culvert lends itself more readily than any other shape to

low allowable headwater situations since the height may be decreased and the total span increased to satisfy the particular location.

3. Arch culverts have application in locations where less obstruction to a waterway is a desirable feature and there is limited cover or overfill and where foundations are adequate for structural support.
4. The culvert should be sized to provide suitable hydraulic performance. The recommended minimum clear height (D) should be 1.5 meters. This will facilitate access for inspection and maintenance and minimize clogging.
5. Pipe culverts diameter ranges from 1.0 to 1.5 meter. Smaller culverts may be used if necessary due to site particular conditions subject to the approval of concerned authorities. subject to the following conditions:
6. The pipe length should be short enough to allow for cleaning it through water jets.
7. The rainwater to be conveyed should not carry large rocks that may clog the culvert.

Table-2: Box Culvert Clear Width and Height Combination

Box Culvert Width (mm)	Box Culvert Height (mm)						
	1000	1500	2000	2500	3000	3500	4000
1000	√	√					
1500	√	√					
2000	√	√	√				
2500	√	√	√	√			
3000		√	√	√	√		
3500			√	√	√	√	
4000			√	√	√	√	√

8. The selection of the material for a culvert is dependent upon several variables (e.g., durability, structural strength, roughness, bedding conditions, abrasion and corrosion resistance, water tightness, cost, availability in the local market, constructability, etc.).
9. Generally, concrete (with or without reinforcement) is the most suitable material because it satisfies the above-mentioned variables more than other material.
10. Pipe culverts are generally less costly and faster to construct than box culverts. Therefore, pipe culverts are preferable where the required discharge capacity and other site constraints permit.

2.3 CULVERTS HYDRAULIC DESIGN CONSIDERATIONS

Any culvert that constricts the natural stream flow will cause a rise in the upstream water surface to some extent. The total flow depth in the stream measured from the culvert inlet invert is termed headwater (HW). Design headwater elevations and selection of design floods should be based on these risk considerations:

- Damage to adjacent property,
- Damage to the culvert and the roadway,
- Traffic interruption,
- Hazard to human life, and
- Damage to stream and floodplain environment.
- It is recommended to keep HW/D less than 1.2. However, culvert installations under high fills may present the designer an opportunity to use high headwater or ponding to attenuate flood peaks.
- If the design flood HW is greater than 1.5 times the culvert clear height, the stability of the embankment must be analyzed because a breach in the highway fill could be quite similar to a dam failure
- The bottom of road pavement layers should be higher than the design headwater elevation.
- Tailwater is the flow depth in the downstream channel measured from the invert at the culvert outlet.
- Culverts should be located and designed for least disruption of the existing flow conditions.
- A number of separate culverts spread over the width of the flooded area may be more appropriate for these conditions. In these locations multiple culverts can be considered to have a common headwater elevation, although this will not be precisely so.
- To prevent siltation the desirable minimum velocity in the culvert should be above 0.90 m/s for the 1 in 2 years storm. A check of velocities should be undertaken as part of design.
- The two major conditions of culvert flow are inlet control and outlet control
- For each type of control, a different combination of factors is used to determine the hydraulic capacity of a culvert.
- A culvert operates with inlet control when the flow capacity is controlled at the entrance by the depth of headwater and the entrance geometry, including the barrel shape, cross sectional area and the inlet edge.
- For a culvert operating with inlet control, the roughness and length of the culvert barrel and outlet conditions (including tailwater) are not factors in

determining culvert hydraulic performance. The entrance edge and the overall entrance geometry have much to do with culvert performance in this type of flow; therefore, special entrance designs can improve hydraulic performance and result in a more efficient and economical culvert

- In outlet control, the culvert hydraulic performance is determined by the factors governing inlet control plus the controlling water surface elevation at the outlet and the slope, length, and roughness of the culvert barrel.
- It is therefore necessary to determine the discharge of the culvert under both inlet and outlet flow conditions and to adopt the lesser of the two discharge values as the design flow.
- Where possible, culverts should be designed to provide acceptable velocities without the need for additional stream bed protection.

Table-3: Maximum Allowable Velocities for Various Stream Bed Materials

Protection Type	Allowable Velocity (m/s)
Concrete	5.0
Asphalt	2.0
Fine sand (d50 ranges 0.06 – 0.20 mm)	0.6
Firm loam	0.9
Gabion	4.5
Gravel 100 mm or grass cover	2.0 - 2.5
Grouted riprap	4.5
Rock-Loose riprap	4.5
sandy loam	0.65
Sandy or silty clay	1.0 - 1.2
Stiff clay	1.2 – 1.5
Stones 150 mm diameter or larger	3.0

- If outlet velocity exceeds 5 m/s, it is unlikely that placement of large stones at culvert outlet will be economic or feasible. In such cases, using energy dissipaters is recommended.

- In addition, the HY-8 culvert evaluation software, also freely available from the FHWA, uses the techniques discussed in HEC-14 to perform scour hole calculations and energy dissipator designs. HEC-14 and HY-8 are highly recommended for energy dissipator design.
- The length of the riprap protection downstream from the outlet depends on the degree of protection desired. The riprap size requirements are based on the below non-dimensional parametric equations:

Circular culvert: $$\frac{\left(\frac{d_{50}}{Diameter}\right)\left(\frac{Tw}{Diameter}\right)^{1.2}}{\left(\frac{Q}{Diameter^{2.5}}\right)} = 0.04166$$

Rectangular culvert: $$\frac{\left(\frac{d_{50}}{Height}\right)\left(\frac{Tw}{Height}\right)^{1.2}}{\left(\frac{Q}{Width * Height^{1.5}}\right)} = 0.025358$$

Where Q is the culvert design flow (in m^3/s), d_{50} is the median diameter of the riprap (in m) at culvert outlet and T_w is the tail water depth in meters.

In no case should the length of protection downstream of the culvert apron be less than 3H (3 times the height of the box culvert) or 3D (3 times the diameter of the pipe culvert), nor does the length of protection need to be greater than 10H or 10D whenever, Q/WH1.5 is less than 4.42 for box culverts or Q/D2.5 is less than 3.31 for pipe culvert, respectively. An average acceptable value for the length of the riprap protection is 5 times the height of the box culvert or 5 times the diameter of the pipe culvert.

3. DATA COLLECTION FOR CULVERTS DESIGN

1) Site survey and locality map
2) Embankment cross-section
3) Roadway profile
4) Photographs, aerial photographs
5) Details from field visit (sediment, debris and scour at existing structure)
6) Design data for nearby structures
7) Studies by other authorities near the site, including small dams, canals, weirs, flood plains, storm drains
8) Recorded and observed flood data.

3.1 STEPS FOR CULVERTS DESIGN

1) Determine the design flood discharge (Q)
2) Choose culvert material, shape, length and entrance type, allowing for minimum and maximum allowable cover heights over the culvert.
3) The hydraulic analysis of culvert could be carried out by using the design aids (nomographs) or by adopting one of the commonly used software

packages such as HY8, HEC-RAS or any widely used commercial software following the FHWA procedures.

4) Determine an initial trial culvert area, either by arbitrary selection or by choosing an outlet velocity (V) from Table 12.5.5.1 and calculating a culvert area (A) from A = Q/V. The selected area should be equal or larger than the minimum allowed area
5) Determine the inlet control headwater depth HWi by using the nomographs shown on Figures 12.5.6.1 and 12.5.6.2 for concrete box and pipe culverts respectively.
6) Once the culvert size has been determined to satisfy inlet control conditions the same culvert dimensions are used to determine the headwater depth (HWo) for outlet control.
7) Compare the two headwater depth values (i.e. HWi and HWo). The higher headwater governs and indicates whether the culvert is flowing with either inlet or outlet control
8) Compute outlet velocity and determine need for channel protection. The average outlet velocity will be the discharge divided by the cross-sectional area of flow at the culvert outlet

3.2 STEPS FOR CULVERTS DEBRI CONTROL



Figure-3: Steel Rail Debris Deflectors

3.3 CULVERT FREEBOAD

1) The minimum vertical clearance between the highest ground level in the wadi and the deck soffit shall be not less than 3.0m regardless of the flood level.

2) For circular pipe, maximum capacity is actually achieved at a flow depth equal to around 94% of the diameter of the pipe. However, it is advisable to design pipes at a flow depth not exceeding 75% of the pipe diameter and keep the remaining spare capacity as a freeboard

4. REFERENCES

[1]. FHWA's Hydraulic Design Series, No.5

[2]. Hydraulic Reference Manual of HY8

[3]. USBR, Design of small dams

[4]. HDS Manual, 2017