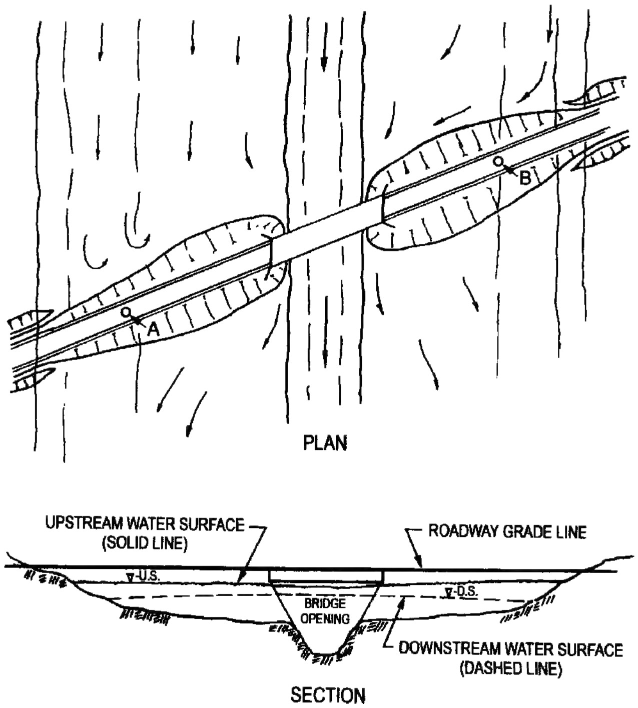

Figure 7-24. Upstream and Downstream Water Surface Elevations at a Skewed Crossing

Figure 7-25. Roadway Cut at the Downstream Extremity of the Floodplain Alleviate Head Differentials across Road at a Skewed Crossing

Large head differentials from the upstream side to downstream side of skewed crossings can be explained by referring to Figure 7-24. Floodwaters upstream of the embankment near location B will be diverted toward the structure because there will be a gradient from B. Downstream, water must flow from the bridge toward B to fill the area downstream of the roadway on the left floodplain. Thus, the water surface elevation upstream at B will be higher than at the bridge and downstream at B will usually be lower than downstream of the bridge.

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Similarly, the water surface elevation on the upstream right floodplain near location A will be approximately equal to the water surface elevation at the bridge plus the velocity head at the bridge. Thus, there will be no flow from A to the bridge along the roadway embankment. On the downstream side, floodwaters will flow from the bridge toward A and, dependent on the velocity head at the bridge, will be lower downstream of A than downstream of the bridge. Therefore, the water surface differential from upstream to downstream will be greater at both A and B than at the bridge.

One-dimensional methods (step backwater) are inadequate to provide a quantitative analysis of water surface elevations up- and downstream of a skewed highway crossing of a stream. Finite element and finite difference models are two-dimensional methods that can be applied in some complex situations. These models enable designers to study the water surface elevations in cross sections rather than in profile only and can identify locations where undesirable head differentials could occur. These are more complex models that require more site information and a greater length of time to use. The accuracy provided by the two-dimensional model is not justified in many cases; thus, a one-dimensional model is used, tempered with sound engineering judgment.

Discussion of the hydraulic analysis of stream crossing systems is provided in Section 7.6.3. Structural features that can have a significant effect on the performance of the system are discussed in Section 7.6.2.3.

7.6.2.2 *Waterway Openings*

The opening(s) provided in the roadway embankment for the purpose of passing stream flow is the other highway component of the highway-stream crossing system. The location and size of waterway opening(s), together with the horizontal and vertical alignment of approach roadways, establish the magnitude of the flood that will not disrupt traffic on the highway.

Other criteria also influence the location and size of waterway openings in the highway-stream crossing system. To the extent practicable, waterway openings should be located and sized to preserve the natural flow distribution of the stream, to avoid damage to the natural and beneficial values associated with the stream, and to avoid creating undue hazards to the highway and other properties.

Concerns other than hydraulic requirements that influence waterway opening location and size include clearances for navigation, roadway geometries, terrain, soil stability at abutments, access to adjacent properties, intersections and interchanges with other roads, separations for other roads or railroads, wetlands, economics, and numerous others. Discussion here will be limited to hydraulic and economic considerations in locating and sizing waterway openings.

7.6.2.2.1 Location

The choice of location of a waterway opening at a stream crossing site with limited floodplain widths is not difficult because it is readily apparent that one opening will suffice or that it is not physically practicable to use more than one opening. Similarly, when approach roadways are not significantly higher than the floodplains, auxiliary waterway openings on the floodplains are either unnecessary or culvert-size openings for local drainage are all that is necessary.

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The location of waterway openings in the highway-stream crossing system is more complex for designs for rare floods and at sites with extensive floodplains. In this discussion, it is assumed that an opening will be provided at the principal channel of the stream and that available options include a wider opening at that location and auxiliary opening(s) on the floodplain or some combination of these options.

Several factors influence decisions on the location of waterway opening(s) to provide for flood passage. Basic objectives in choosing the location(s) of auxiliary opening(s) include maintenance of flow distribution and flow directions to the extent practicable, provision for relatively large flow concentrations in the floodplains, avoidance of diversion of floodplain flow along roadway embankments for long distances, and considerations of backwater and scour damage to the highway and other property. Site conditions, economics, budgetary constraints, and the horizontal alignment of the highway limit the extent to which these objectives can be met. The objectives are complementary in that the purpose in maintaining flow distribution and direction is to minimize damage to the floodplain environment and to avoid excessive backwater and scour. Providing for large flow concentrations achieves similar purposes, as does avoiding long distance diversion along roadway embankments.

Other site-specific factors that influence opening location are local drainage, the possibility of causing a cutoff in a meander bend, other transportation facilities in the vicinity, floodplain use, and the horizontal and vertical alignment of the highway.

The need to provide for local drainage occurs where an area on the floodplain will not drain after the highway is constructed and where the highway alignment intersects a tributary stream upstream of its confluence with the main stream (Figure 7-26). In either case, diversion along the highway fill to the principal stream channel or providing an auxiliary opening on the floodplain is possible. Diversion along the highway embankment can create maintenance problems by increasing the gradient in the tributary channel and by providing a more efficient channel for floodplain flow at the toe of the highway embankment. Headcutting can occur that will endanger the embankment and upstream property, and a delta can form in the principal stream channel, causing it to change its course (Figure 7-27).

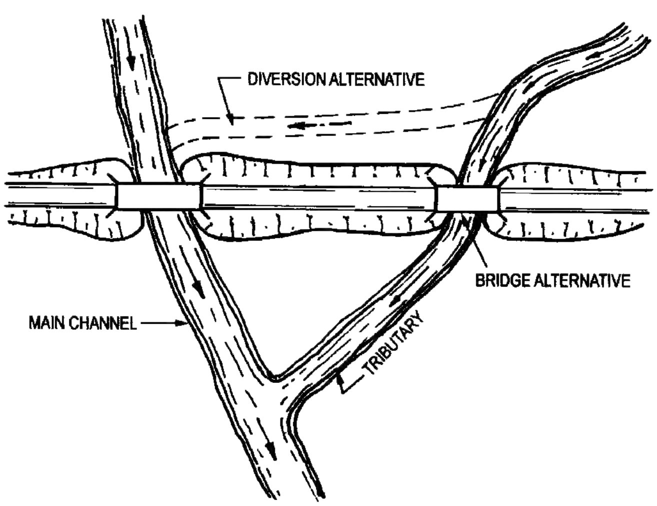

Figure 7-26. Diversion and Bridge Alternatives for Tributary Stream in the Floodplain

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Figure 7-27. Delta Formed in Principal Stream by Diverted Tributary

An opening on the floodplain to provide for the tributary stream or local drainage is the most desirable alternative, if additional costs for construction are warranted. Other factors, such as flow concentration in the floodplain or diversion of floodplain flow for a long distance along the highway embankment, may influence the decision as well. Although the location of the opening on the floodplain will be influenced by the need to provide for local drainage or the tributary, any opening on the floodplain will be subjected to flood flows of the principal stream. The size of the opening may be influenced more by the amount of floodplain flow from the larger stream than by flow from the tributary.

A highway located in the bend of a river, as in Figure 7-28, presents a particularly difficult problem in the location of auxiliary openings. Flow in the floodplain is likely to be concentrated across the mouth of the bend, as illustrated. Because the distance across the bend is shorter than in the channel, the water surface slope is steeper and conveyance in the floodplain is increased relative to conveyance in the channel. An auxiliary opening at this location that severely constricts the flow will cause general scour that could ultimately result in a cutoff of the bend, dependent upon the width across the bend, the length of the bend, land use, and soils. If an opening is necessary, the design usually should be generous to guard against the possibility of scouring velocities. Other measures may also be advisable. Guide banks can make the opening more hydraulically efficient, and armoring the flow line may effectively protect against scour in some instances. Additional auxiliary openings can be used in a long bend to reduce the degree of flow constriction, and the opening can be located away from the mouth of the bend in some instances. Also, elimination of the bend by channel realignment may be possible at some locations. Where the effects of an auxiliary opening at a bend could be especially damaging, physical modeling may be warranted.

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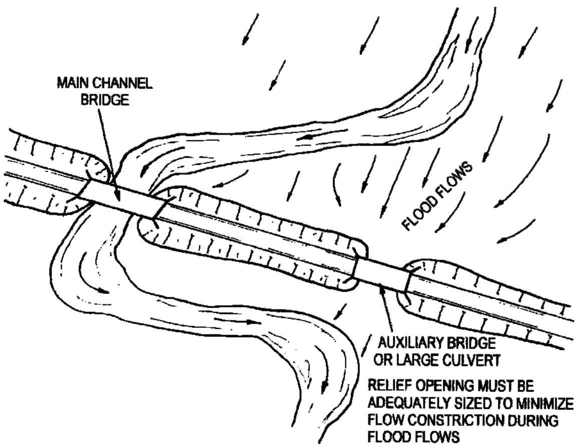

Figure 7-28. Stream Crossing in a Bend

Often, there are existing crossings in the vicinity of the proposed crossing that have altered the flow distribution. To keep the effects of the new crossing on existing flow distribution to a reasonable minimum, considerable weight should be given to the location of existing opening(s), but the size of proposed opening(s) should be based on hydraulic requirements. Where existing auxiliary opening(s) do not accommodate significant flow, decisions on opening(s) in the new crossing should be based on the hydraulic requirements of the crossing system.

Other transportation facilities on the floodplain may require grade separation. This opening on the floodplain will pass floodwaters, and roadway elevations required for separation may significantly alter the magnitude of the flood that must be passed through the proposed highway openings. Also, consideration should be given to the flow constriction at the separation that may cause damage to the other facility (Figure 7-29).

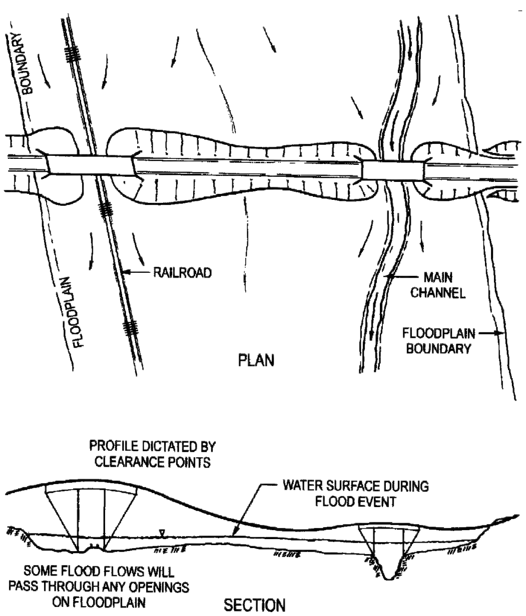

Figure 7-29. Grade Separation for Another Transportation Facility in the Floodplain Will Serve as an Auxiliary Waterway Opening

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Floodplain uses that can influence opening location include development and the need for access across the highway right-of-way. Auxiliary waterway openings may need to be located to accommodate these uses and in recognition of the effects of development on flow distribution and tolerable backwater.

Auxiliary waterway opening(s) or relatively low approach roadway profiles may be necessary to avoid large differences in water surface elevations between the upstream and downstream side of skewed highway crossings of streams with wide floodplains. An opening located at either A or B in Figure 7-24 should be generously sized so that head differentials will be minimized and severe scour will not develop.

7.6.2.2.2 Size

The size of a waterway opening is limited by the boundaries comprised of the streambed and/or floodplain. The embankment ends at each side, and the superstructure of the bridge at the top. There are many characteristics of a crossing site that influence the selection of waterway opening size. These characteristics are used in defining criteria for judging the acceptability of alternative designs of the crossing system as discussed in Section 7.6.1. It is possible that a multitude of roadway profile and water opening alternatives would satisfy the criteria established from characteristics of the site. As an example, if criteria for the crossing include a severe limitation on backwater, this limitation can be satisfied either by using a small opening and a low roadway profile or by bridging all of the stream cross section. It is probable, however, that in most locations, alternatives that are somewhere between these two extremes will also satisfy the criteria established for the site and will prove to be more prudent insofar as the expenditure of public funds is concerned.

The performance of a waterway opening is dependent not only on the boundaries defined by the terrain, the bridge superstructure and the embankment at each end of the bridge but also by water surface elevations. The flood that will flow through the opening without disrupting traffic is determined by the above physical boundaries of the opening and the profile of the crossing.

Both alternative roadway profiles and waterway openings are practicable for many highway-stream crossings. Where this freedom is available, the probability of overtopping is a design decision that can be made considering the economic consequences of the decision. Bridge structural components, foundations, waterway opening size, and approach roadways should be designed so that the alternative stream-crossing system selected results in optimal or near-optimal use of public funds. Capital costs for construction, risks of damage to approach roadways, risks of damage to the bridge from buoyancy, drag, impact loads and scour, the costs of traffic interruption, and risks to other properties should be considered in determining the economic consequences of selecting a design from available alternatives.

The design of many other stream-crossing systems is constrained by social, political, or environmental concerns; engineering considerations, such as geometries; multiple-use purposes, such as navigation, livestock passage, and land access; economic considerations other than optimal use of public funds; policy decisions, such as minimum standards; and topographic controls. Where such constraints are imposed, the alternative crossing design that meets the constraints at the least cost in public funds should be selected. Economic concerns must be considered in selecting an alternative. In either case, foundations, bridge structural components, the size of the waterway opening, protective

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and preventive measures, and the stream-crossing profile should be predicated on capital costs and risk costs for all floods that substantially contribute to those costs.

Waterway openings are most severely taxed by the largest flow that must pass through the opening. This flow rate is approximated at incipient overtopping of the highway-stream crossing system. Therefore, each waterway opening should be sized considering the probability of such an occurrence and the associated risks of damage.

7.6.2.2.3 Auxiliary Openings

The need for auxiliary waterway openings, or relief openings as they are commonly termed, arises on streams with floodplains. The terminology adopted here (i.e., auxiliary openings) is intended to be consistent with the concept of a highway-stream crossing system in which each component has a specific role. The purpose of openings on the floodplain is to pass a portion of the flood flow in the floodplain when the stream reaches a certain stage. It does not provide relief for the principal waterway opening in the sense that an emergency spillway at a dam does, but it has predictable capacity during flood events.

The location of auxiliary openings is discussed in Section 7.6.2.2.1. The size of openings required has not been extensively researched although an effort has been undertaken by the State of Mississippi to study the hydraulic performance of existing multiple bridge systems.

A method currently in use for determining the size of auxiliary openings is described here because it appears to be based on good logic even though the technology for analysis may be weak. The technological weakness is in the use of one-dimensional models to analyze two-dimensional flow. The development of one-dimensional stream tube models and two-dimensional models represents a major step toward more adequate analysis of complex stream crossing systems (*25*).

Auxiliary openings on the floodplain are generally assigned a portion of the total streamflow based on conveyance calculations. Conceptually, the flow will separate at an assumed or a real divide and flow to the appropriate opening. For a normal crossing system at a straight reach of the stream, this flow divide can be accomplished approximately as assumed by sizing all waterway openings so that backwater above each is approximately the same. If any opening is sized so as to create more backwater than another, the divide will not be as planned because the highwater surface at that opening will cause diversion toward another opening.

The complexity in analysis with one-dimensional models comes with crossings that are not normal to the flow direction, with bends and sinuosity in the stream system, and with flow directions that vary along the crossing and with stages in the stream. This describes the usual rather than the unusual crossing, though imaginative use of one-dimensional models will provide an adequate analysis of many crossing systems and woefully inadequate analysis of others. For this reason, it has been recommended (Section 7.6.2.2.1) that auxiliary openings in skewed crossings at either location A or B, Figure 7-24, should be generously sized as judged by the best available method of analysis. Physical or mathematical modeling of complex locations may be available.

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7.6.2.2.4 Replacement Bridges

Investments in replacement bridges constitute an increasing proportion of capital expenditures for highway construction. A wealth of experience may be available at the site of existing bridges relative to the hydrology of the stream, the hydraulic performance of the crossing system and the morphology of the stream. This experience and modern hydrologic, hydraulic, and economic analysis technology should be fully exploited when the replacement crossing system is selected. In particular, floodplain usage may have changed near the crossing site because of the original construction, indicating a need to reevaluate the risk to private property. Traffic volume increases and changes in traffic character may indicate a need to reassess traffic service requirements. Changes in the relative costs of construction, maintenance, and flood damage repair of various components of the crossing system may indicate that an alternative that differs from the existing crossing system should be selected.

Many existing bridges have withstood substantial floods, and studies may indicate that no change in the stream-crossing system is warranted. In such cases, the fact should not be overlooked that the replacement of short spans with longer spans or a truss with a girder design will result in a reduction in the waterway opening if the replacement structure has a deeper superstructure. As a result of the replacement, the risk of backwater damage will be increased, the probability of overtopping will be increased, and there will be a greater hazard of ice and debris damage. If the existing level of traffic service is to be maintained, insofar as interruption by flooding is concerned, and the risks of flood damage to the highway and other property is not to be increased, the grade of the bridge deck should be raised to compensate for the deeper superstructure of the replacement bridge.

7.6.2.3 *Structural Alternatives*

A myriad of structural alternatives are available for use in a highway-stream crossing system when all of the possible combinations of bridge lengths, spans, pier types, and orientation, geometries, parapet designs, and superstructure designs are considered. In addition, at many crossings, multiple bridges or a single bridge may be viable alternatives, or large culverts may be used in lieu of one or more bridges.

The hydraulics of the highway-stream crossing system should be given considerable study in choosing the preferred design from the long list of available alternatives.

7.6.2.3.1 Bridge or Culvert

Occasionally, the waterway opening(s) for a highway-stream crossing can be provided for by either culvert(s) or bridge(s). Estimates of costs and risks associated with each will indicate which structural alternative should be selected on the basis of economics. Other considerations that may influence structure-type selection are listed in Table 7-1 and discussed in subsequent sections.

Table 7-1 lists many of the advantages and disadvantages of bridges and culverts. Those considerations that are associated with the use of culverts are discussed in Reference (*4*), and those associated with bridges are discussed elsewhere in this chapter. Culvert(s) in combination with bridge(s) are used in numerous highway-stream crossings, either to pass flow in a floodplain or to provide for local drainage in the floodplain. Where culverts or small bridges are used in the floodplain in conjunction with a bridge, the potential scour as a result of the head differential from upstream to downstream and the long duration of the hydrograph should be considered (see Figure 7-30).

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Table 7-1. Bridge or Culvert

Bridges	
Advantages	**Disadvantages**
Less susceptible to clogging with drift, ice, and debris.	Require more structural maintenance than culverts.
Waterway increases with rising water surface until water begins to submerge superstructure.	Spill slopes susceptible to erosion and scour damage.
Scour increases waterway opening.	Piers and abutments susceptible to failure from scour.
Flowline is flexible.	Susceptible to ice and frost formation on deck.
Minimal impact on aquatic environment and wetlands.	Bridge railing and parapets hazardous as compared to recovery areas.
Widening does not usually affect hydraulic capacity.	Deck drainage may require frequent maintenance cleanout.
Capacity increases with stage.	Buoyant, drag, and impact forces are hazards to bridges.
	Susceptible to damage from stream meander migration.

Culverts	
Advantages	**Disadvantages**
Provides an uninterrupted view of the road.	Multiple barrel culverts, whose width is considerably wider than the natural approach channel, may silt in and may require periodic cleanout.
Roadside recovery area can be provided.	No increase in waterway as stage rises above soffit.
Grade raises and widening projects sometimes can be accommodated by extending culvert ends.	May clog with drift, debris, or ice.
Require less structural maintenance than bridges.	Possible barrier to fish passage.
Frost and ice usually do not form before other areas experience the same problems.	Susceptible to erosion of fill slopes and scour at outlets.
Capacity increases with stage.	Susceptible to abrasion and corrosion damage.
Capacity can sometimes be increased by installing improved inlets.	Extension may reduce hydraulic capacity.
Usually easier and quicker to build than bridges.	Inlets of flexible culverts susceptible to failure by buoyancy.
Scour is localized, more predictable, and easier to control.	Rigid culverts susceptible to separation at joints.
Can be used to arrest headcutting.	Susceptible to failure by piping and/or infiltration.
Storage can be utilized to reduce peak discharge.	

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Figure 7-30. Scour at a Culvert in the Floodplain

As an example, a culvert at location A or B in Figure 7-24 would have a high outlet velocity because of the large head differential across the roadway, and severe scour could occur at the outlet.

7.6.2.3.2 Piers

Economy of construction usually plays a large role in the determination of spans, pier locations and orientation, and substructure and superstructure design. It is necessary that construction costs always be a factor in the structural design of a bridge to make use of economically available structural materials, but the cost of construction is only one part of the total economic cost of a stream crossing system. There are hydraulic considerations, maintenance costs, and risks of future costs to repair flood damages that should also be factors in making decisions on the number of piers and their location, orientation, and type.

The number of piers in any channel should be limited to a practical minimum, and piers in the channel of small streams should be avoided, if practicable. Piers properly oriented with the flow do not contribute significantly to bridge backwater, but they do contribute to general scour. In some instances, severe scour has developed immediately downstream of bridges because of eddy currents and because piers occupy a significant area in the channel. Lateral and vertical scour also occurs at some locations.

Piers should be aligned with flow direction at flood stage to minimize the opportunity for drift to be caught in piling or columns, to reduce the contraction effect of piers in the waterway, to minimize ice forces and the possibility of ice dams forming at the bridge, and to minimize backwater and local scour (*28*). Pier orientation is difficult where flow direction changes with stage or time. Circular piers, or some variation thereof, are probably the best alternative if orientation at other than flood stage is critical.

Piers located on a bank or in the stream channel near the bank are likely to cause lateral scouring of the bank. Piers located near the stream bank in the floodplain are vulnerable because they can cause bank scour. They are also vulnerable to failure from undermining by meander migration. Piers that must be placed in locations where they will be especially vulnerable to scour damage should be founded at elevations safe from undermining (Figure 7-31).

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