CHAPTER 2. PRINCIPLES OF CULVERT STRUCTURES

SCOPE

This chapter presents a summary of general information on the principles of culverts. The purpose is to provide key background information for personnel responsible for the repair of culverts. It is important for maintenance personnel to understand these principles because it assists in recognizing the basic causes of problems. Also, it aids in the process of evaluating what to do about the problems as well as designing and constructing the repair.

GENERAL

A wide variety of culvert structures are currently in use as stream crossings, underpasses, and other highway and railroad applications. Although modern culverts are made primarily from reinforced concrete, corrugated metal, and, more recently, solid-wall, profile-wall, and reinforced plastic, some culverts constructed with stone masonry, terra cotta, or timber still exist. The emphasis of this chapter and the manual is on modern culvert construction.

Engineering Considerations

The primary purpose of culverts in the highway system is to carry surface, stream, and river water under highway pavements. In order to design a highway culvert, an analysis of the site is performed to determine hydraulic, structural and durability requirements. Consideration is given to requirements and potential problems associated with construction, maintenance, traffic safety and environmental aspects. The selection of the type, shape, and length of culverts and their appurtenances will depend upon many factors including the following types of analysis.

Hydrology - Hydrology is the science that deals with the occurrence and distribution of waters on the earth. In culvert design, it is the process of determining how much flow the culvert should be designed to carry.

a. Hydrologic cycle - This is the name given to the cycle of water in the atmosphere falling to the ground, running off to rivers, lakes, and the ocean and then evaporating back to the atmosphere.

b. Peak flow - Peak flow refers to the maximum amount of water that will arrive at, and flow past, a particular point of land. The peak flow is a major factor in the culvert design process. This value will depend upon many topographic, geological, and environmental factors, including those listed below. For design purposes, peak flow is generally determined on the basis of the maximum storm that may be encountered in some period of time, for example 25, 50, or 100 years. Additional design information is available from AASHTO.[1,2] State drainage manuals generally prescribe the design flood recurrence interval for various culvert applications.

Together, the factors listed below influence the amount of runoff and the amount of time required for water to flow to the point of concern from the most remote part of the drainage area.

- The size, shape, and slope of the drainage area, as illustrated in figure 2.1.

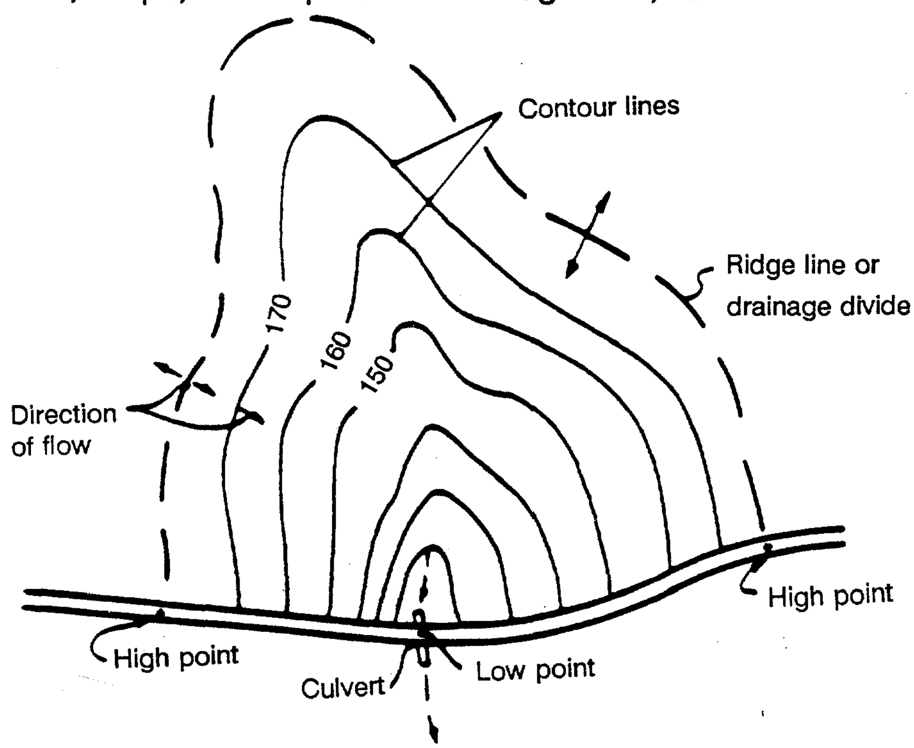


Figure 2.1. Drainage area served by a culvert. [3]

- The rainfall intensity, storm duration, and rainfall distribution within the drainage area;

- Type of land use (open ground, paved, wooded, etc.);

- The type of soil and its degree of saturation or imperviousness;

- Type of precipitation (snow, snow melt, rain) and ambient temperature; and

- Existing flow if a stream is present.

Hydraulics - Design of the culvert, including selection of the shape, size, and length of the culvert, is a complicated process that involves consideration and analysis of many factors that influence how much water may be carried through the culvert. Although inspectors and maintenance personnel should be aware of the various factors, these analyses should be undertaken by an experienced hydraulics engineer.

The factors that affect capacity of a culvert include: headwater depth, tailwater depth, inlet geometry, the slope of the culvert barrel, and the roughness of the culvert barrel. These factors are illustrated in figure 2.2. The various combinations of the factors affecting flow can be grouped into two types of conditions in culverts: inlet control and outlet control.

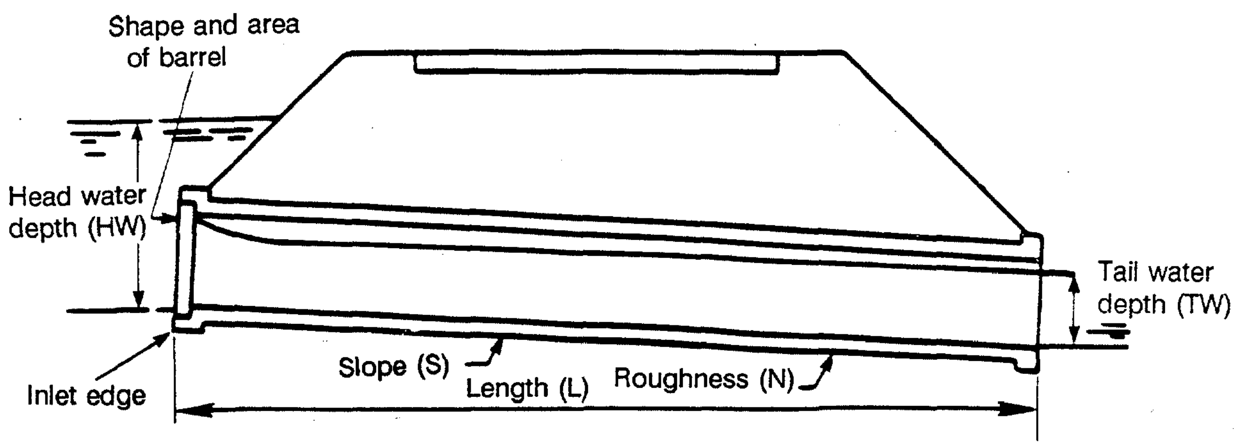


Figure 2.2. Factors affecting culvert discharge.[4]

a. Inlet control - Under inlet control, the capacity of the culvert is controlled at the entrance of the culvert by headwater depth, cross-sectional area, barrel shape, and the configuration of the inlet edge. Inlet control governs the capacity as long as water can flow out of the culvert faster than it can enter the culvert. Typical culvert sections under inlet control are shown in figure 2.3.

Most culverts, except those in flat terrain, are designed to operate under inlet control during peak flows. Since the entrance characteristics govern, minor modifications at the culvert inlet can significantly affect hydraulic capacity. For example, change in the approach alignment of the stream may reduce capacity, while improvement in the inlet edge configuration, or addition of properly designed headwalls and wingwalls may increase the capacity.

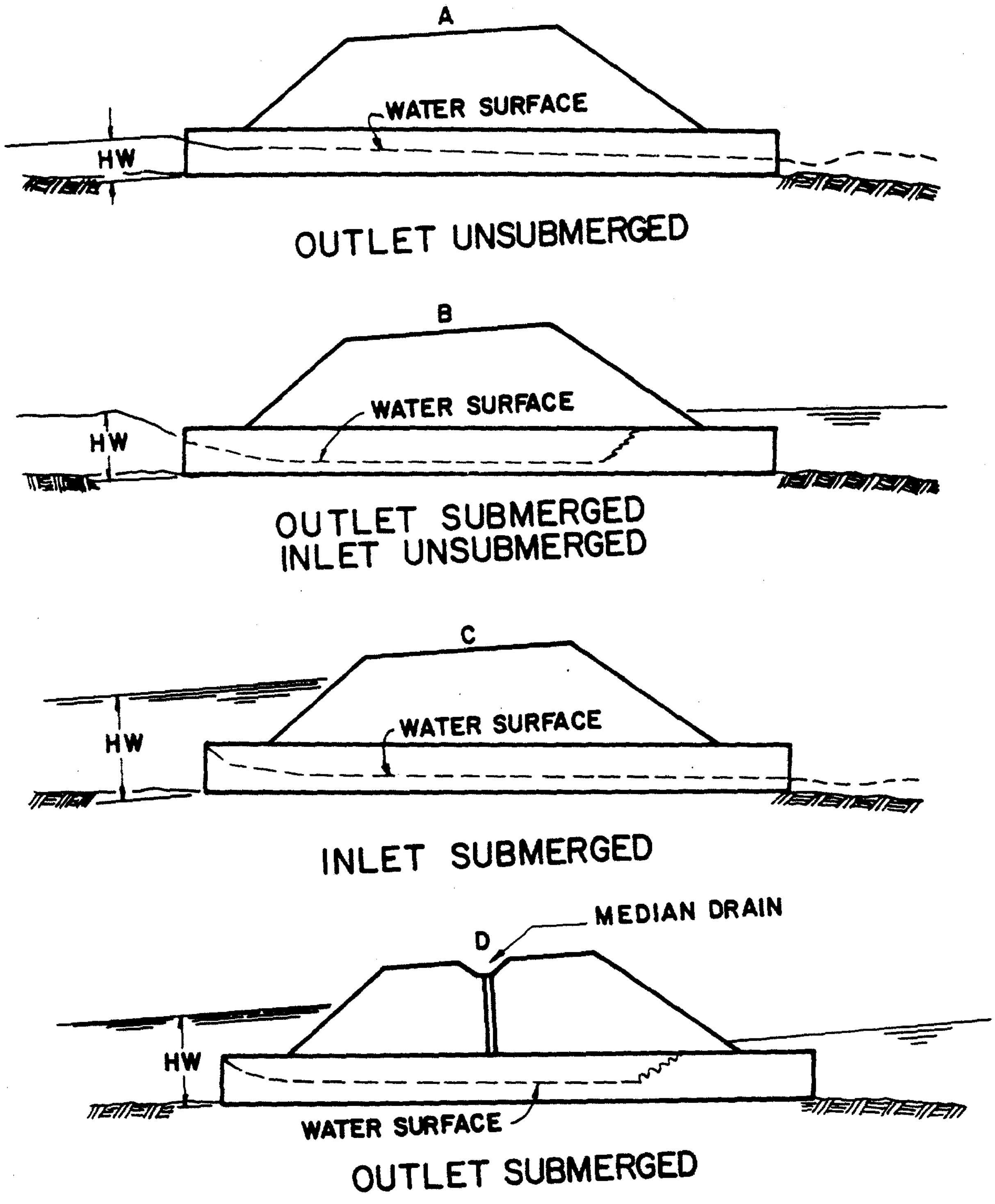


Figure 2.3. Typical culvert section under inlet control.[11]

For inlet control designs, the culvert designer must balance the design peak flow to the culvert location against the allowable depth and spread of backwater. Consideration must also be given to possible changes in land use, which will also influence runoff rates.

b. Outlet control - Under outlet control, water can enter the culvert faster than it can flow through the culvert. The discharge is influenced by the same factors as inlet control plus the tailwater depth and barrel characteristics (slope, length, and roughness). Culverts operating with outlet control usually lie on flat slopes or have high tailwater. When culverts are operating under outlet control, changes in barrel characteristics or tailwater depth may affect capacity. Examples of culverts operating under outlet control are shown in figure 2.4.

c. Special hydraulic conditions - The inlet and outlet of culverts may require protection to withstand the hydraulic forces exerted during peak flows. Inlet ends of flexible pipe culverts that are not adequately protected or anchored may be subject to entrance failures due to buoyant forces. The outlet may require energy dissipators to control erosion and scour and to protect downstream properties. High outlet velocities may cause scour and undermining of the endwall, wingwalls, and the culvert barrel. This erosion can cause end-section drop-off in rigid sectional pipe culverts.

Seeping along the outside of the culvert barrel may remove supporting material. This problem is referred to as "piping" since it creates a hollow void, similar to a pipe. Although piping frequently starts by scour at the inlet end, around or under the entrance features, it may occur because of scour of the embankment above the culvert. Piping can also occur because of water seepage through open joints. Control of piping may require the use of watertight joints and anti-seep collars.

Structural - Structural design of a culvert must be done to ensure that the culvert is strong enough to resist the loads that will be imposed upon it. The strength of a culvert depends on the strength of the materials that are used and the shape of the culvert barrel. For example, a circular shape carries and resists loads differently than a box shape.

a. Loads -In addition to fulfilling their hydraulic functions, culverts must also support the weight of the embankment or fill covering the culvert and loads on the roadway. There are two general types of loads that must be carried by culverts: dead loads and live loads. The amount of both dead and live load that is actually exerted on a culvert depends upon whether it is a rigid or flexible material, the type of material surrounding the culvert, the degree of compaction of the material, and whether special types of structural members are built around the culvert to resist and distribute soil pressures.

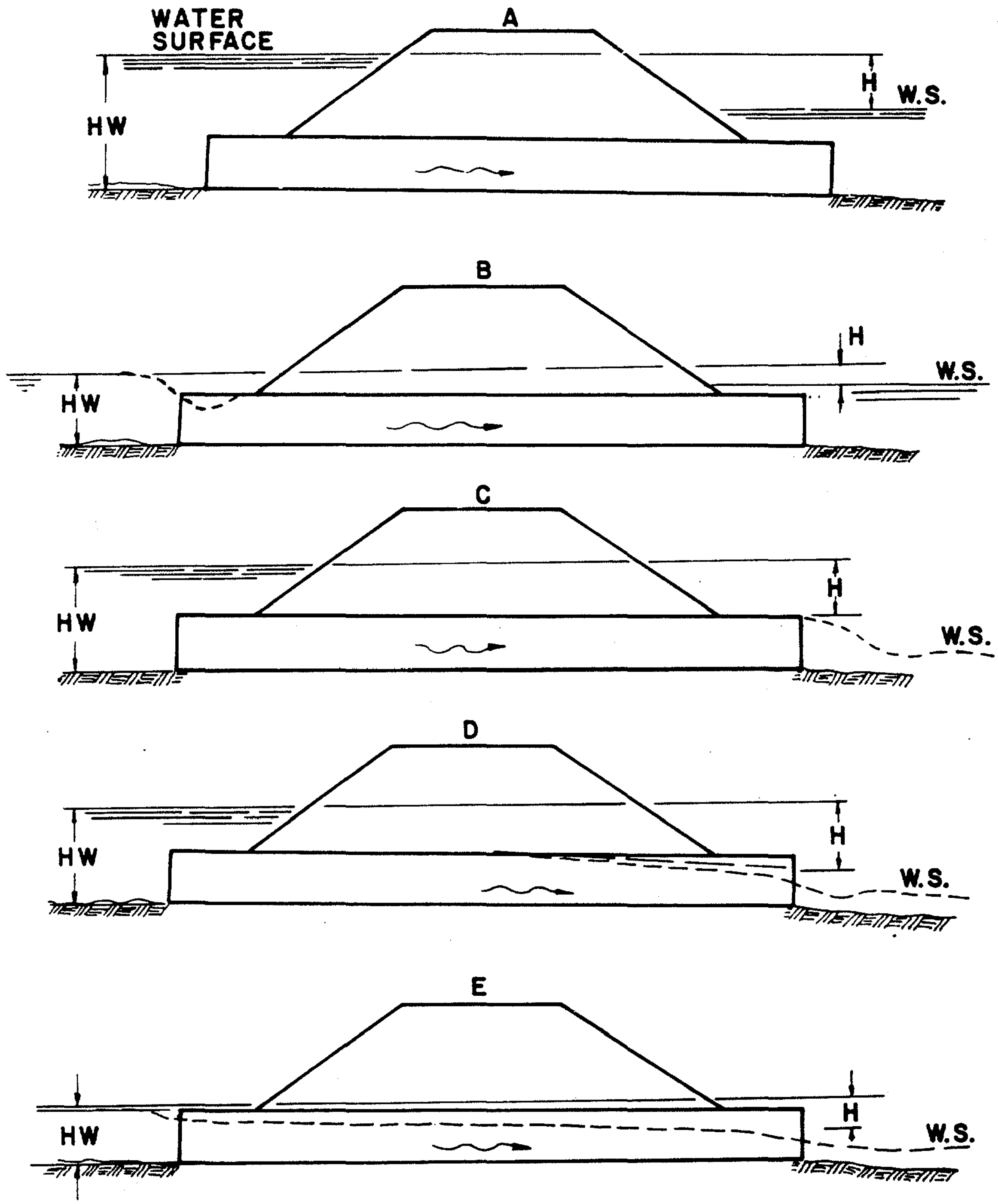


Figure 2.4. Typical culvert section under outlet control.[11]

Dead loads on a culvert include the earth load or weight of the soil over the culvert and any added surcharge loads such as buildings or additional earth fill placed over or adjacent to the culvert alignment. If the actual weight of earth is not known, 120 pounds per cubic foot is generally assumed.

The live loads on a culvert include the loads and forces that act upon the culvert due to vehicular or pedestrian traffic plus an impact factor. The highway wheel loads generally used for analysis are shown in figure 2.5. Actual loads for specific cases are assigned by the designer. The effect of live loads decreases as the height

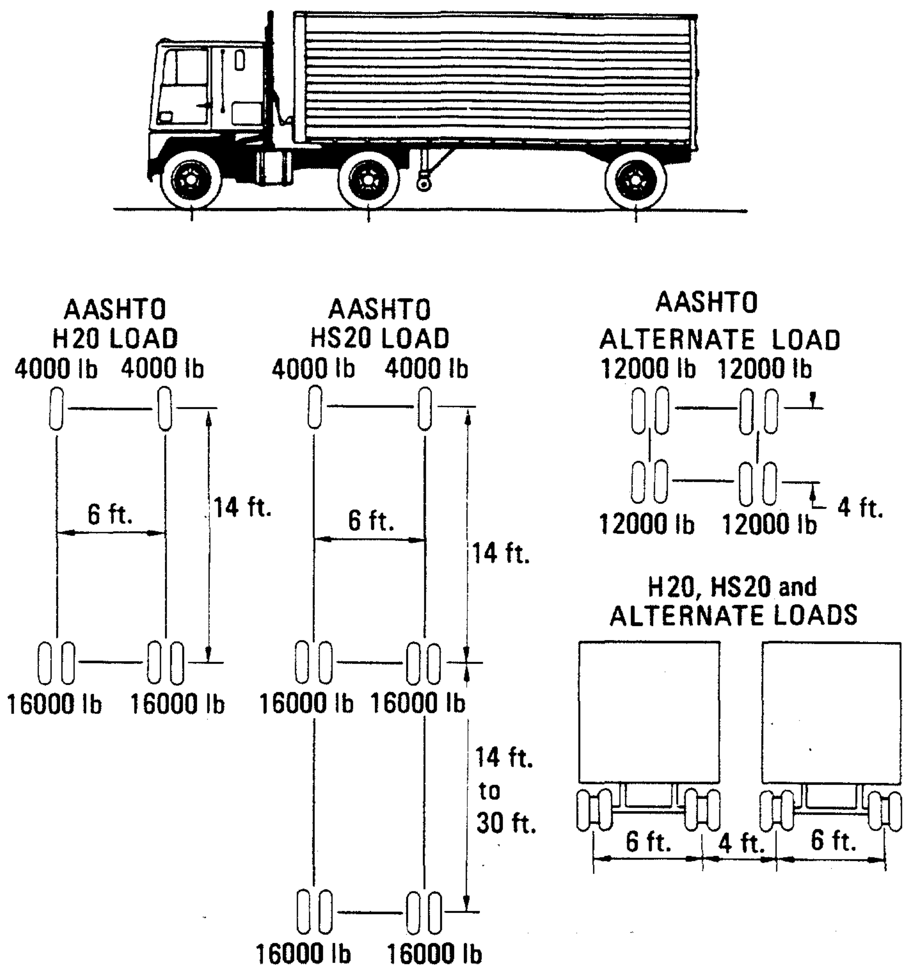


Figure 2.5. AASHTO live load spacing for highway structures.[4]

of cover over the culvert increases. When the cover is more than two feet, concentrated loads may be considered as being spread uniformly over a square with sides 1.75 times the depth of cover. This concept is illustrated in figures 2.6 and 2.7.

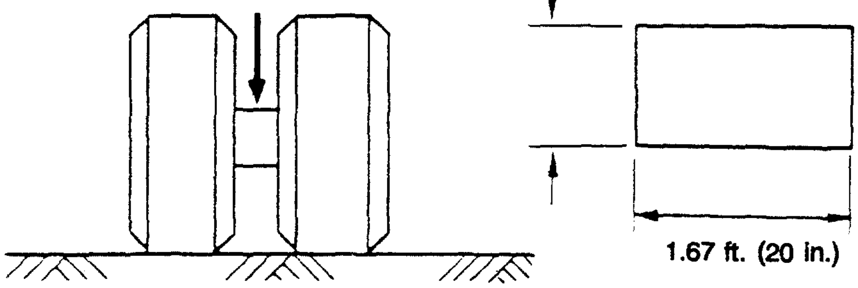


Figure 2.6. Surface contact area for single dual wheel.[2]

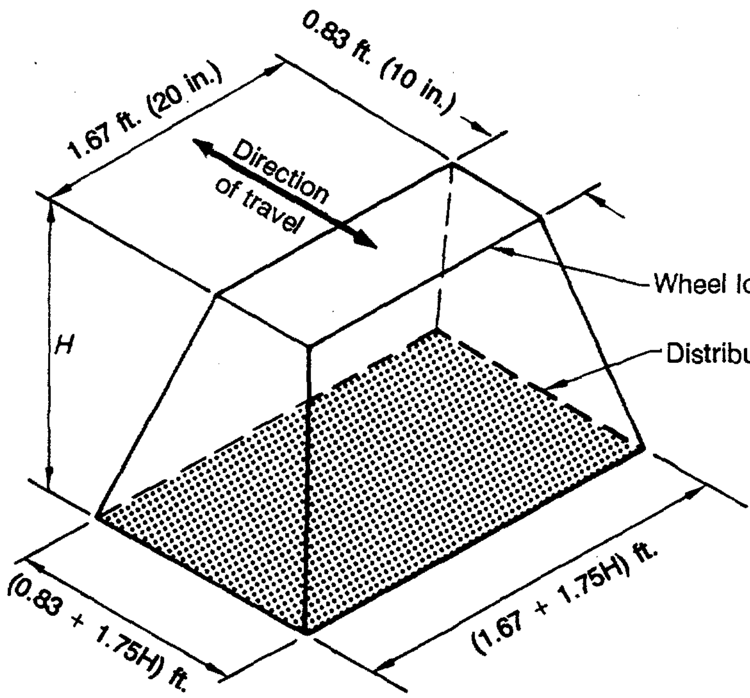
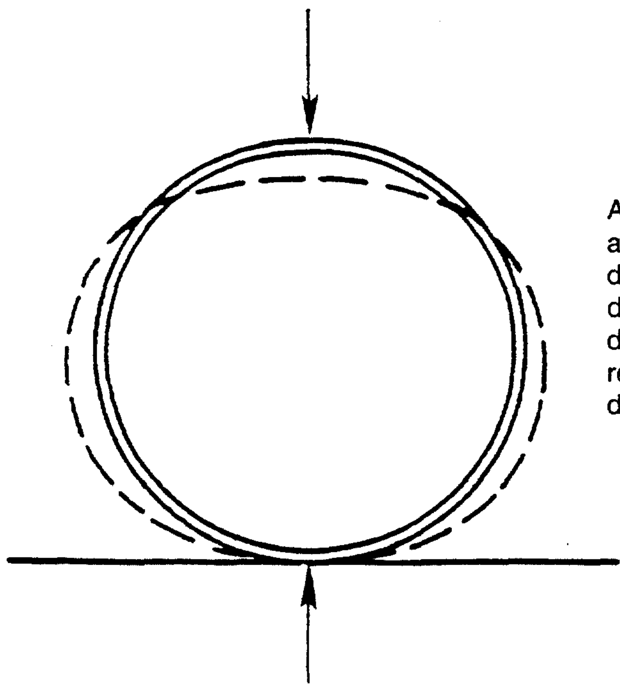


Figure 2.7. Distribution of live load (single dual wheel) for depth of cover H.[4]

b. <u>Flexible culvert behavior</u> - A flexible culvert is a composite structure made up of the culvert barrel and the surrounding soil. The barrel and the soil are both vital elements to the structural performance of the culvert.

Flexible pipe has relatively little bending stiffness or bending strength on its own. As loads are applied to the culvert, it attempts to deflect. In the case of a round pipe, the vertical diameter decreases and the horizontal diameter increases, as shown in figure 2.8.

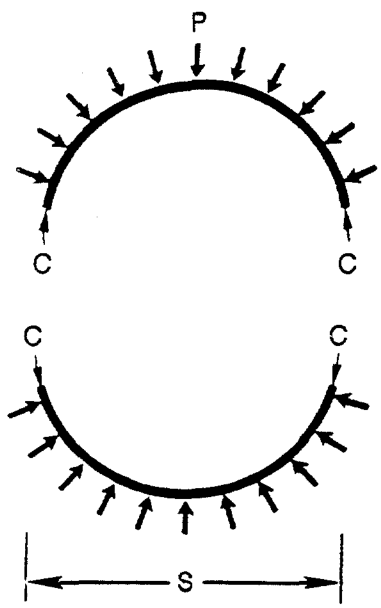


As vertical loads are applied a flexible culvert attempts to deflect. The vertical diameter decreases while the horizontal diameter increases. Soil pressures resist the increase in horizontal diameter.

Figure 2.8. Deflection of flexible culverts.[3]

When good embankment material is well compacted around the culvert, the increase in horizontal diameter of the culvert is resisted by the lateral soil pressure. With round pipe, the result is a relatively uniform radial pressure around the pipe that creates a compressive thrust in the pipe walls. As illustrated in figure 2.9, the compressive thrust is approximately equal to vertical pressure times one-half the span length ($C = P \times S/2$ or $C = P \times R$).

An arc of a flexible round pipe or other shape will be stable as long as adequate soil pressures are achieved, and as long as the soil pressure is resisted by



Summing the vertical forces on half of the pipe at a time shows that

$$C = P \times S/2$$

where

C = Compressive thrust in the culvert wall.

P = Sum of soil pressure acting on the culvert.

S = The span or diameter.

S/2 = The radius (R).

Figure 2.9. Formula for ring compression.[3]

the compressive force C on each end of the arc. Good quality backfill material and proper installation are critical in obtaining a stable soil envelope around a flexible culvert.

In long span culverts the radius (R) is usually large. To prevent excessive deflection due to dead and/or live loads, longitudinal or circumferential stiffeners are sometimes added. The circumferential stiffeners are usually metal ribs bolted to the outside of the culvert. Longitudinal stiffeners may be metal or reinforced concrete, as shown in figure 2.10. The thrust beams are added to the structure prior to backfill. The use of concrete stress-relieving slabs is another method used to achieve longer spans or reduce minimum cover. A stress-relieving slab is cast over the top of the backfill above the structure to distribute live loads to the adjacent soil.

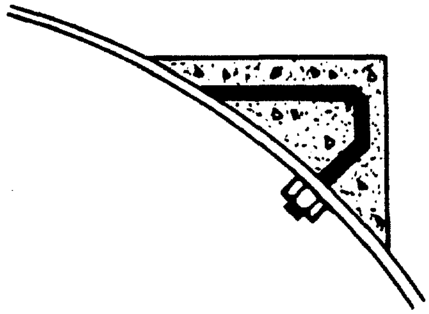


Figure 2.10. Concrete thrust beam used as a longitudinal stiffener.[3]

c. Rigid culvert behavior - The load carrying capacity of rigid culverts is essentially provided by the structural strength of the pipe itself and little benefit from the surrounding earth is required. When vertical loads are applied to a rigid pipe, zones of tension and compression are created as illustrated in figure 2.11. With the exception of non-reinforced circular pipe, reinforcing steel is added to the tension zones to increase the tensile strength of concrete pipe. Shear stress in the haunch area can be critical for heavily loaded rigid pipe on hard foundations, especially if the haunch support is inadequate. Because rigid pipe is stiffer than the surrounding soil, it carries a substantial portion of the load.

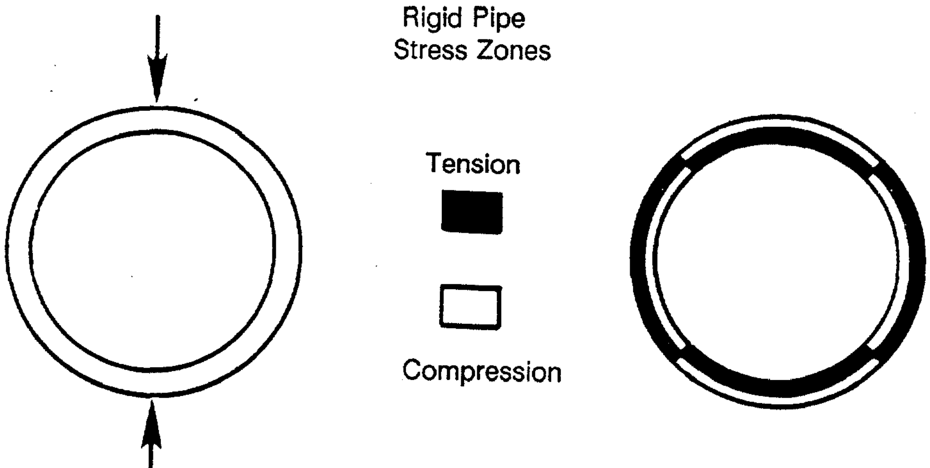


Figure 2.11. Zones of tension and compression in rigid pipes.[4]

The weight of earth that must be carried varies with soil characteristics and installation conditions. The installation conditions can have a significant influence on the loads that must be carried by a rigid culvert. There are two major classes of installation conditions: 1) trench, where culverts are placed in natural ground or compacted fill with a controlled trench width and 2) embankment, where culverts are placed in or covered by an embankment.

In narrow trench installations, the pipe is placed in a relatively narrow trench and covered with backfill material. The backfill tends to settle more than the undisturbed soil beside the trench. Friction between the backfill material and the sides of the trench tends to help support the backfill material, reducing the load on the pipe. In effect the width of the soil column over the pipe is decreased. This concept is illustrated in figure 2.12.

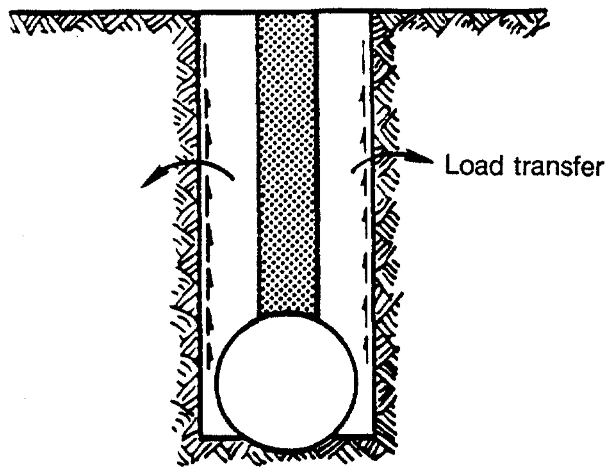


Figure 2.12. Trench installation. Friction on trench sides reduces the size of the column of fill carried by the pipe.[3]

As the trench width increases, the effect of the friction at the sides of the trench is reduced and dead load on the pipe is increased. The amount that the loading is increased depends on trench width and the amount of backfill settlement, which is related to compaction. Poorly compacted soil will settle more than well compacted soil. In a trench that is too wide, poor compaction can result in an increase in the dead load on the pipe. Pipes placed in a shallow bedding on top of the original ground surface and then covered by the embankment material will have loads similar to the very wide trench. Pipes placed in trenches in the original ground prior to being covered by embankment have reduced earth loads similar to those described for the narrow trench.

Durability - Although structural condition is a very important element in the performance of culverts, durability problems are probably the most frequent cause of replacement. Culverts are more likely to "wear away" than fail structurally. Durability is affected by two mechanisms: corrosion and abrasion. Each are discussed in the following sections:

a. Corrosion - Corrosion is the deterioration of metals due to chemical or electrochemical reaction to the environment. Corrosion of culvert materials may occur in many different soils and waters. These soils and waters may contain acids, alkalis, dissolved salts, organics, industrial wastes or chemicals, mine drainage, sanitary effluents, and dissolved or free gases. However, culvert corrosion is generally related to water and the chemicals that have reacted to, become dissolved in, or been transported by the water.

Certain soil and water conditions have been found to be particularly aggressive or hostile to culverts. Extremes in acidity or alkalinity are much more aggressive than more neutral conditions. The term pH is a measure of the relative acidity or alkalinity: 7.0 is neutral, values less than 7.0 are acid, and values greater than 7.0 are alkaline. For culvert purposes, values of less than 5.0 are strongly acid and those greater than 8.5 are strongly alkaline. Acid water stems from two sources: mineral and organic. Mineral acidity comes from sulfurous wells and springs and drainage from coal mines, with the water containing dissolved sulfur and iron sulfide that may form sulfurous and sulfuric acids. Mineral acidity with a pH as strong as 2.3 has been encountered. Organic acidity, which may be found in swampy land and barnyards, may have a pH as low as 4.0. Alkalinity in water is caused by strong minerals and limed and fertilized fields. Acid water is more common to wet climates and alkaline water is more common to dry climates.

The electrical resistivity of soil, which depends largely on the nature and amounts of dissolved salts, also influences the potential for corrosion. The greater the resistance the less the flow of electrical current associated with corrosion. High moisture content and temperature lower the resistivity and increase the potential for corrosion. The use of granular backfill around the entire pipe will increase electrical resistivity and reduce the potential for galvanic corrosion.

Corrosion can attack the inside or outside of the culvert barrel. The chemicals in drainage water can attack the material on the interior of the culvert. Culverts subject to continuous flows or standing water with aggressive chemicals are more likely to be damaged than those with intermittent flows. The exterior of culverts can be attacked by chemicals in the ground water that can originate in the soil, be introduced through contaminates in the backfill soil, or be transported by subsurface flow.

Corrosion affects all metals and alloys, although the rates can vary widely depending both upon the chemical and physical properties of the metal and upon the environmental condition to which it is exposed. When a metal corrodes, a very low voltage electrical current is established between two parts of a metal surface that have different voltage potential. The difference in voltage potential may be caused by slight variations in the material, changes in surface condition, or the presence of foreign materials. The current removes metallic ions from one location and deposits them at another location, causing corrosion, as shown in figure 2.13. The chemicals present in the water greatly influence its effectiveness as an electrolyte.

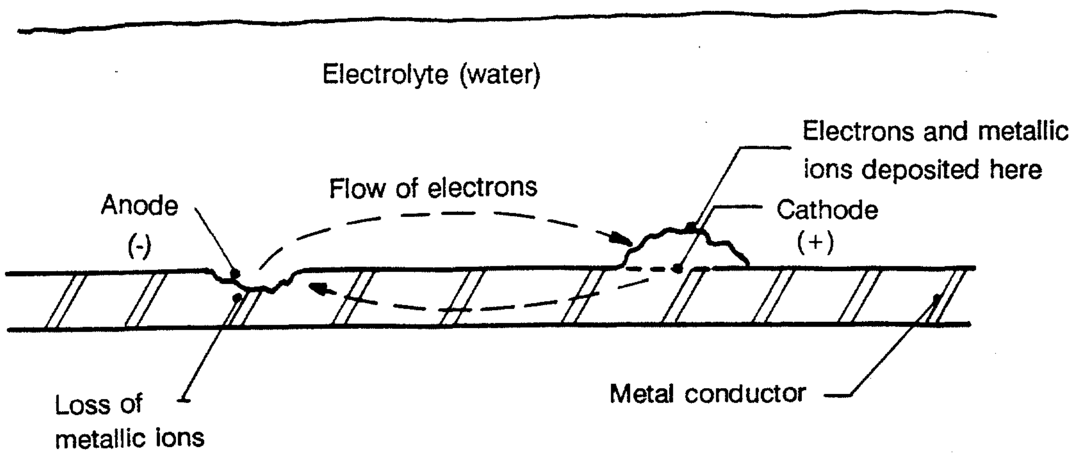


Figure 2.13. The corrosion process.

Although less common than with metal pipe, corrosion can occur in concrete culverts. Metallic corrosion can take place in the reinforcing steel when it is exposed by cracking or spalling, when the concrete cover is inadequate, or when the concrete is porous enough to allow water to contact the reinforcing steel.

If steel corrodes, the corrosion products expand and may cause spalling of the concrete. Corrosion can also take place in the concrete itself. It is not, however, the same type of electrochemical reaction that occurs in metal. Other reactions between the concrete materials and the chemicals present in the stream flow or ground water are involved and can result in deterioration of the concrete.

b. Abrasion - Abrasion is the process of wearing down or grinding away the surface material of culverts as water laden with sand, gravel, or stones flows through a culvert, as illustrated in figure 2.14. Abrasion forces increase as the velocity of the water flowing through a culvert increases; for example, doubling the velocity of a stream flow can cause the abrasive power to become approximately four-fold.

Often corrosion and abrasion operate together to produce far greater deterioration than would result from either alone. Abrasion can accelerate corrosion by removing protective coatings and allowing water-borne chemicals to come into contact with corrodible culvert materials.

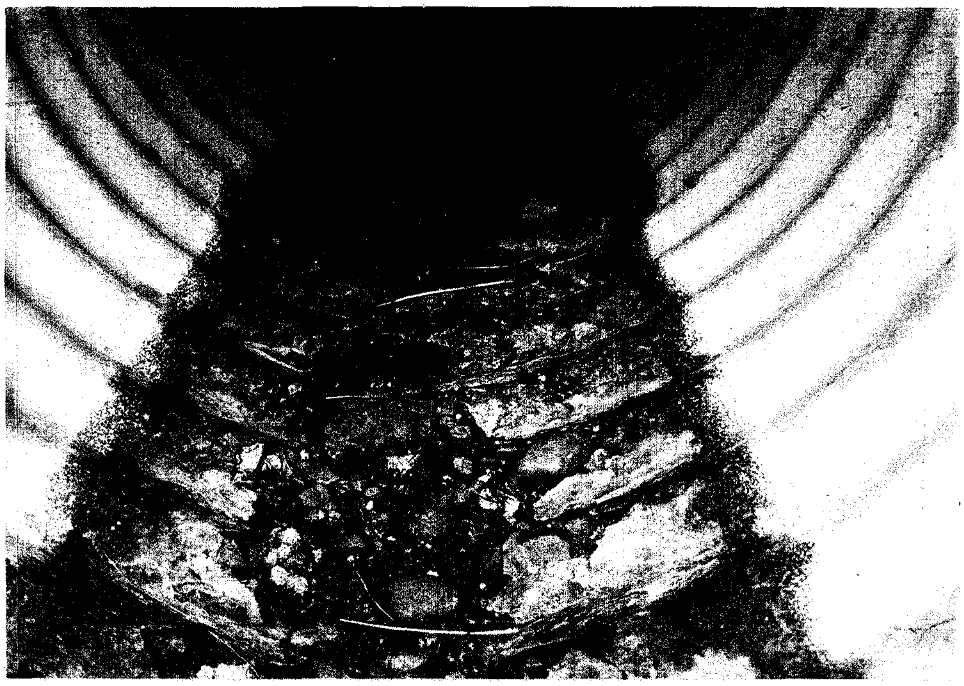


Figure 2.14. Corrugated steel culvert with invert perforation.

Economic Considerations

For the design of new culverts and major culvert repairs, an economic analysis usually includes factors such as construction cost, estimated service life, maintenance cost, replacement cost, risk of failure, and risk of property damage. The most economical culvert is one with the lowest total cost over the design life. It is not necessarily the culvert with the lowest initial cost nor the culvert with the longest service life. Most agencies have policies and/or procedures to guide these analyses. The importance is that short and long term costs should be considered in both original designs and in repairs or replacements.

Since this manual deals primarily with the repair, rehabilitation and retrofit upgrading of existing culverts, it is important to recognize that many additional cost and benefit factors must be considered for such work. The warrants for choosing one procedure over others will depend on many site-specific factors.

Other Factors

In addition to the factors cited above, there are several others of which designers should be cognizant during the design and construction of culverts. The following are three general areas that should be of concern:

Maintenance - Although the subject of maintenance, and the need for it, is discussed in detail in chapter 4, at this point it is appropriate to emphasize the need to consider maintenance needs in the design of culverts. That is, the designs should be such that the need for maintenance and repair work is minimized through the selection of the culvert type and the quality of the materials and construction methods that are used. For example,

- If abrasion problems are anticipated, then the designs should minimize the potential problem by flattening the slopes, providing stilling basins, or providing a tough, abrasion-resistant invert.

- If a problem with sedimentation is expected, it may be possible to steepen slopes or select a culvert shape (such as a box) that is easier to clean out with mechanized equipment.

Safety - Personnel safety should always be of concern during the construction, inspection, maintenance, repair, and rehabilitation of culverts. To the maximum extent possible the designer should highlight potentially hazardous periods of construction for certain types of structures. Inspection, maintenance, and repair personnel should be aware of the possibilities of poor air quality, toxic chemical, animals, and the potential for collapse of unstable structures. The subject of retrofitting culverts to reduce or minimize the dangers for errant vehicles is discussed in more detail in chapter 5.

Geotechnical - During design, particularly for larger culverts (over three to four foot span), the foundation conditions should be investigated to determine such factors as allowable bearing pressure, bedding requirements, and any condition requiring special treatments. In addition, determinations should be made concerning any unusual construction conditions such as groundwater, slope stability, and rock excavation. These factors apply to the end treatments, approaches, and barrel elements. The type, strength, slope, and bedding of soils and rocks all influence the design, construction and maintenance/repair operations.

Environmental - Water quality, the potential for hazardous or toxic materials, wetlands vegetation, and wildlife are other factors for which the highway agency must consider the applicable laws. Again, this applies to design, construction and maintenance/repair. Specific measures for erosion and sediment control, fish and animal passage, and preservation of vegetation are normally required in all types of operation.

Maintenance and Control of Traffic - Designers and maintenance personnel must consider if and how road traffic is to be maintained. This can be a very expensive item of construction and maintenance and must be carefully planned. The amount and type of traffic may require detours and requires safety provisions such as signs and/or barriers. The type and extent of repair work will dictate the measures required.

Adjacent Facilities - Particularly in urban and other developed areas the agency must consider preservation of existing facilities such as buildings, utilities, and site improvements. Measures such as underpinning structures, temporary relocation of utilities and restoration of sidewalks, and landscaping may be required.

CULVERT SHAPES

A wide variety of standard shapes and sizes are available for most culvert materials. Since equivalent openings can be provided by a number of standard shapes, the selection of shape may not be critical in terms of hydraulic performance. Shape selection is often governed by factors such as depth of cover or limited headwater elevation. In such cases a low profile shape may be needed. Other factors such as the potential for clogging by debris, the need for a natural stream bottom, or structural and hydraulic requirements may influence the selection of culvert shape. Each of the common culvert shapes are discussed in the following paragraphs. More details are included in the section on materials.

Circular

The circular shape is the most common shape manufactured for pipe culverts. It is hydraulically and structurally efficient under most conditions. Possible hydraulic drawbacks are that circular pipe generally causes some reduction in stream width during low flows. It may also be more prone to clogging than some other shapes due to the diminishing free surface as the pipe fills beyond the midpoint. With very large diameter corrugated metal pipes, the flexibility of the sidewalls dictates that special care be taken during backfill construction to maintain uniform curvature.

Pipe Arch and Elliptical

Pipe arch and elliptical shapes are often used instead of circular pipe when distance from channel invert to pavement surface is limited or when a wider section is desirable for low flow levels. These shapes may also be prone to clogging as the depth of flow increases and the free surface diminishes. Pipe arch and elliptical shapes are not as structurally efficient as a circular shape. They are normally used in areas with limited vertical clearance and low cover conditions.

Arches

Arch culverts have no culvert barrel material at the bottom and offer less of an obstruction to the waterway than pipe arches and can be used to provide a natural stream bottom where the stream bottom is naturally erosion and abrasion resistant. Foundation conditions must be adequate to support the footings. Riprap is frequently used for scour protection.

Box Sections

Rectangular or square cross-section culverts are easily adaptable to a wide range of site conditions, including sites that require low profile structures. Due to the angular corners, boxes are not as structurally and hydraulically efficient as other culvert shapes.

Multiple Barrels

Multiple barrels are used to obtain adequate hydraulic capacity under low embankments or for wide waterways. In some locations they may be prone to clogging as the area between the barrels tends to catch debris and sediment. When a channel is artificially widened, multiple barrels placed beyond the dominant channel are subject to excessive sedimentation. The span or opening length of multiple barrel culverts includes the distance between barrels as long as that distance is less than half the opening length of the adjacent barrels.

CULVERT MATERIALS

Modern culverts are primarily made with reinforced concrete, corrugated metal, and more recently, solid-wall, profile wall, and reinforced plastic, whereas old culverts may be constructed with stone masonry, terra cotta, or timber. The strength and physical characteristics of the materials depend upon their chemistry and the interrelationship between the constituent materials. Metals are homogeneous isotropic materials whereas concrete and masonry is a mixture or combination of materials. Timber is a fibrous material that has the fibers in a longitudinal direction and significantly different properties in all three directions. The method by which the materials are connected significantly influences whether the strength of the materials may be utilized structurally.

Concrete

Modern culverts may be made with either precast or cast-in-place reinforced concrete. This selection depends primarily upon proximity of a precast concrete plant to the job site and the size and complexity of the culvert design. Precast sections are uniform in size and shape and are made in sections that can easily be transported, lifted, and installed. Cast-in-place concrete construction is often used when ready-mix concrete is available and when the culvert should be constructed without joints. Precast concrete culverts may be made with high strength concrete, whereas cast-in-place concrete culverts may have special reinforcement at critical locations to resist high loads and stresses.

Precast - Precast concrete pipe is manufactured in eight standard shapes: circular, arch, horizontal elliptical, vertical elliptical, pipe arch, box sections, three-sided arch top, and flat top sections, as shown in table 2.1. With the exception of box culverts, concrete culvert pipe is manufactured in up to five standard strength classifications. The higher the classification number the higher the strength. Box culverts are designed for various depths of cover and live loads. All of the standard shapes are manufactured in a wide range of sizes. Circular and elliptical pipes are available with standard sizes as large as 144 inches in diameter, with larger sizes available as special designs. Standard box sections are also available with spans as large as 144 inches. Precast concrete arches on cast-in-place footings are available with spans up to 40 feet. A listing of standard sizes is provided in appendix A.

Cast-in-place - Reinforced culverts that are cast-in-place are typically either rectangular or arch-shaped. The rectangular or box shape is more common and is usually constructed with multiple cells (barrels) to accommodate longer spans. One advantage of cast-in-place construction is that the culvert can be designed to meet the specific requirements of a site. Due to the longer construction time of cast-in-place culverts, precast concrete or corrugated metal culverts are often selected. However, in many areas cast-in-place culverts are more practical and represent a significant number of installations.

Shapes - By the very nature of it, reinforced concrete may be used to make virtually any structural shape desired. Thus, if necessary and feasible, it is possible to make almost any shaped culvert with either precast or cast-in-place reinforced concrete.

Corrugated Steel

Corrugated steel culverts are made with factory-produced corrugated sheet steel. Corrugated pipe culverts are made with factory-produced corrugated pipe sections. Large corrugated culverts are normally field-assembled using structural plate products. Structural plate steel products are available as structural plate pipes, box culverts, or long span structures. Standard shapes for corrugated steel culverts are shown in table 2.2.

Table 2.1. Standard concrete pipe shapes.[2]

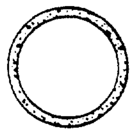
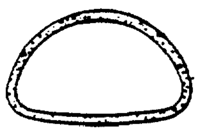
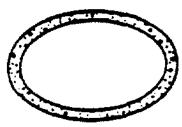
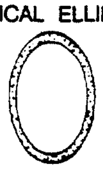
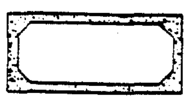
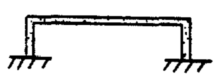
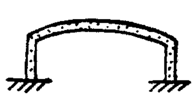
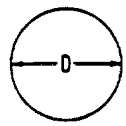
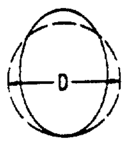
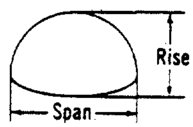
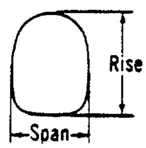
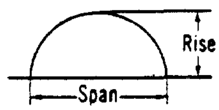
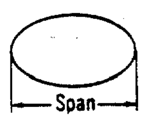
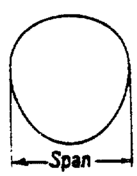
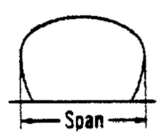
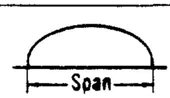
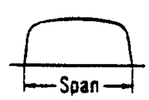
SHAPE	RANGE OF SIZES	COMMON USES
CIRCULAR 	12 to 180 inches reinforced 4 to 36 inches non-reinforced	Culverts, storm drains, and sewers.
PIPE ARCH 	15 to 132 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
HORIZONTAL ELLIPSE 	Span x Rise 18 to 144 inches equivalent diameter	Culverts, storm drains, and sewers. Used where head is limited.
VERTICAL ELLIPSE 	Span x Rise 36 to 144 inches equivalent diameter	Used where lateral clearance is limited.
RECTANGULAR (box sections) 	Span 3ft to 12ft	Culverts, storm drains, and sewers. Used for wide openings with limited head.
ARCH 	Span 24ft to 41ft	Culverts and storm drains. For low, Wide waterway enclosures.
FLAT TOP 3-SIDED 	Span 14ft to 35ft	Culverts and storm drains. For low, Wide waterway enclosures.
ARCH TOP 3-SIDED 	Span 16ft to 36ft	Culverts and storm drains. For low, Wide waterway enclosures.

Table 2.2. Standard corrugated steel culvert shapes.[4]

Shape		Range of Sizes	Common Uses
Round		6 in. – 26 ft.	Culverts, subdrains, sewers, service tunnels, etc. All plates same radius. For medium and high fills (or trenches).
Vertically–elongated (ellipse) 5% is common		4 – 21 ft. nominal; before elongating	Culverts, sewers, service tunnels, recovery tunnels. Plates of varying radii; shop fabrication. For appear–ance and where backfill compaction is only moderate.
Pipe–arch		Span x Rise 17 in. x 13 in. to 20 ft. 7 in. x 13 ft. 2 in.	Where headroom is limited. Has hydraulic advantages at low flows. Corner plate radius. 18 inches or 31 inches for structural plate.
Underpass*		Span x Rise 5 ft. 8 in. x 5 ft. 9 in. to 20 ft. 4 in. x 17 ft. 9 in.	For pedestrians, livestock or vehicles (structural plate).
Arch		Span x Rise 6 ft. x 1 ft. 9 1/2 in. to 25 ft. x 12 ft. 6 in.	For low clearance large waterway opening, and aesthetics (structural plate).
Horizontal Ellipse		Span 7 – 40 ft.	Culverts, grade separations, storm sewers, tunnels.
Pear		Span 25 – 30 ft.	Grade separtaions, culverts, storm sewers, tunnels.
High Profile Arch		Span 20 – 45 ft.	Grade separtaions, culverts, storm sewers, tunnels, ammo ammunition magazines, earth covered storage.
Low Profile Arch		Span 20 – 50 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Box Culverts		Span 10 – 26 ft.	Low–Wide waterway enclosures, culverts, storm sewers.
Specials		Various	For lining old structures or other special purposes. Special fabrication.

*For equal area or clearance, the round shape is generally more economical and simpler to assemble.

Material - Corrugated steel pipe is fabricated from sheets coated with zinc, aluminum, or an aluminum-zinc alloy. It is reasonably lightweight for shipping and comes in a large range of thicknesses and corrugations to provide the appropriate strength. However, it requires controlled backfill for proper soil support. Other options include various coatings and/or pavings for added protection.

Shapes - Corrugated steel may be used for a wide variety of shapes, sizes, and lengths of culverts. The culverts may be made from prefabricated sections that are factory produced or assembled in the field from specially fabricated plates. The shapes may be made from various thicknesses of plate stock.

a. Pipe - Corrugated steel pipe is factory-made in two basic shapes: round and pipe arch. Both round and arch shapes are available in a wide range of standard sizes. Round pipe is available in standard sizes up to 144 inches in diameter. Standard sizes for pipe arch are available in sizes up to the equivalent of 120-inch diameter round pipe. A listing of sizes available for each corrugation is provided in the appendix A. Both shapes are produced in several wall thicknesses, several corrugation sizes, as shown in figure 2.15, and with annular (circumferential) or helical (spiral) corrugations.

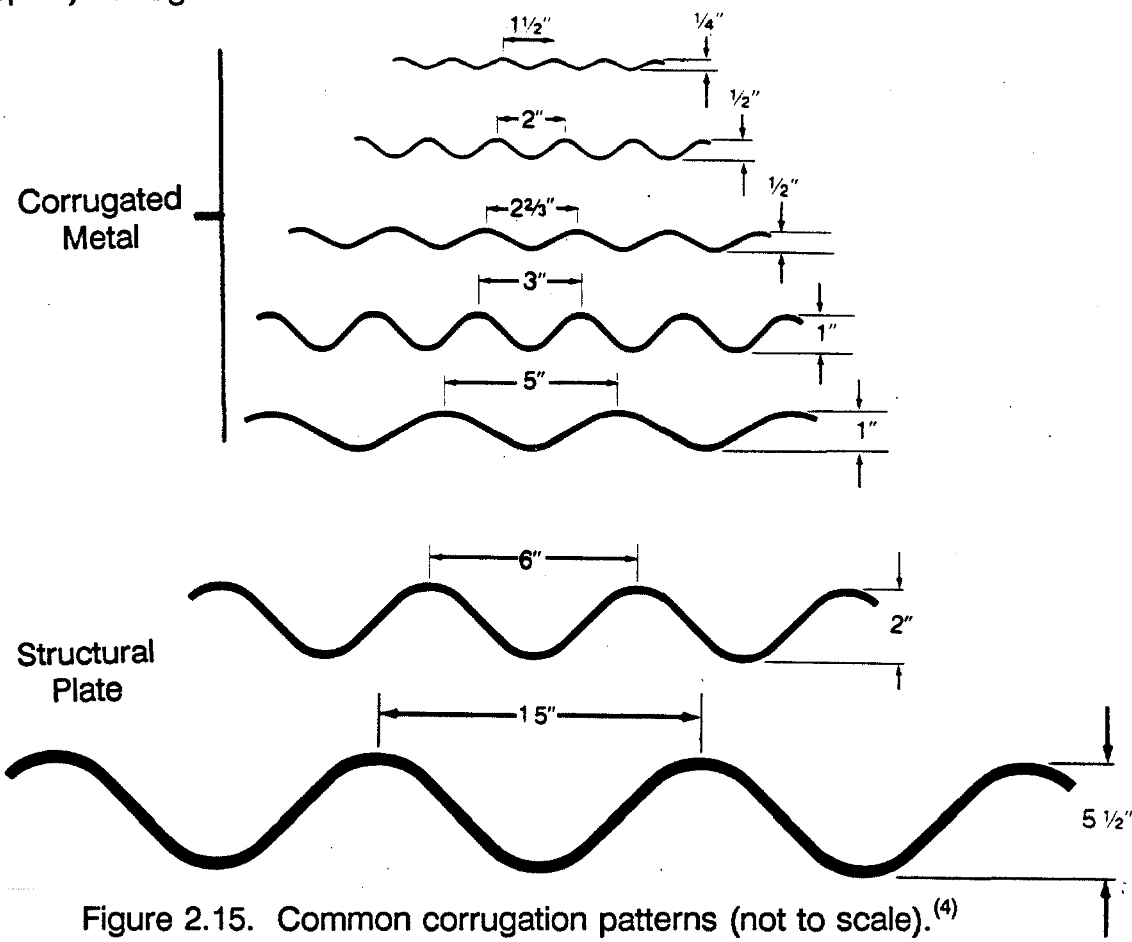


Figure 2.15. Common corrugation patterns (not to scale).[4]

Pipes with annular corrugations have riveted, spot welded, or bolted seams. Pipes with helical corrugations have continuously welded seams or lock seams. Corrugated steel pipe and pipe arch are usually zinc coated (galvanized). Other metallic coatings such as aluminum and aluminum zinc alloy coatings have recently been developed. Additional protective coatings are used with the metallic coating when there are potential corrosion or abrasion problems.

b. Structural plate - Structural plate steel pipes are field-assembled from standard corrugated galvanized steel plates. Standard plates have corrugations with a 6-inch pitch and a depth of 2 inches. Plates are manufactured in a variety of thicknesses and are re-curved for the size and shape of the structure to be erected. Standard plates have a nominal length of either 10 or 12 feet and are produced in standard widths of 3N, 5N, 6N, 7N, and 8N, where N equals 3 pi or 9.6 inches. Widths are measured along the circumference of the structure. Since the circumference of a circle equals pi times the diameter, the use of dimensions expressed in N or pi permits easy conversion from pipe circumference to nominal diameter. For example a 60-inch diameter round pipe has a circumference of 60 pi or 20N and would normally be assembled from four 5N plates. Structural plate pipes are available in four basic shapes: round, pipe arch, arch, and underpass. The standard sizes available range in span from 5 feet to 26 feet. Tables showing typical sizes and dimensions are provided in appendix A.

c. Box - Steel box sections use standard 6 by 2 inch corrugated galvanized steel plates with special reinforcing elements applied to the areas of maximum moment or 15 by 15 1/2 inch corrugated plate without ribs. Steel box culverts are available with spans that range from 9 feet 8 inches to 20 feet 9 inches. Typical sizes and dimensions are listed in appendix A.

d. Long Span - Long span steel structures are assembled using conventional 6 by 2 inch corrugated galvanized steel plates with longitudinal or circumferential stiffening members or 15 by 15 1/2 inch corrugated plate without ribs. There are five standard shapes for long span structures: horizontal elliptical, pipe arch, low profile arch, high profile arch, and pear shape. The long span pipe arch is not commonly used. The span lengths of typical sections range from 19 feet 4 inches to 40 feet. Tables illustrating sizes and dimensions of typical sections are provided in appendix A. Longer spans are available for some shapes as special designs.

Corrugated Aluminum

Corrugated aluminum culverts are constructed from factory assembled corrugated aluminum pipe or field assembled from structural plates. Structural plate aluminum culverts are available as conventional structural plate structures, box culverts, or long span structures.

Material - Corrugated aluminum pipe is fabricated from aluminum-alloy sheets. It is very lightweight for shipping and handling. It has good resistance to corrosion, especially in brackish waters but is subject to abrasion in fast-flowing streams with a significant load of sand or rock. It is generally more flexible than steel, requires greater care in installation, and is less tolerant of less-than-normal cover.

Shapes - Corrugated aluminum may be used for a wide variety of shapes, sizes, and lengths of culverts. The culverts may be made from prefabricated sections that are factory produced or assembled in the field from specially fabricated plates. The shapes may be made from various thickness of plate stock.

a. Pipe - Factory assembled aluminum pipe is available in two basic shapes: round and pipe arch. Both shapes are produced with several different wall thicknesses, several corrugation patterns, and with annular (circumferential) or helical (spiral) corrugations. Round aluminum pipe is available in standard sizes up to 120 inches in nominal diameter. Aluminum arch pipe is available in sizes up to the equivalent of a 96-inch diameter round pipe.

b. Structural plate - Structural plate aluminum pipes are field assembled with 9-inch-pitch by 2.5-inch-depth corrugations. Plates are manufactured in a variety of plate thicknesses and are pre-curved for the specific size and shape of the structure to be erected. Plates are manufactured in lengths of 8N through 18N, where N equals 3 pi or 9.6 inches. Plate length is measured along the circumference of the structure. Standard plates have a net width of 4 feet 6 inches. Structural plate aluminum pipes are produced in five basic shapes: round, pipe arch, arch, pedestrian/animal underpass, and vehicle underpass. A wide range of standard sizes are available for each shape. Spans as large as 30 feet can be obtained for the arch shape. More detailed listing of available sizes and key dimensions are provided in the appendix A.

c. Box - The aluminum box culvert utilizes standard aluminum structural plates with aluminum rib reinforcing added in the areas of maximum moments. Ribs are bolted to the exterior of the aluminum shell during installation. Aluminum box culverts are suitable for shallow depths of fill and are available with spans ranging from 8 feet 9 inches to 25 feet 5 inches. Standard sizes and geometric dimensions are provided in appendix A.

d. Long Span - Long span aluminum structures are assembled using conventional 9- by 2.5-inch corrugated aluminum plates and aluminum rib stiffeners. Long span aluminum structures are available in the same five basic shapes as steel long spans: including horizontal ellipse, pipe arch, low profile arch, high profile arch, and pear shape. The typical sizes for aluminum spans are essentially the same as the typical sizes available for steel long span structures. Spans range from 19 feet 4 inches to 40 feet. Listings of typical sizes and dimensions for each shape are provided in appendix A.

Plastic

"Plastic" pipe is as unspecified a term as is "metal" pipe. There are many types of materials that may be used to produce plastic pipe, and the resulting pipe will have strength and other properties that vary accordingly. The properties of the plastic will depend primarily on the type of base resin that is used as well as the blend (or formulation) of chemicals in the final resin material that is used to produce the pipe. Just as with the design of concrete mixes, it is a common practice to use special additives with the basic resin to facilitate the production process and/or to alter the resulting physical and chemical properties of the finished product.

In general, plastics may be divided into two basic groups: (1) thermoplastics and (2) thermosetting plastics. The primary difference between these classes of material is that thermoplastics may be remelted and reshaped whereas thermosetting plastic cannot be remelted. Thus, the strength and other properties of thermoplastics will depend on the ambient temperature, and thermosetting plastics will retain their strength properties under a wide range of temperatures. The strength of these plastics will depend more on the types of resins that are used than on whether they are thermoplastics or thermosetting plastics.

Although both types of plastic may be used for culvert and drainage products, they are usually constructed from thermoplastic-type materials, which are less expensive and more easily used to manufacture. Two of the most popular types of material that are used are polyvinyl chloride (PVC) and polyethylene (PE). Thermosetting type resins are commonly used for pipe that must handle fluids at high temperatures.

Plastic drainage products may also be classified according to whether they are made just of plastic or whether the plastic is reinforced with fibers, typically glass fibers. The latter may be called "fiberglass" pipe. Since glass fibers have a filament strength of over 300,000 psi, pipe products that are made with long continuous glass fibers will have greater strength properties over unreinforced plastic pipe.

Polyvinyl Chloride (PVC) - Polyvinyl Chloride (PVC) piping is made only from compounds that do not contain plasticizers and minimal quantities of other ingredients. It has been labeled as rigid PVC in the United States to distinguish it from flexible or plasticized PVCs from which such items as laboratory tubing, luggage, and upholstery are made. This pipe exhibits good long-term strength with high stiffness. It is for this reason that PVC has become an important material for both pressure and non-pressure pipe applications. There is a much broader range of PVC fittings, valves, and appurtenances available than in any other plastic. The pipe is manufactured in both solid wall and profile wall in sizes up to 48 inches.

Polyethylene (PE) - Polyethylene (PE) is perhaps the most well known of the plastics in the polyolefin group. These are plastics that are formed by the polymerization of straight chain hydrocarbons that are known as olefins. They include ethylene, propylene, and butylene. PE piping is tough and flexible, even at subfreezing temperatures. PE pipe has good abrasion resistance and is available in solid wall and profile wall with diameters up to 96 inches. It is often used to slipline deteriorating pipes.

Fiberglass - Fiber reinforced plastic (FRP) composite pipe products may be made with a wide range of combinations of resins, glass fibers, and fillers. This class of pipe products is made by (1) filament winding continuous glass fibers and a thermoplastic polyester resin around a cylindrical steel mandrel or by (2) centrifugally casting a mixture of resin, sand, and chopped glass givers against the inside of a rotating steel mold. Figure 2.16 shows the makeup of a filament-wound pipe, that in this case, uses a woven mat type of long continuous glass fibers.

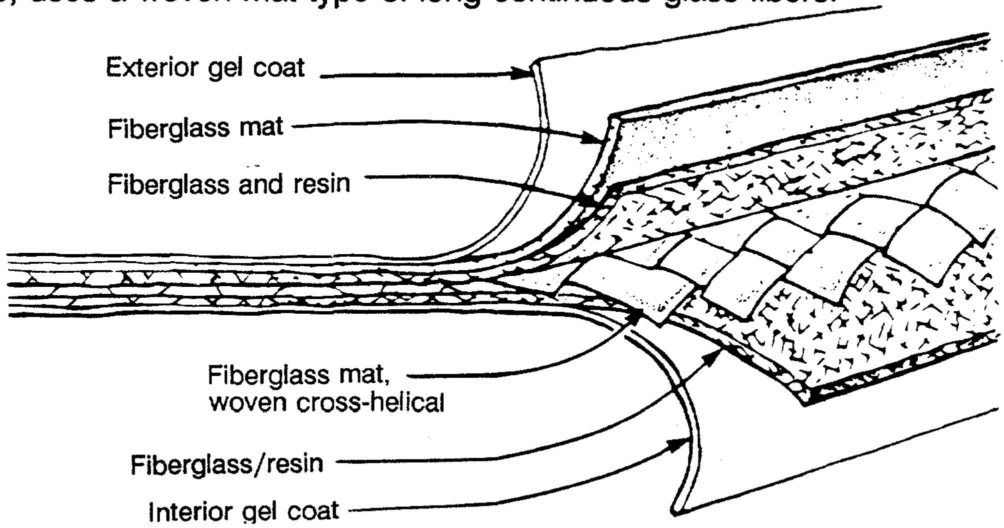


Figure 2.16. Fiberglass-reinforced pipe.[8]

Both types of fiberglass pipe are considered to be premium products that have much greater strength than unreinforced plastic pipe. Although such pipe may be made with a variety of combinations of materials, the finished products are designed to carry full structural loading for several types of site conditions, in compliance with ASTM and other specifications. Fiberglass pipe may be used for both new construction and for structurally relining existing pipelines or culverts. It may also be important to note that fiberglass pipe is very smooth, with a 0.009 Manning Factor, which may provide no reduction in flow capacity for a smaller diameter structural relining of a culvert. Although the resins are resistant to almost all chemicals, special resins may be selected for use in extreme chemical environments, including strong alkalis and acids. Fiberglass pipes, of certain types, are available in a range of sizes from 8 inches to 144 inches in diameter.

Fiber Reinforced Polymer Concrete (FRPC) - This type of pipe, that was developed in Europe 25 years ago, has recently been introduced into American markets, under the trade name of HOBAS™. The pipe may be used for gravity flow and high pressure (up to 250 psi) pipeline applications as well as for sliplining culverts. The pipe is manufactured from chapped glass fiber roving, polyester resin, and sand. The composite wall structure can be varied to produce the necessary wall strength characteristics needed for a variety of types of projects. The HOBAS™ pipe is made in 20 ft lengths, in diameters from 18 to 96 in. and in 9, 18, 36, and 72 psi stiffness classes, in accordance with existing AWWA and ASTM specifications.

The pipe is manufactured by a centrifugal casting method, that produces centrifugal forces 30 times that of gravity and a densely compacted resin, glass fiber and sand pipe product that has a high structural strength. The resin is polymerized by heating the pipe while it is still in the mold. After cooling the pipe is ready for shipment.

Other Materials

Masonry - Stone and brick are durable, low maintenance materials. Prior to the 1920's, both were used frequently in railroad and road construction projects because they were readily available from rock cuts or local brickyards. Although stone and brick are seldom used for constructing culvert barrels, stone is used occasionally for this purpose in locations that have very acid runoff. The most common use of stone is for headwalls where a rustic or scenic appearance is desired. Brick is frequently used in the construction of manholes and inlets in storm drainage systems, because it may easily be built up without the need for formwork.

Vitrified Clay Pipe - Vitrified clay pipe is manufactured from clays and shales that are the mineral aggregates remaining after the weathering process of nature. This weathering process leaches out the soluble and reactive minerals from the rock and soil, leaving an inert material. This chemically inert material is then burned in kilns at 1900-2100 degrees Fahrenheit at which "vitrification" occurs and the clay particles become fused into an inert chemically stable compound.

Vitrified clay pipe is resistant to internal and external attack from acids, alkalies, gases, and solvents. It is resistant to abrasion and scour and will not corrode.

Wood - Wood or timber is a renewable building material available in most locations. It has a high strength-to-weight ratio and, when properly protected, it is very durable. Its strength is influenced by straightness of grain and moisture and it is much stronger parallel to the grain than across the grain.

While green wood is more resilient and flexible than seasoned wood, proper curing decreases shrinkage, increases strength, reduces weight, increases resistance to decay and improved workability. In addition, cured wood is ready for preservation treatment. When adequately protected, wood is a very durable building material. It is sometimes used to construct box culverts where runoff is highly corrosive. It is also used in rustic settings or where other materials are not available.

Cast Iron - Cast iron is iron in which carbon has been dissolved. It is generally no longer used for culvert construction. It has poor tensile strength and is brittle and susceptible to cracking. The shapes are cast and are bulky in comparison to steel. Cast iron does, however, exhibit good corrosion resistance.

Coatings for Culvert Materials

A variety of types of coatings may be used either singularly or in a combination of layers to protect culverts from chemical and/or abrasion attack. The type(s) of coatings will depend upon the type of culvert material and the types of deterioration or distress they incur. The necessity for protective coatings depends upon a number of factors, including:

- Chemistry and acidity (pH) of the adjacent soil;
- Chemistry and acidity (pH) of the water passing through the culvert;
- Particle size and velocity of the solid material being transported through the culvert; and
- Environmental effects including freezing and thawing.

Coatings for metal culverts - Corrugated steel culverts are usually zinc coated (galvanized). Other metallic coatings such as aluminum and aluminum zinc alloy coatings have recently been developed. Protective coatings for metal culverts also include bituminous coatings, bituminous paving, fiber-bonded bituminous coatings, polymer, concrete paving, and concrete coatings. Additional protective coatings are used with the metallic coating when there are serious corrosion or abrasion problems.

a. Bituminous - This is the most common material used to protect corrugated steel pipe against corrosion. This procedure can also increase the resistance of metal pipe to acidic conditions if the coating is properly applied and it remains in place. Careful handling during transportation, storage, and installation is required to avoid damage to the coating. Bituminous coatings can also be damaged by abrasion. Field repairs should be made when bare metal has been exposed. Aramid fibers may be embedded in the zinc coating to improve the adherence to metallic-coated bituminous material pipe. It should be noted that the durability of bituminous coatings is dependent on strict adherence by the fabricator to proper coating procedures.

b. Polymer - There are several types of polymer coatings that may be applied for corrosion and/or abrasion protection. The term polymer generally refers to a variety of types of plastic that may be used either plain "neat" or as a matrix for binding aggregates together, much the same as Portland cement or asphaltic cement are used to make those respective types of concrete. Plain plastic coatings, often epoxies, may be applied directly to the metal or to other surface coatings. Culverts may also be coated with a polymer concrete, which is a mixture of plastic and aggregate. There have also been recent developments for coating metal culverts with fiberglass, which are (for these types of applications) short glass fibers held in a resin matrix. However, the 10 mil thick PVC and polyolefin plastic coatings that may be used to coat metal culverts do not provide increased resistance to abrasion, although polyethylene will to some extent.

c. Concrete/mortar - Metal culverts may be coated with a Portland Cement mortar or concrete for corrosion and abrasion resistance. Concrete of good quality is resistant to many corrosive agents. When the effluent has a pH of 5.0 or less, protective measures are generally required. One problem with using this type of coating is getting a good bond or connection between the metal pipe and the mortar or concrete lining.

d. Galvanizing - Galvanizing refers to the process of coating steel with a layer of zinc. Bare, uncoated, galvanized steel pipe generally performs well when the pH of the soil immediately adjacent to the pipe and the pH of the flow that the pipe will carry are between 6 and 10 and when the electrical resistivity of the soil is 2,000 ohm-cm or greater. Bare galvanized steel pipe should not be used in salt or brackish environments.

e. Aluminum cladding - Steel may also be coated with aluminum for corrosion protection. Aluminum generally performs adequately when the pH of the soil immediately adjacent to the pipe and the pH of the flow that the culvert will carry are between 5 and 9, and when the electrical resistivity of the flow and the minimum electrical resistivity of the soil is 1500 ohm-cm or greater. When backfilled with a clean, granular, well-drained soil, aluminum coated pipe has shown excellent resistance to corrosion, except when exposed to seawater and tidal flow. Aluminum coatings may not perform well in very acid or heavy metal (copper, iron, etc.) environments. An aluminum-zinc coating has been developed that has properties somewhat different than the two individual coatings.

Coatings for concrete culverts - Concrete culverts are rarely coated when they are constructed. However, when they are installed in particularly aggressive chemical environments, they may be coated with epoxy resins or special high density, low porosity concrete materials that have a high resistance to chemicals and chemical attack.

Invert protection - The inverts of corrugated metal culverts are frequently paved to extend the life of the culvert by protecting the invert against corrosion and abrasion. The paving also smooths the inside of the culvert, which improves the hydraulic capacity of such culverts.

a. Bituminous paving - Paving of CMP inverts with bituminous materials has been a common practice for many years. The bituminous coating is usually at least 1/8-inch (3 mm) thick over the inner crest of the corrugations. Generally only the lower quadrant of the pipe interior is paved. Fiber binding is sometimes used to improve the adherence of bituminous material to the metallic-coated pipe. Although bituminous paving has been widely used, it has been found that the coating may deteriorate and spall off after a number of years, particularly in some environments. After the coating starts to deteriorate, corrosion of the culvert will begin.

b. Concrete paving - The invert of culverts may also be paved with plain or reinforced Portland cement concrete. For both new and repair situations this type of paving would normally be applied after the culvert is installed. Although this would normally be done only for corrugated metal pipe culverts, it is occasionally used for precast concrete culverts, to provide additional thickness to resist abrasion and/or corrosion. Metal culvert sections may also be factory produced with a complete concrete lining.

c. Riprap - The inverts of culverts, particularly corrugated metal, may also be covered with riprap for both abrasion resistance and to facilitate fish passage. Use of riprap will have little benefit for corrosion resistance. The size of the riprap that should be used will depend upon the velocity of the water expected to be carried by the culvert, not only during normal flow but also during flood stage. Considerations must also be given to the possibility that use of riprap will worsen potential problems with siltation.

CULVERT INSTALLATION METHODS

There are two major classes of culvert installations, based upon the conditions that influence loads: 1) trenched, where culverts are placed in natural ground or compacted fill with a controlled trench width and 2) embankments, where culverts are usually placed in natural ground but are covered by a constructed embankment. A third method of installation for placing culverts is boring and jacking, used where deep installations are necessary or where conventional open excavation is not practical.

Trenched

Trench installations are made in relatively narrow excavations on a carefully prepared bedding to distribute the load and the culvert is covered with earth backfill that extends to the ground surface. The trench load theory is based on the following assumptions:

- Earth loads on the pipe develop as the backfill settles.
- The resulting earth load on the pipe is equal to the weight of the material above the top of the pipe minus the shearing (frictional) forces on the side of the trench.
- Cohesion is negligible because, with cohesive soils, considerable time must elapse before effective cohesion between the backfill material and the sides of the trench can develop, and with cohesionless soils, would never develop. The assumption of no cohesion yields the maximum probable load on the pipe.
- For a rigid pipe, the side fills may be relatively compressible and the pipe will carry a large portion of the load over the entire width of the trench.
- For rigid pipe, active lateral pressure is neglected, which, in effect, increases the required pipe strength. (However, it should be taken into account if investigations and experience indicate such pressure is significant.

For flexible culverts, a well-compacted soil envelope of adequate width is needed to develop the lateral pressures required to maintain the shape of the culvert. The width is a function of the strength of the surrounding in-situ soil and the size of the pipe.

The backfill load ultimately transmitted to the pipe is a function of the trench width. With rigid culvert placement, the determination of the backfill load is based on the trench width and a pipe strength is selected to withstand that load. If the actual trench width exceeds the width assumed in design, the load on the culvert will be greater than estimated and structural distress may result.

Figure 2.17 illustrates the load carried by a rigid culvert installed in a normal trench installation.

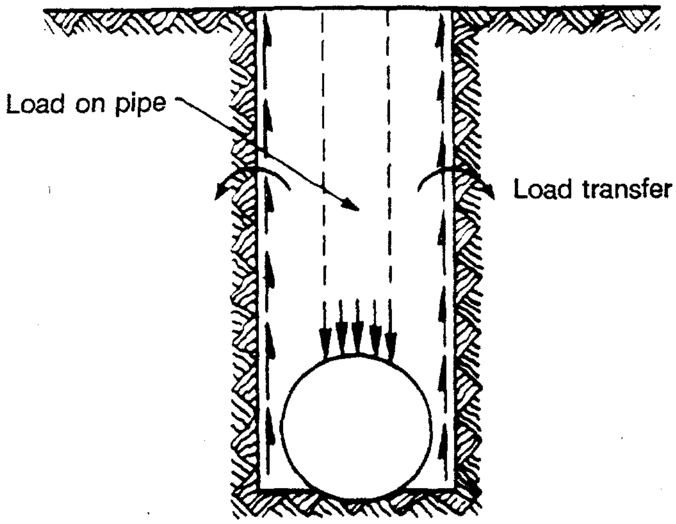


Figure 2.17. Trench installation.[2]

Figure 2.18 illustrates the increased load on the rigid culvert if the width of the trench is increased.

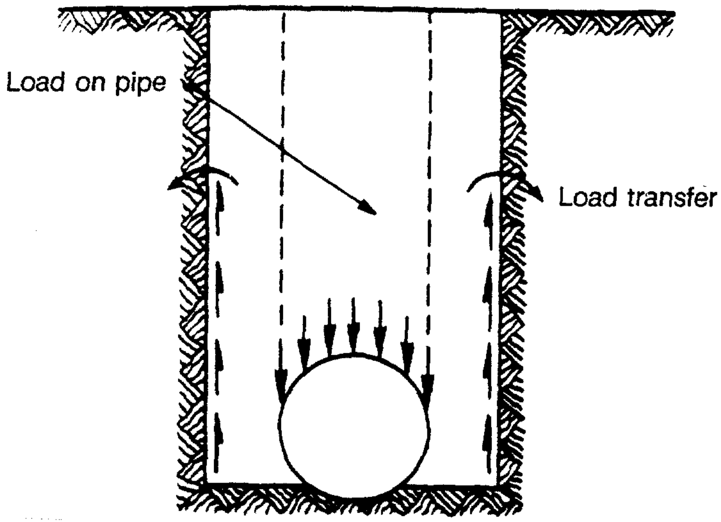


Figure 2.18. Wide trench installation.[4]

If an excessively wide trench is excavated or if the sides are sloped back, the culvert can be installed in a narrow subtrench excavated at the bottom of the wider trench, as shown in figure 2.19, to avoid an increase in the backfill load.

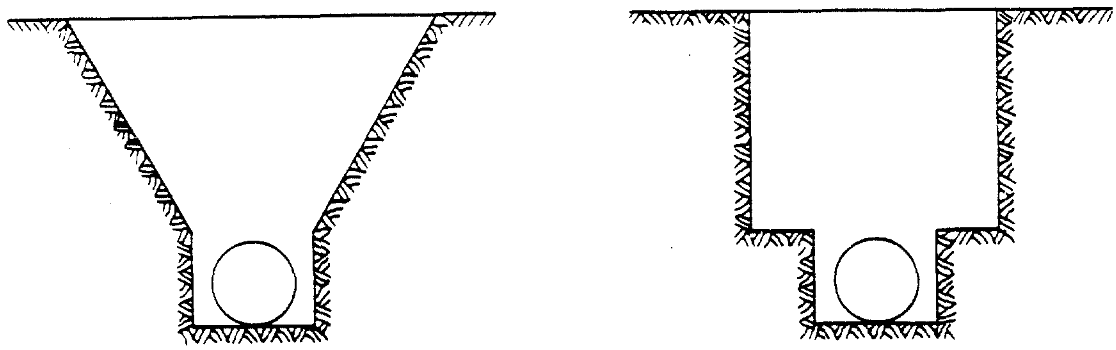


Figure 2.19. Subtrench installation in a wide trench.[2]

Bedding - A stable and uniform foundation is necessary for the satisfactory performance of any culvert. Once a stable and uniform foundation is provided, the bedding should be prepared in accordance with the plans and specifications.

The bedding preparation is critical to both structural performance and service life. An important function of the bedding is to provide uniform support along the barrel of each pipe section. The bed should be placed to uniform grade and line to ensure good vertical alignment and to avoid excessive stresses at joints. The material should be free of rock formations, protruding stones, frozen lumps, roots, and other foreign matter that may cause unequal settlement. When a corrugated metal culvert is being placed, the corrugations should be firmly seated in the foundation material.

Transverse or circumferential cracks in rigid pipe may be caused by poor bedding. Cracks can occur across the bottom of the pipe (broken belly) when the pipe is only supported at the ends of each section. This is generally the result of poor installation practices such as not providing indentions (bell holes) in hard foundation material for the ends of bell and spigot-type pipe or not providing a sufficient depth of suitable bedding material. Cracks may occur across the top of pipe (broken back) when settlement occurs and rocks or other areas of hard foundation material near the midpoint of a pipe section are not adequately covered with suitable bedding material. Transverse cracking is illustrated in figure 2.20.

The bedding distributes the load reaction around the lower periphery of the pipe. The required supporting strength of the pipe is directly related to this load distribution. Pipe set on a flat foundation without bedding results in high load concentration at the bottom of the pipe and is likely to result in shear cracking of the pipe at the five o'clock and seven o'clock locations. Figure 2.21 illustrates how the distribution of the bedding over increasing percentages of the outside diameter can increase the supporting strength of the culvert. Any time a pipe is installed on a flat-bottom foundation, it is essential that the bedding material be uniformly compacted under the haunches of the culvert.

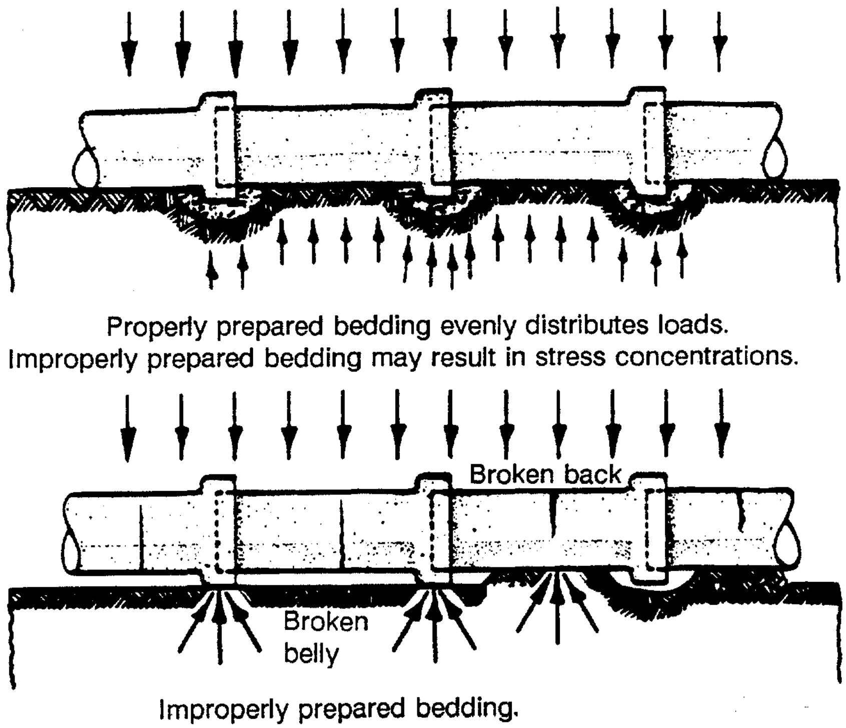


Figure 2.20. Transverse or circumferential cracks.[3]

Backfilling - The backfill is made up of two areas that may require different material and separate compaction criteria. The first area extends from the bedding to approximately 12 inches above the culvert. The second area includes the remaining fill.

The load-carrying capacity of an installed culvert depends largely on the initial backfilling around the culvert. Since proper compaction of backfill material is so important, material and density criteria is often included in the bedding requirements.

For trench installations, where space is limited, tamping by pneumatic or mechanical impact tampers is usually the most effective means of compaction. Impact tampers are most effective for clay soils while granular soils are consolidated best by vibration. Backfill material should be placed in layers approximately six inches deep, deposited alternately on opposite sides of the culvert. Each layer should be compacted carefully, until reaching a height of at least three-fourths of the structure.

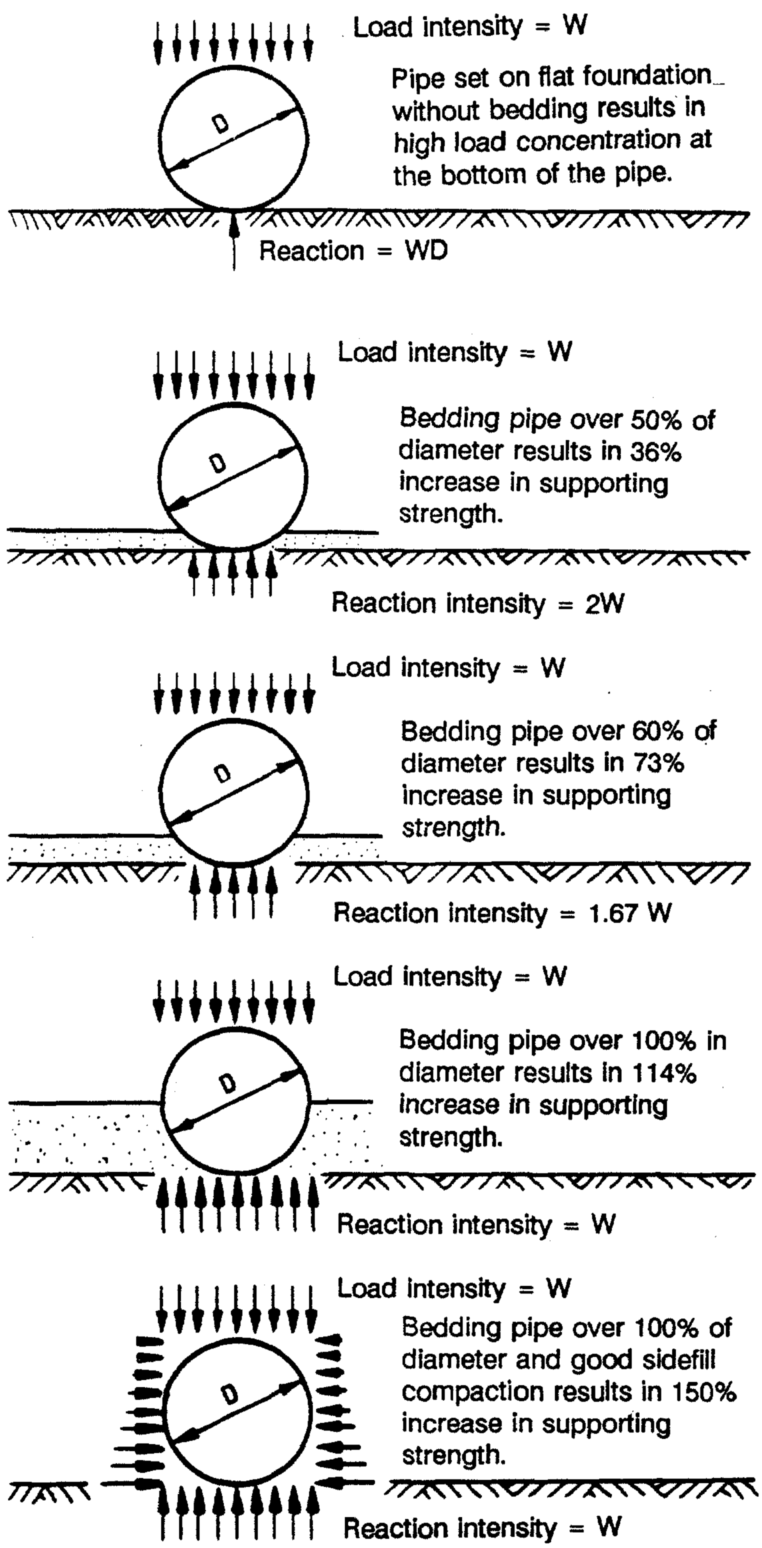


Figure 2.21. Correlation of bedding and supporting strength for rigid pipe.[4]

Embankments

Culverts placed in an embankment are usually bedded in natural ground but are overlaid by a constructed embankment. The required supporting strength of a buried pipe is determined by the total load that is imposed upon the pipe. The magnitude of the load is influenced by the uniformity and stability of the support soil, as well as conditions around and over the pipe. However, the load-carrying capability of rigid culverts is essentially carried by the structural strength of the pipe itself since rigid pipe is stiffer than the surrounding soil. A well-compacted soil envelope is required to develop the lateral pressures necessary to maintain the shape of flexible culverts.

Embankment installations can be divided into three groups: positive projection, negative projection, and induced trench. The essential features of these types of installations are shown in figure 2.22.

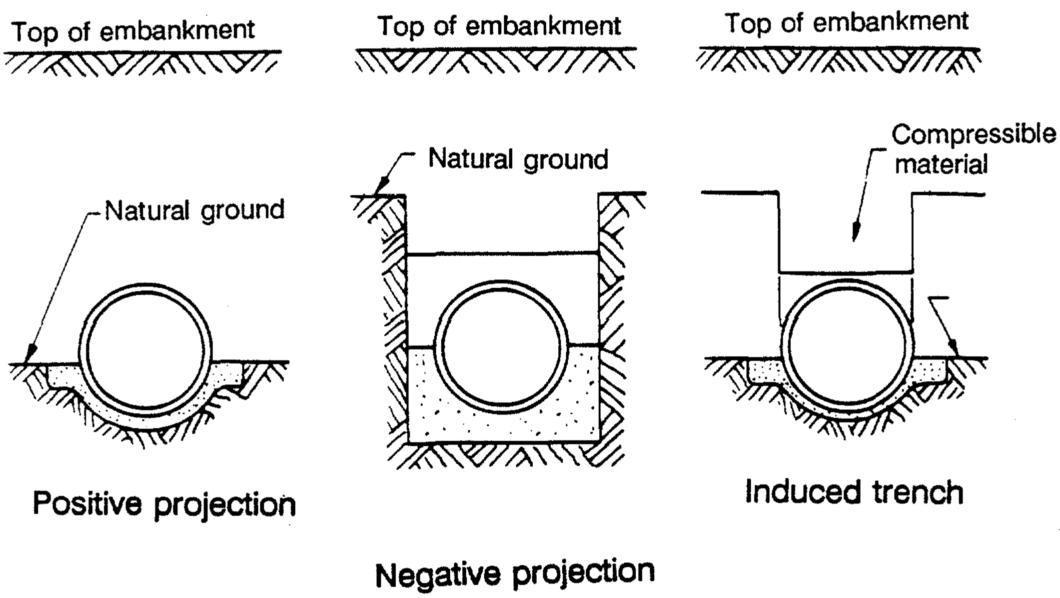


Figure 2.22. Essential features of various types of installation.[4]

Positive projection pipe is installed with the top of the pipe projecting above the surface of the natural ground, or compacted fill, and then covered with earth fill. Negative projection pipe in installed in relatively shallow trenches so that the top of the pipe is below the level of the natural ground or compacted fill. It is then covered with earth fill to the required depth. The induced trench pipe is usually installed as positive projection. However, when the fill has been placed to a depth of at least one pipe diameter over the proposed top of the pipe, a trench is excavated over the pipe and backfilled with a more compressible material.

Bored, Augured or Jacked

The process of tunneling and jacking pipe culverts is used where deep installations are necessary or where conventional open excavation and backfill methods may not be practical.

The usual procedure in jacking pipe is to equip the leading edge with a cutter, or shoe, to protect the pipe. As succeeding lengths of pipe are added between the lead pipe and the jacks, and the pipe is jacked forward, soil is excavated and removed through the pipe. Material is trimmed so that the bore size slightly exceeds the outside diameter of the pipe and excavation does not precede the jacking operation more than is necessary. Such a procedure usually results in minimum disturbance to the natural soils adjacent to the pipe. A typical installation for jacking pipe is shown in figure 2.23.

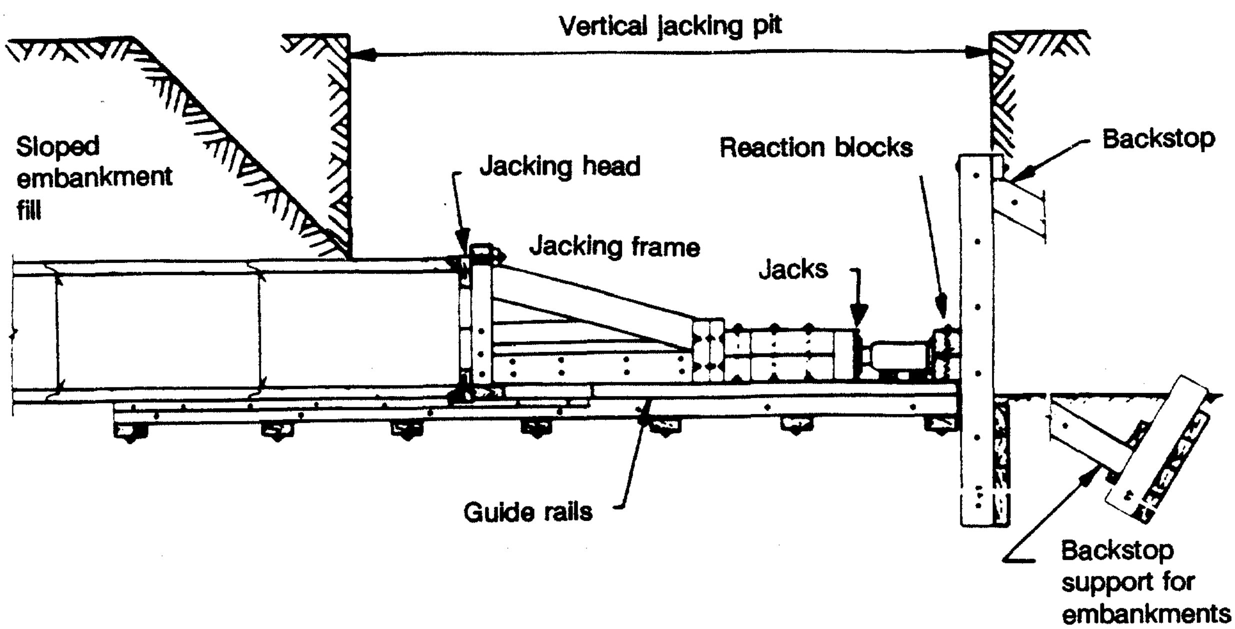


Figure 2.23. Typical jacking installation.[4]

A lubricant, such as a bentonite slurry, is sometimes pumped into the space between the tunnel bore and the outside of the pipe to reduce the frictional resistance. After the jacked piped has reached its final position, grout is frequently pumped into the same space to ensure continuous bearing with the surrounding soil.

Two types of loads are imposed upon concrete pipe installed by the jacking method: the axial load due to the jacking pressures applied during installation; and the earth loading due to the overburden, with some possible influence from live loadings, which generally become effective only after installation is completed.

There are several advantages to jacking pipe:

- Traffic is not interrupted on the overlying roadway.
- Depth of the installation is not a concern.
- Cutting and patching of the pavement can be avoided.
- Minimum disturbance to the natural soils is experienced.
- Loads on the pipe are less than loads in trenched installations.

The disadvantages are:

- Expensive equipment and skilled operators are required.
- There must be adequate room within the right-of-way to construct the jacking pit.

A procedure for jacking concrete pipe is described in appendix B. More detailed information can be found in the *Concrete Pipe Handbook* and *Design Data 13: Jacking Concrete Pipe*, both from the American Concrete Pipe Association.

CULVERT CONSTRUCTION

The performance of culverts and their appurtenances is dependent on practices during installation. Items that require particular attention during design and construction of new culverts and repairs include:

Backfills and Fills

Suitable backfill material and adequate compaction are of critical importance. A well-compacted soil envelope is needed to develop the lateral pressures required to maintain the shape of flexible culverts. Well-compacted backfill is also important to the performance of rigid culverts to prevent such things as settlement of the roadway and movement of water along the barrel. The design must specify material type and degree of compaction. Care should be taken that the backfill material does not contribute to corrosion of the culvert.

Trench Width

Trench width can significantly affect the earth loads on rigid culverts. It is, therefore, important that trench widths be specified on the plans and that the specified width for rigid pipe not be exceeded without authorization from the design engineer.

For flexible culverts a minimum trench width backfilled with premium backfill material is required to provide adequate side support. A narrower width of premium backfill for flexible pipe should not be provided without authorization from the design engineer.

Foundations and Bedding

A foundation capable of providing uniform and stable support is important for both flexible and rigid culverts. Establishing a suitable foundation requires removal and replacement of any hard spots or soft spots. Bedding is needed to level out any irregularities in the foundation and to ensure uniform support. When using flexible culverts, bedding should be shaped to a sufficient width to permit compaction of the remainder of the backfill, and enough loose material should be placed on top of the bedding to fill the corrugations. When using rigid culverts, the bedding should conform to the bedding conditions specified in the plans and should be shaped to allow compaction and to provide clearance for the bell ends on bell and spigot-type rigid pipes. Adequate support is critical in rigid pipe installations, or shear stress may become a problem. The necessary details should be provided by the designer.

Construction Loads

Culverts are generally designed for the loads they must carry after construction is completed. Construction loads may exceed design loads. These heavy loads can cause damage if construction equipment crosses over the culvert installation before adequate fill has been placed or moves too close to the walls, creating unbalanced loadings. Additional protective fill or other measures may be needed for equipment-crossing points.

Camber

In high fills the center of the embankment may settle more than the areas under the embankment side slopes. In such cases it may be necessary to camber the foundation slightly, as shown in figure 2.24. This should be accomplished by using a flat grade on the upstream half of the culvert and a steeper grade on the downstream half of the culvert. The initial grades should not cause water to pond or pocket. The method and dimensions for cambering should be provided by an experienced designer.

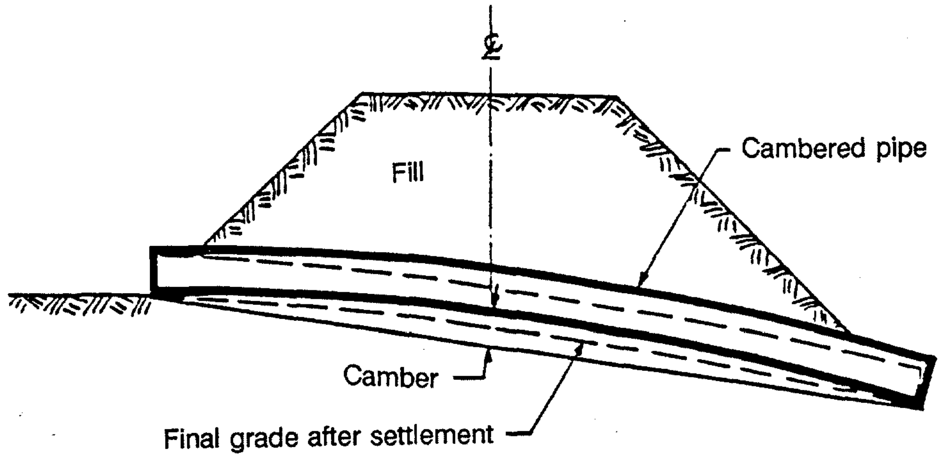


Figure 2.24. Camber allows for settlement of a culvert under a high fill.[6]

Materials

During construction, the materials delivered must be exactly as specified. Inadequate thickness, size, or quality of material can lead to maintenance problems or failure. During installation the materials must be handled properly to prevent defects and loss of intended shape, size, or quality.

CULVERT APPURTENANCES

Culvert appurtenances are those structural and functional portions of the total culvert that improve its flow characteristics and functionality. The following are descriptions of the primary appurtenances that may be added to the barrel of a culvert, regardless of its shape or material.

Endwalls and Wingwalls

Endwalls are built on the ends of the culvert barrels to reinforce the barrel and for protection against erosion of the embankment and scour of the streambed from beneath the end of the culvert barrel. They also act as a counterweight to offset buoyant forces. End walls are normally constructed parallel with the embankments at the ends of the culvert. Although endwalls (headwalls and tailwalls) are usually made of plain or reinforced concrete, they may also be made of timber, stone masonry, corrugated metal, steel sheet piling, gabions, or bagged concrete.

Wingwalls are flared structural walls that extend from the endwalls into the waterway. They function somewhat as the sides of a funnel to channel water into the culvert. The shape and direction of the wingwalls at both the inlet and outlet ends of a culvert are critical to the hydraulic efficiency of the culvert.

Energy Dissipators

Energy dissipators are used to reduce the velocity of water leaving a culvert. This, in turn, reduces the tendency for abrasion and abrasion-related corrosion of metal culverts, scour, and erosion of the streambed and adjacent land. Certain types can also facilitate migration of fish through a culvert.

Energy dissipators should be considered part of a larger design system that includes the culvert, channel protection requirements (both upstream and downstream), and may include a debris-control structure. The general types of energy dissipators include hydraulic jump, forced hydraulic jump, impact, drop structure, stilling well, and riprap. Design information for energy dissipators can be found in Hydraulic Engineering Circular No. 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels.*(7)

Aprons and Scour Protection

Plain or reinforced concrete aprons are frequently constructed at the inlet and outlet ends of culverts for scour protection. Concrete aprons generally extend at least 20 feet into the stream away from the culvert. They may also be sloped downward into the stream bottom with as much as 30 percent of their leading or trailing surfaces being covered by granular streambed material to minimize the potential for scour and undermining of the apron. Another related common practice is to construct a vertical cut-off wall below the entrance and outlet of a culvert for the same purpose. The wall should extend at least two feet into the soil below the culvert and more if the entrance of the culvert is perched above the channel bottom.

Safety Barriers and Grates

Safety is a primary concern in the design and construction of culverts. While structural and hydraulic adequacy is the first consideration, supplementary safety concerns include traffic safety and child safety. The safety of errant vehicles should be provided for by the appropriate location and design of culverts, such as locating culvert ends outside of the safe recovery area or extending culverts through medians if safe distances cannot be maintained. However, for abnormally steep fill slopes or in locations where adequate recovery distance cannot be achieved, the installation of guardrail along the roadside should be considered.

Traversable grates placed over culvert openings can also reduce vehicle impact forces and the likelihood of overturning. If clogging by debris is a problem, fencing around the culvert ends is an alternative solution.

Debris-Control Structures

Water-borne debris usually includes some combination of floating material, suspended sediment, and bedload as described in table 2.3. It can be deposited at the culvert entrance or inside the barrel and can cause the culvert to perform unsatisfactorily or to malfunction. In extreme cases, the result may be failure of the drainage structure or overtopping of the roadway by flood waters, which, in turn, can cause damage to the roadway and adjacent property. Where the waterway opening of a culvert is subject to clogging, a debris-control structure should be an essential part of the hydraulic structure design.

There are several advantages to the use of a debris-control structure. Planned maintenance can be provided on a scheduled basis rather than emergency maintenance required during floods. Washouts or accumulation of drift on the roadway caused by clogged culverts can be prevented. Drift problems can be averted at existing culverts, alleviating damage from buoyant forces. Increasing the size of the culvert to allow passage of the debris is the solution preferred by the Oregon Department of Transportation.

The AASHTO *Model Drainage Manual*[8] states that debris control shall be considered:

- where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris;
- for culverts located in mountainous or steep regions;
- for culverts that are under high fills, and
- where clean-out access is limited. However, access must be available to clean out the debris control device.

Table 2.3. Classification system for debris types.[9]

1.	Very Light Floating Debris or No Debris.
2.	Light Floating Debris - Small limbs or sticks, orchard prunings, tules, and refuse.
3.	Medium Floating Debris - Limbs or large sticks.
4.	Heavy Floating Debris - Logs or trees.
5.	Flowing Debris - Heterogeneous fluid mass of clay, silt, sand, gravel, rock, refuse, or sticks.
6.	Fine Detritus - Fairly uniform bedload of silt, sand, or gravel more or less devoid of floating debris, tending to deposit upon diminution of velocity.
7.	Coarse Detritus - Coarse gravel or rock fragments.
8.	Boulders - Large boulders and large rock fragments carried as a bedload at flood stage.

Three methods can be used to control debris: interception of the debris at or above the culvert inlet, deflection of the debris away from the entrance for detention near the inlet, or passage of the debris through the structure. Common types of debris-control structures are described in table 2.4.

Proper design of a debris-control structure should begin with a preliminary field study. Maintenance personnel should be interviewed to establish the history of debris accumulation. Information gathered should include an estimate of the quantity and the type of debris, future land-use changes that would influence the type and quantity, and an estimation of stream flow velocities in the vicinity of the culvert. An adequate debris storage area should be located with proper access for periodic removal of debris.

Table 2.4. Types of debris control structures.[9]

1. Debris Deflectors - Structures placed at the culvert inlet to deflect the major portion of the debris away from the culvert entrance. They are normally "V"-shaped in plan with the apex upstream.

2. Debris Racks - Structures placed across the stream channel to collect the debris before it reaches the culvert entrance. Debris racks are usually vertical and at right angles to the stream flow, but they may be skewed with the flow or inclined with the vertical.

3. Debris Risers - A closed-type structure placed directly over the culvert inlet to cause deposition of flowing debris and fine detritus before it reaches the culvert inlet. Risers are usually built of metal pipe. Risers are also used as relief devices in the event the entrance becomes plugged with debris.

4. Debris Cribs - Open crib-type structures placed vertically over the culvert inlet in log-cabin fashion to prevent inflow of coarse bedload and light floating debris.

5. Debris Fins - Walls built in the stream channel upstream of the culvert. Their purpose is to align debris, such as logs, with the axis of the culvert so that the debris will pass through the culvert barrel without clogging the inlet. They are sometimes used on bridge piers to deflect drift.

6. Debris Dams and Basins - Structures placed across well-defined channels to form basins that impede the stream flow and provide storage space for deposits of detritus and debris.

7. Floating Drift Boom - Logs or timbers that float on the water surface to collect floating drift. Drift booms require guides or stays to hold them in place laterally. They are limited in use.

8. Combination Devices - A combination of two or more of the preceding debris-control structures at one site to handle more than one type of debris and to provide additional insurance against a clogged culvert inlet.

Table 2.5 is a guide for selecting the type of structure suitable for the various debris classifications. Design information for commonly used debris-control structures can be found in Hydraulic Engineering Circular No. 9, *Debris Control Structures*.[10]

Table 2.5. Guide for selecting type of control structures suitable for various debris classification.[10]

Debris Classification	Type of Structure						
	Deflector	Rack	Riser	Crib	Fin	Dam and Basin	Boom
Light Floating Debris		X		X			X
Medium Floating Debris	X	X					X
Heavy Floating Debris	X				X		
Flowing Debris			X			X	
Fine Detritus			X			X	
Coarse Detritus			X	X		X	
Boulders	X						

Junctions

A junction combines flow from two or more separate culverts or storm sewers into a single culvert barrel. A tributary and a main stream that intersect at a roadway crossing can be combined or joined at a culvert junction. A culvert barrel receiving a drainage pipe collecting runoff from the overlying roadway is an example of a storm sewer/culvert junction.

When analyzing flow conditions, attention should be paid to the timing of the arrival of the peak flow at each entrance. Loss of head may also be important in the hydraulic design of a culvert utilizing a junction. The junction should be configured to minimize turbulence and loss of head.

Erosion protection of culvert foundations and anchorage may be necessary in culverts with natural bottoms. Proper alignment, selective invert paving, and strategically placed energy dissipators within the culvert can alleviate problems with erosion.

Fish Passage

Where fish passage has been provided, it should be maintained as part of the culvert unless it has deteriorated or become non-functional. Changes in these structures will require coordination with the regulatory agency that dictated that fish passage be designed.

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