4.2 Structural Design of Culverts

4.2.1 Introduction

Structural design of a culvert must be performed 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.

4.2.2 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 height of the embankment above the culvert, 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.

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. 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. Actual loads for specific cases are assigned by the designer. The effect of live loads decreases as the height of cover over the culvert increases. For single-span culverts, the effects of live load may be neglected where the depth of fill is more than 2400mm (8 ft) and exceeds the span length; for multiple span culverts, the effects may be neglected where the depth of fill exceeds the distance, between faces of endwalls. Loading determinations should follow the procedures set forth in AASHTO LRFD Bridge Design specifications section 12.6 with an earth load of 2000 kg/m^3 (125 pounds per cubic foot) if the actual weight of earth is not known.

4.2.3 Flexible Culvert Behavior

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 4-4.

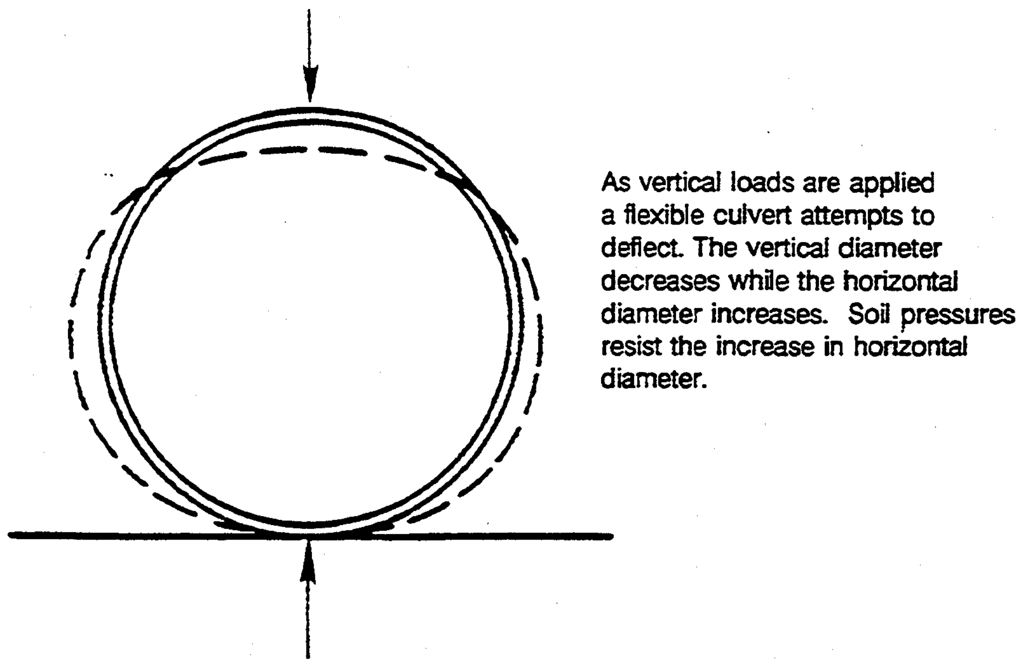

Figure 4-4 Deflection of flexible culverts.

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 4-5, the compressive thrust is approximately equal to vertical pressure times one-half the span length (C = P X S/2 or C = P X 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 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.

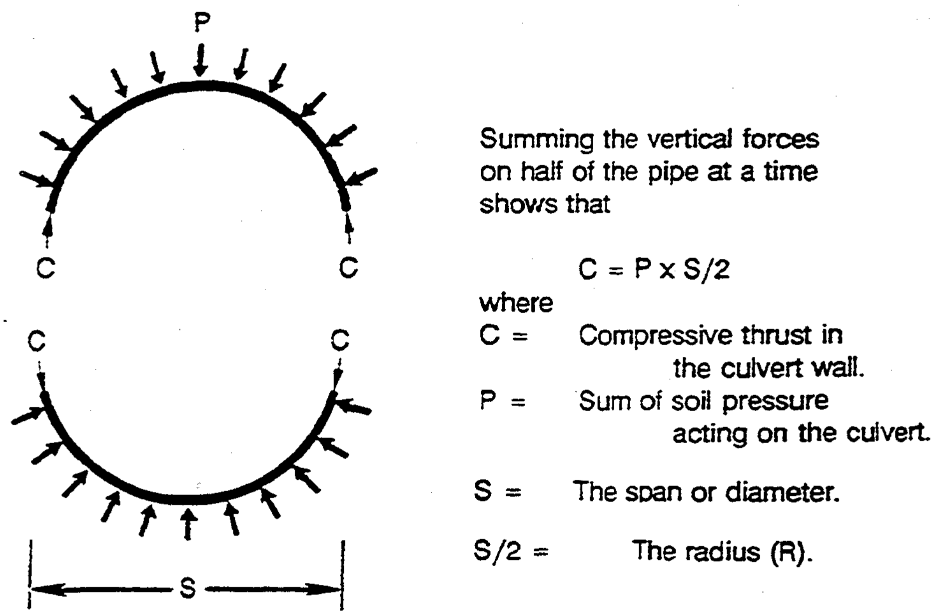

Figure 4-5 Formula for ring compression

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 are reinforced concrete, as shown in Figure 4-6. The thrust beams are added to the structure when backfill reaches their location. 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.

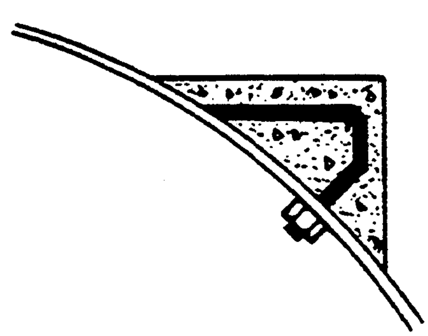

Figure 4-6 Concrete thrust beam used as a longitudinal stiffener

4.2.4 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 4-7. 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.

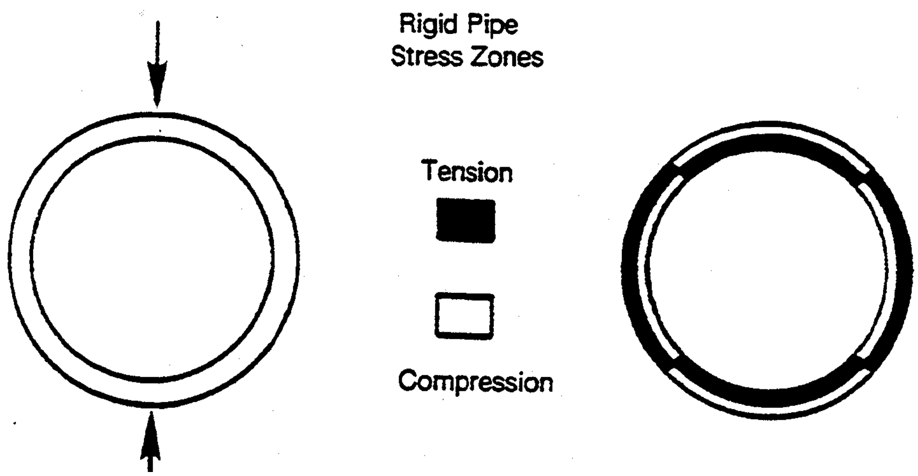

Figure 4-7 Zones of tension and compression in rigid pipes

The weight of each 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 4-8.

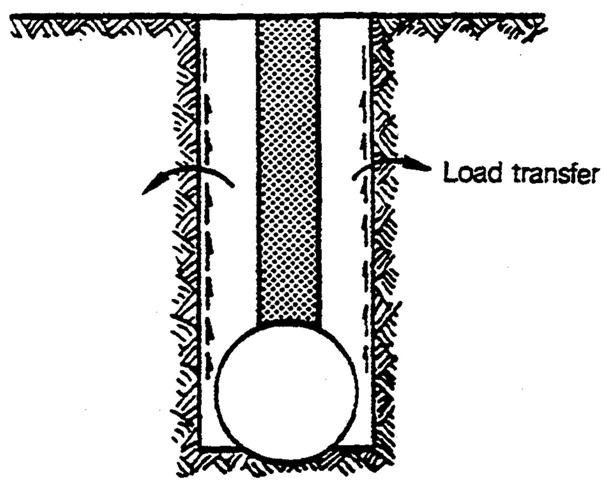

Figure 4-8 Trench installation. Friction on trench sides reduces the size of the column of fill carried by the pipe.

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.

4.2.5 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:

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 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.

Along with pH, water resistivity (R) is an effective way to measure how aggressive the water's chemistry may be. Resistivity of low flow samples can accurately predict the potential corrosivity of drainage runoff. Resistivity above 1500 ohm-cm are considered normal. Resistivity between 500-1500 ohm-cm are considered below normal. Resistivity below 500 ohm-cm should be considered aggressive.

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 4-9. The chemicals present in the water greatly influence its effectiveness as an electrolyte.

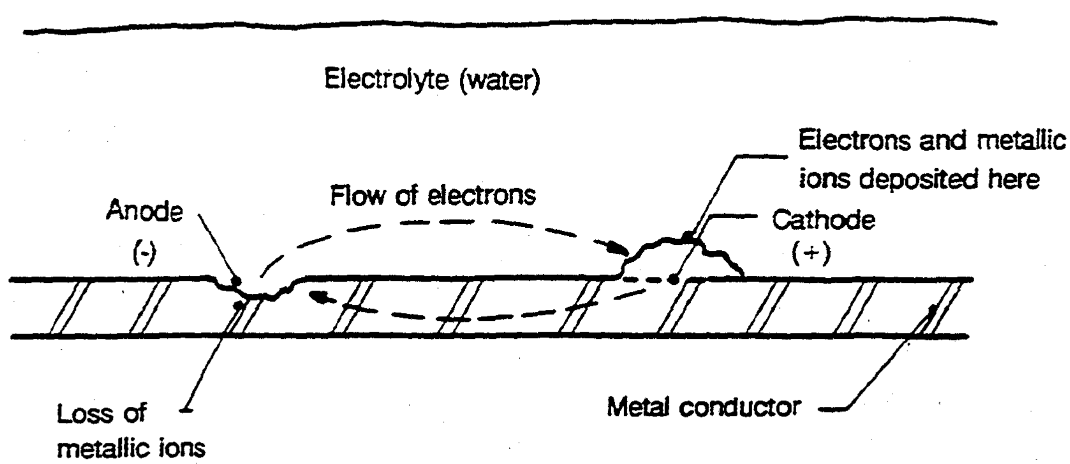

Figure 4-9 The corrosion process

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.

Abrasion

Abrasion is the process of wearing down or grinding away the surface material of culverts as water laden with sand, gravel, or stones flow through a culvert. 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.

4.2.6 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 not the one with the lowest initial cost nor the culvert with the longest service life. The importance is that short and long term costs should be considered in both original designs and in repairs or replacements.

4.2.7 Maintenance

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.

4.2.8 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 identify low flow periods for construction for certain types of structures. Inspection, maintenance, and repair personnel should be aware of the possibilities of poor air quality, toxic and chemical contaminants, animals, and the potential for collapse of unstable structures.

4.2.9 Geotechnical

During design, particularly for larger culverts, 0.9m (3 ft) span or greater, 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.