Implementation of Structural Design of Concrete Box Culverts using the Elastic Analysis

By

Aliya Osman Mohammed Ahmed, B.Sc.

A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Science in Structural Engineering

Civil Engineering Department
University of Khartoum
December 2006
Dedication

To my parents....


Acknowledgement

First of all I am very grateful to God that made it possible the accomplishment of this work. Also for this opportunity I would like to express my deep gratitude and appreciation to my supervisor, Dr. ElHussein Elarabi, Building and Road Research Institute, U of K, for his close supervision, supply of references and constructive guidance.

I would like to expand my thanks and Gratitude to the staff of Building and Road Research Institute (B.R.R.I), U of K for their invaluable help. Also appreciation and thanks to the staff of Civil Engineering Department, U of K for help and advices.

Deep thanks are also to the staff of Civil Engineering Department, Sudan University of Science and Technology for their moral support and assistance.

Words of thanks also extend to my parents, my family, friends and colleagues, for their continuous encouragement.
Abstract

Box culverts are types of bridges used when the discharge in a natural stream crossing a road is small, and where the waterway is on relatively high embankment. They are generally cheaper than bridges, which make them the best solution when the natural streams intersect roadways.

This research work discusses the development of structural design of concrete box culverts, and gives advice on the structural design of buried concrete box structures. The standard requirements in the Design Manual for Roads and Bridges (DMRB, BD31/01) were used in the formulation of the structural design of concrete box culverts. A culvert software has been developed to solve different types of concrete box culverts. This program has been applied to many practical problems. The results obtained by the culvert software were compared with manual solutions of the problems, commercially available software solutions (PROKON) and solved problems. A very good agreement has been achieved.

Based on the results, this program should offer the design engineer a significant saving of both time and effort, without sacrificing accuracy or effectiveness. In addition the research presents requirements for construction, installation and procurement of such structures.
ملخص البحث

العبارات الخرسانية الصندوقية نوع من أنواع الكباري التي تستخدم عندما تكون كمية التصريف المار خلال المجري المائي صغير بحيث الممر المائي على رimensية عالية نسبًا. العبارات في كثير من الأحيان أقل تكلفة من الجسور، مما يجعل الحل الأفضل عند تقاطع المجاري الطبيعية مع الطرق.

يناقش هذا البحث تطوير التصميم الإنشائي للعبارات الخرسانية الصندوقية ويرشد للتصميم الإنشائي للعبارات. استعملت المتطلبات الفيزيائية في دليل التصميم للطرق والجسور (DMRB, BD31/01) في صياغة التصميم الإنشائي للعبارات الخرسانية الصندوقية. تمت كتابة حاسوب العبارات لحل أنواع مختلفة من العبارات. تطبق هذا البرنامج في حل العديد من المسائل العملية. النتائج التي تم الحصول عليها باستخدام حاسوب العبرة قورنت بالحلول اليدوية وبرنامج الحاسوب المتاح تجارياً (بروكن) ومسائل محلولة ووجد أنها معقولة.

إستناداً على هذه النتائج هذا البرنامج يوفر لمهندسي التصميم الكباري من الوقت والجهد دون فقدان الدقة أو الفعالية. كذلك تمت مناقشة متطلبات تشيد وتزيز واتباع هذا النوع من الإنشاءات كما تم توضيح التوصيات لدراسات اللاحقة في هذا البحث.
Chapter One

Introduction

1.1 General Introduction

Box culverts are types of bridges used when the discharge in a drain or channel crossing a road is small, and when the bearing capacity of the soil is low. Culverts are always cheaper than bridges where the discharge opening is less than 15m² and particularly where the road crosses the waterway on relatively high embankment. Box culverts are constructed of reinforced concrete and are either cast-in-place or precast. Most of them are square dimensions; but if not a square, usually have the span length exceeding the opening height. Box culverts may have multiple or single cell openings. They control water flow and drainage for irrigation and municipal services, control storm water, and perform many other services. All the reasons above represent a good motivation to researchers in culvert design method and construction technique.

Sudan, like many other developing countries depends in design on standard design of advanced countries. For concrete box culverts, there are standard drawings which may not appropriate for climatically and soil conditions in Sudan. Since a design process is to make the best solution from the limited resources and under the circumstantial adverse condition, a structural design of concrete box culverts was developed so that to be suitable for Sudan soil conditions. A computer program for analysis and design of single, twin and multiple concrete box culverts was developed in this research work based on the previous researchers work in area of box culvert

Standard drawings for different types of concrete box culverts in Sudan can be deduced by using this program.
### 1.2 Historical Background

Historical records include many references to engineering feats undertaken by ancient civilizations to collect and convey water. Archeological explorations indicate that an understanding of drainage principles existed very early in history. For example, a sewer arch constructed about 3750 B.C. was unearthed in an excavation at Nippur, India. Another excavation in Tell Asmar, near Baghdad, exposed a sewer constructed in 2600 B.C.

Most renowned of these early construction efforts were the aqueducts of Rome. The water carried by these aqueducts was used primarily for drinking. The aqueducts were also used to carry sewage through Rome’s main sewer, the Cloaca Maxima. Built in 800 B.C., and constructed mainly of stone masonry and natural cement, the Cloaca Maxima was the first known man-made waterborne method of sewage disposal. After 2800 years, sections of this concrete sewer are still being utilized (11).

During the first 5000 years of recorded history, the need for sewers, water supply, and drainage was recognized and practical methods of handling the flow of water were developed. From the remains of the ancient structures, it is apparent that the building materials progressed from relatively simple applications of natural materials to cast concrete. In many applications, permanency was a major requirement and concrete was one of the earliest substitutes for natural stone. While not all stone and concrete structures were able to survive the ravages of time, weather and warfare, concrete has an ancient and noble heritage (11).

Public health requirements for water and sewage treatment set the beginnings of the concrete pipe industry in the late 19th and early 20th centuries. Plants were established to manufacture pipe for sewers, transportation facilities, irrigation and drainage of agricultural land, and urban storm water drainage. In 1900 Steel reinforcement in pipe wall represents the single most important advance in concrete pipe technology. In 1960 Changes to the joint geometry lead to the use of a variety of rubber gaskets for bottle tight joints that significantly reduce
leakage and infiltration. 1970 Shorter plant-manufactured junctions used for service connections to facilitate hook-up. 1980 New specifications for precast concrete box culverts and sewers provide pre-approved drainage systems for environmentally sensitive areas, roadways, and mature neighbourhoods. 1990-2000 On the leading edge of software development for engineers and purchasers of drainage systems the advance life cycle coating analysis, trench material estimating and load analysis software is continued (11).

1.3 Objectives of the research

Sudan is a big country with a large area and a lot of natural resources. Recently a great development in construction and building occurred all over the country. This development extended to include design and construction of culverts, and box culverts. More attention and effort for design and construction of box culverts should be made for establishing the basis for preparing standard drawings for concrete box culvert, which will be part of design manual for road and bridges. According to the above, this research is carried to cover the following objectives:

a. Develop and apply a formulation of the structural design for all types of concrete box culverts: single cell, twin cell and multiples.

b. Develop a computer program using FORTRAN language to analyze and design these concrete box culverts.

1.4 Scope and Outlines of Thesis

Chapter one introduces the problem and states the objectives of the study. Chapter two presents general information and literature concerning culverts such as types, shapes, materials, inlets, culvert installation, culvert location, culvert hydraulics and structural design of culverts. Chapter three reviews the structural design of concrete box culvert, discussing load types, loading and
load combination. Also discussing design procedure for structural element, load cases to be considered, special requirements at the serviceability limit state and reinforcement detailing. Chapter four is concerned with the formulation of structural design of culvert and description of the developed FORTRAN program for box culvert so as to meet the objectives mentioned above. Chapter five contains different examples for analysis and design of box culvert by using the culvert software, manual solution and the commercially available software (PROKON). Then the results and discussion for all examples are presented in this chapter. Chapter six states the conclusions of the study and the recommendations for further research work.
Chapter Two

Culverts

2.1 Introduction

The term “culvert” encompasses practically all closed conduits used for drainage with the exception of drains. Culverts must be classed as stock products, in that standard designs are used repeatedly. This is in direct contrast to the situation for bridges that span larger streams, for which special designs are made in almost every case. There are many similarities between bridges and culvert and they perform similar tasks. Culverts, however, usually differentiated from a bridge by virtue of the fact that the top of the culvert does not form a part of the traveled roadway. More frequently culverts are differentiated from bridges on the basis of the span length. On an arbitrary basis, structures having span of 6.1m(20ft) or less will be called culverts; while those having spans more than 6.1m(20ft) will be called bridges. This line of division is by no means standard, and span lengths of from 2.4 to 6.1m(8 to 20 ft) are employed by various organizations as limiting culvert lengths. Culverts also differ from bridges in that they are usually designed to flow full under certain conditions, while bridges are designed to pass floating debris or vessels. However where the waterway opening is less than about 15 m² and particularly where the road crosses the waterway on relative high embankment, a culvert will usually be cheaper than a bridge.

Culverts are to be found in three general locations: at the bottom of depressions where no natural watercourse exists; where natural streams intersect the roadway; and at locations required for passing surface drainage carried in side ditches beneath roads and driveways to adjacent property.
2.2 Basic Characteristics

The structural and hydraulic design of culverts is substantially different from that of bridges, as are the construction, maintenance, repair, and replacement procedures (4). A few of the more significant characteristics of water-carrying culverts are:

- Hydraulic – Culverts are usually designed to operate at peak flows with a submerged inlet to improve hydraulic efficiency. The culvert constricts the flow of the stream and may cause ponding at the upstream or inlet end. The resulting rise in elevation of the water surface produces a head at the inlet that increases the hydraulic capacity of the culvert. The effects of ponding and flow on appurtenant structures, embankments, and abutting properties are important considerations in the design of culverts (4).

- Structural – Culverts are buried in soil and are designed to support the dead load of soil over the culvert as well as live loads of traffic. Either the live load or the dead load may be the most significant load element, depending on the type of culvert, type and thickness of cover, and amount of live load. However, live loads on culverts are generally not as significant as the dead load unless the cover is shallow. Box culverts with shallow cover are examples of the type of installation where live loads are important (4).

In most culvert designs, the soil or embankment material surrounding the culvert plays an important structural role. Lateral soil pressures enhance the culvert’s ability to support vertical loads. The stability of the surrounding soil is important to the structural performance of most culverts (4).

- Maintenance – Because culverts usually constrict flow, there is an increased potential for waterway blockage by debris and sediment, especially for culverts subject to seasonal flow. Multiple barrel culverts are particularly susceptible to debris accumulation. Scour caused by high outlet velocity or turbulence at the inlet end is of concern. As a result of these factors, routine maintenance for culverts primarily involves
the removal of obstructions and the repair of erosion and scour. Other defects from weathering, loads, and age will occur and require routine maintenance \(^{(4)}\).

- **Traffic Safety** – A significant safety feature of many culverts, as compared to bridges, is the elimination of a constriction in the roadway. Culverts can economically be extended so that the standard roadway cross section can be carried over the culvert. However, when the ends are located near traffic lanes or adjacent to a shoulder, guide rail may be required to protect the traffic \(^{(4)}\).

- **Construction** – One of the most significant factors is that culverts are constructed in and through the roadway embankment, and vehicle loads are carried by the combined strengths of the culvert and the surrounding embankment. The trench width, bedding, compaction, and amount of fill over the culvert are important factors that influence the ability of the culvert to carry the design loads. Thus, the construction techniques and quality control of workmanship are critical to the ultimate serviceability and life expectancy of culverts \(^{(4)}\).

- **Durability** – Durability of materials is a significant problem in culverts and other drainage structures. In hostile environments, corrosion and abrasion can cause deterioration of all commonly available culvert materials. Many types of serviceability problems may occur because of scour of streambeds and erosion of embankments adjacent to the culverts \(^{(4)}\).

### 2.3 General Problems with Culverts

There is a wide variety of types of problems that occur with culverts. The problems may be classified by serviceability and strength-related criteria \(^{(4)}\). Listed below are general types of culvert problems \(^{(4)}\):

**Serviceability-related problems:**

- Scour and erosion of streambed and embankments
- Inadequate flow capacity
- Corrosion and abrasion of metal culverts
- Abrasion and deterioration of concrete and masonry culverts
• Sedimentation and blockage by debris
• Separation and/or drop off of sections of modular culverts
• Inadequate length

  Strength-related problems:
• Cracking of rigid culverts
• Undermining and loss of structural support
• Loss of the invert of culverts due to corrosion or abrasion
• Over-deflection and shape deformation of flexible culverts
• Stress cracking of plastic culverts

2.4 Culvert Types

Although there is a very wide range of style and designs of culverts in service, all culverts may be classified into two basic types: rigid (concrete) and flexible (steel). This classification is based on the primary difference in the manner in which structural loads are carried by the culvert and the interrelationship between the culvert structure and the surrounding soil. Rigid culverts are designed to resist bending moment; flexible are not \(^{(4)}\).

Culverts are also often described by their shape, which may be circular, arch, elliptical, or box. The box shape may be made more torsionally rigid by adding internal web walls between the top and bottom surfaces. Culverts may also be made with multiple barrels for additional flow capacity. Most modern culverts are made from either corrugated metal, plastic, or reinforced concrete. Concrete culverts may be of either precast or cast-in place construction, which may be post-tensioned in the field. These materials may be used to construct most of the mentioned structural shapes \(^{(4)}\). The more common culvert types and materials of which they are made shown in Fig (2-1) \(^{(12)}\).
2.5 **Culvert Shapes**

2.5.1 **General**

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 is discussed in the following paragraphs (4).

2.5.2 **Circular Pipes**

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 structure dictates that special care be taken during backfill construction to maintain uniform curvature. However for smaller openings, pipe in stock sizes is generally chosen (4).

2.5.3 **Pipe Arch and Elliptical Shapes**

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\(^{(4)}\).

### 2.5.4 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. The structure should also meet scour design requirements\(^{(4)}\).

### 2.5.5 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\(^{(4)}\).

### 2.5.6 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\(^{(4)}\).
<table>
<thead>
<tr>
<th>Culvert Type</th>
<th>Typical Cross Sections</th>
<th>Common Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe, single or multiple Circular</td>
<td></td>
<td>Corrugated metal, plain or reinforced concrete, vitrified clay, cast iron, asbestos cement</td>
</tr>
<tr>
<td>Elliptical, long axis vertical or horizontal</td>
<td></td>
<td>Corrugated metal, reinforced concrete</td>
</tr>
<tr>
<td>Pipe arch, single or multiple span</td>
<td></td>
<td>Corrugated metal, precast reinforced concrete</td>
</tr>
<tr>
<td>Box culvert, single or multiple span</td>
<td></td>
<td>Reinforced concrete</td>
</tr>
<tr>
<td>Bridge culvert, single or multiple span</td>
<td></td>
<td>Reinforced concrete</td>
</tr>
<tr>
<td>Arch</td>
<td></td>
<td>Reinforced concrete or stone masonry arch on reinforced concrete foundation</td>
</tr>
</tbody>
</table>

Figure 2.1 Common culvert types and materials Metals include galvanized iron and steel and aluminum alloy.
2.6 Culvert Materials

2.6.1 General

Culverts are primarily made with reinforced concrete, corrugated metal, and more recently, solid wall, profile wall, and reinforced plastic. The strength and physical characteristics of the materials depend upon their chemistry and the interrelationship between the constituent materials. Metals and plastic are homogeneous isotropic materials whereas concrete and masonry is a mixture or combination of materials \(^{(4)}\).

The method by which the materials are connected significantly influences whether the strength of the materials may be utilized structurally \(^{(4)}\).

2.6.2 Concrete

Culverts may be made with either precast or cast-in-place reinforced concrete. This selection depends on 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 \(^{(4)}\).

- **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. With the exception of box culverts, concrete culvert pipe is manufactured in up to five standard strength classifications. The higher the classification numbers 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 3600 mm (144 inches) in diameter, with larger sizes available as special designs. Standard box
sections are also available with spans as large as 3600 mm (144 inches). Precast concrete arches on cast-in-place footings are available with spans up to 12.2 m (40 feet) \(^4\).

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 (Figure 2-2) \(^5\). 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 may be more practical. 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 \(^4\).

### 2.6.3 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 \(^4\).

- **Material** – Corrugated steel pipe is fabricated from sheets coated with zinc or aluminum. 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 paving 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 \(^4\).

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 3600 mm (144 inches) in diameter. Standard sizes for pipe arch are available in sizes up to the equivalent of 3000 mm (120 inch) diameter round pipe(Figure 2-3) \(^5\). Both shapes are produced in several wall thicknesses, several corrugation sizes, and with annul (circumferential) or helical (spiral) corrugations \(^4\).

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 coated with zinc (galvanized) or aluminum. Additional protective coatings are used with the metallic coating when there are potential corrosion or abrasion problems \(^4\).

Structural plate – Structural plate steel pipes are field assembled from standard corrugated galvanized steel plates. Standard plates have corrugations with a 150mm (6-inch) pitch and a depth of 50 mm (2 inches). Plates are manufactured in a variety of thicknesses and are pre-curved for the size and shape of the structure to be erected. Standard plates have a nominal length of either 3 m or 3.7m (10 or 12 feet) and are produced in standard widths of 3N, 5N, 6N, 7N, and 8N, where N equals 3 pi = 244 mm (9.6 inches). Widths are measured along the circumference of the structure \(^4\).

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 of 60 pi or 20N and would normally be assembled from four 5N plates. Structural plate pipes are available in six basic shapes: round, pipe arch, arch, vertical ellipse, horizontal ellipse, and underpass. The standard sizes available range in span from 1.5 m 6 to 7.9m (5 feet to 26 feet) \(^4\).
Box – Steel box sections use standard 150 by 50 mm (6 by 2 inch) corrugated galvanized steel plates with special reinforcing elements applied to the areas of maximum moment or 375 by 140 mm (15 by 5 1/2 inches) corrugated plate without ribs. Steel box culverts are available with spans that range from 3m (9 feet 8 inches) to 6.3m (20 feet 9 inches) \(^{(4)}\).

Long span – Long span steel structures are assembled using conventional 150 by 50 mm (6 by 2 inch) corrugated galvanized steel plates with longitudinal or circumferential stiffening members or 375 by 140 mm (15 by 5 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 5.9m (19 feet 4 inches) to 12.2 m (40 feet). Longer spans are available for some shapes as special designs \(^{(4)}\).
Figure 2.2 -- Precast Concrete Box Culvert  
(American Concrete Pipe Association)

Figure 2.3 – Corrugated Metal Arch
2.6.4 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.  

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 3000 mm (120 inches) in nominal diameter. Aluminum arch pipe is available in sizes up to the equivalent of a 2400 mm (96-inch) diameter round pipe.  

Structural plate - Structural plate aluminum pipes are field assembled with 228 mm (9-inch) - pitch by 64 mm (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 SN through 18N, where N equals 3 pi or 244 mm (9.625 inches). Plate length is measured along the circumference of the structure. Standard plates have a net width of 1.4 m (4.5 ft.). 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 is available for each shape. Spans as large as 7.9 m (26 feet) can be obtained for the arch shape (4).

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 2.7 m (8 feet 9 inches) to 7.7m (25 feet 5 inches) (4).

Long Span - Long span aluminum structures are assembled using conventional 225 by 64 mm (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 5.9 m (19 feet 4 inches) to 12.2 m (40 feet) (4).

2.6.5 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 \(^4\).

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 \(^4\).

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 \(^4\).

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 \(^4\).

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 filament strength of over 2067 n/mm\(^2\) (300,000 psi), pipe products that are made with long continuous glass fibers will have greater strength properties over unreinforced plastic pipe \(^4\).

- Polyvinyl Chloride (PVC) - Polyvinyl Chloride 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 PVC 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 1200 mm (48 inches) \(^4\).

- Polyethylene (PE) - Polyethylene 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 butylenes. 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 2400 mm (96 inches). It is often used to slip line deteriorating pipes \(^4\).

### 2.6.6 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 \(^4\).

- 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 1000-2100 degrees Fahrenheit at which “vitrification” occurs and the clay particles become fused into an inert chemically stable compound \(^4\).
Vitrified clay pipe is resistant to internal and external attack from acids, alkalis, gases, and solvents. It is resistant to abrasion and scour and will not corrode.

- 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.

2.6.7 Coatings for Culvert Materials

A variety of types of coatings may be used 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
- Environmental effects including freezing and thawing

- Coatings for metal culverts - Corrugated steel culverts are protected with metallic coatings of zinc (galvanized) or aluminum. 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.

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. Inert 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 \(^4\).

**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 \(^4\).

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

**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 \(^4\).

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.

**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. Aluminum coating Type 2 - 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 (4).

Aluminum coatings may not perform well in very acid or heavy metal (copper, iron, etc.) environments. If the pH is between 6.0 and 8.0, aluminum coated Type 2 is acceptable with resistivity of 100 ohm-cm or greater.

Type 1 aluminum coatings are inappropriate for drainage applications (4).

• **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 (4).

• **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 smoothes the inside of the culvert, which improves the hydraulic capacity of such culverts. Bituminous paving - Paving of CMP inverts with bituminous materials has been a common practice for many years. The bituminous coating is usually at least 3 mm (1/8-inch) 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. 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 (4).

2.7 Culvert Inlets

A multitude of different inlet configurations are utilized on culvert barrels. These include prefabricated and constructed – in-place installations. Commonly used inlet configurations include projecting culvert barrels, cast in-place concrete headwalls, precast or prefabricated end section, and culvert ends mitered to conform to the fill slope (Fig 2-4) (5). Structural stability, aesthetics, erosion control, and fill retention are considerations in the selection of various inlet configurations (5).
2.8 Selection of Culvert Type

The type of culvert selected for use in a given location is dependent upon the hydraulic requirements and the strength required to sustain the weight of a fill or moving wheel loads. After these items have been established, the selection is then largely a matter of economics \(^{(16)}\). Consideration must be given to durability and to the cost of the completed structure, including such items as first cost of manufactured units and costs of transportation and installation. Maintenance costs should also be considered in any over-all comparison of the cost of different culvert types \(^{(18)}\). In brief, a thorough analysis should be made of the ultimate cost of all the different types of culverts that might be selected for use in a given installation. Other things being equal, the culvert selected should be the one that would be expected to show the lowest total cost over the expected life of the structure \(^{(16)}\). At times, however, other factors may control. For example, the presence of corrosive agents in the soil may bar certain materials unless a means

Figure 2.4 – Four Standard Inlet Types (Source: Introduction to Highway Hydraulics, Federal Highway Administration, Washington, DC.)
of protection can be devised. Again, if the structure location is remote, the portability and ease of erection of light, prefabricated metal sections may make them particularly desirable.

Information supplied by the various manufacturers’ associations may be of value in making such a decision. However, selection is best made on the basis of accurate and complete records of construction and maintenance costs of similar structures. Many highway agencies keep records of this type and selection of the most economical culvert type is then made a relatively simple matter.\(^{(16)}\)

### 2.9 Culvert Installation

#### 2.9.1 General

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.\(^{(4)}\)

- **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 \(^{(4)}\).

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 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 \(^{(4)}\).
Figure 2-5 illustrates the load carried by a rigid culvert installed in a normal trench installation \(^{(4)}\).

![Figure 2.5 Trench installation](image)

Figure 2-6 illustrates the increased load on the rigid culvert if the width of the trench is increased \(^{(4)}\).

![Figure 2.6 Wide trench installations](image)
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 2-7, to avoid an increase in the backfill load (4).

**Figure 2.7 Subtrench installations in a wide trench**

- **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 bed 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 \(^\text{(4)}\).

Transverse cracking is illustrated in Figure 2-8. 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. 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 \(^\text{(4)}\).

Properly prepared bedding evenly distributes loads.

Improperly prepared bedding may result in stress concentrations.
Improperly prepared bedding.

Figure 2.8 Transverse or circumferential cracks

- **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 300 mm (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 (4).

  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 not exceeding 150 mm (6 inches) deep, deposited alternately on opposite sides of the culvert (4).

- **Embankments** - Culverts placed in an embankment are usually bedded in natural ground and 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 2-9.

![Diagram of various types of installation](image)

**Figure 2.9 Essential features of various types of installation**

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 is 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 \(^{(4)}\).

**Tunneling**

Tunneling techniques may be appropriate where a drainage structure must pass through an embankment or under a roadway or railway when open cutting is found to be too costly or too disruptive. Steel tunnel liner plates can be used to support an underground excavation. Tunnel liner plates can also be used in the relining of existing structures when access is limited \(^{(4)}\).

### 2.9.2 Culvert Installation Methods

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 \(^{(4)}\):

**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 \(^{(4)}\).

**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 is 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 \(^{(4)}\).
• **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 \(^{(4)}\).

• **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 trench walls, creating unbalanced loadings. Additional protective fill or other measures may be needed for equipment crossing points \(^{(4)}\).

• **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 2-10. 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 coordinated with the Soils and Foundations Section \(^{(4)}\).
• **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 \(^4\).

![Diagram of Cambered Pipe](image)

**Figure 2.10** Camber allows for settlement of a culvert under a high fill

### 2.10 Culvert Location

#### 2.10.1 Principles of Culvert Location

Culvert location is defined as the selection of alignment and grade with respect to both roadway and stream. Proper location is important because it influences adequacy of the opening, maintenance of the culvert, protection from flooding of adjoining improvements, and possible washout of the roadway. Although every culvert installation is unique, the few principles set forth here apply in most cases \(^3\).

An open stream is not always stable. It may be changing its channel, becoming straighter in some places and more sinuous in others. It may be scouring deeper in some places, silting in others. Change of land use upstream by clearing, deforestation, or real estate development can change both stability and flood flow of a stream \(^3\).
Since a culvert is a fixed line in a stream, engineering judgment is necessary in properly locating the structure \(^{(3)}\).

2.10.2 Alignment

The first principle of culvert location is to provide the stream with a direct entrance and a direct exit. Any abrupt change in direction at either end will retard the flow and make a larger structure necessary \(^{(3)}\).

A direct inlet and outlet, if not already existing, can be obtained by a channel change, a skewed alignment, or both. The cost of a channel change may be partly offset by a saving in culvert length or decrease in size. A skewed alignment requires a greater length of culvert, but is usually justified by improving the hydraulic condition and the safety of the road \(^{(3)}\).

The second principle of culvert location is to use reasonable precaution to prevent the stream from changing its course near the ends of the culvert. Otherwise the culvert may become inadequate, cause excessive ponding and possibly washout – any one of which can lead to expensive maintenance of the roadway. Steel end sections, riprap, sod, or paving will help protect the banks from eroding and changing the channel \(^{(3)}\).

Culvert alignment may also be influenced by choice of a grade line. Methods of selecting proper alignment are illustrated in Figures 2-11 and 2-12 \(^{(3)}\).

At roadway intersections and private entrances, culverts should be placed in the direct line of the roadway ditch, especially where ditches are required to carry any considerable amount of storm water \(^{(3)}\).

Culverts for drainage of cut-and-fill sections on long descending grades should be placed on a skew of about 45 degrees across the roadway. Thus the flow of water will not be retarded at the inlet. Broken alignment under a roadway may be advisable on long culverts \(^{(3)}\).

Consideration should be given to entrance and exit conditions. Also, consider increasing the size of the structure to facilitate maintenance and removal of debris that the stream may carry during flood periods.
Changes in alignment may be accomplished by welded miter cuts for bends, either in profile or alignment. When the designer has determined the radius of curvature, the angle of the miter cut can then be determined. Gradual change in alignment can be accomplished by small angle changes at the joints or by field sweeping the coupled lengths of pipe\(^3\).

*Figure 2.11  A channel change can improve alignment and provide more direct flow.*
Figure 2.12 various methods of obtaining correct culvert alignment

(a) Poor Alignment
(b) Good Alignment

(c) Stream should pass under the road at first opportunity.
(d) "Broken-back" alignment. Desirable in some cases.
2.10.3 *Grade*

The ideal grade line for a culvert is one that produces neither silting nor excessive velocities and scour, one that gives the shortest length, and one that makes replacement simplest (Figure 2-13) \(^{(3)}\).

*Figure 2.13 Proper culvert grades are essential to safe functioning of the structure.*
Excessive velocities cause destructive scour downstream and to the culvert structure itself unless protected. The silt carrying capacity of a stream varies as the square of the velocity \(^3\).

Capacity of a culvert with a free outlet (not submerged) is not increased by placement on a slope steeper than its critical slope. (About 1 percent for a 2400 mm pipe.) The capacity is controlled by the amount of water that can get through the inlet \(^3\).

On the other hand, the capacity of a pipe on a very slight gradient and with a submerged outlet is influenced by the head (difference in elevation of water surface at both ends). In this case, the roughness of the culvert interior, in addition to the velocity head and entrance loss, is a factor \(^3\).

A slope of 1 to 2 percent is advisable to give a gradient equal to or greater than the critical slope, provided the velocity falls within permissible limits. In general, a minimum slope of 0.5 percent will avoid sedimentation \(^3\).

In ordinary practice the grade line coincides with the average streambed above and below the culvert. However, deviation for a good purpose is permissible (Figure 2-14) \(^6\).
Figure 2.14 Culvert Alignment and installation detail.
Install culverts at natural stream grade.
2.11 Culvert Hydraulics

2.11.1 Hydraulic Design of Culverts

The purpose of hydraulic design is to provide a drainage facility or system that will adequately and economically provide for the estimated flow throughout the design life without unreasonable risks to the roadway structure or nearby property \(^{(18)}\).

Hydraulic design of culverts involves the following general procedure \(^{(18)}\):

1. Obtain all site data and plot a roadway cross section at the culvert site, including a profile of the stream channel.
2. Establish the culvert invert elevations at the inlet and outlet and determine the culvert length and slope.
3. Determine the allowable headwater depth and the probable depth of tail-water during the design flood.
4. Select a type and size of culvert and the design features of its appurtenances that will accommodate the design flow under the established conditions.
5. Examine the need for energy dissipaters, and, where needed, provide appropriate protective devices to prevent destructive channel erosion.

Whenever a constriction such as a culvert is placed in a natural open channel, there is an increase in the depth of water just upstream of the constriction. The allowable level of the headwater upstream of the culvert entrance is generally the principal control on the culvert size and inlet geometry. The allowable headwater depth depends on the topography and the nature of land use in the culvert vicinity. In establishing the allowable headwater depth, the designer should consider possible harmful effects that flooding may cause, such as damages to the pavement, interruptions to traffic, and inundation of nearby property \(^{(16)}\).
2.11.2 Types of a Culvert Flow

The type of flow occurring in a culvert depends on the total energy available between the inlet and outlet. The available energy consists primarily of the potential energy or the difference in the headwater and tail water elevations. (The velocity in the entrance pool is usually small under ponded conditions and the velocity head or kinetic energy can be assumed to be zero.) The flow that occurs naturally is that which will completely expend all of the available energy. Energy is thus expended at entrances, in friction, in velocity head, and in depth\(^{(16)}\).

The flow characteristics and capacity of a culvert are determined by the location of the control section. A control section in a culvert is similar to a control valve in a pipeline. The control section may be envisioned as the section of the culvert that operates at maximum flow; the other parts of the system have a greater capacity than is actually used\(^{(18)}\).

Laboratory tests and field studies have shown that highway culverts operate with two major types of control: inlet control and outlet control. Examples of flow with inlet control and outlet control are shown, respectively, by Figures 2-15 and 2-16\(^{(7)}\).

2.11.2.1 Culverts Flowing with Inlet Control

Under inlet control, the discharge capacity of a culvert depends primarily on the depth of headwater at the entrance and the entrance geometry (barrel shape, cross-sectional area, and type of inlet edge). Inlet control commonly occurs when the slope of the culvert is steep and the outlet is not submerged\(^{(18)}\).

On the basis of experimental work, analytical relationships have been developed for culverts with inlet control. These relationships are complex, however, and for a given entrance shape and flood condition (i.e., submerged, unsubmerged) are applicable only within a specified range of discharge factors.
for design expedience, the Federal Highway Administration has published a series of nomographs and design charts which are used for design (16).

Figure 2.15 Types of Inlet Control
2.11.2.2 Culverts Flowing with Outlet Control

Maximum flow in a culvert operating with outlet control depends on the depth of headwater and entrance geometry and the additional considerations of the elevation of the tail water at the outlet and the slope, roughness, and length of the culvert. This type of flow most frequently occurs on flat slopes, especially where downstream conditions cause the tail water depth to be greater than the critical depth \(^{(16)}\).

For culverts flowing full, the difference in head between the upstream and downstream water surface \(H\) is equal to the velocity head plus the energy lost at the entrance and in the culvert:

In conventional U.S. units \(^{(18)}\):

\[
H = [1 + Ke \frac{(29 \, n^2 \, L)}{(R^{4/3})}] \frac{(V^2)}{(2g)} \quad (2-1a)
\]

In metric (SI) units \(^{(18)}\):

\[
H = [1 + Ke + \frac{(19.6 \, n^2 \, L)}{(R^{4/3})}] \frac{(V^2)}{(2g)} \quad (2-1b)
\]

Where \(H\) = difference in elevation between the headwater and tail water surfaces, illustrated in Figures 2-16a, 2-16b \(^{(7)}\) or between the headwater surface and the crown of the culvert at the outlet, as shown in Figure 2-16c, ft (m)

\(K_e\) = entrance loss coefficient;

\(n\) = Manning’s roughness coefficient;

\(L\) = length of culvert, ft (m)

\(R\) = hydraulic radius = area/wetted perimeter, ft (m)

\(V\) = velocity, ft/sec (m/sec)

\(g\) = gravity constant. 32.2 ft /sec\(^2\) (9.8 m /sec\(^2\))

Where the critical depth falls below the crown at the outlet, as shown in Figures 2-16d or 2-16e \(^{(7)}\), the headwater can be determined analytically only by tedious and time-consuming backwater computations.
Figure 2.16 Types of Outlet Control
2.11.3 Performance Curves

A culvert at a specific location may operate in a variety of ways, depending on the headwater; culvert diameter, area, and shape; and other physical conditions (e.g., slope, entrance shape, culvert roughness, etc.). Generally speaking, with low headwater, culverts tend to have entrance control and operate like a weir; with high headwater, they tend to operate with outlet control and like an orifice (16).

It is sometimes desirable to develop culvert performance curves that show flow rates versus headwater depth or elevation. The resulting graphical depiction of culvert operation is useful in evaluating the hydraulic capacity of a culvert for various headwaters. Among its uses, the performance curve displays the consequences of higher flow rates at the site and the benefits of inlet improvements. A performance curve can be developed by the following steps (18):

1. Select a range of flow rates and determine the corresponding headwater elevations. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters should be calculated.
2. Combine the inlet and outlet control performance curves to define a single performance curve for the outlet.

Figure 2-17 shows a hypothetical culvert performance curve with roadway overtopping.
2.11.4 Improved Culvert Inlet Design

With inlet control, flow in the culvert barrel is very shallow and the potential capacity of the barrel generally is wasted. Since the barrel is usually the most expensive component of the structure, flow under inlet control tends to be uneconomic. Surveys of culvert design practice by highway agencies indicate that millions of dollars could be saved each year by use of improved inlet design concepts. For more detailed information on this important subject, the reader should refer to the FHWA publication Hydraulic Design of Highway Culverts (18).

Three basic improved inlet designs have been proposed by the FHWA: (1) bevel-edged inlets Figure [2-18a], (2) side-tapered inlets [Figure2-18 b], and (3) slope-tapered inlets [Figure 2-18 c]. These inlets improve hydraulic performance in two ways: (1) by reducing the flow contraction at the culvert inlet and more nearly filling the barrel and (2) by lowering the inlet control section and thus increasing the effective head exerted at the control section for a given headwater pool elevation (18).
- **Bevel-Edged Inlet**
  The bevel-edged inlet is the least sophisticated inlet improvement and the least expensive. The degree of improvement is recommended for use on all culverts, both in inlet and outlet control. For concrete pipe culverts, the groove end, facing upstream, will serve essentially the same purpose as the bevel-edged inlet \(^{(18)}\).

- **Side-Tapered Inlet**
  The side-tapered inlet increases hydraulic efficiency by further reducing the contraction at the inlet control section, normally located near the throat section. The face section is designed to be large enough so as to not restrict the flow. The roof and floor of the inlet are straight-line extensions of the culvert roof and floor, and the tapered sidewalls meet the barrel walls at a smaller angle than the beveled edges (9.5 to 14 degrees vs. 33 to 35 degrees). Because of the slope of the structure, the throat section is somewhat lower than the face, thus concentrating more head on the control section for a given headwater elevation \(^{(18)}\).

- **Slope-Tapered Inlet**
  The slope-tapered inlet incorporates both methods of increasing hydraulic performance: reducing the entrance contraction and lowering the control section. This design provides an efficient control section at the throat, similar to that provided by the side-tapered inlet, and further increases the concentration of head on the throat. The face section remains near the stream bed elevation. And the throat is lowered by incorporating a fall within the inlet structure. This fall reduces the slope of the barrel and increases the required excavation. In addition to their use on new installations, improved inlets, especially beveled- edged and side-tapered inlets, may be added to existing barrels to increase hydraulic performance if the existing inlet is operating in inlet control. Many times this will preclude the construction of a new barrel when the existing culvert is undersized \(^{(18)}\).
Figure 2.18 Improved culvert inlet designs. (a) Bevel – edge inlet
(b) Side – tapered inlet (c) Slope -tapered inlet
2.12 Erosion, Sedimentation, and Debris Control

Natural streams and man made channels are subject to the forces of moving water. Pressure, velocity, and centrifugal forces can be significant depending on the depth of flow, and the slope and sinuosity of the water course. An evolutionary process is the result with the continuous occurrence and dynamic interplay of erosion, sedimentation, and debris movement. This process, referred to as fluvial geomorphology, is accelerated during storm events when stream depths and velocities are high. Inserting a culvert into this dynamic environment requires special attention to the effects of these natural phenomena on the culvert and the effects of the culvert on the stream channel. Past experience has shown significant problems, including erosion at the inlet and outlet, sediment buildup in the barrel, and clogging of the barrel with debris (4).

2.12.1 Scour at Inlets

A culvert barrel normally constricts the natural channel, thereby forcing the flow through a reduced opening. As the flow contracts, vortices and areas of high velocity flow impinge against the upstream slopes of the fill and may tend to scour away the embankment adjacent to the culvert. In many cases, a scour hole also forms upstream of the culvert floor as a result of the acceleration of the flow as it leaves the natural channel and enters the culvert. Upstream slope paving, channel paving, headwalls, wingwalls, and cutoff walls help to protect the slopes and channel bed at the upstream end of the culvert (4). Figure (2-19) depicts a culvert with a headwall and wingwall protecting the inlet against scour (5).

2.12.2 Scour at Outlets

Scour at culvert outlets is a common occurrence (Figure 2-20) (5). The natural channel flow is usually confined to a lesser width and greater depth as it passes through a culvert barrel. An increased velocity results with potentially erosive capabilities as it exits the barrel. Turbulence and erosive eddies form as the flow expands to conform to the natural channel. However, the velocity and
depth of flow at the culvert outlet and the velocity distribution upon reentering
the natural channel are not the only factors which need consideration. The
characteristics of the channel bed and bank material, velocity and depth of flow
in the channel at the culvert outlet, and the amount of sediment and other debris
in the flow are all contributing factors to scour potential. Due to the variation in
expected flows and the difficulty in evaluating some of these factors, scour
prediction is subjective (4).

Figure 2.19 Culvert with Metal Headwall and Wingwalls

Figure 2.20 Scour at Culvert Outlet
Scour in the vicinity of a culvert outlet can be classified into two separate types. The first type is called local scour and is typified by a scour hole produced at the culvert outlet. This is the result of high exit velocities, and the effects extend only a limited distance downstream. Coarse material scoured from the circular or elongated hole is deposited immediately downstream, often forming a low bar. Finer material is transported further downstream. The dimensions of the scour hole change due to sedimentation during low flows and the varying erosive effects of storm events. The scour hole is generally deepest during passage of the peak flow. Methods for predicting scour hole dimensions are found in Chapter 5 of HEC No. 14, "Hydraulic Design of Energy Dissipaters for Culverts and Channels" (4). The second type of scour is classified as general stream degradation. This phenomenon is independent of culvert performance. Natural causes produce a lowering of the stream bed over time. The identification of a degrading stream is an essential part of the original site investigation. Both types of scour can occur simultaneously at a culvert outlet. Protection against scour at culvert outlets varies from limited riprap placement to complex and expensive energy dissipation devices (Figure 2-21) (6). At some locations, use of a rougher culvert material or a flatter slope alleviates the need for a special outlet protection device. Preformed scour holes, approximating the configuration of naturally formed holes, dissipate energy while providing a protective lining to the stream bed (4). Riprapped channel expansions and concrete aprons protect the channel and redistribute or spread the flow (Figure 2-22) (6). Barrel outlet expansions operate in a similar manner. Headwalls and cutoff walls protect the integrity of the fill. When outlet velocities are high enough to create excessive downstream problems, consideration should be given to more complex energy dissipation devices. These include hydraulic jump basins, impact basins, drop structures, and stilling wells. Design information for the general types of energy dissipaters is provided in HEC No. 14(4).
a. Normal metal culvert installation using riprap around the inlet and outlet of culverts. Also use geotextile (filter fabric) or gravel filter beneath the riprap for most installations.

b. Concrete box culvert with concrete wingwalls for inlet/outlet protection and fill retention.

Figure 2.21 Culvert inlet and outlet protection. (Source; Low – Volume Roads Engineering Best Management Practices Field Guide, Low- Volume Roads BMPs).
Figure 2.22 Culvert installation and outlet protection details with splash apron or riprap lined plunge pool. (Source: Low – Volume Roads Engineering Best Management Practices Field Guide, Low- Volume Roads BMPs).
2.12.3. Sedimentation

The companion problem to erosion is sedimentation. Most streams carry a sediment load and tend to deposit this load when their velocities decrease. Therefore, barrel slope and roughness are key indicators of potential problems at culvert sites. Other important factors in sedimentation processes are the magnitude of the discharge and the characteristics of the channel material.

Culverts which are located on and aligned with the natural channel generally do not have a sedimentation problem. A stable channel is expected to balance erosion and sedimentation over time; a culvert resting on such a channel bed behaves in a similar manner. In a degrading channel, erosion, not sedimentation, is a potential problem (4). However, a culvert located in a grading channel may encounter some sediment accumulation (Figure 2-23) (5). Fortunately, storm events tend to cleanse culverts of sediment when increased velocities are experienced. Helical corrugations tend to promote this cleansing effect if the culvert is flowing full (4).

Certain culvert installations may encounter sedimentation problems. The most common of these are multibarrel installations and culverts built with depressions at the entrance. Culverts with more than one barrel may be necessary for wide shallow streams and for low fills. It is well documented that one or more of the barrels will accumulate sediment, particularly the inner barrel in a curved stream alignment. It is desirable for these installations to be straight and aligned with the upstream channel. Culverts built with an upstream depression possess a barrel slope which is less than that of the natural channel. Sedimentation is the likely result, especially during times of low flow. However, self-cleansing usually occurs during periods of high discharge. Both design situations should be approached cautiously with an increased effort in the field investigation stage to obtain a thorough knowledge of stream characteristics and bed-bank materials (4).
2.12.4 Debris Control

Debris is defined as any material moved by a flowing stream. This normally includes some combination of floating material, suspended sediment, and bed load. A stream’s propensity for carrying debris is based upon watershed land uses and certain stream and floodplain characteristics \(^{(5)}\).

A field investigation of the following conditions is warranted.

- Stream velocity, slope, and alignment.
- Presence of shrubs and trees on eroding banks.
- Watershed land uses, particularly logging, cultivation, and construction.
- Stream susceptibility to flash flooding.
- Storage of debris and materials within the flood plain (logs, lumber, solid waste, etc.).

Debris can accumulate at a culvert inlet or become lodged in the inlet or barrel. When this happens, the culvert will fail to perform as designed. Flooding may occur, causing damage to upstream property. Roadway overtopping will create a hazard and an inconvenience to traffic and may lead to roadway and culvert washouts. Maintenance costs will accrue as a result of these circumstances.

Routine design and maintenance precautions may be taken if the debris accumulation potential is minimal. Provision for a smooth, well-designed inlet and avoidance of multiple barrels and skewed inlets will help to align and pass most floating debris. Periodic maintenance at culvert entrances will reduce the chances of severe problems and identify culverts which may require structural solutions \(^{(5)}\).

Three debris control methods are available for culvert sites with more serious risks: interception at or above the culvert inlet protecting culvert performance; deflection of debris away from the entrance to a holding area for eventual removal; and passage of the debris through the culvert \(^{(5)}\).

The latter may be accomplished by oversizing the culvert or utilizing a bridge as a replacement structure. The costs of this solution should be closely compared with other solution methods \(^{(5)}\).
Regardless of the solution method employed, it may be desirable to provide a relief opening either in the form of a vertical riser or a relief culvert placed higher in the embankment. Debris control structures often provide a cost effective solution. Debris interceptors functioning upstream of the culvert entrance include debris racks, floating drift booms, and debris basins.

Debris interceptors functioning at the culvert inlet include debris risers and debris cribs. Debris deflectors vary from a simple inclined steel bar or rail placed in front of the inlet to more complex V-shaped debris deflectors (Figure 2-24) \(^5\). Debris fins are built to help align floating debris with the axis of the culvert to assist in passage of the debris. Design information for commonly employed debris control structures can be found in HEC No. 9, "Debris Control Structures" \(^5\).
Chapter Two  Culverts

Figure 2.23 Sediment Deposition in Culvert

Figure 2.24 Debris Deflector


2.13 Structural Design of Culverts

2.13.1 Introduction

Proper structural design is critical to the performance and service life of a culvert. The structural design of a highway culvert begins with the analysis of moments, thrusts, and shears caused by embankment and traffic loads, and by hydrostatic and hydrodynamic forces. The culvert barrel, acting in harmony with the bedding and fill, must be able to resist these sizeable forces. Anchorage devices, endwalls, and wingwalls are often required to maintain the structural integrity of a culvert barrel by resisting flotation and inlet or outlet movement and distortion (5).

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).  

2.13.2 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 (4). 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 \(^{4}\).

### 2.13.3 General Structural Analysis

Loads affecting culvert barrel design include the culvert weight, fluid loads, earth and pavement loads, and the weight and impact of surface vehicles. Culvert weights per unit length are available from culvert manufacturers. The weight of fluid per unit length can be obtained from the culvert barrel geometry and the unit weight of water \(^{5}\).

The magnitude of the earth and pavement load (dead load) is dependent upon the weight of the prism above the barrel and the soil-structure interaction factor. The soil-structure interaction factor is the ratio of the earth prism load on the culvert to the earth prism weight. Conditions which affect this factor include soil type, backfill compaction, culvert material (rigid or flexible), and the type of culvert installation \(^{5}\). Two common types of culvert installations are depicted in Figure 2-25 \(^{5}\). In the positive projecting embankment installation, the culvert barrel is supported on the original streambed or compacted fill and covered by the embankment material. A negative projecting embankment is similar except that additional load support is gained from the existing banks of a deep stream bed. Each of these installations requires the establishment of an appropriate soil structure interaction factor or the determination of the load by appropriate tests, finite element analysis, or previous experience \(^{5}\).
The weight and impact of surface vehicles is sometimes referred to as the live load. This load is greatest when the depth of fill (cover) over the top of the culvert barrel is small. As the cover increases, the live load decreases and eventually becomes negligible. Pavement designed for heavy duty traffic can significantly reduce the live load imposed on the culvert (5).

The distribution of dead and live load pressures on culvert barrels is dependent upon the shape and culvert material. The pressure distribution on three rigid culvert shapes is depicted in Figure 2-26 (5). In contrast, circular culvert barrels made of flexible material receive the vertical load which pushes the barrel sides against the compacted fill material and mobilizes the passive earth pressure. The result is approximately uniform radial pressure distribution on the barrel. Pipe arches made of flexible material act similarly, but produce increased pressures at the corners (haunches) of the pipe-arch. Special attention to the bearing capacity of the soil at these locations is critical and may dictate embankment heights (5).
Moments, thrusts, and shears at critical locations in the culvert barrel can be determined by elastic structural analysis once the loads and pressure distributions are defined. Reinforced concrete box sections are often analyzed as rigid frames utilizing moment distribution. Rigid circular and elliptical pipe sections require load coefficients based on bedding conditions to properly analyze moments, thrusts, and shears. Flexible culverts are generally designed by semi empirical methods which implicitly include structural analysis aspects within the design method \(^\text{(5)}\).

![Pressure Distribution-Rigid Culverts](image)

**Figure 2.26 Pressure Distribution-Rigid Culverts**

Structural design of the culvert barrel must provide adequate strength to resist the moments, thrusts, and shears determined in the structural analysis. For reinforced concrete barrels, a trial wall thickness is selected, and reinforcing is sized to meet the design requirements. Corrugated metal structures are required to resist ring compression and seam strength. An additional requirement is sufficient stiffness to resist installation loads. Standard wall thickness and corrugation shapes are selected to meet these design requirements \(^\text{(5)}\).
2.13.4 Floatation and Anchorage

Flotation is the term used to describe the failure of a culvert due to the tremendous uplift forces caused by buoyancy. The buoyant force is produced when the pressure outside the culvert is greater than the pressure in the barrel. This occurs in a culvert in inlet control with a submerged upstream end. The phenomenon can also be caused by debris blocking the culvert end or by damage to the inlet. The resulting uplift may cause the outlet or inlet ends of the barrel to rise and bend. Occasionally, the uplift force is great enough to dislodge the embankment. Generally, only flexible barrel materials are vulnerable to failure of this type because of their light weight and lack of resistance to longitudinal bending. Large, projecting or mitered corrugated metal culverts are the most susceptible. In some instances, high entrance velocities will pull the unanchored inlet edges into the culvert barrel, causing blockage and additional damage. Events have been recorded in which the culvert barrel has been turned inside out by the forces of the flow \(^{(5)}\).

A number of precautions can be taken by the designer to guard against flotation and damages due to high inlet velocities. Steep fill slopes which are protected against erosion by slope paving help inlet and outlet stability (Figure 2-27) \(^{(5)}\). Large skews under shallow fills should be avoided. Rigid pipe susceptible to separation at the joints can be protected with commercially available tie bars. When these precautions are not practical or sufficient, anchorage at the culvert ends may be the only recourse. Anchorage is a means of increasing the dead load at the end of a culvert to protect against floatation. Concrete and sheet pile cutoff walls and headwalls are common forms of anchorage. The culvert barrel end must be securely attached to the anchorage device to be effective. Protection against inlet bending, inlet warping, and erosion to fill slopes represent additional benefits of some anchorage techniques \(^{(5)}\).
2.13.5 Headwalls and Endwalls

Culvert barrels are commonly constructed with headwalls and endwalls. These appurtenances are often made of cast-in-place concrete but can also be constructed of precast concrete, corrugated metal, masonry, timber, steel sheet piling, gabions, or bagged concrete. Endwalls are used to shorten the culvert length, maintain the fill material, and reduce erosion of the embankment slope. Endwalls also provide structural protection to inlets and outlets and act as a counterweight to offset buoyant forces. Endwalls tend to inhibit flow of water along the outside surface of the conduit (piping)\(^{(5)}\).

Wingwalls can be used to hydraulic advantage for box culverts by maintaining the approach velocity and alignment, and improving the inlet edge configuration. However, their major advantage is structural in eliminating erosion around a headwall. Additional protection against flotation is provided by the weight of the wingwalls \(^{(5)}\). Common types of headwalls and endwalls are diagramed in Figure (2-28)\(^{(12)}\).

In selecting the size and type of headwalls and endwalls to be used in a given case, matters of economy must be given consideration. In addition, some weight must be given to aesthetic considerations, as the headwall is the principal portion of the average culvert structure which is visible to the traveler \(^{(16)}\).
Figure 2.28 Typical headwalls and end walls for culverts.
2.13.6 Culvert Durability

Culvert material longevity is as important a consideration to a culvert installation as proper hydraulic and structural design. At most locations, the commonly used culvert materials are very durable. However, there are hostile environmental conditions which will deteriorate all culvert materials. The two problems affecting the longevity of culverts due to adverse environmental conditions are abrasion and corrosion. Proper attention must be given to these problems in the design phase. Field inspection of existing culverts on the same or similar streams will prove invaluable in assessing potential problems (5).

The annual cost of a culvert installation is very dependent on its service life. All other conditions being equal, the most durable culvert material should be selected to minimize annual costs. Measures are available to increase the service life of a culvert, such as lining the barrel with a more durable material. When considered, these measures should be included in an economic analysis comparing other culvert materials or other alternatives, including periodic replacement. Periodic replacement of culverts under low fills on secondary roads with light traffic may prove cost effective (5).

2.13.6.1 Abrasion

Abrasion is defined as the erosion of culvert material due primarily to the natural movement of bedload in the stream. The characteristics of the bedload material and the frequency, velocity, and quantities which can be expected are factors to be considered in the design phase. The resistance of various culvert materials to the expected abrasion is then analyzed. Most materials are subject to abrasion when exposed to high velocity, rock laden flows over a period of time. Performance data on other installations in the vicinity may prove to be the most reliable indicator of abrasion potential and culvert material durability (5).

When abrasion problems are expected, several options are available to the designer. Debris control structures can often be used to advantage, although they require periodic maintenance. A liner or bottom reinforcement utilizing excess structural material is another option. Concrete or bituminous lining of
the invert of corrugated metal pipe is a commonly employed method to minimize abrasion. Concrete culverts may require additional cover over reinforcing bars or high strength concrete mixes. The use of metal or wooden planks attached to the culvert bottom normal to the flow will trap and hold bedload materials, thereby providing invert protection. Oversized culvert barrels which are partially buried accomplish the same purpose (5).

2.13.6.2 Corrosion

No culvert material exists which is not subject to deterioration when placed in certain corrosive environments. Galvanized steel culverts are generally subject to deterioration when placed in soils or water where the pH falls outside the range of 6 to 10; aluminum deteriorates outside the range of 4 to 9.) Clay and organic mucks with low electrical resistivities have also proven corrosive to metal culverts. Concrete is adversely affected by alternate wetting and drying with seawater and when exposed to sulfates and certain magnesium salts, and acidic flow with a pH less than 5. Steel deteriorates in saltwater environments. In general, metal culverts are adversely affected by acidic and alkaline conditions in the soil and water, and by high electrical conductivity of the soil. Concrete culverts are sensitive to saltwater environments and to soils containing sulfates and carbonates. A variety of measures can be taken to prevent the reduction of culvert service life in these hostile environments. These measures are generally categorized as appropriate material selection for the environment or the application of protective coatings. For example, aluminum appears to be resistant to corrosion in salt water installations. Experience has been favorable for fiber-bonded galvanized steel culverts in brackish environments. Culverts and linings made of vitrified clay, stainless steel, and bituminized fiber performs well in highly acidic conditions. Variations in the concrete mix, such as higher cement content, help to reduce the deterioration of concrete culverts subject to alkaline soils and water. Concrete tends to perform better than metal in clay or organic muck. In areas of
severe acidity, such as acid mine drainage, concrete box culverts have been protected by fiberglass linings (5).

Bituminous or fiber-bonded coatings on metal culverts may require special consideration. The designer should ascertain that this coating will in fact increase the service life. Delaminating is the primary mode of failure and can occur due to sunlight exposure and abrasion. Damage to the coatings during handling and placing is another consideration. Polymer coatings appear to overcome some of these deficiencies. They have excellent corrosion resistance properties and are generally more abrasion-resistant, less subject to damage in handling and placement, and have fewer manufacturing flaws (5).

2.13.7 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 neither 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).

2.13.8 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).


2.13.9 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 \(^{(4)}\).
Chapter Three

Structural Design of Concrete Box Culverts

3.1 Introduction

Box culvert consists of a reinforced concrete box of a square or rectangular opening with a span usually restricted to 4 m. The top of the box may be at road level or it may be at a depth below the road level if the road is in embankment. If the design discharge is considerable, a single box culvert becomes uneconomical because of the higher thickness of the slab and walls. In such cases, more than one box is cast side-by-side monolithically. A typical view of a box culvert is presented in Figure 3.1(8).

Figure 3.1 Box Culvert - half section and half elevation.
Box culverts are economical for the reasons mentioned below:

- The box is a rigid frame structure and both the horizontal and vertical members are made of a solid slab, which is very simple in construction.
- In case of high embankments, an ordinary bridge will require very heavy abutments that will not only be expensive but also transfer heavy loads to the foundations.
- The box type of structure is suitable for non-perennial streams where scour depth is not significant but subgrade soil is weak.
- The dead load and superimposed load are distributed almost uniformly over a wider area as the bottom slab serves as a raft foundation. Thus reducing pressure on soil.

3.2 Analysis & Design Method

After the hydraulic design of concrete box culvert the required size of culvert is determined with the proper location that matching road levels. Box culverts are analyzed and designed as rigid frames with equal bending moments at the end supports. The moment distribution method is generally adopted for determination of final moments at joints of the frame.

The culvert is analyzed for critical loading conditions, Limit State principles are adopted for the design of the structural elements and the foundation. Both an Ultimate Limit State and serviceability Limit State are considered.

3.3 Design Principles

3.3.1 Limit States

Limit State principles are adopted for structural design of box culvert both, an Ultimate Limit State (ULS) which is represented by the collapse of the structural element concerned, and a serviceability Limit State (SLS) which is represented by the condition beyond which a loss of Utility or cause for public concern may be expected and remedial action required. In particular, crack width shall be limited and there shall not be excessive movement at the joints capable of seriously damaging the carriageway above.
3.3.2 Design Principles of Structural Elements

The design of concrete structural elements is contained in BS 5400: part 4 as implemented by BD 24 (Design Manual for Road and Bridges volume 1, section 3) and supplemented by BD 57 (DMRB) (10).

3.3.3 Design Principles of Foundation

The structure as a whole can fail due to overloading of the soil-structure interface or excessive soil deformations. In order to prevent such failures occurring, two situations shall be investigated prior to carrying out the final structural design, to confirm whether or not the proposed geometry and structural form are suitable, (DMRB) (10).

3.3.3.1 Sliding

The possibility of failure of the structure by sliding on its base shall be investigated at ULS.

3.3.3.2 Bearing Failure and Settlement of the Foundations

The maximum net bearing pressure under the base of the structure under nominal loads shall be checked against the safe bearing pressure of the foundations to ensure that there is an adequate factor of safety against bearing failure of the foundation and to prevent excessive settlement and differential settlement.

3.3.4 Loads

The requirements for Loading are contained in BS5400: Part 2 as implemented by BD 37 (DMRB 1.3) (10). The following loads are used in the design

3.3.4.1 Permanent Loads

Include, dead Loads, superimposed dead Loads, horizontal earth pressure, hydrostatic pressure and buoyancy and differential settlement effects.

3.3.4.2 Vertical Live Loads

Include, HA or HB loads on the carriageway, footway and cycle track loading, accidental wheel loading and construction traffic.

Where:
HA loading is a formula loading representing normal traffic in Great Britain, HB loading is an abnormal vehicle unit loading. Both loadings include impact, (BS 5400: part 2, 1978) \(^{(2)}\).

### 3.3.4.3 Horizontal Live Loads

Include live load Surcharge, traction, temperature effects, parapet collision, accidental skidding and centrifugal load (BS 5400: part 2, 1978).

### 3.3.5 Load Combinations

The load combinations are used in the design is as given in BS 5400: part 2. Only combinations 1, 3 and 4 are applicable to box culvert design as follows:

- **Combination 1**
  - Permanent loads, vertical live loads and horizontal live load surcharge.

- **Combination 3**
  - Load in combination 1 plus temperature effects.

- **Combination 4**
  - Permanent loads and Horizontal live load surcharge plus one of the following: traction, accidental load due to skidding, Centrifugal loads, Loads due to collision with parapets and the associated vertical (primary) live loads.

**Combination 1** is used for highway and foot / cycle track bridges and it will be applicable for box culvert design.

### 3.3.6 Loads Distribution

The concentration is modified if there is any filling above the culvert and, if the depth of filling is \(H_s\), a concentrated load \(P\) can be considered as spread over an area of \(4H_s^2\). When \(H_s\) equals or slightly exceeds half the width of the culvert, the concentrated load is equivalent to a uniformly distributed load of \(P/4H_s^2\) in units of force per units area over a length of culvert equal to \(2H_s\). For values of \(H_s\) of less than half the width of the culvert, the bending moments will be between those due to a uniformly distributed load and those due to a central concentrated load (C.E. Reynolds and J.C. Steedman, 1994 \(^{(15)}\)) see Figure (3.2a)
3.4 Loading

3.4.1 Permanent Loads

3.4.1.1 Dead Loads

The nominal dead load consists of the weight of the materials and parts of the structure that are structural elements excluding superimposed material described below as described by BD 31/01 (DMRB 1.3).

3.4.1.2 Superimposed Dead Load

The nominal superimposed dead load consists of the weight of the soil cover and the road construction materials above the structure. It is applied to the roof of the structure as a uniformly distributed load.

(a) The possible effects of positive arching reducing this load shall be ignored.

(c) Where consolidation or settlement of the fill adjacent to a buried structure will cause negative arching of the fill above the roof, increased loading will be generated on the roof slab. In the absence of reliable estimates of the effects of differential settlement between the structure and the adjacent ground, the superimposed dead load intensities to be applied to the roof of a structure with cover Hs shall be as follows:

(i) The minimum superimposed dead load intensity shall be taken as $\gamma H_s$.

(ii) The maximum superimposed dead load intensity shall be taken as $\beta \gamma H_s$ where:

$$\gamma$$ is the average nominal bulk density of the fill and surfacing and $\beta$ is taken from Figure 3.2b. Or from the equation (3.1) below, for $H_s$ greater than 8, for $H_s$ less than or equal to 8, $\beta$ is taken 1.15 as described by BD 31/01 (DMRB 1.3).

$$\beta = 1.15 + 0.35(H_s - 8)/3$$

(3.1)
Carriageway formation level

Figure 3.2a Live Loads distribution

Figure 3.2b Values of $\beta$ versus values of cover depth

Figure 3.2 Calculation of loads
3.4.1.3 Horizontal Earth Pressure (permanent)

(a) The nominal permanent horizontal earth pressures applied to the side walls of the structure at a depth $H_s$ below ground level is taken as follows:
For combination 1 which is applied in this work:

- A maximum earth pressure equal to $K_o \gamma H_s$ applied simultaneously on both side walls, or
- A minimum earth pressure equal to $0.2 \gamma H_s$ applied simultaneously on both side walls.

(b) Values of Earth Pressure Coefficients

(i) If the backfill properties are not known the following nominal default values are used:

$$K_{\text{min}} = 0.2$$
$$K_a = 0.33$$
$$K_o = 0.6$$
$$K_p = 3.0$$

Where:

- $K_{\text{min}}$ is the minimum credible coefficient for balanced earth pressures,
- $K_a$ is the coefficient of active earth pressure,
- $K_o$ is the coefficient of lateral earth pressure “at rest” and
- $K_p$ is the coefficient of passive earth pressure.

(ii) If the backfill properties are known, the nominal values of $K_a$, $K_o$ and $K_p$ are calculated from BS8002: 1994.

However, as the value of $K_o$ determined using BS8002: 1994 does not account directly for effects such as compaction pressure, thermal expansion and cyclical loading (strain ratcheting) which can lead to a significant increase in earth pressure, the default value of 0.6 is used for $K_o$ (with $\gamma_{FL} = 1.5$) unless such effects are taken into account.

A minimum earth pressure coefficient of not more than 0.2 is used where earth pressures are beneficial.

(iii) Pressures in excess of $K_o$ but not exceeding $0.5K_p$ are used to resist sliding.
3.4.1.4 Hydrostatic Pressure

When appropriate, the effect of hydrostatic pressure and buoyancy is taken into account. The increase in pressure on the back of the walls due to hydrostatic pressure at depth Z metres below water level is taken as in BD 31/01:

\[ 10Z (1-K) \text{kN/m}^2 \]

where:

- \( K \) is the earth pressure coefficient to be used for a given load in the design
- \( 10 \) is a value presented for water density.

3.4.1.5 Settlement

The settlement and differential settlement of the sub-soil under unfactored nominal permanent loads is calculated from BS8004 using the site investigation data. Any differential settlement of the soil that is likely to affect the structure is taken into account\(^{(10)}\).

3.4.2 Live Loads

Vertical Live Loading

3.4.2.1 HA and HB Carriageway Loading

The nominal carriageway loading is HA or HB loading as described in BD 37 (DMRB) and implemented by BD 31/01 (DMRB 1.3)\(^{(10)}\). whichever is the more onerous.

(a) HA Loading

(i) Where the depth of cover (Hs) is 0.6m or less, HA loading shall consist of the HAUDL/KEL combination. No dispersion through the fill of either the HAUDL or the HA knife edge load is applied.

(ii) For cover depths exceeding 0.6m, the HAUDL/KEL combination does not adequately model traffic loading. In these circumstances the HAUDL/KEL combination is replaced by 30 Units of HB loading, dispersed through the fill as described in paragraph (c) below.

(iii) Account is taken of the single 100kN HA wheel load, (dispersed through the fill as described in paragraph (c) below), where this has a more severe effect on the member under consideration than the loads described in (i) or (ii) above.
(b) HB Loading

(i) 45 Units of HB loading is applied on structures on Trunk Roads and Motorways. On structures on other Public Highways, 30 Units is applied unless a higher value is specified.

(ii) A minimum of 30 Units of HB loading is applied to all structures including those that are designated to carry HA loading only.

(c) Dispersal of Wheel and Axle loads through the Fill

(i) All wheel loads is assumed to be uniformly distributed at ground level over a contact area, circular or square in shape, based on an effective pressure of 1.1N/mm².

(ii) Dispersion of a wheel load through the fill is assumed to occur both longitudinally and transversely from the limits of the contact area at ground level to the level of the top of the roof at a slope of 2 vertically to 1 horizontally as shown in Figure 3.3a. Where the dispersion zones of the individual wheels overlap, they are combined and distributed jointly as shown in Figure 3.3a (Zone 2). This applies to adjacent wheels on the same axle and to wheels on succeeding axles.

(iii) Where however any individual wheel is located close to the edge of the structure such that its 2:1 dispersal zone is curtailed by a headwall, the increase in pressure near to the headwall is taken into account. This is done by assuming that the load is dispersed transversely over the curtailed width of the 2:1 dispersal zone, as shown in Figure 3.3b.

(iv) A wheel load not directly over the part of the structure being considered is included if its dispersion zone falls over the part of the structure.

(d) Dispersal of the Wheel and Axle Loads through the Roof Slab.

Where the dispersed width of the wheel or axle at roof level is less than the spacing between adjacent joints (Lj), a further lateral dispersal of the load is made at 45° down to the neutral axis of the roof slab (at depth hna) so that:

- A single wheel is dispersed over a total width of \( C + Hs + 2h_{na} \)
- An axle is dispersed over a total width of \( C + (n-1) S + Hs + 2h_{na} \)
Where:

- $C$ is contact width of a single wheel on the ground,
- $n$ is the number of wheels on an axle,
- $S$ is the wheel spacing and
- $h_{na}$ is the depth from the top of the roof to the neutral axis which may for convenience be approximated to half the overall roof depth.

Dispersion through the slab at $45^\circ$ cannot occur through a longitudinal joint. The above approach does not account for the distribution properties of the structure itself.

### 3.4.2.2 Footway and Cycle Track Loading
(a) Footway and cycle track loading shall consist of a load of $5\,\text{kN/m}^2$ applied over the total area of the footway or cycle track except that this load is reduced, by a factor of 0.8, to $4\,\text{kN/m}^2$ for elements that carry both footway/cycle track loading and carriageway loading as in BD 31/01\(^{(10)}\).

(b) The loading is assumed to be dispersed at a slope of two vertically to one horizontally from the edge of the load to a total width not greater than twice the distance from the centre of the footway to the nearer headwall unless a more rigorous dispersion analysis is undertaken.

### 3.4.2.3 Accidental Wheel Loading on Edge Members
(a) Where the elements of a structure supporting outer verges, footways or cycle tracks are not protected from vehicular traffic by an effective barrier, they are designed to sustain the local effects of the accidental wheel loading described in BD 37 and implemented by BD 31/01 (DMRB 1.3)\(^{(10)}\). Each of the accidental wheel loads are dispersed through the fill using the principles described in section 3.4.2.1 (c) and (d) and Figures 3.3a and 3.3b.

(b) Neither other vertical live load nor dispersed load from the adjacent carriageway need be considered in combination with the accidental wheel loading.
Figure 3.3a

Dispersion of wheel loads through fill
(lateral and longitudinal)

Figure 3.3b

Example of lateral dispersion
through fill adjacent to a side wall
(longitudinal dispersion is as in Figure 3.3a)
3.4.2.4 Loading on Central Reserves
On dual carriageways the portion of structure supporting the central reservation is designed for full HA or HB carriageway loading.

3.4.2.5 Construction Traffic
Under the low cover conditions which prevail during construction, the structure is subjected to load conditions that are more severe than those experienced in normal service. During the design stage therefore, consideration is given to the type of construction traffic likely to be relevant at different stages, and details of the live load capacities of the structure under various depths of cover is recorded on the drawings to ensure that these are not exceeded during construction\(^{(10)}\).

**Horizontal Live Loads**

3.4.2.6 Live Load Surcharge
(a) A horizontal live load surcharge is applied in conjunction with all vertical live loads. The nominal uniform horizontal \((p_{sc})\) is applied to the external walls of the structure is determined from the equation (3.2)\(^{(10)}\):

\[
P_{sc} = K \cdot v_{sc}
\]

Where \(K\) is the value of the nominal earth pressure coefficient from section 3.4.1.3 for the wall under consideration and \(v_{sc}\) is the vertical surcharge pressure applied behind the abutments is taken from table 3.1 below.

<table>
<thead>
<tr>
<th>Vertical LL</th>
<th>(v_{sc})</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA Loading</td>
<td>10KN/m(^2)</td>
</tr>
<tr>
<td>45 Units of HB</td>
<td>20KN/m(^2)</td>
</tr>
<tr>
<td>30 Units of HB</td>
<td>12KN/m(^2)</td>
</tr>
<tr>
<td>Footpath &amp; Cycle Track</td>
<td>5KN/m(^2)</td>
</tr>
<tr>
<td>Accidental Wheel</td>
<td>10KN/m(^2)</td>
</tr>
<tr>
<td>Construction</td>
<td>10KN/m(^2) or as otherwise determined</td>
</tr>
</tbody>
</table>

*Table (3.1) Values of \(v_{sc}\) for different types of vertical live load*
For values between 30 and 45 units of HB the value of $v_{sc}$ is linearly interpolated or obtained by using equation 3.3 below, (C.E. Reynolds and J.C. Steedman, 1994)\(^{(15)}\).

$$v_{sc} = \frac{(j - 5)}{2} \text{ KN/m}^2$$ \hspace{1cm} (3.3)

Where $j$ = number of units of HB load

(b) The same value of nominal live load surcharge with the same partial safety factors $\gamma_{FL}$ and $\gamma_{F3}$ is applied simultaneously to both external walls except as follows:

For calculating the maximum bearing pressure (see Figure 3.5b).

In these cases the live load surcharge pressure is applied on one face only to maximise the effect under consideration.

(c) When the minimum permanent earth pressure is applied on both sides of the structure (see section 3.4.1.3) no live load surcharge is applied to either wall as implemented by BD 31/01\(^{(10)}\) , (see Figure 3.4 c).

### 3.4.2.7 Live Loads Calculation

For uniformly distributed load with density ($F$) and dispersion through the fill from the carriageway formation level to the level of the top of the roof at a slope of 2 vertically to 1 horizontally, the live load effect on floor slab ($F_1$) will be as in equation (3.4) below: \(^{(9)}\).

$$F_1 = \frac{F \cdot L_1}{L_2}$$ \hspace{1cm} (3.4)

Where: $L_1$ is the road width; $L_2$ is the total of (road width and filling depth).

Also for concentrated wheel load ($P$) and dispersion of a wheel load through the fill from the limits of the contact area at carriageway level to the level of the top of the roof at a slope of 2 vertically to 1 horizontally, the equivalent uniformly live load ($F_2$) will be as in equations (3.5a and 3.5b) below: \(^{(9)}\).

Where no interference of the distribution area

$$F_2 = \frac{2 \cdot P}{(2(a+H_s) + x) \cdot H_s}$$ \hspace{1cm} (3.5a)

And, Where there interference of the distribution area

$$F_2 = \frac{2 \cdot P}{(2(a+H_s)-x) \cdot H_s}$$ \hspace{1cm} (3.5b)

Where: $a$ is contact width of a single wheel on the ground,
Hs is the depth of filling and x is distance between dispersions of two wheels, Figures (3.2a) and (3.3).

3.4.3 Load Combinations and Partial Safety Factors for the Design of the Structural Elements

3.4.3.1 Load Combinations used for the Design of Structural Elements

The loads applied simultaneously in any load combination for the design of the structural elements are shown in Table 3.2 (BD31/01, DMRB 1.3) (10).

3.4.3.2 Values of $\gamma_{fl}$ used for the Design of Structural Elements

To obtain the design loads for a given load combination, the relevant nominal loads described in sections 3.4.1 and 3.4.2 are multiplied by the value of $\gamma_{fl}$ given in Table 3.2, except that, for the applied loads causing a relieving effect on the element under consideration, the value of $\gamma_{fl}$ is taken as 1.0.

Where the same nominal values of horizontal earth pressure or live load surcharge are applied simultaneously on both sides of the structure, the same values of $\gamma_{fl}$ (from Table 3.2) is applied to the relevant loads on each side of the structure. See Figures (3.4a - c).

$\gamma_{fl}$ shall be increased to at least 1.2 to compensate for inaccuracies when dead loads are not accurately assessed.

$\gamma_{fl}$ may be reduced to 1.2 and 1.1 for ULS and SLS respectively subject to the approval of the appropriate authority.

3.4.3.3 Values of $\gamma_{f3}$ used in the Design of Structural Elements

(a) The value of $\gamma_{f3}$ at SLS is taken as 1.0
(b) The value to $\gamma_{f3}$ at ULS is taken as 1.1

Except:
(i) For all relieving effects $\gamma_{f3}$ is taken as 1.0
(ii) For disturbing effects at ULS, where plastic methods are used in the analysis, $\gamma_{f3}$ is taken as 1.15, as in BS5400 Part 4(2).
### Loads, Load Combinations and Values of $\gamma_L$ for the Design of Structural Member

**Table 3.2**

<table>
<thead>
<tr>
<th>LOADS</th>
<th>Limit State</th>
<th>$\gamma_L$ Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ULS</td>
<td>SLS</td>
</tr>
<tr>
<td><strong>PERMANENT LOADS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight of concrete</td>
<td>ULS</td>
<td>1.15 1.15 1.15</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>Superimposed pavement construction (top 200mm)</td>
<td>ULS</td>
<td>1.75 1.75 1.75</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.2 1.2 1.2</td>
</tr>
<tr>
<td>Superimposed fill including pavement construction in excess of 200mm</td>
<td>ULS</td>
<td>1.2 1.2 1.2</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>Horizontal earth pressure (using default earth pressure coefficients)</td>
<td>ULS</td>
<td>1.5 1.5 1.5</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>Horizontal earth pressure (using earth pressure coefficients calculated in accordance with BS 8002)</td>
<td>ULS</td>
<td>1.2 1.2 1.2</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>Hydrostatic pressure and buoyancy</td>
<td>ULS</td>
<td>1.10 1.10 1.10</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.10 1.10 1.10</td>
</tr>
<tr>
<td>Settlement</td>
<td>ULS</td>
<td>1.2 1.2 1.2</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td><strong>LIVE LOADS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Live Loads</td>
<td>ULS</td>
<td>1.5 1.25</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.2 1.00</td>
</tr>
<tr>
<td>HA carriageway loading</td>
<td>ULS</td>
<td>1.3 1.10</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.1 1.00</td>
</tr>
<tr>
<td>HB carriageway loading</td>
<td>ULS</td>
<td>1.5 1.25</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00</td>
</tr>
<tr>
<td>Footway and cycle track loads</td>
<td>ULS</td>
<td>1.5 1.25</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.2 1.00</td>
</tr>
<tr>
<td>Accidental wheel loading</td>
<td>ULS</td>
<td>1.15 1.15</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00</td>
</tr>
<tr>
<td>Construction traffic</td>
<td>ULS</td>
<td>1.15 1.15</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00</td>
</tr>
<tr>
<td>Horizontal pressure due to live load surcharge</td>
<td>ULS</td>
<td>1.5 1.5 1.5</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>1.00 1.00 1.00</td>
</tr>
</tbody>
</table>
3.4.4 Load Combination and Partial Safety Factors for the Design of the Foundation

3.4.4.1 Sliding

The loads applied simultaneously for checking the foundation against sliding is as follow: as in BD31/01\(^{(10)}\)

<table>
<thead>
<tr>
<th>Load</th>
<th>(\gamma_{fL}) (ULS)</th>
<th>(\gamma_{f3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum Superimposed Dead Load</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Traction</td>
<td>(HA)/ 1.1(HB)</td>
<td>1.1</td>
</tr>
<tr>
<td>Vertical Live Load associated with Traction</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Disturbing Earth pressure (active)</td>
<td>1.5/1.2*</td>
<td>1.1</td>
</tr>
<tr>
<td>Disturbing Live Load</td>
<td>1.5/1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Surcharge (active)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relieving earth pressure (see 3.5.4.2 (c))</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Table (3.3) Loads for checking the foundation against sliding*

* The value of 1.5 is to be used with the default value of K and 1.2 for the value of K determined in accordance with BS8002 as implemented by BD 31/01\(^{(10)}\). These loads are applied at ULS only, using the values of \(\gamma_{fL}\) and \(\gamma_{f3}\) given above, (see Figure 3.5a).

If the net horizontal force is in the opposite direction to the traction force, sliding need not be considered.

3.4.4.2 Bearing Pressure and Settlement

The bearing pressures and settlements under the foundation are calculated for the following nominal loads as shown in Figure 3.5 b

- Dead Load
- Maximum superimposed dead load
- Maximum horizontal earth pressure on both sides of the box
• Hydrostatic Pressure and Buoyancy
• Vertical Live Loading
• Live Load surcharge on one side of the box only.

3.5 Design

3.5.1 Design of Structural Elements

3.5.1.1 Structural Analysis

(a) The structure is analyzed as a continuous frame, with pin joints where the walls are not continuous or fully integral with the roof slab or base. The stiffness of any corner fillets may be taken into account. Both ULS and SLS are considered.

(b) For boxes, an elastic compressible support is assumed below the base slab except for structures founded on hard material. In the former case the foundation is considered ‘flexible’.

(c) Moments and shears are obtained from the analysis at critical positions around the structure. The most critical positions for shear will normally be at a distance “d” from the inside edge of the fillets (or from the internal corners if there are no fillets),

where d is effective depth to tension reinforcement,

and both shear and coexisting moment is calculated at these and other critical positions, see also section 3.5.3.3.

(d) If a three dimensional model is used consideration is given to the interaction of live loads in adjacent lanes as described in BD 31/01 (10).

3.5.1.2 Stages to be analyzed

Three stages are considered:

(i) The completed structure backfilled up to the top of the roof.

(ii) The structure backfilled to an intermediate level between roof level and finished surface level, at which it is proposed to use the structure for construction traffic.

(iii) The structure, fully backfilled, in service.
3.5.1.3 Load Cases to be considered

(a) Each element of the structure is designed for each of the three stages listed above, using the most onerous of the following Combinations 1 effects:

(i) Permanent loads with maximum or minimum dead load surcharge (excluding differential settlement in Stages i and ii)

(ii) Maximum or minimum horizontal earth pressures

(iii) The appropriate Combination 1 and 3 live loads positioned to give the most severe effect to the element under consideration.

(b) For Combinations 1, the loads cases are applied for the design of the structural elements are shown diagrammatically in Figures (3.4 a-c) as in BD31/01 (10).

Figure 3.4a Maximum Vertical Load with Maximum Horizontal Load
Figure 3.4b  Minimum Vertical Load with Maximum Horizontal Load

Live Load in most onerous position, $\gamma_L$ varies, $\gamma_H = 1.1$

Figure 3.4c  Maximum Vertical Load with Minimum Horizontal Load

Figure 3.4 Load Cases to be Considered
### Figure 3.5a Sliding

Live Load associated with traction in most severe position: $\gamma_h = 1.0$, $\gamma_o = 1.0$

Minimum SDL

$\gamma_h = 1.0$, $\gamma_o = 1.0$

$\gamma_h = 1.25$, $\gamma_o = 1.1$

Box Structures

**Table: Figure 3.5a Sliding**

<table>
<thead>
<tr>
<th>LLSC</th>
<th>Earth</th>
<th>Earth</th>
<th>K = 0.53</th>
<th>K = 0.53</th>
<th>Default Values</th>
<th>$\gamma_h = 1.0$, $\gamma_o = 1.0$</th>
<th>$\gamma_h = 1.5$, $\gamma_o = 1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K = 0.53</td>
<td>$\gamma_h = 1.0$, $\gamma_o = 1.0$</td>
<td>Default Values</td>
<td>$\gamma_h = 1.0$, $\gamma_o = 1.0$</td>
<td>$\gamma_h = 1.5$, $\gamma_o = 1.5$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See clause 4.4.2 (c)

### Figure 3.5b Bearing Pressure (Nominal Loads)

**Figure 3.5**

Box Structures
3.5.2 Special Requirements at the Serviceability Limit State.

3.5.2.1 Crack Control

In Combination 1 at SLS, crack widths are limited in accordance with BS5400 Part 4(2), except that where the cover (Hs) is greater than 0.6m, the crack width is checked for 30 Units of HB rather than HA loading.

3.5.2.2 Early Thermal Cracking

The requirements for the control of early thermal cracking are as specified in BS5400 Part 4(2), BD 31/10 (DMRB 1.3) (10); except that the horizontal steel required for resisting early thermal cracking need not be placed outside the primary longitudinal reinforcement.

3.5.2.3 Deflection

(a) In precast construction, and in in-situ structures, with longitudinal joints that do not comply with section 3.5.2.4 (b) (ii), the net vertical deflection at the midspan of the roof under the combined effects of the elastic deflection of the structure and the short-term settlement of the foundations under the application of vertical live loads at SLS is less than 0.015Hs. This limitation is required to prevent the occurrence of excessive movements at longitudinal joints in structures with low covers, which can seriously damage the overlying carriageway.

(b) Where an assessment of the live load deflection of the roof is required, it is sufficiently accurate to estimate the midspan deflection of the roof using the empirical formula:

$$ \Delta = 20 \frac{M_{\text{max}} S^2}{(T_1)^3} \text{ metres (as in BD 31/01 (10))} \quad (3.6) $$

Where S is the effective span of roof of culvert measured between the centres of the walls in metres, (T1) is the overall depth of the roof in millimeters and M_{max} is the maximum “free span” moment in kN.m/m in the roof due to vertical live load only, at SLS. The free span moment is calculated assuming the roof slab being simply supported over its effective span (S).
(c) The foundation settlement at SLS is taken to be the nominal live load settlement derived as in section 3.4.1.5.

3.5.2.4 Longitudinal Joints
(a) The structures are designed to accommodate all differential movements or to resist the forces set up by such movements.
(b) In most cases, where cast in-situ construction is used, the structure acting as a deep beam is capable of accommodating curvatures induced by differential and longitudinal joints is avoided where possible, for reasons of durability. Where, however, the predicted movements are so large that articulation in the structure is required, the longitudinal joints are designed either:
(i) to accommodate all movements resulting from the differential settlement of the soil as well as the maximum differential live load deflection between sections which are similarly loaded, or
(ii) to allow for the transfer of forces between units or sections joints. This is checked at both ULS and SLS.

3.5.3 Aspects of Reinforcement Design

3.5.3.1 Primary Longitudinal Reinforcement
The longitudinal reinforcement is provided to resist the moments and shears determined from the analysis in accordance with BS5400 Part 4 (2).

3.5.3.2 Transverse Reinforcement in the Soffit of the Roof
Where the dispersed width of the applied load is less than the distance between joints (Lj), transverse reinforcement is provided in the soffit of the roof to resist the transverse bending caused by the local wheel effect. In this case, in the absence of a rigorous analysis, sufficient transverse soffit reinforcement is provided per metre to resist a moment equal to half the longitudinal sagging moment per metre caused by the vertical live load at ULS as in BD 31/01 (10). Where the dispersed width of the applied load is greater than or equal to Lj, the transverse reinforcement shall be in accordance with section 3.5.3.6.
### 3.5.3.3 Longitudinal Steel for Shear

The critical position for shear in a buried box structure is frequently close to a point of contra-flexure, especially in the deck, so that, over a small distance, the tension face may change from one face of the member to the other while the shear force stays sensibly constant. In this case the value of the parameter \(100\frac{A_s}{bd}\) (from BS5400 Part 4) used in the calculation of the shear resistance of the member is based on the area of longitudinal steel in the less heavily reinforced face as implemented by BD31/01 \(^{10}\).

### 3.5.3.4 Anchorage of Longitudinal Steel

Design of anchorage to the longitudinal reinforcement is accordance with BS5400 Part 4 \(^{2}\).

### 3.5.3.5 Reinforcement Details at Corners

(a) For Opening Moments (tension on the inside face)

(i) Where the bending moment applied to the corner of a box culvert causes that to open, the resolved component of the compressive and tensile bending forces in the members on either side of the corner produce a tensile force along the diagonal of the corner which tends to split the outer section of the corner from the main structure, as illustrated in Figure 3.6. As a result, the use of many conventional reinforcement details can lead to the flexural strength of the corner being significantly less than the strength of the adjacent members. These effects shall be taken into account in designing corner reinforcement as implemented by BD31/01 \(^{10}\).

(b) For Closing Moments (tension on the outside face), as described by BD31/01 \(^{10}\).

(i) Where the applied moments tend to close a corner, the area of tension reinforcement provided around the outside of the corner to resist the peak corner moment may been determined on the assumption that the effective depth of the section, \(d_{cnr}\), is the effective depth of the smaller adjacent member plus half the nominal fillet size.
(ii) Where a Type 2 corner detail is provided (Figure 3.7b), the area of the outside legs of either the vertical or the horizontal hairpin bars (but not both) may be considered as contributing to the moment of resistance providing they extend at least an anchorage length beyond the end of the fillet as implemented by BD31/01 (10).

Figure 3.6: Cracking in an Opening Corner
Figure 3.7a Type 1 Corner Detail

Figure 3.7b Type 2 Corner Detail

Figure 3.7 Corner Detail
Where, the area of the horizontal and vertical hairpin bars differ, the smaller area is used in the calculation.

(iii) Care should be taken to ensure that the bearing stress inside the bend of the corner bar does not exceed the limits allowed in BS5400 Part 4. For this purpose the mean radius of the bend may be increased to a value not exceeding \( d_{\text{enr}} \) (Effective depth of corner reinforcement). If a radius in excess of this value is required to satisfy the bearing stress requirements, then the size of the fillet or the area of tensile reinforcement should be increased.

### 3.5.3.6 Minimum Areas of Reinforcement

The minimum area of reinforcement provided in the structural members shall be the accordance to BS5400: part 4 (2).

### 3.5.3.7 Cover to Reinforcement

(a) The nominal cover to be used for cast in-situ structures and for cast in-situ concrete, where the surface is subject to flowing water the cover is based on Table 13 in BS5400 plus 10mm as specified in BD 57 (DMRB 1.3.7) \(^{(10)}\).

(b) Where the concrete is cast directly against the ground (as opposed to on blinding) the nominal cover is based on Table 13 in BS 5400 Part 4\(^{(2)}\) plus a further 40mm.

### 3.5.3.8 Fatigue

(a) Fatigue due to repeated live loading need not be considered for structures where the cover depth (\( H_s \)) is more than one metre. For other structures the requirements are contained in BS5400 Part 4\(^{(2)}\).

(b) For cover depths greater than 0.6m the effective stress range in unwelded reinforcing bars under Load Combination 1 for the SLS is checked for 30 units HB loading instead of HA loading \(^{(10)}\).
3.5.4 Design of Foundations

3.5.4.1 Requirements

Consideration of sliding, global settlement and differential settlement is required to confirm whether or not the proposed geometry and structural form are suitable as described in BD31/01(DMRB 1.3)\textsuperscript{(10)}.

3.5.4.2 Sliding

(a) Requirements

Checks are required to ensure that the structure as a whole does not fail by sliding when subject to traction forces and/or skew effects. Furthermore, where the structure is supported on a number of individual foundations, as opposed to a single combined base slab, each individual foundation is required to remain stable).

(b) Sliding Resistance

This is a ULS check. The loads and partial load factors to be applied are as given in section 3.4.4.1 and Figure 3.5a.

The friction force (FR) that can be developed on the base can be determined from BS802 as follows:

\[ FR = V_{\text{tot}} \tan \delta_b \]  

(3.7)

Where

- \( V_{\text{tot}} \) is the total applied vertical on the footing due to permanent loads less any uplift due to Combination 4 loading and buoyancy.
- \( \delta_b \) is the design angle of base friction described in Clauses 2.2.8 and 3.2.6 of BS802: 1994 as implemented by BD31/01\textsuperscript{(10)}.

In the absence of tests \( \delta_b \) may be determined from

\[ \tan \delta_b = 0.75 \tan \phi \]  

(3.8)

Where \( \phi \) is the design angle of shearing resistance of the material under the slab defined in Clause 3.2.5 of BS802: 1994 as implemented by BD31/01\textsuperscript{(10)}.

(c) The following relationship shall be satisfied for the structure as a whole:

\( (Traction + Disturbing Earth Pressure) \gamma_{fL} \) and \( \gamma_{fS} < (Relieving Earth Pressure) \gamma_{fL} \)
+ FR) where FR is the sliding resistance of the whole base. The relieving earth pressure shall be based on a partial passive resistance coefficient, $K_r$, of 0.6, but in the event of the above criterion for sliding not satisfied with this value of $K_r$, higher values of $K_r$, not exceeding $0.5K_p$, may be used.

### 3.5.4.3 Bearing Pressure

(a) The design shall ensure that the maximum net bearing pressure under the foundations due to nominal loadings does not exceed the allowable net bearing pressure determined in accordance with BS8004 as implemented by BD31/01\textsuperscript{(10)}. This check is to ensure that there is an adequate factor of safety against failure of the founding soil and that settlements are kept within acceptable limits.

(b) The structure shall be able to accommodate any settlements either through movements at the structural joints or through adequate structural strength. In the latter case the stresses arising from differential settlement shall be considered at ULS and SLS as a Combination 1 load using the partial factors of safety given in table 3.2.
3.6 Materials and Construction

3.6.1 Excavation
3.6.1.1 Trench Condition

(a) For a precast structure, excavation in materials other than hard material shall extend to at least 200mm for granular bedding, or to at least 125mm for a concrete blinding with a granular overlay, below the base of the structure. The excavation shall extend at least 300mm beyond the outside wall faces.

(b) For a cast in-situ structure, excavation in materials other than hard material shall extend to at least 75mm below the base of the structure and shall extend at least 300mm beyond the outside wall faces.

(b) For both types of structure, excavation shall, where possible, be benched to a slope no steeper than 1.0 horizontally to 1.0 vertically to a height of not less than 500mm above the top of the structure or to the carriageway formation level, whichever is lower. Where the side slopes are steeper and in close proximity to the finished structure, consideration shall be given to the effects the native ground might have on horizontal earth pressures and thus to the earth pressure parameters that are appropriate for design as described in BD31/01(DMRB 1.3) (10).

3.6.1.2 Embankment Condition

In the embankment situation, when the embankment is built before the structure, the embankment fill shall be benched to a slope no steeper than 0.6 horizontally to 1.0 vertically to a height of not less than 500mm above the top of the structure or to the carriageway formation level, whichever is the lower. When the structure is backfilled before or at the same time as the construction of the embankment, in addition to the above benching requirement the top of the backfilling shall have the same width as that required when the embankment is built first as described in BD31/01(DMRB 1.3) (10).
3.6.2 Blinding and Bedding

(a) All box structures shall be founded on a suitably prepared blinding or bedding layer that shall extend at least 300mm, or 225mm when the excavation is in hard material, beyond the outside wall faces of the structure.

(b) Cast in-situ structures shall be constructed on a blinding layer of Class 20/20 concrete, as described in MCHW1 Series 1700, with a minimum thickness of 75mm\(^{(10)}\).

(c) Precast units founded on other than hard material shall be laid on either a two layer granular bed which shall have a minimum thickness of 200mm or a concrete bed with a granular overlay. In the granular bed the lower 150mm shall be of selected well graded Class 6N material and the upper 50mm shall be of Class 6L material as described in MCHW1 Series 600, except that for Class 6L, only the grading requirement applies and not the other material properties listed in Table 6/1 of MCHW1\(^{(10)}\) (but the sulphate requirements of Clause 601 still apply). Alternatively the lower 150mm may be replaced by a 75mm minimum blinding concrete layer as described in (b) above.

3.6.3 Filling and Compaction

Backfilling for either trench or embankment condition shall be in accordance with Clause 610 (Fill to Structures) of MCHW1\(^{(10)}\). The backfilling material shall be used to a height of 500mm above the structure or to the carriageway formation level, whichever is lower.

3.6.4 Reinforced and Prestressed

The concrete mix shall be Grade 40 or higher. Detailed guidance on the specification of concrete for foundation in aggressive ground is given in part 2 and 3 of BRE special Digest (concrete in aggressive ground) (2001). The digest also recommends additional protective measures for concrete where ground water is mobile and sulfate concentrations are high\(^{(10)}\).
3.6.5 Waterproofing

(a) For both precast and in-situ construction, the top surface, and the top of the adjoining vertical external surfaces to a level of 200mm below the soffit of the top slab, shall be protected with a suitable bridge deck waterproofing system in accordance with MCHW1 Series 2000 \(^{(10)}\).

(b) For precast construction only, all other concrete surfaces of the box structure in contact with soil, backfill, or bedding shall be waterproofed in accordance with the requirements for Below Ground Concrete Surfaces as given in MCHW1 Clauses 2004 and 2006 \(^{(10)}\).

(c) For in-situ construction all other concrete surfaces in contact with soil or backfill shall be waterproofed in accordance with Below Ground Concrete Surfaces as given in MCHW1 Clauses 2004 and 2006 \(^{(10)}\).

3.6.6 Permeable Drainage Layer

A permeable drainage layer in accordance with Clause 513 (Permeable Backing to Earth Retaining Structures) of MCHW1 shall be provided adjacent to all vertical buried concrete faces of box structures which do not carry water or effluent. A perforated drainage pipe, not less than 150mm diameter, with adequate facilities for rodding, shall be incorporated at the bottom of the drainage layer. This drainage pipe shall be connected to a positive outfall. All drainage, to comply with the requirements of MCHW1, Series 500 \(^{(10)}\).

3.6.7 Joints

In situ structure should be jointless unless there are unavoidable construction reasons.

3.6.8 Scour Protection

In the case of culverts the design shall contain adequate provision for preventing scour at the inlet and outlet of the structure. This may include the use of cut off walls below the base slab level and lateral training walls.
Chapter Four

Formulation of the Problem

4.1 Introduction
The problem considered is to analyse and design of concrete box culverts. First the analysis of bending moments per metre length of the culvert was carried out assuming a value for the thickness of the walls and roof. The bending moments were determined by considering the culvert as rigid frame or as a continuous beam of four spans with equal bending moments at the end supports. The bending moments were calculated by considering the possible incidence of the loads and pressures. Generally there are three conditions to consider:

1. Culvert empty: full load and surcharge on the top slab, the weight of the walls, maximum earth pressure and live load surcharge on the walls.
2. Culvert full: full load and surcharge on the top slab, weight of the walls, minimum earth pressure on the walls, maximum horizontal pressure from water in the culvert, and possible upward pressure on the top slab and no lateral pressure due to live load surcharge.
3. Culvert full: full load and surcharge on the top slab, the weight of the walls, maximum earth pressure and live load surcharge on the walls, maximum horizontal pressure from water in the culvert, and possible upward pressure on the top slab.

4.2 Loading
The loads on a box culvert are conveniently divided as follow:

1. A uniformly distributed load on the top slab and an equal reaction from the ground below the bottom slab.
2. A concentrated imposed load on the top slab and an equal reaction from the ground below the bottom slab.
3. An upward pressure on the bottom slab due to the weight of the walls.
4. A triangularly distributed horizontal pressure on each wall due to the increased in earth pressure in the height of the culvert.

5. A uniformly distributed horizontal pressure on each wall due to the pressure from the earth and any surcharge above the level of the roof of the culvert.

6. The internal horizontal and possibly vertical pressure from water in the culvert.

4.3 Design Procedure

Use was made of the moment distribution coefficients already worked out for the designer in table 186 (C.E. Reynolds and J.C. Steedman, 1994)\(^{(15)}\), for the section of the table on highly compressible ground for single culvert. Also use was made of the coefficients by (M.A. Janayni, 1986) in his book “Hydraulic Structures”, for twin culvert. Further was to BS 8007 which incorporates reference to BS8110. The three load conditions outlined in the brief were calculated by using the necessary theories and empirical equations have been discussed in chapter 3. The analysis of bending moments per metre length of the culvert was carried out with the knowledge of the required data which was contained the height and the width of culvert, soil parameters, materials properties and loads values. The maximum values of the bending moments were selected at both Limit State, ULS & SLS for using in reinforcement design and checks in SLS.

While also the safe ground bearing stress was checked at the serviceability Limit State, the flexural reinforcement was designed in the ULS, using the beam equations in BS8110, and then crack was checked to Appendix A2 in BS8007 was carried out on the steel provided. Minimum area of reinforcement should be used was also detailed to BS8110. The ability of the walls of the culvert to carry axial loading was carried out using clause 3.9.3.6.2 (BS81100)\(^{(1)}\) relating to reinforced concrete walls. This clause suggests that for ‘short’ reinforced concrete walls with high out – of plane bending, the sections should be designed as beam to clause 3.4.4.1(BS8110)\(^{(1)}\) which in turn contain the proviso that an axial thrust
of: 0.1*fcu*(cross-sectional area) must be sustained. The minimum area of reinforcement was also detailed.

The shear check in the Ultimate Limit State between the bottom slab and the walls is important; it could result in the tension steel being increased to as much as 1.5%, or shear links being provided, or increasing the thickness of floor and roof slabs, and perhaps compensating the extra self – weight by reducing the thickness of the walls, which would, of course, mean reanalysis the frame .The bearing stress and flotation were also checked as implemented by (R., Westbrook, 1988) (17).

4.4 Program Elements

The program is written using FORTRAN language (is attached in CD). Firstly the program reads the basic data which defining geometry, soil parameters, materials properties and loading. Then calculates the moments and selects the maximum values for designing flexural reinforcement and makes check for cracks, deflection, shear and others important checks at both Ultimate Limit State and serviceability Limit State, by using the theories, empirical equations, and other rules which were mentioned in chapter 3 and in this chapter above, accordance to BS5400, BS8110 and BS 8007 . This program deals with all types of culverts: single cell, twin cell and multiples. The selection is done by the user, when inserting data for the type of culvert.

4.4.1 Flow Diagrams

With reference to Figure (4.1), this segment controls the steps of program to follow, and the calling in order, of all subroutines necessary for the solution of box culvert.

4.4.2 Program Subroutines

The program composed of a main program and two subroutines that satisfy the function of the program. The main program calls the two subroutines Lload and Lload2.
4.4.2.1 Lload Subroutine:

This subroutine calculates the flexure due to vertical live load and live load surcharge for single culvert in case of HA loading or HB loading according to Design manual For Road and Bridges, BD 31/01, The Design of Buried concrete Box and Portal Frames Structures (DMRB 1.3) (10) and BS 5400: part 2 (2).

4.4.2.2 Lload2 Subroutine:

This subroutine calculates the flexure due to vertical live load and live load surcharge for twin culvert in case of HA loading or HB loading according to Design manual For Road and Bridges, BD 31/01, The Design of Buried concrete Box and Portal Frames Structures (DMRB 1.3) (10) and BS 5400: part 2 (2).

4.5 Files Opened by the Program

There are two files used through execution progress of the program:

4.5.1 Inputs Data File

The program reads input data from input data file which involving the required data of structure. The initial values of the height and width of the culvert are entered according to the hydraulic design requirements. The required data are:

- **Culvert dimensions:** [Number of vents (NOV), Wearing coat thickness (WTHICK), Effective Span of culvert (width) (S), Effective Height (HE), Thickness of roof (T1), Thickness of walls (T2), Depth below water level (Z), Concrete covers (C) and Minimum concrete cover (CM)], see figure, 3.2a.

- **Soil parameters:** [Density of soil (γs), Density of road construction materials (γAsph), effective angle of shearing resistance (θ) and safe bearing pressure (SBP)].

- **Materials Properties:** [Density of concrete (γc), Partial safety factor for dead load (γf), Steel Diameter (φ), Radius of bend (RA), Concrete strength (Fcu), Steel strength (Fy), Modulus of elasticity of concrete (Ec) and modulus of elasticity of steel (ES)].
• **Values of live loads:** HA loading (UDL and KEL) and HB loading
  Samples of input data are attached in CD.

### 4.5.2 Outputs Data File

The program types in it the outputs which contain the input data information, the maximum bending moments values, results of checks on ground safe bearing pressure, flexure reinforcement and all results of SLS and ULS checks for cracks, deflection, shear and other checks. Samples of output data are attached in CD.

### 4.6 Variables and User Guides:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOV</td>
<td>Number of culvert vents.</td>
</tr>
<tr>
<td>WTHICK(mm)</td>
<td>Wearing coat thickness.</td>
</tr>
<tr>
<td>H1(m)</td>
<td>Overall height of box side – wall.</td>
</tr>
<tr>
<td>HS(m)</td>
<td>Height of cover from top surface of the roof to the carriageway formation level.</td>
</tr>
<tr>
<td>HE(m)</td>
<td>Effective height of box side – wall measured between the centres of the roof and the base slab.</td>
</tr>
<tr>
<td>S(m)</td>
<td>Effective square span of roof measured between the centres of walls.</td>
</tr>
<tr>
<td>T1(mm)</td>
<td>Thickness of roof slab.</td>
</tr>
<tr>
<td>T2(mm)</td>
<td>Thickness of walls.</td>
</tr>
<tr>
<td>H(m)</td>
<td>Overall height of soil cover and height of box side wall.</td>
</tr>
<tr>
<td>Sc(m)</td>
<td>The clear span of a single span structure, the maximum clear span in a multi span structure.</td>
</tr>
<tr>
<td>Z(m)</td>
<td>Depth below water level.</td>
</tr>
<tr>
<td>C(mm)</td>
<td>The nominal cover to reinforcement.</td>
</tr>
</tbody>
</table>
### Table (4.1) Variables used in the program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM(mm)</td>
<td>The minimum cover to reinforcement.</td>
</tr>
<tr>
<td>G.C(KN/M$^3$)</td>
<td>Density of concrete.</td>
</tr>
<tr>
<td>G.F</td>
<td>Partial safety factor for dead load assessment.</td>
</tr>
<tr>
<td>G.S(KN/M$^3$)</td>
<td>Density of soil.</td>
</tr>
<tr>
<td>G.A(KN/M$^3$)</td>
<td>Density of road construction materials (Asphalt or concrete).</td>
</tr>
<tr>
<td>THETA</td>
<td>Effective angle of shearing resistance.</td>
</tr>
<tr>
<td>VI(mm)</td>
<td>Diameter of reinforcement.</td>
</tr>
<tr>
<td>SBP(KN/M$^2$)</td>
<td>Soil safe bearing pressure.</td>
</tr>
<tr>
<td>Feu(N/mm$^2$)</td>
<td>Strength of concrete.</td>
</tr>
<tr>
<td>Fy(N/mm$^2$)</td>
<td>Yield Strength of reinforcement.</td>
</tr>
<tr>
<td>Ec</td>
<td>Modulus of elasticity of concrete.</td>
</tr>
<tr>
<td>Es</td>
<td>Modulus of elasticity of reinforcement.</td>
</tr>
<tr>
<td>UDL</td>
<td>Uniformly Distributed load described for HA loading in BS 5400:part2.</td>
</tr>
<tr>
<td>KEL</td>
<td>Knife Edge load described for HA loading in BS 5400 “part2.</td>
</tr>
<tr>
<td>RA(mm)</td>
<td>Radius of bend of corner reinforcement bar.</td>
</tr>
<tr>
<td>HB</td>
<td>HB loading accordance to BS 5400:part2.</td>
</tr>
</tbody>
</table>
Figure 4.1 Flow diagrams of the program
Evaluate Flexure Due to Hydrostatic Pressure

Select the Maximum Moment at the SLS

Select the Maximum Moment at the ULS

Print Results in Outputs File

Check Ground Safe Bearing Pressure

Design Slab Roof & Wall

A

Evaluate Flexure Due to Hydrostatic Pressure

Select the Maximum Moment at the SLS

Select the Maximum Moment at the ULS

Print Results in Output File

Check Ground Safe Bearing Pressure

Design Slab Roof & Wall

A

B
Chapter Four

Formulation of The Problem

Check Cracks for Slab at SLS

Check Deflection for Roof Slab

Design Corners

Check Cracks for Corners at SLS

Check Shear for Roof & Base at ULS

Print Outputs at every Stage

End
Chapter Five

Numerical Examples and Results

5.1 Introduction

Culvert software has been developed to solve concrete box culverts problems. Different types of culverts were considered in application phase so as to check the adaptation of the program to different types of box culvert. The results of analysis and design obtained by the program as output were compared with manual solution and results obtained by the commercially available software (PROKON), to check the accuracy of the calculations. Others applications were carried out to compare results obtained by the program with results of solved problems in literature to check the accuracy of the program.

5.2 Results

Seven different culverts were solved by the culvert software. The results of four of them were compared with manual solutions and the commercially available software (PROKON) for load case 1 and load case 2, which represent load case 1 and load case 2 from the three load conditions were mentioned in section 4.1, since load case 1 represents the maximum values of moments at supports and load case 2 represents the maximum values of moments at roof, base and walls. The two load cases are illustrated in Figures (5.1-a,b) The results of others application were compared with solved problems in literature for maximum values of moments at supports, roof, base and walls. All data and outputs files of culvert software are attached in CD, and results of manual solution and the commercially available software (PROKON) are presented in appendix (A).
Chapter Five  

**Numerical Examples and Results**

Live Load in most onerous position: $\gamma_{L}$ varies, $\gamma_{B} = 1.1$

---

**Fig (5.1a) Load case 1**

Live Load in most onerous position: $\gamma_{L}$ varies, $\gamma_{B} = 1.1$

---

**Fig (5.1b) Load case 2**

**Fig (5.1) worse condition of load cases**
5.3 Results and discussion

5.3.1 Example one

Single box culvert

Design information
Box culvert with the following particulars:
Inside dimension: 2x4 m
Road width : 7.5m
Span : 6m
Height of the cover above the box = 0.5m

Soil conditions:
Safe bearing pressure = 200 kN/m²
Density of soil = 16 KN/m³
Angle of repose = 30°

Materials properties:
\( F_{cu} = 25 \text{N/mm}^2 \), \( F_y = 460 \text{N/mm}^2 \)
\( \gamma_{\text{conc}} = 24 \text{KN/m}^3 \), \( \gamma_{\text{Asph}} = 22 \text{KN/m}^3 \)

Thickness of 350mm for roof, base and walls has been assumed.
This example was solved by culvert software and also was solved by manual solution and the commercially available software (PROKON). The final results for load case 1 and load case 2 are listed in tables (A.1-a, b) in appendix (A), the results of the culvert software are shown in the second column of table, while the results of manual solution and the commercially available software (PROKON) are shown in columns 3, 4 respectively, these results are presented in Figures (5.2-a, b)
Example 1 (load case 1)

<table>
<thead>
<tr>
<th>Location</th>
<th>Prog. CULVERT</th>
<th>Prog. MANUAL</th>
<th>Prog. PROKON</th>
</tr>
</thead>
<tbody>
<tr>
<td>A&amp;B</td>
<td>-115.25</td>
<td>-115.25</td>
<td>-115.1</td>
</tr>
<tr>
<td>C&amp;D</td>
<td>-130.47</td>
<td>-130.56</td>
<td>-130.7</td>
</tr>
<tr>
<td>ROOF</td>
<td>137.26</td>
<td>137.62</td>
<td>137.4</td>
</tr>
<tr>
<td>BASE</td>
<td>148.17</td>
<td>148.54</td>
<td>149</td>
</tr>
<tr>
<td>WALLS</td>
<td>-88.96</td>
<td>-88.98</td>
<td>-88.54</td>
</tr>
</tbody>
</table>

Figure (5.2-a)

Example 1 (load case 2)

<table>
<thead>
<tr>
<th>Location</th>
<th>Prog. CULVERT</th>
<th>Prog. MANUAL</th>
<th>Prog. PROKON</th>
</tr>
</thead>
<tbody>
<tr>
<td>A&amp;B</td>
<td>-107.41</td>
<td>-107.42</td>
<td>-107.4</td>
</tr>
<tr>
<td>C&amp;D</td>
<td>-122.149</td>
<td>-122.15</td>
<td>-122.1</td>
</tr>
<tr>
<td>ROOF</td>
<td>145.1</td>
<td>145.45</td>
<td>145.1</td>
</tr>
<tr>
<td>BASE</td>
<td>156.59</td>
<td>156.95</td>
<td>156.6</td>
</tr>
<tr>
<td>WALLS</td>
<td>-115.6</td>
<td>-115.62</td>
<td>-115.55</td>
</tr>
</tbody>
</table>

Figure (5.2-b)

Figure (5.2) comparison between, culvert prog., manual solution and PROKON prog results for example 1.

(a) Values of bending moments for load case 1
(b) Values of bending moments for load case 2
Figures (5.2-a,b) show that the results of culvert software are identical to the exact values of the manual solution and the commercially available software (PROKON) with the same trend line.

5.3.2 Example two

Single box culvert

Design information
Box culvert with the following below:
Inside dimension: 3.5x3.5 m
Road width : 7.5m
Span 4m
Height of soil cover above the box = 1.2m

Soil conditions:
Safe bearing pressure = 200 kN/m²
Density of soil = 18 KN/m³
Angle of repose = 30°

Materials properties:
$F_{cu} = 25N/mm^2$, $F_y = 460N/mm^2$
$\gamma_{conc} = 24KN/m^3$, $\gamma_{Asph} = 22KN/m^3$

Thickness of 500mm for roof, base and walls has been assumed.
This example was solved using culvert software, manual solution and the commercially available software (PROKON). The final results for load case 1 and load case 2 are presented in tables (A.2-a, b) in appendix (A), Columns 2, 3 and 4 represent the results of culvert software, manual and the commercially available software (PROKON) respectively. The comparison of these results are presented in Figures (5.3-a, b)
Example 2 (load case 1)

<table>
<thead>
<tr>
<th></th>
<th>A&amp;B</th>
<th>C&amp;D</th>
<th>ROOF</th>
<th>BASE</th>
<th>WALLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CULVERT PROG.</td>
<td>-131.37</td>
<td>-162.9</td>
<td>131.49</td>
<td>155.19</td>
<td>4.33</td>
</tr>
<tr>
<td>MANUAL</td>
<td>-131.56</td>
<td>-163.98</td>
<td>131.32</td>
<td>155.21</td>
<td>4.27</td>
</tr>
<tr>
<td>PROKON PROG.</td>
<td>-132</td>
<td>-164.4</td>
<td>132</td>
<td>155</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Figure (5.3-a)

Example 2 (load case 2)

<table>
<thead>
<tr>
<th></th>
<th>A&amp;B</th>
<th>C&amp;D</th>
<th>ROOF</th>
<th>BASE</th>
<th>WALLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CULVERT PROG.</td>
<td>-83.41</td>
<td>-111.04</td>
<td>179.45</td>
<td>208.14</td>
<td>-96.57</td>
</tr>
<tr>
<td>MANUAL</td>
<td>-83.63</td>
<td>-111.07</td>
<td>179.27</td>
<td>208.14</td>
<td>-96.61</td>
</tr>
<tr>
<td>PROKON PROG.</td>
<td>-83.9</td>
<td>-112</td>
<td>179</td>
<td>208</td>
<td>-96.58</td>
</tr>
</tbody>
</table>

Figure (5.3-b)

Figure (5.3) comparison between, culvert prog., manual solution and PROKON prog results for example 2.

(a) Values of bending moments for load case 1
(b) Values of bending moments for load case 2
Figures (5.3-a, b) show that the results of culvert software are almost typical to the values of manual solutions and the commercially available software (PROKON).

5.3.3 Example three

Twin box culvert

Design information

Box culvert with the following below:

Inside dimension: 1.3x2.5m
Road width : 7.5m
Span : 6m
Height of embankment above the box = 0.5m

Soil conditions:

Safe bearing pressure = 200 kN/m²
Density of soil = 18 KN/m³
Angle of repose = 30°

Materials properties:

Fcu = 25N/mm², Fy = 460N/mm²
γconc= 24KN/m³, γAsph= 22KN/m³

Thickness of 250mm for roof, base and walls has been assumed.

This example was solved by culvert software, and the final results were listed in column 2 in table (A.3-a, b) in appendix (A). The final results of manual solution and the commercially available software (PROKON) are shown in columns 3 and 4. Results obtained by culvert software were compared with that obtained by manual and the commercially available software (PROKON) in Figures (5.4-a, b).
Example 3 (load case 1)

Figure (5.4-a)

Example 3 (load case 2)

Figure (5.4-b)

Figure (5.4) comparison between culvert prog, manual solution and PROKON prog results for example 3.

(a) Values of bending moments for load case 1
(b) Values of bending moments for load case 2
Figures (5.4-a,b) show that the results obtained by culvert software are almost approaching to the values obtained by manual and the commercially available software (PROKON) with very slight difference in values.

### 5.3.4 Example four

**Twin box culvert**

**Design information**

Box culvert with the following below:

- Inside dimension: 2mx4m
- Road width: 7.5m
- Span: 8m
- Height of embankment above the box = 1.5m

**Soil conditions:**

- Safe bearing pressure = 200 kN/m²
- Density of soil = 16 KN/m³
- Angle of repose = 30°

**Materials properties:**

- $F_{cu} = 25N/mm²$, $F_y = 460N/mm²$
- $\gamma_{conc} = 24KN/m³$, $\gamma_{Asph} = 22KN/m³$

Thickness of 350mm for roof, base and walls has been assumed.

This example was solved by culvert software, and the final results were listed in column 2 in table (A.4-a, b) in appendix (A). The final results of manual solution and the commercially available software (PROKON) are shown in columns 3 and 4. Results obtained by culvert software were compared with that obtained by manual and the commercially available software (PROKON) in Figures (5.5-a,b).
Example 4 (load case 1)

Example 4 (load case 2)

Figure (5.5-a)

Figure (5.5-b)

Figure (5.5) comparison between culvert prog., manual solution and PROKON prog. results for example 4.

(a) Values of bending moments for load case 1
(b) Values of bending moments for load case 2
Figures (5. 5-a, b) shows that the results obtained by culvert software are almost same as the values obtained by manual solutions and the commercially available software (PROKON).

5.3.5 Example five

Design information

Box culvert with the following information:

<table>
<thead>
<tr>
<th>Design Information</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear span</td>
<td>3m</td>
</tr>
<tr>
<td>Height of event</td>
<td>3m</td>
</tr>
<tr>
<td>Dead load</td>
<td>14 KN/m²</td>
</tr>
<tr>
<td>Live load</td>
<td>37 KN/m²</td>
</tr>
</tbody>
</table>

Soil conditions:

- Density of soil = 18 KN/m³
- Angle of repose = 30°

Materials properties:

- Fcu = 30N/mm², Fy = 460N/mm²
- $\gamma_{\text{conc}} = 25$ KN/m³

Thickness of 300mm for roof, base and walls has been assumed.

This example is a solved problem (8). The results of maximum bending moments at supports, roof, base and walls obtained by culvert software, and are tabulated in table (A.5) in appendix (A) with those values of the solution of the problem and compared with them in Figure (5.6).
Figure (5.6) shows that the values of maximum moments obtained by culvert software are almost typical to the exact solution of the problem. That means these results are in very good agreement with the exact results.

**Example 5 (MAX. MOMENTS)**

<table>
<thead>
<tr>
<th></th>
<th>A&amp;B</th>
<th>C&amp;D</th>
<th>ROOF</th>
<th>BASE</th>
<th>WALLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CULVERT PROG.</td>
<td>-36.6</td>
<td>-47.71</td>
<td>55.36</td>
<td>66.17</td>
<td>-31.69</td>
</tr>
<tr>
<td>SOLVED PROBLEM</td>
<td>-36.6</td>
<td>-47.715</td>
<td>55.218</td>
<td>65.997</td>
<td>-31.42</td>
</tr>
</tbody>
</table>

*Figure (5.6) comparison between results of culvert software and solved problem for example 5*
5.3.6 Example six

*Design information*

Box culvert with the following information:
Inside dimension: 3m x 3m
Dead load : 12.8 KN/m²
Live load : 50 KN/m²

*Soil conditions:*
Density of soil = 18 KN/m³
Angle of repose = 30°

*Materials properties:*
F_{cu} = 25 N/mm² , F_{y} = 460 N/mm²
γ_{conc} = 24 KN/m³

Thickness of 300mm for roof, base and walls has been assumed.
This example is a solved problem \(^{(14)}\). The values of maximum bending moments at supports, roof, base and walls obtained by culvert software, and the solution of the problem are shown in table (A.6) in appendix (A) and listed in columns 2 and 3 respectively. The results of culvert software were compared with the exact solution in Figure (5.7).
Figure (5.7) shows that the values of maximum moments obtained by culvert software are almost identical to the exact solution of the problem. This shows that these results are satisfactory.

**Example 6 (MAX. MOMENTS)**

<table>
<thead>
<tr>
<th></th>
<th>A&amp;B</th>
<th>C&amp;D</th>
<th>ROOF</th>
<th>BASE</th>
<th>WALLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CULVERT PROG.</td>
<td>-43.67</td>
<td>-54.37</td>
<td>65.91</td>
<td>76.31</td>
<td>-37.14</td>
</tr>
<tr>
<td>SOLVED PROBLEM</td>
<td>-43.67</td>
<td>-54.43</td>
<td>65.63</td>
<td>76.1</td>
<td>-37.17</td>
</tr>
</tbody>
</table>

*Figure (5.7) comparison between results of culvert software and solved problem for example 6*
5.3.7 Example seven

**Design information**
Box culvert with the following information:
Inside dimension: 3mx2m
The cover soil above box = 7m
(No live load, hydrostatic loads are to be considered as live loads)

**Soil conditions:**
Safe bearing pressure = 150KN/m²
Density of soil = 20 KN/m³
Angle of repose = 25°

**Materials properties:**
Fcu = 30N/mm² , Fy = 460N/mm²
γ _concrete_ = 25 KN/m³

Thickness of 250mm for roof, base and walls has been assumed.
This example is a solved problem (17). The values of maximum bending moments at supports, roof, base and walls were obtained by culvert software, and listed with the exact solution of the in table (A.7) in appendix (A). These values were compared with the exact solution in Figure (5.8).
Figure (5.8) shows that the values of maximum moments obtained by culvert software are rather identical to the exact solution of the problem. This shows that these results are acceptable.
Chapter Six

Conclusions and Recommendations

6.1. Conclusions

In this study a structural design software program has been developed for concrete box culverts. This program is used to solve seven examples of different types of culverts. The application is used for solving a wide range of problems. From this study the following conclusions are drawn:

a. A structural design of concrete box culverts of single, twin and multiples was developed which is suitable for Sudan soil conditions.

b. Although there is a wide variety of culverts shapes and materials, concrete box culverts are best choice for durability and economical reasons.

c. Method of analysis of Box culverts are different from other bridges, since they are analyzed and designed as rigid frames with equal bending moments at the end supports. The moment distribution method is used for determination of final moments at joints of the frame.

d. The results of analysis for single box culverts using the moment distribution coefficients\(^{(15)}\) gave accurate results when compared to analysis using commercially available software (PROKON).

e. The results of analysis using the moment distribution coefficients proposed by M.A. Janayni\(^ {9}\), for both twin and multiples culverts gave acceptable results when compared to analysis using commercially available software (PROKON).

f. The program has been applied to many types of culverts. Compared with manual solution, commercially available software (PROKON) and solved problems in literature, the program results are very close to the exact solution.
Chapter Six                                                                 Conclusion & Recommendations

6.2. Recommendations

Based on this study, there are many other aspects of design can be elaborated and thus the following recommendations are put forward for further study:

a. The formulation of structural design of concrete box culverts can be developed to include structural design of headwalls and wingwalls for concrete box culverts.

b. Special subroutines can be added or the program can be linked with another program to give graphic representation of inputs and outputs.

c. This program can be developed by using visual basic program to enter the data easily.

d. The limitations of the developed formulation could be widened to include the portal frame structures; this kind of buried rectangular structures which are more realized in the event of rock foundation.

g. This application forms an efficient tool to prepare standard drawings for concrete box culverts in Sudan that will make them suitable to be part of design manual for roads and bridges to improve road management.

h. Use of this formulation of structural design of concrete box culverts saves time and money, improves road planning and management and also minimizes risk when selection is based on climatic conditions.