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Avon Catchment Council

Report on IWM004 - Protection of Transport Assets

Culvert Material and Design

July 2007

Final Report

INFRASTRUCTURE | MINING & INDUSTRY | DEFENCE | PROPERTY & BUILDINGS | ENVIRONMENT

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Executive Summary

This document is a desktop study of culvert material and design in the context of the Avon River basin (ARB), prepared for the Avon Catchment Council's Surface Water Management project (IWM 006). The changing hydrology of the Avon catchment and the associated water quality issues prompted the inclusion of the following Management Action Target in the project's scope:

- L1 MAT 3.2 Assess alternative culvert materials and designs to suit changed catchment hydrology by 2007;

The often-poor water quality associated with surface water flows in the ARB can lead to the premature degradation of road assets. This can impose a significant, and at times unnecessary, cost on Shires across the catchment.

Salt affects around 14,100 km of roads across Western Australia, a figure that is predicted to rise to 27,920 km by 2050. In 1999, it was estimated that salt affected around 230 km of main roads in the south west of Western Australia, which represents around 3 % of the regional Main road network. The area of salt-affected land was expected to double between 1999 and 2019 and as such, a proportional increase in the length of salt affected road could also be expected. Conservative estimates suggest that this increase could represent an additional $50 - $100 million, over this period, in routine maintenance and reconstruction costs.

The purpose of this report is to highlight the different culvert materials and treatments that are available, which can extend the service life of these assets and hence, reduce the frequency with which they must be replaced. The properties of reinforced concrete, corrugated metal and high-density polyethylene culverts are discussed in terms of their relative performance in various conditions. Protective measures that can be employed to improve the service life of these materials are also discussed.

The most important finding of this desktop study is that the selection of appropriate culvert materials and correct culvert installation can significantly increase the service life of these structures. Although the up-front cost associated with the purchase of higher quality materials is often greater, this can be offset by their superior performance and longevity.

Additionally, culvert design, in terms of layout and entry/exit characteristics is discussed in relation to improving the longevity of culverts.

It should be noted that the advice provided in this document is indicative only. The characteristics of each site are different and the quality of flows at different locations can significantly influence the performance of the various culvert materials. As such, advice should be sought from the manufacturer of a product before it is used for a particular application.

1. Introduction

GHD were contracted by the Avon Catchment Council to deliver the Protection of Transport Assets Project IWM 004. This project forms a part of the integrated water management component of the 2006 – 2008 Avon Catchment Council Investment Plan.

1.1 Background

The Protection of Transport Assets Project includes the following components:

- An inventory of transport assets within the region.
- An investigation of the risk of high water tables and flooding for transport infrastructure is known within each local government area.
- An assessment of alternative culvert materials and designs to suit changed catchment hydrology.
- An evaluation of methods of road risk assessment.
- Transport asset planning included in 30 Local Area Plans.
- An education package focusing on the understanding of the links between catchment management and the protection of key infrastructure.
- Ten demonstration sites displaying preventative management options for transport assets.
- Monitoring of road assets at risk of salinity.

The project aspires to produce the following outcomes; the assessment of engineering and revegetation options for groundwater reduction beneath roads, and the identification of priority roads for preservative action through regional transport policy.

1.2 Management Action Target

The Management Action Target (MAT) relevant to this report is:

- L1 MAT 3.2 Assess alternative culvert materials and designs to suit changed catchment hydrology by 2007;

1.3 Objective

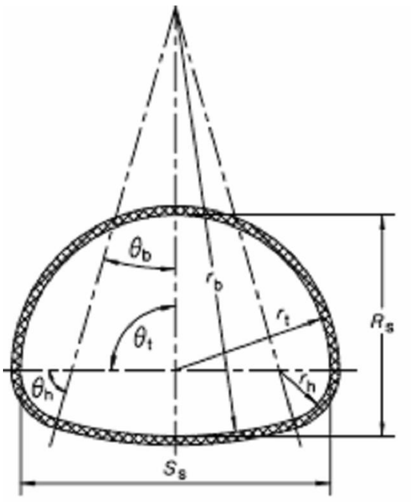
This paper documents the outcomes of a desktop assessment of culvert materials and designs for changed catchment conditions, including increased waterlogging and salinity. This document provides background information relevant to local government authorities within the region, and will be relevant to the development of demonstration sites within the Protection of Transport Assets Project IWM 004.

2. Background

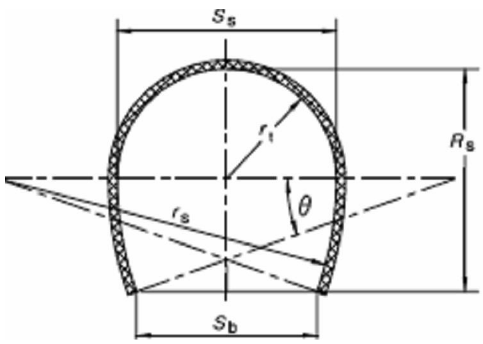
Culverts are road structures that enable water to flow from one side of a road to the other, with minimal disruption to road traffic and damage to adjacent property. There are two basic types of culvert:

1. *Box Culverts* are rectangular and comprise walls to retain lateral earth pressure, a roof to support vertical loading and a floor slab.
2. *Pipe Culverts* are generally circular conduits but may be elliptical or pipe-arch in shape (refer Figure 2-1). These culverts resist lateral and vertical forces as axial loads in an annular fashion.

Figure 2-1 Diagram of Pipe-arch and Elliptical Arch Culverts (Source: AS 2041 Buried Corrugated Metal Structures)



Pipe Arch Culvert



Elliptical Arch Culvert

Culverts are generally constructed of reinforced concrete, corrugated metal or high-density plastics. Each of these materials has associated benefits and disadvantages. Ease of transport, durability and ease of installation are all desirable characteristics of a culvert. The hydraulic properties of the conduit material are also important in selecting an appropriate product.

Culvert installation is a straightforward procedure. However, on occasion not enough thought is given to culvert design. The location, alignment, size and number of culverts to be installed must be considered prior to implementation. Design must account for the impacts on the upstream and downstream environments. If the culvert is too small, it may cause upstream ponding and similarly, downstream erosion, because the flow velocity is too high. Unless a culvert is to have a bed of natural material, then flow rates should be designed to prevent sedimentation and/or scour of the flow passage.

The design life of the pavement and the culvert itself should be considered and finally, the economics of any alternative designs will govern the culvert selection.

Silting, corrosion, abrasion and structural integrity affect culvert lifespan and efficiency. The accumulation of sediment in a culvert reduces the flow passage, often to the point where flow is critically impeded. This silting can undermine the function of the culvert and reduce its effective lifespan.

Corrosion refers to chemical action that degrades the culvert. The three culvert materials discussed above are affected to varying degrees by different chemicals. For example, salt will prematurely rust a steel pipe and acid will adversely affect a concrete structure. Abrasion is the physical erosion of the culvert by sediment transported in the flow. Structural integrity refers to the culvert maintaining its ability to support the loads applied to it. Impact, creep and the effects of corrosion and abrasion can all contribute to a structure losing its integrity, which in turn affects the condition of the roads it supports.

Water quality in the Avon River Basin (ARB) is frequently very poor. It may be saline and/or acidic and may contain deleterious substances such as sulphur. Water of this quality will potentially result in the premature degradation of culvert assets, especially if its effects are not accounted for in the design process. The purpose of this paper is to highlight the issues associated with culvert design in the ARB with respect to the aggressive soil and water conditions endemic to the region.

3. Culvert Materials

Three materials dominate the range of culvert products:

1. *Reinforced Concrete*
2. *Corrugated Metal*
3. *High Density Plastic*

The materials have their respective merits and applications and an appropriate selection can save time and money over the life of the culvert. The advantages of the materials, the mechanisms that degrade them and methods for maximising their durability are discussed below.

3.1 Reinforced Concrete

Reinforced concrete is the most commonly employed culvert material in the ARB. It is particularly popular for large flows, where box culverts are often employed.

Figure 3-1 Concrete Box Culverts Under Railway (Source: Australasia Railway Corporation)

In isolation, concrete performs poorly in tension but very well in compression. Therefore, steel reinforcing is cast into the tension zones of a concrete structure to provide tensile strength.

When considering the durability of a structure, the performance of both the concrete and the reinforcement must be taken into account. Often, concrete deterioration is accompanied by corrosion of the reinforcement.

3.1.1 Deterioration Mechanisms

Bucea, Khatri and Sirivivatnanon (2005) identify three possible deterioration mechanisms for reinforced concrete. They are "'chemical attack', 'physical attack' and chemical change of concrete leading to 'corrosion of steel reinforcement'."

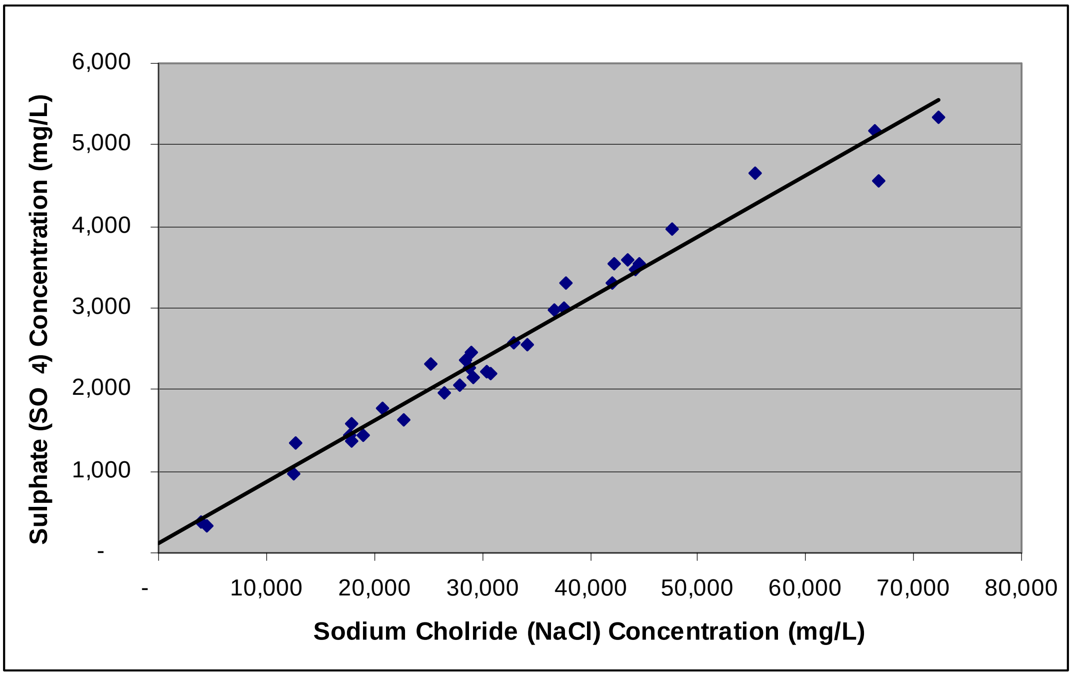
Chemical Attack

Chemical attack can be the result of acid solutions or the ingress of salt into the cementitious material that bonds the aggregate of the concrete. The salts or acid subsequently react with the cement hydrates. These reactions result in the attrition of the cement matrix and may also lead to the accelerated corrosion of the steel reinforcement.

In terms of salt ingress, sulfates pose the greatest chemical hazard to the performance of concrete. There are two chemical processes whereby sulfates can damage concrete. The first involves the formation of ettringite and the second is associated with gypsum formation. Both processes involve the reaction of sulfates with the cementitious material of the concrete. The resulting chemical products (ettringite and gypsum) occupy a greater physical space than the original cement matrix, causing expansion and cracking. The process resulting in gypsum formation also has an associated strength and mass loss. Cement Concrete and Aggregates Australia defines attack from calcium, sodium and potassium sulfates as 'moderate' whilst magnesium and ammonium sulfate attack are considered more severe.

The continued effect of this deterioration enables the sulfate ions to penetrate further into the concrete, which allows the affected area to spread. Chemical attack of this nature requires a renewable source of sulfates. That is, concrete that is immersed in static sulfate groundwater will generally not suffer greatly. However, in culvert design, the replenishment of reaction products is continual and thus, the process may cause significant damage.

Figure 3-2 Sulphate and Sodium Chloride Concentrations of Groundwater Samples Collected from the Quairading and Brookton Shires (*Source: Department of Water)*



Groundwater samples collected and analysed by the Department of Water suggest a correlation between sulphate and sodium chloride (major salt component) concentrations in groundwater samples.

Table 3-1 Severity of Sulphate Attack at Varying Concentrations

Concentration of Sulphate	Degree of Attack
150 mg/L	negligible
150 to 1,000 mg/L	mild but positive
1,000 to 2,000 mg/L	considerable
> 2,000 mg/L	Severe

(Swenson 1971)

As much of the groundwater within the ARB has a sodium chloride concentration of greater than 12,000 mg/L, it is likely that sulphate concentrations are generally sufficient to cause either considerable or severe damage to concrete structures.

Acid Attack

While sulphate attacks constituents of the cement paste, acid solutions impact the entire cement matrix. Acids react with the cement hydrate and form water-soluble salts that are subsequently leached from the concrete matrix, resulting in a decreased material strength and physical erosion of the concrete structure. The Australian Centre for Construction Innovation has performed tests that show concrete may lose up to 45 % of its compressive strength after prolonged exposure to acid conditions.

In contrast to sulfate attack, the permeability of the concrete is not a factor in determining the severity of the agent's effects. The rate of acid attack is a function of the nature of the acid, its pH and the solubility of the salts that are formed in the reaction between the acid and the material. It is therefore difficult to provide specific rules of thumb regarding the likely severity of attack from groundwater within the ARB. Suffice to say that particularly low pH groundwater within the region presents a significant risk to concrete structures.

Physical Attack

Physical attack occurs as a result of the diffusion of a salt solution into the concrete structure and subsequent re-crystallisation of the salt as the structure dries. "Crystallisation and re-crystallisation of certain salts can generate expansive forces which result in the physical break down of the porous medium" (Bucea, Khatri and Sirivivatnanon, 2005).

Chloride and sulfate salts are both capable of physical degradation of concrete structures. The capillary suction of these salts into the concrete results in their deposition within the cementitious material. In contrast to chemical attack, physical damage does not involve a reaction between the cement and the introduced chemicals. Physical damage is caused by a phase change, which sees salts precipitate out of solution into the pore space of the concrete. The accompanying expansive forces can 'fret away' the outer layer of concrete, exposing a fresh surface and so the process continues.

Corrosion of Steel Reinforcement

Steel reinforcement is protected from corrosion by the concrete placed around it. The concrete not only forms a physical barrier to the ingress of corrosive substances, but also provides a strong alkaline environment for the steel. The alkaline nature of the concrete results in the formation of a highly impermeable oxide layer on the surface of the reinforcement, which prevents corrosion. A reduction in the alkalinity of the concrete, which prevents formation of this oxide layer, or the ingress of salts into the concrete matrix are the two main processes that can impair the steel protection (*Guide to Residential Slabs and Footings in Saline Environments*, 2005).

A reduction in the pH level of concrete can occur in acid soils. Cement Concrete and Aggregates Australia indicate that alkalinity leaching is unlikely to occur in most concrete structures because a flow of water is required to remove or flush out soluble alkalis. A culvert is subject to flowing water which when contaminated with acid groundwater, may result in the leaching of alkalis from the concrete. However, the presence of chloride salts presents the greatest potential risk of steel corrosion. Despite the concrete cover and the alkaline nature of the cementitious material, if the concentration of chloride ions reaches a high enough level, then corrosion will be initiated. "*For corrosion of reinforcement to be initiated and continue, three major conditions must exist simultaneously, viz the presence of salts (eg chlorides), moisture and oxygen*" (*Guide to Residential Slabs and Footings in Saline Environments*, 2005). Culverts subject to flows contaminated by groundwater within the Avon River Basin provide the ideal conditions for the corrosion of steel reinforcement.

3.1.2 Protection Measures

There are two processes that ensure the durability of a concrete structure:

1. *The design and specification of the structure by the engineer to account for the specifics of the site, and*
2. *The construction and installation of the element according to recommended practice and Specification.*

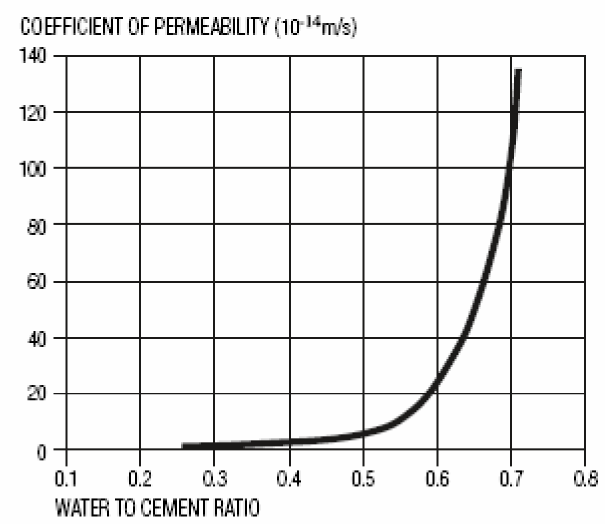
1. Engineering Design

The *Australia Standard for Concrete Structures* (AS 3600) provides guidelines concerning the correct design and construction of concrete structures. Other relevant documents include The *Building Code of Australia* (BCA) and *Residential Slabs and Footings* (AS 2870). For concrete pipes, AS 4058 *Reinforced Concrete Pipe* and AS 3725 *Loads on Buried Concrete Pipe* are the governing standards. AS 1597.2 covers the design of precast box culverts, whilst position paper AP-127/97 concerns *Concrete Structures Durability, Inspection and Maintenance Procedures*.

Concrete Strength & Cover Specification

Minimising the permeability of a concrete is key to improving its durability. Lower permeability concrete provides a stronger barrier to the ingress of aggressive agents that can cause physical and chemical attack or corrode reinforcement. Permeability is related to the water/cement ratio of the concrete. As the water/cement ratio is increased, so the permeability of the resulting concrete increases (refer to Figure 3-3 below).

Figure 3-3 Coefficient of Permeability versus Water to Cement Ratio (Source: Cement Concrete & Aggregates Australia)



Concrete compressive strength (f'$_c$) is also closely related to the water/cement ratio. Consequently, it can be used as a proxy to specify the desired permeability range of a concrete mix. Cement Concrete and Aggregates Australia identify five soil salinity classes and provide a recommended concrete grade for each. Table 3-1 provides a basis for selecting a sufficient grade of concrete for a saline site. By taking account of the site salinity, the engineer can specify an appropriate grade of concrete to enhance the service life of the asset. It should be noted that Table 3-1 refers specifically to slabs on ground. The intention of its inclusion is to illustrate the need for higher concrete grades in more saline sites. AS 1597.2 *Precast Reinforced Concrete Box Culverts* specifies a minimum of Grade N40 concrete be used in the manufacture of concrete box culverts.

Table 3-2 Recommended Concrete Strengths for Various Salinity Classes (Source: Cement Concrete and Aggregates Australia)

EC_e range (dS/m)	**Salinity class** (from Table 2)	**Concrete grade**
<2	Non-saline	N20
2–4	Slightly-saline	N20
4–8	Moderately saline	N25
8–16	Very saline	N32
>16	Highly saline	≥N40

AS 3600 stipulates the required cover to reinforcement and concrete grade for structures in different applications. Exposure conditions are classified according to the aggressiveness of the soil at the site, the presence of deleterious substances in the atmosphere and the likelihood of the element encountering water.

As previously mentioned, the concrete itself provides a physical barrier that protects the reinforcement from corrosion. In aggressive sites, the thickness of the concrete barrier, known as cover, should be increased accordingly, to account for the nature of the agents present. *Clause 2.10* of AS 1597.2 adopts the requirements presented in Table 3-2 for cover to reinforcement. It follows from the previous discussion of concrete permeability that cover is specified as a function of both concrete strength and how aggressive the site conditions are. It should be noted that the above discussion, and the recommendations of AS 1597.2, are based on a nominal service life of 40-60 years.

Table 3-3 Required Concrete Cover for Precast Concrete Box Culverts (Source: AS 1597.2)

TABLE 2.4
REQUIRED COVER

Exposure classification (see AS 3600)	Required cover, mm Characteristic strength (f_c')		
	40 MPa	50 MPa	60 MPa
A1, A2, B1	25	25	25
B2	40	30	25
C	—	45	30

To further enhance the longevity of a structure, the designer may opt for galvanised, stainless steel or epoxy-coated reinforcement. The latter two are expensive options and additionally, epoxy coating is rare. Consequently, these options are unlikely to be employed. A more cost-effective method would be to increase the grade of concrete used.

Protective Coatings

Protective coatings are available that can be applied to the concrete surface immediately after installation to mitigate deterioration, or as part of a repair process after deterioration has been identified. The objective of applying a protective coating is to prevent the ingress of water, oxygen or other deleterious substances such as chlorides. Desirable characteristics of a protective coating include: strong adherence to concrete, UV resistance and the ability to accommodate movement in the concrete structure.

Typical components of protective coatings include: polyurethane resins, polymer modified cementitious material, epoxy resins, chlorinated resins, acrylic resins, vinyl ester and bituminous material (AP – 127/97 *Concrete Structures Durability, Inspection and Maintenance Procedures*).

Impregnating Materials

Impregnating materials are distinct from protective coatings in that they do not form a film over the concrete surface. These materials permeate the concrete and react with the moisture and silicates in the cement to form a waterproof barrier in the surface layer of the concrete. Therefore, water that may be carrying chlorides or sulfates is prevented from entering the concrete structure.

Additives and Admixtures

Agents are often added to concrete in order to improve its qualities. Superplasticisers can help to enhance strength and wetting agents improve the workability of the material. In a similar manner, substances can be added to concrete that improve its durability.

Substances such as fly ash, blast furnace slag, calcium sulfate and silica fume are additives that are used to improve certain characteristics of Portland cement.

Of particular relevance to the ARB is Sulfate resistant (SR) cement, which is designed to improve concrete performance in environments that present a risk of sulfate attack. SR cement also “provides additional protection where the concrete is subject to an aggressive environment such as salt water or chemically active soils” (Readymix). SR cement has a reduced permeability and consequently, the ingress of chloride ions is limited, which reduces the risk of corrosion of the steel reinforcement.

The designation of a cement as sulfate resisting is not merely based on its blend of constituents. This used to be the case, as it has been known for a long time that maintaining low alumina content leads to cement that performs better under sulfate attack. This knowledge led to the initial development of standards for sulfate resistant cement, which limited the concentration of C_3A (tricalcium aluminate) to 5%.

However, the specification of sulfate resisting cement has moved from a specification of chemical constituents, to characterisation of the cement in terms of its sulfate resisting performance. The test procedure for sulfate resistant cement has now been amended to an expansion test, following exposure to a standard sodium sulfate solution, according to AS 3972.

“Studies have shown that cements potentially containing less calcium hydroxide on hydration perform well in sulfate exposure, e.g. certain portland/blast furnace slag cements and portland/fly ash cements. The effectiveness of these cements in enhancing the sulfate resistance of concrete has been the subject of extensive work and many explanations for the improvement have been offered.” (Cement Concrete and Aggregates Australia, 2005). In addition to the cement blend, the water / cement ratio, cement content and the curing of the concrete have significant influence on the final sulfate resistance of the material.

2. Concrete Placement and Handling

In addition to good design, the physical construction of a concrete asset is important from a durability standpoint. The majority of concrete culverts will be precast elements and so be constructed under quality-controlled conditions. The two main concerns associated with the construction of concrete elements are the compaction and curing of the concrete.

Compaction

Compaction expels air in the concrete mix and packs the aggregate closer together, resulting in a denser mix. Proper compaction enhances the strength of the concrete and reduces its permeability (by promoting a more homogeneous pore distribution, there are less adjoining pores). Consequently, the durability of the material is improved.

Curing

The process of controlling the loss of moisture from a wet concrete mix as it dries is known as *curing*. Concrete may be cured by continually spraying it with water, covering it with plastic or a damp cloth or by applying membrane compounds to its surface. Appropriate curing of a mix is an important process in achieving the desired properties of the final product.

The process of *hydration*, which is used to describe the chemical reaction between the cement and the water, is directly affected by the loss of moisture from the mix as it hardens. The properties of a concrete mix are dependent on the degree of hydration that is achieved and as such, curing is an important consideration for obtaining the desired concrete properties.

Maximising hydration through correct curing is an effective method of increasing ultimate strength and reducing permeability as Figure 3-4 and Figure 3-5 illustrate.

Figure 3-4 Effect of Curing on Concrete Compressive Strength (Source: Cement Concrete & Aggregates Australia)

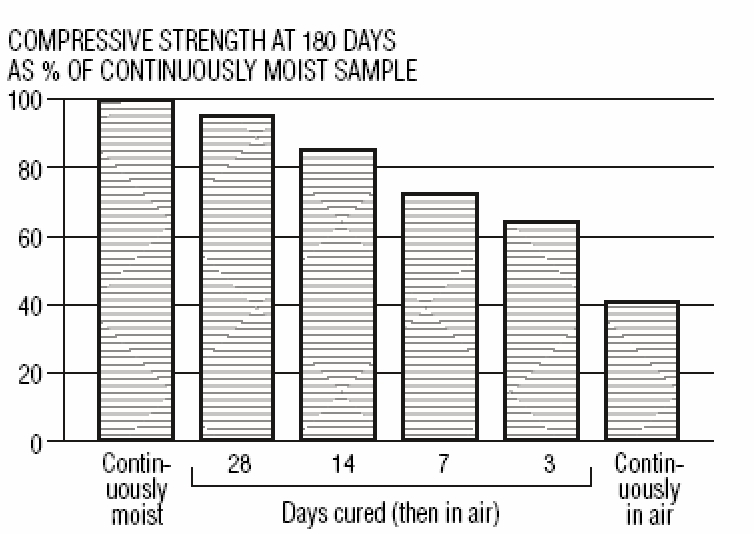
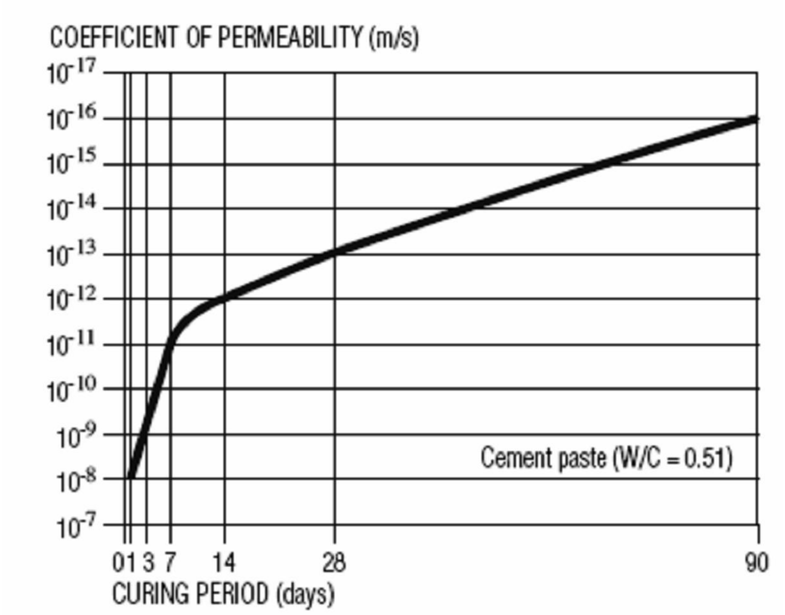


Figure 3-5 Effect of Curing on the Permeability of the Cement Paste (Source: Cement Concrete & Aggregates Australia)



The importance of curing becomes more relevant in saline environments. Poorly hydrated cement will produce a vulnerable surface that is more susceptible to physical attack from salts and chemical attack from sulfates. It will also be less effective in impeding the ingress of substances such as chloride ions that lead to reinforcement corrosion.

3.1.3 Hydraulic Performance of Concrete Culverts

The ability of water to flow through a conduit is critical in culvert design. Hydraulic performance is dependent on a number of variables, one of which is the material the culvert is constructed from. A material has an associated *Manning's "n"*, which measures the surface roughness, or resistance of the wetted perimeter to flow.

It is often thought that amongst smooth pipes, concrete does not perform as well as steel and plastic pipe. However, Walters (2003) states "In culvert conditions, surface roughness of nominally smooth bore pipes has no influence in most practical installations – "smooth" in this sense meaning free from deliberate circumferential or helical corrugation. In all culvert conditions…the maximum discharge capacity is virtually unaffected by variations in pipe surface roughness from Manning's "n" equal to 0.008 mm to "n" equals 0.012 mm. This means that all nominally smooth bore pipes, concrete, steel tube or plastic perform equally hydraulically." Therefore, in the majority of culvert applications, hydraulic performance should not deter the use of concrete pipe.

3.1.4 Summary of Concrete Culvert Use

There are a number of substances endemic to the Avon River Basin that can accelerate the degradation of concrete structures, through chemical and physical decay of the concrete and via corrosion of the reinforcement. However, despite these agents, appropriate design and construction can increase the longevity of a structure by improving its resistance to attack.

3.2 Corrugated Metal Pipe (CMP)

Metal pipes are often used as culverts. Their walls are generally corrugated to provide the strength required to withstand the horizontal and vertical loads imposed upon them. Weight advantage is the main benefit to the use of metal pipes over reinforced concrete. Contech™ (a metal pipe manufacturer) claim their corrugated aluminium pipes weigh 1/35 as much as reinforced concrete. This results in time savings and economic savings, through increased ease of transport and installation. Metal pipes can also be manufactured in longer lengths because of their lower weight. Longer lengths mean fewer joins are required and the barrel is easier to install. Steel corrugated pipes are most common, although aluminium and other products are also used.

Corrugated Metal Pipe deterioration is due to a combination of corrosive and abrasive processes. It is difficult to assess the relative performance of different CMP because the interaction of corrosion and abrasion is not well defined. When metals corrode, they form an oxide layer on their surface, the properties of which are different to the parent material. The metal oxide may inhibit further corrosion but may be removed by an abrasive bed load, exposing fresh material to eroding agents. The hardness of the oxide is also likely to be different to that of the base metal, which will affect the resistance of the conduit to abrasion. For example, aluminium oxide (alumina) is harder than aluminium but the corrosion product from steel is less resistant than its parent, which increases the severity of the corrosion/abrasion cycle.

Given the susceptibility of metals to corrosion and abrasion, CMP is often afforded surface protection such as galvanising or a polymer coating. The relative merits of different metals and protective coatings are discussed below.

3.2.1 Deterioration Mechanisms

The deterioration of corrugated metal pipe takes place in a similar manner to the corrosion of steel reinforcement in reinforced concrete. There are a number of factors that can contribute to the accelerated deterioration of the base metal:

- *The presence of moisture.*

The presence of dissolved salts that can act as electrolytes to assist the oxidation process.

- *An acidic environment.*
- *Suspended solids in the flow.*
- *An increased flow velocity.*

- *Higher temperatures result in higher rates of corrosion.*

Different areas of a culvert are exposed to different conditions and consequently, deteriorate at varying rates. *Buried Corrugated Metal Structures* (AS/NZS 2041) discusses three exposure conditions and the associated corrosion rates in these areas for CMP:

1. Soil side corrosion is in the order of 10 to 30 µm per year for unprotected steel (although it should be noted that this range is highly dependent on soil conditions).
2. Corrosion on the internal surface of the pipe, above the level to which water normally rises is generally minimal.
3. The internal surface of the pipe that is regularly submerged is subject to both corrosion and abrasion.

3.2.2 Protective Measures

The Australian Standard for *Buried Corrugated Metal Structures* encompasses the design of CMP in culvert applications. The standard provides guidance on the design and installation of corrugated metal pipes and devotes an appendix to “Durability Design and Protective Systems.”

The type of backfill used to compact around the culvert plays an important role in determining the structure’s service life. Ideally, the material should be free draining, to prevent the build-up of moisture behind the culvert and should have limited linear shrinkage (a maximum value of 8% is specified). Linear shrinkage is limited so as to minimise the effects on the culvert of expansion and contraction experienced by the backfill upon wetting and drying.

The code also outlines the materials that may be used in the manufacture of class 1 and class 2 products. It further specifies the surface treatments that may be used to protect the metal substrate against corrosion and/or abrasion. These treatments are outlined below and their benefits and disadvantages are discussed.

Galvanised

The treatment of steel with a protective zinc coating is known as galvanising. The zinc corrodes preferentially to steel, meaning the coating provides sacrificial protection to the steel substrate. Galvanising has long been the preferred protective treatment for steel in Australia. This preference is founded on a number of benefits that are provided by zinc coating:

- *Its resistance to the destructive influence of UV and solar radiation.*
- *The predictability of its rate of corrosion, which enables the service life of an element to be determined with reasonable accuracy.*
- *Its performance in wet environments, which is far superior to untreated steel.*

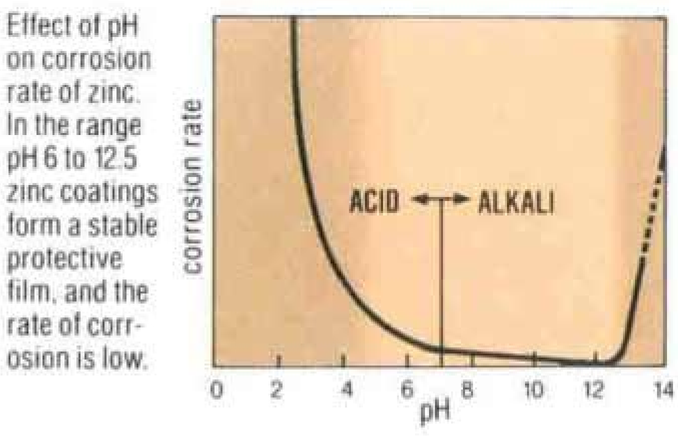
- *The homogeneous coating that can be achieved on a steel surface by hot-dip galvanising is generally better than the coverage provided by paints. Other treatments often perform poorly at sharp corners of an object, or toward its edges.*
- *The steel under a galvanised coating will not corrode until the zinc treatment has been eroded. Conversely, under conventional paint treatments, the underlying steel may corrode unnoticed beneath the protective layer.*
- *Its compatibility with additional paint treatments, which can further enhance the protection afforded to the steel member.*
- *Its abrasion resistance.*

Galvanising has been employed on corrugated steel pipe culverts since the early 1900's and its preponderance has lead to it becoming the benchmark for comparison of other surface treatments.

However, despite the benefits associated with galvanising, culverts in the Avon River Basin will be exposed to conditions that still pose a risk to the corrosion of the underlying steel. The corrosion of galvanised steel is accelerated by the presence of salts and moisture, so the prevalence of saline flows will reduce the lifespan of the protective layer.

Of greater importance to some areas is the effect that acid has on galvanising. Zinc performs well in the pH range six to twelve, but its rate of corrosion increases rapidly in acidic environments (refer figure 3-6). Flows with pH levels less than five are not uncommon in the ARB.

Figure 3-6 Effect of pH on the Corrosion of Zinc (Source: Galvaniser's Association of Australia)



Aluminised

Aluminised steel is also used as a culvert material. "The addition of aluminium to iron results in a significant increase in oxidation resistance, due to the formation of a uniform alumina layer" (Xu, 2002). The formation of Al_2O_3 also aids in the corrosion protection of the steel base. Therefore, aluminised material performs well where there is a high chloride ion concentration.

It is difficult to compare the performance of aluminised steel to galvanised steel. Ault and Ellor (1996) note, "There is very little standardisation in the methodology used to test and evaluate culverts." The means of comparison are largely qualitative and are therefore subjective and the culverts being contrasted are not subject to identical flows. However, Ault and Ellor (1996) quote field studies that suggest aluminised culverts perform 6.2 times better than their galvanised counterparts. They also highlight a laboratory study conducted by the Florida Department of Transport that found aluminised culverts were 2.9 times better than galvanised ones. However, it is thought that galvanised CMP performs better in abrasive conditions than aluminised steel.

It is generally agreed that in abrasive conditions, plain metallic coatings (galvanising and aluminising) need to be augmented by a polymer coating (polymer coatings are discussed below). However, manufacturers have experienced difficulty in the polymer coating of aluminised culverts and studies have shown that polymer pre-coating showed less adhesion to aluminised steel than galvanised steel. A New York Department of Transport study concluded, "polymer coating over aluminium is deficient and should not be used." Therefore, in situations where abrasive bed loads are apparent, polymer-coated, galvanised steel is probably preferable to aluminised steel.

Galvalume

In addition to galvanised and aluminised pipes, a combination of the two coatings is available, known as 'galvalume.' In this process, the steel is coated with an alloy of aluminium and zinc. In field tests quoted by Ault and Ellor (1996), galvalume was performing better than galvanised steel in 16 sites of nine-year-old culverts.

Aluminium Alloy

Aluminium alloy (Alclad) culverts such as Alucor TM, manufactured by Roundel TM, are aluminium alloy substrate culverts with a protective aluminium or aluminium alloy surface layer. On both surfaces of the culvert, there exists "a metallurgically bonded aluminium or aluminium alloy coating which is anodic to the core alloy to which it is bonded, thus electrolytically protecting the core alloy against corrosion" (Ullrich Aluminium, [Online]).

The major advantages of aluminium alloy culverts include:

- *A relatively low weight compared to other products (approximately 30% of the weight of galvanised corrugated steel pipe, according to Roundel).*
- *Low weight leads to economic transportation and rapid installation.*
- *Good corrosion and abrasion resistance can be expected from Aluminium alloy culverts in environments with pH ranges of 4 – 9 and salinity equal to seawater.*

As previously mentioned, the aluminium coating protects the alloy core from both physical and electrochemical corrosion. An oxide that forms on the surface of the coating when it is exposed to air, affords this protection. The advantage of this oxide barrier is that it is self – healing; if it receives minor damage from an abrasive bed load or if the barrel is damaged in the installation process, it will reform.

It should be noted that appropriate fasteners must be used in conjunction with aluminium alloy culvert barrels. Galvanised steel fasteners have been shown to be compatible, but non-conducting coatings should be used to insulate other metal-to-metal fastening systems. Robustness is a further problem associated with the use of aluminium alloy barrels. Stones can damage the pipe surface and even penetrate the pipe during backfilling. Incorrect compaction around the culvert can lead to deflection of the conduit shape.

Bituminous Coating

A bituminous, asphalt coating can be applied to any of the aforementioned products. Bituminous coating is useful as a moisture barrier and generally increases the service life of an asset in a corrosive flow. The California Highway Design Manual suggests that bituminous coating acts as a good inhibitor for soil-side corrosion. This is an important benefit for the assets in the ARB, where arid regions prevail.

Two downfalls of bituminous coatings are:

1. They degrade in ultraviolet light and
2. There are difficulties associated with the installation of bituminous CMP because of its tacky coating and increased weight.

Protective Films

Corrugated Metal Pipes may be pre-coated with a protective film, which provides an impervious barrier to moisture and corrosive agents that may damage the metal substrate of a culvert, in addition to providing protection against abrasion. An example of a pre-coated product is BHP's Hydrorib© culvert, which is coated with Trenchcoat©, a product of the Dow chemical company. Trenchcoat© is the marketed name for an ethylene acrylic acid copolymer which displays exceptional resistance to acids, salts and other chemicals that are deleterious to the metal substrate.

Polymer coatings such as Trenchcoat© generally perform better than bituminous-coated pipe and are approximately one third of the additional weight of their bituminous counterparts. A further benefit of many protective coatings is that they are not as susceptible to damage from ultraviolet light as bituminous coatings. Contech, a North American culvert manufacturer uses Trenchcoat© in the production of its 'polymer coated steel' product range. Contech quotes a study of a 22-year-old specimen that did not display any significant ultraviolet degradation after that period of time (2005, Contech Construction Products).

The major problem with polymer application is that it takes place before pipe corrugation occurs. There is some evidence that making the extreme bends in the seams of the culvert can damage the polymer pre-coating. This imperfection may be exposed under heavily abrasive, or low pH conditions.

Epoxy Coating

Epoxy coating is a form of protective film, but is distinct from polymers such as Trenchcoat©.

Studies have indicated that epoxy coating performs better than polymer coatings in low pH discharges and in aggressive sites. However, Epoxy does exhibit poor durability when boulders are present in the bed load. Although, it possesses superior abrasion resistance to polymer coatings, it is brittle by nature, making it susceptible to impact damage.

3.2.3 Hydraulic Performance

By definition, a corrugated metal pipe has ridges and troughs on the internal (and external) walls that directly affect the hydraulic performance of the culvert. At low flow velocities, corrugations do not pose a problem. However, where higher flow rates are required, the hydraulic performance of the pipe may have to be improved. In these instances, lining the pipe (or at least the invert) with a bituminous material, concrete or even a metal liner can create a smooth barrel (refer to Figure 3-7 and Figure 3-8) with improved hydraulic performance. The lining of Corrugated Metal Pipes for improved hydraulic performance can also have the benefit of improved service life (Refer section 3.2.2).

Figure 3-7 Concrete Paving of the Invert of a Culvert (Source: AS 2041, *Buried Corrugated Metal Pipes*)

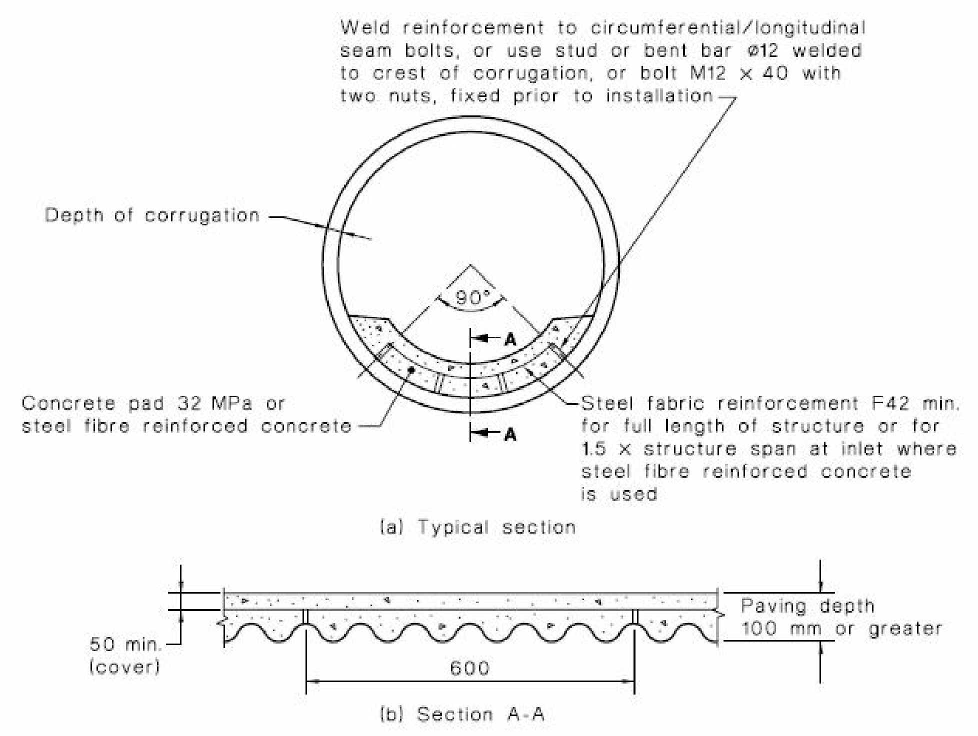
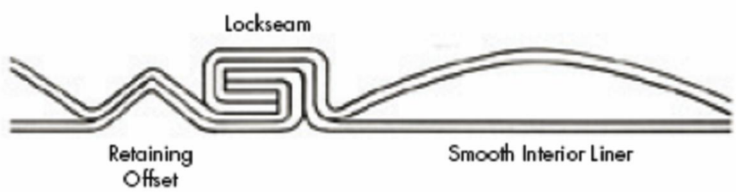


Figure 3-8 Section Through Steel Lined Corrugated Metal Pipe (Source: Contech Construction Products)



3.3 High Density Polyethylene Pipe

High Density Polyethylene (HDPE) pipe is classified as a flexible pipe and as such, it has different design considerations to reinforced concrete pipes, which are termed rigid. HDPE pipes afford a number of benefits to the designer, largely because they are chemically inert and also because of their lower relative weight. Lighter relative weight is an advantage because it reduces transport and installation costs and because lighter machinery is required to install the pipes, they can be used in a broader range of applications, where access to larger machinery may be limited. However, in areas where there is a high water table, the buoyancy of HDPE pipes may present a problem. In these cases, the designer must ensure that the weight of material above the pipe exceeds the buoyancy forces (usually with a factor of safety of two).

HDPE pipe is highly resistant to abrasion compared to other pipe materials and consequently, is frequently used where steep batters are involved. HDPE is immune to attack from Acid sulfate soils and from saline flows, which presents a significant advantage to its use in the ARB where these conditions are prevalent.

AS 2566.1 *Buried Flexible Pipelines* concerns the design of culverts from HDPE pipe.

3.3.1 Failure Mechanisms

Despite the stable chemical nature of HDPE pipe, there are limitations to its use, which relate to either the failure of the culvert or of the pavement over the conduit. Being a flexible pipe, HDPE relies on the backfill placed around it for adequate side support to resist applied vertical loads. Soft clays, expansive soils or soils with high organic matter content may be unsuitable for use as backfill. In these cases, a wide trench filled with higher quality backfill may be necessary.

The effects of pipe deflection should also be taken into account when designing an HDPE culvert. The flexible nature of the pipe means that when minimal cover is given to the culvert, it may deflect under loading, placing stress on the road pavement that may ultimately lead to failure of the road surface. High temperatures exacerbate the flexible nature of HDPE pipes as the stiffness of the plastic is reduced with increasing temperature (refer table 3-2).

Table 3-4 Effect of Temperature on the Stiffness of HDPE Pipe (Source: VicRoads)

Temperature (degrees C)	Stiffness De-Rating Factor
20	1.00
25	0.94
30	0.90
35	0.85
40	0.80
45	0.75

AS 2566.1 specifies four criteria pertaining to the design of flexible pipes:

1. Vertical pipe movement,
2. Ring stress,
3. Ring strain and
4. Buckling resistance.

Each of the above criteria has associated limits that govern the specification of pipe, however, the standard also states “Local buckling, fatigue and the effect of pipe deflection on the settlement of pavements shall be considered where appropriate” (AS 2566.1, *Buried Flexible Pipelines*).

Care should also be taken in the storage of HDPE pipes to ensure they maintain their performance after installation. Pipes should be stacked according to the manufacturer’s specification because after prolonged exposure to direct sunlight the pipes are susceptible to bowing. Additionally, the rubber rings that are used in the pipe jointing system are susceptible to UV degradation.

3.3.2 Protective Measures

The embedment characteristics of the culvert are key to ensuring its performance. Section C3 of the supplement to AS 2566.1, “Embedment Characteristics,” provides detailed advice on the appropriate material to use for bedding and backfill of flexible pipes. The basis of this advice is to provide good quality bedding material to prevent excessive or uneven settlement and to ensure proper compaction of the backfill. Compacting the backfill enables the soil to provide sufficient lateral support to the conduit and maintain the required finished road surface.

3.3.3 Hydraulic Performance

HDPE barrels exhibit extremely good hydraulic performance. Section 3.1.3 indicated that there is marginal difference in the performance of pipes with Manning’s “n” values between 0.008 and 0.012 mm. The “n” value for HDPE pipes is generally taken to be 0.008 mm, placing it at the bottom end of this range. Therefore, when superior hydraulic performance is necessary, the selection of an HDPE pipe may be prudent.

4. Culvert Design; Layout & Entry/Exit Characteristics

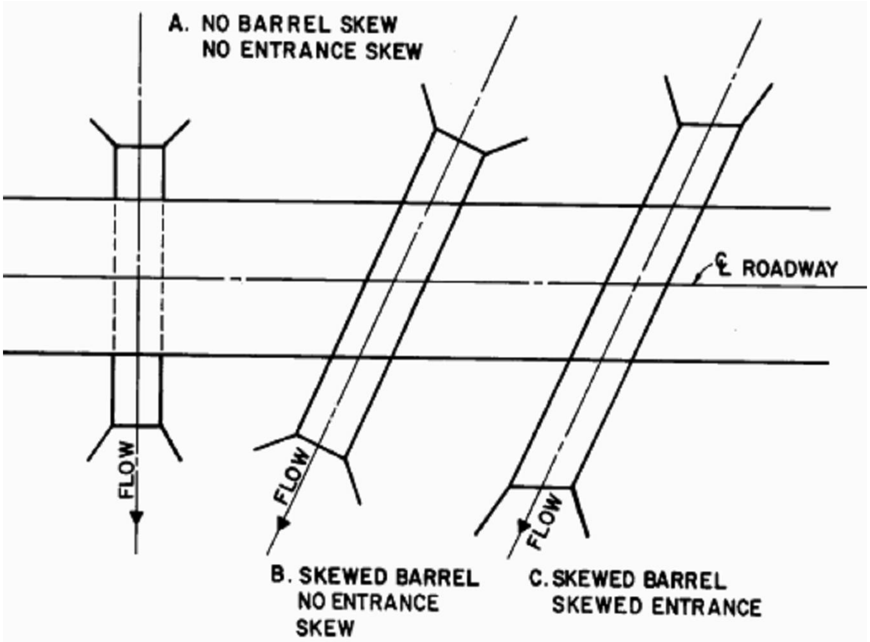
A huge number of variables impact on the design of a culvert and many of them are difficult to quantify, simply because of the imprecise nature of a stream channel. There is a multitude of satisfactory ways that a stream crossing can be designed. Different systems will give rise to different flow velocities, headwater and tailwater conditions and design flow conditions. The objective of this section is to provide a brief outline of the issues that should be considered in the design of a culvert system. More detailed information should be sought from other literature if a system is to be designed for implementation.

Culverts represent a narrowing of the natural stream path and result in a constriction to flow. Consequently, erosion often occurs at either the inlet or outlet of a culvert, or both, as the flow velocity increases in response to the constriction. This erosion in itself can affect the service life of the asset – a problem that is not just confined to the Avon River Basin. However, the deterioration of the culvert material may be accelerated as a result of erosion. Erosion can cause scour holes to form at either end of the culvert, which can cause ponding at the site of the culvert. The potentially harsh nature of the possible water flows in the ARB means that prolonged exposure of the culvert to water that has ponded around the element (rather than flowing downstream) will further degrade the structure. Additionally, high velocity, erosive flows will result in more harsh abrasion of the culvert barrel that can strip protective coatings and expose the base material to corrosive agents.

Sedimentation and the deposition of debris can result in a similar problem to erosion. The accumulation of material in a culvert that eventually impedes flow also creates ponding and means the culvert barrel is submerged for longer than is necessary.

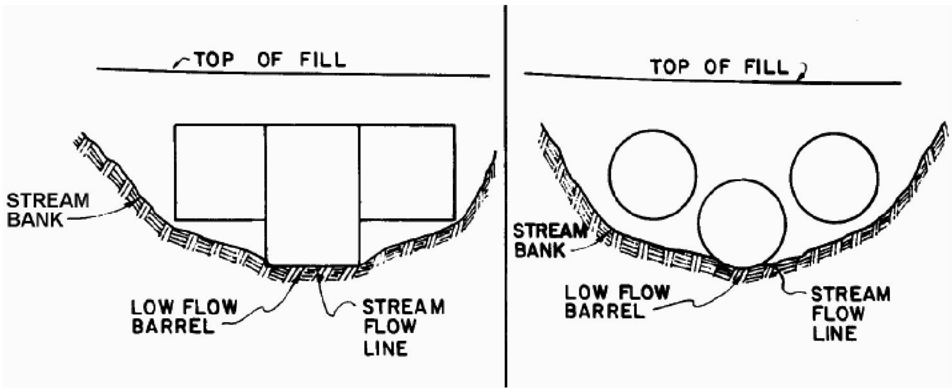
Sedimentation and erosion are affected by the size and number of barrels that are installed in a stream crossing, the orientation of the culvert/s in relation to the natural stream path, the skew of the barrel inlet in relation to the barrel and the type of inlet/entrance that has been installed (refer Figure 4-1).

Figure 4-1 Diagrammatic Explanation of Entrance and Barrel Skew (Source: Norman, Houghtalen & Johnston)



Often, when multiple culverts are installed, the middle culvert is susceptible to sedimentation. To overcome this issue, multiple barrel culverts are often installed at different levels (refer Figure 4-2). During low flows, all of the water passes through one culvert and it maintains a self-cleaning velocity. During high flows, the other barrels provide the required flow capacity.

Figure 4-2 Multiple Barrel Culverts With One Low Flow Barrel (Source: Norman, Houghtalen & Johnston)



5. Impact of Salinity on Road Assets

Saline soils and saline flows result in the premature degradation of transport infrastructure. There are multiple deterioration mechanisms related to the action of moisture and salts on transport assets. Other deleterious substances that are often associated with salt affected regions can also react with construction materials in an adverse manner.

5.1 Extent, Predicted Expansion and Cost of Salinity

Dryland salinity is already a national problem in its current state of development. Alarmingly, it is forecast to expand significantly in coming years. The National Land and Water Resources Audit (NLWRA) of 2000 indicates that 4,363,000 ha of land was affected, or at risk of salinity and this figure is expected to climb to 8,800,000 ha by the year 2050. As a rule-of-thumb, the cost of salinity is approximated at $1 million per 500 ha of salt affected land.

Table 5-1below indicates that the length of roads that lie in areas affected by salinity is predicted to increase in line with the aforementioned expansion of dryland salinity.

Table 5-1 Length of Road in Salinity Affected Regions in Western Australia (Source: NIWRA 2000)

Year	2000	2020	2050
Roads (km) within salinity affected areas	14,100	16,660	27,920

The dire economic consequences of such a rise in the length of road subject to saline soils and saline flows is highlighted by a study conducted by the Australian Bureau of Agriculture and Resource Economics (ABARE). This study examined a Victorian municipality and found that up to 20 % of a council's road and bridge expenditure could be attributed to salinity repair. The significant economic cost of salinity damage to roads is further highlighted in ARRB special report 57, which indicates that salinity and high water tables affect about 230 km of main roads in Western Australia. This figure is set to double in 10 to 20 years if current trends continue. The result is a subsequent $50 to $100 million increase in routine maintenance over this period.

5.2 Deterioration Mechanisms

The effect of rising water tables and the accompanying rise of salts can significantly reduce the lifespan of road pavements. Paul Johansen (Road Traffic Authority) indicates that salinity can decrease the lifespan of a road by a factor of seven. When the water table rises to within the capillary zone of the pavement surface, capillary action has the ability to draw salts in solution to the road surface, where they are deposited. A pavement that is within the capillary zone of influence is effectively in contact with the groundwater at the site. Indicative capillary zones for various materials are provided below:

Table 5-2 Guide to Height of Capillary Zone Above Water Table for Various Soil Types (Source: Austroads, 2004)

Soil Type	Height of Capillary Zone Above Water Table
Sands: Non Plastic Soils	1m
Sandy Clays, Silts; Plasticity Index < 20%	3m
Heavy Clays; Plasticity Index > 40%	7m

The damage caused to road pavements by salt has been the subject of numerous studies, but the exact deterioration mechanism remains the subject of conjecture because there is often a number of interlinked, contributing processes.

"Water ingress into road structures, whether it contains a high salt content or not, is the principle cause of pavement failure" in salt affected catchments (*Salinity and Rising Water Tables – Risks for Road Assets*, Austroads, 2004). If the moisture content of one of the road layers (the sub-grade, the sub-base or the base) reaches its plastic limit, then it will experience an appreciable reduction in strength and stiffness. The road layer in question then becomes susceptible to remoulding under traffic loads. The ensuing deformation under applied loading means the road layers above it have to stretch in concert with this lower layer. Continual stressing of the upper pavement results in fatigue damage that expresses itself as a general loss of cohesion in subsurface layers, or in cracking of the seal. Once the seal begins to crack, the problem is exacerbated as the pavement becomes exposed to surface water flows, which accelerate the deterioration.

Prior to pavement construction, the strength of a road sub base is generally assessed according to its California Bearing Ratio (CBR). The road design incorporates the CBR into the calculation of the required sub base thickness. A material's CBR is reduced when it becomes soaked. In many cases, roads in the ARB were designed when water tables were at lower levels, or were designed without taking expected water table rise into account. Consequently, following groundwater rise, they are inadequately designed and hence, susceptible to the type of deterioration described above.

When salt is present in the groundwater under a road, additional deterioration mechanisms are introduced. The rate of disintegration (due to the presence of salts) of a road surface is a function of the type and concentration of salt/s present and the material used in the construction of the road. Salts can cause clays in the road basecourse to flocculate, which can reduce the shear strength of the affected material. Main Roads Western Australia describes this type of distress as "fluffing or powdering of the basecourse" and states "this presents itself as a loss of all cohesion immediately beneath the surfacing. The result is a lack of bond between the surface treatment and the base and an unstable layer subject to failure under traffic" (Main Roads, 2003).

Salt is also often responsible for damage caused to bituminous surfaces. The New South Wales Department of Natural Resources identifies a two-step process for the deterioration of bituminous seals under the action of saline solution and re-crystallisation:

1. *Build up of pressure within the aggregate particles* – Salts in solution enter the pore space of the road aggregate as water is drawn toward the road surface by capillary rise. The dissolved salts react with the aggregate, forming various compounds (the composition of which, depends on the nature of the material) that occupy a larger volume than the available pore space. Consequently, a force is exerted on the aggregate, which can eventually lead to cracking of the aggregate particles, allowing more water to penetrate, which enables the process to be repeated. The continued reaction between the introduced salt and the aggregate results in a build up of pressure under the seal. This leads to deformation of the seal, which often presents as 'blisters' on the road surface. These blisters are prone to rupturing, which then allows water into the pavement and accelerated evaporation from the road surface. As well as speeding up the salt crystallisation process, loss of surface integrity is a precursor to the development of potholes and loss of pavement strength.
2. *Degradation of Aggregate Particles* – As mentioned above, the processes that result in the development of salt crystals and other compounds (that are the product of the reaction between salts and the pavement sub course) cause the eventual breakdown of the aggregate particles. This physical process increases the amount of fines present in the road material, which in turn increases its plasticity and reduces its strength. The base particles also become more rounded, which reduces their capacity for mechanical interlock. This alteration of the physical properties of the basecourse reduces the ability of the road to resist traffic loading and subsequently, the longevity of the road is reduced.

The NSW Department of Natural resources also identifies the formation of halite (sodium chloride) crystals, referred to as whiskers, directly under the seal of pavements in saline areas as a potential mechanism for road damage. Whiskers have been observed in laboratory conditions, but the frequency of their development in real-life situations remains relatively unknown. In any case, they have been shown to exert significant pressure on the seal, ultimately lifting it from the base.

In addition to damaging road base materials and potentially bituminous seals, waterlogging and salinity also have the propensity to destroy roadside vegetation. Vegetation serves the important purpose of drawing water from within the soil profile and subsequently emitting this moisture through the process of evapo-transpiration. This prevents the saturation of the pavement sub base, thus maintaining the integrity of the road structure.

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