Durability and Performance of Gravity Pipes: A State-of-the-Art Literature Review

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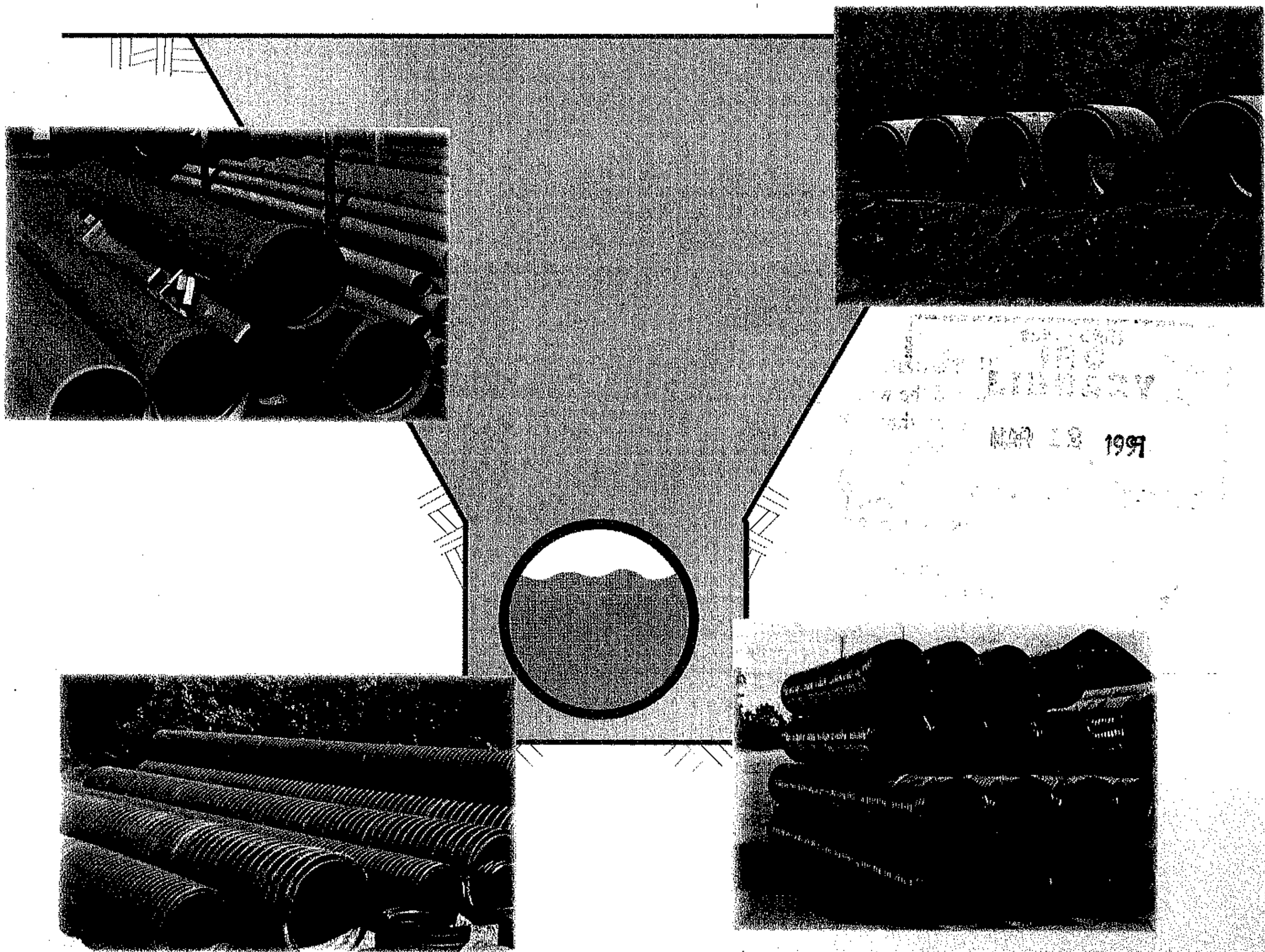

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Executive Summary

A state-of-the-art literature review was carried out on the durability and performance of gravity sewer pipes, 450 to 900 mm in diameter, made of reinforced concrete, corrugated steel, PVC and HDPE. The objective of this review was to present a perspective of the four pipe types in terms of differences in material characteristics, load-carrying mechanisms, design approaches, installation procedures, and resistance to chemical, biological and mechanical deterioration. Reinforced-concrete pipe is classified as rigid pipe, whereas corrugated steel, PVC and HDPE pipes are classified as flexible pipes. All pipes can perform well, but the conditions for satisfactory long-term performance are different and unique for each. In general, cracking is the performance criterion for rigid concrete pipe, and deflection, that for flexible pipe.

Rigid pipe is designed to be stiffer than the surrounding soil, and to resist the applied loads by its inherent strength. Flexible pipe relies on the capacity of the surrounding soil to carry a major portion of the applied load through ring deformation to activate the lateral passive resistance of the soil. As a result, backfill quality and compaction are the most important factors in ensuring satisfactory performance of flexible pipe. Rigid concrete pipe requires good embedment for load distribution; flexible pipe requires the utmost effort in backfilling and compaction, and is more prone to distresses/ failures during and after installation. Adequate QA/QC inspection during installation of flexible pipe is essential.

Corrosion and abrasion are the primary causes for distresses/failures of corrugated steel pipe. Protective coatings add only marginally to its performance. Nevertheless, corrugated steel pipe is still the dominant choice for culvert applications in Canadian highway systems.

PVC and HDPE pipes offer good resistance to chemical and biological attacks in most corrosive environments. They also have a superior abrasion resistance. Other material characteristics unique to plastic pipe include creep, brittleness at low temperatures and UV degradation. Long-term performance of plastic pipe, however, remains to be seen; it has existed for only a short time.

Reinforced-concrete pipe has a long track record of satisfactory performance in most soil conditions, according to reports about its service life. Concrete pipe has a superior impact and fire resistance, and is less sensitive to excavation for installing new pipes adjacently. However, it has been well recognized that concrete material is susceptible to chemical and biological attack. Methods for improved corrosion characteristic of concrete pipe include the use of both high-quality concrete and coatings and liners. Other innovations include flat-base pipe to deal with poor bedding conditions.

Although much information about individual pipes is available, reported comparative studies about the long-term performance of various pipes are scarce. In addition, there are no accepted definitions for service life and failure, short of collapse. There are more reported studies on culverts than on sewer pipe, possibly because of limited access to sewer systems.

1 Introduction

Given that durability is the ability to last for a long time with the original qualities retained (Ring, 1984), pipe performance and durability are of great concern to cities and municipalities in the construction of new, buried infrastructure pipeline systems. Durable pipe will minimize the cost of future maintenance and rehabilitation.

Municipal engineers involved in underground pipeline design are faced with having to choose the most suitable pipe material from among various products for a particular project. This has become more and more challenging. Not only are so many products available and new products introduced, but also engineers have to sort through claims and counterclaims of various pipe suppliers and manufacturers, or their associations, about the products (Jeyapalan *et al.*, 1997). In current practice, the choice of pipe material is mainly based on the initial material and installation costs, and on previous experience. It is encouraging to note that, according to a recent survey (NRC, 1997), an increasing number of designers consider both the initial cost and the life-cycle cost.

1.1 Scope

To achieve satisfactory long-term performance, one must understand the factors that affect performance and durability of buried pipe. Although many durability studies about individual pipe products have been reported, only a few of them are comparative (CERF, 1992). The objective of this literature review is to collect and compile information about pipe durability and performance, and to attempt to place, where possible, various factors on a comparable scale. Pipes included in this study are gravity storm and sanitary sewer pipes made of reinforced concrete, corrugated steel, PVC and HDPE, with diameters ranging from 450 mm (18 in.) to 900 mm (36 in.).

This report contains the findings for pipe durability, based on the literature review of the four types of storm/sanitary sewer pipes with respect to:

- design and products;
- effect of installation process, including excavation, bedding, backfill and compaction;
- effect of environmental conditions on pipe materials, including chemical and biological attack, abrasion, and temperature; and
- performance criteria and service life.

The results of this study aim to provide municipal engineers with perspectives on the four material types and aid them in their selection of the most appropriate pipe product for a particular project.

In Section 2, pipe products and their design are reviewed. In Section 3, bedding and backfill types and installation procedures are examined. The discussions on resistance of pipes to chemical and biological attacks, as well as abrasion and fire resistance, are presented in Section 4. Section 5 outlines performance criteria and limits, and the service life for various pipe materials. Included in Section 6 is a summary.

Note: For the sake of simplicity, the phrase "sewer pipe" used herein means culvert, storm and sanitary sewers. Distinction between the three types is made only where necessary.

1.2 Pipe Application

The main function of a sewer pipe is to transport sewage or surface water from one place to another: from collection points to an effluent treatment facility, for example, or from one side of a highway to another in a natural water course. Earlier underground pipe systems were primarily rigid and usually made of concrete. New materials such as corrugated steel, PVC and HDPE were gradually introduced into the market about 50 years ago (Uni-Bell, 1993). Currently, reinforced-concrete pipe is used for both sewer and culvert applications. Corrugated steel and HDPE pipes are mainly used for culverts; PVC pipe is used only in sanitary sewer systems.

At present, flexible pipes – mainly PVC and HDPE pipes – account for about 90% of all new installations where pipes with a diameter of less than 300 mm (12 in.) are required (Uni-Bell, 1993). According to the survey results (NRC, 1997), 58% of the large-diameter (450 to 900 mm) sewer pipes installed in the last 5 years in Canada were reinforced-concrete pipe, whereas PVC pipe made up 24.4%. For highway culverts, reinforced-concrete pipe was used for only 2% of the installations. Corrugated steel pipe had the highest culvert market share: 29% (NRC, 1997). Although HDPE culverts have been used in Ontario highways in recent years, the survey results did not include this information because it was not available.

2 Pipe Design and Products

In the design of underground pipe systems, you must recognize that an integral relationship exists between the behaviour of the pipe and the behaviour of the soil in which it is buried. On that tenet, two general pipe designs are based, namely whether the pipe material is rigid or flexible. In this review, reinforced-concrete pipe is referred to as rigid pipe; HDPE, PVC, and corrugated steel pipes as flexible pipe. This classification is consistent with that adopted by the Ontario Provincial Standards (OPSS 421, 1995), which states that flexible pipe is a pipe that can deflect more than 2% without cracking. Such a definition, though arbitrary, is widely used (Moser *et al.*, 1977).

Rigid-pipe design requires the pipe to be stiffer than the surrounding soil; it is designed and installed to resist the applied loads. Flexible-pipe design relies on the capacity of the surrounding soil to carry a major portion of the applied load. The design of the pipe products, the installation procedures, and the quality and compaction of bedding and backfill materials are all integral parts of the structural design of both rigid and flexible underground pipe systems.

In any engineering design, the particular application and performance limits of the material under consideration must be known, so that the design basis – whether flexible or rigid – can be chosen. Besides knowledge of the site conditions, a designer/engineer must have an understanding of

- the various pipe materials and products,
- the proper installation procedures and
- the influence of trench width, quality and compaction of bedding and backfill materials

to ensure a proper pipe system design.

This section discusses the design of the various pipe products and their applications within the scope of this study, but will not deal with the fabrication processes involved.

2.1 Design with Reinforced-Concrete Pipe

Rigid pipe for culverts, storm drains and sewers is designed to transmit the load on the pipe through the pipe walls to the foundation soil below. Design steps include:

1. Determine the earth load and the live load.
2. Select the bedding requirement.
3. Determine the load factor.
4. Apply a safety factor (1.0 for reinforced-concrete pipe for a 0.03-mm crack D-load, 1.5 or 1.25, depending on pipe class, for an ultimate D-load). (See Table 2.1 for details.)
5. Select the appropriate pipe strength.

Design earth loads for rigid pipe have traditionally been determined using the Marston load theory (Marston, 1930):

$$W = C\gamma B^2 \qquad (2.1)$$

where,

W = backfill load (kN/m),
C = load factor,

γ = unit weight of backfill material (kN/m^3), and
B = trench width at top of pipe (m).

Load factor and trench width are defined differently for trench and embankment installations (Marston, 1930; Spangler and Handy, 1973; ASCE/WPCF, 1982). For trench installation, the load factor (C) is defined as

$$C = \frac{1 - e^{-2K\mu'(H/B)}}{2K\mu'} \qquad (2.2)$$

where,
K = ratio of active lateral to vertical soil pressure,
μ' = coefficient of friction between fill material and sides of trench,
H = height of backfill above top of pipe (m).

As indicated by Equation 2.2, the earth load above the pipe increases as the trench width increases, until the width reaches the transition width. At that point, the vertical earth pressure in the trench condition agrees with that in the positive projection condition (Marston, 1930; Spangler and Handy, 1973; Uni-Bell, 1979; Moser, 1990; OCPA, 1986). In Figure 1, the earth load above rigid pipe is compared to that above flexible pipe.

Design bedding factors are incorporated in Marston's theory (see Equation 2.3). All of these bedding factors were obtained by comparing the results of the failure loads of individual pipes in a compression machine (three-edge-bearing test), to the failure loads of similar pipes in simulated bedding (see Table 3.2 for examples of the bedding factor). The

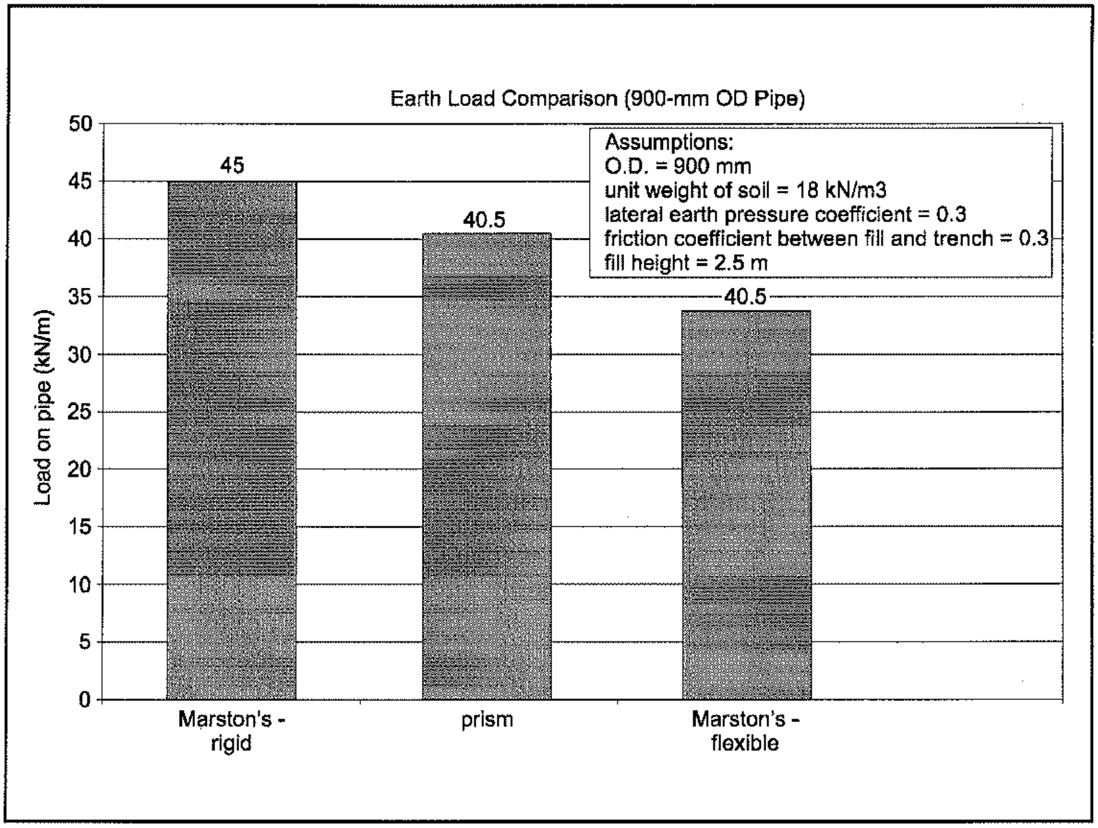

Figure 1. A comparison of earth load above rigid pipe and above flexible pipe

three-edge-bearing strength is the load per unit length required to cause crushing or cracking of the test specimen of pipe. The Marston load to cause failure is usually greater than the three-edge-bearing strength, and depends on how the pipe is bedded.

$$\text{Bedding Factor} = \frac{\text{field strength}}{3\text{–edge bearing strength}} \quad (2.3)$$

Early tests of pipes in simulated bedding (Marston and Anderson, 1913) did not incorporate the horizontal forces that provide support to the pipe, when buried in the ground. In this regard, the rigid-pipe industry (Bland and Sheppard, 1985) has sponsored research to decrease bedding factors. It should be realized that the bedding factor varies with the type of bedding selected. For a cost-effective design, either a higher bedding factor or a pipe of lower strength is used, when the bedding is of higher quality. (See Section 3.3 for further discussions on bedding factors.)

One of the recent improvements in the design of buried concrete pipe is a Soil-Pipe Interaction Design and Analysis program called SPIDA, developed through the American Concrete Pipe Association (Heger *et al.*, 1985). The pipe wall is designed to resist the moments, thrusts and shears determined by the soil-structure interaction finite-element analysis. This design software is based on a strength and crack control design procedure that was specifically designed for circular reinforced-concrete pipe (Heger, 1982). The use of SPIDA has reduced the cost of reinforcement and wall thickness in some cases.

Reinforced-concrete pipe is designed and manufactured according to the D-load specifications (CAN/CSA-A257.2-M92; ASTM C 76M-90). The D-load concept provides a strength classification independent of pipe diameter. The D-load test measures the maximum three-edge-bearing test load supported by the pipe section, before a crack occurs that has a width of 0.3 mm, measured at close intervals, throughout a length of at least 0.3 m. The ultimate D-load is the maximum three-edge-bearing test load supported by a pipe, expressed in Newtons per linear metre per mm of inside diameter. (Table 2.1 shows the D-loads of five pipe classes as given in the standards.)

Table 2.1. D-load Specification for Reinforced-Concrete Pipe (CAN/CSA-A257.2-M92; ASTM C 76M-92)

Class	To Produce a 0.3-mm Crack		Ultimate Load	
	D-Load (N/m/-mm)	Factor of Safety	D-Load (N/m/-mm)	Factor of Safety
40-D	40.0	1.0	60.0	1.5
50-D	50.0	1.0	75.0	1.5
65-D	65.0	1.0	100.0	1.5
100-D	100.0	1.0	150.0	1.5
140-D	140.0	1.0	175.0	1.25

Reinforced-concrete pipe contains reinforcing steel cages to increase its tensile strength, and is typically available in sections 2.44 m long, with various diameters and wall thicknesses. Concrete pipe and related products are produced from low-water-content (zero-slump) concrete, which is often referred to as dry-cast concrete (Willis, 1969). OPSS 1821 (1993) defines dry-cast concrete as having a slump ≤20 mm at the time of placing. Modern automated equipment is used to vibrate or compact the concrete into tubular forms. The end product is a high-quality, dense concrete pipe.

Materials for the concrete mixtures are specified in CAN/CSA-A257.2 and ASTM C 76M. A considerable part of the industry uses fly-ash from blast furnaces and silica fume additives to produce concrete with low permeability and high resistance to the acidic, corrosive environment of sewer systems. According to Rebeiz (1996), both spray coating applied to inner surfaces, and polymer-modified concrete have been used to increase corrosion characteristics of concrete pipe, although the effectiveness of such techniques is not entirely satisfactory. Neither method is commonly used in Canada.

Reinforcement designs are specified in ACI 318 and in AASHTO Section 8 - Reinforced-Concrete Design. Quality control of the finished, circular pipe is specified in CAN/CSA-A257.2 and ASTM C 655M by the D-load strength concept. Concrete pipe in North America is manufactured to design standards and quality control procedures developed by AASHTO, ACI, ANSI, AREA, ASCE, ASTM, AWWA, BNQ and CSA. During the last 20 years, a lot of effort has been expended on improving the quality and consistency of concrete-pipe manufacturing. This effort included tightening the standards and specifications for materials, dimensions and tolerances, and quality control. These standards, along with pipe associations' pre-qualification requirements, have increased the consistency and quality of products manufactured by the pipe industry, and have increased the confidence of municipal and highway engineers toward the use of these products.

Pre-qualification of manufacturers has been recently introduced in Canada, following the German quality standard (FBS). For pre-qualification, a committee is required to inspect the proponent's plant, materials used in manufacturing quality control procedures, qualifications of personnel, and the pipe units, including dimensions and tolerances. The committee in Ontario is composed of a member from each of OCPA, OPS, MEA and MTO. Upon compliance to the pre-qualification requirements, a certificate is issued, which will remain valid for 12 months. (Concrete-pipe manufacturers and associations have also produced software programs for design professionals.)

2.2 Design with Flexible Pipe

Flexible-pipe products include corrugated steel, polyethylene and polyvinyl chloride pipes for culverts, storm drains and gravity sewers.

Smooth-walled, plastic pipes were used before advances in extrusion and gluing processes allowed for the inclusion of fillers, recycled materials, ribs and profiles of various shapes and sizes. These advances allowed plastic-pipe producers to market pipes more competitively. By the mid-1980s, the ring stiffness of large-diameter plastic pipes was so low that special installation and handling procedures were required. Contractors had difficulty installing these pipes, and the resulting field performance did not meet expectations (Jeyapalan, 1990).

2.2.1 Basis of Structural Design

Flexible pipe is designed to prevent the following faults or defects:

- material degradation or environmental stress cracking,
- seam separation due to excessive ring compression,
- wall crushing due to excessive external pressure,
- buckling due to excessive external pressure and/or internal vacuum,
- excessive deflections leading to leaking joints, and
- excessive flexural and compressive or tensile strains, leading to yield.

It is also designed to transmit a major part of the load on the pipe to the soil at the sides of the pipe. Flexible pipe responds to external loads by deflection. As the load increases, the vertical diameter of the pipe decreases, and the horizontal diameter increases. The increase in horizontal diameter is resisted by the stiffness of the soil at the sides of the pipe. In this regard, there is a five-part design method for flexible-pipe design laid out in AWWA C950 to determine:

1. pipe stiffness,
2. pipe deflection,
3. pipe wall flexural strain,
4. pipe wall total strain, and
5. buckling.

In flexible-pipe design, engineering professionals must realize that the pipe-soil structural interaction is the major component of the design. The flexible-pipe industry uses Spangler's deflection equation (Equation 2.4), Watkin's strain equation (Equation 2.5) (Jeyapalan *et al.*, 1987) and Luscher's buckling equation (Equation 2.6) for most designs in North America, with the exception of metal culverts. [The development of the soil-culvert interaction design method by Duncan (1978) was a significant advance.]

$$\Delta y_s = \frac{LkP}{EI / R^3 + 0.061E'} \quad (2.4)$$

$$\varepsilon w = D_f(t/D)(\Delta y_s/D) \quad (2.5)$$

$$q_a = (1/SF)(32)^{1/2} R_w B'E'S \quad (2.6)$$

where,

- B' = soil support factor
- D = pipe diameter
- D_f = strain factor
- E = modulus of elasticity of pipe
- E' = modulus of soil reaction
- I = moment of inertia of pipe
- L = deformation lag factor
- P = load on pipe
- P_{cr} = critical buckling pressure
- q_a = critical buckling load
- R = mean radius of pipe
- R_w = groundwater factor
- S = pipe stiffness
- SF = safety factor
- t = pipe wall thickness
- ε_w = Watkins pipe wall strain
- Δy_s = change in vertical diameter

One of the assumptions for Spangler's deflection formula, and for the theory of flexible-pipe design, is that the pipe deforms into an elliptical shape with the horizontal deflection equal to the vertical deflection (Howard, 1981; Kienow and Prevost, 1983; Uni-Bell, 1982; Spangler and Handy, 1973). Field observations and measurements of satisfactory flexible pipes have confirmed that the assumed deformation is indeed elliptical, or approximately elliptical (Watkins and Shupe, 1990; Howard, 1981). Flexible pipe, however, can deform non-elliptically, if the stiffness at the sides of the pipe is large compared to the stiffness of the pipe (Howard, 1981; Kienow and Prevost, 1988), or because of non-uniform soil support around the pipe, a condition arising from improper compaction (Greenwood and Lang, 1990). Although a flexible pipe may not fail because of squaring, the squaring increases the potential of local buckling at the top of the pipe as a result of reduced buckling strength in flexible pipe (Kienow and Prevost, 1983, 1988; Jeyapalan and Boldon, 1986). Another reason for squaring of plastic pipe that should be avoided is the high strain levels caused by rectangular deformation. It may accelerate strain corrosion failure of plastic pipes (Kienow and Prevost, 1983).

When a flexible pipe is installed in a trench whose conditions with thoroughly compacted sidefills have essentially the same degree of stiffness as the pipe itself, the earth load (kN/m) on the flexible pipe can be calculated using Marston's theory (Marston, 1930; Spangler and Handy, 1973):

$$W = C\gamma BB_d \quad (2.7)$$

where,

B_d = horizontal breadth (outside) width of the pipe (m),

B, C and γ are defined as before.

Equation 2.7 provides the minimum earth load on flexible pipe (Moser, 1990). According to Moser, a more realistic design load, which is larger in magnitude than the minimum earth load, is the soil prism load (p) defined as:

$$p = \gamma H \quad (2.8)$$

where H = height of soil above the pipe

Figure 1 shows a comparison of earth loads calculated using Equations 2.1, 2.7, and 2.8.

Pipe stiffness is an important issue in the flexible-pipe industry. Terms such as stiffness factor, pipe stiffness factor, pipe class, ring stiffness constant, flexibility factor and pipe series have been developed by various pipe groups. Pipe stiffness is affected by the behaviour of the pipe material and the pipe wall geometry (smooth-walled, double-walled, corrugated, rib-walled, profile-walled, etc.). Corrugated, rib- and profile-walled pipes are designed and manufactured to minimize the use of material by increasing the section modulus of the pipe wall. Solid-walled plastic pipes are extruded. Rib- and profile-walled pipes are manufactured either by extrusion or by a combination of extrusion and a continuous winding of the specially designed profiles on a mandrel. It is estimated (Taprogge, 1981) that rib- and profile-walled pipe can provide the same stiffness, or resistance to external loading, with up to a 40% decrease in wall material compared to solid-walled pipe. The rib- and profile-walled concept was first introduced in Germany about 25 years ago (Taprogge, 1981). There are seven types of rib- and profile-walled PVC and HDPE pipe designs available in North America (Sargand *et al.*, 1996). Smaller diameter (< 375 mm), open, profile-walled pipes (truss pipes) have been filled with other materials (i.e., light-weight concrete) to increase the rigidity of the pipe wall and thus produce a semi-rigid pipe. This has led to a pipe that would crack more easily during deformation.

The soil modulus (E') used in the flexible-pipe design equations was derived from data obtained from laboratory and field tests conducted by Howard (1977) of the U.S. Bureau of Reclamation and Moser (1990) of Utah State University. In Europe, engineers use Leonhardt's factor to adjust the E' value as a function of the trench width, and the ratio of E' of the native soil (outside of the trench) to that of the backfill (in the trench). Migration of fines from the native soil into trench bedding and backfill material around flexible pipes may be of concern. There is considerable controversy in the literature regarding the selection of values for E'. Most authors agree that E' is not an intrinsic property of the surrounding soil, but is best determined through finite element back calculation from full-scale field tests. All agree that a pipe system design should be carried out by experienced engineers who are familiar with the geotechnical and structural principles of pipe design and soil-structure interaction.

Fatigue of plastic material under repeated stress applications may be a factor in the design of shallow culverts under road embankments. PVC and polyethylene pipes can fail at stresses lower than the normal strength of the material, if a repeated stress application occurs continuously at a sufficiently high frequency and magnitude (Uni-Bell, 1990). Local buckling and tearing phenomena in corrugated and profile-walled pipes have been studied by Moore (1994a, 1994b, 1996) and Moore and Hu (1995).

2.2.2 Corrugated Steel Pipe

Corrugated steel pipe is constructed from corrugated plate steel with a continuous seam. Types available are helical corrugations and annular corrugations and spirally rib-walled pipes. The seams are lock-seamed or continuously welded for helical corrugated pipe, and rivetted or spot-welded for annular corrugated pipe. Spirally rib-walled pipe is formed using the lock-seaming process. Double-walled pipe and bitumen- or concrete-lined pipe with smooth interior walls are available for improved hydraulics. Material specifications and quality control tests are specified by AASHTO, AISI, ASTM, BNQ and CSA.

Coatings

One of the biggest concerns related to corrugated steel pipe systems is corrosion. Coatings and linings to prevent corrosion, applied before installation or when in place, include zinc or aluminum (in galvanizing), polymer, Portland cement and bitumen. The coatings and linings do not significantly contribute toward strength and stiffness and are, therefore, usually ignored in calculations.

After the pipe diameter has been determined for the expected hydraulic flow, structural designs must be carried out. In corrugated steel pipe, this specifically relates to the corrugation profile and the thickness of steel. The pipe is designed to resist compressive thrust in the pipe wall and to prevent yielding, buckling or seam failures. Design criteria for corrugated steel pipe include (ASTM A 796-93; Wolf and Townsend, 1970):

- deflection of pipe, calculated using Spangler's equation (see Equation 2.4),
- wall thrust,
- critical buckling of pipe wall,
- longitudinal seam strength, and
- handling and installation strength.

Charts are available for the design of various wall configurations and thicknesses.

2.2.3 PVC Pipe

PVC pipe has been in use in North America for sewerage and drainage since 1952, but has shown its greatest expansion in use since the early 1970s. It is by far the most widely used thermoplastic pipe. Thermoplastic materials like PVC can be heated and reshaped. PVC pipe is made from a blend of materials whose major ingredient is polyvinyl chloride. Other ingredients that may be compounded with the PVC resin are stabilizers, pigments, lubricants, processing aids and fillers. Cell classification (ASTM D 1784, D 3915 and D 4396) is used to identify PVC piping materials, and required minimum property values.

Quality Control

Quality control tests include:

- extrusion quality tests (ASTM D 2152, F 1057),
- inside diameter and wall thickness (ASTM D 2122),
- the quick burst test (ASTM D 1599),
- flattening test (ASTM F 794),
- impact test (ASTM D 2444) and
- a test for pipe stiffness (ASTM D 2412).

PVC pipe is available in solid-, profile- and rib-walled configurations. Solid-walled pipe is available up to 675 mm in diameter, profile wall up to 1200 mm, and ribbed wall up to 750 mm. Uni-Bell (1995) has developed design software entitled "External Load Designs for Flexible Conduits."

2.2.4 HDPE Pipe

Polyethylene is in the polyolefin family of thermoplastics. Its use as a pipe material began as a "substitute material" for metals in the post-war years of the 1940s. The resin material used to manufacture pipe is in the form of pellets that are normally coloured black for gravity sewers, drains and culverts.

Some grades of polyethylene may crack or craze when subjected either to certain levels of stress or to certain chemicals. This phenomenon is known as environmental stress-cracking. HDPE (Type III, Class C, Category 5, P34) is considered a weather- and stress-crack-resistant material. Pipe specifications include minimum cell classifications (ASTM D 3350) and material specifications (ASTM F 894, D 1248).

Solid-walled pipe is available in diameters up to 1200 mm, and profile-walled pipe up to 3000 mm. Polyethylene pipes of such a large diameter, however, have a very low pipe stiffness, and care must be taken in handling and placing them to avoid over-deflection and buckling, particularly while the soil is being placed and compacted around the pipe.

2.3 Design Considerations for Creep Characteristics

Creep is the continuing deflection of a pipe, over time, under sustained loading. With all plastic, flexible pipes when subjected to a load, the modulus of elasticity decreases with time. This results in increasing pipe strains, increasing vertical deflections and decreasing pipe stiffness (Jeyapalan and Boldon, 1986). (Table 2.2 shows the long-term modulus of elasticity for PVC and HDPE pipe.) The short-term modulus of HDPE is given in the range from 690 to 900 MPa (100,000 to 130,000 psi), whereas the long-term modulus varies from 140 to 210 MPa (20,000 to 30,000 psi) (PPI, 1993). It is the long-term modulus of elasticity values that should be used in calculating long-term pipe deflections and critical buckling pressures.

Table 2.2. Long-term modulus of elasticity (Kienow and Prevost, 1983)

Material	Modulus of Elasticity after 50 Years
PVC	33% of initial
HDPE	16% of initial

In addition, flexible pipes continue to deflect after they have been installed and a vertical load (trench fill or embankment fill) has been fully applied. And they do so until the soil around the pipe has fully densified (compacted and consolidated). These construction-induced deflections need also to be taken into consideration during design.

2.4 Summary

The design and installation of pipe systems for gravity pipelines are based on two design concepts: either rigid or flexible. The rigid-pipe design concept requires that the pipe be designed so that it is stiffer than the surrounding soil and resistant to applied loads through its strength. Its strength is, of course, affected by the quality of the concrete, the wall thickness and the steel reinforcement. The flexible-pipe design concept allows the pipe to deform and relies on the capacity of the surrounding soil to support a major portion of the applied load. Pipes of different strengths, different wall configurations and different stiffnesses are being manufactured. (Table 2.3 summarizes the design differences between rigid concrete pipe and flexible pipe.)

Other design concepts for semi-rigid or very flexible pipe are being proposed, but they have not influenced the basic design and installation procedures (Howard, 1996). It is well recognized that the design of the pipe products, the installation procedures, the quality and compaction of bedding, the choice of backfill material are all integral parts of the structural design of both rigid and flexible underground pipe systems. It is also important to point out that a properly designed and installed pipe, regardless of pipe material, will perform satisfactorily.

3 Installation Procedures

The literature review of engineering issues related to installation of concrete, PVC, HDPE, and corrugated steel pipes for sewers (sanitary

Table 2.3. Comparison of pipe design

Parameters	Rigid Pipe (Concrete)	Flexible Pipe
Earth Load	Marston load	Prism load
Load Carrying Mechanism	Support earth load by inherent strength in the pipe material.	Rely on lateral soil resistance for stability and support to carry earth load.
Bedding & Backfill	Important in distributing the load and minimizing stress concentrations.	Critical, and part of pipe load-carrying system.
Design Approach	Strength governs. Three-edge-bearing strength is used. Earth load is determined by Marston's equation.	Deflection governs. Strain is a critical factor. Deflection can be determined by Spangler's equation.
Creep	Negligible	All plastic pipes have decreasing modulus of elasticity, with time, when subjected to sustained loads. Long-term modulus (% initial value) PVC HDPE 33% 16%

and storm) and culverts is presented in this section. In general, pipe installation by trenching consists of excavation, preparation of pipe bedding, placement of the pipe, joining the pipes, and backfilling. Installation in embankment conditions is similar, except that shallow excavation may be required only to improve the bedding (see Figure 2). Installation must be carefully designed and planned, since it has a significant impact on construction costs and pipe performance. For example, trench width, bedding, and haunching are important factors that control the stresses and deformation of the pipe. Pipes are also subjected to adverse conditions (low temperature, impact loads, and ultraviolet radiation) at the construction site.

3.1 Joints

All sewer pipes are manufactured in a limited length (normally 2.4 m) and are joined in trenches to form continuous conduits. Light-weight pipes have fewer joints than heavy-weight ones. These joints must provide:

1. resistance to infiltration of groundwater or soil,
2. resistance to exfiltration,
3. flexibility to accommodate lateral deflection or longitudinal movement without creating leakage problems,
4. resistance to shear stresses between adjacent pipes,
5. hydraulic continuity, and
6. ease of installation.

3.1.1 Rigid Concrete Pipe

Large-diameter, precast-concrete pipe is constructed in short lengths to reduce the weight of the pipe for easy transportation, storage and placement. This means that there are more joints in a concrete pipe system than in a flexible-pipe system of the same linear length. More joints allow the pipe system to be less rigid longitudinally. On the other hand, the effort required to join concrete pipe sections in the trench is more than that required to join flexible-pipe sections (Jeyapalan and Boldon, 1986). Joint configurations include bell and spigot, or tongue and groove joints, with some packing such as rubber gaskets, cement mortar, a preformed or trowel-applied mastic compound. Rubber gaskets are specified by CAN/CSA-A257.3, and ASTM C 443, C 877.

3.1.2 Flexible Pipe

PVC pipe is joined either with a compressed gasket or with solvent cement (Howard, 1996). Corrugated or profiled HDPE pipe can be joined with coupling bands and preformed gaskets, whereas plain HDPE pipe can be joined with either gasketed bell-spigot joints or couplings. Although not often used for gravity pipe applications, butt fusion is another method of joining HDPE pipe sections (Howard, 1996).

For corrugated steel pipe, common joining methods include steel coupling bands with neoprene gaskets or bitumen sealants (NCSPA, 1989), flanges, sleeves and threaded sections, and butt welding (Howard, 1996). Gaskets include O-rings, sleeves (sponge or neoprene), strips (butyl or neoprene) and mastic sealant. Joints must be designed according to: AASHTO Bridge Design Specification Section 26.4.2. They must have adequate shear strength, flexural strength, tensile strength, joint overlap, and soil- and watertightness.

The light weight of plastic pipe, compared to that of concrete pipe, permits the use of longer sections, and the pipes can be cut at the job site for length adjustment, resulting in less joining effort and added flexibility during installation.

3.2 Selection of Trench Width

The geometry of a trench (bottom width, depth, and slope) has a significant impact on the construction cost and design of the pipe. In particular, trench width influences the earth pressures and the stiffness of the soil that support the pipe (Hodges and Enyart, 1993; McGrath *et al.*, 1990). According to McGrath *et al.*, (1990), if the native soil is soft and the trench width is less than five times the pipe diameter, the composite soil stiffness will be

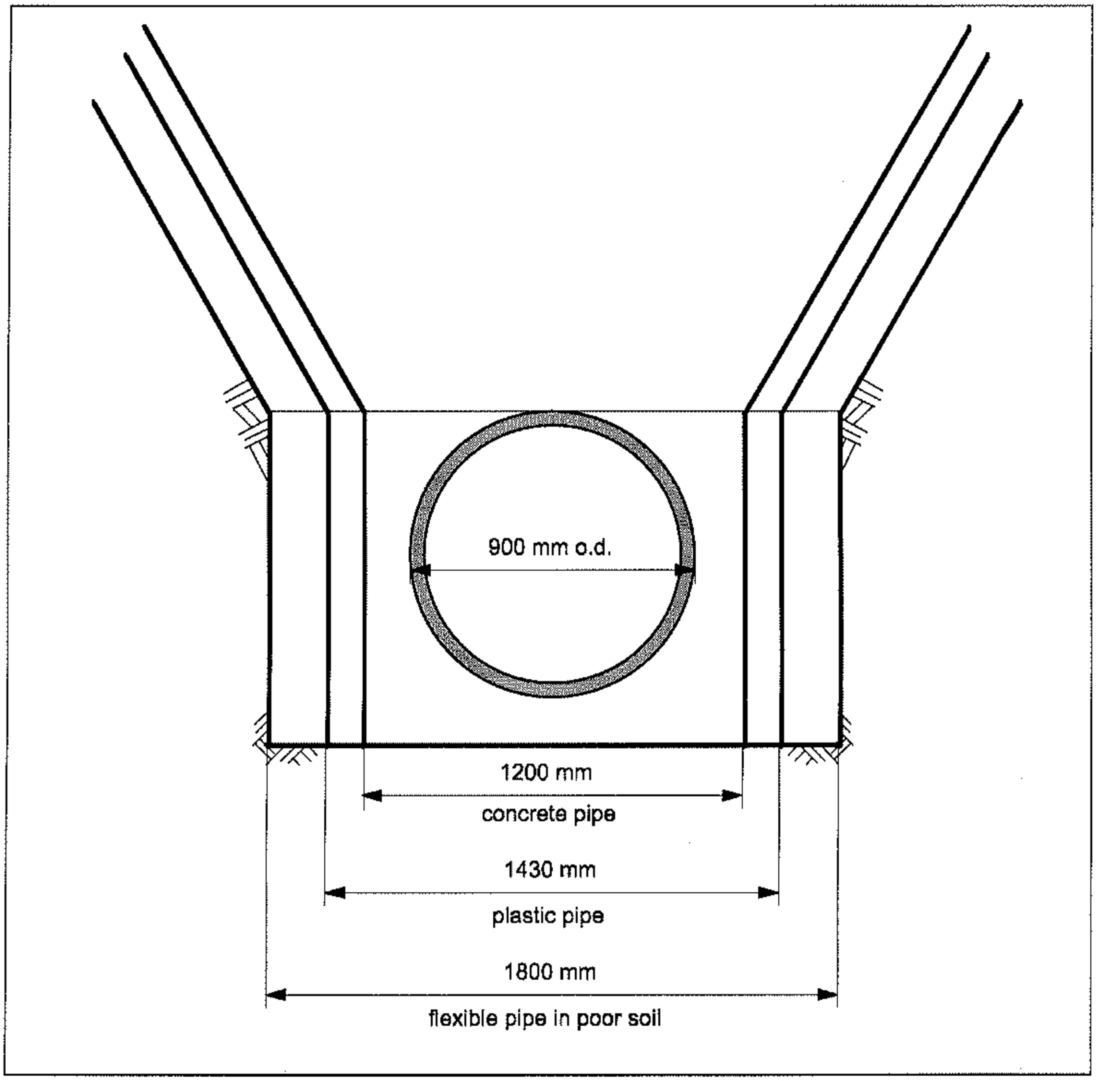

Figure 2. Illustration of trench backfill terminology

lower than the stiffness of the backfill. It is, in general, suggested to make the trench as narrow as possible to reduce the earth load, while maintaining reasonable work space for proper compaction. The trench width in this report refers to the width at the top of the pipe (see Figure 2). For backfill terminology, refer to ASTM D 2321-89, and for terminology for the pipe, refer to ASCE Standard (1993).

3.2.1 Rigid Concrete Pipe

As the trench width increases, the vertical earth pressure on a rigid pipe increases until the width reaches the transition width. At that point, the vertical earth pressure in a trench condition agrees with that in a positive projection condition (Spangler, 1973; Spangler and Handy, 1973; Uni-Bell, 1979; Moser, 1990). The Concrete Pipe Design Manual (OCPA, 1986) states that the backfill load depends directly on the trench width. The designer usually assumes a certain trench width to determine the earth load and then selects a pipe strength capable of withstanding this load. The maximum trench width is usually established on the plans or standard drawings.

Where the maximum trench width is not indicated, the width should be as narrow as possible, with adequate side clearance to ensure proper compaction (OCPA, 1986). The Concrete Pipe Handbook (ACPA, 1988) suggests that the side width should not be more than one-third of the inside diameter (ID), and never less than 150 mm.

ASCE Standards (1993) for concrete pipe, on the other hand, provide a different guideline for trench width. The standard recommends four types of backfill methods where the quality of the embedment increases from Type-4 to Type-1. The low-quality embedment, such as Type-4, requires less compaction, while it requires higher pipe strength. However, the minimum clearance on each side of the pipe is the same for all four types: one-sixth of the outside diameter (OD). Thus, the trench width depends only on the pipe diameter and not on the type of backfill methods, even though it is expected that Type-4 requires the least trench width among the four types, since Type-4 requires no compaction.

Example for Concrete Pipe

(ASCE Standards, 1993):
Concrete Pipe OD = 900 mm
Minimum trench width = OD + 300 mm
= 900 +300 = 1200 mm

3.2.2 Flexible Pipe (HDPE, PVC, Corrugated Steel Pipes)

Although the earth load on a flexible pipe increases as the depth increases, it is less than that acting on a rigid pipe, according to the theory developed by Marston (1930). The installation guide for polyethylene (PE) pipe states that widening the trench does not cause the earth load to be greater than the prism load on the pipe (see Equation 2.8), and that the trench width is determined by practical considerations for allowing sufficient work space (PPI, 1996). Similarly, the earth load may be conservatively taken as the soil prism load for the design of PVC and corrugated steel pipes (Moser, 1995; NCSPA, 1989; ASTM A 796-93; Uni-Bell, 1993).

A minimum trench width for the embedment of plastic pipe is required to provide adequate work space for careful compaction. ASTM D 2321-89 states that the minimum trench width should not be less than the greater of either the outer diameter (OD) of the pipe plus 400 mm, or the OD times 1.25 plus 300 mm. A slightly smaller trench width (460 mm plus the OD) is recommended for PE pipe by the Plastic Pipe Institute (PPI, 1996). For corrugated steel pipe, trench width should be as narrow as possible (NCSPA, 1989), however, no specific methods for determining the width are indicated. Watkins (1995) examined the trench width requirement for flexible pipe installed in poor native soils. He concludes that in poor soils, a minimum trench width of sidefill of OD/2 from the pipe to the walls of the trench, or from the pipe to the windrow slopes of the embedment in an embankment, should be used for flexible pipe.

Example for Plastic Pipe

Plastic pipe OD = 900 mm
ASTM D 2321-89:
a) OD + 400 = 900 + 400 = 1300 mm
b) 1.25(OD) + 300 = 1.25(900) + 300 = 1425 mm
$\therefore$ *Minimum trench width = greater of (a) and (b) = 1425 mm*
PPI (1996):
Minimum trench width = OD + 460 = 1360 mm

Watkins (1995) flexible pipe, OD = 900 mm:
Minimum trench width = 2(OD) = 1800 mm

These guidelines do not take into account the stability of backfill and natural soils. Shariff and Chambers (1991) suggest that the ASTM standard be revised to specify the minimum trench widths, depending on the stability of the backfill materials and native soils. (Figure 3 shows the comparison of trench width for concrete, PVC and HDPE pipe.)

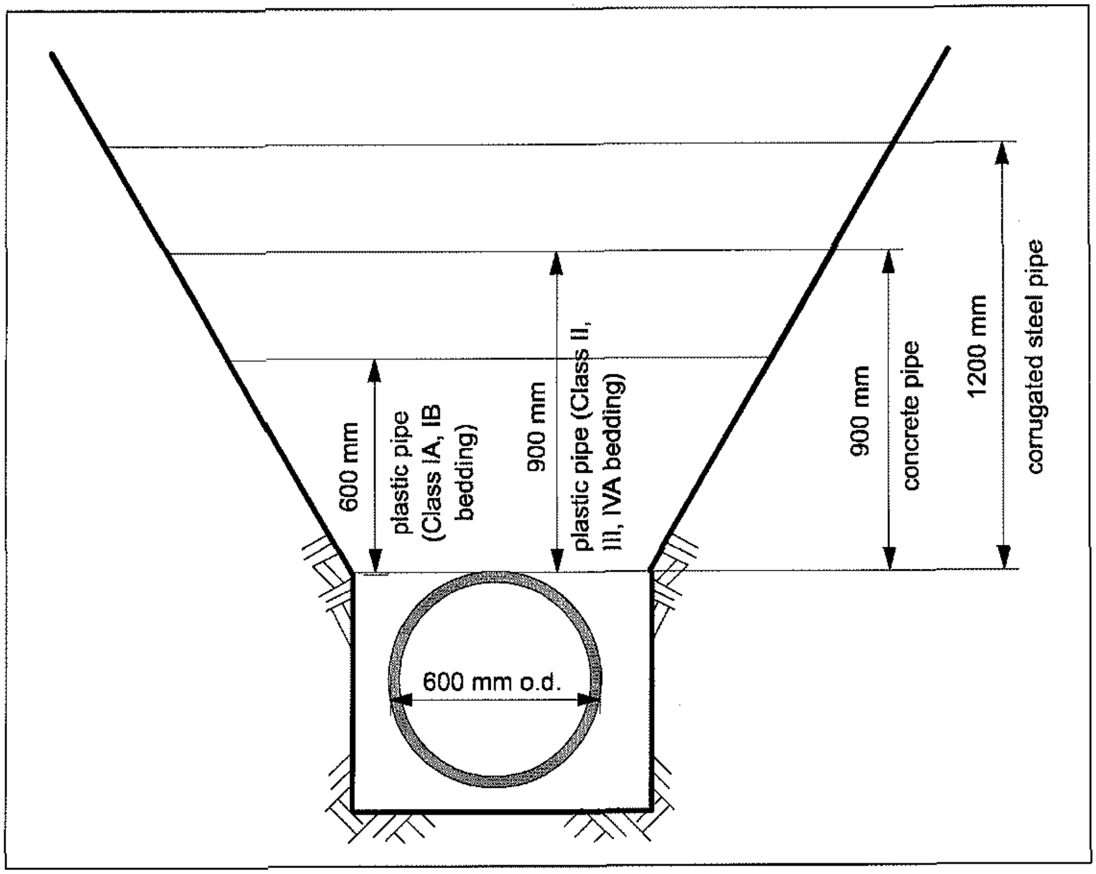

Figure 3. A comparison of trench width for concrete, PVC and HDPE pipe

3.3 Bedding and Backfilling

Bedding (or embedment) and backfilling (initial and final backfilling) is a critical procedure for trench or embankment installation, not only to ensure the structural stability of the pipe, but also to prevent distresses to the adjacent surface structures. As well, the selection of the bedding materials and the compaction methods affects construction costs. Low-quality bedding materials, though less expensive, require more compaction effort and the use of a stronger pipe. The designer may also consider using controlled low-strength material (CLSM or unshrinkable fill), if the native soil is poor, and if it is more expensive to import granular materials. Recommended backfilling practices and past studies for rigid and flexible pipes are summarized and compared in this section.

3.3.1 Rigid Concrete Pipe

The supporting strength of buried concrete pipe depends on the quality of contact between the pipe and the bedding (Hodges and Enyart, 1993). Compaction and materials below the springline of a concrete pipe have a significant effect on the pipe, compared to those above the springline to the top of the grade level (Meyer *et al.*, 1993). This is why standards and manuals provide detailed compaction guidelines for the haunching and bedding regions.

Of the four different types of bedding methods specified in the ASCE Standards (1993), the lowest class (Type 4) requires only low-quality materials with no compaction (except CL soil backfill), whereas the highest class (Type 1) requires well-graded sand compacted to 95% Standard Proctor (see Table 3.1). (Soil type symbols used here are according to ASTM D

2321-89). These bedding types apply to both trench and embankment conditions.

Note that the use of different bedding types results in different earth pressure distributions around the pipe. Therefore, pipe strengths need to be designed based on the bedding type. The earth pressure distributions for each embedment type are available in the ASCE Standards, based on theoretical and experimental studies (Heger *et al.*, 1985). The standards indicate that a lower-class type of bedding requires higher pipe strength, or vice versa. Since cost to achieve high soil stiffness is a major economic factor (McGrath *et al.*, 1990), this lower-grade of bedding will be advantageous when high-quality material is costly to obtain. A successful case history of using the lower-grade bedding (Type 4) was reported by Meyer *et al.* (1993).

Table 3.1. ASCE (1993) Standard installation type and specified compaction

Embedment Type	Haunch and Outer Bedding
1	95% SW*
2	90% SW, or 95% ML
3	85% SW, 90% ML or 95% CL
4	no compaction required except CL, use 85% CL

*Soil type symbols according to ASTM D 2321-89

Special care is required for the middle bedding (underneath the pipe invert shown in Figure 2), in which the soil has to be kept loose in order to transfer the loads to the haunch area, thereby reducing stress concentration at the invert of the pipe (ASCE Standard, 1993; Meyer *et al.*, 1993). Excessive compaction of the middle bedding and insufficient compaction of the haunch area can result in unnecessary pipe cracking (Wilson, 1985).

The traditional methods of concrete pipe installation, as described in the handbooks (ACPA, 1988; OCPA, 1986), also provide four major bedding types: Type A to D (see Table 3.2). Type A is referred to concrete bedding and haunching, Type B and C specify granular bedding. Type D is a flat bottom with little requirement to shape the foundation. Each bedding type is associated with a different bedding factor, which determines the required pipe strength measured by the three-edge-bearing test. To obtain the required pipe strength, the estimated vertical load on the pipe is divided by the bedding factor. The higher the bedding factor, the lower the required three-edge-bearing strength. For example, Type D low-quality bedding has a low bedding factor and, therefore, requires a pipe with a high three-edge-bearing strength. Thus, the designer has the option to select a low-quality bedding with a high-strength concrete pipe, or vice versa.

Table 3.2. OCPA (1986) Bedding type and bedding factor

Bedding Type	Bedding Factor
A	2.8 to 4.8*
B	1.9
C	1.5
D	1.1

* Depending on amount of reinforcement in the concrete bedding or arching

These four bedding types also apply to the embankment installation. However, for Type B and C, two additional options of bedding are provided: one is for shallow bedding with shaped foundation, while the other specifies bedding up to the springline.

3.3.2 Flexible HDPE, PVC and Corrugated Steel Pipes

The stability and load-carrying capability of flexible pipe depend on the lateral support of sidefills. Satisfactory performance of flexible pipe requires careful installation procedures for bedding, haunching, backfilling and compaction around the pipe. While requiring adequate compaction for long-term performance, flexible pipe can be distorted beyond the specified limits through too much compaction (Uni-Bell, 1982; Howard, 1981). It is essential to have adequate on-site inspection during the installation of flexible pipe to ensure the required level of compaction and uniform deformation of the pipe, while maintaining the degree of deflection within the limits. Zorn and Berg (1990) conducted a field test of thin-walled PVC pipe (110 mm, t/D = 0.024) and found that the compaction-induced deformation was the principal deformation component during trench reinstatement. The magnitudes of compaction-induced deformations, however, were not reported. Although Kawabata and Mhori (1995) monitored the deflection of a polyethylene pipe during installation, using 80-kg tampers, the compaction-induced deflection was not differentiated from that due to the earth load. A case history of excessive deflection of a corrugated steel pipe was reported by Sehn and Duncan (1994). The corrugated steel pipe (1830 mm in diameter), buried at a depth of 5 m, deflected by 14% (of nominal diameter) during construction and had to be replaced. The excessive deflection was attributed to a significant reduction in the lateral support strength of silt, due to the vibration effect. McGrath and Selig (1994), on the other hand, reported a case of excessive upward deflection of a flexible, reinforced, thermoplastic pipe. This pipe (3600 mm in diameter) deflected beyond the specified limit of 3%, because of excessive compaction of the haunch zones, something that should have been more carefully monitored during construction.

The long-term deflection of flexible pipe is controlled by soil stiffness, rather than the pipe flexural stiffness (McGrath *et al.*, 1990). For example, polyethylene and PVC pipes may deflect beyond the 7.5% limit (ASTM D 3034-93), if the compaction of the embedment is insufficient (Lang and Howard, 1985; Howard, 1990). Preparation of the haunch zone is particularly important, because the contact area between the bedding and the pipe is a major factor that controls the deflection of the pipe (Spangler, 1973). Selection of the backfill material is also important from an economical point of view. Poor, fine-grained soil is, for example, inexpensive, but expensive to compact, whereas compaction cost of coarse-grained soils is low, but the material is expensive (Selig, 1988). In addition, the use of poor materials leads to the requirement for stiffer (or thicker) pipes, which may cost more. Detailed backfill methods for thermoplastic pipes (PE and PVC pipes) are given in ASTM D 2321-89, in which backfill soils are classified into five major types, and their recommended usage is given for different backfill areas (see Table 3.3).

One of the issues regarding rib- and profile-walled pipe is the relationship between the geometrical design of the pipe wall and the gradation of the backfill (Sargand *et al.*, 1996). This study found that poor compaction around the pipe may occur, if the rib/corrugation spacing is the same as the maximum particle size. The actual contact area between the pipe and the backfill was the smallest under this condition. This poor side compaction resulted in a large initial pipe deformation rate, until the backfill became denser as the springline region moved outward.

Table 3.3. ASTM D 2321-89 Bedding class for plastic pipe

Class	Description
IA	manufactured aggregates: open-graded, clean
IB	manufactured, processed aggregates, dense-graded, clean
II	coarse-grained soils, clean, (GW, GP, SW, SP) or coarse-grained soils, borderline clean with fines (GW-GC, SP-SM)
III	coarse-grained soils with fines (GM, GC, SM, SC)
IVA	fine-grained soils (inorganic) (ML, CL)
IVB	fine-grained soils (inorganic) (MH, CH)
V	organic soils, or highly organic (OL, OH, PT)

For corrugated steel pipe, general recommendations such as avoiding the use of poor soils and performing adequate compaction are stated. However, configuration of bedding, haunching, final backfilling and materials are not specified in detail (ASTM A 796-93; NCSPA, 1989; Wolf and Townsend, 1970).

The quality of backfilling is crucial not only for the pipe, but also for the adjacent surface structures. Excessive settlements may occur because of inadequate compaction and the use of poor backfill materials (Eugene, 1972; Cameron Advisory Service Ltd., 1985; Johnson, 1992). Note that large deflections of large thermoplastic pipe itself may lead to excessive surface settlements (Erdos, 1990). The deflection limit for thermoplastic pipe is established not only to prevent distress to the pipe but also to limit surface settlements. However, no quantitative studies on the effects of deflection of large thermoplastic pipe on the surface structures have been reported.

General principles for the backfilling operation apply to both trench and embankment installation. There are, however, no manuals or handbooks available that describe the specific procedures for installing PE pipe under embankment conditions. Several recommended bedding procedures for corrugated steel pipe for compressible soils or hard rock are available (ASTM A 796-93; NCSPA, 1989; Wolf and Townsend, 1970).

3.3.3 Use of Controlled Low-Strength Material

Construction costs associated with backfilling may be reduced by using a controlled, low-strength material (CLSM). This material, also known as unshrinkable fill, is a mixture of Portland cement, aggregates, water, and optional admixtures (ACI committee, 1994). It is normally designed to have a compressive strength of less than 0.4 MPa, so that trenches can be easily re-excavated for repair and renewal. Howard (1994a, 1994b) describes the use of CLSM for both rigid and flexible pipes to fill the haunch area to simplify the backfilling procedure. A successful case history of using CLSM as bedding for concrete drainage pipe (380 to 2,400 mm in diameter) is reported by Clem *et al.* (1994). CLSM contributed to reducing the installation cost because no compaction was required, and because the trench was kept narrow (150 mm wider than the pipe). Care must, however, be taken when using CLSM in cold regions because its use may result in differential frost heave and freezing of water in pipes due to its relatively high thermal conductivity (Rajani *et al.*, 1995). Another problem is that the use of CLSM tends to float the pipe, particularly if the pipe is light-weight, such as plastic and corrugated steel pipes. It may be necessary to place CLSM in several steps to prevent flotation.

3.3.4 Comparison of Flexible and Concrete Pipes

The quality of bedding and haunching has significant effects on the stresses and deformation of both flexible and concrete pipes. Flexible pipe cannot maintain its structural stability and load-carrying capability without adequate support from the surrounding soils. By contrast, concrete pipe is basically designed to carry the loads itself. In addition, uniform elliptical deformation of flexible pipe is critical in maintaining its stability. Hence, careful backfilling and quality control are essential for installing flexible pipe, but are less stringent for concrete pipe. With concrete pipe, the designer can choose a low-quality backfill with a high-strength pipe, or vice versa, to arrive at an economical installation, while assuring adequate performance of the pipe and the reinstated trench. These general principles of backfilling apply to both trench and embankment conditions. No manuals or handbooks are available that describe the installation procedures for PE and PVC pipes in embankment conditions. Such guidelines may be needed in the future, since compaction in the absence of a trench wall may require different procedures. The use of CLSM may reduce the installation cost for both flexible and rigid pipes. However, flotation may be a problem in the case of flexible pipe, and frozen service may be of concern for buried pipe in cold regions.

3.4 Minimum Cover Before Use of Heavy Compactor

Field tests and analyses suggest that the use of a heavy compactor for backfilling may induce considerable stresses and deformations in the pipes (Duncan and Seed, 1986; Kuraoka and

Rajani, 1996). The thickness of the soil cover is the dominant factor that controls the intensity of the load imposed on the pipe. The finite element analyses performed by Seed and Duncan (1985) indicate that a compactor operated over a 600-mm cover produces much less compaction-induced pressure than the same compactor operated over a 300-mm cover. These studies lead to guidelines for minimum cover thickness for the initial backfill. For example, the Ontario Provincial Standard (OPSS 514) stipulates a minimum cover of 900 mm for all types of pipes, whether trench or embankment conditions.

Cover thickness affects the degree of compaction of the first backfill layer above the pipe, because the compactability depends on the lift thickness. A lift thickness of 300 mm is recommended for both flexible and rigid pipes (Ontario Provincial Standards, 1995), which is consistent with the findings of Fukuoka *et al.* (1987). A lift thickness of soil greater than 300 mm is not compacted well, when a light manual vibratory compactor is used.

3.4.1 *Concrete Pipe*

The ASCE standard recommends a minimum cover thickness of 900 mm or one pipe diameter, whichever is greater.

For OD = 600 mm,
minimum cover = greater of 900 mm
or OD = 900 mm

This minimum cover is consistent with the OPSS 514, and is found to be conservative according to a field test performed by Poucher *et al.* (1976). This field test was carried out in recognition of fine-cracking in installed pipes manufactured in conformance with the ASTM C 76 standard, and having passed the required plant load bearing tests and inspections. One possible contributing factor to the cracking was the effect of vibratory compaction. Reinforced-concrete pipe of 1370 mm (54 in.) in diameter was subjected to vibratory compaction loads while varying the backfilling material, lift thickness, and methods and degree of compaction. Of particular concern was whether the pipe would crack under vibratory compaction. The minimum cover used for the test was 300 mm. The cover thickness was found to be the dominant factor that determines the dynamic load acting on the pipe. The stresses induced by the dynamic load with a 300-mm cover were 2.5 times those with a 900-mm cover. However, no cracking was observed in all cases.

3.4.2 HDPE, PVC and Corrugated Steel Pipes

For thermoplastic pipe, the minimum cover thickness is recommended to be between 600 mm and 900 mm, depending on the class of embedment (see Table 3.3). Corrugated steel pipe, on the other hand, requires a minimum cover of 1200 mm prior to the use of heavy construction equipment above it (Wolf and Townsend, 1970). The National Corrugated Steel Pipe Association (NCSPA, 1989) indicates that the minimum cover ranges from 700 to 1400 mm, depending on the maximum axle loads and the pipe span.

For plastic pipe of OD = 600 mm:
minimum cover =
greater of 900 mm and OD
therefore 900 mm (Class II, III, IVA)
For corrugated steel pipe of OD = 600 mm
minimum cover = 1200 mm

Minimum Cover ($H_{minimum}$) for Plastic Pipe of OD = 600 mm:
= greater of 600 mm and OD 600 mm (Class IA, IB)
= greater of 900 mm and OD 900 mm (Class II, III, IVA)
Minimum Cover ($H_{minimum}$) for Corrugated Steel Pipe of OD = 600 mm:
= 1200 mm

3.5 Other Factors During Construction

During construction, sewer pipes may be subjected to adverse conditions such as impact loading, low temperatures and ultraviolet radiation. These factors are briefly discussed in the following text.

3.5.1 Impact Resistance

During construction, pipes are required to withstand forces that are normally expected during shipment, handling and installation. For example, a pipe may be subjected to impact forces imposed by construction machinery or falling hard objects.

Concrete pipe is rigid, and can withstand normal handling and installation forces. The dynamic compressive strength of concrete is actually higher than the static strength (Freedman, 1985). However, rough handling can cause cracking in concrete pipe.

Corrugated steel pipe is required to withstand impact loads during handling and installation (ASTM A 796-93). The impact resistance for corrugated steel pipe is defined as handling and installation strength, and measured by the flexibility requirement. Pipes designed and manufactured according to the standard should have adequate impact resistance.

PVC has a low impact resistance: 0.026 Nm/mm (0.5 lbf•ft•in^{-1}) according to ASTM D 256 (Titow, 1990). Insufficient fusion of the PVC feedstock during pipe extrusion and non-homogeneity in both additive and filler dispersion also have negative effects on the mechanical strength of the pipe (Titow, 1990). The impact strength of PVC can be increased up to about 1.07 Nm/mm (20 lbf•ft•in^{-1}) during extrusion, by blending the PVC feedstock with an impact modifier, such as acrylonitrile-butadiene-styrene (Titow, 1990). Impact modifiers may, however, reduce chemical resistance, increase susceptibility to oxidation, and increase permeability.

HDPE. The impact resistance of HDPE ranges from 0.27 to 0.80 Nm/mm (from 5 to 15 lbf•ft•in^{-1}) (Vasile and Seymour, 1993), that is 10 to 30 times that of PVC. In practice, this greater resistance translates into relatively low breakage rates during handling and installation. However, the impact resistance of HDPE can be reduced significantly, much like that of PVC, by oxidation due to sunlight or by overheating during extrusion (Moore *et al.*, 1988).

3.5.2 Temperature Effect

Guidelines and handbooks for installation and design of concrete pipe do not address the effects of temperature on its strength characteristics. However, it is well established that both compressive and tensile strengths of normal-strength concrete increase substantially (50% or more) as temperature decreases from room temperature to temperatures ranging from -20 to -30°C (Freedman, 1985; Lee *et al.*, 1989; Miura, 1989).

The impact strength of concrete is found to increase at freezing temperature. Reinforced- and unreinforced-concrete beams were tested for bending (with a falling weight), and the reinforcing bar was tested with the Charpy notched bar impact bend test (Kivekas and Korhonen, 1986). The impact strength of the unreinforced-concrete beam at -40°C increased by 100% relative to the impact strength at 20°C. However, the reinforced concrete did not exhibit a pronounced increase in the impact strength at low temperature (-40°C), because of the ductility provided by the reinforcing steel. Hence, it has been concluded that reinforced-concrete pipe will not break in a brittle manner under impact loads.

The impact strength of PVC decreases as the temperature decreases (AWWA M23). At 0°C, the impact strength is 70% to 80% of that obtained at 23°C. Within the range from 23 to 16°C, the strength and the elastic modulus are found to increase (AWWA M23, 1980). While the minimum installation temperature of -18°C is recommended (PPI, 1990), great care must be taken when installing PVC pipe at sub-zero temperatures. Polyethylene, however, is reported to be relatively resistant to impact loads at sub-zero temperatures (PPI, 1993). A minimum installation temperature of -34°C is recommended for polyethylene (PE) pipe (PPI, 1990). The reference temperature for the strength and elastic modulus measurement is 23°C.

While the impact strength of a metal decreases with temperature (Hertzberg, 1989), the effect of low temperature on the impact strength of corrugated steel pipe has not been addressed in manuals or handbooks.

3.5.3 Effect of Ultraviolet Radiation

Plastic pipe, when exposed for a long time to ultraviolet (UV) radiation, which occurs at the ends of culverts, can incur surface damage (UV degradation or photo-oxidation). The UV degradation may include colour change, a slight increase in tensile strength and elastic modulus, and a decrease in impact strength. Hence, exposure to sunlight should be kept to a minimum. Degradation effects of UV radiation can be prevented by the use of UV stabilizers and colorant. A properly compounded PVC material was demonstrated at the Cherry Plaza Hotel, Orlando, Florida. There, PVC pipe used in the air-conditioning system located on the roof has shown no deterioration, even after being exposed to sunlight for more than 20,000 hours (PPI, 1973). Walker (1981) reported a 2-year study of the effects of natural UV radiation on the mechanical properties of PVC pipe, and found that both tensile strength and modulus of elasticity remained virtually unchanged after 2 years of exposure to sunlight. Impact strength, however, declined by 20.3% over the 2-year test period. A reduction of 3.7% was reported in impact resistance, when the pipes were exposed to sunlight for 2 months. Walker also maintains that even with the reduction, the impact strength of PVC pipe is still higher than that of other commonly used sewer pipe products. However, Walker did not clarify what the other commonly used sewer pipe products were.

The surface of PE is also sensitive to the photo-oxidative action of sunlight. However, this degradation is not initiated by PE but by traces of processing aids, metallic impurities, and fillers (Vasile and Seymour, 1993). The use of UV-stabilizers, which vary widely in efficiency, can protect PE for up to 1 year against sunlight exposure (Moore *et al.*, 1988).

There are no reports of UV degradation of concrete and corrugated steel pipes. The UV effect on these two materials is believed to be negligible.

3.6 Adjacent Excavation

The influence of new excavations on existing buried utilities has been well recognized (Bert *et al.*, 1974). Because of the load-carrying mechanism of the flexible pipe, the installation of underground utilities has a greater impact on adjacent, existing, buried, flexible pipe than on rigid pipe. Once exposed, flexible pipe must be backfilled and compacted with the same degree of care as the original installation to restore its stability and pipe-soil load-carrying system (Nesbeitt, 1978). Due to loss of lateral support, partial excavation and exposure of flexible pipe is likely to result in excessive deformation, and may lead to collapse. Installation of an adjacent pipe was the cause for up to 20% local deflection of a PVC sewer pipe in France (Alferink *et al.*, 1995). As pointed out by Moser and Kellogg (1993), the other difficulty is not only to locate existing plastic pipe in the ground, but also to prevent damage while doing so. Alferink *et al.* (1995) also experienced difficulties in locating buried PVC pipes in their performance study in several European countries.

Existing buried, rigid pipe such as concrete pipe, however, is less sensitive to re-excavation and backfilling, because of its inherent strength. Depending on the location, partial exposure of concrete pipe does not usually cause significant distress to the pipe. The trench reinstatement operation is not so critical as for flexible pipe.

Table 3.4 Installation parameters of various pipes

Installation Parameter	Rigid Pipe (Concrete)	Flexible Pipe
Trench width	As narrow as possible. Earth load increases as the trench width increases, till transition width. Less width required for work space.	Earth load does not increase with width beyond the prism limits. Sufficient width is required to carry out careful compaction.
Joints	Bell-spigot joints with gaskets. More joints due to short sections.	**Plastic pipe:** Elastomeric seal or solvent cement. Easy cutting for length adjustment.fewer joints. **CSP:** Steel coupling bands with neoprene gaskets or bitumen sealants. Welding.
Minimum cover	900 mm required before use of a heavy compactor. Damage due to compaction not reported.	**Plastic pipe:** 900 mm required before use of a heavy compactor. Over compaction may cause excessive deflection. **CSP:** Minimum cover ranging from 700 to 1400 mm.
Operation	May require additional equipment and manpower to handle heavier pipe sections. Requires less compaction effort.	Requires adequate on-site inspection. Requires maximum effort for effective compaction. Ease of transportation and handling.
Temperature effect	Strength increases as temperature decreases in the range of -20 to -30°C. Impact strength also increases with decrease in temperature.	**HDPE:** Minimum installation temperature is -34°C. Impact strength is not affected significantly by low temperature. **PVC:** Minimum installation temperature is -18°C. Impact strength is reduced by up to 30% when temperature decreases from 23 to 0°C.
UV degradation	UV degradation is negligible.	**Plastic pipe:** Susceptible to UV degradation in long-term exposure.
Adjacent excavation	Less sensitive to re-excavation and backfilling. Depending upon the location, partial exposure usually does not cause significant distress to the pipes.	Once exposed, flexible pipe must be backfilled and compacted with great care, according to the original specifications to restore its strength. Partial excavation and exposure is likely to result in excessive deformation.

3.7 Summary of Installation Procedures

Pipe installation by trenching consists of excavation, preparation of bedding, placement of the pipe, joining of pipe sections, and backfilling. Installation in an embankment condition is similar except that shallow excavation may be required only to improve bedding conditions. Installation must be carefully designed and planned, since it has a significant impact on the construction costs and pipe performance. Trench width, bedding, and haunching are important factors that control the stresses and deformation of the pipe. Pipes may also be subjected to adverse conditions, such as low temperatures, impact loads, and UV radiation, at the construction site, before being fully installed. Installation procedures for different pipes are summarized and compared in Table 3.4.

4 Resistance and Vulnerability Characteristics

Pipe used in sanitary engineering structures usually has a comparatively long and maintenance-free service life. However, the service life depends on many factors. Sewer pipe failures due to physical, chemical, electrochemical and bacterial attack from both the inside – the carried sewage – and outside – in the soil where it is buried (Rossouw, 1979;

Stutterheim, 1962) have been noted. The source of the chemicals in sewage varies, depending on whether the pipe is used to transport industrial or domestic sewage.

In domestic sewers, the pipe may be subjected to chemicals and processes such as:

- Hydrogen sulfide (H_2S),
- Sulfuric acid (H_2SO_4),
- Chloride ions,
- Sulfate ions,
- Lime leaching, and
- Carbonation.

In industrial sewers, the pipe may be subjected to:

- Acids,
- Alkali,
- Organic chemicals such as aromatics and hydrocarbons, and
- Industrial wastes.

Depending on locations, the soils may contain chemicals, such as:

- Chloride ions,
- Diluted acids,
- Soil chemicals, and
- Bacteria (bio-corrosion)

The resistance of a pipe to physical, chemical and other forms of attack varies because of the differences in material characteristics. For example, steel pipe is always subjected to corrosion when not protected, whereas concrete pipe may suffer severe deterioration because of sulfate attack. Plastic pipe may degrade because of exposure to certain solvents. Various influences on the durability of different pipes are reviewed in this section.

4.1 Chemical Vulnerability of Concrete Pipe

Concrete comprises four primary ingredients: Portland cement, water, sand and coarse aggregate. The first two combine chemically to form a gel-like mixture of complex hydrates, which not only bind the sand and aggregate particles together, but also provide a highly water-impermeable product with a high alkaline environment (Ramachandran and Feldman, 1984). Concrete and reinforced-concrete pipes have given excellent service under a wide variety of conditions. They are resistant to many liquids and soil conditions. However, because of the nature of concrete material, chemical and bio-chemical attacks have been the cause of many failures of concrete sewer pipe (Stutterheim and Van Aardt, 1953).

Both domestic and industrial sewers contain many aggressive chemicals that can cause the corrosion of reinforced-concrete pipe. For instance, inorganic and organic acids may be present in effluents or in the subsoil of an industrial area, or they may be formed above the water line in the sewage, because of a 2-stage bacterial activity (Parker, 1951; Ramaswamy and Jain, 1984). Sulfate ions and other chemicals may also exist in the soil and potentially cause chemical corrosion of concrete on the outside walls. In general, chemical attack can be categorized according to the following corrosion reactions:

- Sulfate ion attack,
- Leaching, and
- Acid attack,

4.1.1 Sulfate Ion Attack

Some soils contain sulfates, such as sodium sulfate, calcium sulfate and magnesium sulfate. Sulfate attack is likely to initiate at the exterior pipe surface, when the concrete pipe has been embedded in soil containing a high concentration of sulfate ions (Burnett, 1974). Because it is the groundwater that dissolves and carries sulfate into the soil, sulfate attack on concrete structures occurs only when the groundwater level rises above the pipe invert (CG&S, 1996).

The physico-chemical processes involved in a sulfate attack on concrete pipe are initially manifested as a characteristic whitish appearance on the concrete surface. Damage usually begins at the edges and is followed by progressive cracking and spalling, which eventually reduces the concrete to a friable or even a soft state. In some instances, there is a significant loss of load-bearing capability, leading to structural failure of the concrete pipe. The strength loss is usually attributable to a reduction of the adhesive ability of the principal hydration product, C-S-H gel (calcium silicate hydrates). Cracking and spalling are generally associated with expansive reactions; the reactions between sulfates and aluminates in the cement (Mehta, 1986, 1989, 1994; Reading, 1982; Gollop and Taylor, 1992; Min and Mingshu, 1994; Wang, 1994). A comprehensive description of the physical and chemical processes in a sulfate attack on concrete is beyond the scope of this report. However, it is generally agreed that the underlying mechanisms in the sulfate attack on concrete involve reactions between aluminate hydrates and sulfates, resulting in expansion and eventually in total disintegration of the concrete matrix (Mehta, 1986, 1989, 1994; Matti and Al-Adeeb, 1985).

Sulfate attack can also be insidious from industrial and domestic sewer effluents. However, it is most likely sulfuric acid corrosion due to the bacterial activity in the sewers, as discussed later.

4.1.2 Leaching

Alkali oxides, K_2O and Na_2O, free lime, $Ca(OH)_2$ can leach out the constituents of concrete. The C-S-H gel is also subjected to leaching. The leaching of the concrete constituents, especially $Ca(OH)_2$, increases the porosity of the concrete matrix (Ballim and Alexander, 1991). As a result, the concrete has lower strength (Biczok, 1967), and ingress of other deleterious chemical species, such as sulfate and chloride ions, is accelerated.

The chemistry of both the sewer and the groundwater surrounding the concrete influences the leaching rate of concrete. Leaching increases as the pH of the sewage and groundwater decreases. The pH drop of sewage and groundwater is especially prevalent when bicarbonates are present from CO_2 dissolution or vegetation decay. Studies suggest that a groundwater concentration of 20 ppm, or more, of dissolved CO_2, is sufficient to cause significant deterioration of concrete through leaching (Biczok, 1967). The flow velocity of sewage and groundwater is also an important consideration for leaching. For constant rapidly flowing water, $Ca(OH)_2$ is continuously leached from the concrete, leading to bacteria-induced sulfuric acid attack and corrosion of steel reinforcement in concrete pipe.

4.1.3 Acid Corrosion

Acid corrosion is the most significant concern for concrete sewage pipes. This type of corrosion occurs mainly at the interior surface above the flow line of the pipe, due to the aggressive nature of the sewage.

There are two major causes of internal corrosion in a sanitary sewer. One is the conventional acid attack, caused by low-pH industrial waste discharged directly into the sewer system. The industrial sewer may carry organic acid, such as carbonic and acetic acids etc. and inorganic acid, including sulfuric, nitric and hydrochloric acids, ammonium compounds and phenols. The other is generally referred to as aerobic bacteria-induced sulfuric acid corrosion (Milde *et al.*, 1988; Sand *et al.*, 1994; Kienow and Allen, 1993; Meyer and Ledbetter, 1970; Parker, 1951; Hawthorn, 1970). Details will be discussed later in this section.

Sulfuric acid reacts with any cement that depends upon calcium silicates and aluminates for cementation (Perkins, 1979, 1981). It appears that the constituents of Portland cement (hydrated and unhydrated) are dissolved by sulfuric acid, leaving mainly sulfates of calcium, alumina and iron, and free silica as a soft pasty mass. The effect of dilute sulfuric acid on Portland cement concrete is as follows (Perkins, 1979, 1981; Meyer and Ledbetter, 1970): Siliceous aggregates, which are most commonly used, are less affected by sulfuric acid. Aggregates such as limestone or dolomite, are attacked by sulfuric acid with the formation of calcium and magnesium sulfates. Hydrated calcium silicates, aluminates and ferrites, these compounds are broken down, finally, to form the various sulfates of calcium, aluminum and iron, together with amorphous silica, in the case of calcium silicate hydrates. Calcium hydroxide, calcium aluminates and unhydrated cement particles these materials are broken down by sulfuric acid to form sulfates. Calcium hydroxide reacts with the acid to form gypsum ($CaSO_4.2H_2O$). Gypsum reacts with some of the hydrated calcium aluminates to form ettringite, which has larger volumes than the substances from which it is formed. This resultant increase in volume can cause expansion of the concrete, with attendant cracking and deterioration, i.e., sulfate attack.

4.2 Electro-Chemical Corrosion of Steel

Steel corrosion can be accelerated in the presence of many aggressive chemicals, such as chloride ions, inorganic acids or low-pH and high-humidity environments. In the following discussion, some of the major concerns relevant to corrosion of both reinforcing steel in reinforced-concrete and corrugated steel pipes, are addressed. They are:

- Chloride ion attack,
- pH reduction, and
- Acid attack.

Corrosion of steel is an electro-chemical process where the metallic iron is oxidized to form iron oxide or ferrous/ferric ions, depending on the pH value of the environment. In such a process (anodic reaction), metallic iron gives up electrons, which are consumed in oxygen reduction or hydrogen evolution reactions (cathodic reactions) (Rosenberg *et al.*, 1989).

For example, in an acidic environment, steel dissolution occurs:

Anodic Reaction: $Fe === Fe_2+ + 2e$ (4.1)

Cathodic Reaction: $2H+ + 2e === H_2$ (4.2)

In an alkali environment, steel forms an oxide film:

Anodic Reaction: $Fe + 2\ OH^- === Fe(OH)_2 + 2e$ (4.3)

Cathodic Reaction: $O_2 + 2H_2O + 4e === 4OH^-$ (4.4)

Steel dissolution is severe in acidic solution, but it can be stabilized in an alkaline solution, because of the oxide film formed on the surface. However, this protective film can be broken in the presence of such aggressive ions as chloride ion and the reduction of pH below 8. Reinforced concrete has a concrete cover which not only acts as a physical barrier to protect the reinforcing steel from aggressive chemicals, but also provides a highly alkaline environment, which inhibits the reinforcing steel from corrosion. Therefore, bare steel sewer pipe is very vulnerable to aggressive chemical attack. Thanks to the protection of coatings that are applied to the surface of steel, corrugated steel pipe has better corrosion resistance than if it were without coating. The durability of coating has a great impact on the performance of the corrugated steel pipe. For instance, sacrificial metallic coating will perform very differently, compared to epoxy coating, in an acidic environment.

4.2.1 Chloride Attack

It is well known that the chloride ion is one of the most aggressive ions that can cause severe steel corrosion (Cady, 1977; Rosenberg *et al.*, 1989; Slater, 1983; Cady and Weyers, 1983). Chloride ions can be introduced on contact with sewer pipe from:

- Industrial and domestic sewers,
- Underground water, and
- Soil environment.

In the environment with the pH > 8, it is generally believed that chloride ions interact with the hydrous oxide layer, in competition with OH- ions. The reactions may be written:

$$[Fe(OH)_2] + 2Cl^- === [FeCl_2] + 2OH^- \quad (4.5)$$

followed by:

$$[FeCl_2] + 2OH^- === [Fe(OH)_2] + 2Cl^- \quad (4.6a)$$

or

$$[FeCl_2] + 2H_2O === [Fe(OH)_2] + 2HCl \quad (4.6b)$$

The chloride ion destroys the iron oxide film to form a highly water-soluble product, $FeCl_2$, which diffuses from the steel surface and reacts with any encountered OH- or H_2O to form the corrosion product, $Fe(OH)_2$. The consumption of chloride ions in the reaction described by Equation 4.5 is balanced by the release of chloride ions, Equations 4.6a or b; the presence of the ions promotes the disruption of the oxide layer through the looping reaction process. The product of Equation 4.5, $[FeCl_2]$, accelerates the disruption, due to its high solubility and reduction of local pH. The overall result is an acceleration of steel dissolution (Gu *et al.*, 1994). Therefore, bare steel pipe for sewage systems is not durable, unless protective coatings are applied. The reinforced-concrete pipe is, to a certain degree, vulnerable to chloride ingress from the external environment. The chloride enters concrete through a combination of convection, diffusion and capillary suction. Convection is limited to those instances when a hydrostatic pressure difference drives chlorides into the concrete. Diffusion is the dominant mechanism when concrete is saturated, and a chloride concentration gradient exists. However, because the alkaline environment of the concrete, reinforcing steel is protected by a passive oxide layer (probably Fe_2O_3). The large ohmic resistance of this layer severely limits corrosion to approximately 0.001 μm/a (Conway, 1965). Chloride ions can break down the protective layer. The overall results are corrosion of reinforcing steel, cracking and spalling of the concrete due to volume expansion of more than six times, as the iron oxides are transformed to higher oxidation states (hydrated ferric oxides) (Rosenberg *et al.*, 1989).

4.2.2 pH Reduction

In accordance with the Pourbaix diagram, a potential-pH plot, which demonstrates the corrosion phenomena of a metal as the potential and pH values change, steel will be protected by its oxide film, when pH >9 in the absence of aggressive ions (Pourbaix, 1966). This oxide film will become unstable when the pH is reduced below 8. In an acidic environment (pH = 1 to 3), steel will undergo severe dissolution. Therefore, any chemical in the sewer or soil that causes a reduction of pH value would result in severe corrosion damage.

4.2.3 Acid Attack on Steel

Acid can be present in the groundwater, in the effluent carried by the pipeline, or generated through bacterial activity. Steel pipe material is vulnerable to acid attack. Severe dissolution of iron can occur, even in very dilute acid solution. Therefore, bare steel pipe is not recommended for use in sewer systems, unless it is coated with polymeric, plastic, bitumastic or other organic coating materials (Pyskadlo, 1989).

4.3 Chemical Resistance of PVC

The chemical resistance of unmodified PVC is considered high, as demonstrated by a 3-hour test of immersion in 70% sulfuric acid, which had little effect on the mechanical properties of PVC (Uni-Bell, 1982). Sulfuric acid is commonly found in sanitary sewer systems, as discussed in the preceding section. A 2-year study of small PVC sewer pipe specimens with a 5% fixed deflection and immersed in sulfuric acid solution showed a minimal effect on the pipe stiffness (Sharff and DelloRusso, 1994). However, long-term exposure to low concentrations of the acid causes surface discolouration (Alferink *et al.*, 1995) typical of degradation (Titow, 1990). The 50-year effect of combined exposures to chemical and mechanical action on the mechanical properties of PVC remains undetermined. PVC may be affected by certain solvents such as aromatic or chlorinated hydrocarbons, ketones and esters. These solvents swell or dissolve PVC. Hence, the permeation of organic chemicals, such as dry-cleaning fluids and pesticides, through

PVC pipe is not uncommon (Berens, 1985; Pfau, 1985; Crum, 1985). A case involving the penetration of PVC pipe by degreaser products was reported (AWWA Mainstream, 1984). Blends of PVC are somewhat less solvent-resistant than unmodified PVC (Titow, 1990). The presence of metallic impurities and filler can also reduce the chemical resistance (Owen, 1984).

4.4 Chemical Resistance of HDPE

HDPE is more crystalline and more chemically resistant than low-density polyethylene (LDPE) (Trotignon *et al.*, 1985), and it has a good resistance to a wide range of chemicals. Polyethylene is, however, affected by sulfuric acid (Mercier and Maréchal, 1993), an oxidizer produced in low concentration by aerobic bacteria. It may then be expected that long-term exposure to low concentrations of sulfuric acid would affect PE pipe, including HDPE pipe, especially when combined with other mechanical stresses. Alone, a deformation of 5% to 12 % can induce rapid mechanical degradation (Vasile and Seymour, 1993). The immersion of LDPE in a salt solution can promote oxidation (Henry and Garton, 1989), indicating that de-icing salt used on roadways may eventually affect the performance of buried HDPE pipe, once the salt has migrated through the top soil.

Being a hydrocarbon, HDPE is an apolar polymer and therefore is affected by apolar solvents such as alcohols, detergents, halogens and aromatics (PPI, 1993), and chemicals such as petroleum products and gasoline. These solvents can swell HDPE and permeate through the pipe wall (Selleck and Marinas, 1991; Lee, 1986; Veenendaal and Dibbetts, 1981; Holsen *et al.*, 1991a, 1991b). Permeation may take from one day to several weeks, depending on the chemical, its concentration, the soil type and the quality of the pipe material. Under certain conditions of temperature and stress in the presence of certain chemicals, polyethylene may begin to crack sooner than at the same temperature and stress but in the absence of these chemicals. This phenomenon is referred to as environmental stress cracking. Environmental stress cracking involves the development of cracks that grow slowly and propagate over time. The above-mentioned apolar materials are identified as stress- cracking agents for polyethylene (PPI, 1993). There is also concern in placing polyethylene pipe in hydrocarbon-contaminated ground, which can create a risk of stress-cracking (Beech, 1994).

4.5 Biological Deterioration

Biological deterioration refers to material breakdown promoted by the presence of bacteria. It is known that many types of bacteria thrive in the interior walls of a sewer pipe. This section reviews briefly the effects of certain types of bacteria on the pipe material considered within the scope of this study.

4.5.1 Concrete and Corrugated Steel Pipe
Many publications have addressed the deterioration of concrete by bacteria-induced corrosion, since it has a great impact on the service-life of concrete sewer pipe (Patenaude, 1986; Kobrin, 1976; Sallal *et al.*, 1984; Kikuchi *et al.*, 1995; Mori *et al.*, 1991, 1992; Cho and Mori 1995). The mechanism of bacteria-induced corrosion is not always clear. However, this corrosion process can (Kobrin, 1976):

- produce acids - such as sulfuric, formic and acetic acids,
- destroy protective coatings,
- create corrosion cells - differential aeration (oxygen) and ion concentration cells are notable examples,
- produce hydrogen sulfide (H^2S),
- concentrate anions and cations, and
- oxidize metal to ions.

The bacteria that induce corrosion in sewer systems are usually among the following three groups (Kobrin, 1976):

sulfate reducers	Perhaps this is the most publicized class of corrosive bacteria. They reduce sulfates to hydrogen sulfide.

acid producers This kind of bacteria can oxidize sulfur compounds to sulfuric acid.

metal ion concentrators/ oxidizers Iron and manganese bacteria are examples of this class.They generally take in energy by oxidizing metal such as steel.

Sulfur-reducing bacteria are able to reduce the sulfates in the sewer and produce hydrogen sulfide as a waste product. These bacteria are anaerobic. Another group of bacteria, *Thiobacillus sp.*, take the reduced sulfur and oxidize it back to sulfuric acid, which destroys concrete (Kienow and Allen, 1993; Meyer and Ledbetter, 1970; Parker, 1951; Hawthorn, 1970; Sand *et al.*, 1984). These bacteria are likely to be found in all sewage systems. Certain conditions must prevail before the sulfur bacteria can become established on the concrete surface and begin the process of corrosion. Sufficient moisture is essential to prevent the desiccation of the bacteria. There must be an adequate supply of hydrogen sulfide, carbon dioxide, nitrogen compounds and oxygen.

H_2S formation in sewers. In sewers, H_2S is produced biologically from compounds containing organic sulfur formed from the hydrolysis of proteins or from the degradation of soap, cellulose, starch, etc. This process occurs, under anaerobic conditions, with a large number of species of sulfate-reducing bacteria in sewage (Parker, 1951).

H_2S fixation and conversion on concrete sewer walls. The next step of the corrosion process is both the fixation of the H_2S in the sewer atmosphere on the walls above the sewage, and its conversion to sulfuric acid. This part of the corrosion process may be explained as follows: the exposed walls of new concrete sewers with an initial pH 11 to 13, on exposure to a sewer atmosphere containing hydrogen sulfide, are subject to a two-fold chemical change. Normal carbonation lowers the pH to 8.4, and fixation of hydrogen sulfide and polythionic acids further lowers the pH to about 7.5. As the pH drops below 9.0, the group of bacteria referred to as *Thiobacillus X* multiply, and their oxidation of thiosulfate and polythionate to sulfur and sulfuric acid results in a rapid drop in pH. This continues until the pH falls below 5.0, when *Thiobacillus concretivorus* produces high concentrations of sulfuric acid; the pH frequently drops as low as 1 (Parker, 1951). This acid attack can cause severe damage to concrete, and it can also damage the corrugated steel pipe with metallic zinc coating.

4.5.2 Resistance of PVC to Microbial Attack

PVC pipe has good resistance to microbial attack, although it may be susceptible to degradation, if it contains vulnerable additives (PPI, 1989). Processing acids of low molecular weight, which typically contain oxygen, are biodegradable (Titow, 1990; PPI, 1989). However, biodegradation can be avoided, if proper attention is paid to the selection of additives. Alternatively, special additives that protect PVC pipe against microbiological attack may be used.

4.5.3 Resistance of HDPE to Microbial Attack

PE is highly resistant to microbial attack (PPI, 1989; Vasile and Seymour, 1993). Degradation of HDPE pipe may, nonetheless, occur as some additives serve to feed bacteria. The oxygen of many additives, combined with their low molecular weight, increases the biodegradability of the pipe (Titow, 1990). As with PVC pipe, biodegradation of HDPE pipe can be minimized, if proper additives are selected.

4.6 Mechanical Resistance

In addition to adverse conditions that are normally expected during construction (see Section 3.6), this section discusses factors that are normally expected during operations of buried sewer pipe. These factors include abrasion, humidity and temperature, and fire.

4.6.1 Resistance to Abrasion

Abrasion resistance is the ability of a material to withstand mechanical erosion, a process that tends to progressively remove material from its surface. Storm drain and sewer effluent usually contains grit, or other hard suspended materials, which constantly strike against the interior surface of the pipe. Abrasion has been identified as one of the most important influences on the durability of culverts (Hurd, 1986; Meacham *et al.*, 1982; Bowser-Morner, Inc., 1990). Conditions affecting abrasion include concentration of solids, flow velocity, duration and frequency of maximum velocity, pipe diameter, and coating (Jarvenkyla and Haavisto, 1993a; Perkins, 1979; Meacham *et al.*, 1982). Abrasion increases as the flow velocity increases, since the flow becomes more turbulent and the solid particles hit the pipe wall more directly and vigorously. Abrasion also increases with increased pipe diameter (Jarvenkyla and Haavisto, 1993a). Coatings can provide certain degrees of protection of the pipe against the abrasive action of the carried fluid.

The corrosive environments may accelerate the material abrasion, or *vice versa*. Liquid in motion is a more effective solvent than it would be were it stationary. Extensive research has been carried out on the abrasion resistance of concrete (Laplante *et al.*, 1991; Fernandez and Malhotra, 1990; Sadegzdeh *et al.*, 1987; Perkins, 1979; Hyde *et al.*, 1969). Concrete pipe is subjected to physical abrasion when velocities are in the range of 20 to 40 m/s (Perkins, 1979; Hyde *et al.*, 1969). Cavitation, due to abrasive action of the flow, can occur and cause very serious damage to concrete pipe (Perkins, 1979). A maximum flow velocity of approximately 2.5 to 3.0 m/s does not cause significant wear of concrete pipe. The low abrasion resistance of concrete pipe is attributed to the brittle nature of the material (Jarvenkyla and Haavisto, 1993a). It was suggested that the type of coarse aggregate is the most important constituent concerning concrete abrasion resistance. The water/cement ratio and the use of silica fume are of secondary importance (Laplante *et al.*, 1991). Addition of slag would decrease the abrasion resistance (Fernandez and Malhotra, 1990).

Abrasion is considered one of the most important contributors to the failures of corrugated steel culverts (Missouri Highway and Transportation Department, 1987; Hurd, 1984, 1986; Noyce and Ritchie, 1979). To resist abrasion and corrosion, corrugated steel pipe is usually protected with either coating or coating plus invert paving (NCSPA, 1989). In a comparative test, the steel pipe was shown to have a higher abrasion resistance than the concrete pipe (see Table 4.1) (Jarvenkyla and Haavisto, 1993a).

Plastic pipe is highly resistant to abrasion, in general (Dicks *et al.*, 1983; Richards, 1984; Jarvenkyla and Haavisto, 1993a, 1993b; Chambers and Heger, 1980). The long-chain molecules that make up the polymer chain serve as a basis for a trampoline response, when impacted by running and tumbling aggregates, resulting in less machining action (Jarvenkyla and Haavisto, 1993a).

While the abrasion resistance of PVC sewer pipe is considered good, based on long-term studies (Eckstein, 1988; Alferink *et al.*, 1996; Alferink *et al.*, 1995), that of HDPE often ranks first in wear resistance, when compared to other polymers (Anderson and Williamson, 1985). In a sliding-sphere wear test, the wear resistance of HDPE was twice that of PVC (Eiss and Potter, 1985). According to the Plastic Pipe Institute (PPI, 1993), HDPE is three to five times more resistant than steel pipe. Field evaluations of HDPE pipe also confirmed its superior abrasion resistance (Hurd, 1986; Goddard, 1990).

Table 4.1 shows the ranking of the four types of materials in terms of abrasion resistance based on reported wear characteristics of these pipe materials under laboratory test conditions. Abrasion resistance of HDPE pipe ranks the highest, whereas that of concrete pipe the lowest on the relative scale.

Table 4.1. Abrasion resistance of various pipe materials (According to data by Jarvenkyla and Haavisto, 1993a)

Pipe Material	Abrasion Resistance Ranking
HDPE	4 (best)
PVC	3
Corrugated Steel	2
Concrete	1

It should be pointed out that the abrasion rate is not as important as the residual strength of the pipe after a certain time. For instance, a loss of 12.7 mm (1/2 in.) of concrete in concrete pipe may not lead to structural failure, while a loss of the same amount in PVC, HDPE or CS pipes may mean a total loss of wall thickness. This literature review did not find any references that contain a comparative abrasion study of various pipes within the context of residual strength. Such research is highly recommended. Nevertheless, experience of the concrete pipe manufacturers is that abrasion is not a problem for concrete pipe. Jarvenkyla and Haavisto (1993b) remarked that practical studies have revealed that no abrasion, or only very little wear, is to be expected during the service life of a pipeline.

4.6.2 Humidity and Temperature

Typical environmental conditions in many sewer systems are high humidity (100% RH) and high atmospheric temperature (>30°C) (Saricimen *et al.*, 1987). In such an environment, hydrogen sulfide released from the sewage is absorbed by the film of moisture on the unsubmerged sewer structures, where in the presence of aerobic bacteria, it is converted to sulfuric acid. Severe deterioration of concrete and steel pipe materials occurs (as discussed earlier in this section), although concrete and corrugated steel materials themselves are not directly affected by humidity and temperature.

Although buried pipe is not exposed to freeze-thaw conditions when installed in sewer lines below the frost penetration depth, pipes installed as culverts are subjected to weathering conditions. Made with dry-cast concrete, precast concrete pipe is generally of high quality and not subjected to significant freeze-thaw weathering (Potter, 1988). There is no documented experience of problems associated with freeze-thaw damage in dry-cast concrete pipe. Nevertheless, the potential of such damage has been recognized by ACPA (1988). In this literature review, no reports on research conducted on the freeze-thaw damage potential of circular concrete pipe were found, except a laboratory study on dry-cast concrete box culverts by Abdulshafi *et al.* (1995). Dry-cast box culverts, which are produced using non-air-entrained concrete, show unsatisfactory freeze-thaw durability characteristics in laboratory conditions (Abdulshafi *et al.*, 1995). Further research is needed to study *in-situ* and laboratory freeze-thaw durability characteristics of circular concrete pipe.

PVC pipe is prone to thermal degradation (Titow, 1990; Owen, 1984). At processing temperatures, PVC degrades by evolution of hydrogen chloride (HCl) and polyene formation. The latter causes PVC to develop a yellow to red colour. The corrosive HCl must be neutralized with proper additives, if cascading degradation is to be avoided. As a result, PVC cannot be heat-processed without suitable stabilizers. The stabilizers may also prevent in-service oxidation. Alferink *et al.* (1996) have shown that after 30 years of service, the level of thermal degradation of the pipe could be traced back to the extrusion process; the oxidation level had seemingly not progressed from the initial level during service.

Despite its chemical inertness, PE is sensitive to thermal oxidation (Alferink *et al.*, 1996). HDPE is much less sensitive than LDPE. In either case, the extrusion at 160°C>T>260°C, requires the blending of antioxidants and heat stabilizers with the PE feedstock.

4.6.3 Fire Resistance

Fires and explosions in sewers in urban areas are not unusual (Philbin and Vickery, 1993).

Sewer pipes are subjected to fire hazards that can be initiated in sewage containing industrial chemicals and liquid hydrocarbons, or as a result of traffic accidents involving fire and gasoline spillage.

Concrete pipe does not support combustion, and can withstand extremely high temperatures. Numerous incidences of fires in sewers constructed with concrete pipe have occurred. The pipe sustained little or no damage (Ohio Concrete Pipe Association, 1979).

Steel is also a nonflammable material. However, petroleum-based linings and coating materials, such as asphalt, bitumen, plastics, and coal tar, used for corrosion protection of corrugated pipes, are flammable (ACPA, 1992; Ohio Concrete Pipe Association, 1979). In a hostile fire environment, steel pipe can suffer damage from burning linings and coatings.

Both PVC and HDPE pipes will burn where the air flow is adequate such as in culverts, storm drains and sewers (Smith and Brady-Williamson, 1997; ACPA, 1983; Chambers and Heger, 1980), although PVC has been identified as a material with one of the lowest flammability ratings among common plastics (Curtis, 1977). Other concerns include the evolution of acidic fumes and smoke that accompany thermal degradation, when plastics are exposed to fire.

HDPE deforms at temperatures above 120°C and melts completely at 135°C. Polyethylene burns when exposed to a flame, because it is a hydrocarbon (PPI, 1993). HDPE pipe has been recognized as a fire hazard and is therefore not recommended for use in drain and sewer systems, because of the difficulty of fire control, confinement and extinguishment (Philbin and Vickery, 1993). In a flammability test carried out by the North Carolina Department of Transportation (1991), one end of a corrugated HDPE culvert pipe was exposed to fire, and within 1 minute, the pipe was engulfed in flames. The pipe was observed to fuel the fire, and burn continuously throughout its entire length. Conclusion: any application where the ends of HDPE pipe are exposed, such as culvert applications, makes it susceptible to fire damage (North Carolina Department of Transportation, 1991).

According to ACPA (1982), the Hardwood Plywood Manufacturers Association conducted independent fire resistance testing according to ASTM E 84. Reinforced-concrete and corrugated steel pipes with asphalt lining and coating, corrugated steel pipe with polymeric lining and coating, rib-walled PVC pipe, PVC solid-walled pipe and rib-walled HDPE pipe were included in the comparative fire testing. (Two other pipes included in the testing were corrugated aluminum pipe and ABS pipe.) Table 4.2 summarizes, in part, the fire resistance characteristics of the tested pipe materials (ACPA, 1982). The higher the flame spread index, the lower the fire resistance (ASTM E 84 - 94).

4.7 Comparison of Resistance Characteristics

The long-term performance and durability of sewer pipes are directly related to their

Table 4.2. Fire resistance of various pipe materials

Material	Flame Spread Index	Smoke Density Index	Fire Resistance Ranking*
Concrete pipe	0	0	6 (best)
Rib-walled PVC sewer pipe	10	10	5
PVC sewer pipe	20	330	4
CSP with polymeric coating	35	580	3
Rib-walled HDPE pipe	60	820	2
CSP with asphalt coating	80	860	1

*Fire resistance ranking, not in the original table, is added to indicate relative fire resistance performance. The best performance ranks the highest.

Table 4.3. Corrosion susceptibility of various pipes

Corrosion Type	Pipe			
	Reinforced-Concrete	Steel	HDPE	PVC
Acid Corrosion	✓	✓	✓ (Note 1)	
Sulfate Ion Corrosion	✓			
Chloride Ion Corrosion	✓	✓		
Leaching	✓			
Bacteria-Induced Corrosion	✓	✓	✓ (Note 2)	✓ (Note 2)
Certain Solvents			✓ (Note 1)	✓ (Note 3)
Environmental Stress Cracking			✓	

Notes:

1. HDPE pipe is stable in the presence of most acids and bases. However, it is affected by apolar solvents and chemicals, such as petroleum products and gasoline. Long-term exposure to low concentrations of sulfuric acid may also affect the properties of HDPE.
2. Both PVC and HDPE pipes have high resistance to bacteria attack. However, some additives in these plastic materials promote bacteria growth and cause biodegradation of the materials.
3. PVC pipe has good resistance to most chemical attacks, except aromatic or chlorinated hydrocarbons, ketones and esters.

Table 4.4. Physical resistance of various pipes

Type of Resistance	Pipe			
	Concrete	Corrugated Steel	HDPE	PVC
Abrasion resistance	low	low	high, 2 and 3 times more resistant than PVC and steel pipe, respectively	high
Fire resistance	high	Most coatings used for corrosion protection are flammable.	flammable	flammable with lower flammability rating than HDPE
Freeze-thaw resistance	(Note)			

Note It is not certain whether concrete culvert pipe is subjected to freeze-thaw damage. Testing is required to clarify this.

resistance to various chemical and biological attacks. Sources and concentrations of chemicals in sewage can vary depending on whether the sewer carries industrial or domestic effluent. On the other hand, soils in certain geographic areas are known to contain high concentrations of sulfates.

In general, concrete and corrugated steel pipes are more vulnerable to chemical attack than PVC and HDPE pipes. High resistance to chemical attack is the most attractive feature regarding the use of plastic pipes in sewer systems. Corrosion susceptibility of the four pipe materials is summarized in Table 4.3.

Physical resistance to abrasion and fire also plays an important role in the performance and durability of sewer and culvert pipes. Resistance to abrasion and fire of the four pipes is compared in Table 4.4.

5 Performance Criteria and Service Life

In any engineering design, the performance criteria of the material being considered must be established, so that the design basis appropriate for the applications and the environment can be chosen. The particular application will dictate which material performance limit is critical. For different pipes, the design approaches, installation procedures and resistance characteristics are different (as discussed in the preceding sections), as well as the performance criteria or limits, and distress modes.

Durability is one of the most important factors in selecting an appropriate pipe material, and service life is an indicator of pipe durability. Various state departments of transportation in the US have conducted durability studies on culvert in the last 20 years, and the data of those studies have been used to establish service life prediction models (Hurd, 1988; Meacham *et al.*, 1982; CERF, 1992). Although researchers may disagree about the findings of various durability studies of buried pipe, they all admit that estimating the service life of a pipe is a complex task because of a lack of accepted definitions and standards in rating, inspection and maintenance (CERF, 1992).

Much attention has been directed toward the durability of buried pipe, but the vagaries of climate, soils and geology, fluid impurities, construction materials and the construction process itself have prevented the development of a systematic and practical theory for predicting performance (ACPA, 1988). In this section, the performance criteria and service life predictions are discussed, based on a compilation of reported data and published information.

Percentage deflection, used herein, refers to the amount of deflection expressed as a percentage of the base inside diameter of a pipe, unless stated otherwise.

5.1 Performance Criteria

The two basic requirements for the performance of any structure are strength and serviceability. However, universally agreeable sets of performance criteria do not exist, and the performance criteria used by one researcher are often challenged by another. Although reports on pipe replacement and failures are available, individual judgments in determining the need for replacement or failures were not reported, and were certainly not based on comparable grounds.

It is important to realize that performance criteria for storm drains and sanitary drains are different. Perforations, leaky cracks and leaky joints in a storm drain may not be of consequence, while in a sanitary sewer line, they may be critical (NCSPA, 1989). This is because of contamination due to exfiltration, or an increase in infiltration/inflow (I/I) in sanitary systems, which can significantly increase operating costs in wastewater treatment (Scheller *et al.*, 1994; Anderson, 1996; NCSPA, 1989).

Glossary of Terms

Durability: Durability is the ability of a pipe to withstand, to a satisfactory degree, the effects of service conditions to which it is subjected (Bealey, 1987). Or simply, it is the ability of a pipe to resist wear and decay.

Service Life: Service life is defined as the number of years of relatively maintenance-free performance (Ring, 1984; NCHRP, 1978). According to this definition, service life does not equal the number of years to failure.

Failure: There is no widely agreed-upon definition for failure of a buried pipe, short of collapse, as pointed out in the reports by the National Cooperative Highway Research Program (NCHRP, 1978) and the Civil Engineering Research Foundation (CERF, 1992). Deterioration constitutes failure when a weakened structure collapses, or threatens the stability of soil backfill or embankment. Although a pipe may have reached its service life, there may be many more years until failure. However, the level of maintenance/ repair required after reaching service life may be such that replacement is justified well before failure occurs.

5.1.1 Concrete Pipe

Cracking is considered an indicator of durability and performance for concrete pipe. If a reinforced-concrete pipe develops a 0.3-mm crack after installation, it has neither failed nor is it in danger of imminent collapse. Such a crack is an indication that the pipe and reinforcement are performing as intended. The criterion of a 0.3-mm crack is intended only as a quality control measure and was never intended as a criterion of field performance (Spangler and Handy, 1973: ASTM C 76M-90; CAN/CSA-A257.2-M92; ACPA, 1988). Surface cracks up to 0.6 mm wide that do not completely penetrate a pipe wall with a minimum of 25-mm cover over the reinforcement has the same durability characteristics as an uncracked pipe (ACPA, 1988). Autogenous healing is the ability of concrete to repair itself or to heal cracks in the presence of moisture. Such a chemical process involves the formation of calcium carbonate crystals. This formation occurs when the carbon dioxide in the surrounding soil, air and water carbonates the free calcium oxide in the cement, and the calcium hydroxide liberated by the hydration of the tricalcium silicate of the cement. Precipitation of these insoluble calcium carbonate crystals onto the crack surface eventually fills and seals the crack (ACPA, 1988; OCPA, 1986). Except for cases where no distresses are apparent and cases where the pipe has collapsed, the performance criteria based on crack width for gravity concrete pipe have not been well established. In current practice, the distress criteria for concrete pipe are determined by the engineer, and they vary from project to project.

From the point of view of serviceability, the development of cracks with active leakage can be considered the end of maintenance-free performance, because repairs are warranted to stop infiltration or exfiltration. From the point of view of structural stability, a cracked section of an unreinforced-concrete pipe, with or without active leaks, may be stable as compression arches. On the other hand, unsymmetrical, external loading or internal surcharge loading may cause the otherwise stable arch sections to collapse. A cracked, reinforced-concrete pipe is not a concern, unless corrosion of the reinforcing steel occurs at crack locations (Spangler and Handy, 1973). Such a condition will cause spalling of the concrete cover and eventually reduce pipe strength.

Distress modes of concrete pipe include cracking, disjointing, loss of material and integrity due to corrosion, abrasion and collapse.

5.1.2 Corrugated Steel Pipe

The criteria for the durability of storm and sanitary sewers of corrugated steel pipe have been related to the time of structural collapse. They have also been related to the time when perforations occur, which may require maintenance and repair. Leakage results in contamination or instability of the backfill or embankment material. Each of the foregone criteria is applicable to situations that exist in certain geographic locations (NCSPA, 1989). As discussed earlier in this section, perforations in a storm drain are not as critical as their occurrence in a sanitary sewer. A traditional performance limit on deflection of corrugated steel pipe is 5% of either the horizontal or vertical diameter. This limit is based on earlier observations of imminent collapse at deflections of about 25% (Spangler and Handy, 1973; Chambers and Heger, 1980; Wolf and Townsend, 1970; ASCE/WPCF, 1982). By limiting the deflection to 5%, a factor of safety of 4 is achieved (Spangler and Handy, 1973; Prevost and Kienow, 1988a).

Distress modes of corrugated steel pipe include yielding, buckling, seam opening, loss of material and integrity because of corrosion and abrasion. Apart from the obvious failure form of collapse, a culvert pipe that has a corroded or abraded invert or a pipe that is severely pitted and perforated may still be capable of supporting its backfill and cover. It does, however, constitute a high risk and warrants prompt repair or replacement (NCHRP, 1978).

5.1.3 Plastic Pipe

Like corrugated steel pipe, deflection is the performance criterion. The magnitudes of allowable deflections, as percentages of nominal inside diameters of pipe, should be based on the following performance limits (Chambers and Heger, 1980):

Function. Large deflections near or at the pipe spigot may cause loss of seal of gasketed joints. Information on allowable deflections for this case should be available from the manufacturer. The reduced diameter associated with excessive deflection may restrict standard-sized cleaning equipment. The reduced area of a deflected pipe also reduces flow capacity, but no significant loss occurs until deflections are very large and unacceptable for other reasons.

Loss of pavement support. If a buried pipe deflects excessively, it can result in pavement deterioration because of loss of subgrade support.

Strength. The deflection of a pipe indicates flexural stress and strain in the pipe wall. Thus, by selecting a deflection limit for a plastic pipe, an approximate limit is indirectly placed on stress and strain. Since excessive stress or strain may result in failure, the deflection limit is related to the strength limit of the pipe.

For PVC pipe, the accepted performance limit is a final deflection of 7.5% (Uni-Bell, 1990; ASTM D 3034-93; Howard, 1996; Moser *et al.*, 1977). According to Uni-Bell (1990), a factor of safety of 4 is incorporated into this performance limit. Some case studies show that localized and large deformation (20% ovalization) occurred in PVC drain pipes, without service interruption (Alferink *et al.*, 1995; Jeyapalan and Boldon, 1986). Others show failure of plastic pipes at deflections of less than 5% (Kienow and Prevost, 1988). For HDPE pipe, a 5% deflection limit is used for acceptance after 30 days of installation, although PE pipe in gravity applications can usually withstand much larger deflections without impairment (PPI, 1996; Howard, 1996). The 5% performance limit is also used for long-term deflection (Howard *et al.*, 1995). The current Canadian codes specify a maximum deflection limit of 7.5% for plastic pipe in general (CAN/CSA-B182.1-M92; BNQ, 1983; MEQ, 1989; Nazar, 1988). Prevost and Kienow (1988b) recommend the use of a 5% deflection limit for all flexible pipe with regard to pipe stability. Texas Natural Resource Conservation Commission (1993) specifies a 5% short-term deflection limit for all flexible pipes. Greenbook (1994) gives the allowable deflection limit as a function of pipe size for all plastic pipe except ABS or PVC composite pipe. The larger the diameter, the smaller the specified limit. For plastic pipes with nominal diameters in the range of 305 mm (12 in.) to 760 mm (30 in.), the allowable short-term deflection limit is 4%; while for pipes with diameters between 760 mm (30 in.) and 1525 mm (60 in.), the limit is reduced to 3%. It should be pointed out that in current practice, the deflection limit for plastic pipe is mainly determined by the engineer (Watkins and Reeve, 1980) and can vary from project to project.

Jeyapalan and Boldon (1986) give the following reasons for limiting an initial deflection of 5% for flexible pipe:

- If the pipe is poorly restrained laterally (e.g., poor compaction or weak embedment materials used), excessive deflection may occur, leading to reverse curvature at the crown.
- Flexible plastic pipe will continue to deflect with time, due to its creep characteristics (as discussed in Section 2 of this report). Limiting initial deflection to 5% helps to prevent excessive deformation over the design life of the pipe.
- It will maintain a substantial factor of safety against structural collapse.
- Excessive deflection could cause infiltration and exfiltration to occur as joints become unsealed.

Distress modes of both PVC and HDPE pipes include wall buckling, wall crushing, excessive ring deflection, cracking or uplift of the pipe (Watkins and Reeve, 1980; Hanna and Cucheran, 1991; Grieco and Johnson, 1991; Kirby, 1981; Moore, 1993). Collapse and inverse curvature caused by external loading are considered failure of plastic pipe (Uni-Bell, 1990).

5.2 Culvert Distress and Service Life

Culverts have been used extensively under highways for more than 75 years. Although many studies on their performance have been carried out, predicting their service life is difficult because of the constant evolution in the materials used, the coatings and the different variables that affect erosion, corrosion or structural support (Ring, 1984; Meacham *et al.*, 1982). Culvert pipes used today have a wide range of diameters and thicknesses to fulfill their functional requirements. Failures in culverts usually occur as a result of sulfate attack, corrosion, abrasion, or improper selection of backfill (Hadipriono *et al.*, 1988).

According to Hurd (1984), influences on culvert durability are

- pipe size, material type, and thickness of pipe wall;
- type of pipe protection;
- depth and velocity of dry-weather flow;
- presence of abrasive materials;
- amount and type of sediment or debris, or both;
- pH of water, streambed, and embankment; and
- electrical resistivity of water, streambed, and embankment.

5.2.1 Concrete Culverts

Concrete culvert failures occur because of underdesign, movement of the surrounding soil, acid attack in water with pH values below 4.5, sulfate attack or improper backfill (Heger, 1994; Hill and Laumann, 1994; Meacham *et al.*, 1982). The results are shown as flexural cracking, cracks in diagonal and radial tension, or loss of material and impermeability (Heger, 1994; Hill and Laumann, 1994; Hadipriono *et al.*, 1988). As discussed in the preceding sections, concrete pipe may be subject to chemical and biological attack, abrasion, and potential freeze-thaw deterioration. Concrete culverts located in an environment where runoffs have a pH of lower than 5.0 (Hurd, 1985) deteriorate faster, as do concrete culverts submerged in stagnant water for a long time (Jacobs, 1984). Based on its own data and a review of other studies, the Missouri Highway and Transportation Department (1987) concludes that reinforced-concrete culverts have a service life of at least 100 years for soil conditions encountered in that state. The Ohio Department of Transportation (Meacham *et al.*, 1982) studied 545 concrete culverts within its boundaries and developed a service-life prediction equation that takes water pH and pipe slope into consideration. For a water pH >5.0, the predicted service life of concrete culvert is over 100 years, regardless of pipe slope. Jacobs (1984) reports that the service life of concrete culvert in Maine is between 65 and 70 years. In acidic-flow sites, with the water pH between 4.5 and 7.0, the minimum predicted service life of concrete culvert is 50 years (Hurd, 1985). Hadipriono *et al.* (1988) studied the data from the Ohio Department of Transportation and arrived at an expected service life of 86 years for concrete culverts. They cautioned that the prediction equation would be of value for cost analysis, but not for the service-life prediction of a particular concrete culvert. Potter (1988) concludes in his study that the service life of concrete culvert increases from 50 years to over 100 years, when the pH increases from 4 to 9.

5.2.2 Corrugated Steel Culverts

Corrugated steel culverts have a great sensitivity to their environments, and their service life depends mainly on the abrasion and the corrosion process (Missouri Highway and Transportation Department, 1987; Hurd, 1984, 1986; Noyce and Ritchie, 1979). They fail primarily by corroding through the lower flow line section of the pipe (invert), and the corrosion progresses slowly along the culvert

(Beaton and Stratfull, 1962; Jacobs, 1984; Jackson, 1990). The pH and resistivity (conductivity) are referenced most often as factors responsible for influencing the service life of corrugated steel culverts. There are also a few documented cases on longitudinal uplift of corrugated steel culverts (Lohnes *et al.*, 1995; Ohio Concrete Pipe Association, 1979). In other cases, the cause of distress was attributed to a combination of compaction and the *in situ* soil type, such as the effect of compaction on silty soils (Sehn and Duncan, 1995).

In an analysis by the Missouri Highway and Transport Department (1987), based on 525 reports, the newest corrugated steel pipe that had to be replaced was 20 years old, and the oldest was 59 years, with an average age of 46.6 years. Potter (1988) estimates that the service life of corrugated steel culverts with coating is 50 years. Without coating, corrugated steel culverts may have a service life of only 26 years (Jacobs, 1984). Based on a study of 685 corrugated steel culverts, the Ohio Department of Transportation (Meacham *et al.*, 1982) reported that the average service life for bituminous coating is 3.16 years, while it is 18.7 years for bituminous coating plus invert paving. Jackson (1990) indicates that corrugated steel culverts experienced significant pitting after 25 years of service. NCSPA (1989) cited the result of a survey conducted by the American Iron and Steel Institute in 1978. According to it, the age of corrugated steel culverts ranged between 16 and 65 years, with an average of 33 years. CORRPRO (1991) examined the durability of corrugated steel pipe on the soil side only, and concluded that corrugated steel pipe has a soil-side service life of over 100 years. CORRPRO also pointed out that the water side (inside) of corrugated steel pipe is subject to erosion, corrosion and wetting/drying cycles, all of which affect service life of corrugated steel pipe. Riveted steel pipes with aluminized coating protection (Type 2), installed between 1952 and 1953, were evaluated to determine their performance and durability (Bednar, 1996). Based on this study, the service life of aluminized steel pipe is projected to be well beyond 50 years. The coating condition indicates service life of over 75 years (Bednar, 1996).

5.2.3 HDPE Culverts

Plastic culverts are mainly made of corrugated HDPE. Improper installation was identified as the main cause of problems with HDPE culverts (Hurd, 1986). A 9-year performance review of a culvert 610 mm (24 in.) in diameter was conducted in Ohio by Goddard (1990). In this review, the culvert was used to drain very acidic mine runoff. Its pH ranged from 2.5 to 4.0. The acidic flow had no significant effect on the HDPE culvert. As shown in many investigations, plastic pipes can perform well under high soil cover, if they are properly installed (Watkins, 1990; Selig, 1995; Hashash and Selig, 1990; Walton, 1989; Watkins and Shupe, 1990). However, the service life of HDPE culverts can, at best, only be estimated because they have existed for such a relatively short time. CPPA (1995) estimated a minimum service life of 70 years for corrugated polyethylene pipe.

5.3 Distresses and Service Life of Sewer Pipes

In sanitary sewer pipes, leakage is more consequential than in drainage culverts and storm sewers because infiltration/inflow of groundwater can significantly increase the volume of wastewater for treatment. Exfiltration of effluent from such sewer pipes, on the other hand, is likely to cause contamination of the groundwater. Factors that affect the durability of sewer pipe include (Bjorklund and Janson, 1981):

- differential settlements,
- poor-quality pipes,
- corrosion,
- poor workmanship,
- external damage,
- improper design,
- chemical reaction, and
- movement of the ground due to freeze and thaw.

5.3.1 Concrete Sewer Pipe

Concrete sewer pipe may be subjected to deterioration from various conditions, including sulfate attack, abrasion, and corrosion of the reinforcing steel by acid and chlorides (Potter, 1988), as discussed in the preceding sections. The corrosive effects of H_2S promoted by excessive deposition can be minimized by regular cleaning of the sewer lines with a chlorine solution (Beck, 1996). Corrosion may also be prevented by providing a chemically inert lining or by injecting air, oxygen, or hydrogen peroxide into the sewage (Kienow and Pomeroy, 1978). Installation of the pipes along a steeper slope, thus obtaining a faster flow, is another way of minimizing corrosion.

The service life of reinforced-concrete sewer pipe varies significantly. There are few detailed studies about the durability of concrete sewer pipe, although concrete culverts have been studied extensively. This lack of study is probably due to difficult access to sewer lines. Some concrete sewer pipes were reported to have lasted over 99 years (PCA, 1968).

5.3.2 Plastic Sewer Pipe

Deflection is a factor indicative of the performance of flexible pipe. As stated by Thoda *et al.* (1995), in this case for HDPE pipe, deflection can be caused by the type of installation, the type and density of backfilling soils, area of backfilling, and thickness of sand bedding.

Other investigations related to collapse, crushing of pipe insulation, external squeezing and bursting in one case that was attributed to excess pore pressures developed during freeze-back, were reported (Hanna and Cucheran, 1991; Grieco and Johnson, 1991; Kirby, 1981).

The allowable strain permits HDPE pipe to undergo much higher deflection than other flexible pipe materials (Petroff, 1984). In a Swedish study, PE pipe was shown to have a much lower failure rate than PVC (Bjorklund and Janson, 1981). Although lower in strength for static-pressure conditions, the ductility and toughness of PE allows it to better endure cyclic stressing caused by transient or cyclic pressures (Mruk, 1987). But, it has been demonstrated that vertical elongation of very flexible pipes can occur during compaction (Jeyapalan and Boldon, 1986). A flexible pipe embedded in stiff soil can deform in an odd, rather than elliptical shape, causing high strains within the pipe wall (Jeyapalan and Boldon, 1986). Thinness of the wall together with low pipe stiffness can lead to local buckling.

A survey conducted by the College of Engineering at Utah State University on PVC pipe found that 50% of the problems occurred in the first year (Moser and Kellogg, 1993). The authors also stated that damage due to UV exposure appeared to be minor.

As already remarked, there is a general lack of information about the service life for plastic pipe (Erdos, 1990). This is because plastic pipe was first used in the mid-1960s (Moser *et al.*, 1991), whereas concrete pipe has been around for over a century (ACPA, 1988). Eckstein (1987) reported a case study that involved testing of a 100-mm (4-in.) diameter PVC water pipe after 22 years in the ground. The pipe passed all the requirements and specifications existing at the time of testing. Bauer (1990) reported another case study on a 15-year-old, 250-mm (10-in.) diameter PVC sewer pipe. Again the PVC pipe passed all the requirements and specifications. Walton and Elzink (1989) studied the performance of PVC pipes with diameters ranging from 244 to 457 mm installed in England, Denmark, the Netherlands, and Scotland. The age of the PVC pipes varied from 13 years to 20 years. All the pipes studied performed well. Long-term deflections of those PVC pipes were reported to vary from 2% to 14%. The estimated service life of PVC pipe is over 50 years (Alferink *et al.*, 1996).

Deformation measurements of 12-year-old HDPE sewer pipes were taken in West Germany (Gaube and Mueller, 1981). The pipes with diameters ranging from 800 to 1400 mm were installed and backfilled with compacted and uncompacted sandy and silty soils. The 10-year measured deformations of the pipes, in compacted backfills, were reported to vary from 1.5% to 2.6%, while those in uncompacted backfills were reported to vary from 4.5% to 8.8%. The projected maximum 50-year deformations were 4.5% for compacted and 13.5% for uncompacted backfill. It has been concluded that long-term deformation of 6% (the German requirement) over 50 years will not be exceeded, provided the proper soil and filling conditions are applied.

5.4 Summary

5.4.1 Performance Criteria

The performance criteria or limits, and distress modes are different for different pipes. The performance criteria are different for storm sewers and sanitary sewers. Furthermore, different organizations and researchers have different performance criteria. There is a lack of accepted definitions for service life, durability and failure, and of accepted standards in rating, inspection and maintenance. As a result, individual judgment plays an important part in determining the need for repair or replacement of existing pipes.

5.4.2 Service Life

The service life of both concrete and corrugated steel culverts is reported to vary in wide ranges, whereas the service life of plastic pipes is purely an estimate. Figure 4 shows the service life for the studied pipes, based either on reported data or on reported estimates, regardless of the soil and groundwater environment in the vicinity of the pipes.

Table 5.1 summarizes the performance criteria and limits for various pipes considered in this study.

Table 5.1. Performance criteria and limits of various pipes

Type of Pipe	Performance Criteria and Limits
Reinforced-concrete pipe	collapse development of leaky cracks wall crushing joint separation
Corrugated steel pipe	collapse perforation buckling 5% deflection exceeded joint separation
PVC	collapse inverse curvature buckling 7.5% deflection exceeded wall crushing joint separation
HDPE	collapse inverse curvature buckling 5% deflection exceeded wall crushing joint separation

6 Summary and Discussion

A literature review has been conducted with respect to pipe materials, their performance and durability. Material, design, installation procedure, resistance to chemical and biological attack, and resistance to abrasion, impact and fire have major effects on the pipe performance. In this section, the effects of those factors are summarized. In addition, pipe durability and protective measures for concrete sewer pipe are discussed.

6.1 Effect of Various Factors

6.1.1 Design

Design approaches and criteria differ between rigid concrete pipe and flexible (corrugated steel, PVC and HDPE) pipe, as shown in Table 2.3. Rigid pipe supports the earth load by its inherent strength, whereas flexible pipe relies on the lateral support and arching effect of soil to support the earth load. As a result, embedment is considered part of the load-

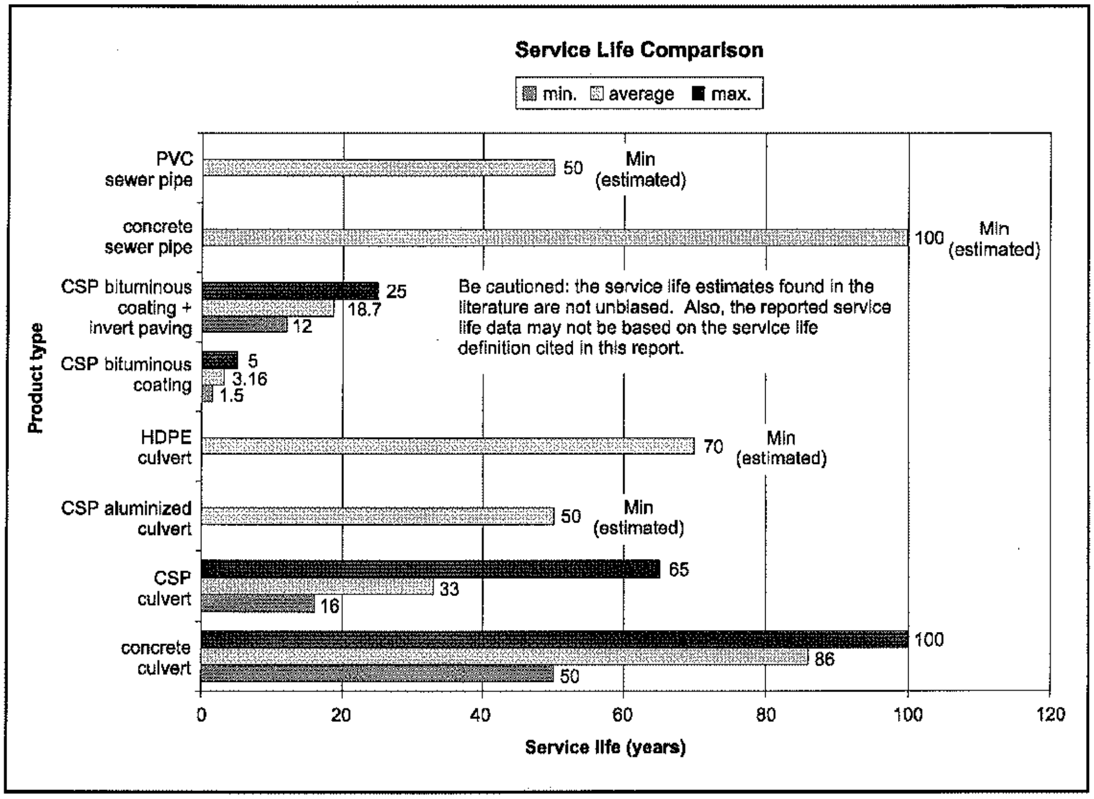

Figure 4. A comparison of the service life of studied pipes

carrying system for flexible pipe. Also, the difference in behaviours between rigid concrete pipe and flexible pipe results in a different governing design criterion, namely, strength for rigid and deflection for flexible pipes. Long-term creep characteristics are unique to plastic pipe.

6.1.2 Installation

Pipe installation is critical in achieving the specified short- and long-term performance. While easier to handle, flexible pipes such as CSP, PVC and HDPE require a wider trench and more careful backfilling and compaction. Too little compaction results in insufficient lateral support, and the pipe will deform beyond specified limits under full external loading. Too much compaction during installation, in turn, may cause excessive deformation, squaring, or even collapse of the pipe. Concrete pipe is heavier and requires more joints because the sections are shorter than for flexible pipes. Installed rigid concrete pipe is less sensitive to re-excavation and backfilling than flexible pipe during connection or installation of adjacent underground utilities (see Table 3.4 for a summary of installation procedures for different pipes).

6.1.3 Chemical and Biological Resistance

In general, concrete and corrugated steel pipes are more vulnerable to chemical and biological attack than PVC and HDPE pipes. High resistance to chemical attack is the most attractive feature of plastic pipe. Corrosion susceptibility of the four pipes is summarized in Table 4.3.

6.1.4 Physical Resistance

Physical resistance to abrasion and fire also plays an important role in the performance and durability of sewer and culvert pipes. Resistance to abrasion and fire of the four pipes is compared in Table 4.4.

6.2 Performance Criteria and Service Life

6.2.1 Performance Criteria

For different pipes, the performance criteria or limits and distress modes are different. The performance criteria also differ between storm drains and sanitary drains. Furthermore, different organizations and researchers have different performance criteria. This points to a lack of accepted definitions for service life, durability and failure, and of accepted standards in rating, inspection and maintenance. As a result, individual judgment plays an important part in determining the need for repair or replacement of existing pipes. Table 5.1 summarizes the performance criteria and limits for various pipes under this study.

6.2.2 Service Life

The service life of both concrete and CSP culverts is reported to vary widely, whereas the service life of plastic pipe is only an estimate. Figure 4 shows the service life for the studied pipes, based either on reported data or on reported estimates, regardless of the soil and groundwater environment in which the pipes are installed. Caution is warranted about the reported service life data. They may not be based on the same service life definition cited in this report.

6.3 Discussion about Pipe Durability

Durability is just one of many factors that determine the selection and use of pipe products for storm and sanitary sewer applications. And durability itself is influenced by a range of factors, as shown and reviewed in this report. To ensure satisfactory long-term performance, the design engineer must understand the advantages and disadvantages of different pipe products. Site conditions (such as the chemical characteristics of soil and groundwater), pipe slope, and abrasion characteristics of the carried fluid are critical factors. So is the selection of embedment materials and quality of installation; they are of utmost important in ensuring satisfactory and long-lasting performance. The literature indicates that no matter how well the pipe-soil system is designed, and how good the backfill quality, poor installation and poor workmanship will no doubt result in premature distresses or even failures. Pipe manufacturers need not only supply quality products, they should also be actively involved in quality assurance during installation of their products.

The most suitable pipe material chosen for a particular project depends on (Jeyapalan *et al.*, 1997):

- native geotechnical conditions,
- corrosion aggressiveness of the site,
- flow characteristics and abrasion potential,
- bedding and backfill requirements,
- ease of construction,
- quality control and assurance,
- surface stability requirement,
- seismic requirement,
- material availability,
- initial and long-term cost considerations,
- maintenance,
- future expansions and connections, and
- vandalism or security.

Some factors that are more important at one site may not be so at another site. For example, where the flow has a low pH (say, less than 3), corrosion is critical and highly corrosion-resistant materials, such as plastic pipe, or coated or lined reinforced-concrete pipe, would be considered more appropriate. Where corrosion is not critical, initial cost estimates and life-cycle cost analysis should be carried out to determine the most viable material option. Where there is a high risk of fire, highly fire-resistant pipes, such as concrete pipe, are better choices than plastic pipe. A single pipe that is suitable for all practical applications and conditions in urban infrastructure remains yet to be developed.

6.4 Protective Measures for Concrete Pipe

Although concrete pipe has been used for various applications in storm and sanitary sewer systems for over a century, and is still considered one of the viable choices for most applications, its susceptibility to chemical and biological attack has been well recognized. To mitigate the corrosion of concrete sewer pipe and to prolong its service life in corrosive environments, many protective measures have been developed and applied. (Parker, 1951; Thornton JR., 1978; Kienow and Kienow, 1991). In general, these protective measures include:

- design modifications, and
- coatings and liners.

6.4.1 Concrete Design Modification

Proper concrete design can increase the chemical resistance of the concrete and reinforcement. This can be achieved by adherence to the following:

- Control of the concrete quality, especially permeability. High cement content, a low water/cement ratio, proper compacting and curing, and control of cracking during service are among the important factors that contribute to the low permeability of concrete.

- The use of special cements such as sulfate-resistant cement or polymer-modified concrete. For severe sulfate attack, ASTM Type V Portland cement (<5% C_3A) is often used (Lawrence, 1990, 1992). The Canadian equivalent is Type-50 cement.

- The use of blended cements, e.g., Portland blast-furnace slag cements with more than 70% slag, and Portland-pozzolan cements with at least 25% highly siliceous pozzolan such as volcanic ash, calcined clay, and low-calcium fly ash. Under chemical attack, blended cements perform better than unblended cements, Furthermore, the incorporation of a pozzolan or slag helps to reduce the permeability of the cement hydration product by a pore-refinement mechanism (Hooton and Emery, 1990; Frearson and Higgins, 1982; Samanta and Chatterjee, 1982; Hughes, 1985).

- Increase of the thickness of cover over the steel reinforcement to give more protection to the reinforced steel, as well as to the concrete pipe.

6.4.2 Coatings and Liners

Coatings, wrappings and liners provide good protection to concrete pipe against physical, chemical and biological attacks (Kienow and Kienow, 1991). The most common applications are briefly described below:

Thin polymeric, plastic, bitumastic and other organic coatings can be applied to pipe by dipping, flood-coating, brush painting, spraying or electrostatic deposition (Pankhurst, 1973; Kawakami *et al.*, 1989). Wrappings of prefabricated tape or bands of material are sometimes applied to pipe or joint areas by hand or machine, either spirally or longitudinally, in discrete layers to provide good protection. Precautions are taken both at the factory and in the field to ensure that there are no "holidays" in coatings and wrappings. Adequate supervision is very important because, apart from errors in application, wrapped or coated pipes can be mechanically damaged during pipe-laying.

Lining materials are often used as protective materials (Kalenborn, 1989; Kienow and Kienow, 1991; Kienow and Pomeroy, 1979). As opposed to adhesion, liners depend on mechanical locking with the rigid pipe to remain in position, so that the pipe surface is protected. PVC, HDPE and bitumen liners have been used in Canada and the US for protecting sanitary sewers of precast-concrete pipe.

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